SATELLITE ALTIMETER WIND SPEED ESTIMATION AND TROPICAL CYCLONE CHARACTERIZATION USING MACHINE LEARNING

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Built Environment and Surveying
Universiti Teknologi Malaysia

FEBRUARY 2022

DEDICATION

All Praises to Almighty Allah, Alhamdulillah.

"Ask Lord for beneficial knowledge and seek refuge with Lord from knowledge that does not bring benefit."

– Prophet Muhammad S.A.W.

The journey of my study and the completion of this thesis is dedicated to;

My Father, Mohd Sharoni Ismail, who's introduced me to the Ph.D. world.

My Mother, Kamilah Sarlan, who's never stop praying for me.

My Parents in-law, Abd Samad and Seniah, who're always believe in me.

My Wife, Nur Syazni Amirah, who's always the main support throughout this journey.

My Siblings, who're always there for me when I need them.

My Sons, Aqif Syahid and Aniq Syamil who're cheered me up and keep me strong.

You are all the inspiration behind all that I do, and the source of all that is good in my life.

ACKNOWLEDGEMENT

In the name of Allah S.W.T, the Most Beneficent and Merciful. First and foremost, I would like to express my fullest grateful to God for the love and strength He given to me to complete this Ph.D. study successfully. I am so much thankful for His blessing in nourishing my family and me stays in good health conditions.

I want to take this opportunity to convey my full appreciation to my main supervisor, Dr. Mohd Nadzri Bin Md Reba, for his encouragement, guidance, critics and friendship. Without his continue support and interest, this study would far from completed as presented here. Thanks to all staffs of the Geoscience and Digital Earth Center (INSTeG), Universiti Teknologi Malaysia (UTM) who gave me the full commitment and access to the laboratory and research facilities. I wish to also extend my acknowledgement to the Pusat Pengajian Sains Fizik, Universiti Sains Malaysia (USM) and the Ministry of Higher Education Malaysia with the financial support provided.

Not to forget, my deepest appreciation to my fellow postgraduate students who had been very helpful in sharing their knowledge and experiences. I would like to recognize the invaluable assistance, hospitality and friendship that you all provide during my study. May Allah shower us with success and great completion in our study.

I also wish to express my indebtedness to my beloved parents Mohd Sharoni Ismail and Kamilah Sarlan, my wife Nur Syazni Amirah, my siblings, and my sons Aqif Syahid and Aniq Syamil for their unfailing support and continuous love throughout my years of study. This accomplishment would not have been possible without them. Lastly, I want to thank those not mentioned here for their continuous prayers and support to give me strength in completing my Ph.D journey. Thank you and may Allah bless you with endless happiness.

