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International Journal of Oceanography & Aquaculture
ISSN: 2577-4050

Monthly and Spatial Distribution of Ocean Wave Parameters in the Bay of Bengal Using ERA5 Reanalysis Data

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Research Article
Volume 5 Issue 1
Received Date: November 28, 2020
Published Date: February 25, 2021
DOI: 10.23880/ijoac-16000200

Abstract

The purpose of this study is to assess the spatial distribution of ocean wave parameters, and their correlation and anomalies in the Bay of Bengal (BoB) using about 40 years of ERA5 reanalysis data. Collected data were analyzed by using geographic information system (GIS) and computer programming languages. It is revealed that higher values of SWH (2.50–2.58m) dominated the central, southern and south-western BoB during June–August. The monthly climatological mean of MSS and Cd are ranged from 0–0.013 and 0.0006–0.0016 respectively in the study area. WSP were higher (10.31–10.84m/s) in south-western BoB during June–August. Tm is higher (11.23–11.03s) during April–September in southern and south–eastern BoB. Lower Tm (2.36–2.73s) is found in western and eastern BoB. SWH, WSP, Tm, MSS and Cd have unfolded significant impact on each other during most of the month. Strong anomaly has been reflected in the SWH, WSP, and Tm during March–April.

Keywords: Ocean Wave Parameters; Bay of Bengal; CDS Toolbox; ERA5; Spatial Distribution; Anomaly

Abbreviations: OTSR: Optimum Tracking of Ship Routes; IO: Indian Ocean; Cd: Coefficient of Drag; MSS: Mean Square Slope; SWH: Significant Wave Heights; CDS: Climate Data Store; WSP: Wind Speed; ECMWF: European Centre for Medium-Range Weather Forecasts; CAMS: Copernicus Atmosphere Monitoring Service; GIS: Geographic Information System; BoB: Bay of Bengal.

Introduction

A precise knowledge and proper understanding of long–term pattern and climatological analysis of ocean wave on regional and local scales plays an exigent role in various applications, such as coastal and ocean engineering, physical oceanography, climate projection, marine weather forecasting, coastal morphodynamics, sustainable coastal zone management, shipping routes, marine exploitation, marine industry, development of marine environment, and the planning of marine operations and the marine industry [1-5]. Information on ocean surface waves is necessary for naval operation or warfare, rescue operations, optimum tracking of ship routes (OTSR), design and development of harbors, wave climate assessment and recreation [6]. The investigation on wave climate is very applicable as a reference for the assessment of wave energy resource development [7]. As change in wave climate is one of the most essential indictor of change in pattern of wind, sea surface temperature and pressure, investigation on long–term trend in wave climate has profound importance [8]. Therefore, study on the long–term variability of wave parameters such wave height, square slope, and period is essential for such applications. Extreme ocean wave heights can provoke coastal sea level extremes and flooding, cause destruction to coastal structures and therefore, to reduce such risk, proper understanding of ocean wave height variability is must needed [9]. Winds blowing over the sea surface generate surface waves playing an important role in the air–sea interaction process in a coupled ocean–atmosphere system and IPCC-AR5 (Intergovernmental Panel on Climate Change-Fifth Assessment Report) emphasized the importance of wind-waves as they play a vital role in the transfer of energy across the air–sea interface.

Long-term study and proper presentation of wave climate requires about 30 years of datasets [10] and long-term data for wind and waves provide an opportunity to understand the inter-annual, intra-seasonal and decadal variability [11].

Important ocean waves data such as significant height of combined wind waves and swell (SWH), mean period of combined wind waves and swell (Tm), mean square slope of waves (MSS), coefficient of drag with waves (Cd), and ocean surface stress equivalent 10m neutral wind speed (WSP) are investigated in this study. Cd is a type of counteraction due to the atmospheric exertion of waves where MSS and standard slope of combined wind and swell waves are connected to each other. MSS and Cd are both dimensionless parameters [12].

BoB experience coexistence of wind seas and swells [4]. Weather system of BoB is divided into three categories: a) fair weather or pre-monsoon period from February to May, b) southwest or summer monsoon period from June to September and northeast or post-monsoon period from October to January, where the sea-state or surface waves during the fair weather period is usually calm [11,13]. Changes in wave height in the BoB arouse upgraded tropical cyclone activity in June, July and August during the Indian monsoon [9]. BoB is more vulnerable to tropical cyclones, forming over the Bay with primary maximum in October, November and December and secondary maximum during April and May, can cause large inter-annual variations in wave parameters [10,14,15]. BoB is an area of spatial variation in wave climate. Due to sheltering of Sri Lankan Island, surface waves in the southern BoB do not reach the major part of the southeast coast [16] and the south-western BoB have low-wave height compared to the northern BoB [13].

Several attempts have been made in order to study the pattern and variability of ocean wave climate in the Indian Ocean region associated with BoB. Sreelakshmi and Bhaskaran [1] studied regional wise characteristic of significant wave height for the Indian Ocean (IO) based on space borne measurements (1992–2016), ERA-5 (1992–2018), and NCEP WWIII global run (1997–2018). Kumar, et al. [9] examined seasonal extreme significant wave heights (SWH) in the IO over the period 1957–2010 utilizing ERA-20C reanalysis data. Sadhukhan, et al. [7] carried out a comprehensive analysis of long–term wave climate in the western BoB, based on the distribution of significant wave height using monthly averaged satellite and WAM model for 20 years (1996–2015). Gupta, et al. [17] investigated dipole behaviour in maximum significant wave height and mean significant wave height over the Southern Indian Ocean, using 24 years of satellite altimeter data (1992–2015). Patra and Bhaskaran [11] analyzed the temporal variability in domain averaged wind speed, significant wave height, using satellite altimeter data (1992–2012) and mean wave period, using ERA-Interim (1992–2012) and ERA-20C (1992–2010) over the head BoB region.

Materials and Methods

The study area, BoB, which is a northern extended arm of the Indian Ocean, located between latitudes 5°N and 22°N and longitudes 80°E and 100°E occupying an area of about 2.2 million km^2 [18].

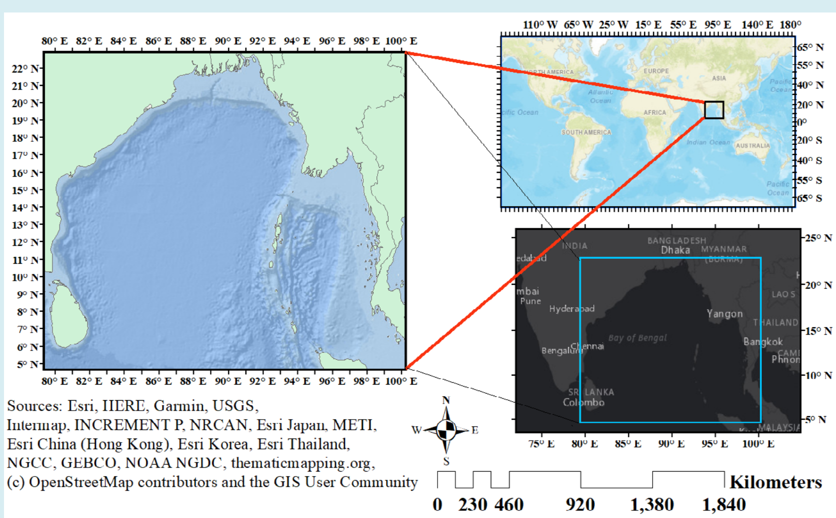

Figure 1: Location of the Study Area, the Bay of Bengal.

ERA5 hourly data of ocean wave parameters on single levels from 1979 to 2019 for the BoB are used in this study. Data are available in Copernicus Climate Change Service Climate Data Store (CDS) website [19]. The fifth generation reanalysis data, which is named ERA5, distributed by European Centre for Medium-Range Weather Forecasts (ECMWF) with higher spatial and temporal resolution (Figure 1) [1].

Data are analyzed spatially in monthly perspective by using python scripts in CDS Toolbox, R and ArcMap 10.5. Spatial trend and anomaly of ocean wave parameters are presented in image format in order.

Results and Discussion

Spatial distribution of the ocean wave parameters in monthly climatological perspective, and their correlation and anomalies in the BoB have been carried out in this research (Table 1).

Month	Highest Value of Climatological Mean					Lowest Value of Climatological Mean				
	SWH	WSP	MSS	Cd	Tm	SWH	WSP	MSS	Cd	Tm
January	1.62	7.74	0.008	0.0012	10.24	0.12	2.07	0	0.0006	2.36
February	1.45	6.56	0.006	0.0011	10.36	0.14	2.09	0	0.0006	2.36
March	1.41	6.42	0.005	0.0011	10.74	0.14	2.12	0	0.0006	2.37
April	1.56	8.07	0.008	0.0012	11.23	0.14	2.15	0	0.0006	2.43
May	2.22	9.06	0.01	0.0014	11.74	0.17	2.23	0	0.0007	2.61
June	2.58	10.84	0.013	0.0016	11.07	0.15	2.3	0	0.007	2.62
July	2.55	10.49	0.013	0.0016	11.05	0.16	2.27	0	0.0007	2.67
August	2.5	10.31	0.012	0.0015	11.03	0.17	2.21	0	0.0009	2.73
September	2.29	9.52	0.011	0.0014	11.08	0.15	2.11	0	0.0006	2.62
October	1.9	6.77	0.007	0.0011	10.76	0.11	2.05	0	0.0006	2.62
November	1.63	6.72	0.006	0.0011	10.27	0.1	2.03	0	0.0006	2.4
December	1.63	7.37	0.007	0.0011	10.15	0.1	2.03	0	0.0006	2.33

Table 1: Highest Value of Monthly Climatological Mean of Wave Parameters.

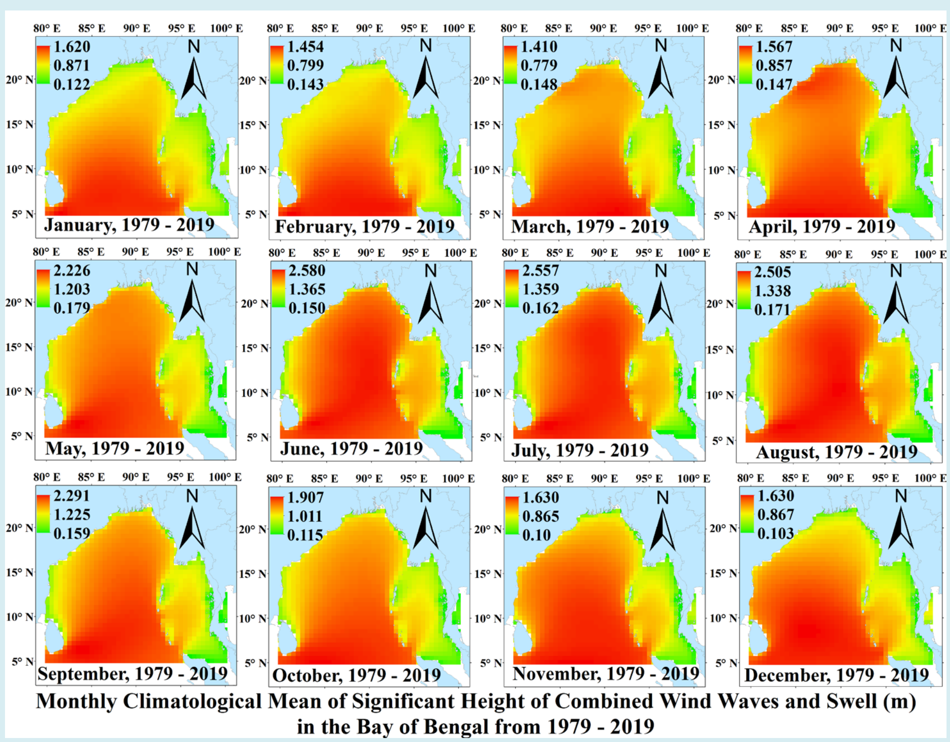

Figure 2: Spatial distribution of SWH (m) from 1979–2019 in the BoB.

SWH is higher in June (2.58m), July (2.55m), and August (2.50m) found in central, southern and south-western BoB. SWH is more than 2m found in May and September. Lower SWH (0.10–0.179m) is found in eastern and western BoB for every month. Higher values of WSP are found in June (10.84 m/s), July (10.495) and August (10.317) in south-western BoB while lower WSP is found in northern, eastern and south–eastern BoB. During September–October, western BoB is being dominated by lower WSP. The range of monthly values of MSS and Cd in the BoB are between 0–0.013 and 0.0006–0.0016 respectively. North-western BoB during March–April; south-western BoB during January–February and May–October; and western BoB during November–December are being dominated by high Cd and MSS due to the strong positive influence of WSP. Highest value of Tm 11.23s is revealed in southern and south–eastern BoB during April. Tm between (11.03–11.14s) is also found in southern BoB during May–September. Lower values (2.33–2.73s) of Tm are found in western and eastern BoB during every month due to lower SWH. March, April and May have indicated strong anomaly in the ocean wave parameters in most years and it is due to the influence of tropical cyclones (TCs) activity in the BoB as TCs significantly provoke variation in wave parameters in the BoB [10,14,15] (Figures 2-6 & Table 2).

Months	Correlation Between Parameters Value of R						
	SWH & WSP	SWH & Tm	SWH & Cd	SWH & MSS	WSP & Cd	WSP & MSS	Cd & MSS
January	0.88	0.55	0.87	0.95	1	0.97	0.97
February	0.83	0.69	0.83		1	0.96	0.96
March	0.29	0.84	0.3	0.58	1	0.91	0.92
April	0.23	0.78	0.23	0.41	1	0.96	0.97
May	0.72	0.84	0.68	0.82	0.99	0.97	0.96
June	0.83	0.84	0.78	0.89	0.99	0.98	0.96
July	0.85	0.87	0.78	0.91	0.99	0.97	0.96
August	0.84	0.87	0.8	0.91	0.99	0.97	0.96
September	0.82	0.85	0.8	0.9	1	0.97	0.97
October	0.82	0.78	0.77	0.89	1	0.96	0.96
November	0.58	0.63	0.58	0.76	1	0.96	0.95
December	0.76	0.49	0.75	0.87	1	0.97	0.95

Table 2: Correlation between Ocean Wave Parameters.

