

**ASSESSING THE WAVE CLIMATE VARIABILITY ALONG WITH LARGE
SCALE CLIMATE INDICES IN THE PACIFIC OCEAN**

M.Sc. THESIS

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Department of Civil Engineering

Coastal Science and Engineering Programme

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**PASİFİK OKYANUSU DALGA İKLİMİ DEĞİŞKENLİĞİNE BÜYÜK
ÖLÇEKLİ İKLİM İNDİSLERİNİN ETKİSİNİN DEĞERLENDİRİLMESİ**

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To my parents,

FOREWORD

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ABBREVIATIONS

ENSO	: El Nino / Southern Oscillation
NAO	: North Atlantic Oscillation
WAM	: Wave Model
NOAA	: National Oceanic and Atmospheric Administration
ECMWF	: European Center for Medium-Range Weather Forecasts
CDIP	: Coastal Data Information Program
COADS	: Comprehensive Ocean-Atmosphere Data Set
Nino 3.4	: East Central Tropical Pacific SST
SST	: Sea Surface Temperature
PDO	: Pacific Decadal Oscillation
PNA	: Pacific North America
MEI	: Multivariate ENSO Index
CWT	: Continuous Wavelet Transform
XWT	: Cross-Wavelet Transform
NE	: North East
ONI	: Oceanic Nino Index
NC	: North Carolina
ESRL	: Earth System Research Laboratory
PSD	: Physical Sciences Division
DOG	: Derivative of a Gaussian
CORREL	: Correlation

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ASSESSING THE WAVE CLIMATE VARIABILITY ALONG WITH LARGE SCALE CLIMATE INDICES IN THE PACIFIC OCEAN

SUMMARY

Wave variability and connections with climate indices were analyzed in the Pacific Ocean. Monthly significant wave data from five stations were used. The dominant modes of significant wave height variability were determined by continuous wavelet transform. The wave climate variability along with large scale climate indices was investigated at 5 buoy stations located in the Pacific Ocean. The monthly mean values of H_s indicates that the summer seasons have the lower wave height and the winter season have the higher wave height.

The trend test analysis on both significant wave heights H_s and climate indices by using the XLSTAT software and Mann-Kendall trend test method demonstrated that there is no trend in buoy stations and the indices of Niño 3.4, PNA, MEI, PDO, except SOI that there is a significant increasing in this index.

In the monthly correlation between significant wave heights and climate indices it is found that, there is weak correlations between significant wave height and MEI index with a correlation coefficient of $r = 0.32$ in the Santa Maria region (46011) and with a correlation coefficient of $r = 0.31$ in the Papa region (46006). Also, there is weak correlation between H_s and PNA index with a correlation coefficient of $r = 0.43$ in the buoy (46011) which is located in the region of Papa. The cross correlation analysis also is done over the data and it is figured out that there is a strong correlation between climate waves and climate indices in compare of normal correlation.

The wavelet power spectrum was determined from the data of length of 38, 37, 36, 32, and 18 years in buoys 46002, 46005, 46006, 46011, and 46059, respectively. This analysis illustrated that there is a significant power at annual scale during whole measurement period of significant wave height in 4 stations. And, also in 46011, there is a significant power at annual scale during the whole measurement period of significant wave height except between 1989-1991 years. Furthermore, the power spectrum analysis illustrated that there is an annual cycle in stations and climate indices.

Cross-wavelet power spectrum is used to measure the relationship between two time series. This spectrum was employed to explore the possible effects of ENSO events on the wave climate variation. The results of the cross-wavelet transform analysis in this study demonstrated that there is anti-phase behavior between the significant wave heights and climate indices in 46002 and 46011 buoys. Also, it is found that wave climate variabilites have in-phase behavior with PDO index in 46005, and in-phase behavior with SOI in 46006 and 46059.

PASİFİK OKYANUSU DALGA İKLİM DEĞİŞKENLİĞİNE BÜYÜK ÖLÇEKLİ İKLİM İNDİSLERİNİN ETKİSİNİN DEĞERLENDİRİLMESİ

ÖZET

İklim değışikliğı okyanuslardaki fiziksel olaylar ve bunlardan dalga iklimi üzerinde farklı yönlerden etkili olmaktadır. Dalga ikliminin etkilendiğı husaslardan başlıca hava ve okyanus sıcaklığının artışı, yağış paternlerinin değışimi ve kayması, fırtınalar ve kuraklıklarda meydana gelen sıklık ve şiddet değışimi, akışların azalması ve denizlerde su seviyesinin günden güne yükselmesi olarak belirlenebilir.

Pasifik okyanusunun dalga iklimi üzerinde etkili olan uzun surely ısınma ve soğuma döngülerinin Pasifik okyanusunun orta ve doğu ekvator bölgelerinde etkili oldukları bilinmektedir. ENSO olgusunun sıcak fazı olarak adlandırılan El Niño olayı esnasında ABD'nin güney sahilleri ve Güney Amerika'nın bazı bölgelerinde yağışlı mevsimlere sebep olurken, Batı Pasifik bölgesinde kuraklığa neden olmaktadır. La Niña ise ENSO olgusunun soğuk fazı olarak adlandırılır ve iklimsel olarak El Niño olayının karşıtı şeklinde etkiler oluşturmaktadır.

Atmosfer ısınmasının El Niño ve La Niña olgularının sıklığı, süresi ve şiddeti üzerinde etkilidir. Nitekim atmosferin ısınması sonucunda ısının okyanusa transfer olması okyanuslarda soğuk ve sıcak dönemler arasındaki sıcaklık farkına yol açmaktadır.

El Niño olgusu küresel hava koşulları ve okyanuslarda ve özellikle balıkçılık üzerinde belirgin etkilere sahiptir. NOAA'nın belirttiğine göre orta ve doğu tropic Pasifik bölgesinde suların periyodik olarak ısınması olarak tanımlanan El Niño olgusu ortalma her 2 ila 5 yılda bir meydana gelip ve genellikle 12 ay süresince devam ettiği söylenmektedir.

El Niño'nun oluşturacağı etkiler okyanus ısınmasının şiddeti ve genişliği ve yılın hangi zaman diliminde meydana geldiğı gibi birçok faktöre bağlıdır. Genel görüşün tersine El Niño olgusunun tüm etkilerinin olumsuz olmadığı yanı sıra bu olgunun Atlantik'de kasırgaların aktifleşmesi üzerinde pozitif etkiler oluşturduğu söylenebilir. Ayrıca bu olgunun etkileri altında ABD'nin güneydoğusundaki kurak bölgelerde kış mevsimlerinin yağmurlu geçmesi ve kuzey kısımlarında ise ağır kış şartlarının önlenmesi olumlu etkiler olarak gözlemlenmiştir. Bunlara ilave olarak Florida'da medana gelen büyük yangınların riskinin azalması söylenebilir.

El Niño'nun negatif etkilerinden ise California'da kış fırtınalarının zararı ve ABD'nin güney kısımlarında fırtınaların azalmasını söylemek mümkündür. Ayrıca geçmişte meydana gelmiş bazı El Niño olgular Orta ve Güney Amerika'da taşkınlar ve zemin kaymalarına ve İndonezya'da ise kuraklığa sebep olmuşlar.

Bir El Niño olgusu belirgin bir şekilde okyanusun batı sahilindeki üretkenliği azaltmaktadır. Bu durum bu olgunun sebep olduğu derin suların yukarıya doğru pompalanması ile soğuması ve dolayısı ile beslenme açısından zengin olan suların azalması ile açıklanmaktadır. Bu besin kaynakları hareketli deniz besin ağını

oluşturmakta ve bu kaynakta meydana gelen azalmalar çeşitli kuşlar, balıklar ve diğer deniz canlılarının hayatını olumsuz yönde etkileyebilir.

Bu bilgiler ışığında Pasifik okyanusunda dalga iklimi El Niño Kuzey Salınımı (ENSO) gibi büyük ölçekli iklim değişikliği olgularından etkileneceği görülmektedir. Bu durum dalga iklimini etkileyen büyük ölçekli atmosferik olaylarının iyi anlaşılması ve değerlendirilmesi kıyı mühendisleri açısından büyük önem taşımaktadır.

Bu tez çalışmasının ana hedefi Pasifik okyanusunda 37, 36, 32 ve 18 yıl sürelerinde aylık belirgin dalga yüksekliği değişimi ve ENSO verilerine dayanarak sinoptik ölçekte belirgin dalga yüksekliğinin baskın durumlarının belirlenmesidir. Büyük ölçekli bir iklim olgusu olan ENSO olgusunun ekvatoriyel Pasifik bölgesinde dalga iklimi üzerindeki etkileri sürekli dalgacık ve çapraz dalgacık analizleri ile değerlendirilmiştir.

Bu çalışma kapsamında Pasifik okyanusunda dalga iklimi değişimi büyük ölçekli iklim göstergelerine dayanan 5 farklı şamındıra ölçüm istasyonunun yüksek çözünürlü verilerine dayanarak analiz edilmiştir. Bu bağlamda Pasifikokyanusunda yerleştirilen 46002'no.lu istasyonunun 1975-2012; 46005 no.lu istasyonunun 1976-2012; 46006 no.lu istasyonunun 1977-2012; 46011 no.lu istasyonunun 1981-2012 ve 46059 no.lu istasyonunun 1994-2012 yılları arasındaki ölçülen değerleri ele alınmıştır. Analizler WAM dalga modelinin MATLAB, XLSTAT ve EXCEL programlarından yararlanarak yapılmıştır.

5 istasyon için aylık belirgin dalga yüksekliği, Niño 3.4, PDO, MEI, SOI, ve PNA göstergelerinin verileri NOAA'dan elde edilmiştir.

Yapılan istatistiksel analizlerin sonucu korelasyon katsayısı göz önünde bulundurulduğunda belirgin dalga yüksekliği ve 5 iklim göstergesi arasında herhangi bir ilişkinin görülmediğini yansıtmaktadır.

Aylık ortalama H_s değerlerin belirlenmesi için H_s değerleri her ay için ayrı ayrı zamana bağlı olarak regresiyona tabii tutulmuştur. Tüm regresiyon sonuçları %95'lik güven seviyesi ile istatistiksel olarak kabul edilebilir sayılmışlardır. Sonuçlara göre farklı mevsimlerde farklı belirgin dalga yüksekliği şablonlarının görülmesi mümkündür. Bu doğrultuda yaz aylarında belirgin dalga yüksekliği değişimleri minimum olurken, kış aylarında bu değişim büyük yükseliş şeklinde karşımıza çıkmaktadır.

Mann-Kendall Trend Testi ile XLSTAT programı kapsamında yapılan trend analizleri hem belirgin dalga yüksekliği hem iklim göstergelerinde herhangi bir eğilimli değişimin söz konusu olmadığını göstermektedir.

46002 no.lu istasyon için 37 yıllık; 46005 nolu istasyon için 36 yıllık; 46006 no.lu istasyonu için 35 yıllık, 46011 nolu istasyon için 32 yıllık ve 46059 no.lu istasyon için 18 yıllık verilerinin sürekli dalgacık dönüşümleri MATLAB programı vasıtasıyla yapılmıştır. Analizler tüm 5 şamandıradaki belirgin dalga yüksekliği ve iklim göstergeleri ölçümlemlerinde yıllık bazda belirgin bir kuvvetin oluştuğunu göstermektedir. Buna göre MEI için 1938-1989 yılları arasında 45-60 aylık dönemde, 1989-1997 yılları arasında 58-64 aylık dönemde; Nano 3.4 için 1983-1991 yılları arasında 45-60 aylık dönemde, 1991-1997 yılları arasında 58-64 aylık dönemde, 1997-2001 yılları arasında 32-68 aylık dönemde; PNA için 1979-1984 yılları arasında 35-48 aylık dönemde; SIO için 1982-1984 yılları arasında 26-30 aylık dönemde, 1981-1989 yılları arasında 48-62 aylık dönemlerde, 1991-1999 yılları arasında 120-200 aylık dönemde, 1996-1998 yılları arasında 32-35 aylık dönemde ve 2008-2009 yılları

arasında 30-34 aylık dönemde belirgin kuvvet tespit edilmiştir. Ayrıca PDO için herhangi bir belirgin kuvvet görülmemiştir.

Çapraz dalgacık analizini sonuçları belirgin dalga yüksekliği (H_s) ve göstergeler arasında karşı-faz davranışının aynı-faz davranışından daha çok olduğu yönündedir. Buna göre 46002 no.lu istasyonda 1983-1989 yılları arasında 45-60 aylık dönemde, 1989-1997 yılları arasında 58-64 aylık dönemde ve 1997-1999 yılları arasında 45-60 aylık dönemde belirgin kuvvet gözlemlenmiştir. 46005 no.lu istasyonda 1983-1991 yılları arasında 45-60 aylık dönemde, 1991-1997 yılları arasında 58-64 aylık dönemde ve 1997-2001 yılları arasında 32-64 aylık dönemde belirgin kuvvet görülmüştür. 46006 no.lu istasyonda PDO'da herhangi bir belirgin kuvvet gözlemlenmemişken 46011 no.lu istasyonda 1979-1984 yılları arasında 35-84 aylık dönemde ve 1986-1991 yılları arasında 48-64 aylık dönemde belirgin kuvvet tespit edilmiştir. 46059 no.lu istasyonda 1982-1984 yılları arasında 26-30 aylık dönemde, 1981-1989 yılları arasında 45-62 aylık dönemde, 1991-1999 yılları arasında 120-200 aylık dönemde, 1996-1998 yılları arasında 32-35 aylık dönemde ve 2008-2009 yılları arasında 30-34 aylık dönemde belirgin kuvvet gözlemlenmiştir.

Sinoptik ölçekli baskın değişim periyotları ölçülmüş belirgin dalga yüksekliği verilerinin kullanımı ile açıklanmıştır. Dalgacık kuvvet spektrumları her yıl için belirlenmiştir. Bu doğrultuda spektrumlarda özellikle ENSO yılları esnasında nispeten büyük bir yiliçi değişimi görülmüştür. ENSO'nun dalga yüksekliğinin değişimi üzerinde oluşturacağı etkilerin azaltılması amacıyla belirgin dalga yüksekliği ENSO göstergeleri ile etkileşimli olarak dalgacık analizlerinde kullanılmıştır. Şamandıralarda aylık bazda ölçülen H_s zaman serilerinde 46002, 46005 ve 46006 istasyonlarında artma ve 46059 istasyonunda azalma eğilimi gözlemlenirken 46011 istasyonunda herhangi bir eğilim görülmemiştir.

Bu durum daha önce H_s verileri üzerinde yapılmış Mann-Kendall trend analizinin sonuçlarıyla (herhangi bir trend olmadığı) örtüşmemektedir. Aylık ortalama H_s değerlerinde yaz aylarında minimum değişim oranı görülürken kış aylarında maksimum değişim oranı söz konusudur. Ayrıca dalga yüksekliğinin dalgacık kuvvet spektrumları güçlü El Niño yılı, La Niña yılı ve normal yıllar için araştırılmıştır. Buna göre dalgacık kuvvetinin ENSO yılları esnasında normal yıllara nazaran büyük periyotlu ve yüksek ölçekli belirgin kuvvetler gibi değişimler görülmüştür. Bu doğrultuda sonuçların ENSO aktivitelerinin okyanus dalga iklimi etkilediğini gösterdiği için ENSO göstergeleri belirgin dalga yüksekliği tahminlerinde kullanılabilecektir. Ancak büyük ölçekli iklim göstergeleri ve sinoptik ölçekli dalga yüksekliği değişimleri arasında yüksek derecede bir non-lineer ilişki söz konusudur.

1. INTRODUCTION

Climate changes play a crucial role in oceans and affect nearly every aspects of ocean processes and patterns including wave climates. Increasing ocean temperatures and air, converting rainfall patterns, changing intensities and frequencies of storms and drought, decreasing streamflows, rising sea levels are the causes, which is influencing the wave climates in the oceans.

In the surface waters of the central and eastern equatorial Pacific Ocean, there is a long duration of warming and cooling cycle that affects on wave climates in the Pacific Ocean. El Niño is the warm phase of ENSO that brings wetter conditions across the southern tier of the United States and parts of South America, and drought in the Western Pacific. La Niña is the cold phase of ENSO that global climate impacts of La Niña tend to be opposite those of El Niño.

The warming of the atmosphere have an impact on the frequency, duration, and severity of El Niño and La Niña events. As the atmosphere warms, heat, would be transferred to the oceans, with the potential for increased extremes between cold and warm periods.

El Niño has a significant affect on global weather, ocean states. El Niño, which is the period of warming of central and eastern tropical Pacific waters, occurs every two to five years and generally lasts about 12 months.

El Niño's impacts is depend on a diversity factors, such as intensity and extent of ocean warming, and the time of year. Opposite of popular belief, all of the El Niño's effects are not negative. On the other side, El Niño can help to suppress Atlantic hurricane activity. In the United States, it typically brings beneficial winter precipitation to the arid Southwest, less wintry weather across the North, and a reduced risk of Florida wildfires.

The negative impacts of El Niño's included damaging winter storms. El Niño, also produce severe flooding and mudslides in Central and South America, and drought in Indonesia.

El Niño event may significantly reduce ocean productivity by limiting weather patterns that cause upwelling in the ocean.

According to the above description wave climate in the Pacific Ocean is open to possible effects of large scale climate events such as El Niño Southern Oscillation (ENSO). Therefore, it is important to understand the effect of large scale atmospheric events on wave climate for ocean engineering operations.

1.1 Purpose of Thesis

The main purpose of this the thesis is to investigate the Pacific Ocean significant wave heights variability along with the large scale climate indices to determine the dominant modes of significant wave height variability on the synoptic scale. The effect of ENSO which is a large scale event occurred in equatorial Pacific on wave climate is evaluated using continuous wavelet and cross wavelet analysis.

1.2 Literature Review

Bauer (2001) applied 13 years ECMWF wind data with period from 1981 to 1993 to study the mean sea state and its dominant modes of variability in the North Atlantic and in the North Sea. The wind data was done with the WAM model which analyses from the atmosphere model of European Centre for Medium Range Weather Forecast. Reasonable high correlation were found between significant wave height in the North Atlantic and NOA index, especially during the winter season and a low correlation were found in monthly data. The 6 h time series of wind and wave height data shared a considerable contributions of different strength from synoptic scale variability, mainly in winter. On the other hand, by reanalyzing the dominant periods of the synoptic-scale variability and measured data of wind speed and significant wave height from 1981 to 1993 with 1 year sections representing anomalies from the seasonal cycle show relatively large interannual changes which The dominant period of variability derived from the 13 time series varies between 8 and 54 days.

Dodet et al., (2009) investigated wave climate variability in the North-East Atlantic Ocean over the last six decades by using 57 year hindcast (1953-2009) which all of the data were taken from NOAA. In this study they have used spectral wave model forced by analyzing space and time wave climate variability. The model was forced with 6-h wind fields from the NCEP/NCAR reanalysis project. In the first analysis by using

large and long-period waves for winters and smaller and shorter-period for summers, a strong seasonal variability was revealed. On the other hand, they found that the northward shift of the storm path in summer results in wave directions norther than in winter, also they found a strong positive correlation between H_s and the NAO index at northern latitude ($R=0.91$), a negative correlation at southern latitude ($R=-0.6$), and no significant correlation for mean wave direction Mwd.

Peter et al., (2010) have analyzed on wave data collected in deep water off the coast of the U.S. Pacific Northwest, mainly by two buoy stations of NOAA data buoy center to in detail the progressive increase in wave heights off the coast of the and the range of methodologies available for incorporating that increase into the extreme value assessments employed in engineering and coastal hazard applications. In this study buoy data have been analyzed to wave climate by employing various time-dependent extreme value models for directly computing the progressive increase in the 25 to 100 year projections. By analyzing the data both the linear regressions of increasing annual averages and the evolving probability distribution of the SWH climate, demonstrating the non-stationarity of the Pacific Northwest wave climate, translate into substantial increases in extreme value projections, important in coastal engineering design and in quantifying coastal hazards. On the other hand, the most intense month in the wave record, in terms of monthly mean values, was February 1999 with a 5.4 m monthly that the result of four major storms systems that contributed to significant erosion along PNW beaches. They also have developed a combined time series by filling the data gaps in buoy 46005 with data from buoy 46002 which is obtained 29 out 32 years good data year criterion.

Dragani et al., (2010) have studied on south-eastern south American continental shelf between 32°S and 40°S with the data of (1996-2006) and topex (1993-2001) for determining a feasible increase in wind wave heights. The numerical wave model (SWAN) is used for this study for real approximation of wave parameters. According to implementation of ncep/ncar surface wind with period of 1971-2005, they found that the yearly H_{rms} has a considerable trends in the both inner continental shelf and contiguous ocean with the most observation between 1991 to 2000 and 1981 to 1990 in a period if ten years by considerable difference (0.20m, 9%) which is occur in the 34°S - 48°W and also positive values over the entire model domain. Ruggiero et al. (2000) studied the long-term variability of deep-water wave buoy data in the U.S.

Pacific Northwest. They found that the annual averages of deep-water significant wave heights have increased at a rate of approximately 0.015 m/yr since the mid-1970s.

Gower (2002) studied time series of sea surface temperature, wind speed, and significant wave height H_s from meteorological buoys off the west coast of Canada and the adjacent United States which are considered by interannual variability and trends. It was found that both the wind speed and the wave height data show an increasing trend with more statistical significance. Mendez et al. (2006) used a time-dependent statistical model to estimate long-term positive trends in the frequency and intensity of severe storm waves. Menendez et al. (2008) used hourly significant wave height data to estimate the seasonal-to-interannual variability of extreme significant wave height. They found a modest but statistically significant positive relationship between extreme wave heights and El Niño variability for the buoys in the eastern North Pacific off the US West Coast.

Mackay et al. (2010) investigated the effect of interannual and climatic changes in wave climate on the predictability of long-term mean ocean wave energy is examined for an area off the north coast of Scotland.

2. STUDY AREA AND DATA

2.1 Study Area

Wave statistics (heights and periods) and some meteorological information have been measured in the North Pacific using wave buoys and sensor arrays. Measured time series of significant wave height with monthly resolution were used in this study. The data have been collected by the National Oceanic and Atmospheric Administration (NOAA), which is operated by the National Data Buoy Center (NDBC), and by the Coastal Data Information Program (CDIP) of Scripps Institution of Oceanography. Data from 5 stations located in deep sea and coastal areas were analyzed. The location map of the study area is shown in (Figure 2.1). Unimpaired data sets are preferred for the analysis. Missing data was completed by using the nearest bouys data for each of the station.

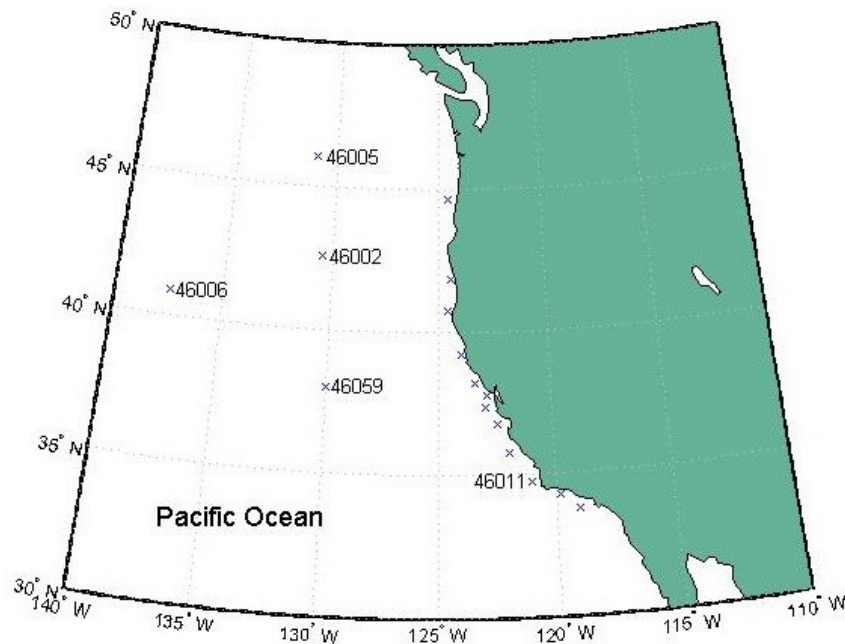


Figure 2.1 : Location map of study area

The buoys cover the region between the the Gulf of Alaska and Southern California, and are located in both deep and shallow water. Three of the buoys have been in operation since the min to late 1972s, while the remaining two have data that extend back to the early 1980s, and 1990s. (Table 2.1) describe the general characteristics of each buoy site, including the water depth, location, and period of operation. As can be seen from (Figure 2.1) the chosen sites are distributed relatively evenly along the West Coast of North America.

Table 2.1 : Wave buoy sites characteristics.

Station	Location	Water Depth (m)	Watch Circle Radius (m)	Period of Operation
46002	Oregon (Lat. 42.57 N; Long -130.46 W)	3525	3144.6	1975 - 2012
46005	Washington (Lat. 46.05 N; Long -131.02 W)	2779.8	2541.8	1976 - 2012
46006	PAPA (Lat. 40.89 N; Long -137.45 W)	4023	3603.7	1977 - 2012
46011	Santa Maria (Lat. 34.88 N; Long -120.87 W)	188.4	204.83	1981 - 2012
46059	California (Lat. 37.98 N; Long -130.00 W)	4599.4	3344.9	1994 - 2012

2.2 National Oceanic and Atmospheric Administration (NOAA)

National Oceanic and Atmospheric Administration is a science-based agency which has the responsibility to predict changes in the oceanic and atmospheric environments and living marine resources, and to provide related data, information, and services to the public, industry, the research community, and other government agencies. The main purpose of NOAA's efforts is providing information about operational environmental warning, forecast, prediction, assessment, and information management responsibilities. In this study all of the significant wave heights data and climate indices data has taken from this agency site (NOAA, 2014).

2.3 El Niño / southern oscillation (ENSO)

The climate pattern of El Niño, explains the unusual warming of surface waters along the tropical west coast of South America. El Niño has an impact on ocean temperatures, speed and strength of ocean currents, and local weather from Australia to South America. The phenomenon of El Niño occurs irregularly at two- to seven-year intervals, and it is not a regular cycle in the sense that ocean tides are. With the Southern Oscillation, El Niño occurs simultaneously. The Southern Oscillation is a change in atmospheric pressure over the tropical eastern and western Pacific Ocean. In the eastern tropical Pacific (El Niño) when coastal waters become warmer, atmospheric pressure diminishes in the eastern Pacific and increases in the western Pacific (Southern Oscillation). El Niño events are indicated by sea-surface temperature increases of more than 0.5 degrees Celsius for at least five successive three-month seasons. Figure 2.2 shows the intensity of El Niño events varies from weak temperature increases about 2-3 degrees Celsius with only moderate local effects on weather and climate to very strong increases 8-10 degrees Celsius associated with worldwide climatic changes (NOAA, 2014).

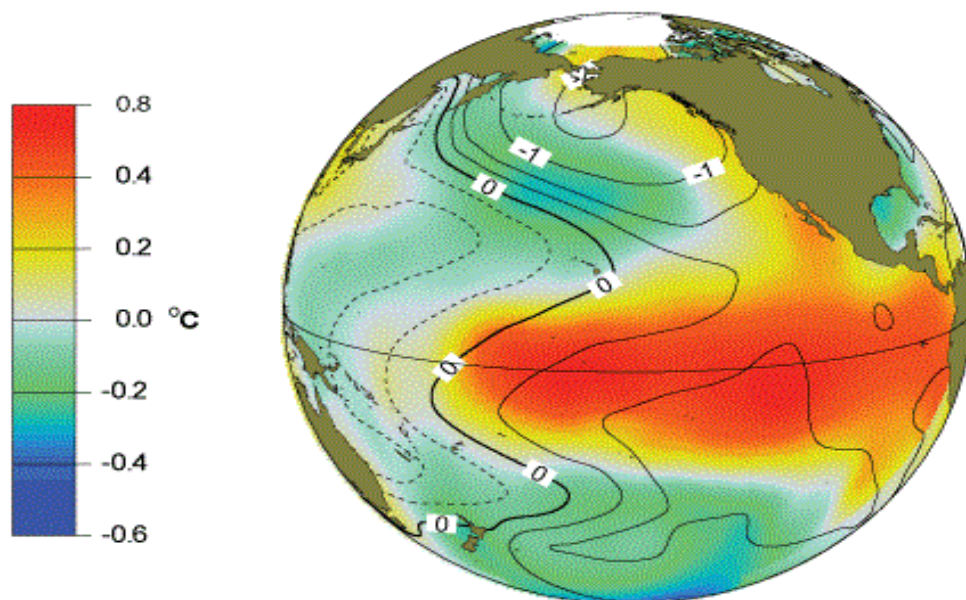


Figure 2.2 : A warm phase ENSO (El Niño). The spatial pattern of anomalies in sea surface temperature (shading, degrees Celsius) and sea level pressure (contours).

2.4 East central tropical Pacific SST (Niño 3.4)

El Niño (La Niña) is a phenomenon in the equatorial Pacific Ocean characterized by a five consecutive 3-month running mean of sea surface temperature (SST) anomalies in the Niño 3.4 region that is above (below) the threshold of $+0.5^{\circ}\text{C}$ (-0.5°C). This standard of measure is known as the Oceanic Niño Index (ONI), (Figure 2.3). El Niño have classified based on SST anomalies exceeding with a pre-selected threshold in a certain region of the equatorial Pacific. The Niño 3.4 region is the most used commonly region. The most commonly used threshold is a positive SST departure from normal greater or equal than to $+0.5^{\circ}\text{C}$. This region encompasses the western half of the equatorial cold tongue region, it provides a good measure of important changes in SST and SST gradients that result in changes in the pattern of deep tropical convection and atmospheric circulation. The criteria, that is often used to classify El Niño episodes, is that five consecutive 3-month running mean SST anomalies exceed the threshold. An SST anomaly of $+0.5^{\circ}\text{C}$ in the Niño3.4 region is sufficient to reach threshold from late March to mid-June. During the remainder of the year a larger SST anomaly, up to $+1.5^{\circ}\text{C}$ in November-December-January, is required in order to reach the threshold to support persistent deep convection in that region (NOAA, 2014).

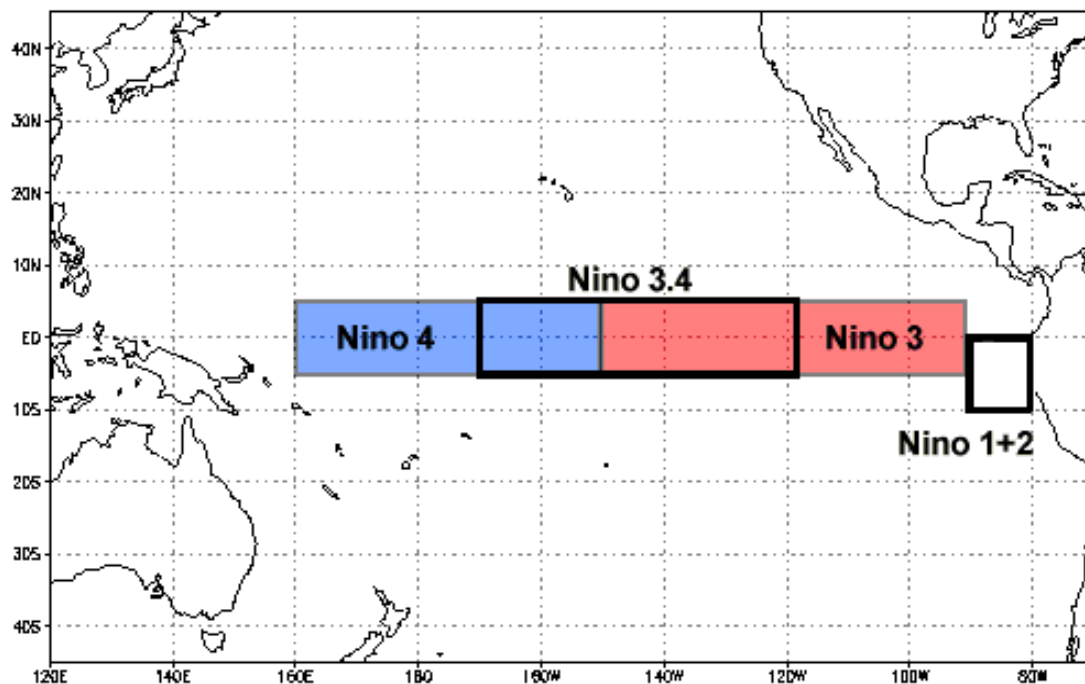


Figure 2.3 : Niño regions.

2.5 Southern oscillation index (SOI)

The Southern Oscillation Index SOI is an index that is based on the difference in air pressure between Darwin and Tahiti. The SOI is one measure of the large-scale fluctuations in air pressure occurring between the western and eastern tropical Pacific (i.e., the state of the Southern Oscillation) during El Niño and La Niña episodes (Figure 2.4). A consistently negative SOI often indicates the presence of an El Niño and a consistently positive SOI often indicates the presence of a La Niña. A La Niña occurs when sea surface temperatures to the north of Australia are warmer than normal and trade winds across the Pacific Ocean strengthen. This is the opposite of an El Niño, and subsequently, the results of both La Niña and El Niño are also opposite. Sustained positive values of the SOI above +8 are typical of a La Niña episode. They are associated with stronger Pacific trade winds and warmer sea temperatures to the north of Australia. Waters in the central and eastern tropical Pacific Ocean become cooler during this time. Together these give an increased probability that eastern and northern Australia will be wetter than normal (NOAA, 2014).