ABSTRACT

Sea surface wind speed (U_{10}) is one of the vital variables for tropical cyclone analysis in providing accurate wind intensity information to the warning center. However, rough sea state condition, has caused the U_{10} observations by buoy to become unreliable. Although satellite altimeter can measure U_{10}, the operational Gourrion algorithm was designed for normal sea state conditions. Extreme ocean-atmospheric interaction worsen by the rain contamination on the altimeter signal has impaired the quality of the derived U_{10}, hence putting low attention in tropical cyclone study. This operational U_{10} product which only incorporates the backscatter and the surface wave height at Ku-band as principal parameters is insufficient to emulate a complex cyclone environment. Though higher U_{10} regime saturated at 20 ms^{-1} and heavy rainy conditions have reduced the U_{10} accuracy, other ocean-related parameters are worth considering. Therefore, this study was aimed to analyse the altimeter ocean-related parameters and thus estimate high accuracy U_{10} for tropical cyclone wind characterization. This study established a relationship between parameters response from Joint Altimetry Satellite Oceanography Network (Jason)-2 and Jason-3; and the coincident U_{10} from Meteorological Operational (MetOp)-A and MetOp-B scatterometers in 350 tropical cyclones captured between 2015 and 2018 globally. Quantitative assessment on the quality of altimeter C-band parameters and other simultaneously observed radiometric ocean parameters namely brightness temperatures at 18.7, 23.8, and 34.0 GHz, water vapor content, and liquid water content related to extreme U_{10} were presented. Correlation of C-band parameters to U_{10} outperformed that of the Ku-band counterpart by at least 29% and the inclusion of radiometric parameters contributed to a significant error reduction of about 48%. New and high accuracy U_{10} models were developed using Multiple Linear Regression and machine learning techniques namely Artificial Neural Network, Support Vector Machine, and Gaussian Process Regression. The Gaussian Process Regression with all parameters considered was proved to be the best model that could estimate U_{10} up to 35 ± 1 ms^{-1} with the improvement of 35% and 75% inside the rain and at the higher U_{10} regime respectively. The study clearly presented the tropical cyclone wind characters that could now be objectively estimated. The uncertainty of the derived maximum sustained wind speed intensity could be reduced to 70% compared to that of operational U_{10}. The storm center location, eye width, radius of inner and outer circle relatively at 50-knot and 30-knot respectively were distinguishable and well agreed to the reported tropical cyclone best-track. This study successfully established the fundamental analysis on the performance of altimetry and radiometry parameters acquired by Jason mission and integrate them to represent the tropical cyclone environment. The fine-scale altimeter along-track resolution of extracted tropical cyclone wind characters is exclusively demonstrated and has become a vital complement to the optical satellite image observation.

ABSTRAK

Kelajuan angin permukaan laut (U_{10}) adalah salah satu pemboleh ubah penting untuk menganalisis siklon tropika dalam membekalkan maklumat intensiti angin yang tepat kepada agensi bencana. Walau bagaimanapun, keadaan laut yang bergelora telah menyebabkan U_{10} yang diukur oleh pelampung tidak boleh diguna pakai. Walaupun altimeter satelit dapat mengukur U_{10}, algoritma operasi Gourrion telah direka untuk keadaan laut yang normal. Hubungan laut-atmosfera yang melampau diburukkan dengan gangguan hujan terhadap gelombang altimeter telah menurunkan kualiti pengukuran U_{10} yang diperoleh, justeru, ia kurang dipertimbangkan dalam kajian siklon tropika. Produk operasi U_{10} yang hanya melibatkan serakbalik dan ketinggian gelombang permukaan laut pada jalur Ku sebagai parameter utama adalah tidak mencukupi untuk menyamai persekitaran siklon yang kompleks. Walaupun rejim U_{10} yang tinggi telah tepu pada 20 ms^{-1} dan keadaan hujan lebat telah mengurangkan ketepatan U_{10}, parameter berkaitan dengan lautan perlu dipertimbangkan. Oleh itu, kajian ini bertujuan untuk menganalisis parameter berkaitan lautan dari altimeter dan menganggarkan ketepatan tinggi U_{10} untuk pencirian angin siklon tropika. Kajian ini membentuk hubungan antara tindak balas parameter dari *Joint Altimetry Satellite Oceanography Network* (Jason) -2 dan Jason-3 dan U_{10} yang sepadan dari *Meteorological Operational Satellite* (MetOp) -A dan MetOp-B scatterometer dalam 350 siklon tropika yang dirakamkan pada 2015 dan 2018 secara global. Penilaian kuantitatif terhadap kualiti parameter di altimeter jalur C dan parameter lautan yang dicerap oleh radiometer iaitu suhu kecerahan pada 18.7, 23.8 dan 34.0 GHz, kandungan wap air dan kandungan air atmosfera yang berkaitan dengan terhadap siklon tropika ditunjukkan. Korelasi parameter jalur C terhadap U_{10} telah mengatasi korelasi jalur Ku sekurang-kurangnya 29% dan penglibatan parameter dari radiometer menyumbang kepada pengurangan selisih sebanyak 48%. Model U_{10} baharu dan lebih tepat telah dibangunkan menggunakan teknik Regresi Linear Berganda dan teknik pembelajaran mesin iaitu Rangkaian Neural Buatan, Mesin Vektor Sokongan dan Regresi Proses Gaussian. Regresi Proses Gaussian dengan semua parameter yang dipertimbangkan telah terbukti sebagai model yang terbaik untuk mengira U_{10} sehingga 35 ± 1 ms^{-1} dengan penambahbaikan sekurang-kurangnya 35% dan 75% di dalam hujan dan pada rejim U_{10} yang lebih tinggi. Kajian ini jelas menunjukkan ciri angin siklon tropika yang kini boleh dikira secara objektif. Ralat keamatan kelajuan angin maksimum mampan yang diterbitkan boleh dikurangkan kepada 70% berbanding dengan keamatan dari U_{10} sedia ada. Lokasi pusat ribut, lebar mata ribut, jejari bulatan dalam dan luar siklon pada 50-knot dan 30- knot masing-masing boleh dibezakan dan dipersetujui terhadap landasan terbaik siklon tropika yang dilaporkan. Kajian ini berjaya mewujudkan analisis asas mengenai prestasi parameter dari altimeter dan radiometer yang diperoleh oleh satelit Jason dan menghimpunkan parameter ini untuk menggambarkan persekitaran siklon tropika. Resolusi altimeter berskala halus sepanjang trek dalam ciri angin siklon tropika telah diterbitkan secara eksklusif dan menjadi pelengkap utama kepada pemantuan imej satelit optik.