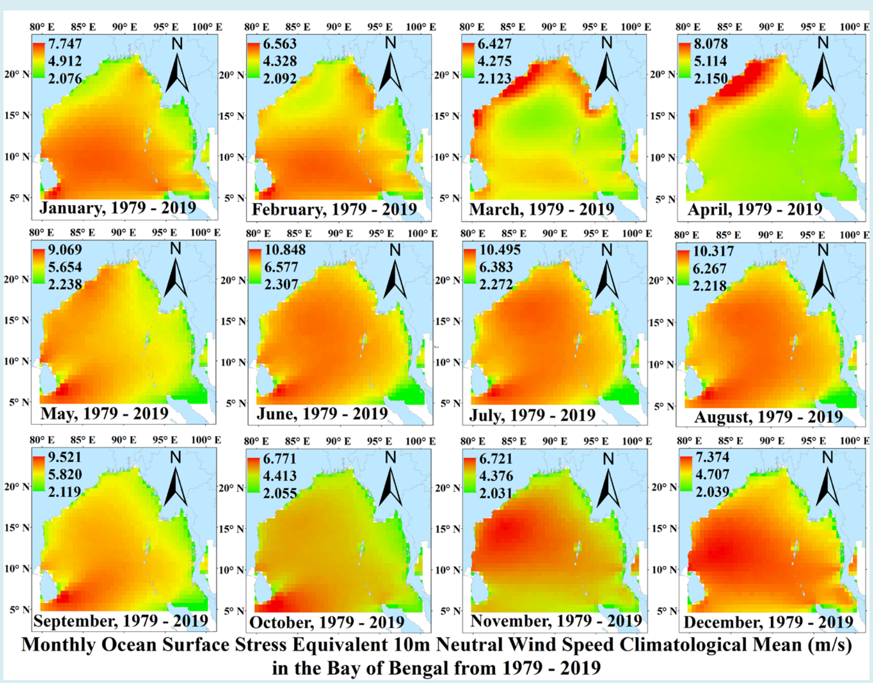

Figure 3: Spatial distribution of WSP (m/s) from 1979–2019 in the BoB.

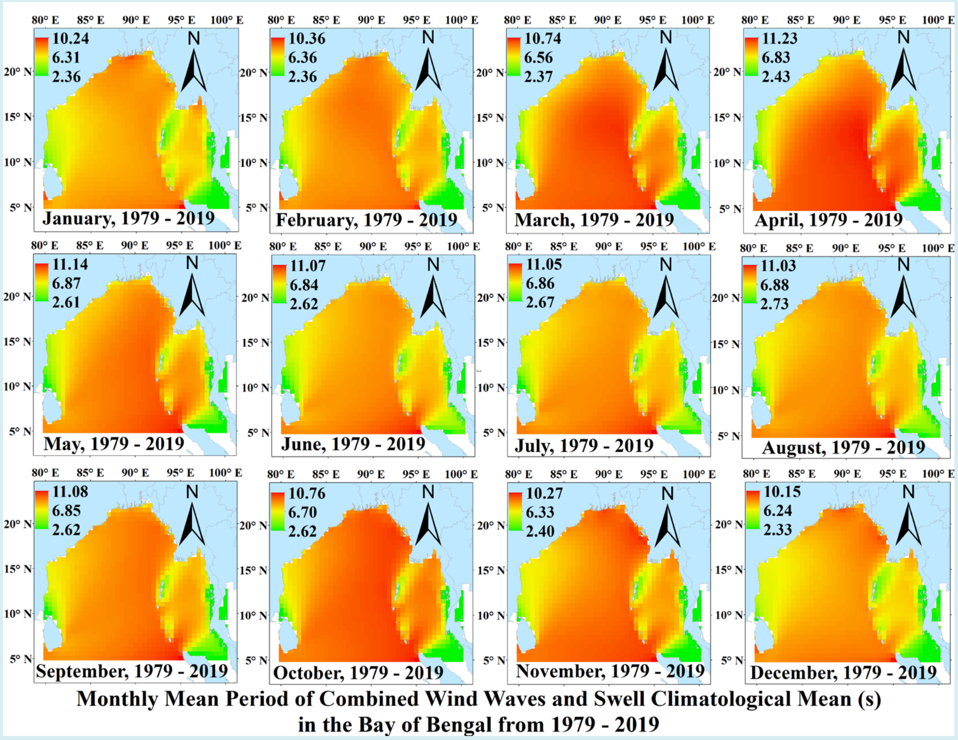

Figure 4: Spatial distribution of Tm (s) from 1979–2019 in the BoB.

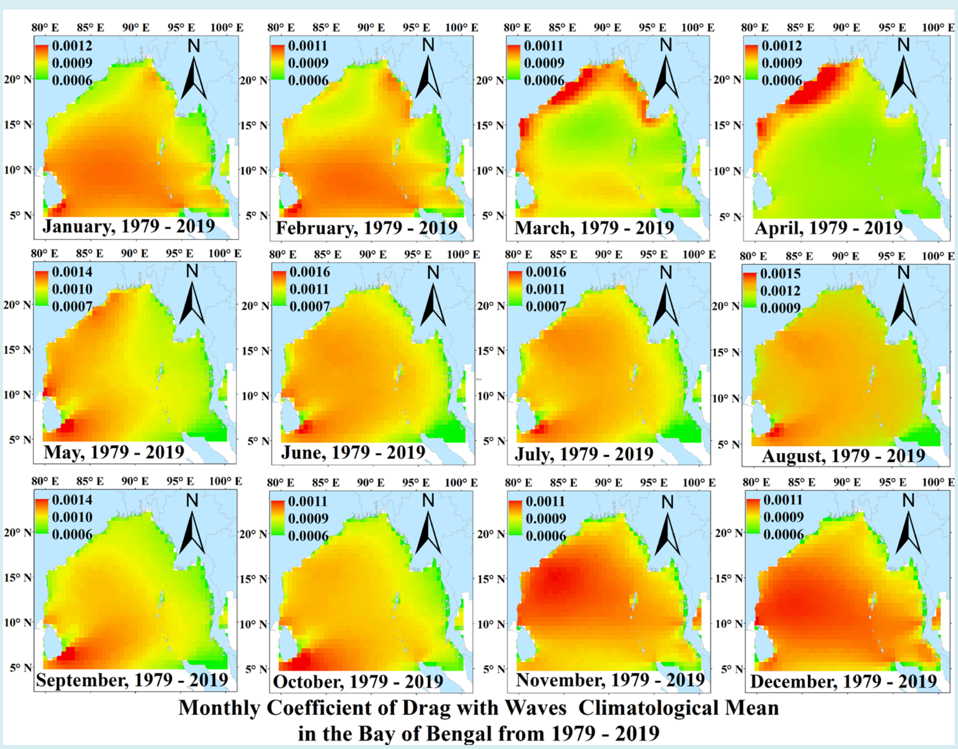

Figure 5: Spatial distribution of Cd from 1979–2019 in the BoB.

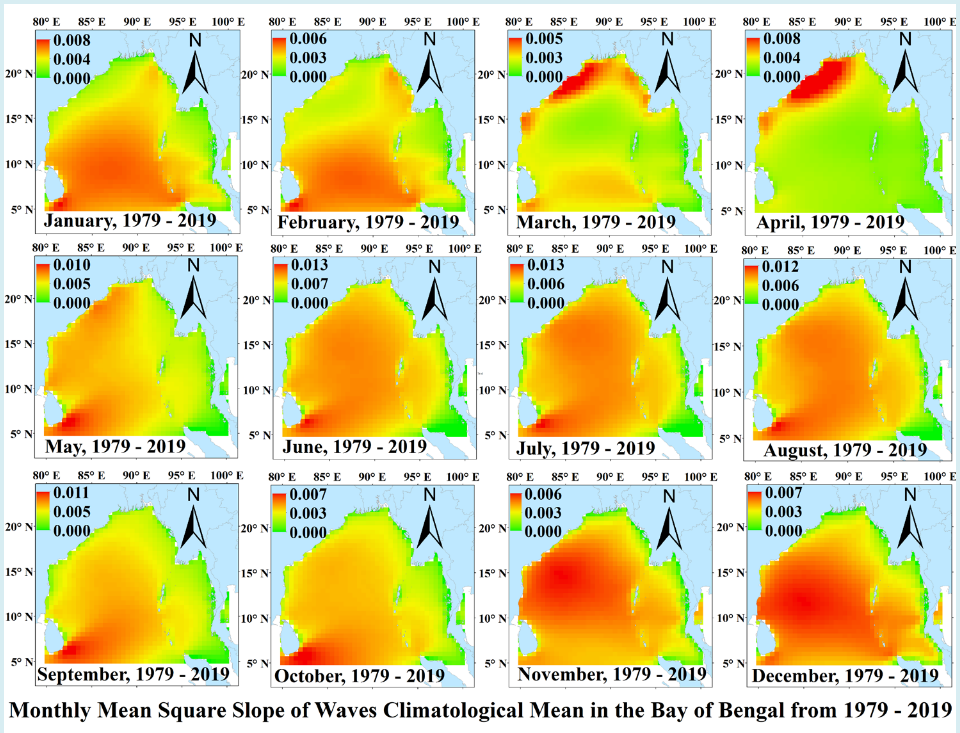

Figure 6: Spatial distribution of MSS from 1979–2019 in the BoB.

Correlations of the parameters (SWH, WSP, Tm, MSS, and Cd) according to Pearson's method are developed in this study. SWH and WSP have revealed strong positive correlation for every month except March–April while SWH and Tm have also revealed strong positive correlation during each month. WSP and MSS, WSP and Cd, as well as MSS and Cd have developed perfect positive correlation for every month. SWH with MSS and Cd have also showed strong positive correlation during most of the month. The anomaly in the SWH, WSP, and Tm varies between –0.40 and 0.38, –1.80 and 1.54, and –1.04 and 1.11 respectively. Maximum positive and negative anomalies of SWH and WSP are found during May, 1985 and April, 1987 respectively while maximum positive and negative anomalies of Tm are observed during September, 2019 and September, 2003 respectively [20] (Figures 7-90).

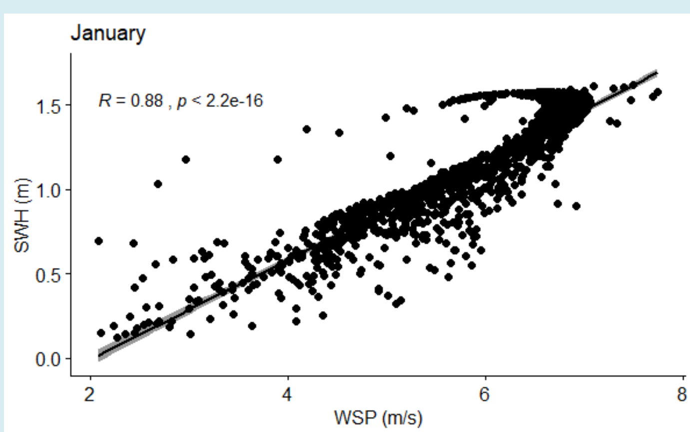

Figure 7: Correlation between WSP (m/s) and SWH (m) in January.

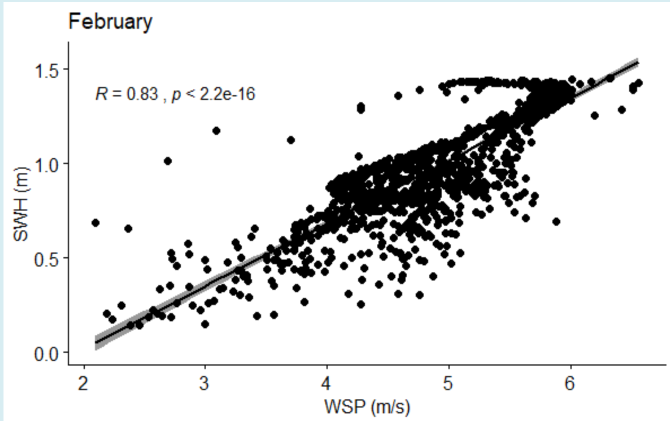

Figure 8: Correlation between WSP (m/s) and SWH (m) in February.

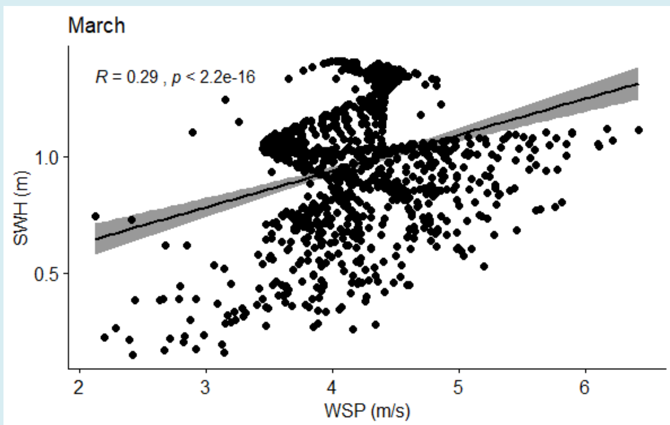

Figure 9: Correlation between WSP (m/s) and SWH (m) in March.