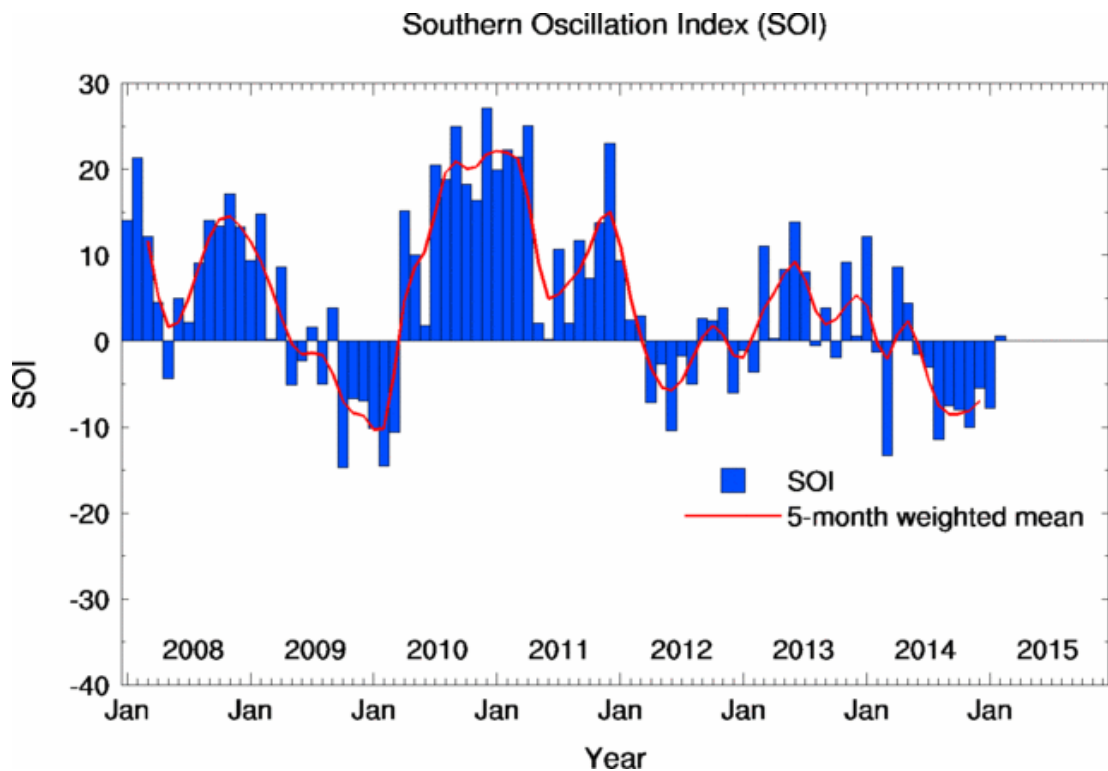


Figure 2.4 : Monthly value of the southern oscillation index in recent years.

2.6 Pacific north American index (PNA)

The Pacific North American (PNA) is one of the most recognized, influential climate patterns in the Northern Hemisphere mid-latitudes beyond the tropics. It consists of anomalies in the geopotential height fields (typically at 700 or 500mb) observed over the western and eastern United States. It is important to note that the PNA has been found to be strongly influenced by the El Niño-Southern Oscillation (ENSO) phenomenon. The positive phase of the PNA pattern tends to be associated with Pacific warm episodes (El Niño), and the negative phase tends to be associated with Pacific cold episodes (La Niña). According research at the Shanghai Cooperation Organization a positive PNA, especially during an El Niño year, produces an above average number of winter weather events in North Carolina (NC) (NOAA, 2014).

2.6.1 Positive (PNA)

The The positive phase consists of above normal geopotential heights over the western U.S. and below normal geopotential heights over the eastern U.S. This correlates to ridging over the western U.S., and deep troughing over the east. The net result of the height field pattern in this phase is that it forces cold air residing in Canada to plunge southeastward, which results in below normal temperatures over the eastern U.S. and above normal temperatures over the western U.S (Figure 2.5).

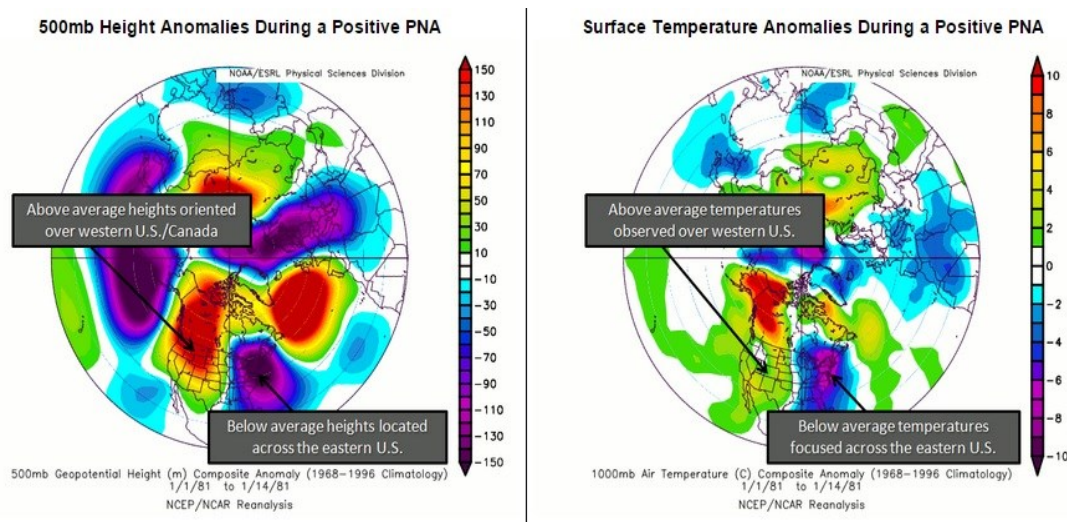


Figure 2.5 : Pacific north American index (Positive phase).

In the positive phase, above average geopotential heights oriented over the western U.S., and below average geopotential heights oriented across the eastern U.S. This results in warm air moving much farther north than normal over the western U.S., while cold, Canadian air is forced southward over the eastern U.S. resulting in below normal temperatures (NOAA, 2014).

2.6.2 Negative (PNA)

The negative phase features troughing and below normal geopotential heights (Geopotential height approximates the actual height of a pressure surface above mean sea-level) over the western U.S. and ridging with above normal geopotential heights over the eastern U.S. The result is below average temperatures for the western U.S., and above average temperatures over the eastern U.S (Figure 2.6).

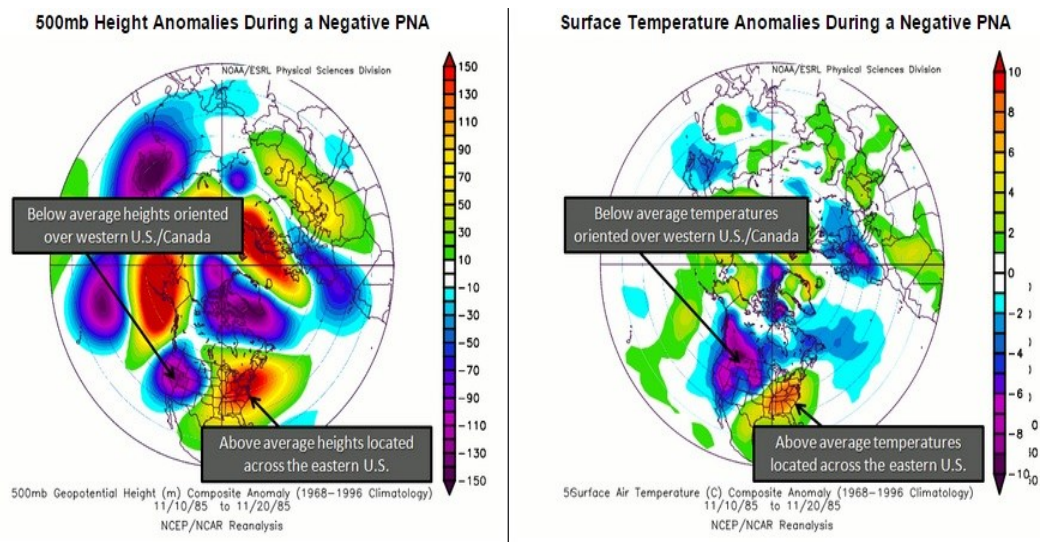


Figure 2.6 : Pacific north American index (Negative phase).

The negative phase of the PNA pattern features below average geopotential heights over the western U.S. and above average geopotential heights across the eastern U.S. This results in deep troughing over the western U.S., which allows cold air from western Canada to drain southward into this region. In the eastern U.S., warm, moist air from the Gulf of Mexico and the Atlantic Ocean is able to travel northward, often resulting in above normal temperatures and more conditions that are humid.

2.7 Multivariate ENSO index (MEI)

Multivariate ENSO Index (MEI), based on six main observed variables over the tropical Pacific is one of the best monitoring ENSO than the SOI or various SST indices, because the MEI integrates more information than other climate indices and it reflects the nature of the coupled ocean-atmosphere system better than either component. On the other hand, it is less vulnerable to occasional data glitches in the monthly update cycles. Sea-level pressure (P), zonal (U) and meridional (V) components of the surface wind, sea surface temperature (S), surface air temperature (A), and total cloudiness fraction of the sky (C) are the six variables. These observations have been collected and published in comprehensive ocean-atmosphere data set (COADS) for many years. The MEI is computed distinctly for each of twelve monthly seasons (Dec/Jan, Jan/Feb,..., Nov/Dec). After spatially filtering the individual fields into clusters (Wolter, 1987), the MEI is calculated as the first unrotated Principal Component (PC) of all six observed fields combined. This is accomplished by normalizing the total variance of each field first, and then performing the extraction of the first PC on the co-variance matrix of the combined fields (Wolter and Timlin, 1993). In order to keep the MEI comparable, all seasonal values are standardized with respect to each season and to the 1950-93 reference period. The MEI is extended during the first week of the following month based on near-real time marine ship and buoy observations (courtesy of Diane Stokes at NCEP) summarized into COADS-compatible 2-degree monthly statistics at NOAA-ESRL PSD. The cold ENSO phase represents with negative values of the MEI, a.k.a. La Niña, and positive MEI values represent the warm ENSO phase (El Niño). (Figure 2.7) shows a sample of MEI time series which has taken from NOAA (NOAA, 2014).

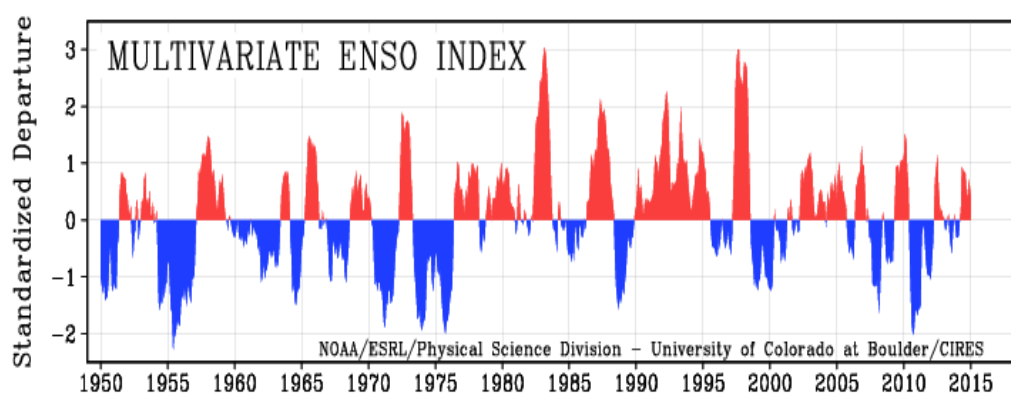


Figure 2.7 : Multivariate ENSO Index of recent years.

2.8 Pacific decadal oscillation (PDO)

The PDO is defined as the leading empirical orthogonal function (EOF) of mean November through March SST anomalies for the Pacific Ocean to the north of 20N latitude. For the EOF calculation, the global mean SST anomaly was first removed for each month in order to reduce the influence of the long-term trends in the data. The extreme phases of the PDO have been classified as being either warm or cool when it is parallel with the ENSO phenomenon which as defined by ocean temperature anomalies in the northeast and tropical Pacific Ocean. The PDO has a positive value 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 and the PDO has a negative 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. (Figure 2.8) shows the positive and negative phase of PDO. Two main characteristics distinguish PDO from El Niño/Southern Oscillation (ENSO): first, 20th century PDO events persisted for 20 to 30 years, while typical ENSO events persisted for 6 to 18 months; second, the climate fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signature exist in the tropics – the opposite is true for ENSO. Several independent studies find evidence for both cool and warm of the PDO cycles in the past century; cool PDO regimes prevailed from 1890-1924 and again from 1947-1976, while warm PDO regimes dominated from 1925-1946 and from 1977 through (at least) the mid 1990's (NOAA, 2014).

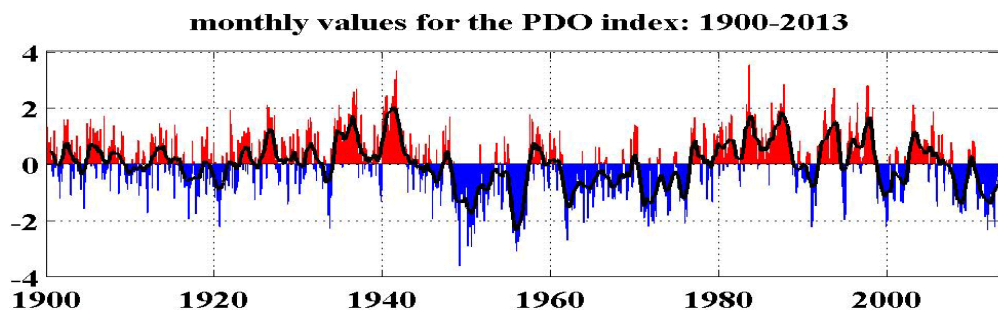


Figure 2.8 : Typical wintertime sea surface temperature (colors), sea level pressure (counturs) and surface windstress (arrows) anomaly patterns during warm and coll phase of PDO.

3. METHODOLOGY

3.1 Wavelet analysis

Wavelet analysis is a method to decompose a time series into time-frequency space. This view gives interesting insights into the dominant modes of a time series and how those modes vary over time.

Wavelets are clear tools for harmonic analysis. Due to their many uses, the word ‘wavelet’ comes with different connotations to users in different fields. The wavelet transform is a recent advance in signal processing that has attracted much attention since its theoretical development in 1984 by Grossman and Morlet (1984). Its use has increased rapidly as an alternative to the Fourier Transform (FT) in preserving local, non-periodic, multi-scaled phenomena. It has advantage over classical spectral analysis, because it allows analyzing different scales of temporal variability and it does not need a stationary series. Thus, it is appropriated to analyze irregular distributed events and time series that contain non-stationary power at many different frequencies. Then, it is becoming a common tool for analyzing localized variations of power within a time series.

3.1.1 Motivation

For more understanding the theory of the wavelet analysis I start with an example that applies the tools that will be explained later on. I figure out that this is an unorthodox way to start my study, but I hope that this will help to motivate the reader to invest some time in the rest of this thesis.

The possibility of tracing transitional changes across time most is one of the most common argument to legitimize the use of wavelet analysis over spectral analysis. It is estimating the power spectrum as a function of time. To illustrate this, consider the following highly stylized experiment with simulated data. I generated 37, 36, 35, 32, and 18 years of monthly data according to the following data generating process:

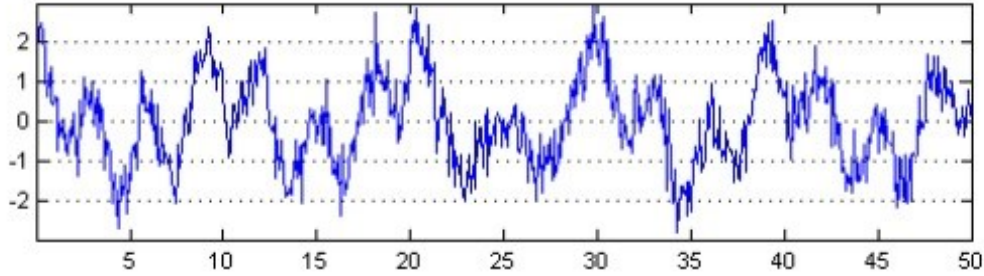
$$y_t = \cos\left(\frac{2\pi}{p_1}t\right) + \cos\left(\frac{2\pi}{p_2}t\right) + \varepsilon_t \quad t = \frac{1}{12}, \frac{2}{12}, \dots, 37, 36, 35, 32, 18, \quad (3.1)$$

Where $p_1 = 10$ and $p_2 = 5$, if $20 \leq t \leq 30$, and $p_2 = 3$, otherwise.

Equation (3.1) tells us that the time series y_t is the sum of two periodic components. The first periodic component represents a 10 year cycle, while the second periodic component shows some transit dynamics. In the beginning, it presents a 3 year cycle that, temporarily, changes to a 5 year cycle between the second and the third decades.

This change in the dynamics is nearly impossible to spot in Figure 3.1. Furthermore, if we use the traditional spectral analysis, the information on the transit dynamics is completely lost (Aguiar & Soares, 2011).

(a) Series $y_t = \cos\left(\frac{2\pi}{p_1}t\right) + \cos\left(\frac{2\pi}{p_2}t\right) + \varepsilon_t$



(b) Wavelet power spectrum

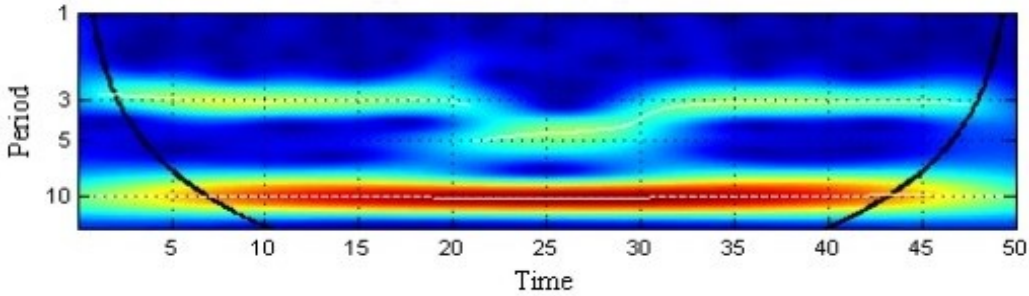


Figure 3.1 : a) $y_t = \cos\left(\frac{2\pi}{p_1}t\right) + \cos\left(\frac{2\pi}{p_2}t\right) + \varepsilon_t$. b) Wavelet power spectrum of y_t . The cone of influence, which indicates the region affected by edge effects, is shown with a thick black line. The color code for power ranges from blue (low power) to red (high power). The white lines show the maxima of the undulations of the wavelet power spectrum.

Figure 3.1b shows the wavelet power spectrum. On the horizontal axis, we have the time dimension. The vertical axis gives us the period. The power is given by the color. The color code for power ranges from blue (low power) to red (high power). Regions with warm colors represent areas of high power. The white lines show the maxima of the undulations of the wavelet power spectrum, therefore giving us an estimate of the cycle period. Both the red color and the black contour tell us that this is strong and statistically significant. We are able to spot the three year period cycle that occurs between time zero and 20, again, between time 30 and 50. Finally, we are also able to spot a yellow region between time 20 and 30, with the white stripes identifying the cycle of period five. This means that a cycle of roughly 5-year periodicity, relatively important in explaining the total variance of the time series and taking place between year 20 and 30, was hidden by the Fourier power spectrum estimate. It clearly illustrates that the big advantages of wavelet analysis over spectral analysis. While the Fourier transform is silent about changes that happen across time, with wavelets we are able to estimate the power spectrum as a function of time and, therefore, we do not lose the time dimension. The wavelet power spectrum is able to capture not only the 3-year and 10-year cycles, but also to capture the change that occurred between years 20 and 30.

3.1.2 Wavelets

There are several mathematical transformations that can be applied, among which the Fourier transforms are probably by far the most popular. However, the wavelet transform can be used to analyze time series that contain non-stationary power at many different frequencies (Torrence & Compo, 1998), because the wavelet analysis maintains time and frequency localization in a signal analysis by decomposing or transforming a one-dimensional time series into a diffuse two-dimensional time-frequency image, simultaneously. Then, it is possible to get information on both the amplitude of any “periodic” signals within the series, and how this amplitude varies with time. Examples of basic waves or mother wavelets, as they are known in the literature, are shown in Figure 3.2. These mother wavelets have the advantage of incorporating a wave of a certain period, as well as being finite in extent.

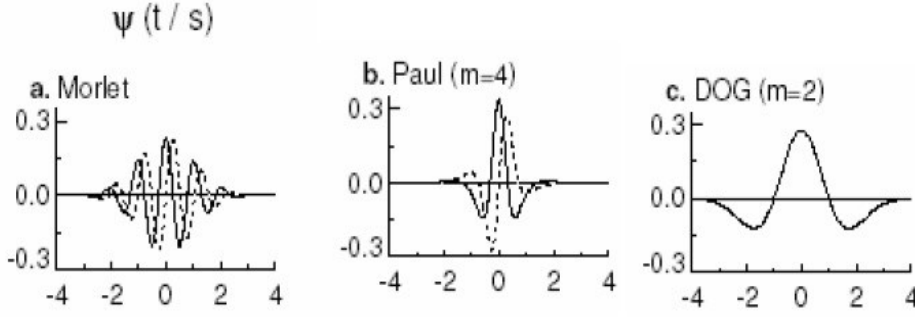


Figure 3.2 : Mother wavelets: (a) Morlet, real and imaginary parts in solid and dashed lines. Respectively; (b) Paul, with $m=4$; (c) DOG-Derivative of a Gaussian, with $m=2$.

The wavelet analysis always uses a wavelet of the exact same shape, only the size scales is up or down with the size of the window. In addition to the amplitude of any periodic signals, it is worth to get information on the phase. In practice, the Morlet wavelet shown in Figure 3.2. 1a is defined as the product of a complex exponential wave and a Gaussian envelope:

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\eta^2/2} \quad (3.2)$$

where $\Psi_0(\eta)$ is the wavelet value at non-dimensional time η and ω_0 is the non-dimensional frequency, equal to 6 in this study in order to satisfy an admissibility condition; i.e., the function must have zero mean and be localized in both time and frequency space to be “admissible” as a wavelet. This is the basic wavelet function, but it will be now needed some way to change the overall size as well as slide the entire wavelet along in time. Thus, the “scaled wavelets” are defined as:

$$\psi\left[\frac{(n'-n)\delta t}{s}\right] = \left(\frac{\delta t}{s}\right)^{1/2} \psi_0\left[\frac{(n'-n)\delta t}{s}\right] \quad (3.2)$$

where s is the “dilation” parameter used to change the scale, and n is the translation parameter used to slide in time. The factor of $s^{-1/2}$ is a normalization to keep the total energy of the scaled wavelet constant. We are given a time series X , with values of x_n at time index n . Each value is separated in time by a constant time interval δ_t . The wavelet transform $W_n(s)$ is just the inner product (or convolution) of the wavelet function with the original time series:

$$W_n(s) = \sum_{n'=0}^{n-1} x_{n'} \psi^* \left[\frac{(n' - n)\delta t}{s} \right] \quad (3.4)$$

where the asterisk (*) denotes complex conjugate.

By sliding this wavelet along the time series, a new time series of the projection amplitude versus time can be constructed. Finally, the "scale" of the wavelet can be varied by changing its width. Technical details used in different mother wavelets can be seen in appropriate literature (Torrence & Compo, 1998).

3.1.3 Morlet Wavelet

There are two popular continuous wavelet called the Mexican hat and the Morlet wavelet. The continuous wavelet influence the time and the scale resolution of the decomposition that is related to the frequency decomposition and this issue is the key issue to choice of the continuous wavelet method. There are differences between the Morlet wavelet and Mexican hat wavelet. For expecting a high frequency resolution the Morlet wavelet is the best method for this , because it is very well localized in scale and then in frequencies. In contrast, the Mexican hat wavelet has a good time localization due to it can isolate a single bump, but a poor frequency localization.

The Morlet wavelet have chosen for this thesis applications, $\varphi(t) = \pi^{-\frac{1}{4}} \exp(-i2\pi f_0 t) \exp\left(\frac{-t^2}{2}\right)$.

The relation between the frequency and the wavelet scale in some particular mother wavelets can be derived analytically (Meyers et al. 1993). For the Morlet wavelet this equivalence is done by:

$$\frac{1}{f} = \frac{4\pi a}{\omega_0 + \sqrt{2 + \omega_0^2}} \quad (3.5)$$

with ω_0 the central angular frequency of the wavelet ($\omega_0 = 2\pi f_0$). Then with ω_0 around 2π , the wavelet scale a is therefore inversely proportional to the central frequency of the wavelet $f \approx 1/a$. This greatly simplifies the interpretation of the wavelet analysis and one can replace, in all equations, the scale a by the frequency f or the period $p = 1/f$.

There are advantages of using the Morlet wavelet, because it has both real and imaginary parts and it allows to separation of the phase and the amplitude of the studied signal. As $W_x(f, \tau)$ is a complex number, we can write $W_x(f, \tau)$ in terms of its phase $\phi_s(f, \tau)$ and modulus $|W_x(f, \tau)|$. The phase of the Morlet transform varies cyclically between $-\pi$ and π over the duration of the component waveforms and is defined as:

$$\phi_s(f, \tau) = \tan^{-1} \frac{\text{Im}ag(W_x(f, \tau))}{\text{Re}al(W_x(f, \tau))} \quad (3.6)$$

For real-valued wavelet functions, the imaginary part is constantly zero and the phase is, therefore, undefined. Hence, in order to separate the phase and amplitude information of a time series, it is important to make use of complex wavelets. In this case, it is convenient to choose a wavelet $\psi(t)$ whose Fourier transform is supported on the positive real-axis only, i.e. is such that $\psi(\omega) = 0$ for $\omega < 0$. A wavelet satisfying this property is called analytic or progressive. When ψ is analytical and $x(t)$ is real, reconstruction formulas involving only positive values of the scale parameter s are still available; in particular, if the wavelet satisfies $0 < |K_\psi| < \infty$, where $K_\psi := \int_0^\infty \frac{\Psi^*(\omega)}{\omega} d\omega$, then one can use the following reconstruction formula, known as the Morlet formula, which is particularly useful for numerical applications:

$$x(t) = 2 \text{Re}al \left[\frac{1}{K_\psi} \int_0^\infty W_x(t, s) \frac{ds}{s^{3/2}} \right] \quad (3.7)$$

3.2 Continuous wavelet transform (CWT)

Wavelet spectrum analysis can be used to estimate dominant modes of many different frequencies which in this study is used for analyzing significant wave heights and indices. The power distribution obtained from the wavelet spectrum varies in time and scale. For wavelet transform, first a wavelet function $\psi(t)$ called mother wavelet is defined. Here, the wavelet power spectra are computed with the so-called Morlet function. The function is used for both wavelet decomposition and composition transforms (Torrence & Compo, 1998).

3.2.1 The wavelet analyzing of continuous wavelet transform

Let's consider a complex-valued function ψ satisfying the following conditions:

$$\int_{-\infty}^{\infty} |\psi(t)|^2 dt < \infty \quad (3.8)$$

$$c_{\psi} = 2\pi \int_{-\infty}^{\infty} \frac{|\psi(\omega)|^2}{|\omega|} d\omega < \infty \quad (3.9)$$

where ψ is the Fourier transform of ψ . The first condition implies finite energy of the function ψ , and the second condition, the admissibility condition, implies that if (ω) is smooth then $\psi(0) = 0$.

If ψ satisfies the conditions described above, then the wavelet transform of a real signal $s(t)$ with respect to the wavelet function $\psi(t)$ is and because a wavelet function $\psi(\eta)$ that changes with a non-dimensional time parameter η can be expressed as:

$$\psi(\eta) = \psi(\tau, s) = s^{-1/2} \psi\left(\frac{t-\tau}{s}\right) \quad (3.10)$$

where (t) is time, and τ and s are position and scale parameters, respectively. The successive wavelet transform (continuous wavelet transform, CWT) of finite energy signal or time series $x(t)$ is defined as:

$$W(\tau, s) = s^{-1/2} \int_{-\infty}^{+\infty} x(t) \psi^*\left(\frac{t-\tau}{s}\right) dt \quad (3.11)$$

where $*$ corresponds to the complex conjugate. High frequency components of the significant wave height series are determined from lower scales that correspond to a compressed wavelet. On the other hand stretched version of a wavelet gives the low-frequency behavior of series. Wavelet analysis has been used in several areas such as medicine (Rosso, et al., 2002) and traffic engineering (Huang, 2003).

The idea behind the CWT is to apply the wavelet as a band pass filter to the time series. The wavelet is stretched in time by varying its scale.

3.3 Cross-wavelet transform (XWT)

In many applications, one is interested in detecting and quantifying relationship between two non-stationary time series. The concepts of cross-wavelet power, wavelet coherency and wavelet phase-difference are natural generalizations of the basic wavelet analysis tools that enable us to appropriately deal with the time-frequency dependencies between two time series.

3.3.1 Cross-wavelet transform and cross-wavelet power

The cross-wavelet transform (XWT) of two time series, $x(t)$ and $y(t)$, with wavelet transforms $W_x(f, \tau)$ and $W_y(f, \tau)$ is simply the multiplication of the first complex wavelet transform with the complex conjugate of the second, first introduced by Hudgins, Friehe and Mayer (1993), is simply defined as:

$$W_{xy} = W_x(f, \tau)W_y^*(f, \tau) \quad (3.12)$$

where $f \approx \frac{1}{a}$ when $f_0 = 2\pi$ for the Morlet wavelet, and W_x and W_y are the wavelet transforms of x and y , respectively. Also the wavelet scale, a is inversely proportional to the central frequency of the wavelet (f_0).

The cross-wavelet power is:

$$(WXP)_{xy} = |W_{xy}| \quad (3.13)$$

while a wavelet power spectrum depicts the variance of a time series with times of large variance showing large power, the cross wavelet power of two time series depicts the covariance between these time series. Additionally, cross wavelet power has a known distribution of confidence levels which is proportional to the square root of the product of two X^2 distributions (Torrence & Compo 1998). This allow cross wavelet power to be used as a quantified measure of the similarity of power between two time series.

3.3.2 The complex wavelet coherency of cross-wavelet transform

In analogy with the concept of coherency used in Fourier analysis, given two time series $x(t)$ and $y(t)$ one can define their complex wavelet coherency Q_{xy} by:

$$Q_{xy} = \frac{|S(W_{xy})|}{\left[S(|W_x|^2) S(|W_y|^2) \right]^{1/2}} \quad (3.14)$$

where S denotes a smoothing operator in both time and scale; smoothing is necessary, because, otherwise, coherency would be identically one at all scales and times. Time and scale smoothing can be achieved by convolution with appropriate windows.

3.3.3 Wavelet coherency and phase-difference

The complex wavelet coherency can be written in polar form, as $Q_{xy} = |Q_{xy}|e^{i\phi_{xy}}$. The absolute value of the complex wavelet coherency is called the wavelet coherency and is denoted by R_{xy} , i.e.

$$R_{xy}(f, \tau) = \frac{|S(W_{xy}(f, \tau))|}{\left[S(|W_x(f, \tau)|^2) S(|W_y(f, \tau)|^2) \right]^{1/2}} \quad (3.15)$$

with $0 \leq R_{xy}(f, \tau) \leq 1$. The angle $\phi_{xy}(f, \tau)$ of the complex coherency is called the phase-difference (phase lead of x over y), i.e.

$$\phi_{xy}(f, \tau) = \text{Arc tan} \left(\frac{\text{Im ag} \left(S(W_{xy}(f, \tau)) \right)}{\text{Re al} \left(S(W_{xy}(f, \tau)) \right)} \right) \quad (3.16)$$

by slighting different definition of the formula (3.16) to $\text{Arctan} \left(\frac{\Im(S(W_{xy}(f, \tau)))}{\Re(S(W_{xy}(f, \tau)))} \right)$. In

this case, one has $\phi_{xy}(f, \tau) = \phi_x - \phi_y$, hence the name phase-difference. The advantage of this definition is that because the phase-difference is not affected by the smoothing choice, it is consistent with the individual phases.

A phase-difference of zero indicates that the time series move together at the specified time frequency; if $\phi_{xy} \in (0, \frac{\pi}{2})$, then the series move in phase, but the time series x leads y ; if $\phi_{xy}(f, \tau) \in (-\frac{\pi}{2}, 0)$, then it is y that is leading; a phase-difference of π (or $-\pi$) indicates as anti-phase relation (Figure 3.3).

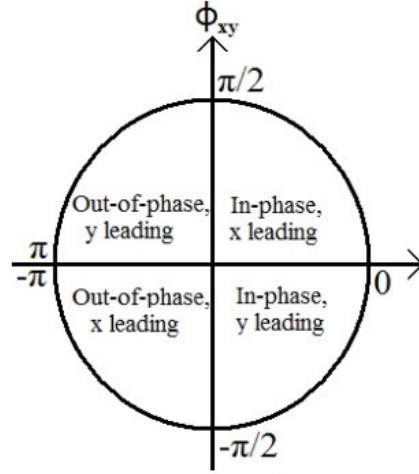


Figure 3.3 : Phase-difference circle

If $\phi_{xy}(f, \tau) \in \left(\frac{\pi}{2}, \pi\right)$, then y is leading; time series x is leading if $\phi_{xy}(f, \tau) \in \left(-\pi, \frac{\pi}{2}\right)$. This is illustrated in (Figure 3.3).

One can easily convert the phase-difference into the instantaneous time-lag between the two time series x and y :

$$(\Delta T)_{xy}(f, \tau) = \frac{\phi_{xy}(f, \tau)}{\omega(f)} \quad (3.17)$$

where $\omega(f)$ is the angular frequency that corresponds to the scale f .

3.4 Software requirements

The programs of thesis for this study were written in Matlab 2011b. The written programs is used for analyzing continuous wavelet transform and cross-wavelet transform.

3.5 Mann-Kendall trend tests analysis

For determining the rates over the time period of years between 1975-2012 years in the station of 46002, 1976-2012 in 46005, 1977-2012 in 46006, 1980-2012 in 46011, 1994-2012 in 46059, and also the periods operation of 1975-2012 in NINO 3.4, SOI, PNA, MEI, PDO, indices to determine if a series observation of a random variable is generally increasing, decreasing, and stable or no trend with time.