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LIST OF ABBREVIATIONS

ADT	-	Advanced Dvorak Technique
AMR	-	Advanced Microwave Radiometer
ANN	-	Artificial Neural Network
AODT	-	Advanced Objective Dvorak Technique
ASCAT	-	Advanced Scatterometer
AVISO	-	Archiving, Validation, and Interpretation of Satellite Oceanography Data
CI	-	Current Intensity
CPHC	-	Central Pacific Hurricane Center
DT	-	Dvorak Technique
ECMWF	-	European Centre for Medium-Range Weather Forecast
EUMETSAT	-	European Organisation Exploitation of Meteorological Satellite
ESA	-	European Space Agency
GDR	-	Geophysical Data Record
GMF	-	Geophysical Model Function
GMS	-	Geostationary Meteorological Satellite
GPR	-	Gaussian Process Regression
GPS	-	Global Positioning System
IBTrACS	-	International Best Track Archive for Climate Stewardship
IFOV	-	Instantaneous Field of View
JASON	-	Joint Altimetry Satellite Oceanography Network
JMA	-	Japan Meteorological Agency
JTWC	-	Joint Typhoon Warning Center
METOP	-	Meteorological Operational Satellite
ML	-	Machine Learning
MLR	-	Multiple Linear Regression
MSLP	-	Mean Sea Level Pressure

MSW	-	Maximum Sustained Wind
NASA	-	National Aeronautics and Space Administration
NHC	-	National Hurricane Center
NOAA	-	National Oceanic and Atmospheric Administration
NRCS	-	Normalize Radar Cross Section
ODT	-	Objective Dvorak Technique
PODAAC	-	Physical Oceanography Distributed Active Archive Center
RIC	-	Radius of Inner Circle
RMW	-	Radius of Maximum Wind
ROC	-	Radius of Outer Circle
RSMC	-	Regional Specialized Meteorological Centers
SFMR	-	Stepped Frequency Microwave Radiometer
SSHS	-	Saffir-Simpson Hurricane Scale
SVM	-	Support Vector Machine
TC	-	Tropical Cyclone
TCBT	-	Tropical Cyclone Best-Track
TCWC	-	Tropical Cyclone Warning Center
TD	-	Tropical Depression
TS	-	Tropical Storm
WMO	-	World Meteorological Organization