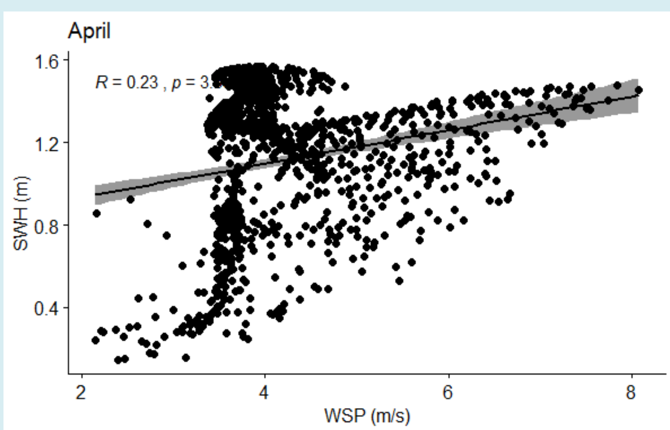

Figure 10: Correlation between WSP (m/s) and SWH (m) in April.

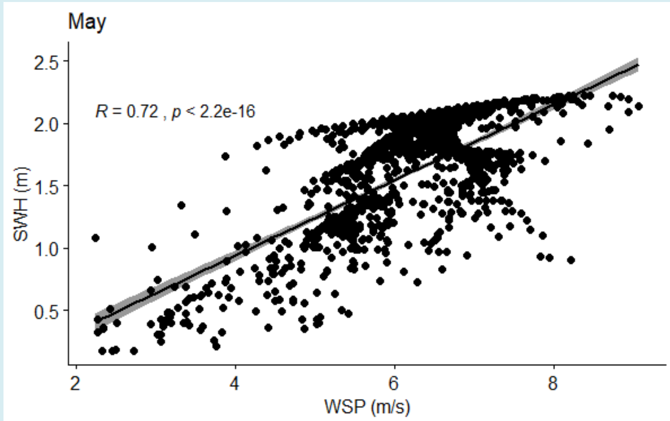

Figure 11: Correlation between WSP (m/s) and SWH (m) in May.

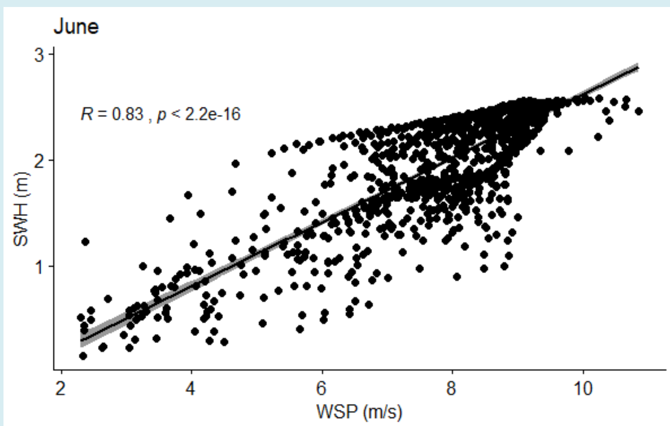

Figure 12: Correlation between WSP (m/s) and SWH (m) in June.

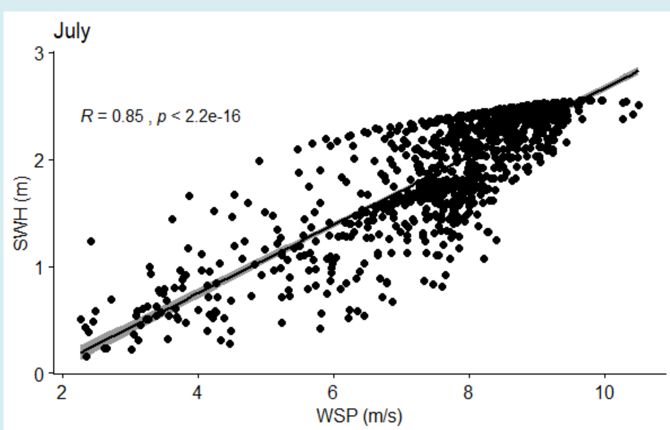

Figure 13: Correlation between WSP (m/s) and SWH (m) in July.

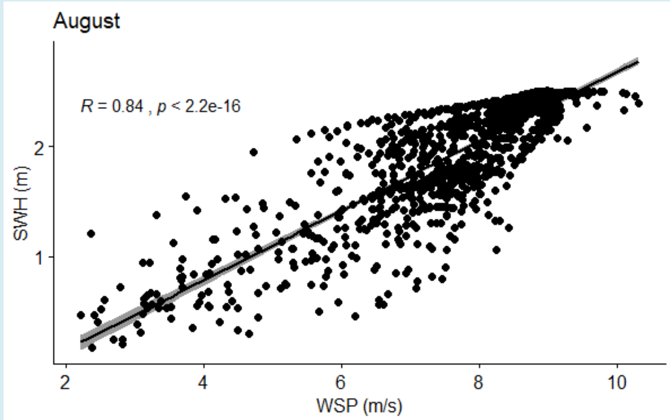

Figure 14: Correlation between WSP (m/s) and SWH (m) in August.

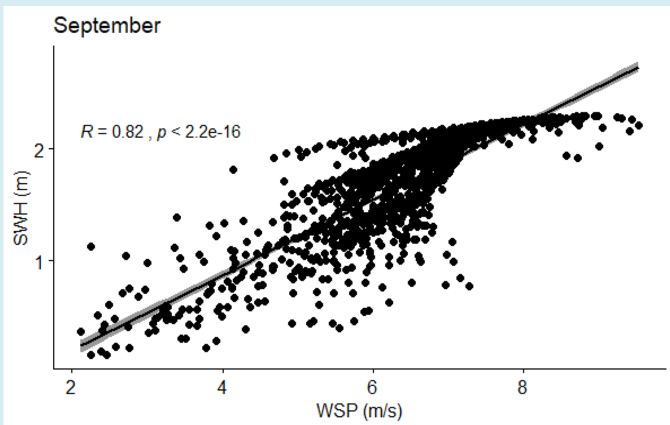

Figure 15: Correlation between WSP (m/s) and SWH (m) in September.

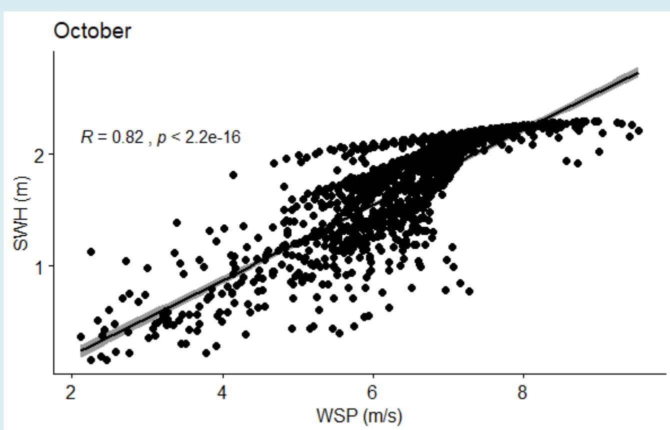

Figure 16: Correlation between WSP (m/s) and SWH (m) in October.

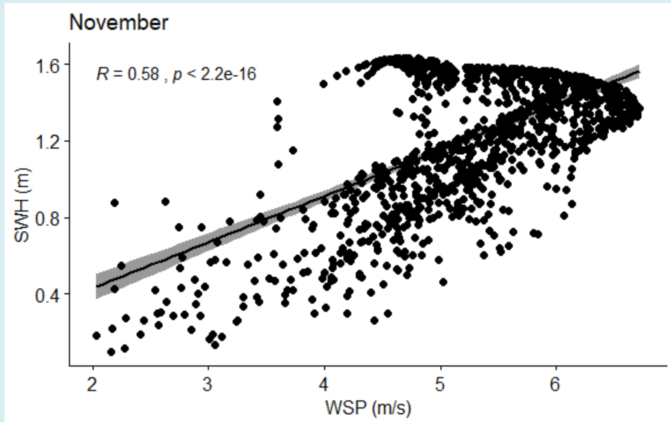

Figure 17: Correlation between WSP (m/s) and SWH (m) in November.

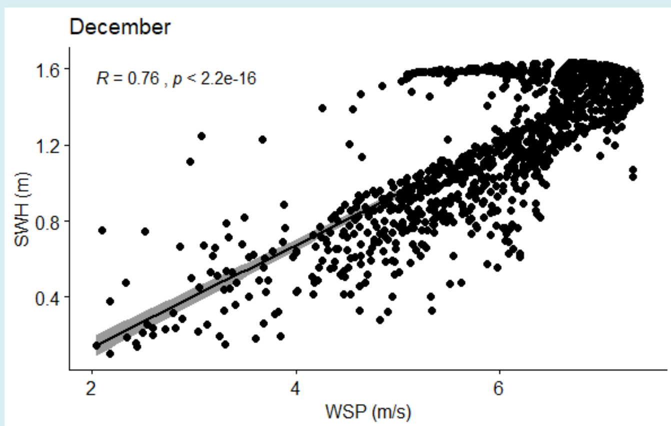

Figure 18: Correlation between WSP (m/s) and SWH (m) in December.

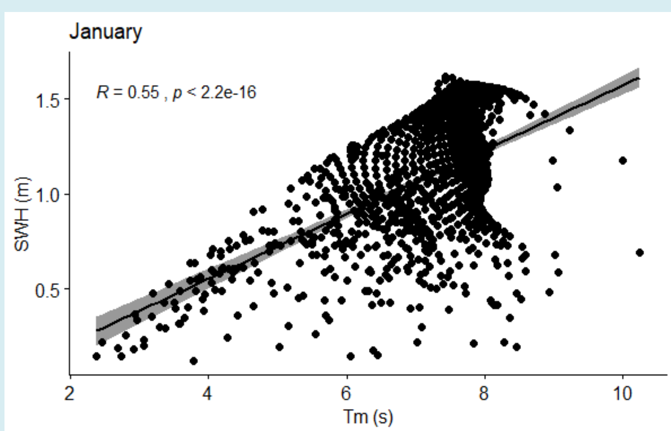

Figure 19: Correlation between SWH (m) and Tm (s) in January.

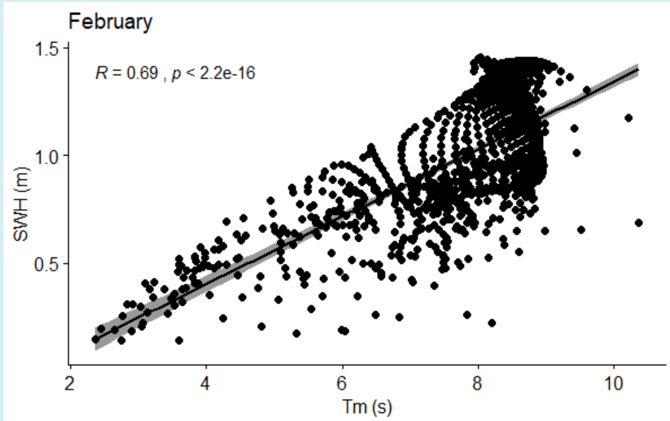

Figure 20: Correlation between WSP (m/s) and SWH (m) in February.

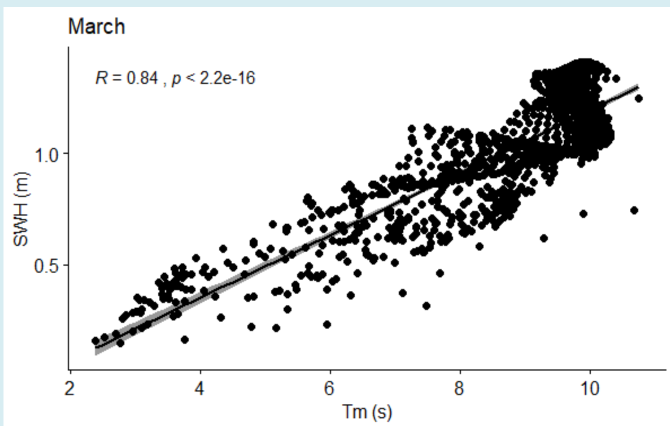

Figure 21: Correlation between SWH (m) and Tm (s) in March.

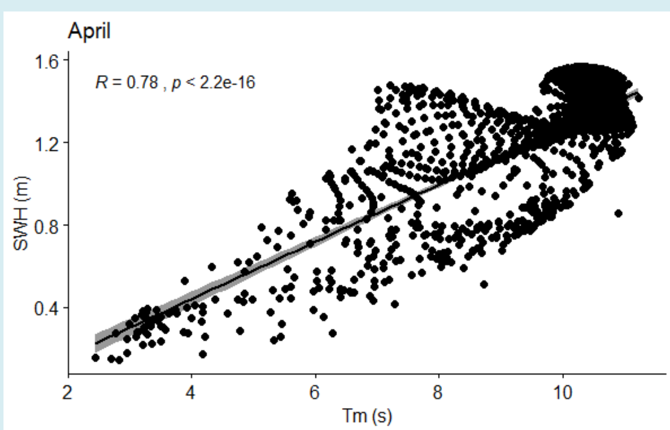

Figure 22: Correlation between SWH (m) and Tm (s) in April.

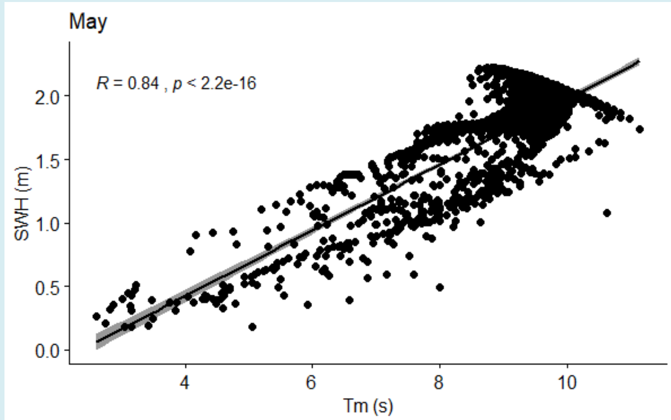

Figure 23: Correlation between SWH (m) and Tm (s) in May.