3.5.1 Test analysis

3.5.1.1 Calculation of the Mann-Kendall statistic(S)

The Mann-Kendall test is a non-parametric identifying trends in time series data. The test compares the relative magnitudes of sample data rather than the data values themselves (Gilbert, 1987).

One benefit of this test is that the data need not conform to any particular distribution. Moreover, data reported as non-detects can be included by assigning them a common value that is smaller than the smallest measured value in the data set. The procedure that will be described in the subsequent paragraphs assumes that there exists only one data value per time period. When multiple data points exist for a single time period, the median value is used. The data values are evaluated as an ordered time series. Each data value is compared to all subsequent data values. The initial value of the Mann-Kendall statistic, S, is assumed to be 0 (e.g., no trend). If a data value from a later time period is higher than a data value from an earlier time period, S is incremented by 1. On the other hand, if the data value from a later time period is lower than a data value sampled earlier, S is decremented by 1. The net result of all such increments and decrements yields the final value of S.

Let $x_1, x_2, \dots, x_n$ represent n data points where x_j represents the data point at time j.

Then the Mann-Kendall statistic (S) is given by:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sign}(x_j - x_k) \quad (3.18)$$

where:

$$\begin{aligned} \text{sign}(x_j - x_k) &= 1 \text{ if } x_j - x_k > 0 \\ &= 0 \text{ if } x_j - x_k = 0 \\ &= -1 \text{ if } x_j - x_k < 0 \end{aligned} \quad (3.19)$$

A very high positive value of S is an indicator of an increasing trend, and a very low negative value indicates a decreasing trend. However, it is necessary to compute the probability associated with S and the sample size, n, to statistically quantify the significance of the trend.

Kendall (1975, p55) describes a normal-approximation test that could be used for datasets with more than 10 values, provided there are not many tied values within the data set. The test procedure is as follows:

$$VAR(s) = \left[\frac{1}{18} n(n-1)(2n+5) - \sum_{p=1}^g t_p(t_p-1)(2t_p+5) \right] \quad (3.20)$$

Where n is the number of data points, g is the number of tied groups (a tied group is a set of sample data having the same value), and t_p is the number of data points in the p^{th} group.

The computational procedure for the Mann Kendall test considers the time series of n data points and T_i and T_j as two subsets of data where $i = 1, 2, 3, \dots, n-1$ and $j = i+1, i+2, i+3, \dots, n$. The data values are evaluated as an ordered time series. Each data value is compared with all subsequent data values. If a data value from a later time period is higher than a data value from an earlier time period, the statistic S is incremented by 1. On the other hand, if the data value from a later time period is lower than a data value sampled earlier, S is decremented by 1. The net result of all such increments and decrements yields the final value of S .

In the Mann-Kendall trend test if $n \leq 10$, an exact test should be computed, but if $n > 10$, we should use a large sample approximation for the test statistic and in this study we used the second (n) conditional.

- The large sample approximation Z_s is given by:

$$\begin{aligned} Z_s &= \frac{S-1}{\sigma_s} \quad \text{if } S > 0 \\ Z_s &= 0 \quad \text{if } S = 0 \\ Z_s &= \frac{S+1}{\sigma_s} \quad \text{if } S < 0 \end{aligned} \quad (3.21)$$

- The σ_s is given by:

$$\sigma_s = \sqrt{\left(\frac{n}{18}\right)(n-1)(2n+5)} \quad (3.22)$$

The null hypothesis is rejected at significance level α if $Z_s > Z_{crit}$ where Z_{crit} is the critical value of the standard normal distribution with probability of exceedance of $\alpha/2$.

- Compute the probability associated with this normalized test statistic. The probability density function for a normal distribution with a mean of 0 and a standard deviation of 1 is given by the following equation:

$$f(z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} \quad (3.23)$$

Also, the seasonality trend test is done over the buoy stations data and climate indices by using the monthly data with seasonality of 12 months.

3.5.2 XLSTAT software requirements and data analysis

3.5.2.1 Test hypotheses

- The null hypothesis H_0 for these tests is that there is no trend in the series.
- The three alternative hypotheses are that there is a negative, non-null, or positive trend.

The Mann-Kendall tests are based on the calculation of Kendall's tau measure of association between two samples, which is itself based on the ranks with the samples. The computations assume that the observations are independent. In this study the yearly series data was taken for the Mann-Kendall test. First the Kendall's tau is calculated and then the variance of the statistic by assuming the series are independent or dependent, which requires the calculation of variance. XLSTAT usually allows both (serial dependence or not). For calculating the p-value of this test, a normal approximation to the distribution of the average Kendall tau was used in the XLSTAT.

3.5.2.2 Trend test results

A spreadsheet-based macro developed using XLSTAT within an Excel spreadsheet was employed in this study. This tool was used for processing the input time-series data for performing trend analysis and report the results.

Table 3.1 : Mann-Kendall Trend Test Results

Station	Data Point	Min Value	Max Value	M-K Statistic (S)	Normalized Test Statistic (Z)	P-value	Result	Seasonal	
								P-value	Result
46002	37	2.1	3	126	1.63	0.1	NoTrend	0.0014	Increasing
46005	36	2.3	3.1	157	2.12	0.1341	NoTrend	0.0067	Increasing
46006	35	2.3	3.4	210	2.97	0.0689	NoTrend	0.0004	Increasing
46011	32	1.8	2.4	164	2.64	0.1926	NoTrend	0.6404	NoTrend
46059	18	2.6	3	-51	-1.89	0.9695	NoTrend	0.1657	NoTrend
Nino 3.4	37	-1.2	2.3	-46	-0.59	0.8526	NoTrend	0.5209	NoTrend
SOI	37	-1.5	2.3	112	1.45	0.0279	Increasing	0.1462	NoTrend
PNA	37	-0.7	-0.77	42	0.54	0.4478	NoTrend	0.1305	NoTrend
MEI	37	-0.9	1.7	-104	-1.35	0.9666	NoTrend	0.1547	NoTrend
PDO	37	-1.3	1.8	-170	-2.21	0.9955	NoTrend	0.0065	Increasing

As you see in the (Table 3.1). The significant wave heights of the buoy stations and climate indices was analyzed using the XLSTAT macro tools. Statistically significant increasing trends were observed at SOI. The remaining 9 data which is including 5 buoy stations and 4 climate indices did not have a trend that was statistically significant. The results of the seasonality trend test indicated that there is a increasing trend in 46002, 46005, 46006, and PDO in compare to the trend test in the overall series. On the other hand, it can be seen that the SOI has no trend in seasonality test in the compare of normal trend test which there is increasing trend in this climate index.

According to this test, the null hypothesis H_0 assumes that there is no trend (the data is independent and randomly ordered) and this is tested against the alternative hypothesis H_1 , which assumes that there is a trend.

3.6 Correlation coefficient (Pearson)

Correlation coefficient (r) analysis were done for determining how both two variables, significant wave heights and climate indices are positively or inversely relatetd together, also to define the degree to which the variables tend to move toghether.

The correlation coefficient (r) directly related to the coefficient of determination r^2 in the obvious way.

$$r = \pm\sqrt{r^2} \quad (3.24)$$

The sign of r depends on the sign of the estimated slope coefficient b_1 .

- If b_1 is negative, the r takes a negative sign.
- If b_1 is positive, the r takes a positive sign.

That is, the estimated slope and the correlation coefficient r always share the same sign. Furthermore, correlation standardizes the measure of interdependence between two variables and, consequently, it could help us to know that how closely the two variables move (PreMBA analytical methods). The correlation measurement, called a correlation coefficient, will always take on a value between 1 and -1 :

- If the correlation coefficient is one, the variables have a perfect positive correlation. This means that if one variable moves a given amount, the second moves proportionally in the same direction. A positive correlation coefficient less than one indicates a less than perfect positive correlation, with the strength of the correlation growing as the number approaches one.
- If correlation coefficient is zero, no relationship exists between the variables. If one variable moves, you can make no predictions about the movement of the other variable; they are uncorrelated.
- If correlation coefficient is -1 , the variables are perfectly negatively correlated (or inversely correlated) and move in opposition to each other. If one variable increases, the other variable decreases proportionally. A negative correlation coefficient greater than -1 indicates a less than perfect negative correlation, with the strength of the correlation growing as the number approaches -1 .

One advantages of of r is that it is unitless, allowing researchers to make sense of correlation coefficients calculated on different data sets with different units. The "unitless-ness" of the measure can be seen from an alternative formula for r , namely:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (3.25)$$

where:

- Containing n values
- x_i dataset of $\{X_1, \dots, X_n\}$

- y_i dataset of $\{Y_1, \dots, Y_n\}$
- $\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$
- $\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i$

This formula r is used for the Microsoft Excel function CORREL.

The guidelines to interpreting Pearson's correlation coefficient is shown in (Table 3.2). There are three strength of condition in this method which is called small, medium, and large.

Table 3.2: Correlation coefficient guideline.

Strength of Association	Coefficient, r	
	Positive	Negative
Small	0.1 to 0.3	-0.1 to -0.3
Medium	0.3 to 0.5	-0.3 to -0.5
Large	0.5 to 1.0	-0.5 to -1.0

3.7 Standard deviation

The standard deviation is a numerical value used to indicate how widely individuals in a group vary. If individual observations vary greatly from the group mean, the standard deviation is big; and vice versa.

It is important to distinguish between the standard deviation of a population and the standard deviation of a sample. They have different notation, and they are computed differently. The standard deviation of a population is denoted by σ and the standard deviation of a sample, by s .

$$\sigma = \sqrt{\sum (X_i - \bar{X})^2 / N} \quad (3.26)$$

where σ is the population standard deviation, $\bar{X}$ is the population mean, X_i is the i th element from the population, and N is the number of elements in the population.

The standard deviation of a sample is defined by slightly different formula:

$$\sigma = \sqrt{\sum \frac{(X_i - \bar{X})^2}{N-1}} \quad (3.27)$$

where s is the sample standard deviation, $\bar{x}$ is the sample mean, x_i is the i th element from the sample, and n is the number of elements in the sample. Using this equation, the standard deviation of the sample is an unbiased estimate of the standard deviation of the population.

And finally, the standard deviation is equal to the square root of the variance.

3.8 Temporal variability of wave climate

The monthly significant wave height and wave climate indices from January to December series were chosen for this analysis that they reflect the seasonal period in Pacific Ocean. Monthly mean wave height data from 1975 to 2012 are used in the station of 46002, 1976 to 2012 in 46005, 1977 to 2012 in 46006, 1981 to 2012 in 46011, and 1994 to 2012 in the station of 46059 to analyze the temporal variability of H_s . Seasonal mean significant wave heights are determined by averaging the Dec-Jan-Feb monthly values for winter, Mar-Apr-May for spring, Jun-Jul-Aug for summer, and Sep-Oct-Nov for autumn.

The mean significant wave height for all buoys is then found by averaging the overall monthly H_s values. As stated before, the absolute value gives information on the power at a certain scale and a certain time. (Figures 3.4 to 3.13) show the variation of monthly wave conditions for the buoys 46002, 46005, 46006, 46011, 46059, and also for the indices of MEI, PDO, SOI, NINO 3.4, and PNA, respectively.

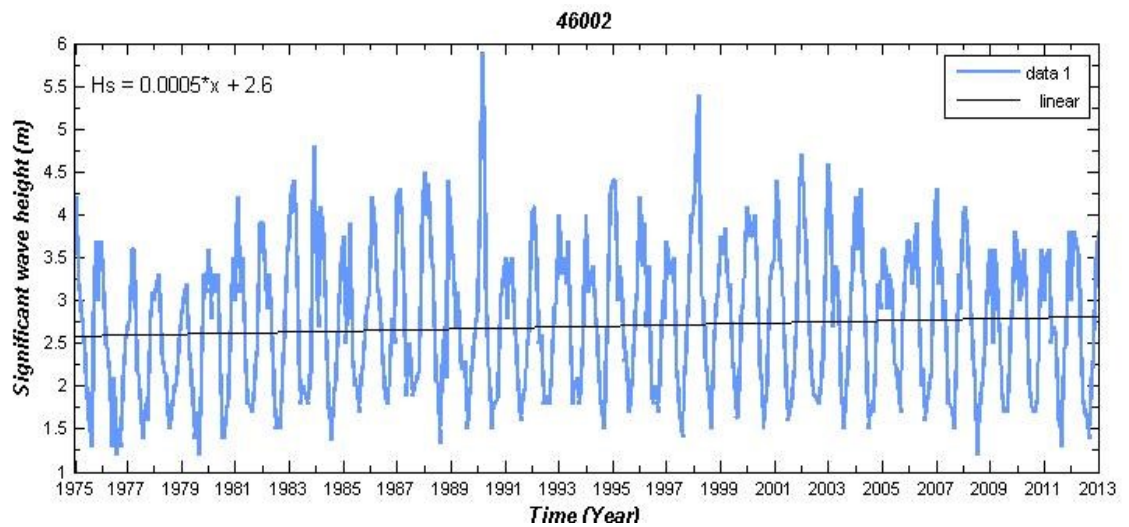


Figure 3.4 : The time series of significant wave height in 46002.

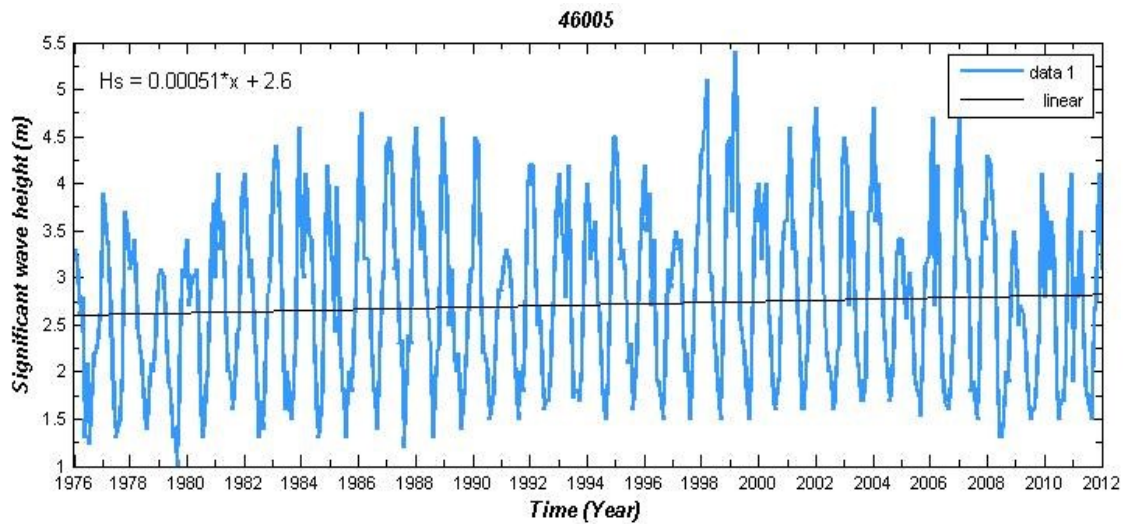


Figure 3.5 : The time series of significant wave height in 46005.

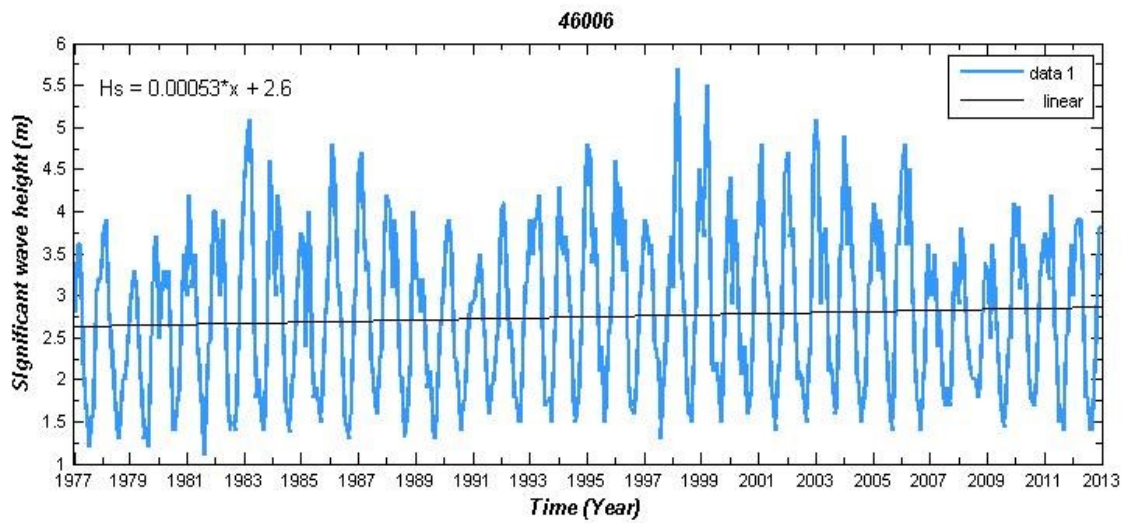


Figure 3.6 : The time series of significant wave height in 46006.

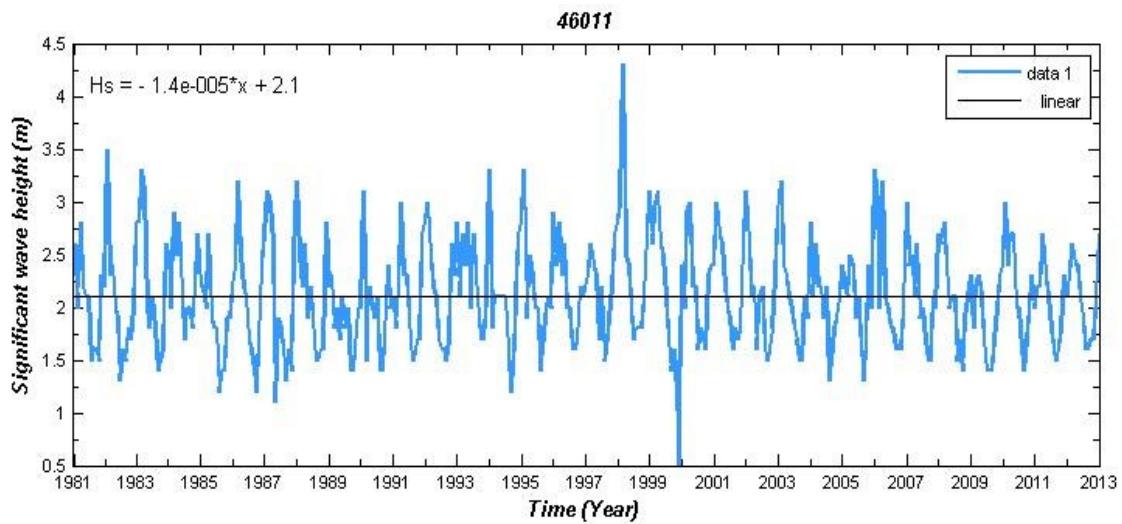


Figure 3.7 : The time series of significant wave height in 46011.

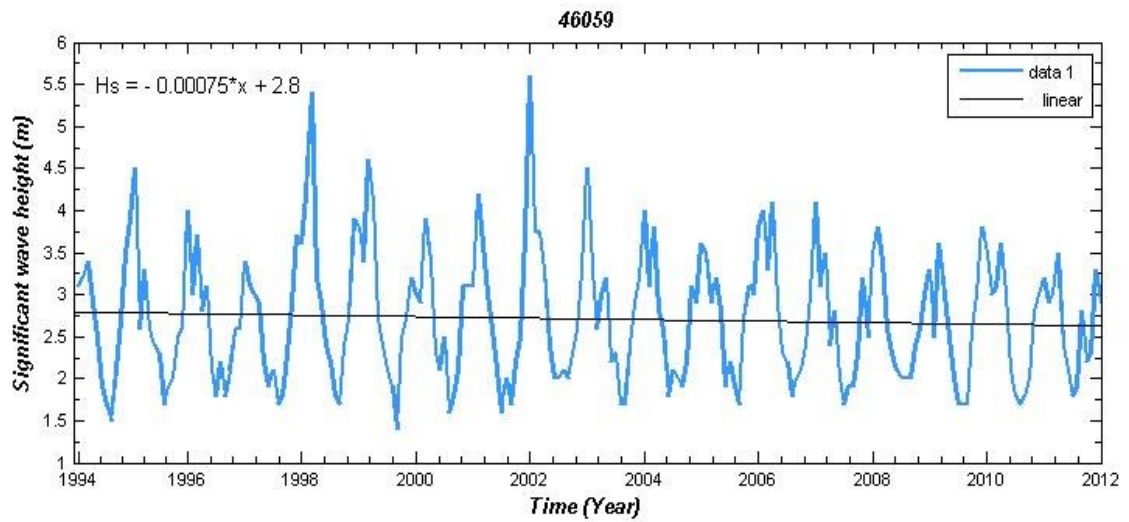


Figure 3.8 : The time series of significant wave height in 46059.

Table 3.3 shows the highest and lowest wave height in buoys.

Table 3.3 : Highest and lowest wave height of Buoys

Station	High Value (m)	Year	Low Value (m)	Year
46002	5.9	1990	1.2	1979, 1979, 2008
46005	5.4	1999	1	1979
46006	5.7	1998	1.1	1981
46011	4.3	1998	0.5	1991
46059	5.6	2001	1.4	1999, 2012

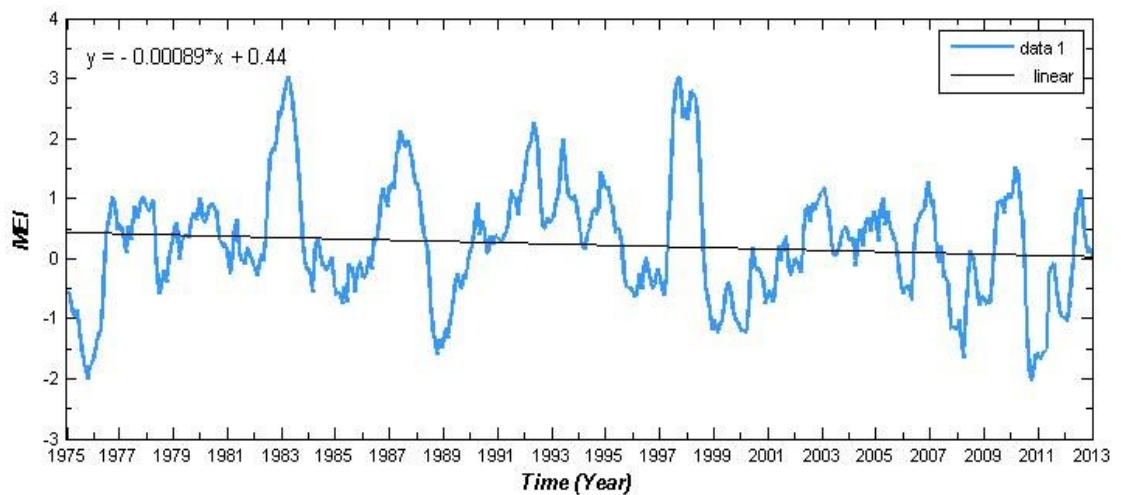


Figure 3.9 : The normlized time series of (MEI) from 1975 to 2012.

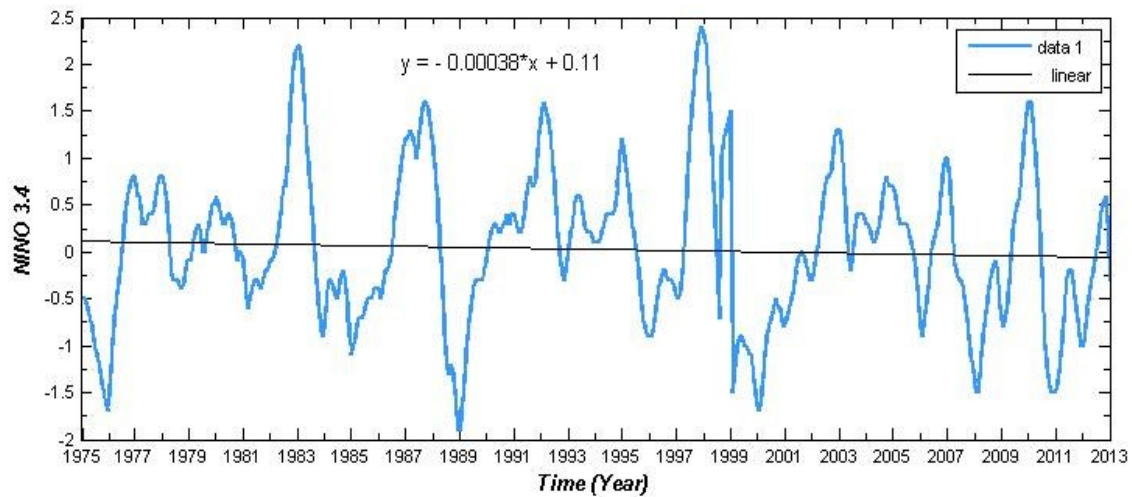


Figure 3.10 : The normalized time series of (Niño 3.4) from 1975 to 2012.

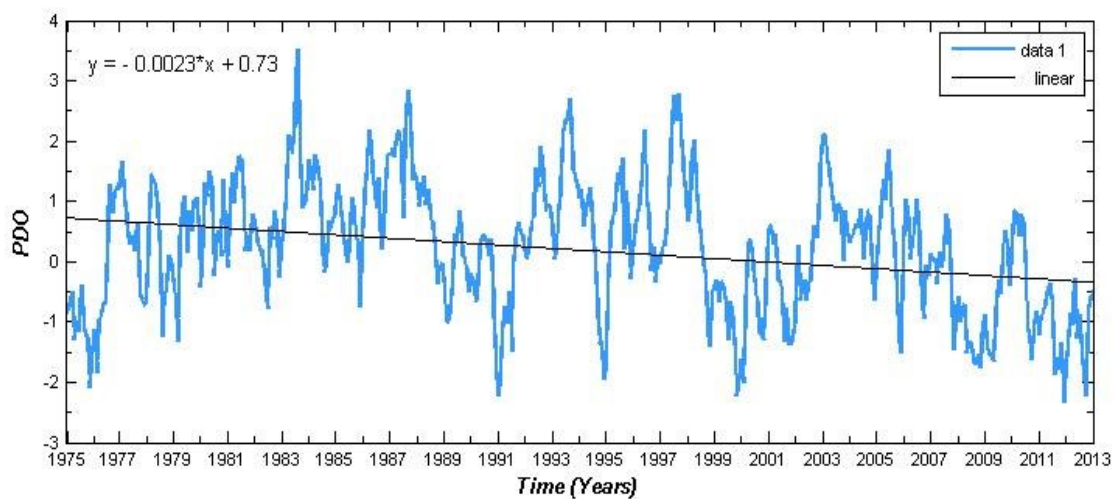


Figure 3.11 : The normalized time series of (PDO) from 1975 to 2012.

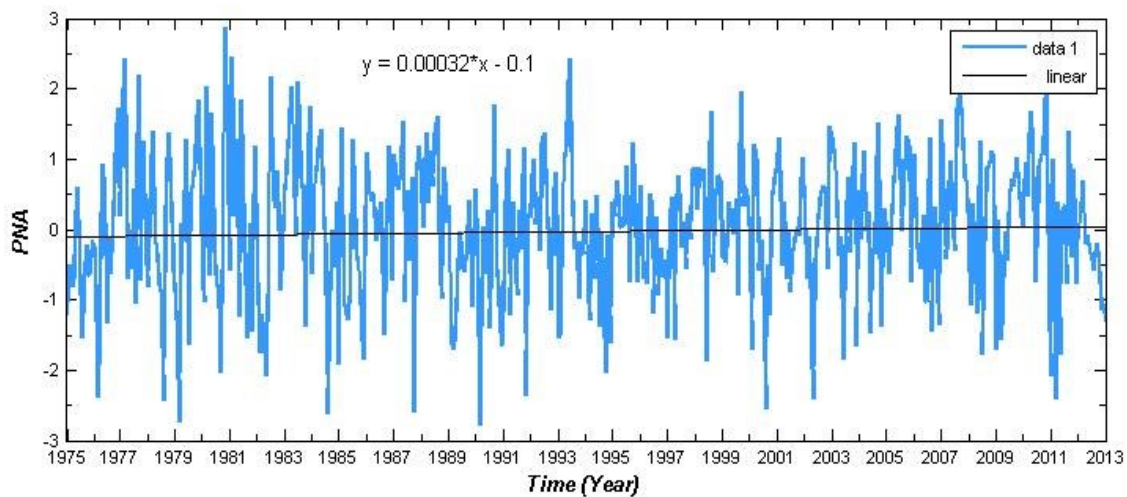


Figure 3.12 : The normalized time series of (PNA) from 1975 to 2012.

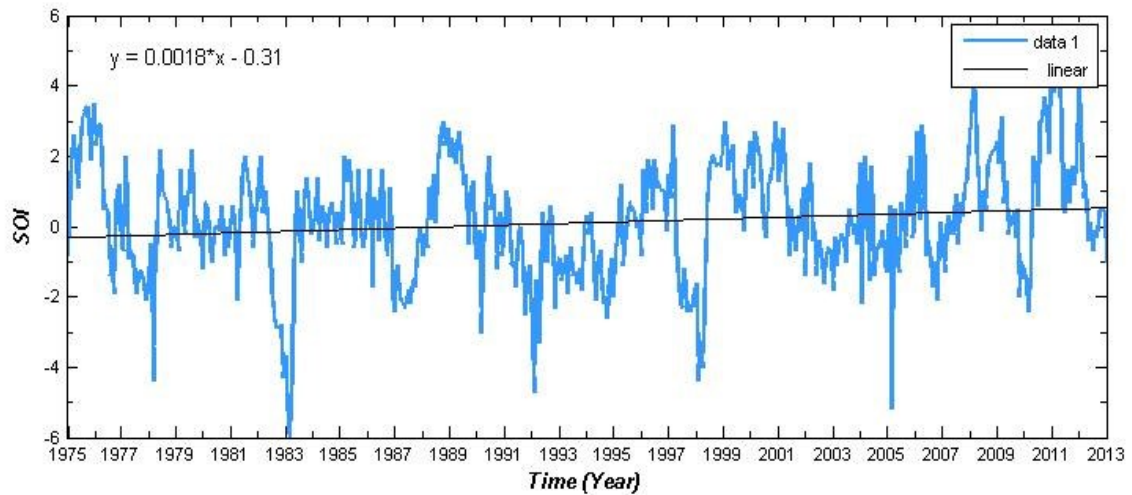


Figure 3.13 : The normalized time series of (SOI) from 1975 to 2012.

Table 3.4 indicates the heighest and lowest climeate indices value.

Table 3.4 : High and low values of climate indices.

Station	High Value (+)	Year	Low Value (-)	Year
MEI	3	1983, 1997	2	2010
Niño3.4	2.4	1997	1.9	1988
PDO	3.51	1983	2.33	2011
PNA	2.87	1980	2.78	1990
SOI	4.8	2010	6	1983

3.8.1 Annual mean and winter wave heights

Annual mean values of the significant wave heights H_s and the mean winter significant wave heights (WH_s) determined for each of the buoys (in which all 12 consecutive months) are plotted against time in Figures 3.14 to 3.18; linear regression lines have been fitted to the data, to distinguish the board temporal patterns. Also (Table 3.5) lists the regression slopes and statistical significance of the regression lines determined by an analysis of variance (ANOVA), for each data plot.

Oregon buoy 46002, shows a small increase in the annual average H_s and the WH_s since 1975 (Figure 3.14). However, the Mann-Kendall trend tests and the ANOVA test

reveal that these trends are not statistically significant at the 0.05% level (see Tables 3.1 and 3.2). The graph does provide some insight into the inter-annual variability of wave heights in the Orgeon, indicated by the variance of the waves about the regression line, as well as possible decadal variability in wave heights. In general, wave heights were generally lower during the mid 1970s, around 2.83 m during the winter months, and there followed a progressive increase in the wave heights that peaked around 4.57 m during the late 1980s and 1990s. Throughout the 1990s and 2000s, wave heights decreased slightly, though remaining higher than those measured during the latter half of the 1970s.

The 46005 and 46006 buoys are characterized by marked weak increase in the annual average H_s and average winter WH_s , indicated by the prominent poor upward sloping regression lines (Figure 3.15 and 3.16). These trends as the same of (Figure 3.14) and (Tables 3.1 and 3.2), are not statistically significant at the 0.05% level. Furthermore, (Figure 13.4) shows during 1982, the wave heights increased significantly, reaching prominent heights during 1983, 1988, associated with 1982-1983, 1987-1988, EI Nino respectively. It can be seen that the 1997-1998 EI Nino stand out as having generated the largest average wave heights at 46002. And, also reveals that La Niña events appear to have had a negligible influence on the wave height statistics in 46002.

The annual average of H_s for the 46005 buoy increased at a rate of 0.0063 m.yr^{-1} from 1976, while the annual winter average WH_s increased by 0.0043 m.yr^{-1} .