LIST OF SYMBOLS

U_{10}	-	Wind Speed at 10-meter from Sea Surface (ms^{-1})
U^*_{10}	-	Calibrated Wind Speed at 10-m from Sea Surface (ms^{-1})
σ	-	Altimeter Backscatter (dB)
σ_{Ku}	-	Altimeter Backscatter at Ku-Band (dB)
σ_C	-	Altimeter Backscatter at C-Band (dB)
H_S	-	Altimeter Significant Waves Height (m)
$H_{S,Ku}$	-	Altimeter Significant Waves Height at Ku-Band (m)
$H_{S,C}$	-	Altimeter Significant Waves Height at C-Band (m)
T_B	-	Radiometer Brightness Temperature (K)
$T_{B,18}$	-	Radiometer Brightness Temperature at 18.7 GHz (K)
$T_{B,23}$	-	Radiometer Brightness Temperatureat 23.8 GHz (K)
$T_{B,34}$	-	Radiometer Brightness Temperature at 34.0 GHz (K)
W_L	-	Radiometer Liquid Water Content (kgm^{-2})
W_V	-	Radiometer Water Vapor Content (kgm^{-2})
R30kt	-	Wind Radius at 30-kt threshold (km)
R50kt	-	Wind Radius at 50-kt threshold (km)

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CHAPTER 1

INTRODUCTION

1.1 Study Background

Tropical cyclone (TC) is among the most catastrophic natural phenomena known to humankind. This synoptic rotating storm is formed over a tropical region fueled by warm surface ocean water with a temperature of 26°C or higher. Tropical cyclone always brings together abnormally high wind speed of more than 18 ms^{-1} and intense rain up to 50 $mmhr^{-1}$ with the confluence of the extremely low mean sea level pressure (MSLP) reaching up to 880 mbar. These, in turn, drive the ocean response in the form of extreme waves, storm surge and rough currents. When an intense tropical cyclone made landfall, the accompanying storm surge, strong wind, and heavy rains combined have caused enormous number of fatalities with the highest events were recorded in the northern Indian Ocean, western North Pacific and western North Atlantic (Needham *et al.*, 2015). Table 1.1 indicating the Northwestern Pacific, the Northeast Pacific and the Atlantic Ocean are the most active regions for tropical cyclone activity (Landsea and Franklin, 2013). For instance, Typhoon Haiyan in 2013 was one of the most powerful typhoons ever to make landfall in recorded history. This gigantic typhoon with a diameter of more than 600 km has hit the Philippine archipelago and was responsible for 6,300 fatalities, 1,061 missing and 28,689 injuries in the aftermath (Lagmay *et al.*, 2015). With consistently increasing of the sea surface temperature over the past three decades, future projections based on theory and high-resolution dynamical model indicated the global average of the tropical cyclone will be shifting towards stronger intensity with an upward trend of 2 to 11 % by 2100 (Emanuel, 2005; Elsner *et al.*, 2008; Knutson *et al.*, 2010; Walsh *et al.*, 2016). Even worse, the global population density in coastal zones is projected to increase from 87 people/km^2 in 2000 to 134 people/km^2 by 2050 has put more lives at risk by tropical cyclone impacts (Shi and Singh, 2003).

Table 1.1 Annual averaged number of tropical cyclone occurrences in global ocean basins. (Landsea and Franklin, 2013).