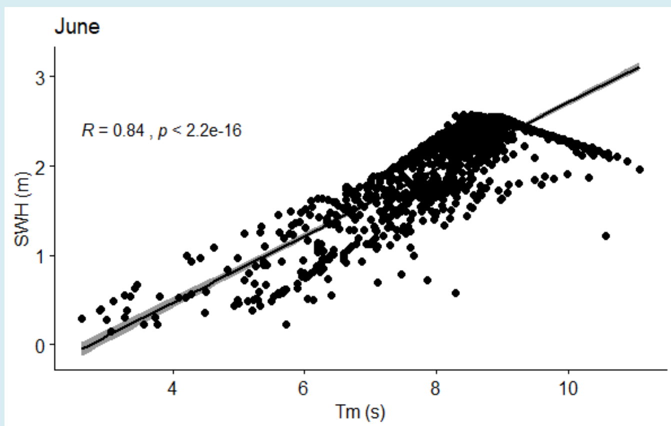

Figure 24: Correlation between SWH (m) and Tm (s) in June.

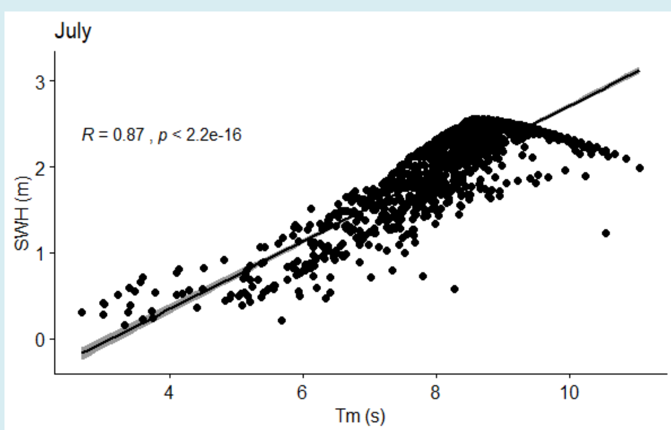

Figure 25: Correlation between SWH (m) and Tm (s) in July.

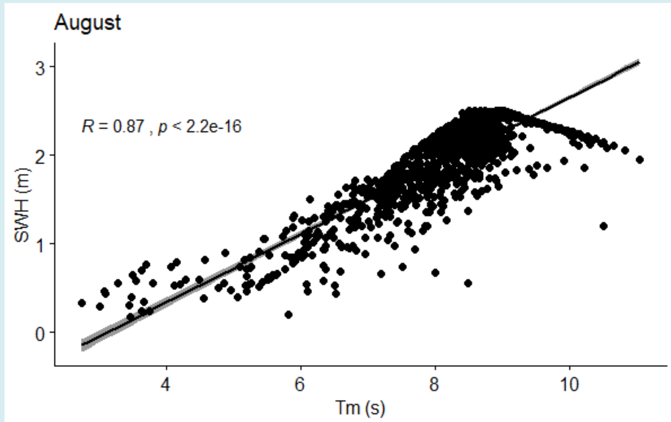

Figure 26: Correlation between SWH (m) and Tm (s) in August.

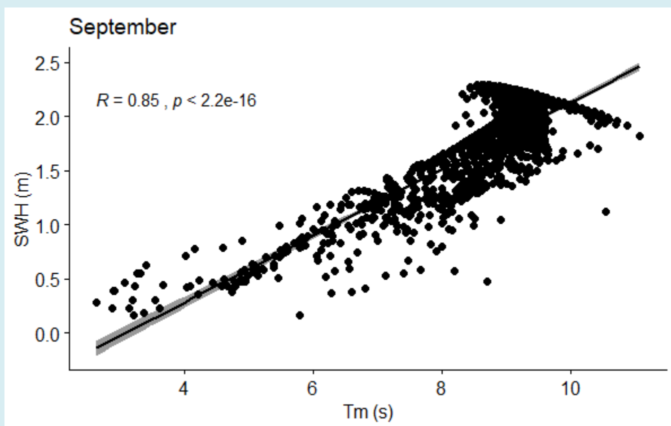

Figure 27: Correlation between SWH (m) and Tm (s) in September.

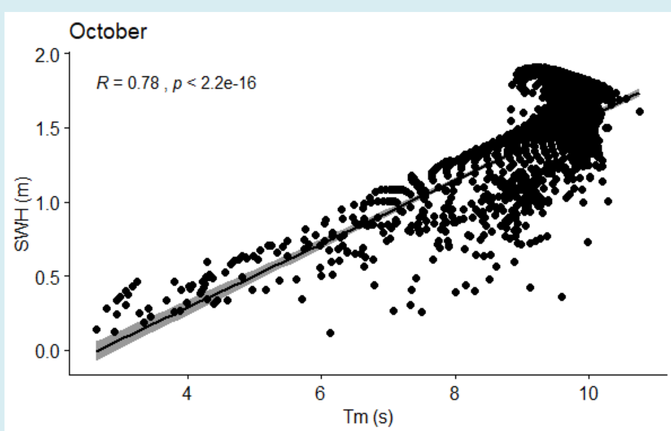

Figure 28: Correlation between SWH (m) and Tm (s) in October.

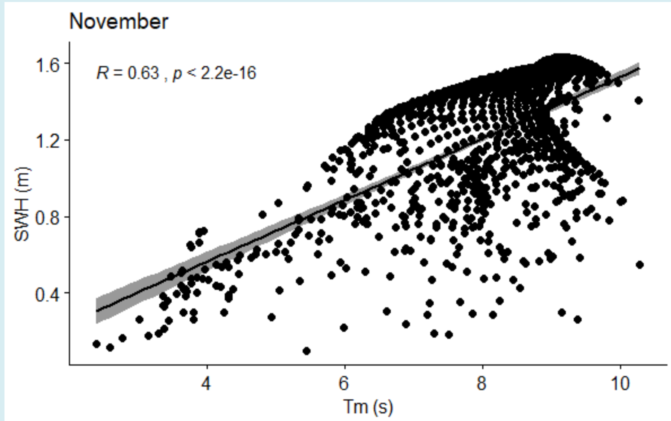

Figure 29: Correlation between SWH (m) and Tm (s) in November.

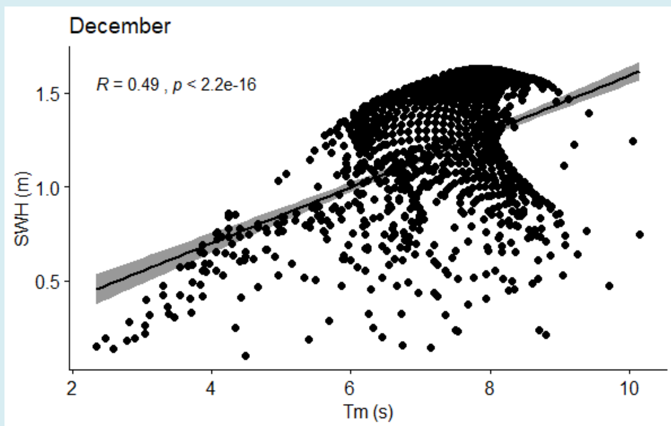

Figure 30: Correlation between SWH (m) and Tm (s) in December.

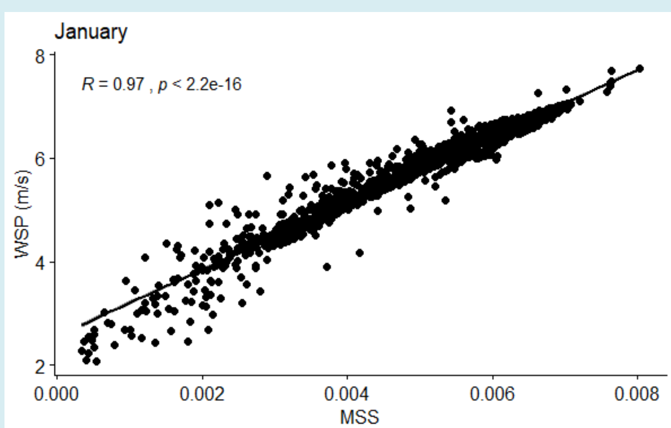

Figure 31: Correlation between WSP (m/s) and MSS in January.

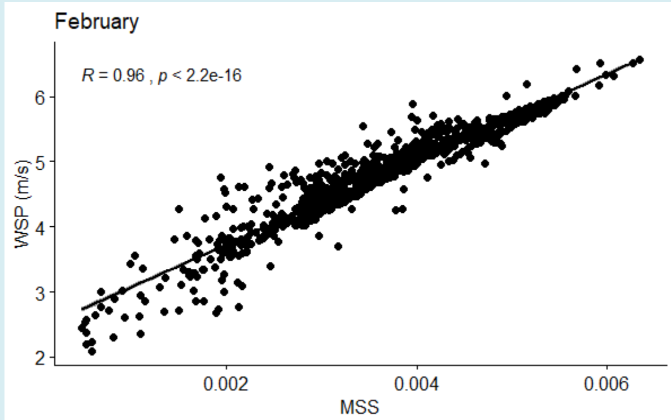

Figure 32: Correlation between WSP (m/s) and MSS in February.

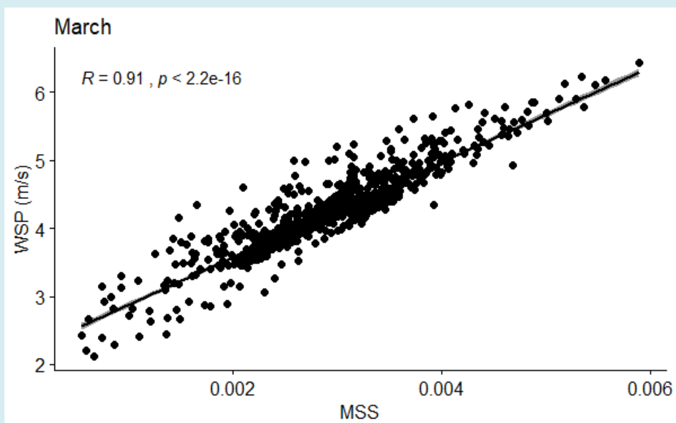

Figure 33: Correlation between WSP (m/s) and MSS in March.

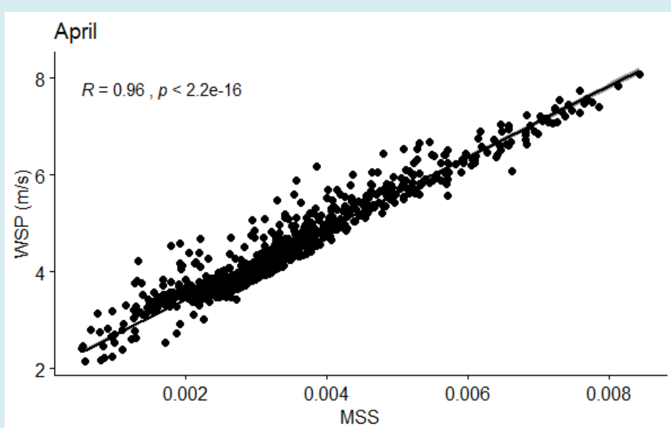

Figure 34: Correlation between WSP (m/s) and MSS in April.

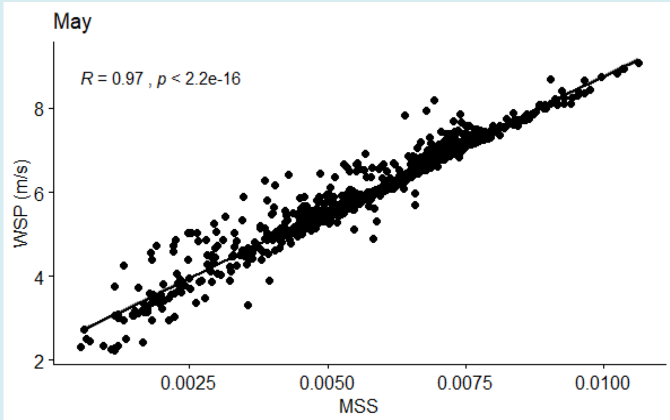

Figure 35: Correlation between WSP (m/s) and MSS in May.

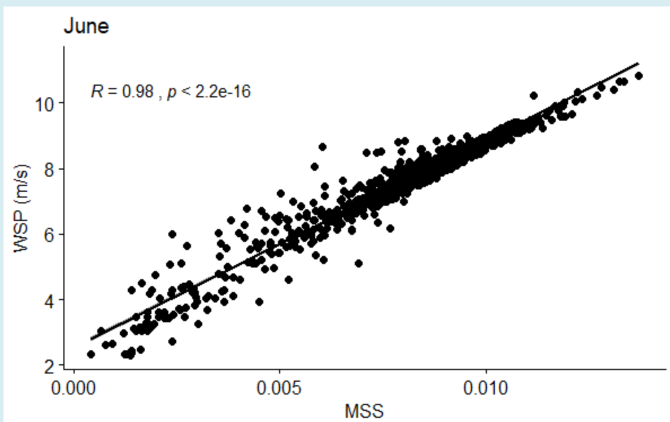

Figure 36: Correlation between WSP (m/s) and MSS in June.