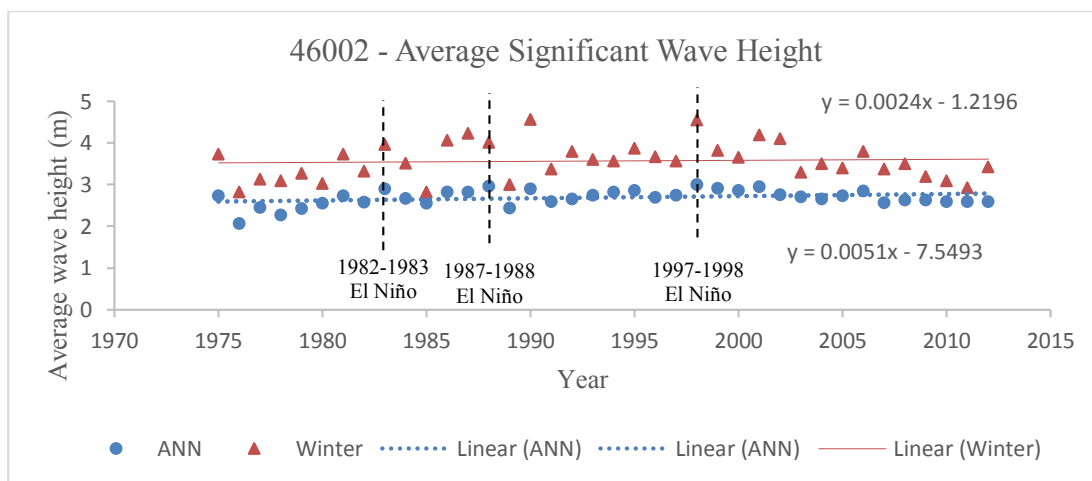


Figure 3.14 : The annual average significant wave heights H_s and the annual average winter WH_s for the Oregon 46002 buoy.

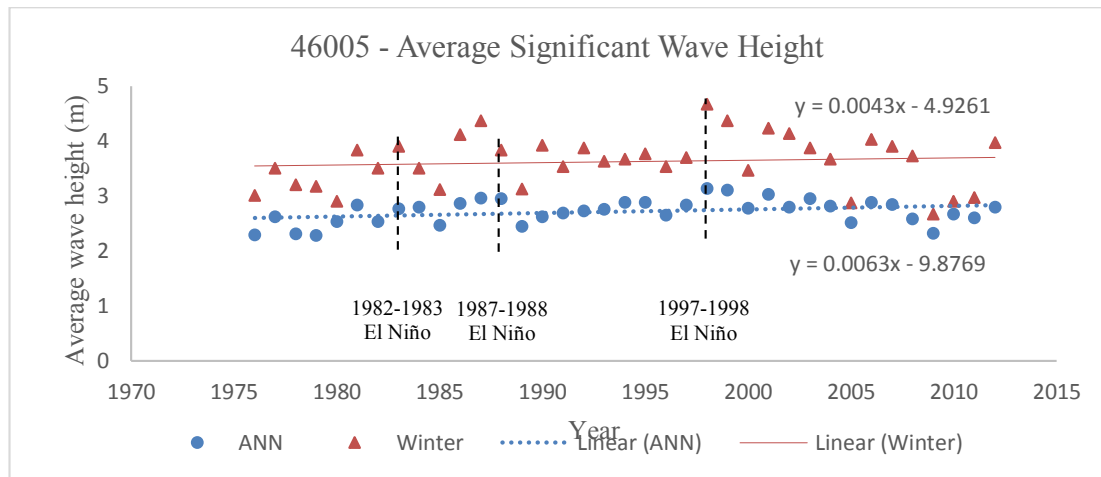


Figure 3.15 : The annual average significant wave heights H_s and the annual average winter WH_s for the 46005 buoy.

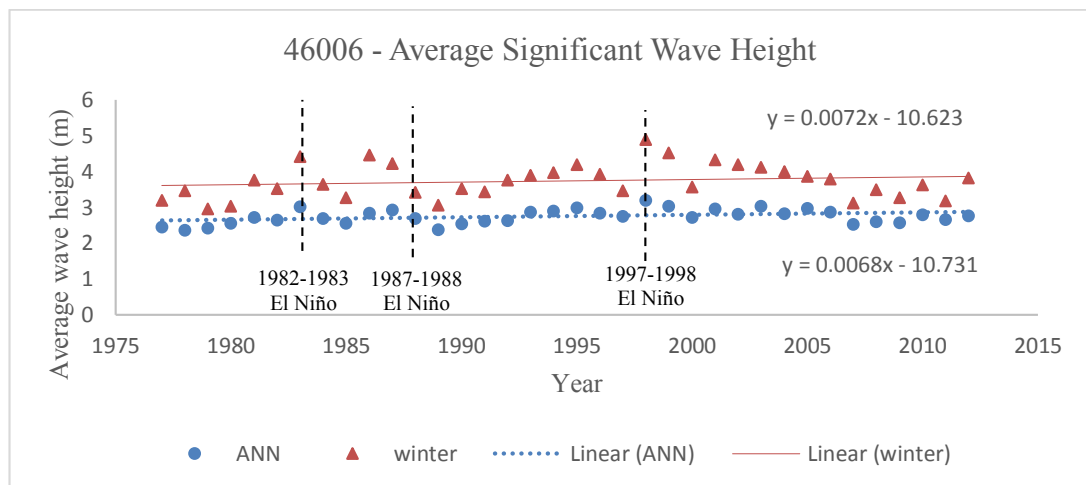


Figure 3.16 : The annual average significant wave heights H_s and the annual average winter WH_s for the 46006 buoy.

The plotted data for both buoys reveal a significant jump in the wave heights from mid 1970s to the late of 1990s (Figure 3.15 and 3.16). From the late of 1990s to 2005 WH_s gradually decreased with time, while the annual average H_s increased. Furthermore, (Figures 13.5) and (3.16) as the same of (Figure 13.4) indicate that, the wave heights increased significantly, during 1983, 1988, associated with 1982-1983, 1987-1988, El Nino respectively. Also, it is found that the 1997-1998 El Nino generated the largest average wave heights at 46005. While, the La Niña also generated above average wave conditions in both 46005 and 46006.

The buoy 46011 shows little evidence for an increase in the annual average H_s and a decrease in the average winter WH_s (Figure 3.17). The negatively sloping regression

line fitted to the data. The result suggests that the annual average WH_s has declined at a rate of $-0.0016 \text{ m. yr}^{-1}$ with time at this particular site.

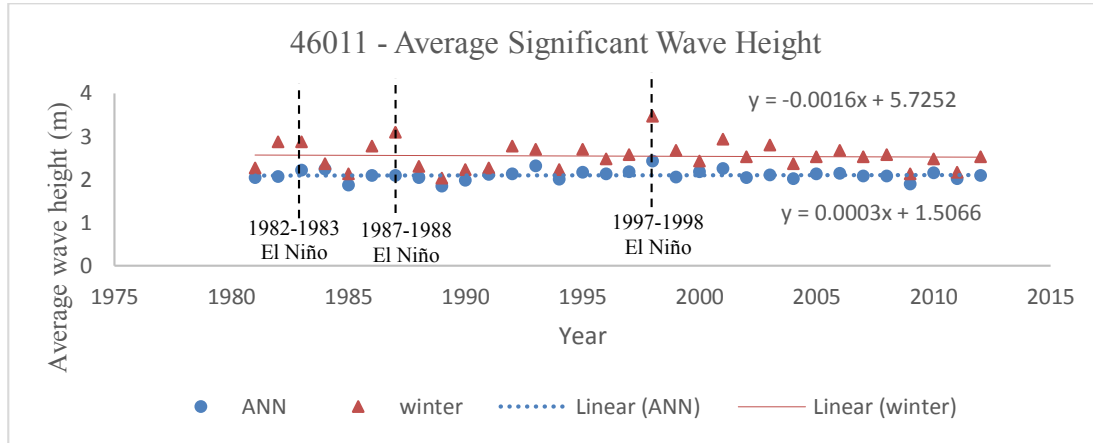


Figure 3.17 : The annual average significant wave heights H_s and the annual average winter WH_s for the 46011 buoy.

The wave climate in buoy 46059 is also characterized by a decreasing trend in the average winter WH_s at a rate of $-0.0267 \text{ m. yr}^{-1}$ as shown in (Figure 3.18). Also, a negatively sloping regression line in the annual average H_s at a rate of $-0.0083 \text{ m. yr}^{-1}$.

Furthermore, in (Figure 3.17) the apparent decrease in the annual average H_s is identified at 46011, given the absence of wave height data measured during the 1987-1988 El Niño winters. The other important feature of (Figure 3.17) is the much larger average wave heights produced by the 1997-1998 El Niño, while the La Niña also caused above average wave conditions in 46011.

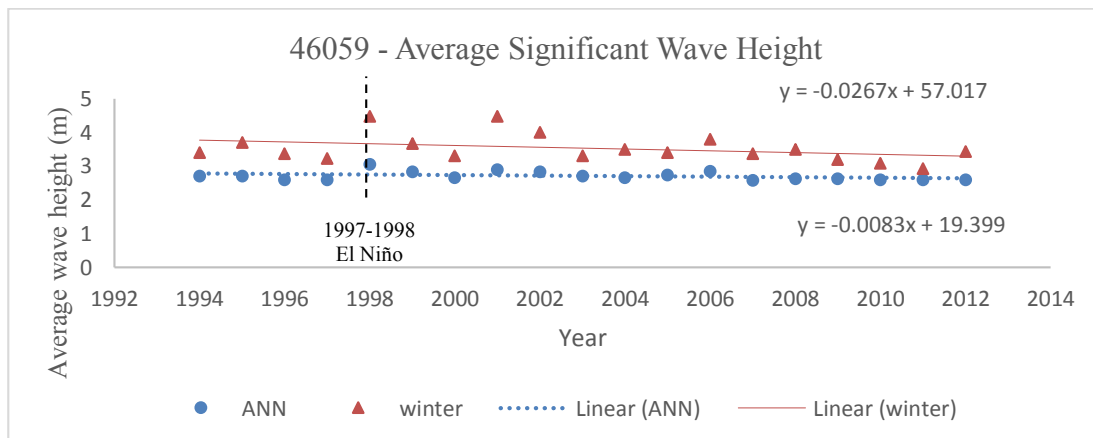


Figure 3.18 : The annual average significant wave heights H_s and the annual average winter WH_s for the 46059 buoy.

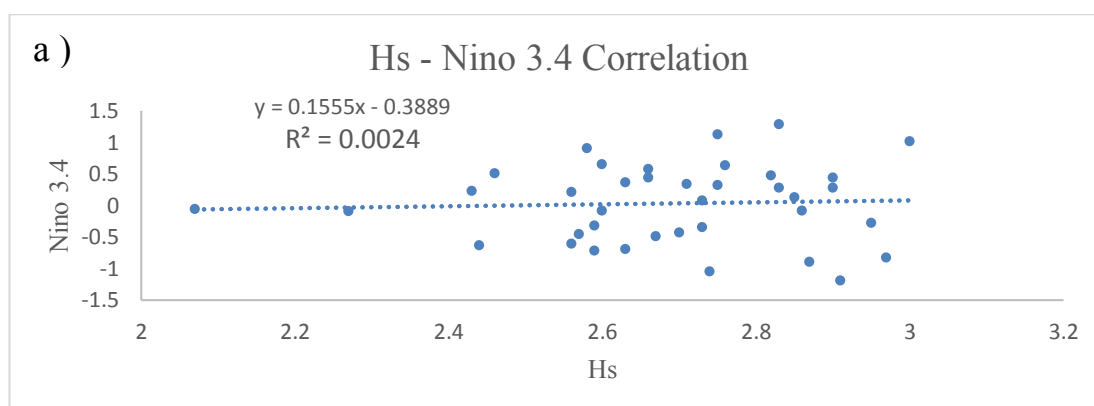
As can be seen in (Figure 3.18) the wave heights increased significantly during 1997-1998 El Niño and decreased during 1999-2000 La Niña.

Table 3.5 : Statistical properties of buoys 46002, 46005, 46006, 46011, and 46059.

Seasons	46002		46005		46006		46011		46059	
	Mean (m)	Std. Dev (m)	Mean (m)	Std. Dev (m)	Mean (m)	Std. Dev (m)	Mean (m)	Std. Dev (m)	Mean (m)	Std. Dev (m)
Spring (MAM)	2.69	0.27	2.71	0.3	2.83	0.33	2.23	0.19	2.67	0.23
Summer (JJA)	1.73	0.15	1.67	0.14	1.65	0.15	1.7	0.15	1.9	0.13
Fall (SON)	2.75	0.29	2.87	0.3	2.78	0.26	1.92	0.21	2.73	0.19
Winter (DJF)	3.61	0.43	3.63	0.47	3.74	0.47	2.55	0.31	3.53	0.41
Combined	2.69	0.73	2.71	0.77	2.82	0.81	2.1	0.39	2.7	0.63

3.9 Correlations between significant wave heights and climate indices

To identify the relative influence of the climate indices on the Pacific wave climate, the annual wave height for each of the NOAA wave buoys were correlated against the Nino 3.4, MEI, PDO, PNA, and SOI (Figure 3.18) for the station 46002, and the rest of figures between H_s and climate indices for other buoy stations is shown in the Appendix section.



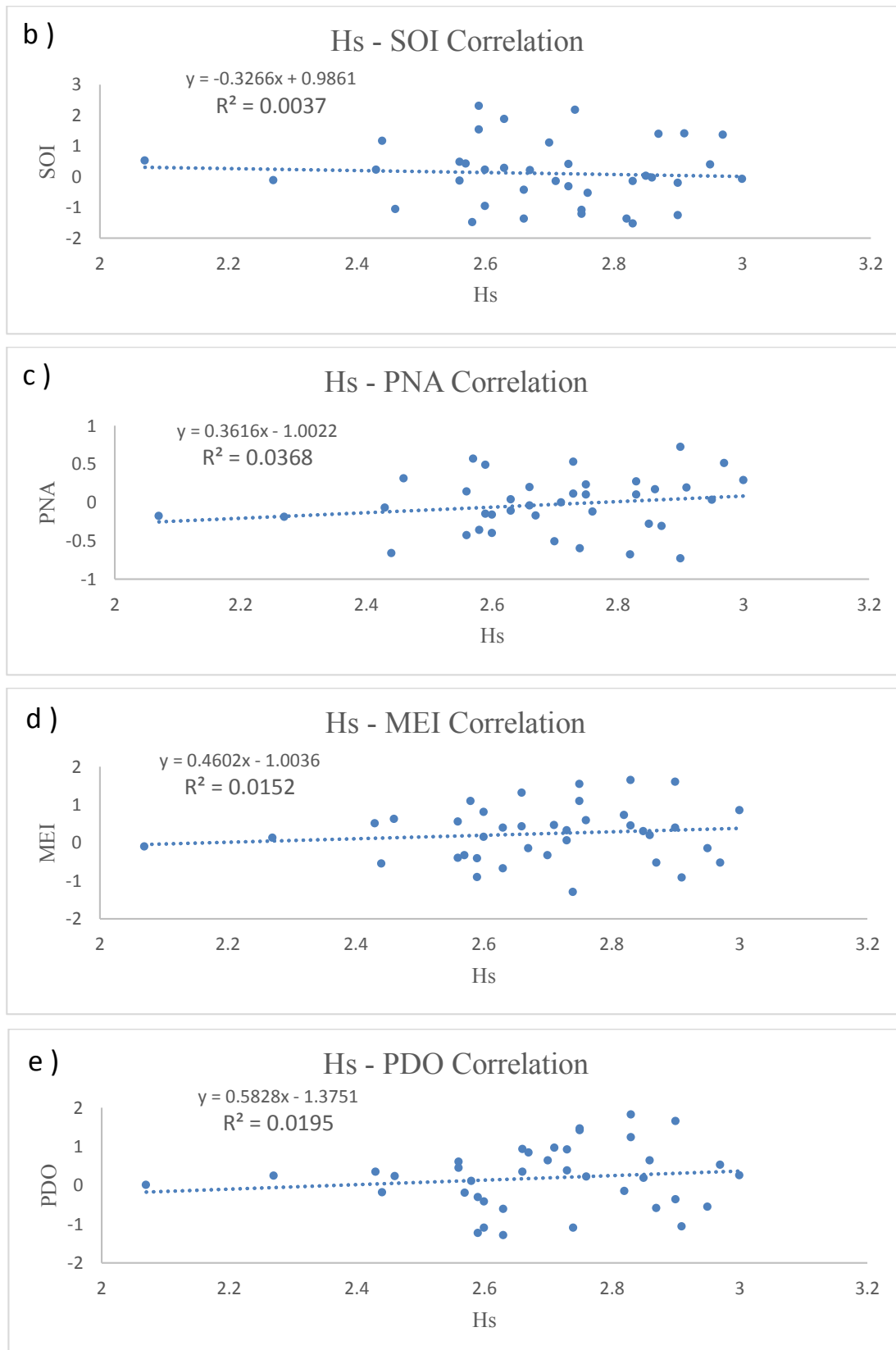


Figure 3.19 : Correlation analysis between annual wave heights and climate indices in buoy 46002. a) Correlation of H_s and Nino3.4. b) Correlation of H_s and SOI. c) Correlation of H_s and PNA. d) Correlation of H_s and MEI. e) Correlation of H_s and PDO.

Figure 3.19 illustrates that there is a less scatter in 46002 wave data. It can be seen that there is a positive correlation between the significant wave height and climate indices which is shown in Figures (3.19 a, b, c, d, and e) respectively. It also suggests that this region is influenced by large storm events during average years, events that can exceed any influence associated with strong El Niño phase.

Scatterplot of the significant wave height and Nino 3.4 in (Figure 3.19 a) shows that in the anomalies of -1.19 which is known cool phase La Niña conditions, the mean wave height is 2.91 m and in the warm phase El Niño conditions, the mean wave height is about 3 m in 46002 buoy. The maximum monthly mean wave height 3 m is observed when the anomaly of the Nino 3.4 was 1.02 in 1998, and the minimum wave height 2.07 m when the anomaly of the Nino 3.4 was -0.06 in 1976.

Figure 3.19b indicates that in negative values of the SOI with the values of -1.49 the wave height in this climate condition, is 2.58 m in 1982, and in the positive values of SOI which is equal 2.31 the wave height is 2.59 m in 2010 and 2011. The highest mean wave height 3 m of this station is found when the warming of the central and eastern tropical Pacific Ocean was in the value of -0.07. On the other hand, the lowest wave height 2.07 m of this buoy is observed in the condition of La Niña when the value of the SOI was 0.52 in 1976.

The results of other correlations between significant wave heights and climate indices scatterplots is given in (Table 3.7).

The first five columns from the left side of (Table 3.6) show the annual wave height of buoys in different conditions of climate indices. It can be seen that in negative value conditions Nino 3.4 index has significant effects on wave climate in the Pacific Ocean. Also it is figured out that Nino 3.4 climate index has more effect on climate wave in 1999 in all buoy stations. Furthermore, the end four columns of (Table 3.6) indicates that in which year and in which climate indices wave heights are high and low in the regions of buoys.

Table 3.6 : Climate indices effects on mean wave height in annual conditions.

Station		Index	H_S (m)	Year		Index	H_S (m)	Year
46002	Nino 3.4	-1.19	2.91	1999	Nino 3.4	-0.06	2.07	1976
		1.29	2.83	1987		1.02	3	1998
	SOI	-1.49	2.58	1982	SOI	-0.52	2.07	1976
		2.31	2.59	2011		-0.07	3	1998
	PNA	-0.73	2.9	1990	PNA	-0.18	2.07	1976
		0.72	2.9	1983		0.29	3	1998
	MEI	-1.3	2.74	1975	MEI	-0.11	2.07	1976
		1.65	2.83	1987		0.85	3	1998
	PDO	-1.29	2.63	2008	PDO	0.01	2.07	1976
		1.82	2.83	1987		0.25	3	1998
46005	Nino 3.4	-1.19	3.11	1999	Nino 3.4	1.02	3.14	1998
		1.29	2.96	1987		0.23	2.28	1979
	SOI	-1.53	2.96	1987	SOI	-0.07	3.14	1998
		2.31	2.6	2011		0.23	2.28	1979
	PNA	-0.73	2.62	1990	PNA	0.29	3.14	1998
		0.72	2.77	1983		-0.07	2.28	1979
	MEI	-0.92	3.11	1999	MEI	0.85	3.14	1998
		1.65	2.96	1987		0.51	2.28	1979
	PDO	-1.29	2.58	2008	PDO	0.25	3.14	1998
		1.82	2.96	1987		0.34	2.28	1979
46006	Nino 3.4	-1.19	3.04	1999	Nino 3.4	1.02	3.2	1998
		1.29	2.93	1987		-0.09	2.37	1978
	SOI	-1.53	2.93	1987	SOI	-0.07	3.2	1998
		2.31	2.67	2011		-0.12	2.37	1978
	PNA	-0.73	2.55	1990	PNA	0.29	3.2	1998
		0.72	3.02	1983		-0.19	2.37	1978
	MEI	-0.92	3.04	1999	MEI	0.85	3.2	1998
		1.65	2.93	1987		0.12	2.37	1978
	PDO	-1.29	2.6	2008	PDO	0.25	3.2	1998
		1.82	2.93	1987		0.24	2.37	1978
46011	Nino 3.4	-1.19	2.06	1999	Nino 3.4	1.02	2.43	1998
		1.29	2.09	1987		-0.63	1.17	1989
	SOI	-1.53	2.09	1987	SOI	-0.07	2.43	1998
		2.31	2.02	2011		1.17	1.17	1989
	PNA	-0.73	1.98	1990	PNA	0.29	2.43	1998
		0.72	2.21	1983		-0.66	1.17	1989
	MEI	-0.92	2.06	1999	MEI	0.85	2.43	1998
		1.65	2.09	1987		-0.55	1.17	1989
	PDO	-1.29	2.08	2008	PDO	0.25	2.43	1998
		1.82	2.09	1987		-0.18	1.17	1989
46059	Nino 3.4	-1.19	2.83	1999	Nino 3.4	1.02	3.05	1998
		1.13	2.6	1997		-0.45	2.57	2007
	SOI	-1.37	2.7	1994	SOI	-0.07	3.05	1998
		2.32	2.59	2011		0.43	2.57	2007
	PNA	-0.68	2.7	1994	PNA	0.29	3.05	1998
		0.57	2.57	2007		0.57	2.57	2007
	MEI	-0.92	2.83	1999	MEI	0.85	3.05	1998
		1.54	2.6	1997		-0.33	2.57	2007
	PDO	-1.29	2.63	2008	PDO	0.25	3.05	1998
		1.46	2.6	1997		-0.2	2.57	2007

By using annual means of H_s extracted from the wave data set for each statistically significant correlations of five buoy stations and climate indices are shown in (Table 3.8).

Table 3.7 : Means and Correlations between significant wave heights and climate indices.

Station	Era	Region	Mean (Hs)	Mean (Index)	Index	R	Cross Correlation
46002	1975-2012	Oregon	2.68	0.03	NINO3.4	0.05	0.2
				0.11	SOI	-0.06	-0.17
				-0.03	PNA	0.19	0.2
				0.23	MEI	0.12	0.22
				0.19	PDO	0.14	0.31
46005	1976-2012	Washington	2.71	0.06	NINO3.4	0.06	0.12
				0.05	SOI	-0.1	-0.09
				-0.01	PNA	0.28	0.13
				0.28	MEI	0.1	0.16
				0.23	PDO	0.16	0.24
46006	1977-2012	PAPA	2.74	0.06	NINO3.4	0.18	0.13
				0.04	SOI	-0.14	-0.07
				-0.01	PNA	0.31	0.14
				0.29	MEI	0.2	0.15
				0.23	PDO	0.23	0.26
46011	1981-2012	Santa Maria	2.1	0.04	NINO3.4	0.25	0.16
				0.08	SOI	-0.22	-0.12
				-0.02	PNA	0.43	0.1
				0.027	MEI	0.32	0.2
				0.22	PDO	0.29	0.22
46059	1994-2012	California	2.7	-0.03	NINO3.4	0.28	0.2
				0.36	SOI	-0.24	-0.17
				-0.01	PNA	0.1	0.17
				0.09	MEI	0.23	0.21
				-0.11	PDO	0.09	0.3

Annually mean values of these five climate indices were downloaded from the NOAA sources referenced previously.

By the inspection of (Table 3.7) and (Table 3.2) it was concluded that, there is a medium correlations between significant wave height and MEI with a correlation coefficient of $r = 0.32$ in 46011 and with correlation coefficient of $r = 0.31$ in 46006. Also, there is a medium correlation between H_s and PNA with a correlation coefficient of $r = 0.43$ in 46011. However, other climate indices yields smaller correlations with significant wave heights.

It is to be noted that, SOI is weakly and negatively correlated with significant wave height in all buoys that is significant at the 95% confidence level.

Although correlation analysis provides an opportunity to investigate the relationship between chosen pair of time series, it is not able to show how climate indices influence the wave height simultaneously.

Also, the cross correlation is done over the data for identifying a long correlation between climate wave and climate indices data for a shorter, known feature. The method basically underlies implementations of the Fourier transformation that measure of similarity of two series as a function of the lag of one relative to the other.

The results of the cross correlation is shown in (Table 3.8). it could be concluded that in some of the analysis the correlation between climate waves and climate indices in cross correlation is higher in the compare of normal correlation between to indices. As can be seen in 46002 the correlation between H_s and Nino3.4 in the term of cross correlation is equal 0.2 which is higher than the result of normal correlation that is equal 0.05.

4. RESULTS AND DISCUSSIONS

Synoptic scale is one of the best large scale because it is a horizontal length scale that ranges from several hundred to several thousand kilometers. For this reason synoptic scale is used to analyze wave variability in 5 buoy stations located in the Pacific Ocean. The stations were selected from different regions of the Pacific Ocean. With regard to this issue, the buoy stations were divided into three parts. First part consists of three buoys which are located in Southeast Papa, Santa Maria, and West California coasts, the second part covers the offshore of West Washington coasts, and the third part covers the offshore of the West Oregon coasts.

4.1 Wavelet power spectrum and spectral analysis

The local wavelet power spectrum analysis were implemented to significant wave height and large scale climate indices time series. While the wave height series are taken from 5 buoy stations, Niño3.4, SOI, PNA, MEI, and PDO are used as climate indices. The wavelet power spectrum plots are shown in Figures 4.1 to 4.10. The left-axis is the period (in month) in local wavelet power spectrum plots corresponding to the wavelet scale on the right axis. The bottom axis illustrates time (year) in analysis. The shaded countours are at normalized variances of 1, 2, 5, and 10. The colors code for power values from dark blue (low values) to dark red (high values). The thick black contour lines indicate significantly enhanced wavelet power at 95% confidence with respect to fitted red noise. The hatched regions on either end indicate the cone of influence, where edge effects become important.

The spectral plots are used to identify periodic behavior in time series. Spectral plots provides the clearst means of identifying periodic components. The bottom axis illustrates frequency, ranging from frequency 0 (the constant or mean term) to frequency 0.5 (the term for a cycle of two observations), and left axis shows spectral density.

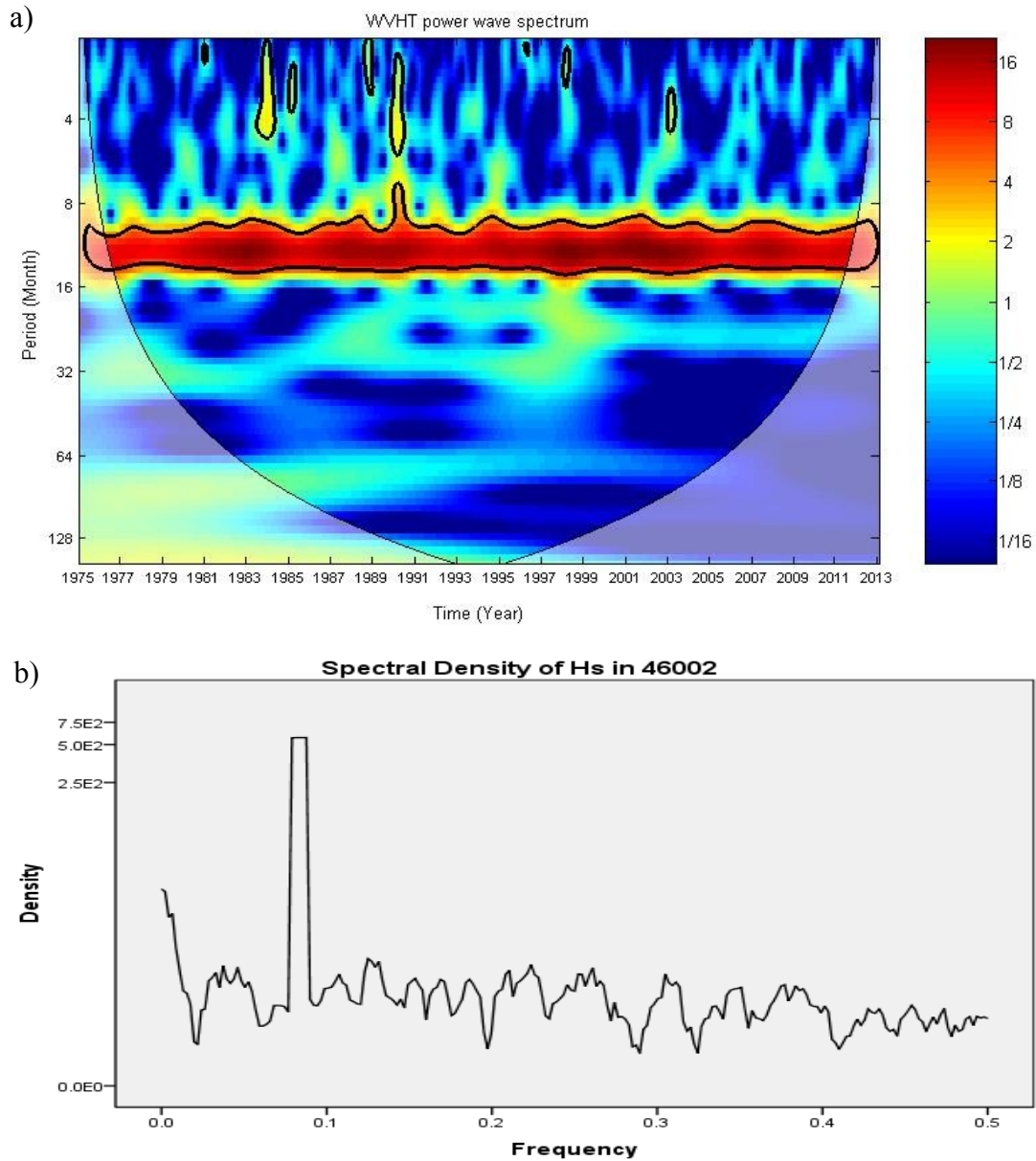


Figure 4.1 : a) Wavelet power spectrum (Morlet wavelet). b) Power spectral density of the significant wave height in 46002.

Figure 4.1a displays the wavelet power spectrum of significant wave height, which is measured between 1975-2012 years in buoy 46002. The analysis of wavelet power spectra in this station shows that there is a significant power at annual scale during whole measurement period of significant wave height. In the (Figure 4.1b) the plot of power spectral density shows there is a sequence of peaks, which is illustrated that there is an annual cycle in this station, with a period of 12 corresponds to a frequency of $1/12$ (or 0.083).

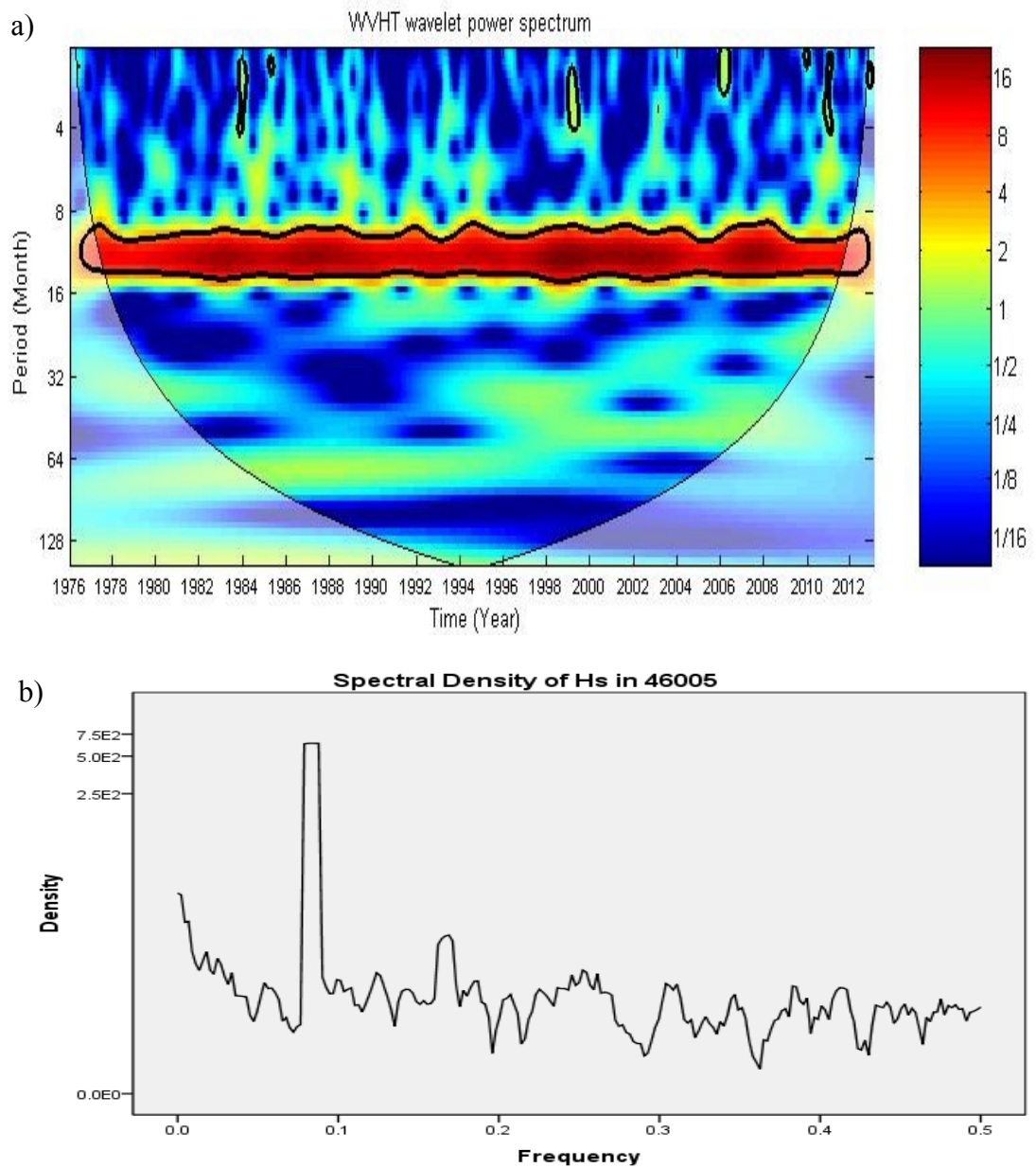


Figure 4.2 : a) Wavelet power spectrum (Morlet wavelet). b) Power spectral density of the significant wave height in 46005.