Basin	Tropical Storm, Wind >17 ms^{-1} Average	Tropical Storm, Wind >17 ms^{-1} Percentage (%)	Hurricane, Wind >33 ms^{-1} Average	Hurricane, Wind >33 ms^{-1} Percentage (%)
Atlantic	12.1	14.1	6.4	13.6
NE Pacific	16.6	19.3	8.9	19.0
NW Pacific	26.0	30.2	16.5	35.2
North Indian	4.8	5.6	1.5	3.2
SW Indian	9.3	10.8	5.0	10.7
Australia, SE Indian	7.5	8.7	3.6	7.7
Australia, SW Pacific	9.9	11.5	5.2	11.1
Total	86	100	46.9	100

Appreciating the advent of satellite remote sensing, in modern world, there is no single tropical cyclone that has gone undetected. Since the 1970s, a major advance in monitoring tropical cyclone from space emerged with the influential work of the National Oceanic and Atmospheric Administration (NOAA) scientist Vern Dvorak (Dvorak, 1975). Monitoring based on subjective image (visible and infrared) pattern recognition technique from geostationary meteorological satellites permits an estimation of tropical cyclone density using the satellite cloud patterns and brightness temperature which is commonly known as the Dvorak Technique (DT). The DT was later enhanced by an improved computer-based objective algorithms routine using infrared satellite image that led to the development of the Objective Dvorak Technique (ODT) (Velden *et al.*, 1998). However, significant inadequacy of ODT in estimating intensity below hurricane (33 ms^{-1}) and typhoon (28.5 ms^{-1}) strength with complex manual interpretation analysis to locate the eye of storm position in the algorithm have resulted to the development of the Advanced Objective Dvorak Technique (AODT) (Olander *et al.*, 2004). The AODT has capability to automatically estimate the tropical cyclone intensity regardless of the lifecycle stages which inspired the later work by Olander and Velden (2007) in development of fully automated computer-based objective called Advanced Dvorak Technique (ADT). This technique significantly exceeds the limitation of all DT variants and continuously serving to provide tropical cyclone intensity guidance in many tropical cyclone warning centres globally, with minimal regional modifications (Velden *et al.*, 2006; Knaff *et al.*, 2011). Following the advancement series of DT, Current Intensity (CI) and Saffir-Simpson Hurricane Scale (SSHS) as shown in Table 1.2 were often considered as emergency state indicators for response team to make necessary action based on the potential damage caused by the landfalling tropical cyclone.

Implementing continuous work on series of Dvorak techniques, remote sensing images have been the major sources of information in resolving tropical cyclone characters. In addition, the low-altitude (3 km) flying aircraft equipped with dropwindsondes and Stepped Frequency Microwave Radiometer (SFMR) instruments is regularly deployed to estimate higher density and highly accurate tropical cyclone parameters specifically over the Atlantic basin. Although MSLP is considered the most accurate and reliable TC parameter that can be measured, it is more informative to relate tropical cyclone destructive potential to the maximum wind speed near to the surface of which the damaging strength of landfall tropical cyclone can be deduced (Kossin and Velden, 2004). Following this understanding, few works have been done to develop a wind-pressure relationship for tropical cyclone events (Knaff and Zehr, 2007; Courtney, 2009; Choi *et al.*, 2016). For this reason, agencies such as Joint Typhoon Warning Center (JTWC), the Central Pacific Hurricane Center (CPHC) and the National Hurricane Center (NHC) define the tropical cyclone intensity as the 1-min maximum sustained wind (MSW) at 10 m height above the sea surface (U_{10}) – a difficult quantity to measure from an aerial satellite image. The MSW and radius of maximum wind (RMW) collectively resolve the wind radii extent of significant wind speed thresholds at 34-, 50-, and 64-kt (1 kt = 0.514 ms^{-1}) wind radii which currently used over the Atlantic. An intensive study by Wang and Wu (2004) has classified tropical cyclone structure based on wind speed and pressure parameters, including low-level cyclonic circulation (such as the outermost closed isobar, or radius of MSW 15 ms^{-1}), RMW and eyewall (symmetric or asymmetric). On contrary to Wang and Wu (2004) who defined the inner core structure has twice the radius of RMW (which includes deep eyewall clouds, storm eye and convective asymmetric eyewall), Maclay *et al.* (2008) traditionally described the inner core by the eye diameter and RMW only. Although the wind speed at 10 meter height from the sea surface – called U_{10} – inside the tropical cyclone can be estimated, it is highly challenging task to infer the storm structure from the U_{10} estimates.