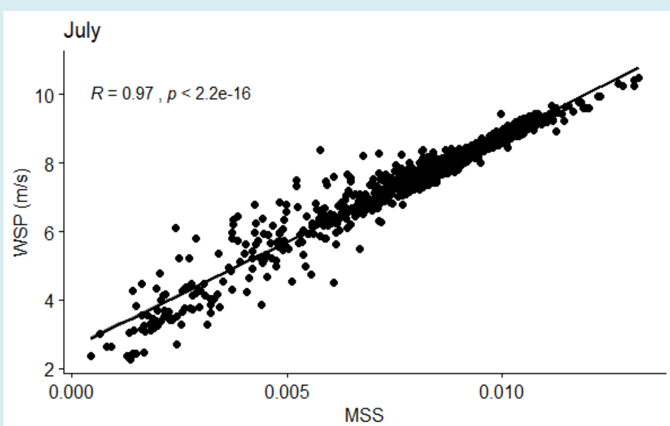

Figure 37: Correlation between WSP (m/s) and MSS in July.

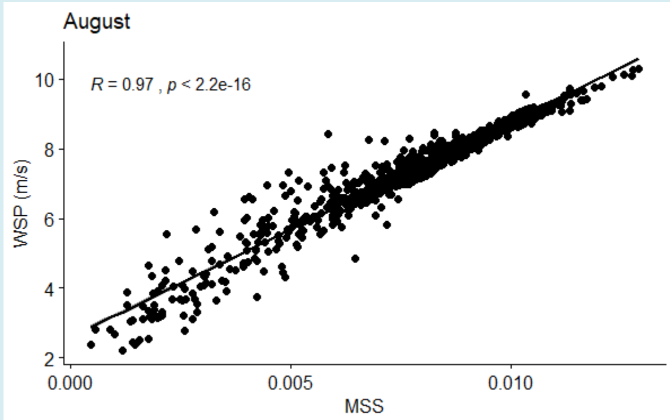

Figure 38: Correlation between WSP (m/s) and MSS in August.

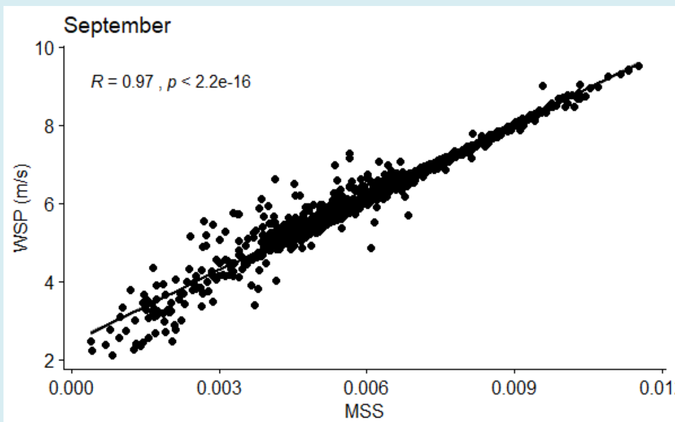

Figure 39: Correlation between WSP (m/s) and MSS in September.

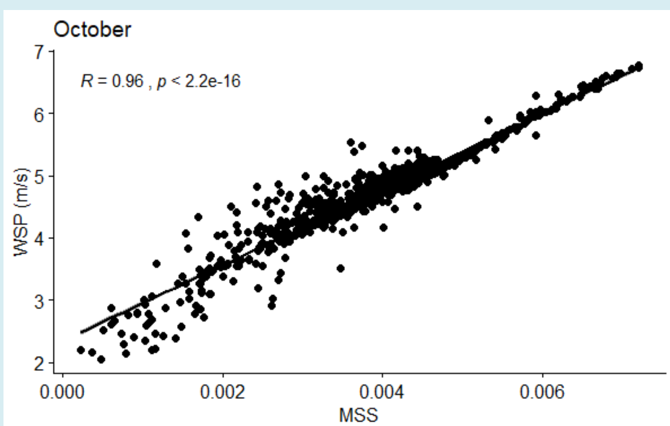

Figure 40: Correlation between WSP (m/s) and MSS in October.

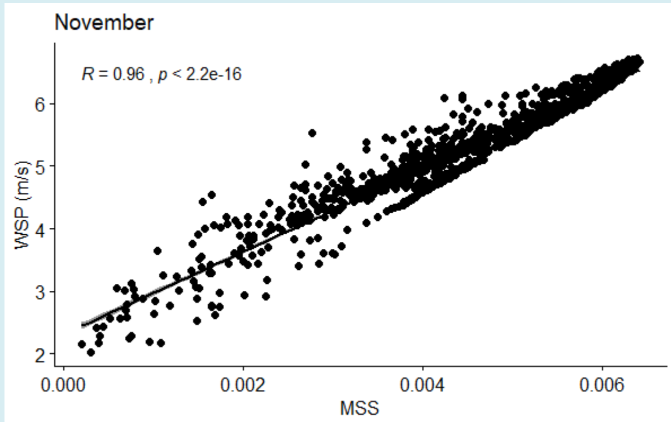

Figure 41: Correlation between WSP (m/s) and MSS in November.

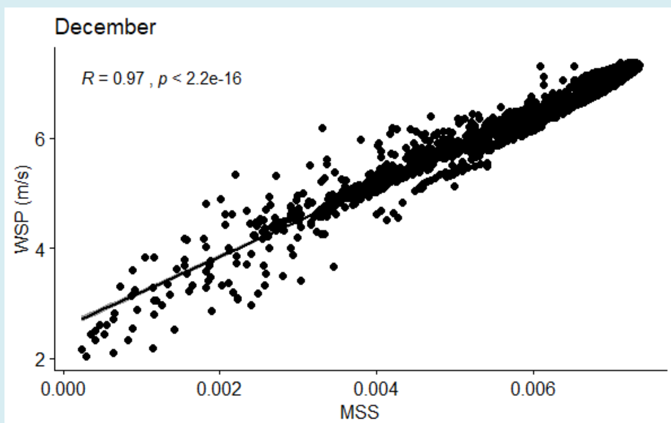

Figure 42: Correlation between WSP (m/s) and MSS in December.

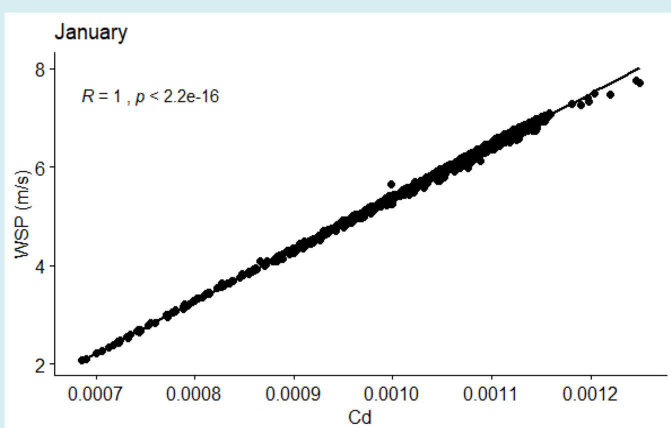

Figure 43: Correlation between WSP (m/s) and Cd in January.

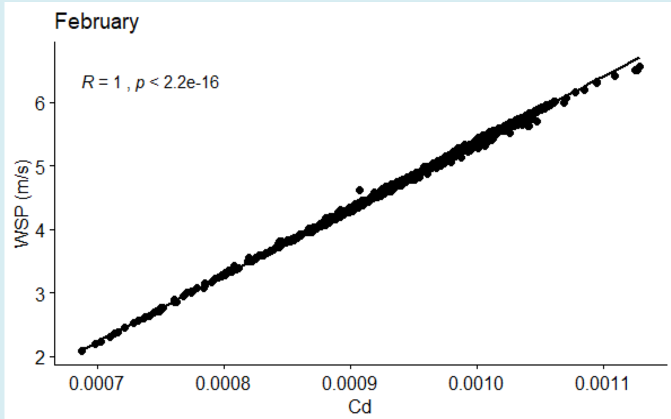

Figure 44: Correlation between WSP (m/s) and Cd in February.

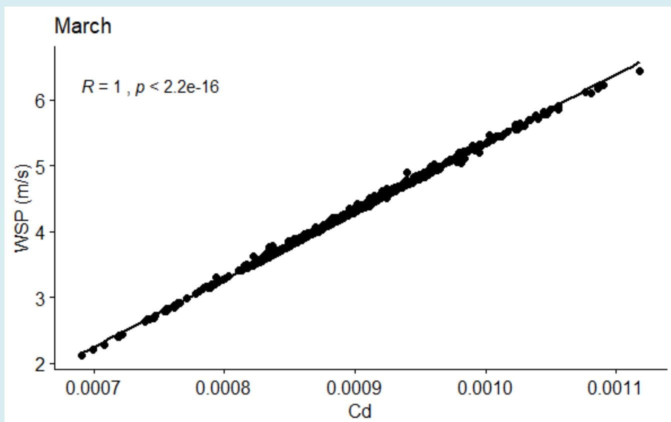

Figure 45: Correlation between WSP (m/s) and Cd in March.

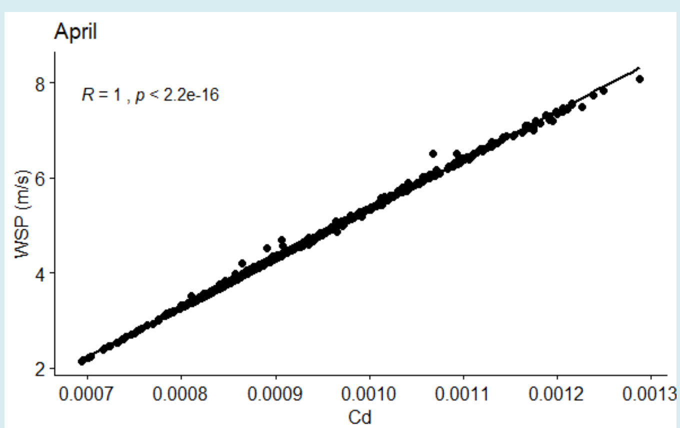

Figure 46: Correlation between WSP (m/s) and Cd in April.

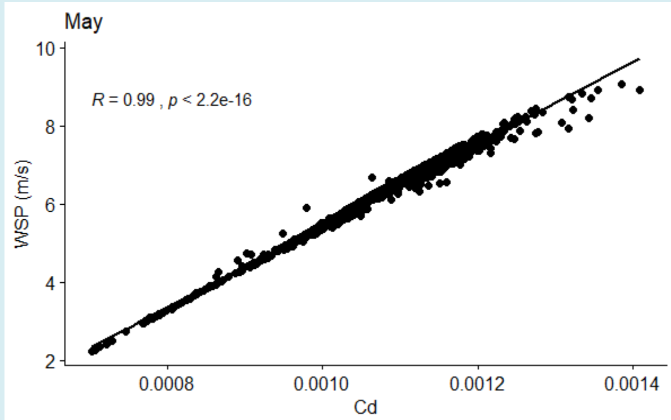

Figure 47: Correlation between WSP (m/s) and Cd in May.

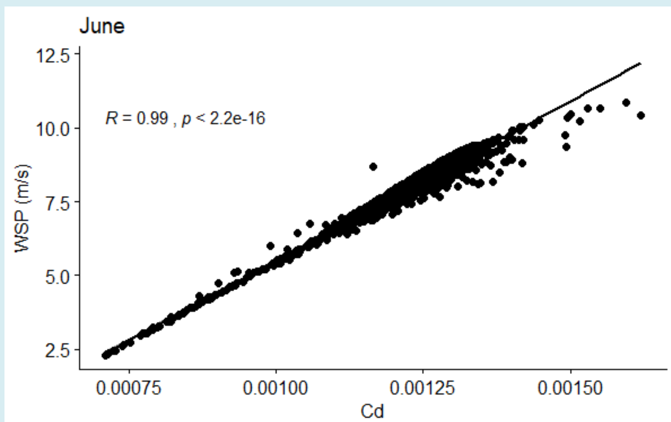

Figure 48: Correlation between WSP (m/s) and Cd in June.

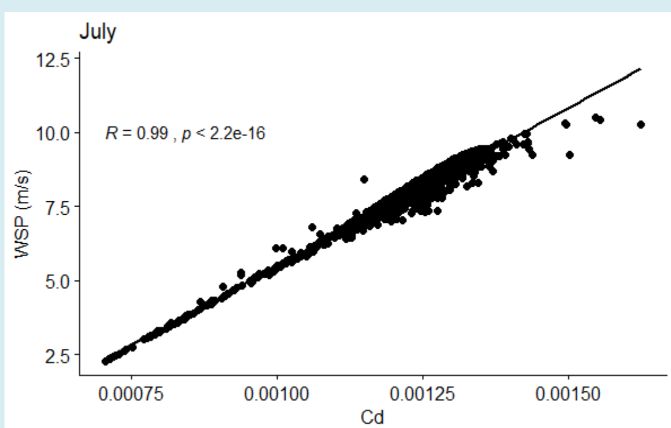

Figure 49: Correlation between WSP (m/s) and Cd in July.

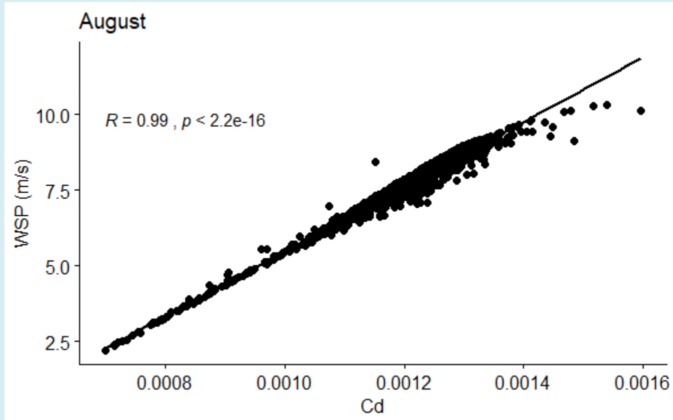

Figure 50: Correlation between WSP (m/s) and Cd in August.