Figure 4.2a shows the wavelet power spectrum of significant wave height from time series of 1976 to 2012 in 46005. There is a significant power at annual scale during whole measurement period of significant wave height. As the same of 46002, the plot of power spectral analysis in 46005 indicated that there is an annual cycle in this station station (Figure 4.2b).

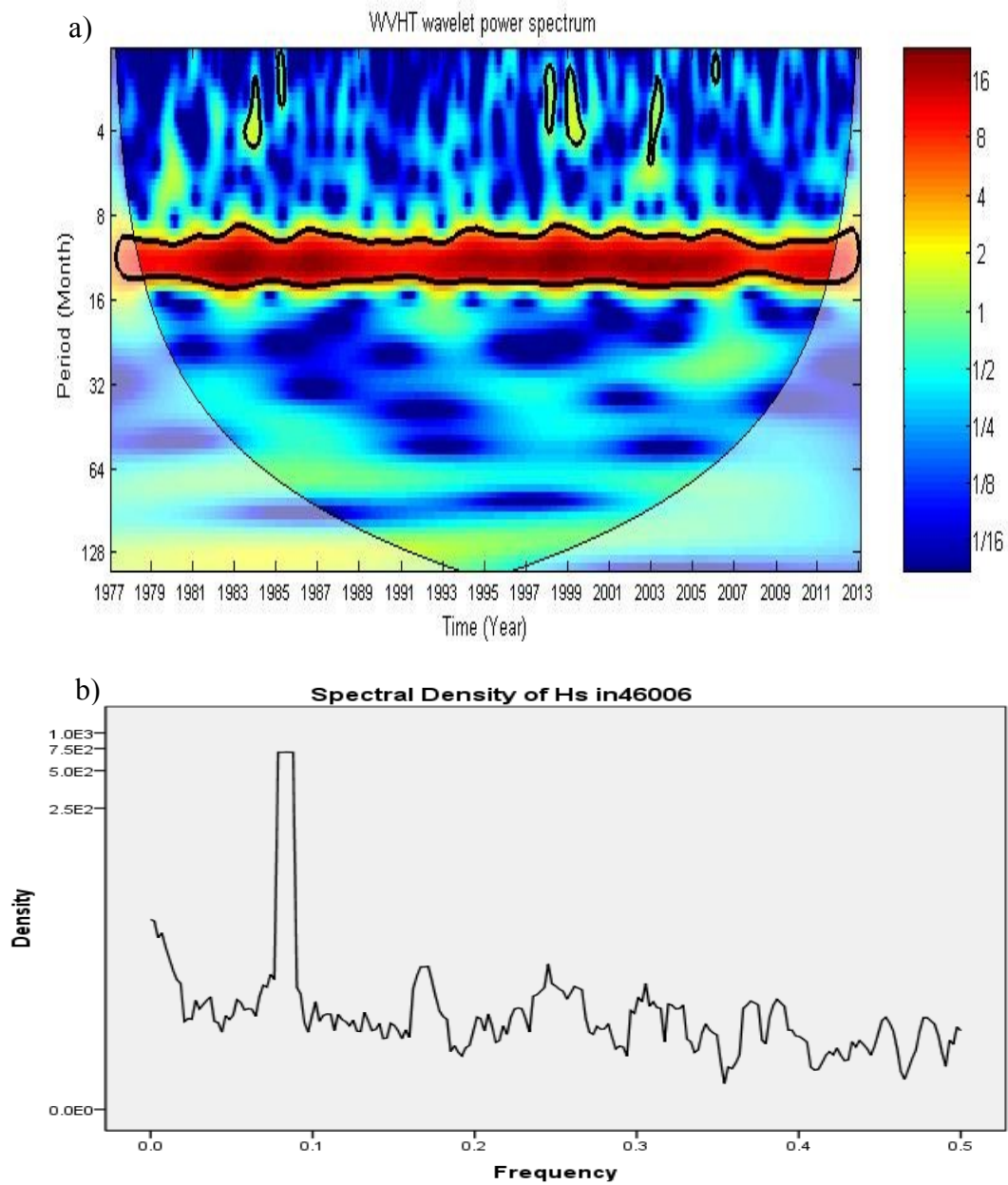


Figure 4.3 : a) Wavelet power spectrum (Morlet wavelet). b) Power spectral density of the significant wave height in 46006.

The wavelet power spectrum of significant wave height in 46006 between 1976 to 2012 years in (Figure 4.3a). The result of this analysis in this station is the same as 46002 and 46005. Also, it can be seen an annual cycle in this station (Figure 4.3b).

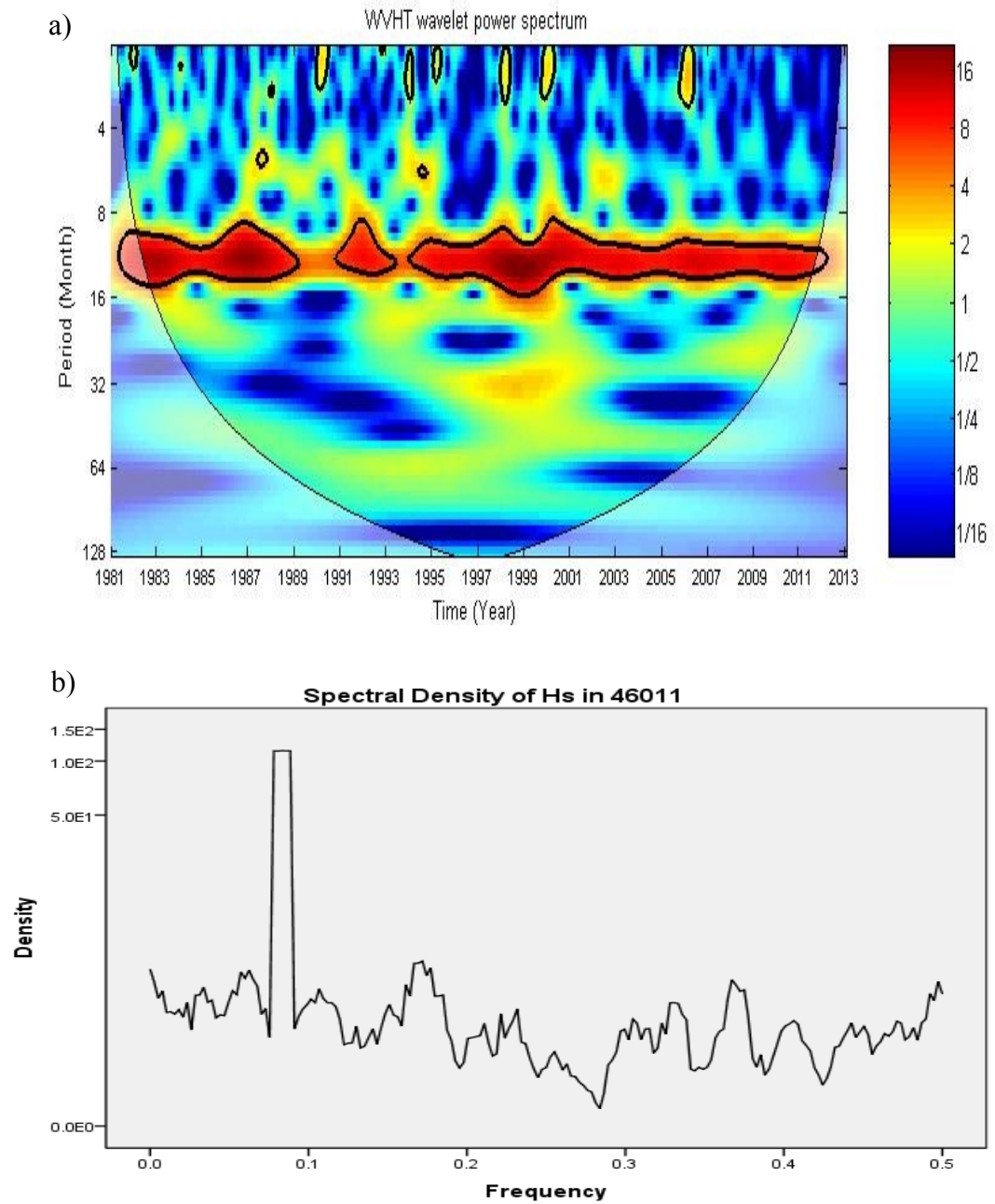


Figure 4.4 : a) Wavelet power spectrum (Morlet wavelet). b) Power spectral density of significant wave height in 46011.

Figure 4.4a shows the wavelet power spectrum of significant wave height in 46011 between 1977 to 2012 years. It is found that, there is a significant power at 8-16 month band in different years. The significant regions is observed from 1983-1989, 1991-1993, and 1994-1995. Also, (Figure 4.4b) shows an annual cycle in this sation.

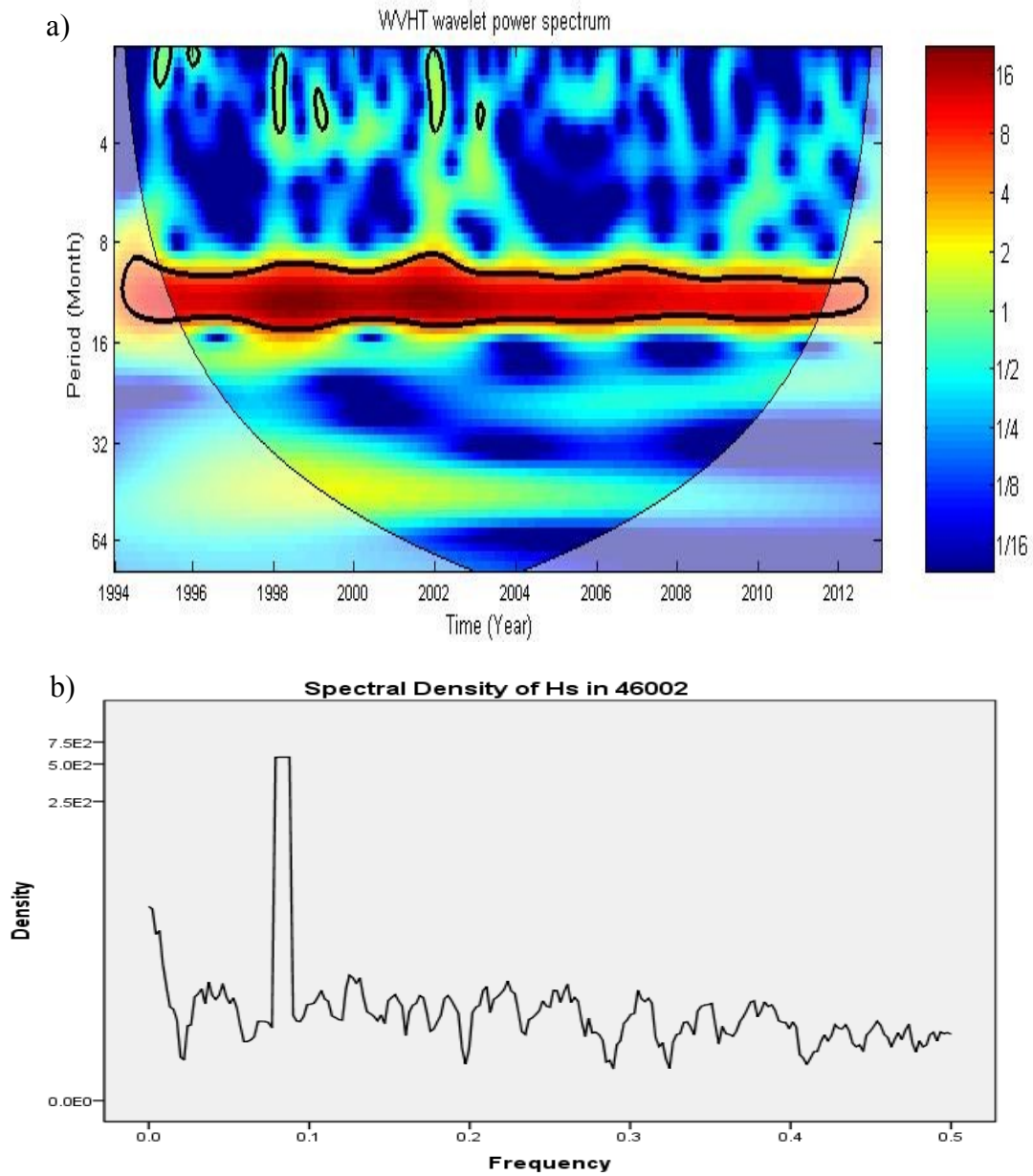


Figure 4.5 : a) Wavelet power spectrum (Morlet wavelet). b) Power spectral density of significant wave height in 46059.

Figure 4.5a indicates the wavelet power spectrum of significant wave height at 46059 between 1977 to 2012 years. The results show that there is a significant power at 8-16 month band in whole of the years and an annual cycle in this station (Figure 4.5b).

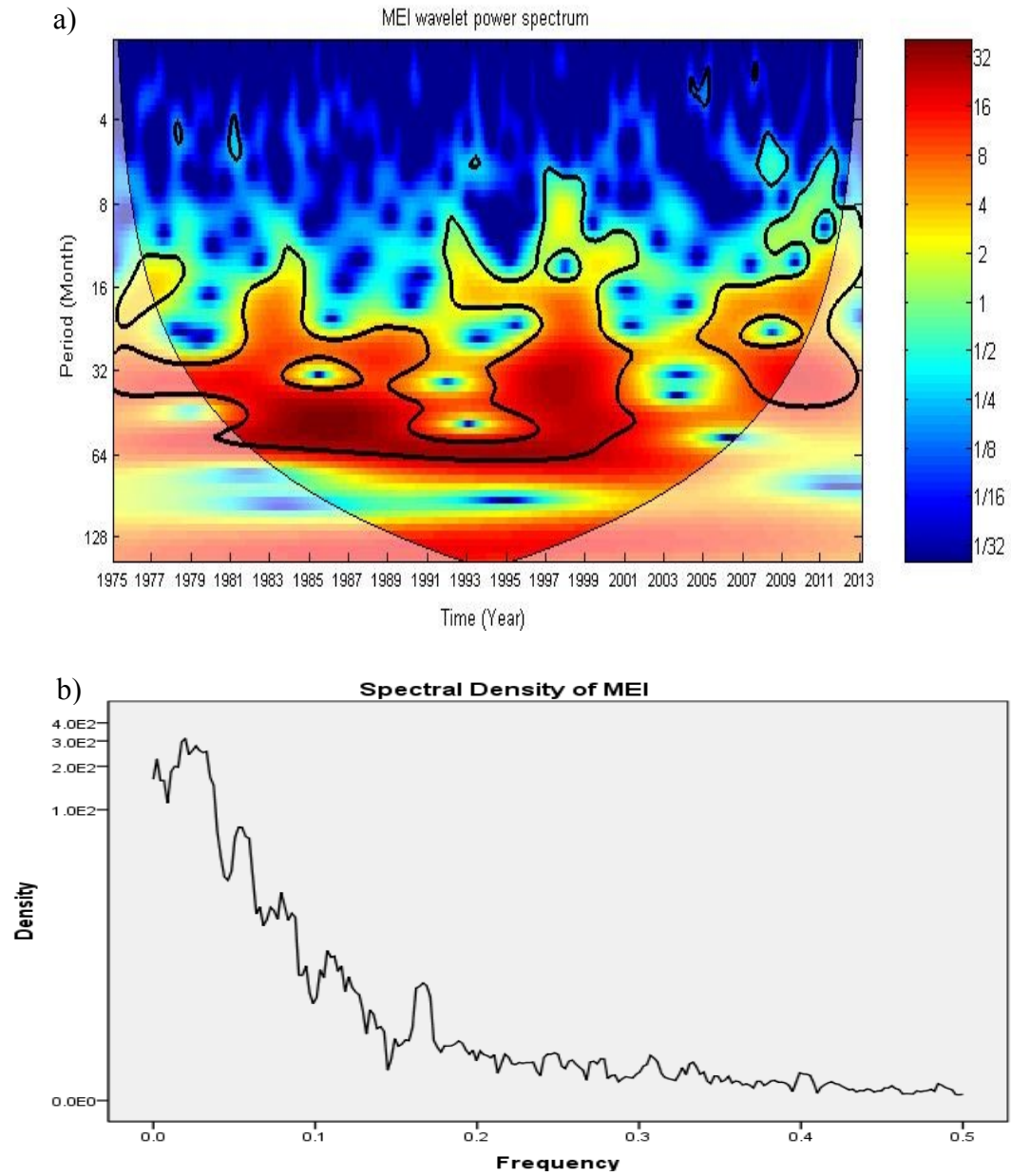


Figure 4.6 : a) Wavelet power spectrum (Morlet wavelet). b) Power spectral density of multivariate ENSO index (MEI).

The wavelet power spectrum between 1975 to 2012 years is shown for MEI, in (Figure 4.6a). The power is extensively distributed. A significant power can be seen at 45 to 60 months band between 1983-1989 years, 58-64 months band between 1989-1997 yr, and 32-64 months band between 1997-1999 yr. The plot of power spectral density shows that there is no an annula cycle in this climate index (Figure 4.6b).

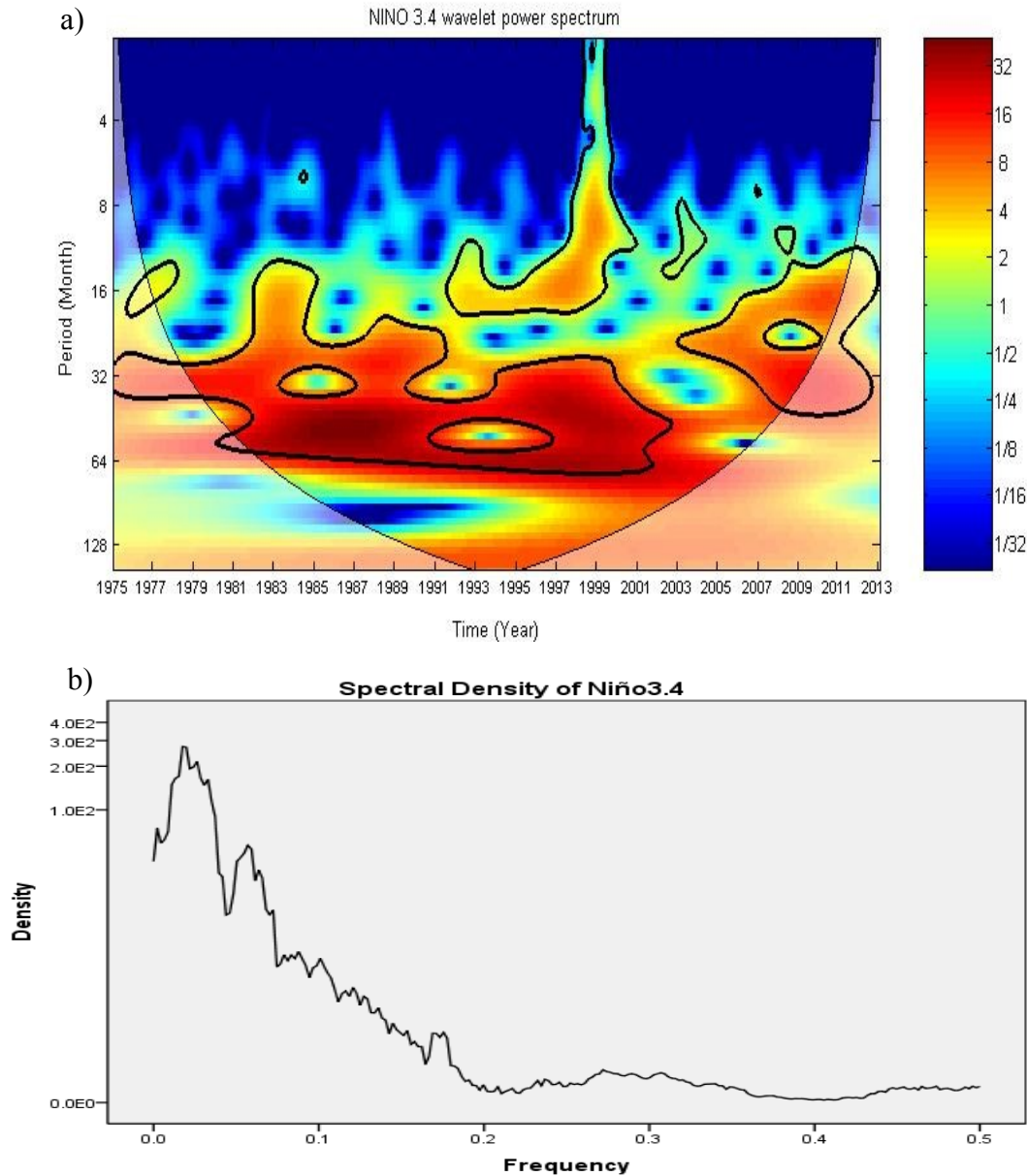


Figure 4.7 : a) Wavelet power spectrum (Morlet wavelet). b) Power spectral density of east central Pacific SST (Niño3.4).

The wavelet power spectrum between 1975 to 2012 years for Niño3.4 is shown in (Figure 4.7a). The power of Niño3.4 is broadly distributed similar to MEI. A high significant power can be seen at 45-60 months band between 1983-1991 years, 58-64 months between 1991-1997 yr and 32-64 months between 1997-2001 yr. Also, it is found that, the low power of this indice are in the 1983-1987, 1991-1997, and 2001-2007 years. On the other hand, it is figured out that there is no an annual cycle in this index (Figure 4.7b).

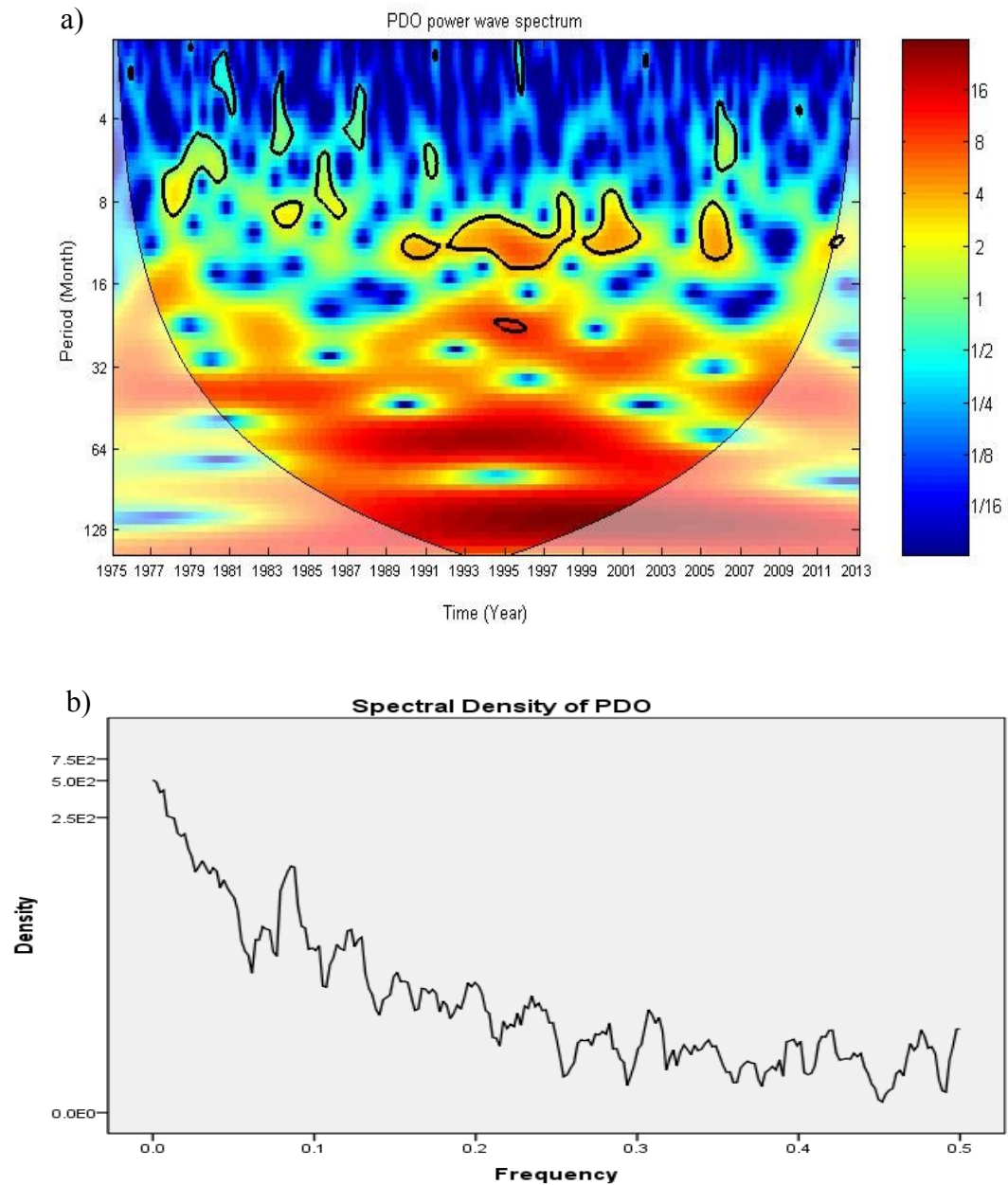


Figure 4.8 : a) Wavelet power spectrum (Morlet wavelet). b) Power spectral density of Pacific decadal oscillation index (PDO).

The wavelet power spectrum obtained from the normalized time series of 1975 to 2012 is shown for PDO index, in (Figure 4.8). This figure indicates that, there is no significant power in the PDO other than the annual cycle which is also not pronounced. Also, the plot of power spectral analysis indicates that there is an annual cycle in this index (0.083) (Figure 4.8b).

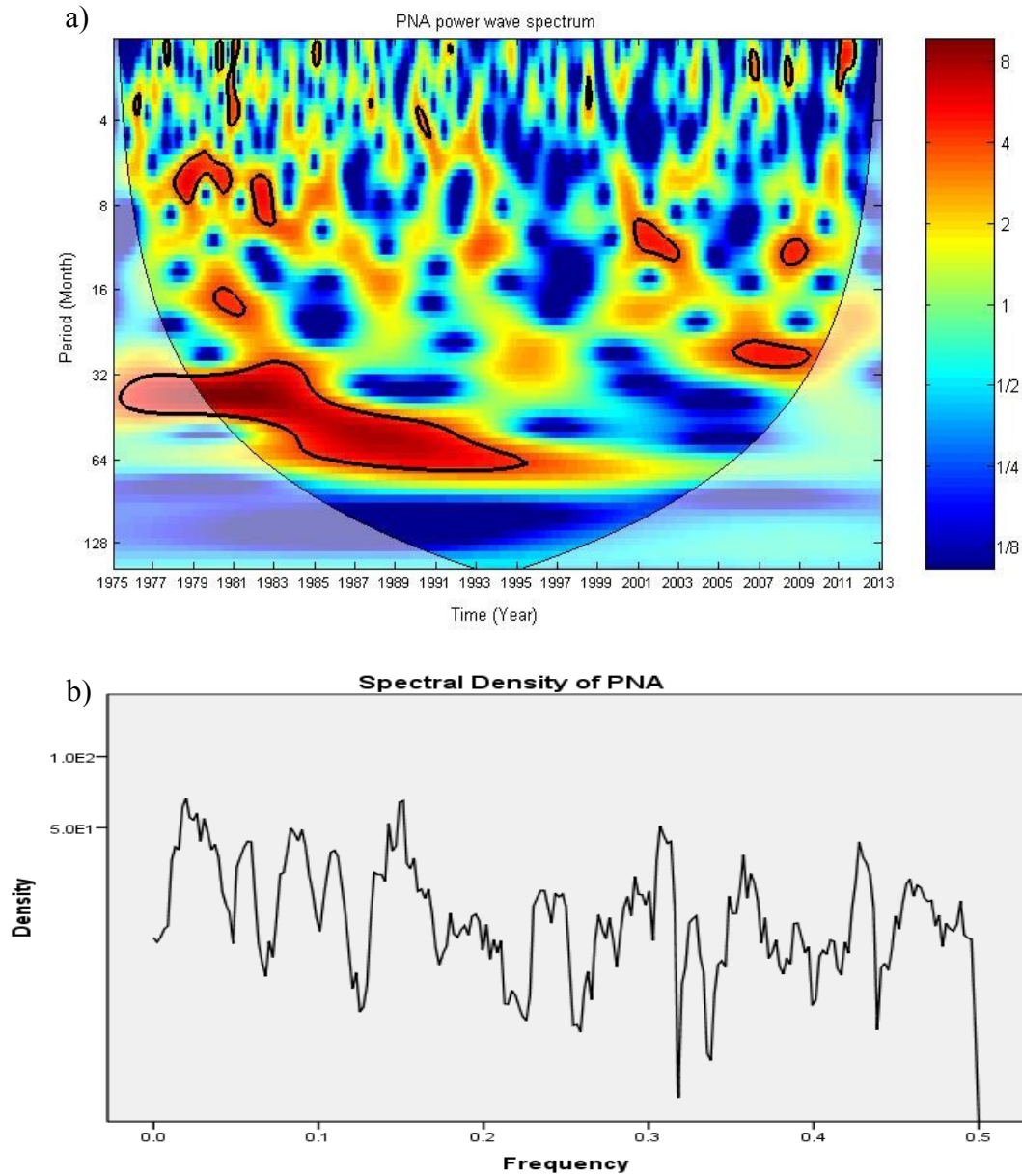


Figure 4.9 : a) Wavelet power spectrum (Morlet wavelet). b) Power spectral density of Pacific north American index (PNA).

The wavelet power spectrum of PNA index between 1975 to 2012 years is shown, in (Figure 4.9a). The power of PNA is distributed in some years and bands. A significant power can be seen at 35 to 48 months band between 1979-1984 yr, and 48-64 months band between 1986-1991 yr. Also, it can be seen that, the low power of this index are in the 1995-2005 and there is no an annual cycle in this index (Figure 4.9b).

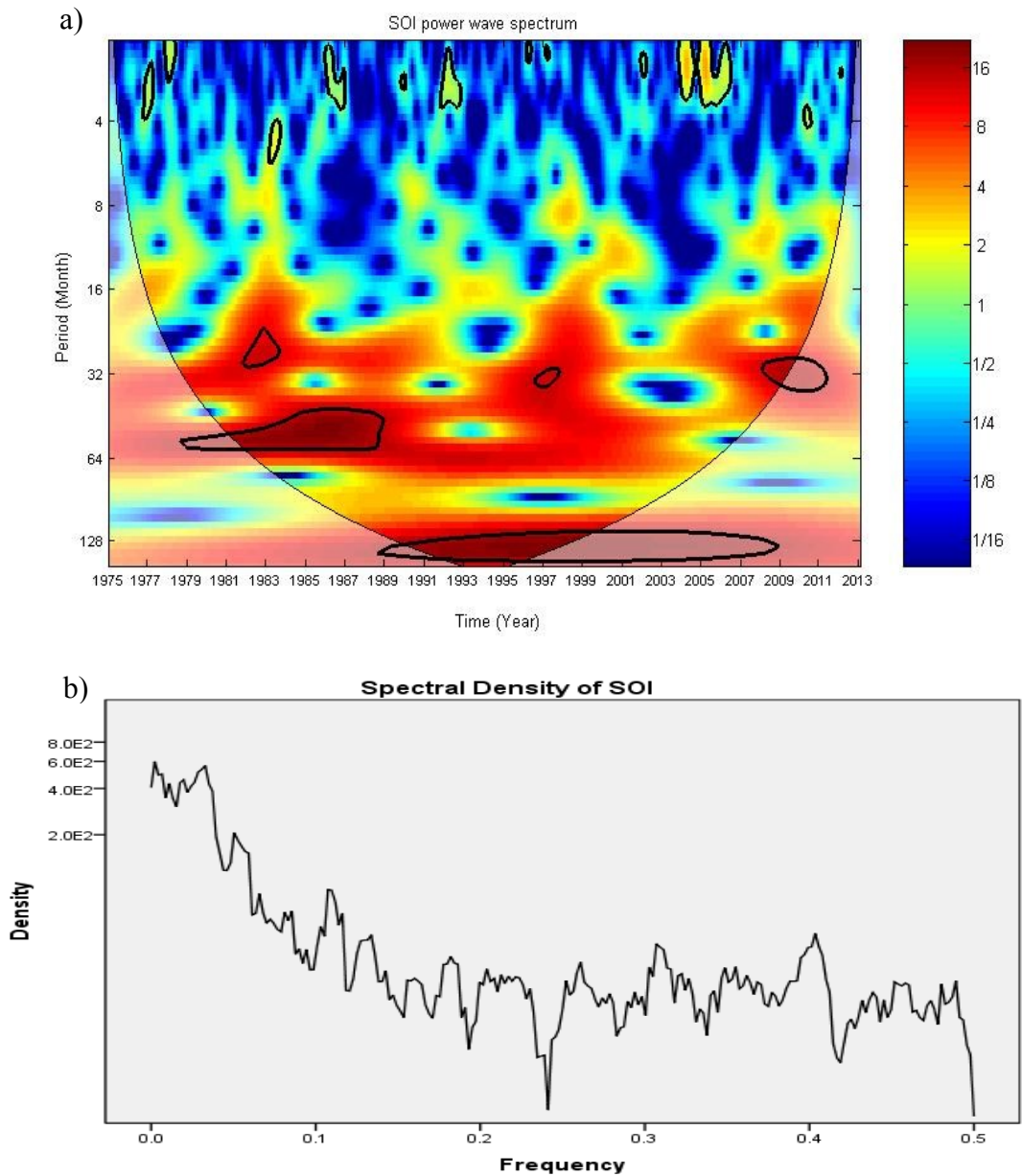


Figure 4.10 : a) Wavelet power spectrum (Morlet wavelet). b) Power spectral density of southern oscillation index (SOI).