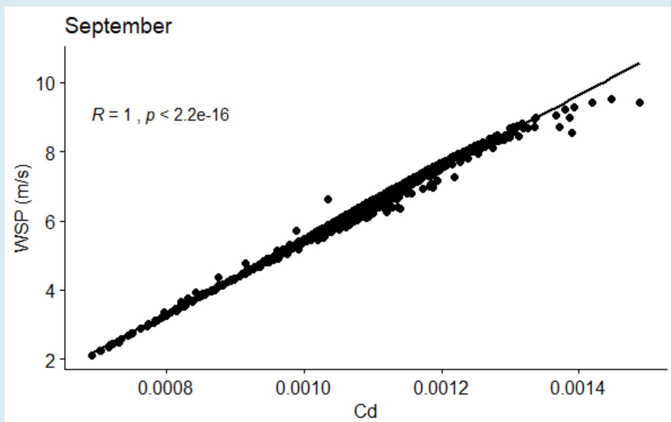

Figure 51: Correlation between WSP (m/s) and Cd in September.

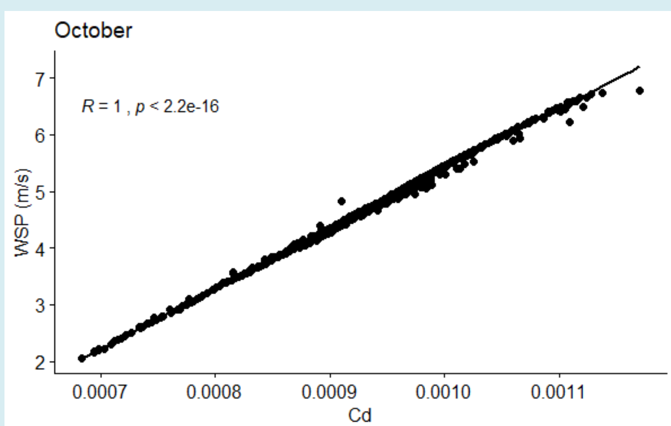

Figure 52: Correlation between WSP (m/s) and Cd in October.

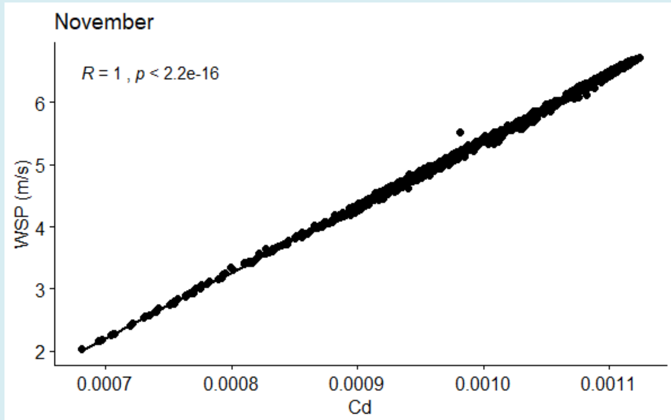

Figure 53: Correlation between WSP (m/s) and Cd in November.

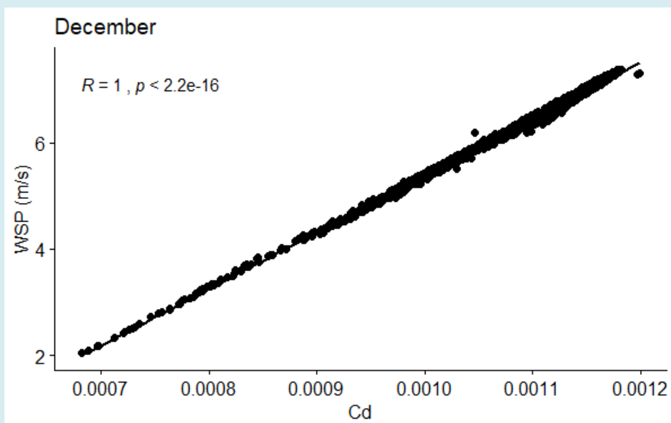

Figure 54: Correlation between WSP (m/s) and Cd in December.

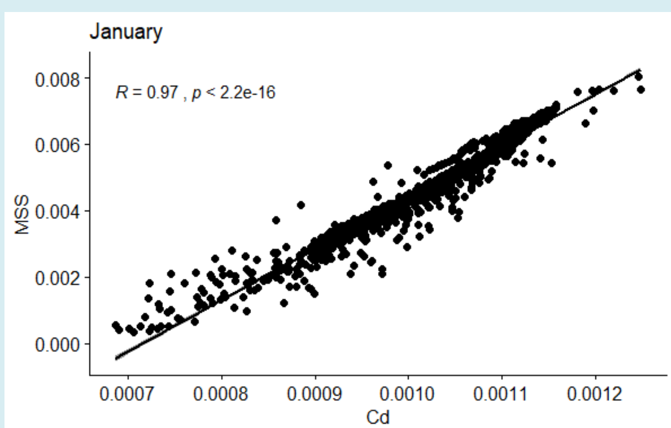

Figure 55: Correlation between Cd and MSS in January.

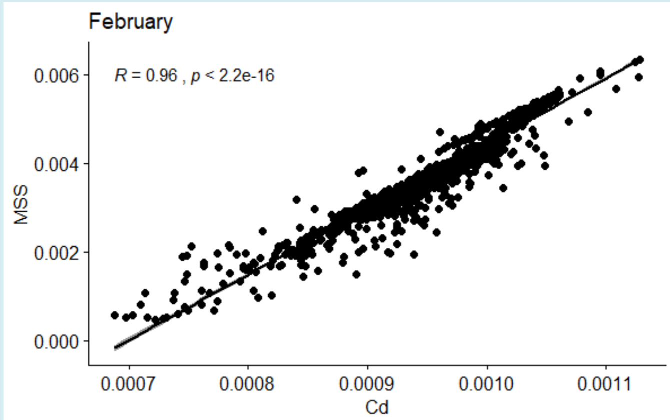

Figure 56: Correlation between Cd and MSS in February.

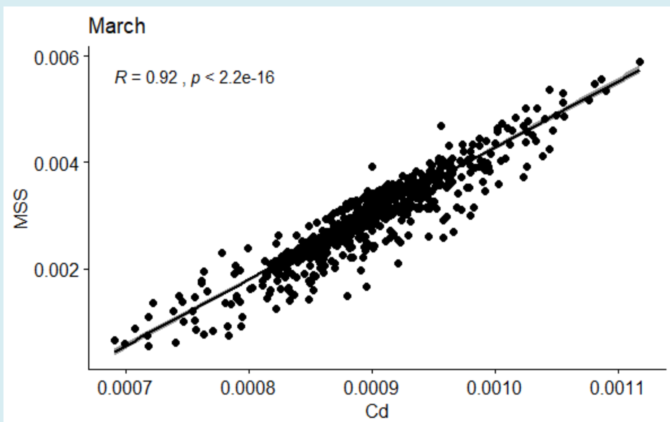

Figure 57: Correlation between Cd and MSS in March.

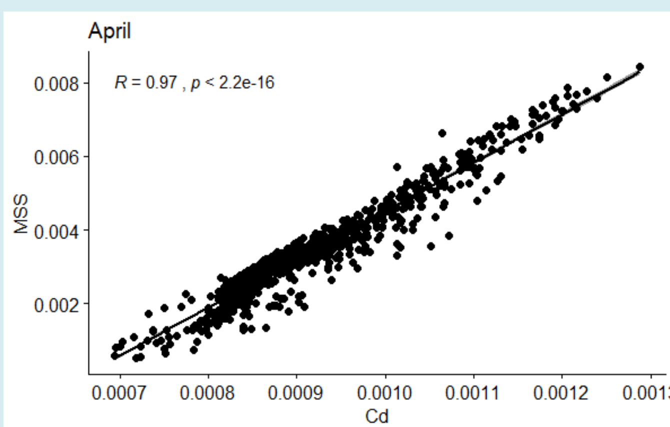

Figure 58: Correlation between Cd and MSS in April.

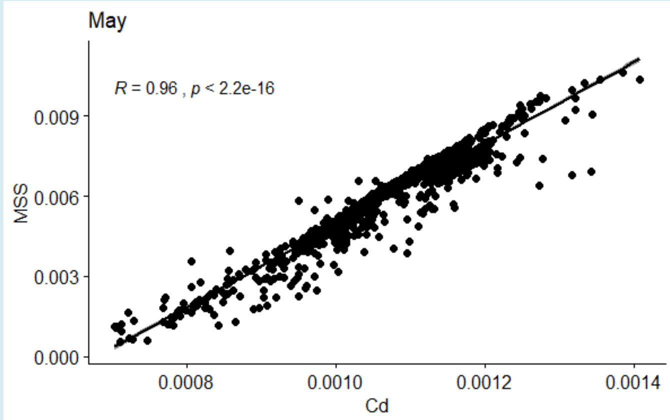

Figure 59: Correlation between Cd and MSS in May.

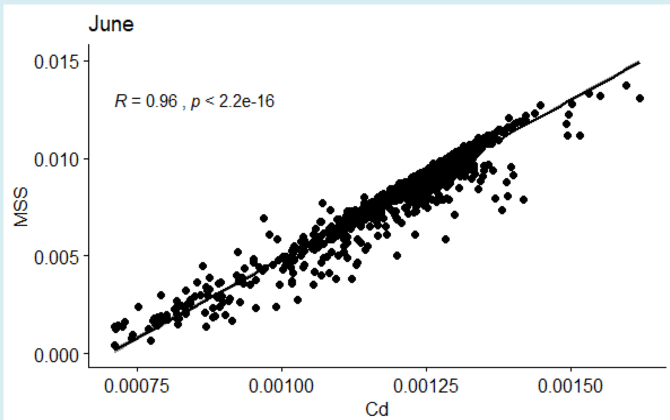

Figure 60: Correlation between Cd and MSS in June.

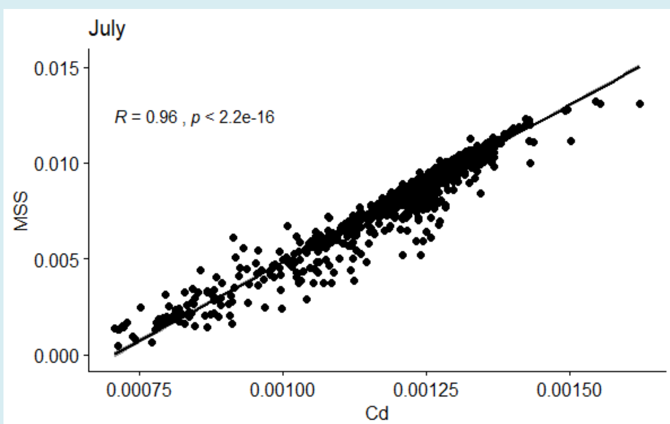

Figure 61: Correlation between Cd and MSS in July.

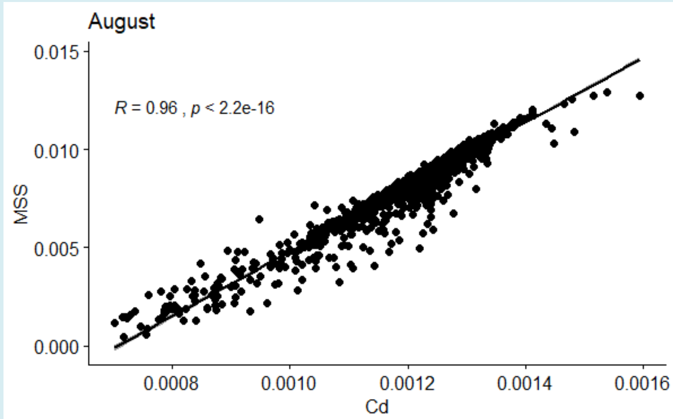

Figure 62: Correlation between Cd and MSS in August.

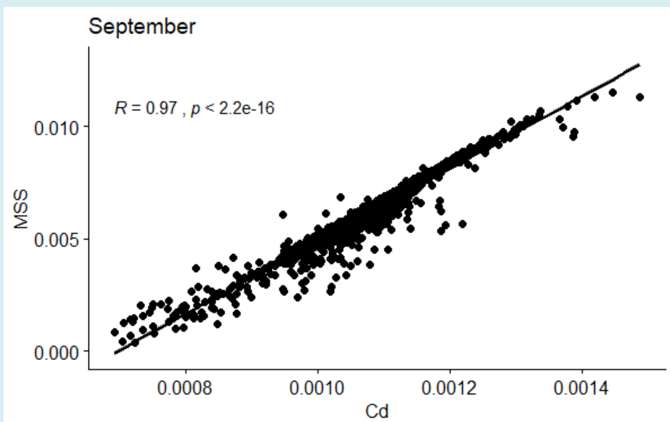

Figure 63: Correlation between Cd and MSS in September.

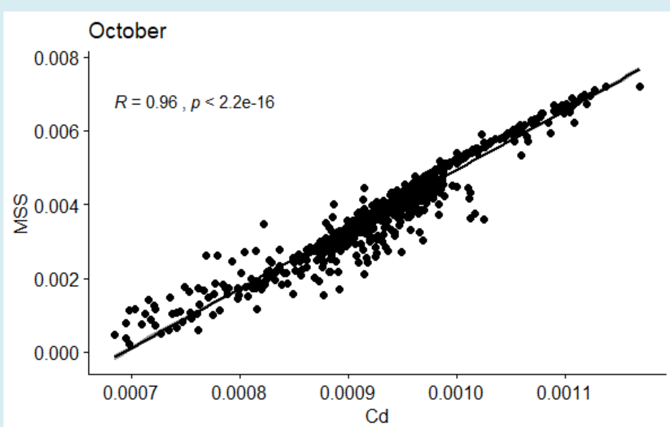

Figure 64: Correlation between Cd and MSS in October.