Figure 4.10a shows the wavelet power spectrum of SOI between 1975 to 2012 years. The power of PNA is considerably distributed in some years and bands in this index. A significant power can be seen at 26 to 30 months band in the years between 1982-1984, 45-62 months band between 1981-1989, 120 to 200 months band between 1991-1999, 32-35 months band between 1996-1998, and 30-34 months band between 2008-2009. The power spectral analysis indicates that there is no annual cycle in this index (Figure 4.10b).

4.2 Wavelet coherency and phase

The wavelet coherency is used to identify both frequency bands and time intervals within which climate indices and significant wave heights are covering. The equation for wavelet coherency and phase are given in the methodology (3.3). Henceforth, the term coherency refers to the wavelet coherency.

To analyze the correlation between H_s and climate indices, cross wavelet transform was employed. All of the available data is applied in the transform because the coefficients of a signal in the continuous transform are multiplied with another signal by the complex conjugate of the coefficients. All of the analysis were done for all 5 stations between the significant wave heights and climate indices.

In the cross wavelet transform analysis between significant wave heights data and climate indices, arrows indicate the relationship between indices. The vectors indicate the phase difference between climate indices. Rightwards arrows indicate in-phase, bottom-right arrows indicate a small lead of x , and leftward arrows indicates anti-phase. The thick black contour is the 5% significance level. Calculated mean angle and 95% confidence interval of the wavelet coherence are $358^\circ \pm 2^\circ$ confirming the rather narrow phase angle distribution. Cross-hatched regions indicate the cone of influence.

Figures 4.11 to 4.16 shows the wavelet coherency between significant wave heights of 46002 buoy and Niño3.4, PNA, MEI, SOI, and PDO indices. Others, cross wavelet analysis figures are shown in Appendix section, which include the plots of wavelet coherency between H_s and climate indices in the stations of 46005, 46006, 46011, and 46059.

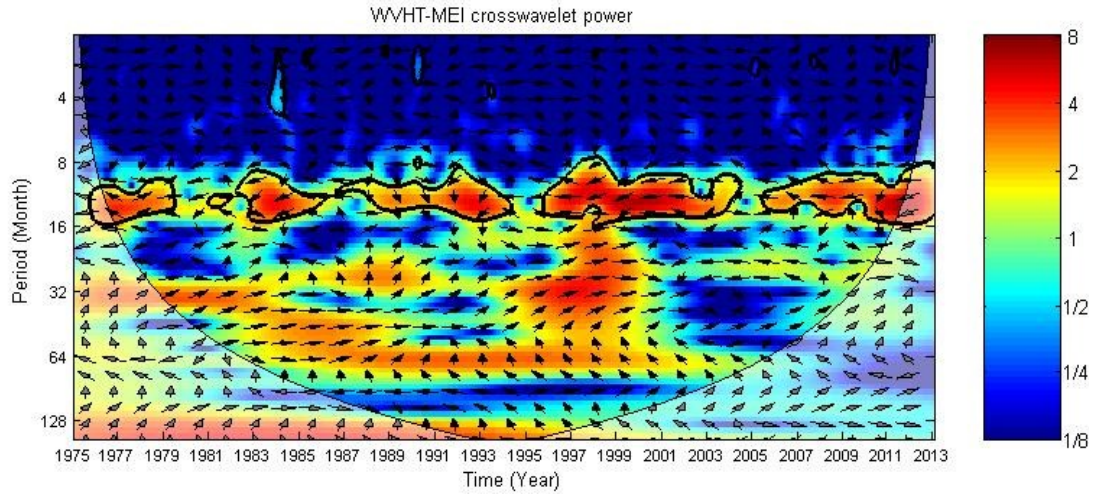


Figure 4.11 : The cross wavelet transform between significant wave height and Multivariate ENSO Index in the Orgeon buoy (46002).

The wavelet coherency between significant wave height of 46002 buoy and (MEI) is shown in (Figure 4.11). The H_s and MEI show high coherency in the 8-16 month band, with rather low coherency outside of these periods from 1980-1983, 1995-1996, and 2004-2005 years. Since 1975-1980, 1984-1994, 1996-2003, and 2006-2012 years there is a shift in the period of maximum coherence from around 8 month up to around 16 month. It is suggest that independent processes (noise) drive at the smallest and largest scales. Furthermore, it could be concluded that there is a more influence coherency in 1996-2003 years in 12 month band. It can be seen that all significant sections show anti-phase behavior.

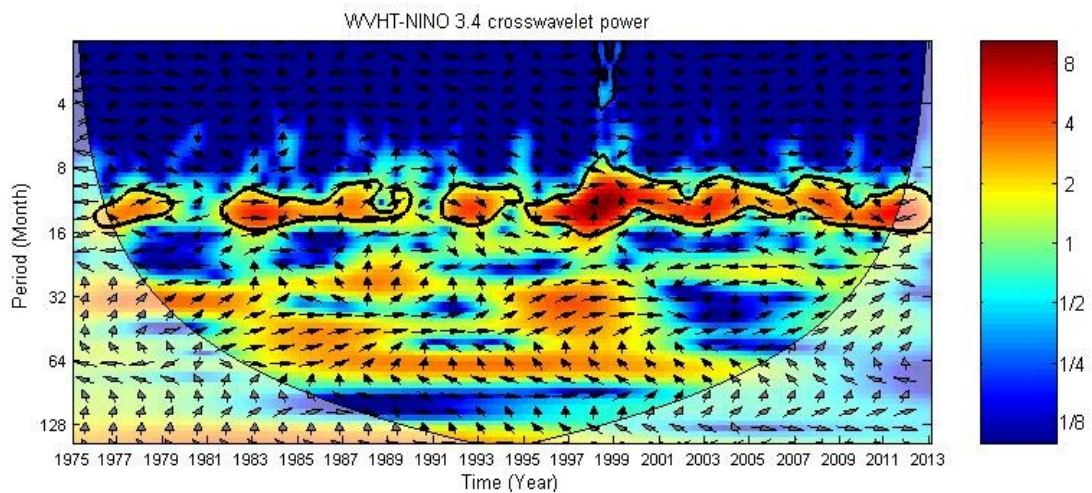


Figure 4.12 : The cross wavelet transform between significant wave height and East Central Pacific SST (Niño3.4) in Orgeon buoy 46002.

The wavelet coherency between significant wave height of 46002 buoy and Niño3.4 is shown in (Figure 4.12). The H_s and Niño3.4 show high coherency in the 8-16 month band, with rather low coherency outside of these periods from 1979-1981, and in 1988-1991 years. Since 1976-1979, 1982-1988, and 1991-2012 years there is a shift in the period of maximum coherence from around 8 month up to around 16 month. It is suggested that independent processes (noise) drive at the smallest and largest scales. Furthermore, it could be concluded that there is a more influence coherency between 1997-2000 years at 10 to 14 month band. It can be seen that all significant sections show anti-phase behavior except between 1982-1984 years which there is a in-phase behavior in this section.

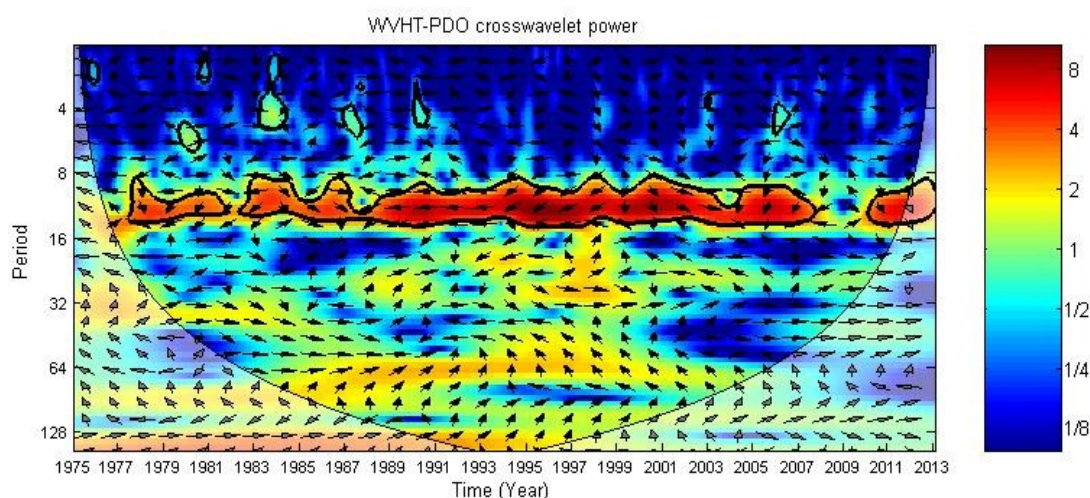


Figure 4.13 : The cross wavelet transform between significant wave height and Pacific decadal oscillation Index (PDO) in Orgeon buoy (46002).

The wavelet coherency between significant wave height of 46002 buoy and PDO index (PDO) is shown in (Figure 4.13). The H_s and PDO show high coherency in the 8-16 month band, with rather low coherency outside of these periods from 2007-2010 years. Since 1977-2010, and 2010-2012 years there is a shift in the period of maximum coherence from around 8 month up to around 16 month. It is suggested that independent processes (noise) drive at the smallest and largest scales. Furthermore, it could be concluded that there is a more influence coherency in 1989-2003 years in 10 to 12 month band. It can be seen that all significant sections show anti-phase behavior in whole of the analysis years.

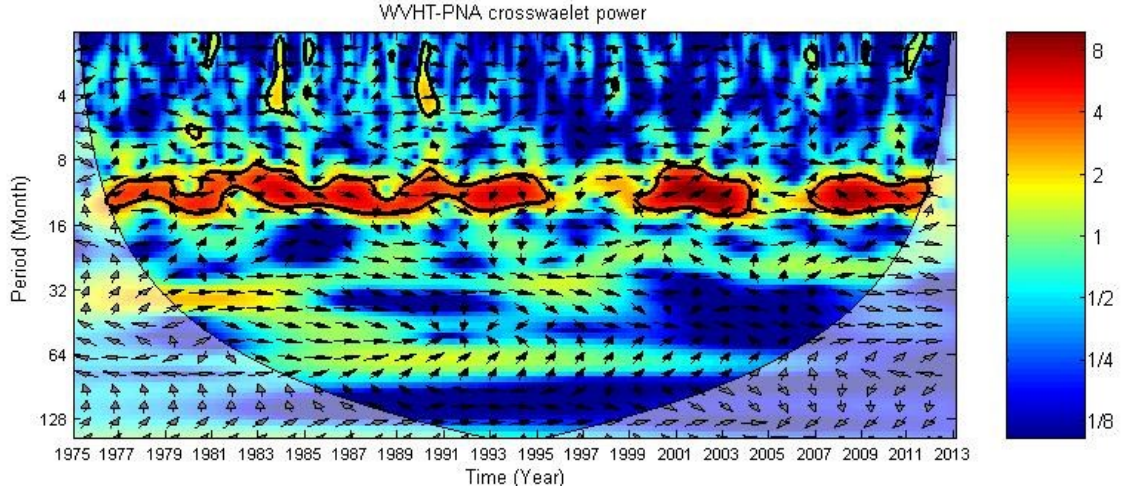


Figure 4.14 : The cross wavelet transform between significant wave height and Pacific north American index (PNA) in Orgeon buoy (46002).

The wavelet coherency between significant wave height of 46002 buoy and PNA index is shown in (Figure 4.14). The H_s and pna show high coherency in the 8-16 month band, with rather low coherency outside of these periods from 1996-1999, and 2004-2007 years. Since 1977-1996, 1999-2004, and 2007-2012 years there is a shift in the period of maximum coherence from around 8 month up to around 16 month. It is suggest that independent processes (noise) drive at the smallest and largest scales. Furthermore, it could be concluded that there is a more influence coherency in 1999-2004 years in 10 to 14 month band, and also in 2008-2009 years in 12 month band. In phase analysis it can be seen that all significant sections show anti-phase behavior in whole of the analysis years.

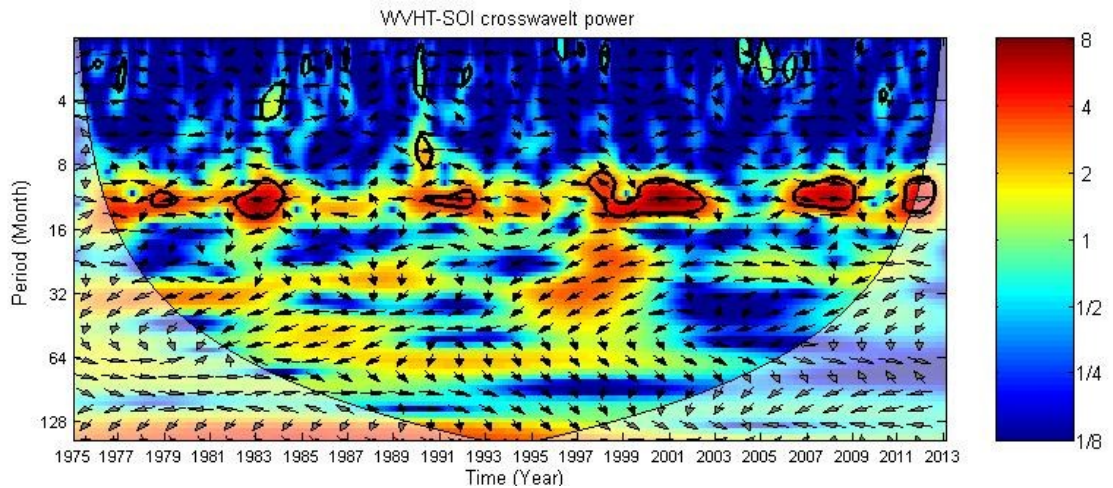


Figure 4.15 : The cross wavelet transform between significant wave height and Southern oscillation index SOI in Orgeon buoy (46002).

The wavelet coherency between significant wave height of 46002 buoy and SOI is shown in (Figure 4.15). The H_s and SOI show high coherency in the 8-16 month band, with rather low coherency outside of these periods from 1977-1979, 1979-1981, 1984-1990, 1992-1997, 2002-2004, and 2009-2012 years. Since 1979, 1982-1984, 1990-1992, 1997-2002, 2004-2009, and 2012 years there is a shift in the period of maximum coherence from around 8 month up to around 16 month. It is suggest that independent processes (noise) drive at the smallest and largest scales. Additionally, it could be concluded that there is a more influence coherency in 1983, 2001, and 2006 years in 12 month band. In the phase analysis it can be seen that all significant sections show in-phase behavior in whole of the analysis years except in the years of 1982-1984 that there is a anti-phase behavior.

The results of wavelet coherency between H_s and climate indices in 46005, 46006, 46011, 46059 buoys are shown in (Table 4.1 to Table 4.4) respectively.

Table 4.1 : Cross-wavelet between H_s and climate indices in 46005.

Station	Period	Index	Band (Month)	High Coherency (Year)	Phase
46005	1976-2012	H_s & Nino 3.4	8 to 16	1978-1979, 1982-1989, 1992-2012	In-phase
		H_s & SOI	8 to 16	1978-1979, 1982-1984, 1991-1993, 1998-2002, 2006-2009, 2011	Anti-phase
		H_s & PNA	8 to 16	1977-1996, 1999-2004, 2007-2012	Anti-phase
		H_s & MEI	8 to 16	1977-1980, 1983-1995, 1996-2005, 2006-2012	Anti-phase
		H_s & PDO	8 to 16	1977-1982, 1983-2008, 2010-2012	Anti-phase

There is anti-phase behavior between significant wave height and SOI, PNA, MEI, and PDO indices, while there is in-phase behavior between H_s and Niño3.4 in 12-15 month band between 1982-1983 years (see Table 4.1). It is be noted that, in plots of coherency analysis which is shown in (Figures B.1 to B.5) there is a dark red area which tells us most significant power occurs in this area. The significant cross wavelet power in 46005 buoy station are as follows:

1997-2000 years at 10-14 month band in Niño3.4, 2000-2002 years at 11-13 month band in SOI, 2000-2003 and 2008-2009 yr at 10-13 month band in PNA, 1999-2002 yr at 11-13 month band in MEI, and 1994-2002 yr at 10-13 month band in PDO.

Table 4.2 : Cross-wavelet between H_s and climate indices in 46006.

Station	Period	Index	Band (Month)	High Coherency (Year)	Phase
46006	1977-2012	H_s & Nino 3.4	8 to 16	1978-1980, 1982-1989, 1991-2012	Anti-phase
		H_s & SOI	8 to 16	1978-1980, 1982-1984, 1992, 1996-2003, 2006-2009	In-phase
		H_s & PNA	8 to 16	1978-1996, 1999-2004, 2007-2012	Anti-phase
		H_s & MEI	8 to 16	1978-1980, 1982-1995, 1996-2012	Anti-phase
		H_s & PDO	8 to 16	1978-2008, 2010-2012	Anti-phase

There is anti-phase behavior between significant wave height and Niño3.4, PNA, MEI, and PDO indices, while there is in-phase behavior between H_s and SOI in 12 month band in 2000-2003, and 2006-2009 years (See Table 4.2). The plots of coherency analysis for this station is shown in (Figures B.6 to B.10). The significant cross wavelet power in 46006 buoy station are as follows:

1998-2000 years at 9-14 month band in Niño3.4, 1982-1984, and 2000-2003 yr at 12-14 month band in SOI, 2000-2003 yr at 10-14 month band in PNA, 1999-2001 yr at 12 month band in MEI, and 1994-1998 yr at 11-14 month band in PDO. Furthermore, it is found that the PDO index impact significantly on the wave climate in this buoy, while has less effect on the wave climate whole the 36 years.

Table 4.3 : Cross-wavelet between H_s and climate indices in 46011.

Station	Period	Index	Band (Month)	High Coherency (Year)	Phase
46011	1981-2012	H_s & Nino 3.4	8 to 16	1982-1988, 1992-1994, 1996-2012	Anti-phase
		H_s & SOI	8 to 16	1982-1984, 1998-2002, 2006-2009	Anti-phase
		H_s & PNA	8 to 16	1982-1989, 1991-1995, 1999-2004, 2007-2012	Anti-phase
		H_s & MEI	8 to 16	1982-1988, 1991-1994, 1996-2003, 2006-2012	Anti-phase
		H_s & PDO	8 to 16	1982-1988, 1989-2008, 2011-2012	Anti-phase

As can be seen from the (Table 4.3) and Figures (B.11 to B. 15), there is no in-phase behavior between H_s and climate indices in the cross-wavelet analysis between significant wave heights of buoy 46011 and climate indice. PDO index has considerabe

effect on the wave climate in this buoy, while has less effect on the wave climate. The significant cross wavelet power in 46011 buoy station are as follows:

1997-1999 years at 30-33 month band in Niño3.4, 1998-2002 yr at 12-15 month band in SOI, 1987, 2000-2003, and 2008-2009 yr at 10-14 month band in PNA, 1996-2001 yr at 26-34 month band in MEI, and 1995-2002 yr at 10-14 month band in PDO.

Table 4.4 : Cross-wavelet between H_s and climate indices in 46059.

Station	Period	Index	Band (Month)	High Coherency (Year)	Phase
46059	1994-2012	H_s & Nino 3.4	8 to 16	1995-2011	Anti-phase
		H_s & SOI	8 to 16	1998-2002, 2006-2009, 2011	In-phase
		H_s & PNA	8 to 16	1999-2004, 2006-2011	Anti-phase
		H_s & MEI	8 to 16	1996-2004, 2006-2012	Anti-phase
		H_s & PDO	8 to 16	1995-2008, 2010-2012	Anti-phase

Table 4.4 and Figures B.16 to B.20 indicates that in the cross-wavelet analysis between significant wave height of buoy 46059 and climate indices, there is in-phase behavior between H_s and SOI in 2000-2002 and 2006-2009 yr in 12 month band, while there is no in-phase behavior in rest of the H_s and climate indices. PDO index and Pacific North American has less effect on the wave climate in this buoy, while the others have significant effect on the wave climate whole the 18 years. The significant cross wavelet power in 46059 buoy station are as follows:

1997-1999 years at 8-16 month band in Niño3.4, 2000-2002 yr at 10-14 month band in SOI, 2001-2003 yr at 10-14 month band in PNA, 1999-2001 yr at 12-15 month band in MEI, 1995-1998 yr at 12-14 month band, 1999-2002 yr in 10-13 month band, and 2005-2006 yr at 12-14 month band in PDO.

5. CONCLUSIONS

In order to detect the possible effects of ENSO events on the wave height variability, the wavelet analysis was applied to significant wave height and large scale climate indices. Five buoy stations were used for this investigation which includes 46002, 46005, 46006, 46011, and 46059. The large scale climate indices which are the Niño3.4, PDO index, MEI, PNA index, and SOI were used to detect possible correlations between these climate indices and significant wave heights. Also, dominant periods of significant wave height variability were investigated using measured buoy data.

Mann-Kendall trend test analysis was employed to determine trends in both wave heights and climate indices, using the normilzed time series analysis. The Mann-Kendall trend test with decide on a probability level of significance (95% typically) was done over the significant wave heights data on the buoy stations data. The results of the trend test indicated that there is no trend in buoy stations and Nino 3.4, MEI, PDO, PNA indices. On the other hand, SOI index has an increasing trend. In comparison to trend test analysis the seasonal trend test indicated that there was an increasing trend in 46002, 46005, 46006, and PDO, but in the SOI there was no trend in opposite of normal trend test that there was an increasing trend in this index.

Temporal variability of wave climate was analyzed considering the seasonal avareged mean significant wave heights. It is found that the summer seasons have the lowest dispersion of significant wave height compared with the winter seasons which have the highest dispersion of significant wave height. Furthermore, the standard deviation of significant wave height shows that there is a considerable temporal variability at buoy stations.

The annual mean values of the significant wave heights H_s and the mean winter significant wave heights WH_s determined for each of the buoy stations. In Oregon buoy 46002, it is found that wave heights were generally lower during the mid 1970s, around 2.83 m during the winter months, and there followed a progressive increase in

the wave heights that peaked around 4.57 m during the late 1980s and 1990s. In 46005 buoy the annual average of H_s increased at a rate of $0.0063 \text{ m. yr}^{-1}$ since 1976, while the annual winter average WH_s increased by $0.0043 \text{ m. yr}^{-1}$. The annual average of WH_s measured in 46006 buoy increased at a rate of $0.0072 \text{ m. yr}^{-1}$, and the annual average of H_s increased at a rate of $0.0068 \text{ m. yr}^{-1}$. The Santa Maria buoy 46011 shows a little evidence for an increase in the annual average of H_s and a decrease in the average winter of WH_s . On the other hand, the wave climate in 46059 illustrated that there is a decreasing in the average winter of WH_s at a rate of $-0.0267 \text{ m. yr}^{-1}$, and a negatively sloping regression line in the annual average of H_s at a rate of $-0.0083 \text{ m. yr}^{-1}$.

The buoy stations have been characterized by unusually wave conditions due to the severity of the El Niño and La Niña since 1982. Analysis of the temporal and spatial variability of the wave statistics has also demonstrated a dependence of the annual wave conditions in Pacific Ocean buoys on the climate spectrum ranging between El Niño and La Niñas. The analysis demonstrated that there does appear to be a regional influence of El Niño /La Niña. La Niña appear to dominate the buoy measurements in Pacific Ocean. And, also it is found that the strong El Niño, as occurred during 1982-83, 1987-88, and 1997-98 which is during 1997-98 El Niño having generated the largest average wave heights at 46002, 46005, 46006, and 46011 except 46059. While the La Niña events appear to have had a negligible influence on the wave height statistics.

The wavelet power spectra are determined for each station. According to the power spectra analysis of MEI and Nino 3.4 there is a variable significant power at 32 to 64 month band between 1983-2001 years. Also, there is a noticeable power band at 35 to 48 month from 1979-1984, and 26 to 30 month from 1982-1989 for PNA and SOI, respectively. It should be noted that there is no considerable power in the PDO other than annual cycle which is also not pronounced. From the results of the wavelet spectra, it can be concluded that there are relatively large interannual changes in the spectra especially in ENSO years. The power spectral density analysis illustrated that there is an annual cycle in buoy stations wave data and climate indices.

In the cross-wavelet analysis between significant wave height of 46002 buoy and MEI, it is found that, there is a high coherency in 8-16 month band, Since 1975-1980, 1984-1994, 1996-2003, and 2006-2012 years, and a more influence coherency in 1996-2003

years in 12 month band. Also, it was observed that there is a anti-phase behavior between H_s and climate indices in this station. The results of cross-wavelet analysis in 46005 illustrated that there is anti-phase behavior between significant wave height and SOI, PNA, MEI, and PDO indices, while there is in-phase behavior between H_s and Niño3.4 in 12-15 month band in 1982-1983 years. In the cross-wavelet transform of 46006 buoys station it is figured out that there is anti-phase behavior between significant wave height and Niño3.4, PNA, MEI, and PDO indices, and there is in-phase behavior between H_s and SOI in 12 month band in 2000-2003, and 2006-2009 years. Also, it is found that there is significant impact of PDO index on the wave climate in this buoy, while the SOI has less effect on the wave climate considering the whole the 36 years. In 46011, there was not in-phase behavior between H_s and climate indices in the cross-wavelet analysis. Finally, the analysis between significant wave height of buoy 46059 and climate indices indicates that, there is in-phase behavior between H_s and SOI in 2000-2002 and 2006-2009 yr in 12 months band, while there is no in-phase behavior between in rest of the H_s and climate indices.

Large-scale climate indices influence the wave climate especially in El-Nino years. During La-Nina years, there is no significant effects on wave climate compared to El Nino events. To understand the possible influence of climate indices over H_s will be useful in several studies. It suggests that El Nino / La Nina events could produce wind patterns that can force extreme wave events in the Pacific Ocean. The results illustrated the strong link between the ocean and atmospheric climate dynamics, since inter-annual and long-term of H_s variabilities. The importance of the annual cycle may also reflect the impact of mid-winter suppression of cyclone growth at higher latitudes. The wavelet power spectrum and spectral analysis illustrated that there is an annual cycle in all 5-buoy stations that by using those analysis it is possible to predict the events of past and future wave climate in Pacific Ocean. Furthermore, integrating climate indices in the prediction of significant wave height would be very advantageous in the Pacific Ocean.

REFERENCES

- Aguiar, L., Soares, M. J.** (2011). The continuous wavelet transform: A primer. NIPE WP 16/2011.
- Bauer, E.** (2001). Interannual changes of the ocean wave variability in the North Atlantic and in the North Sea, *Climate Research* 18, 63–69.
- Bjerknes, J.** (1996). A possible response of the atmospheric Hadley circulation to equatorial anomalies in ocean temperature, *Tellus*, 18, 820–829.
- Dodet, G., Bertin, X., and Taborda, R.** (2010). Wave climate variability in the North-East Atlantic Ocean over the last six decades, *Ocean Modelling* 31, 120–131.
- Dragani, W. C., Martin, P. B., Simionato, C. G., and Campos, M. I.** (2010). Are wind wave heights increasing in south-eastern south American continental shelf between 32°S and 40°S? *Continental Shelf Research* 30, 481–490.
- Etemad-Shahidi, A. And Mahjoobi, J.,** (2009). Comparison between M5' Model Tree and Neural Networks for Prediction of Significant Wave Height in Lake Superior, *Ocean Engineering*, 36,1175-1181.
- Fernandez-Macho, J.** (2012). Wavelet multiple correlation and cross-correlation: A multiscale analysis of Eurozone stock markets, *Physica A: Statistical Mechanics and its Applications*, 391(4), 1097-1104.
- Gower, J. F. R.** (2002). Temperature, wind and wave climatologies, and trends from marine meteorological buoys in the Northeast Pacific. *Journal of Climate* 15, 3709-3718.
- Grinsted, A., Moore, J. C., and Jevrejeva, S.** (2004). Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Processes in Geophysics* (2004) 11:561-566. SRef-ID: 1607 – 7946/npg/2004-11-561.
- Hudgins, L., Friehe, C. A., and Mayer, M. E.** (1993). Wavelet transform and Atmospheric Turbulence, Volume 71, Number 20.
- Huang, D-W.** (2003). Wavelet analysis in a traffic model, *Physica A: Statistical Mechanics and its Applications*, 329(1–2), 298-308.
- Izaguirre, C., Mendez, F. J., Menendez, M., and Losada, I. J.** (2011). Global extreme wave height variability based on saellite data. *Geophysical research letters*, VOL. 38, L10607, doi:10.1029/2011GL047302.
- Liu, Y., Liang, X. San., and Weisberg, R. H.** (2006). Rectification of the bias in the wavelet power spectrum. DOI: 10.1175/2007JTECHO511.1.

- Liu, P. C.** (1994). Wavelet spectrum analysis and ocean wind waves. In: Foufoula-Georgiou E, Kumar P (eds) Wavelets in geophysics. Academic Press, San Diego, p 151–166.
- Mackay, E. B. L., Bahaj, A. S., and Challenor, P. G.** (2010). Uncertainty in wave energy resource assessment. Part 2: Variability and predictability, Renewable Energy 35, 1809–1819.
- Mahjoobi, J. and Mosabbeh, E. A.** (2009). Prediction of significant wave height using regressive support vector machines, Ocean Engineering, 36(5), 339-347.
- Mendez, F. J., Menendez, M., Luceno, A., and Losada, I. J.** (2006). Estimation of the long- term variability of extreme significant wave height using a time dependent POT model. Journal of Geophysical Research 111 (C07024), doi:10.1029/2005JC003344.
- Menendez, M. F. J., Mendez, I. J. Losada, and Graham, N. E.** (2008). Variability of extreme wave heights in the northeast Pacific Ocean based on buoy measurements, Geophys. Res. Lett., 35, L22607, doi:10.1029/2008GL035394
- Ozger, M.** (2010). Significant wave height forecasting using wavelet fuzzy logic approach, Ocean Engineering, 37(16), 1443–1451.
- Ozger, M., and Sen, Z.** (2007). Prediction of wave parameters by fuzzy logic approach. Ocean Engineering 34, 460–469.
- Ozger, M.** (2011). Scaling characteristics of ocean wave height time series, Physica A: Statistical Mechanics and its Applications, 390,(6) 981-989.
- Robert, M., Hirsch, James, R. Slack, and Richard, A. S.** (1982). Techniques of Trend Analysis for Monthly Water Quality Data. VOL. 18, NO. 1, PAGES 107-121.
- Rosso, O. A., Martin, M. T., Plastino, A.** (2002). Brain electrical activity analysis using wavelet-based informational tools, Physica A: Statistical Mechanics and its Applications, 313(3–4), 587-608.
- Rozynski, G.** (2010). Long-term evolution of Baltic Sea wave climate near a coastal segment in Poland; its drivers and impacts, Ocean Engineering 37, 186–199.
- Ruggiero, P., Komar, P. D., and Allan, J. C.** (2010). Increasing wave heights and extreme value projections: The wave climate of the U.S. Pacific Northwest, Coastal Engineering 57, 539–552.
- S.Jevrejeva, J. C., Moore and A. Grinsted.** (2003). Influence of the Arctic Oscillation and El Nino-Souther Oscillation (ENSO) on ice conditions in the Baltic Sea. VOL. 108, NO. D21, 4677, doi:10.1029/2003JD003417, 2003.
- Torrence, C., and Compo, G. P.** (1998). A practical guide to wavelet analysis. Bull. Amer. Meteor. Soc., 79, 61–78.
- Url-1** <<http://www.ndbc.noaa.gov/hmd.shtml>>, date retrieved 20.08.2014.

APPENDICES

APPENDIX A: Correlations between Significant wave heights and climate indices Maps.

APPENDIX B: Cross-wavelet analysis Maps.

APPENDIX A

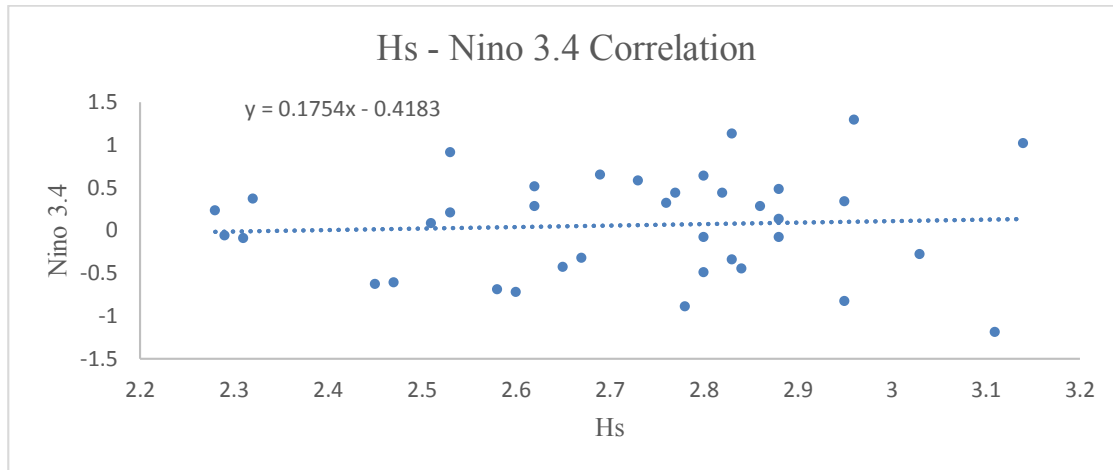


Figure A.1 : Annually Correlation between H_s and (Niño3.4) in 46005.