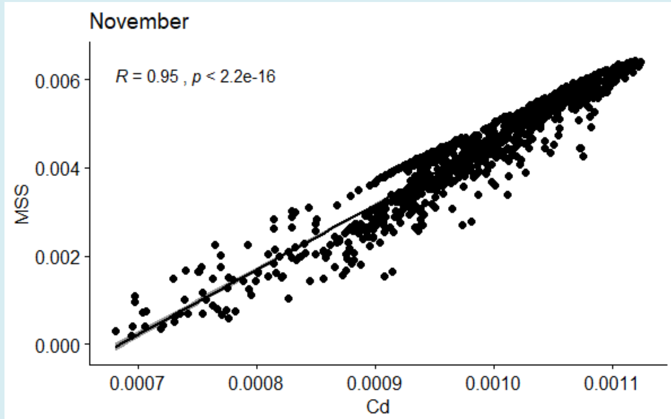

Figure 65: Correlation between Cd and MSS in November.

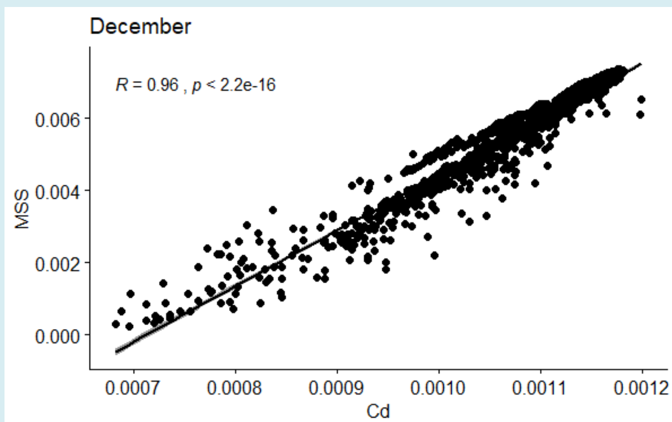

Figure 66: Correlation between Cd and MSS in December.

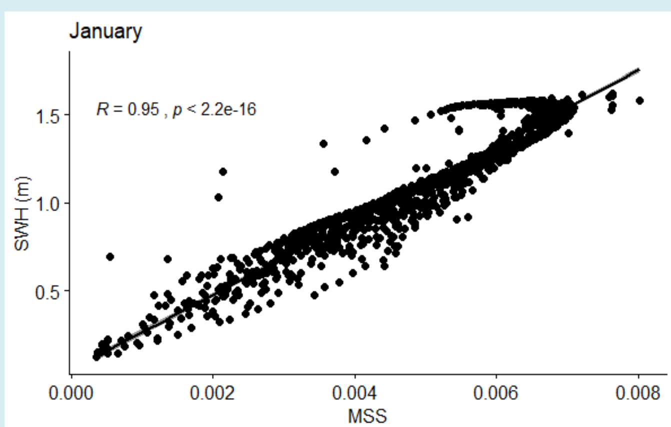

Figure 67: Correlation between SWH (m) and MSS in January.

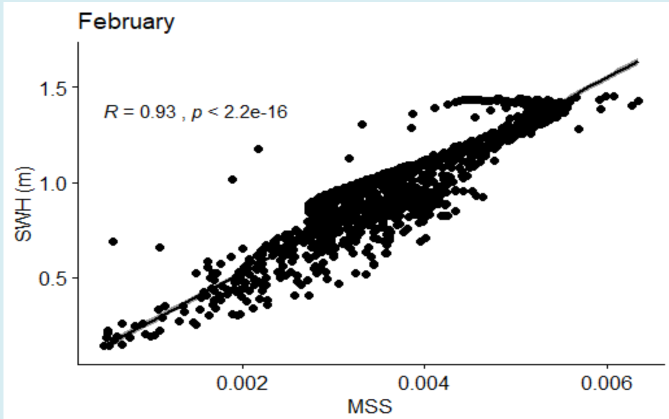

Figure 68: Correlation between SWH (m) and MSS in February.

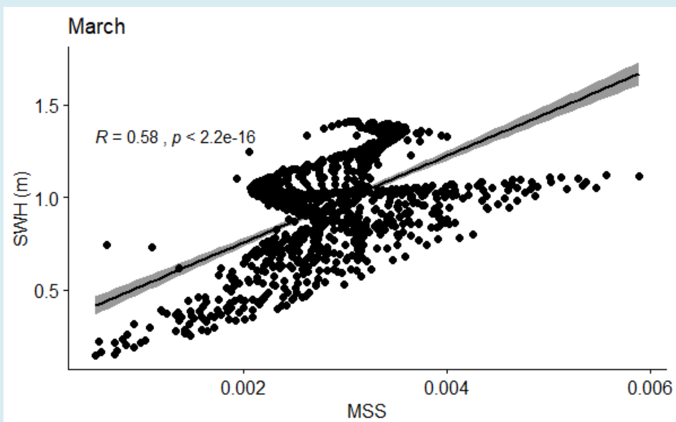

Figure 69: Correlation between SWH (m) and MSS in March.

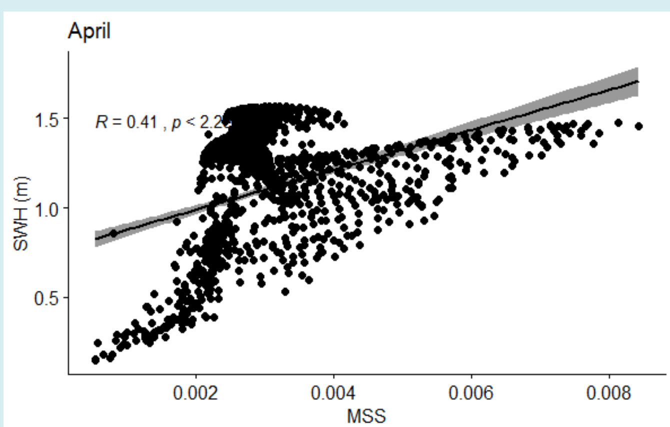

Figure 70: Correlation between SWH (m) and MSS in April.

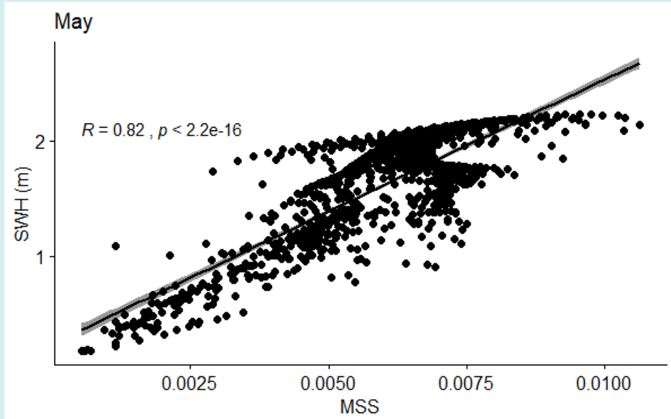

Figure 71: Correlation between SWH (m) and MSS in May.

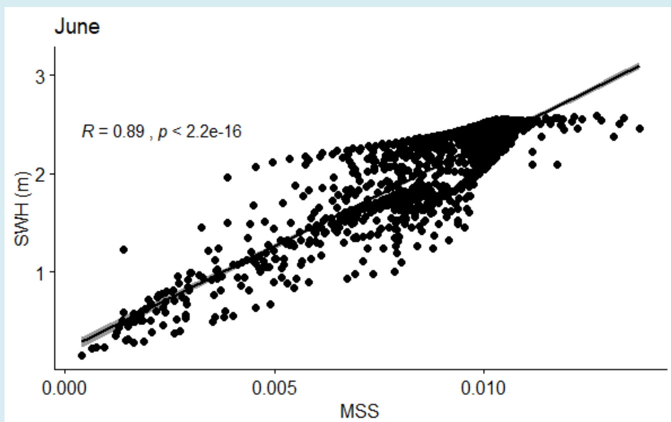

Figure 72: Correlation between SWH (m) and MSS in June.

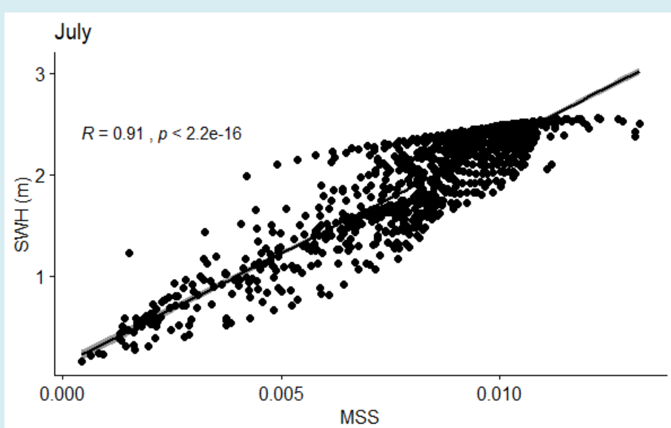

Figure 73: Correlation between SWH (m) and MSS in July.

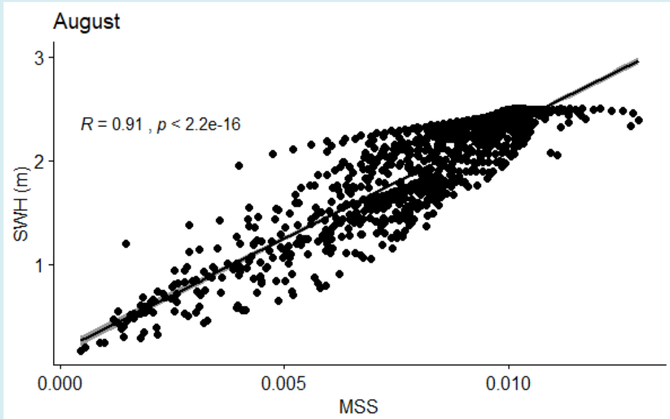

Figure 74: Correlation between SWH (m) and MSS in August.

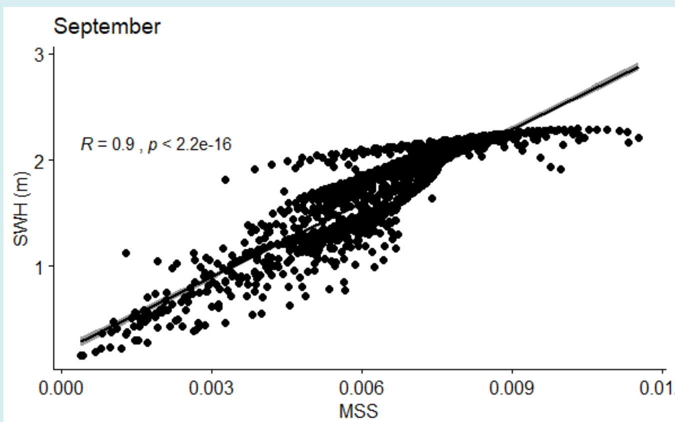

Figure 75: Correlation between SWH (m) and MSS in September.

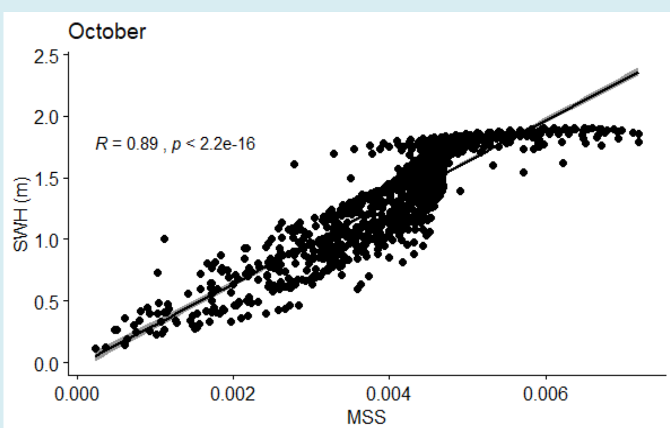

Figure 76: Correlation between SWH (m) and MSS in October.

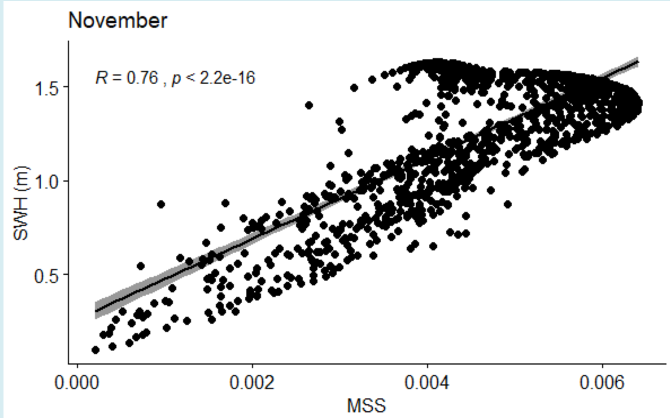

Figure 77: Correlation between SWH (m) and MSS in November.

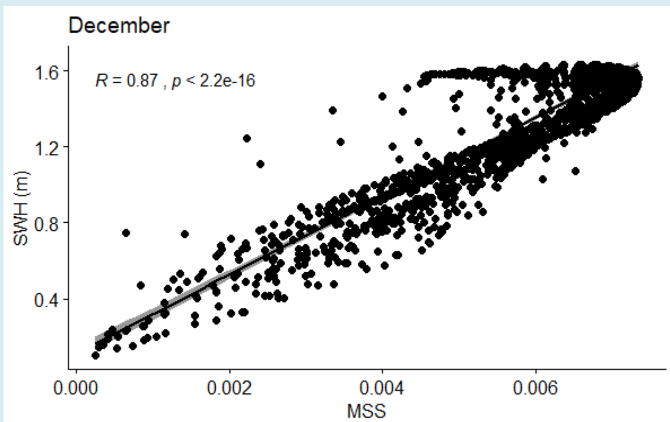

Figure 78: Correlation between SWH (m) and MSS in December.