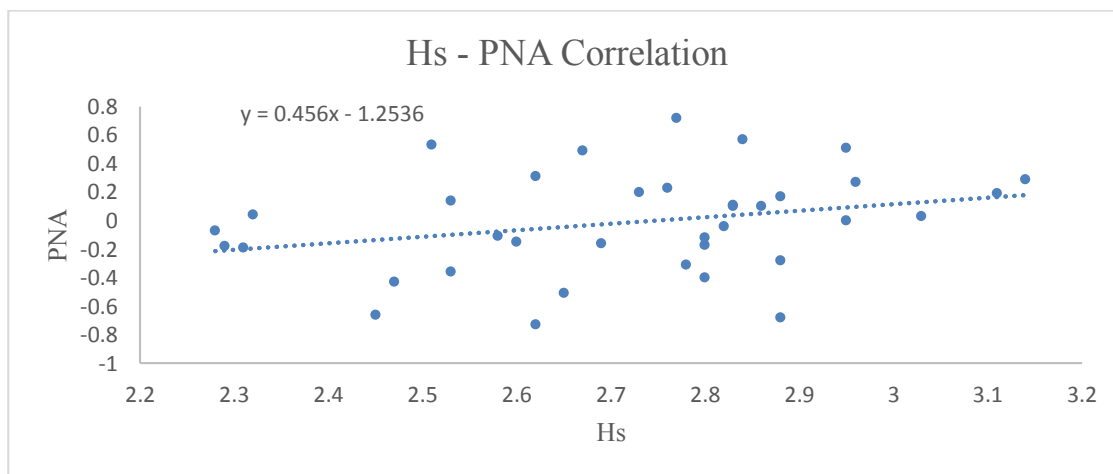


Figure A.2 : Annually Correlation between H_s and (PNA) in 46005.

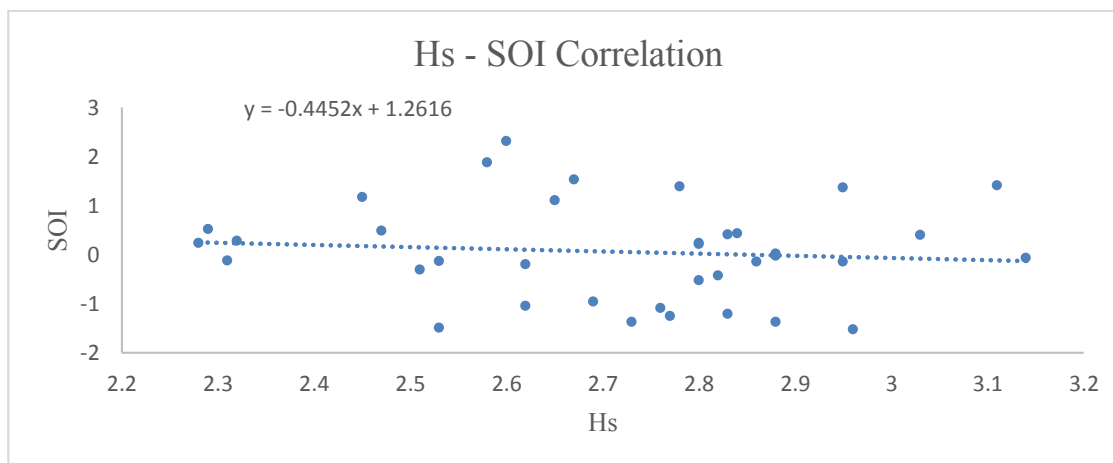


Figure A.3 : Annually Correlation between H_s and (SOI) in 46005.

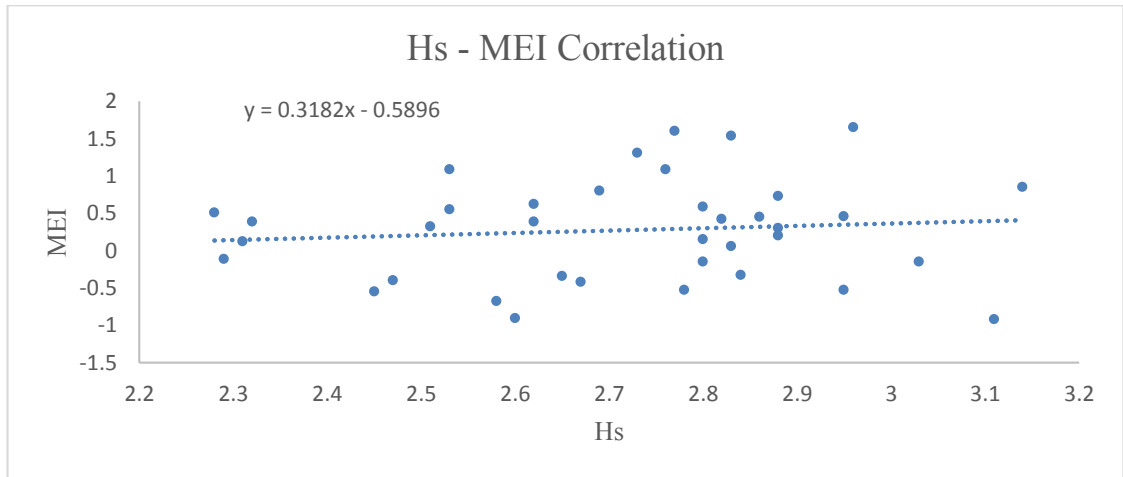


Figure A.4 : Annually Correlation between H_s and (MEI) in 46005.

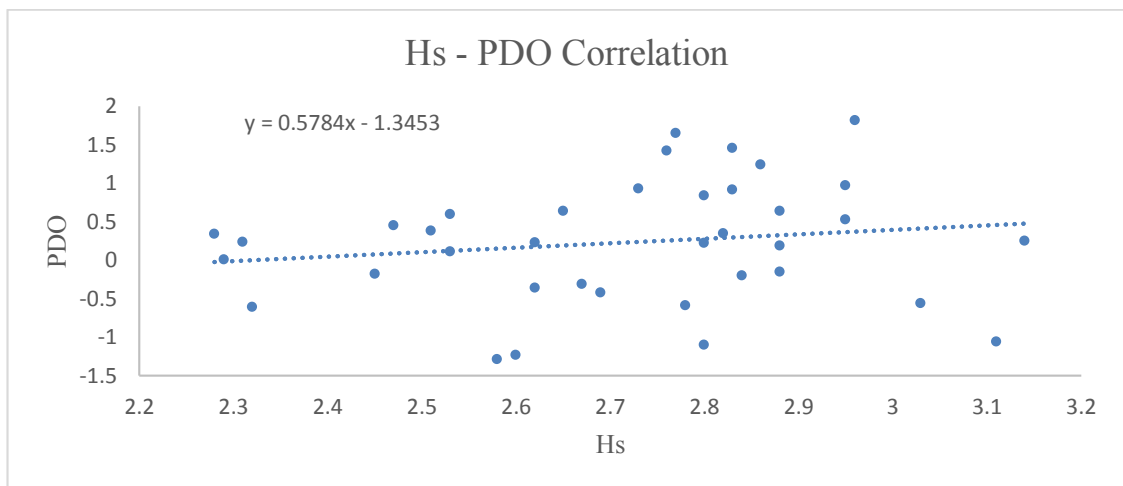


Figure A.5 : Annually Correlation between H_s and (PDO) in 46005.

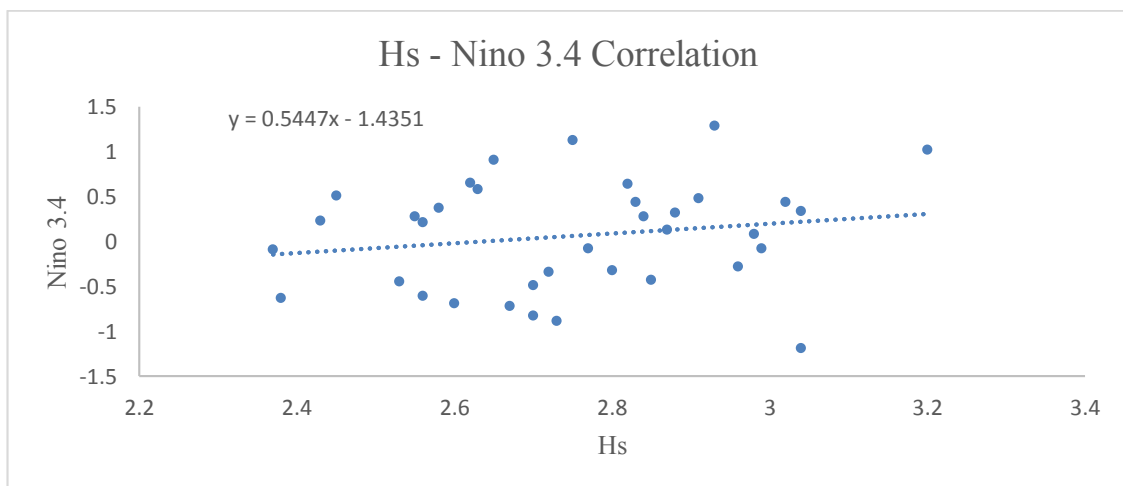


Figure A.6 : Annually Correlation between H_s and (Niño3.4) in 46006.

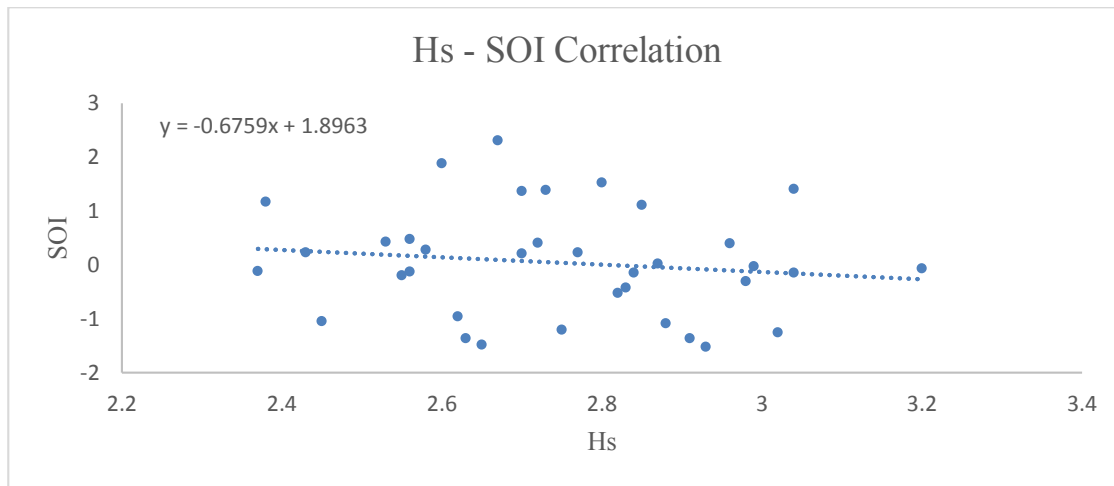


Figure A.7 : Annually Correlation between H_s and (SOI) in 46006.

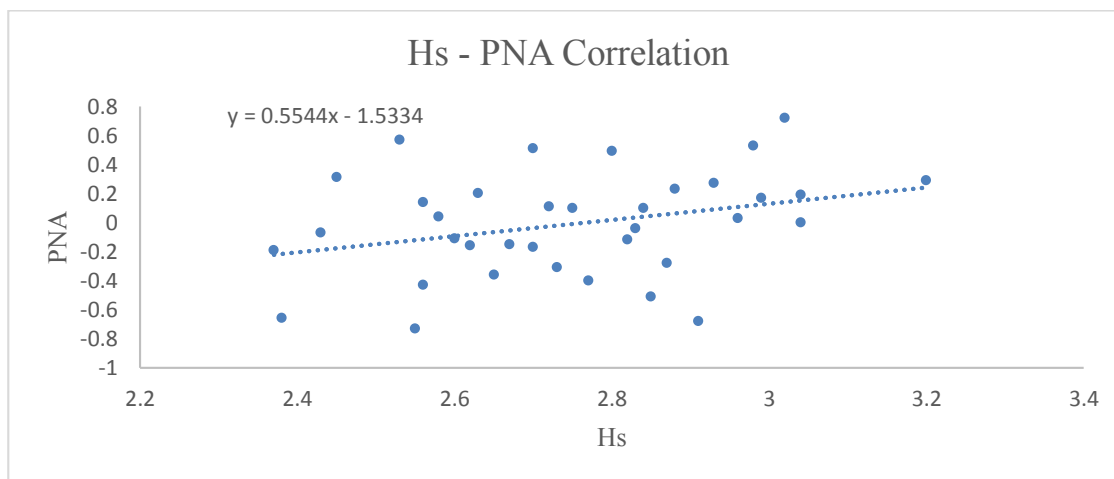


Figure A.8 : Annually Correlation between H_s and (PNA) in 46006.

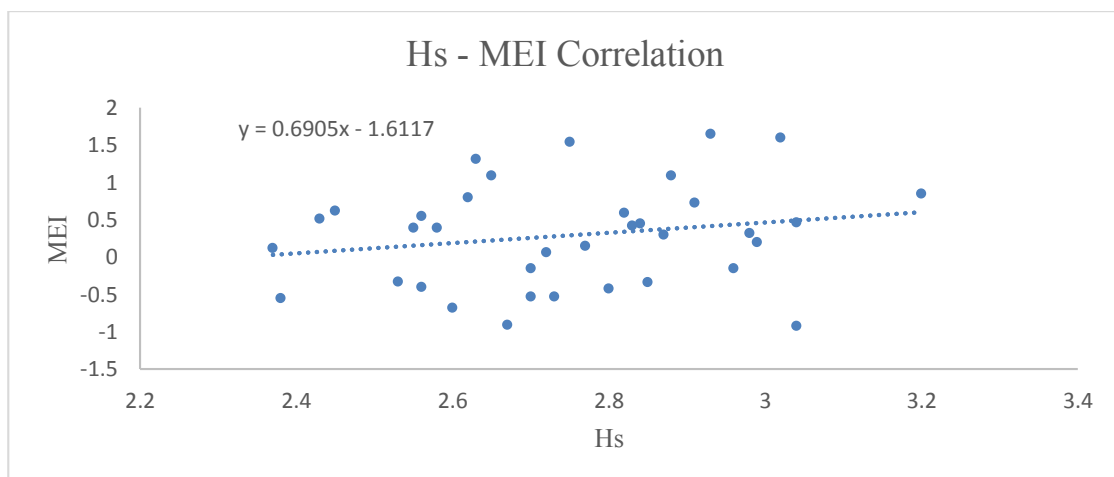


Figure A.9 : Annually Correlation between H_s and (MEI) in 46006.

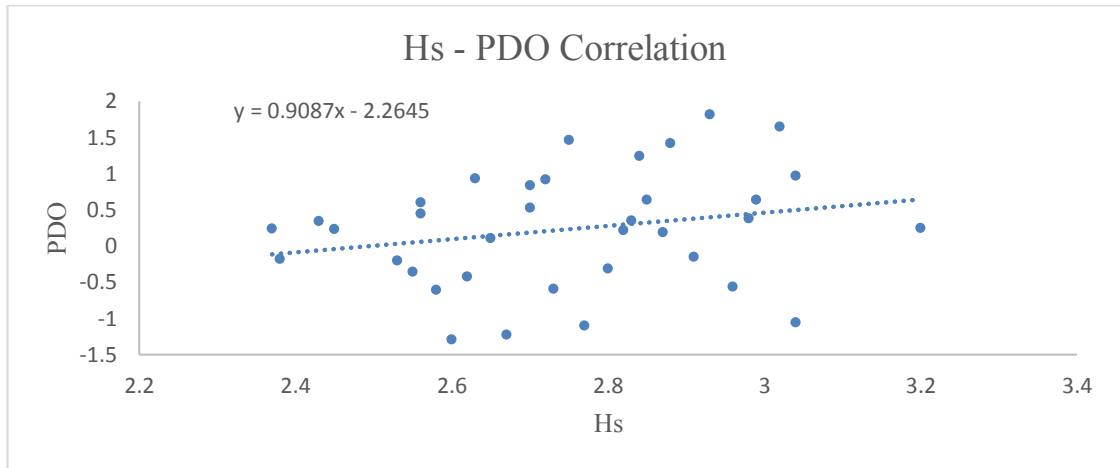


Figure A.10 : Annually Correlation between H_s and (PDO) in 46006.

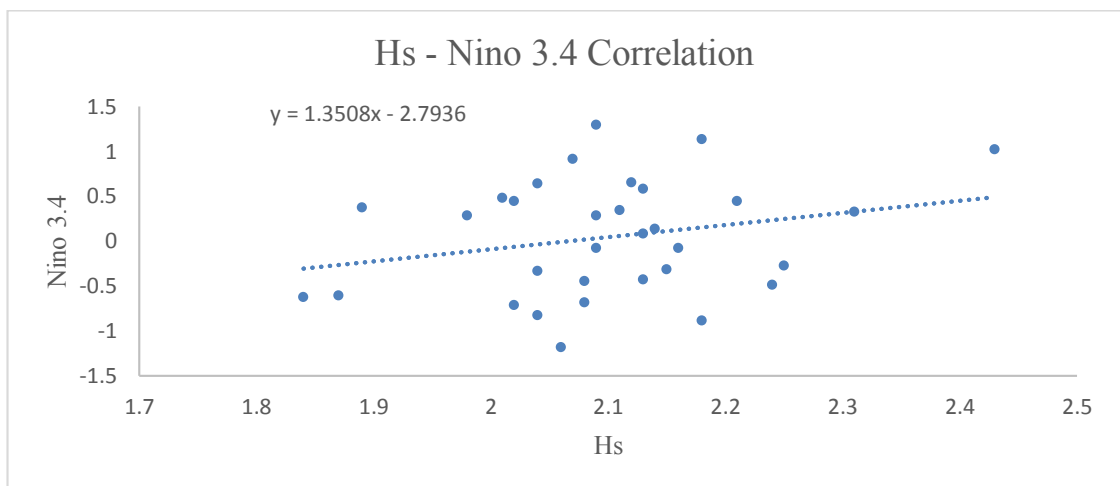


Figure A.11 : Annually Correlation between H_s and (Niño3.4) in 46011.

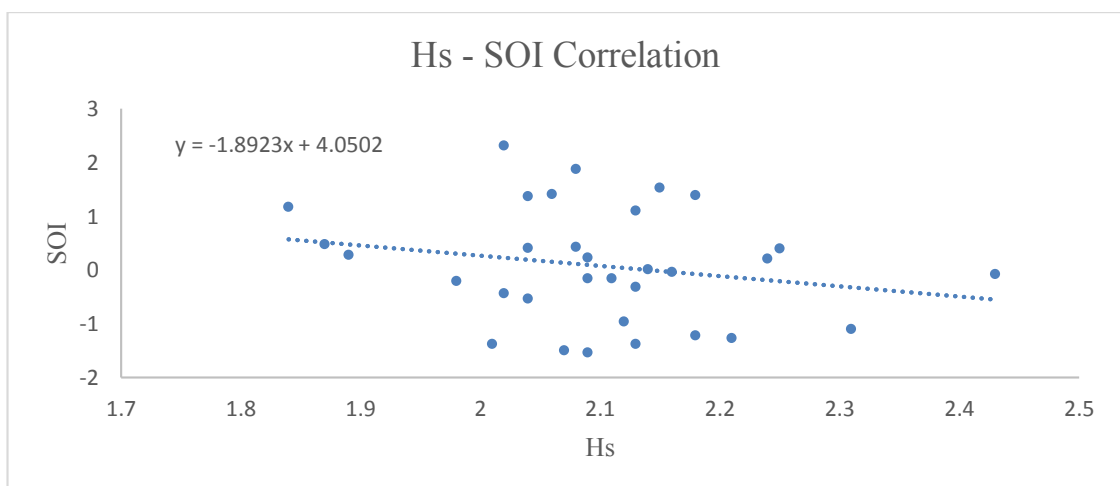


Figure A.12 : Annually Correlation between H_s and (SOI) in 46011.

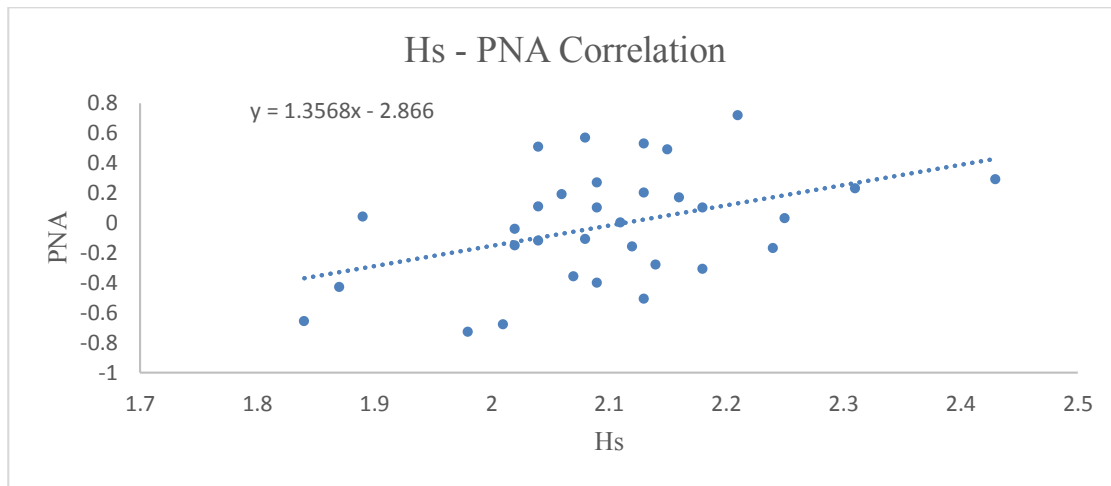


Figure A.13 : Annually Correlation between H_s and (PNA) in 46011.

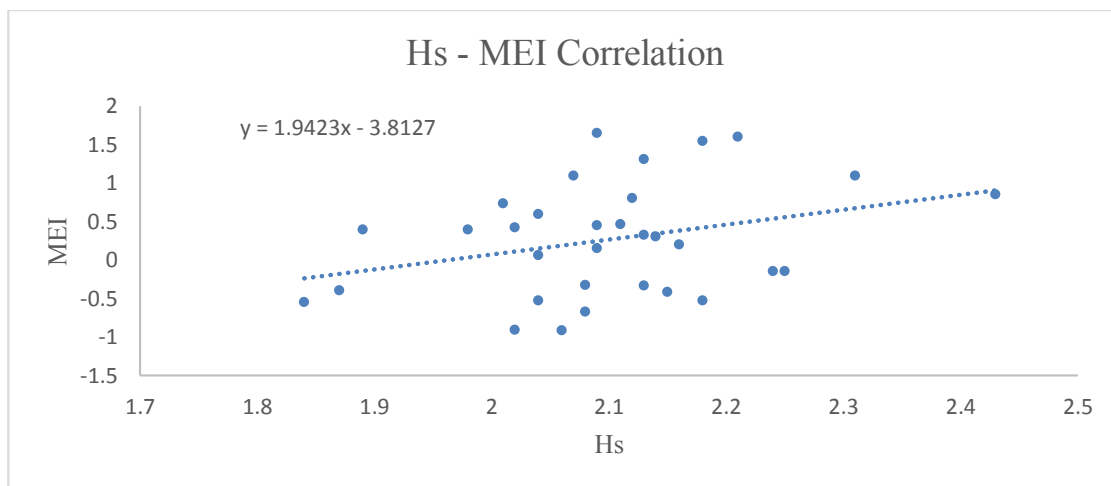


Figure A.14 : Annually Correlation between H_s and (MEI) in 46011.

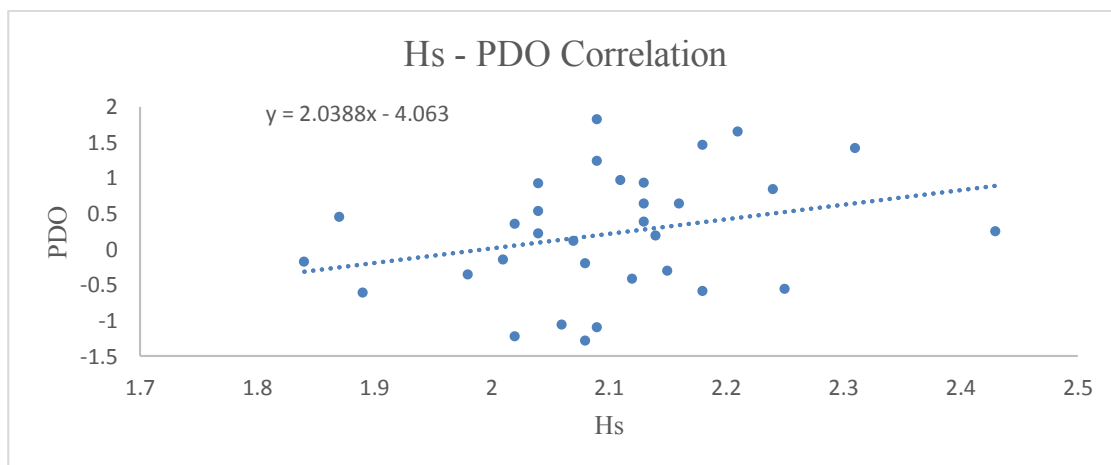


Figure A.15 : Annually Correlation between H_s and (PDO) in 46011.

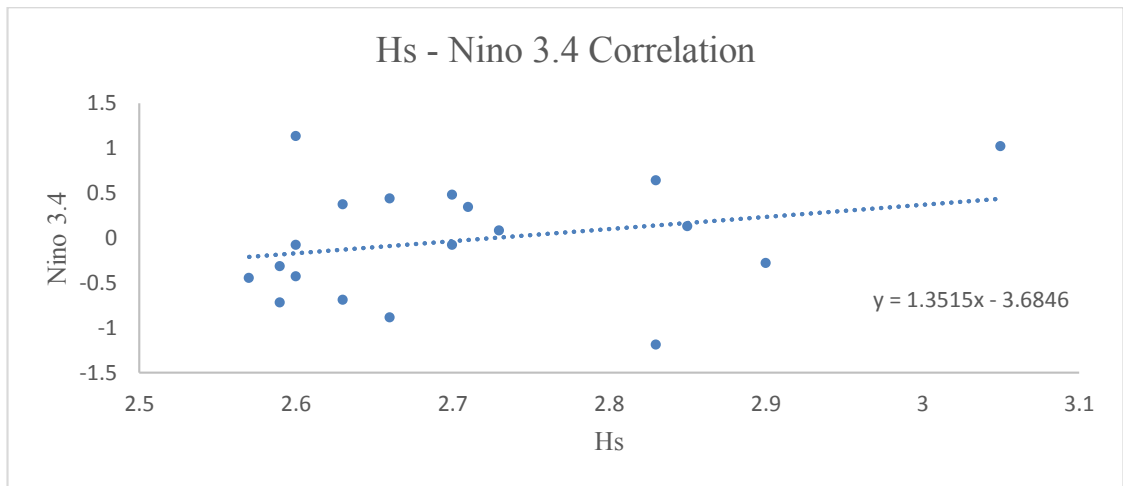


Figure A.16 : Annually Correlation between H_s and (Niño3.4) in 46059.

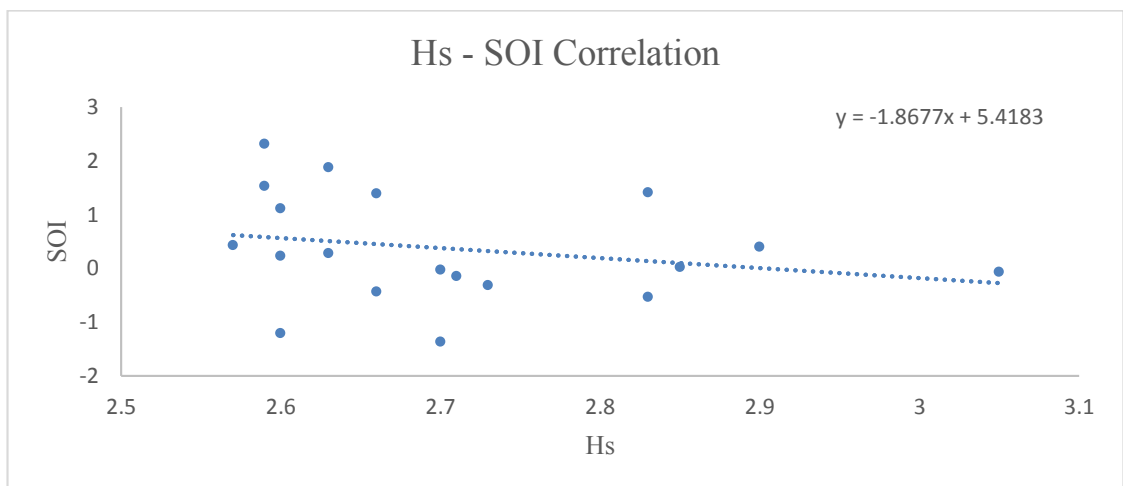


Figure A.17 : Annually Correlation between H_s and (SOI) in 46059.

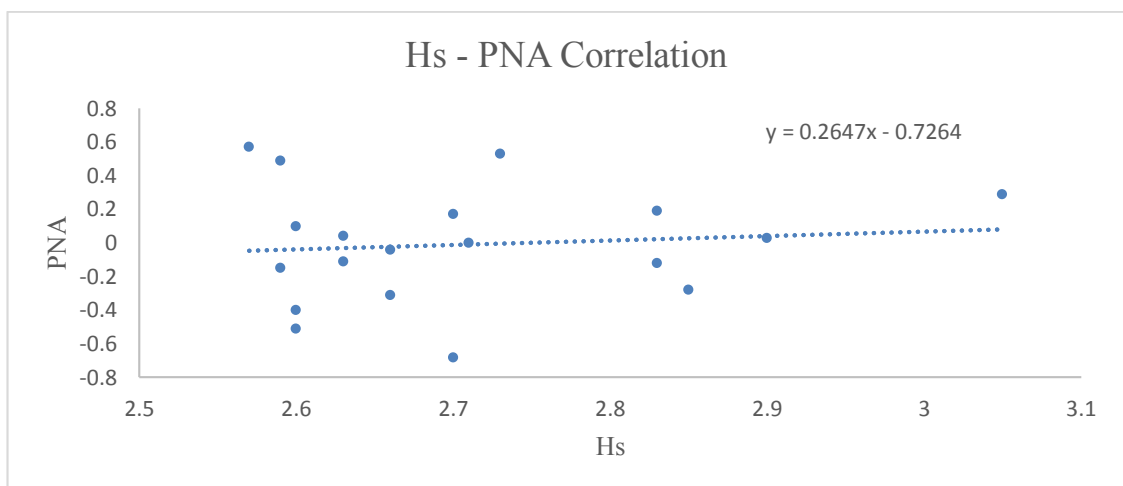


Figure A.18 : Annually Correlation between H_s and (PNA) in 46059.

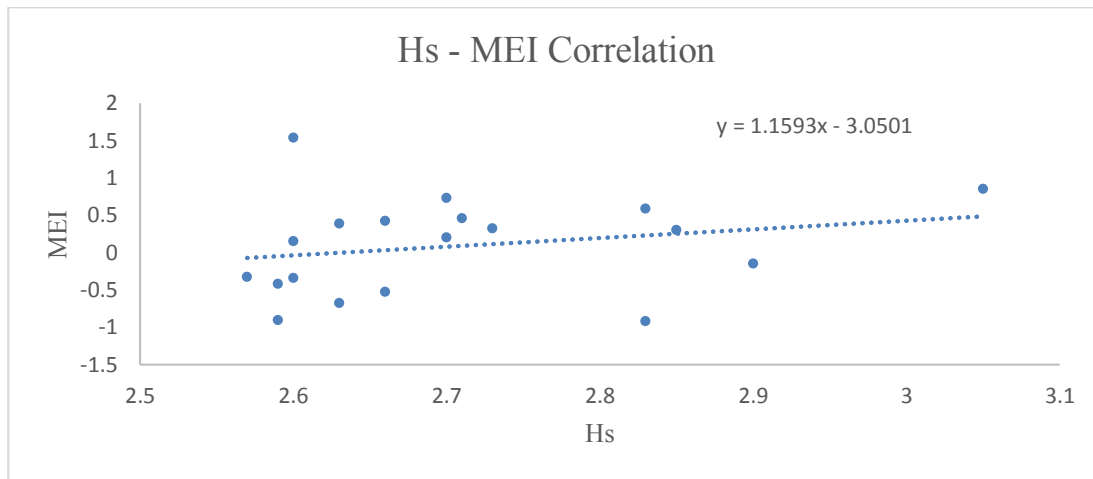


Figure A.19 : Annually Correlation between H_s and (MEI) in 46059.

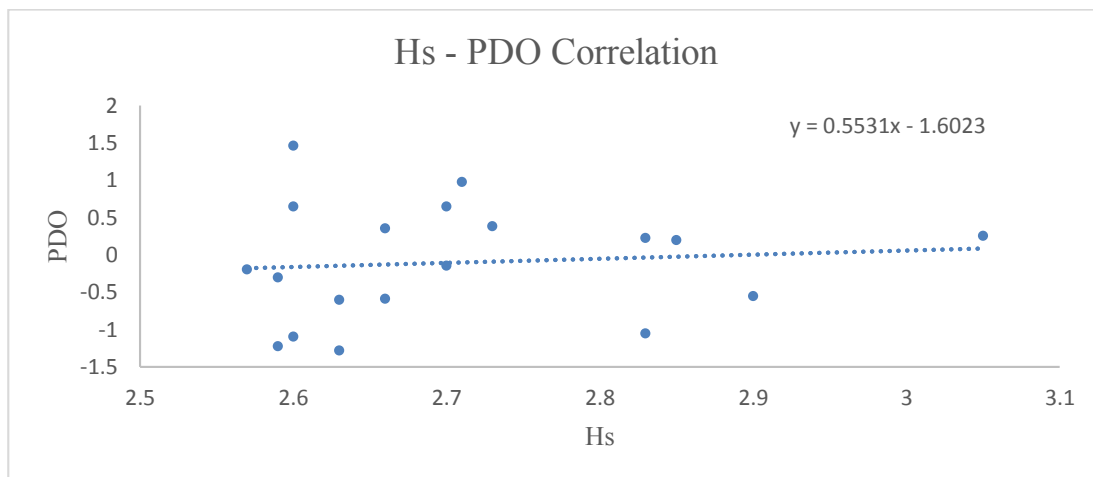


Figure A.20 : Annually Correlation between H_s and (PDO) in 46059.

APPENDIX B

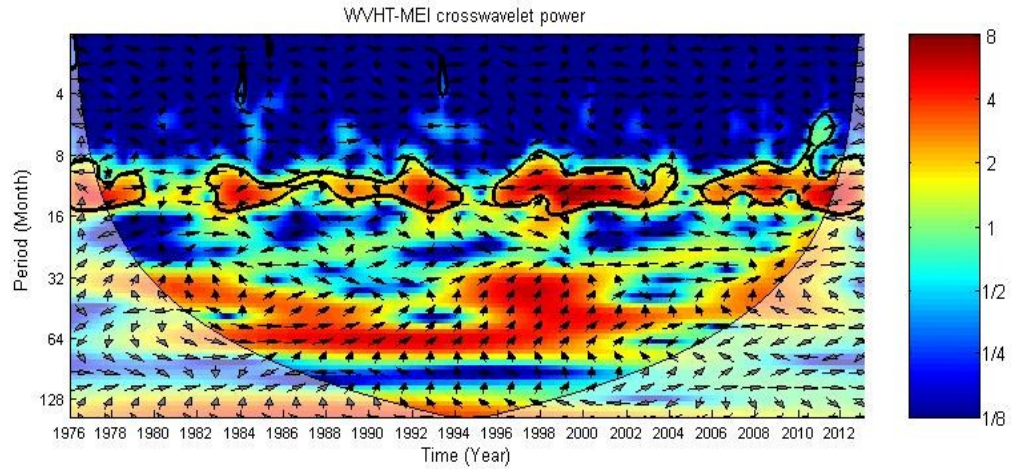


Figure B.1 : Cross-wavelet transform between H_s and MEI in 46005.

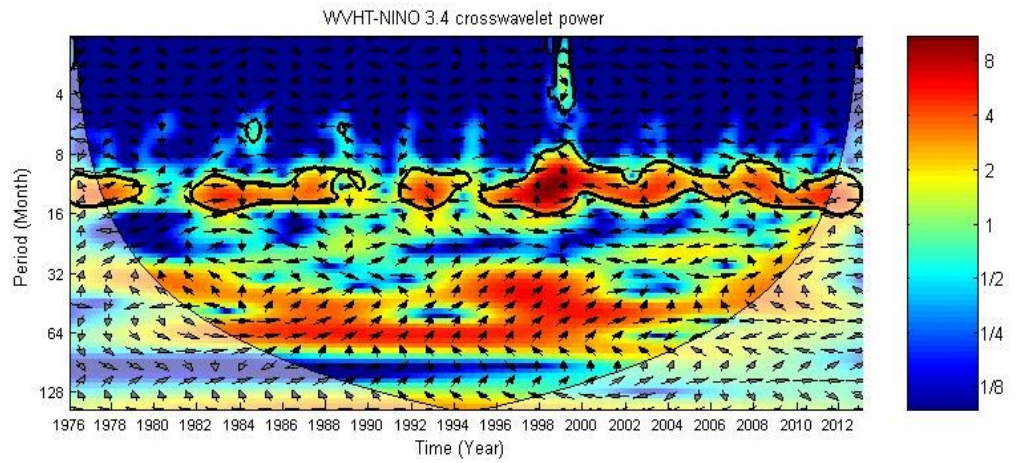


Figure B.2 : Cross-wavelet transform between H_s and Niño3.4 in 46005.

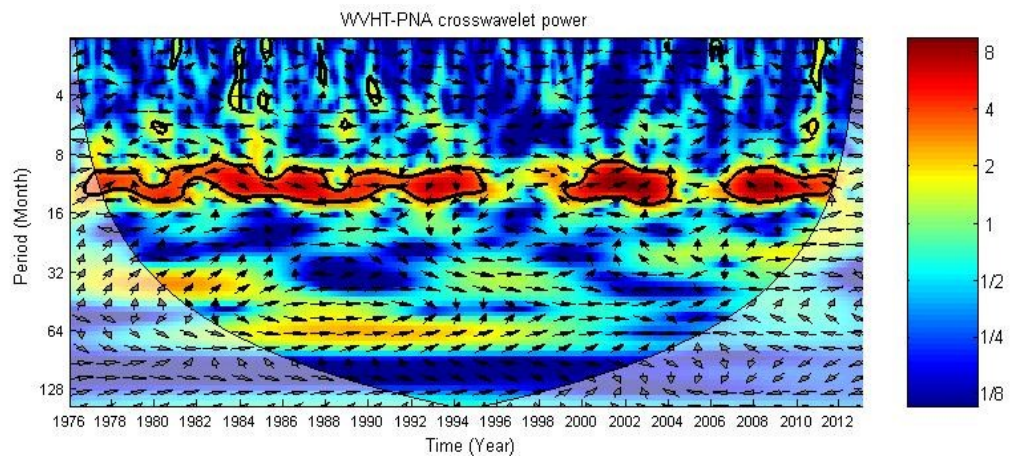


Figure B.3 : Cross-wavelet transform between H_s and PNA in 46005.

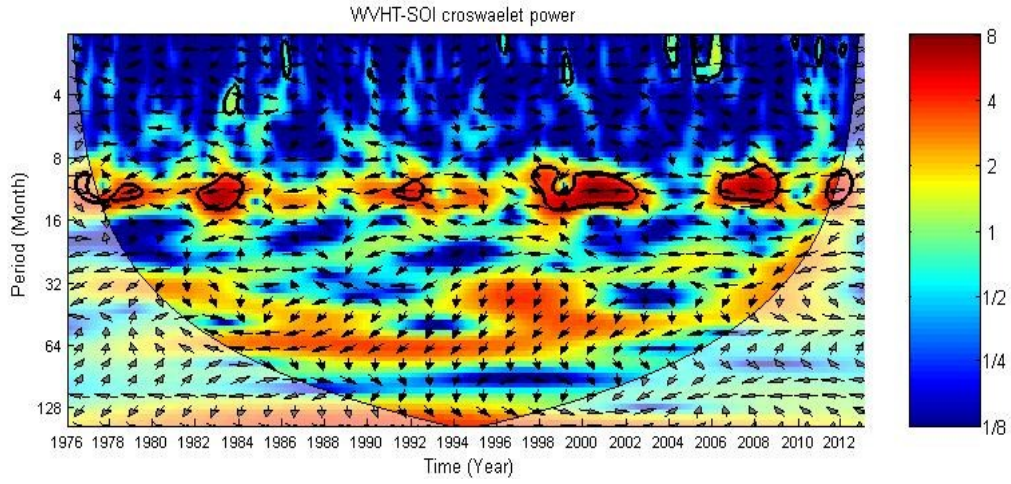


Figure B.4 : Cross-wavelet transform between H_s and SOI in 46005.

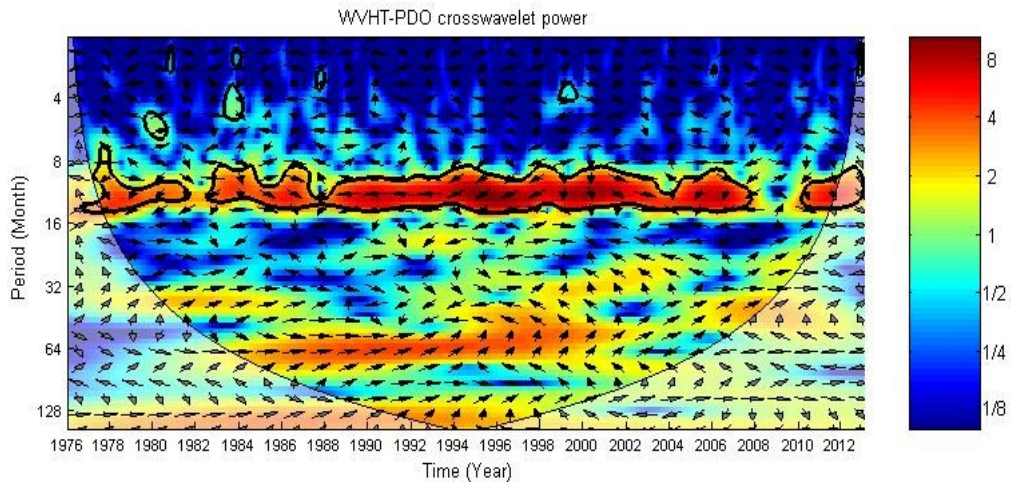


Figure B.5 : Cross-wavelet transform between H_s and PDO in 46005.

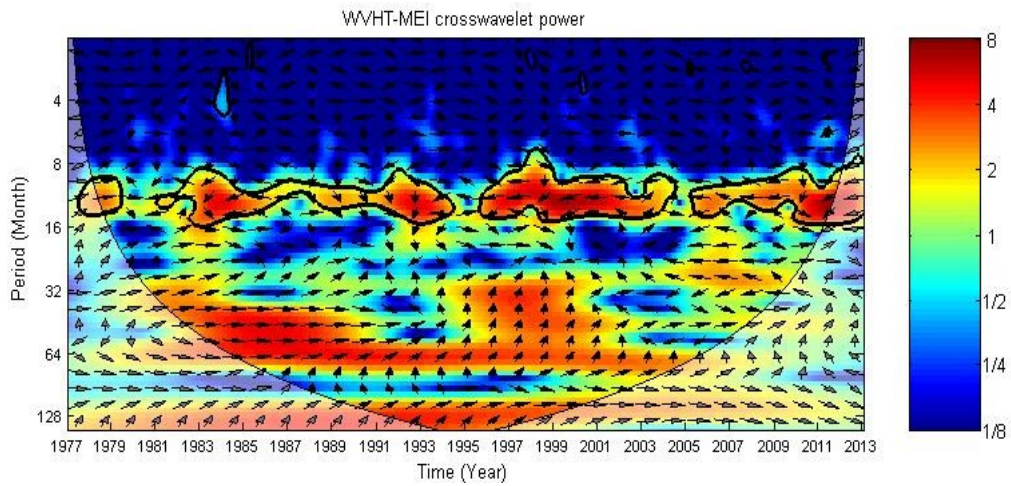


Figure B.6 : Cross-wavelet transform between H_s and MEI in 46006.

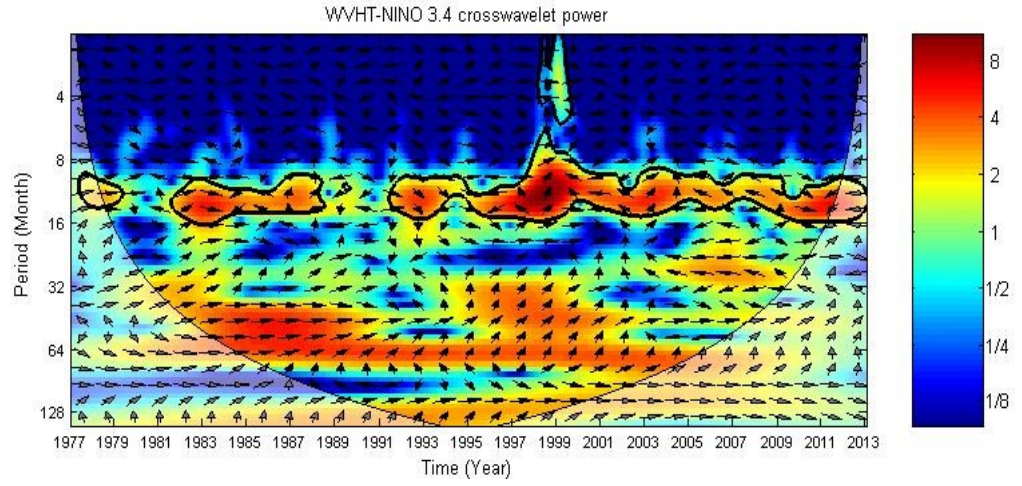


Figure B.7 : Cross-wavelet transform between H_s and Niño3.4 in 46006.

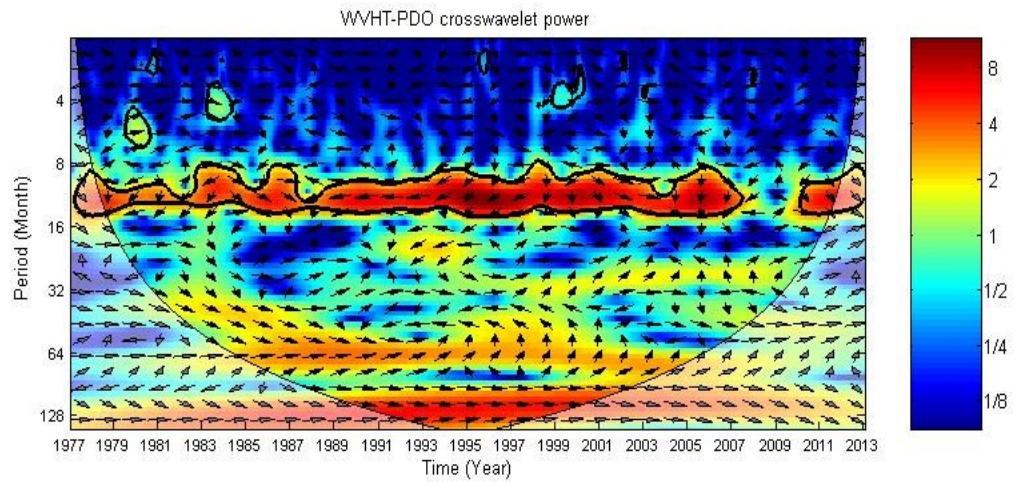


Figure B.8 : Cross-wavelet transform between H_s and PDO in 46006.

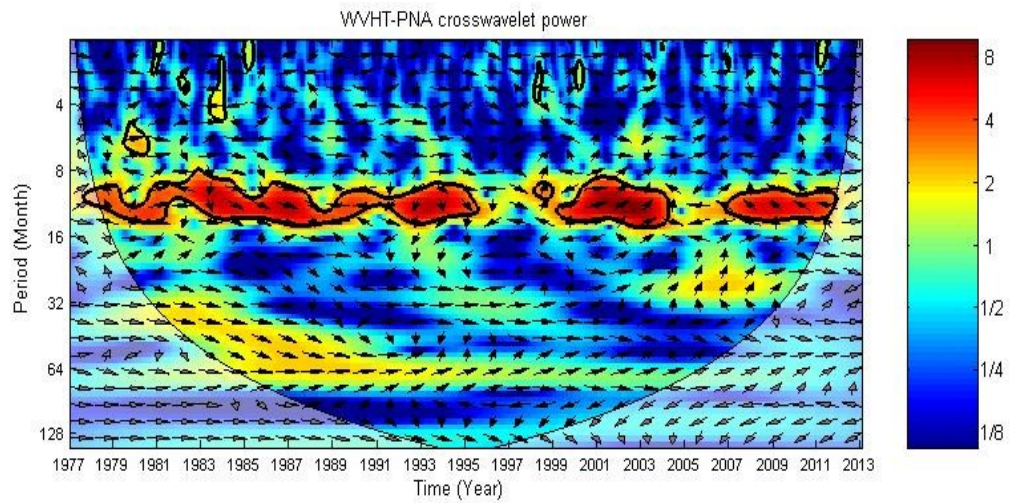


Figure B.9 : Cross-wavelet transform between H_s and PNA in 46006.

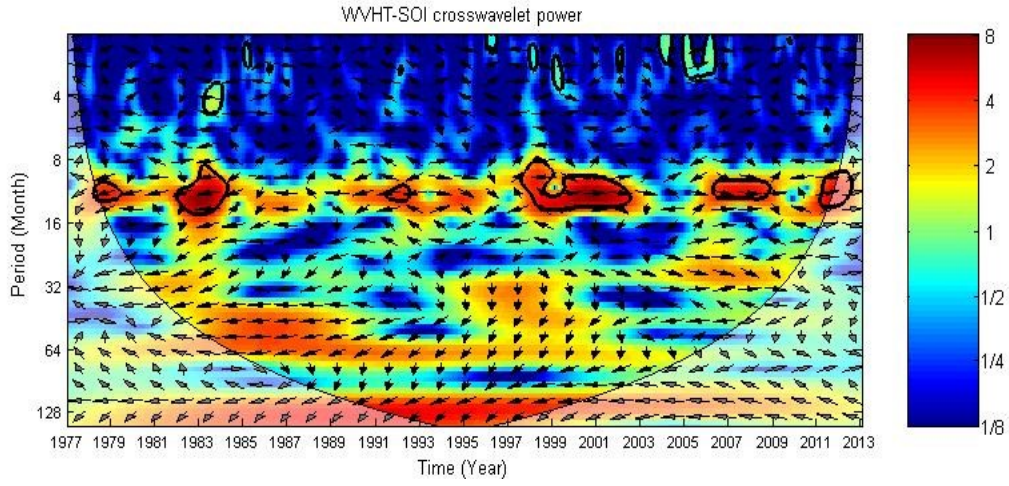


Figure B.10 : Cross-wavelet transform between H_s and SOI in 46006.

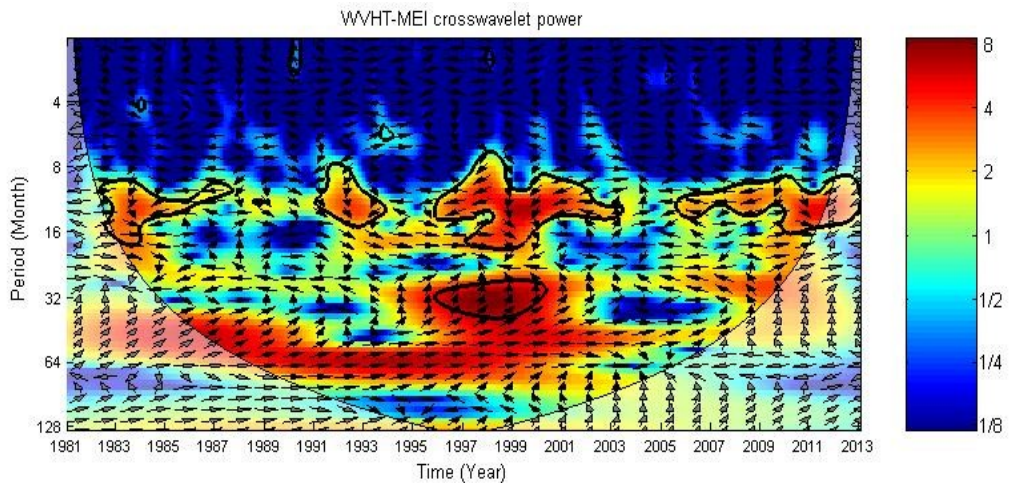


Figure B.11 : Cross-wavelet transform between H_s and MEI in 46011.

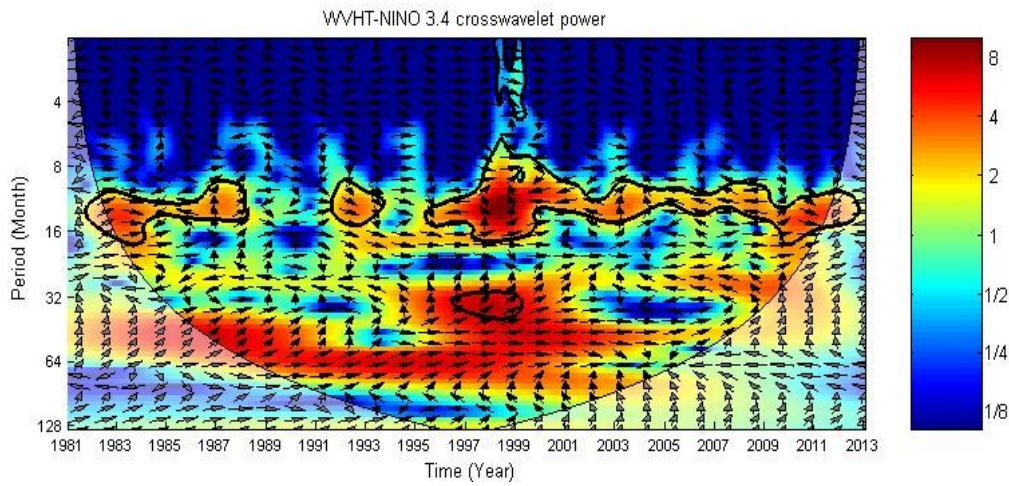


Figure B.12 : Cross-wavelet transform between H_s and Niño 3.4 in 46011.

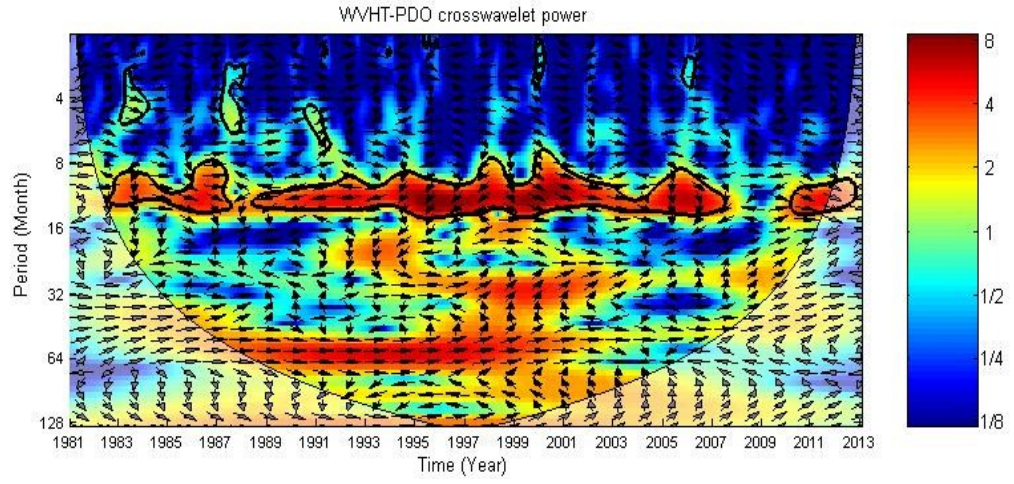


Figure B.13 : Cross-wavelet transform between H_s and PDO in 46011.

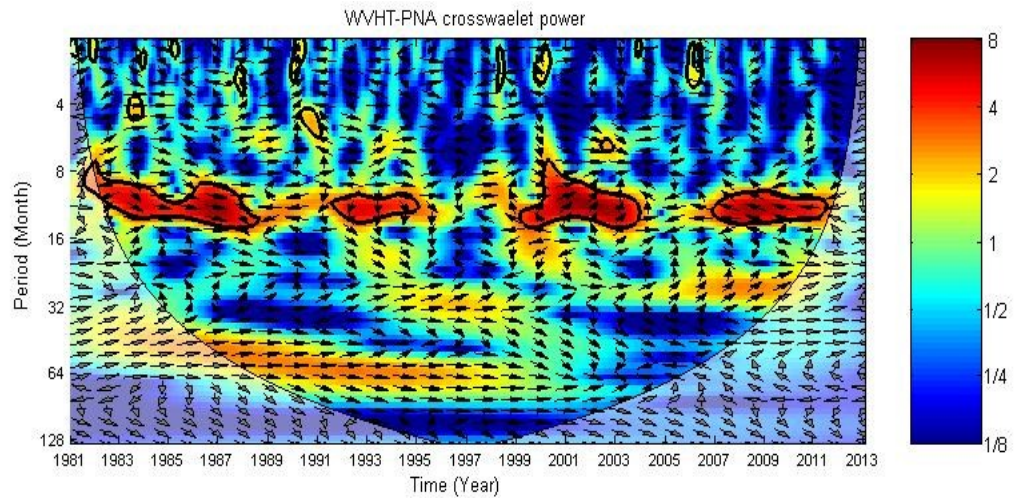


Figure B.14 : Cross-wavelet transform between H_s and PNA in 46011.

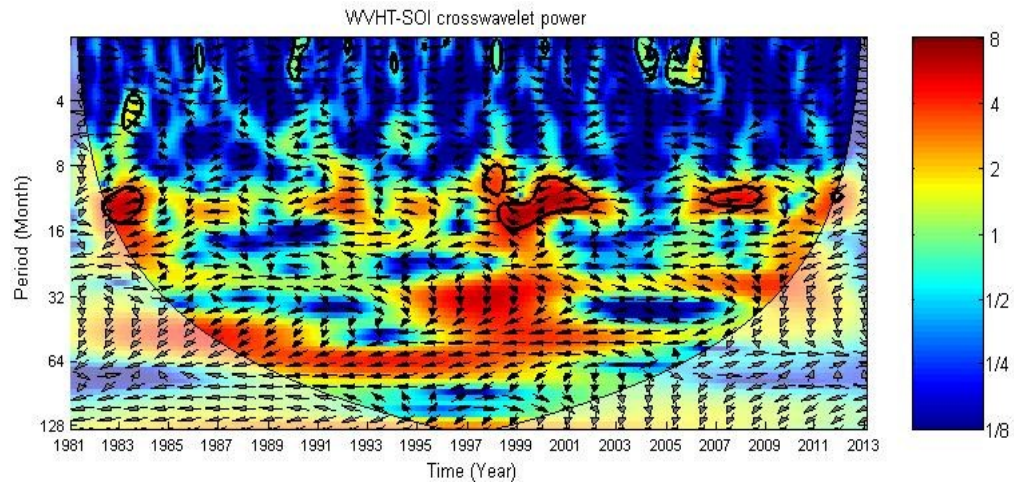


Figure B.15 : Cross-wavelet transform between H_s and SOI in 46011.

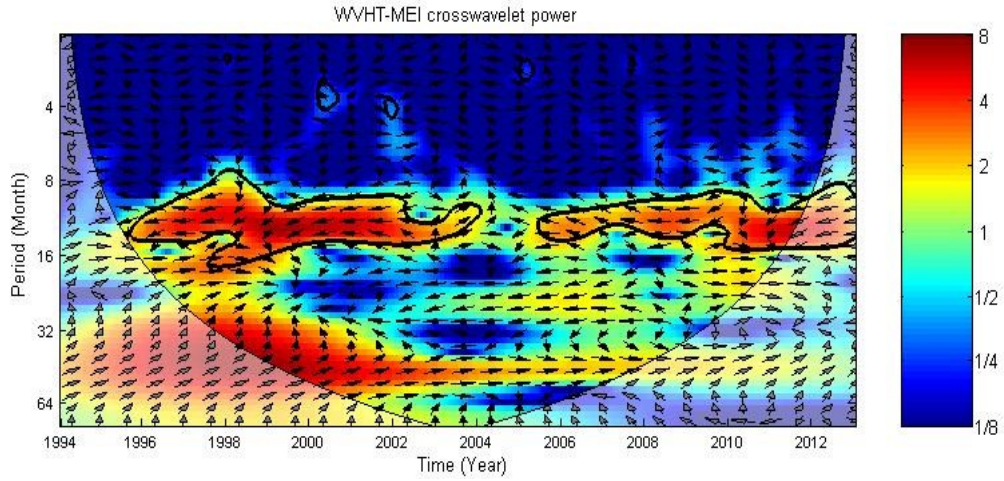


Figure B.16 : Cross-wavelet transform between H_s and MEI in 46059.

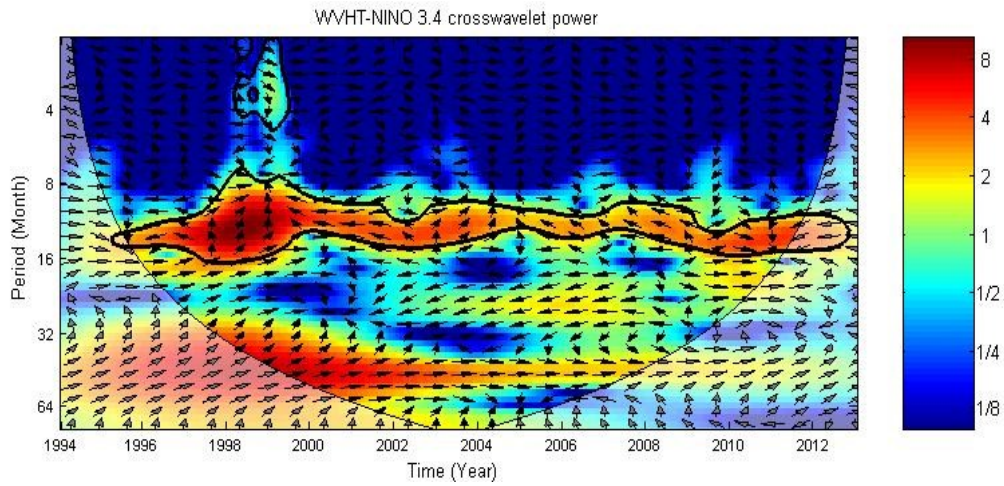


Figure B.17 : Cross-wavelet transform between H_s and Niño3.4 in 46059.

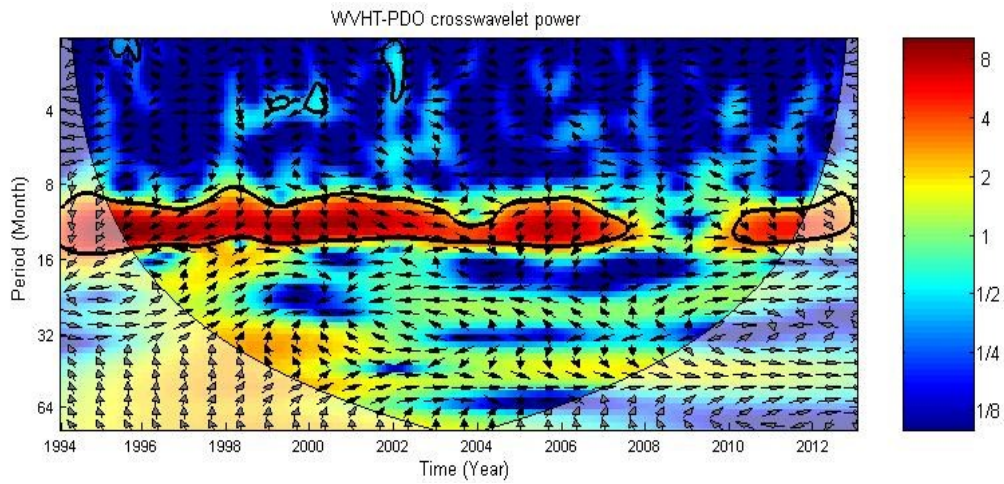


Figure B.18 : Cross-wavelet transform between H_s and PDO in 46059.

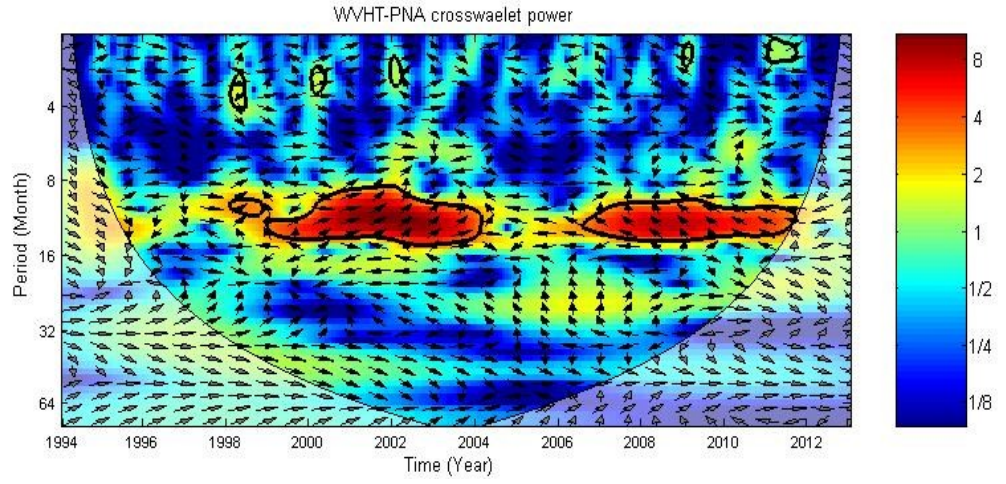


Figure B.19 : Cross-wavelet transform between H_s and PNA in 46059.

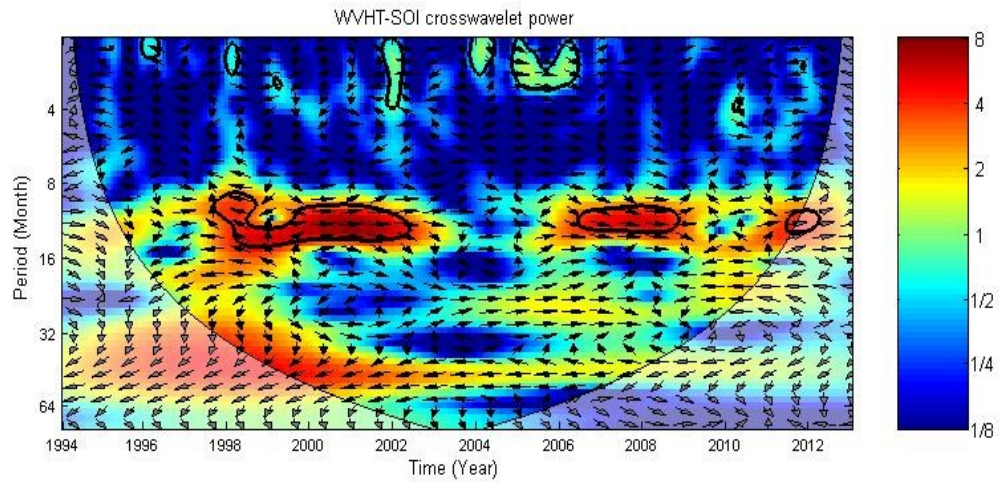


Figure B.20 : Cross-wavelet transform between H_s and SOI in 46059.

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