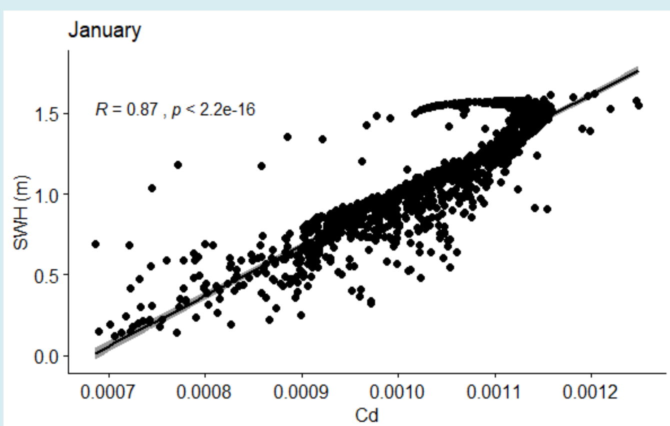

Figure 79: Correlation between SWH (m) and Cd in January.

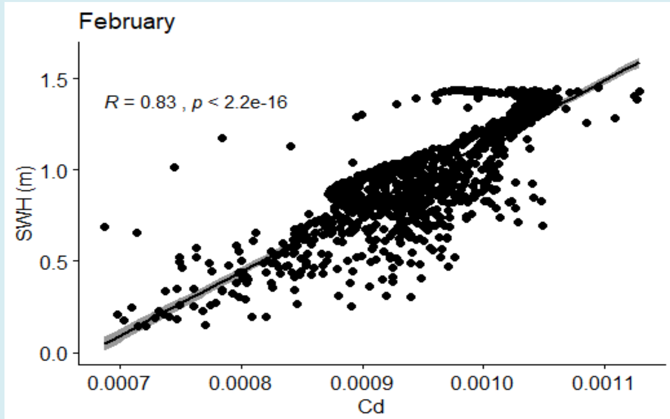

Figure 80: Correlation between SWH (m) and Cd in February.

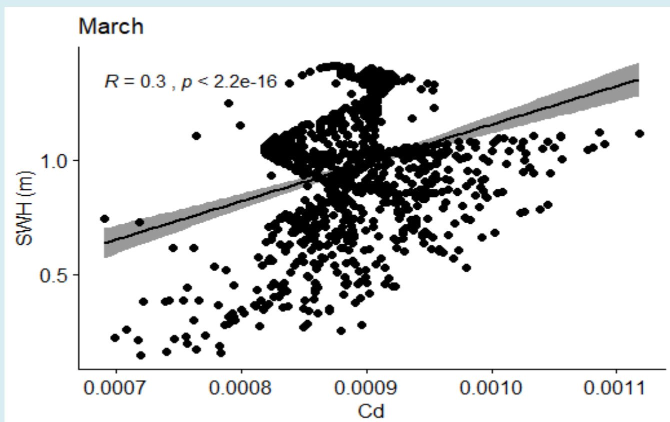

Figure 81: Correlation between SWH (m) and Cd in March.

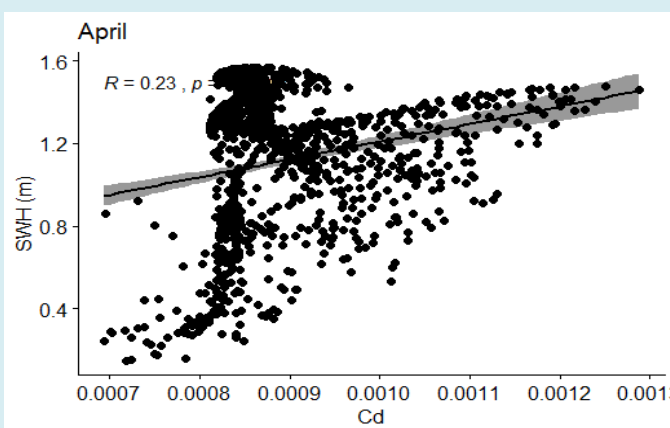

Figure 82: Correlation between SWH (m) and Cd in April.

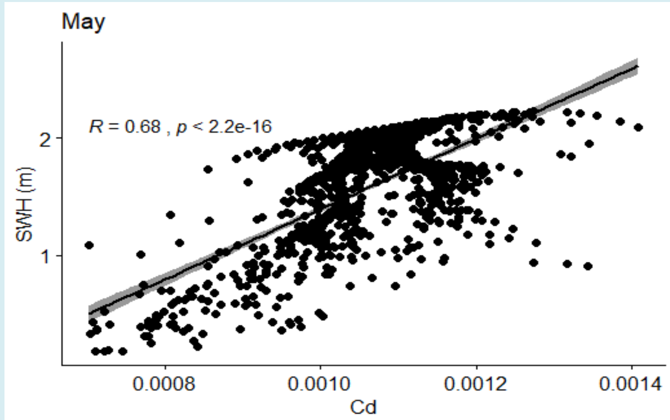

Figure 83: Correlation between SWH (m) and Cd in May.

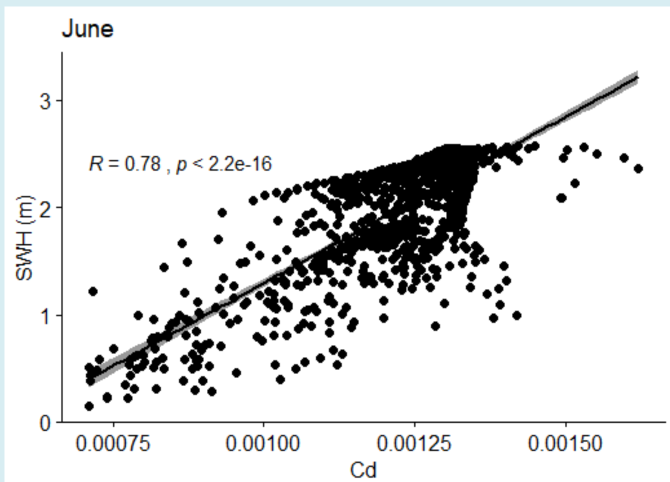

Figure 84: Correlation between SWH (m) and Cd in June.

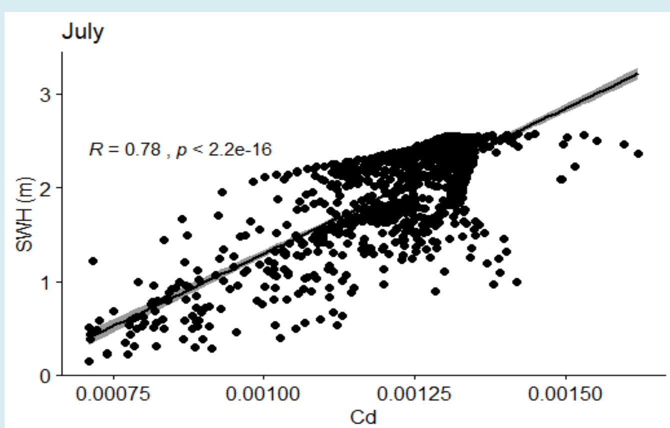

Figure 85: Correlation between SWH (m) and Cd in July.

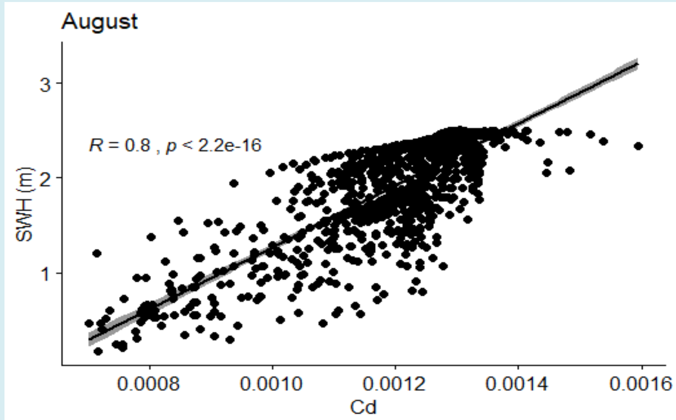

Figure 86: Correlation between SWH (m) and Cd in August.

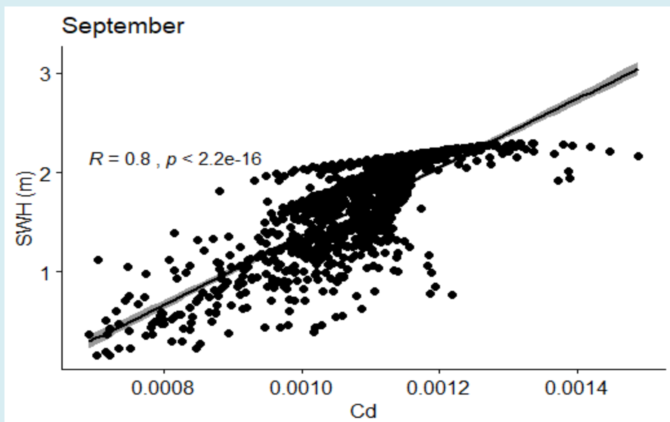

Figure 87: Correlation between SWH (m) and Cd in September.

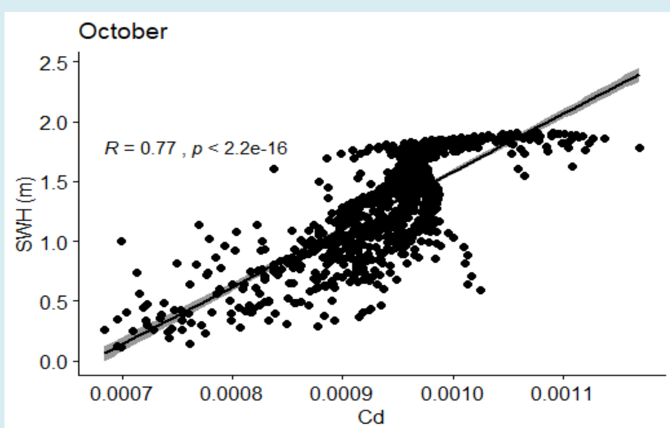

Figure 88: Correlation between SWH (m) and Cd in October.

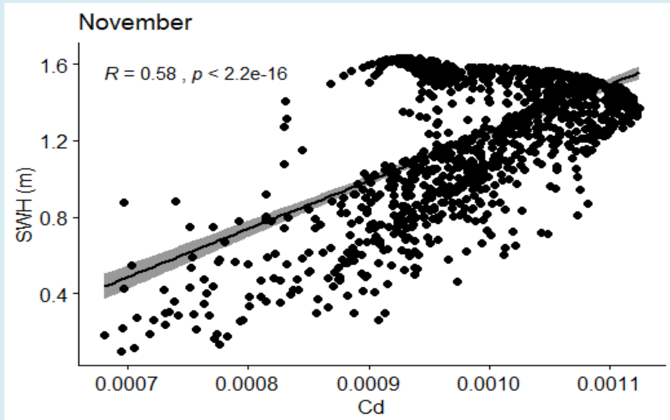

Figure 89: Correlation between SWH (m) and Cd in November.

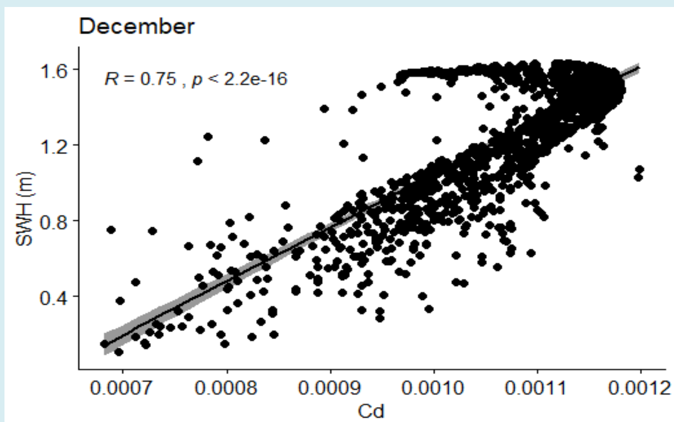

Figure 90: Correlation between SWH (m) and Cd in December.

Conclusion

Monthly climatological mean of the wave parameters in spatial perspective, and their anomaly, and correlation have been revealed throughout this research. It is unfolded that SWH, WSP, Tm, MSS and Cd are closely interlinked. The values of SWH and WSP are higher during June–August. Central and southern BoB are the regions of high SWH. WSP dominates the south-western BoB. SWH is higher in south-western BoB due to higher WSP for almost every month; but in case of March–April, high SWH dominate the north-western BoB due to the positive influence of WSP. The Western and Eastern BoB are the regions of lower Tm in most of the months. Cd and MSS are strongly controlled by WSP and SWH in most parts of the BoB.

As the knowledge of long–term climatological analysis of ocean waves has profound significance on applied oceanogolical sectors and any change in one parameter can significantly affect the other, it was essential to carry out the investigation regarding these parameters. Decoding 40 years of data, and their analysis and visualization was a challenging job during this research. The challenge is overcome with the help of python scripts in CDS toolbox, R, and ArcMap Software. Authors like to declare that there is no conflict of interest and no funding was taken from any organization for this research.

Acknowledgement

Authors acknowledge the Copernicus Atmosphere Monitoring Service (CAMS), Copernicus Climate Change Service (C3S) and Copernicus Climate Data Store for making data freely available and for providing technical support, which are both being run by the European Centre for Medium Range Weather Forecasting (ECMWF).

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