Even though much information of TC intensity, location and tracks delivered from various remote sensing measurements to the warning centres, there is little to no improvement of operational forecasting tropical cyclone intensity (Landsea and Cangialosi, 2018). The fact that tropical cyclone intensity is having a direct relationship with the wind speed, it demands this utmost important parameter be primarily and objectively estimated. Although the previously mentioned technique provides an acceptable estimation of tropical cyclone intensity, none of these includes any direct measurement of U_{10} to estimate the MSW. This is because the images provided by the satellite have restricted the estimation of highly dynamic sea surface wind speed beneath the expansive cloud covers inside the extreme tropical cyclone. The limitation of cloud-top pattern and infrared imagery in the series of DT has led Quilfen *et al.* (2010) to conclude and reconsider that aircraft reconnaissance and satellite microwave data are crucial and providing complement observations for wind speed parameter.

To illustrate this capability, several studies had derived U_{10} from microwave radiometer (Bessho *et al.*, 2006; Sriver *et al.*, 2008), scatterometer (Chavas and Emanuel, 2010; Chan and Chan, 2012; Klotz and Jiang, 2016; Liu and Tang, 2016) and altimeter (Quilfen *et al.*, 2006; Carrère *et al.*, 2009) to analyse the tropical cyclone characters. Both active and passive microwave analyses had shown promising results to be assimilated and operationally used. However, the challenges of retrieving the wind speed from these sensors are consistently restricted by the condition of high U_{10} (> 15 ms^{-1}) in which the sea surface was no longer simply related to the wind. Additional attenuation of the backscatter induced by the precipitation inside the tropical cyclone had reduced the accuracy of the reflected backscatter. With the ongoing development of more accurate U_{10} retrieval algorithms for radiometer (Mai *et al.*, 2016; Yin *et al.*, 2017), scatterometer (Fore *et al.*, 2012; Alsweiss *et al.*, 2014; Stiles *et al.*, 2014) and altimeter (Quilfen *et al.*, 2011; Gu *et al.*, 2011; Qin *et al.*, 2014), this can lead to the potential synergy between active and passive measurements to determine the tropical cyclone wind character eventually. Polar-orbiting radiometer, scatterometer and altimeter are potential in assisting and providing vital U_{10} information under extreme environment such as tropical cyclone globally.

Table 1.2 Dvorak current intensity chart for tropical cyclone (NOAA).

Current Intensity (CI)	**Mean Wind Speed (knots)**	**(ms^{-1})**	**Mean Sea Level Pressure Atlantic (mb)**	**Pacific (mb)**	**Saffir Simpson Category**
1.0	25	13	-	-	-
1.5	25	13	-	-	-
2.0	30	15	1009	1000	-
2.5	35	18	1005	997	-
3.0	45	23	1000	991	-
3.5	55	28	994	984	-
4.0	65	33	987	976	1 (64-83 kts)
4.5	77	40	979	966	2 (84-96 kts)
5.0	90	46	970	954	2 (84-96 kts)
5.5	102	52	960	941	3 (97-113 kts)
6.0	115	59	948	927	4 (114-135 kts)
6.5	127	65	935	914	
7.0	140	72	921	898	
7.5	155	80	906	879	5 (136+kts)
8.0	170	87	890	858	

1.2 Research Motivations

The availability of in-situ (e.g., anemometer on buoy) U_{10} measurement is scarce and unfeasible in almost all basins for tropical cyclone analysis. In lieu of in-situ observations, visible and infrared images provide synoptic and temporal information for monitoring and tracking the tropical cyclone. Since the early 1970s, the satellite DT persistently exploits the satellite cloud image pattern (e.g., eye, shear, banded, central dense overcast) and infrared cloud-top temperature to estimate the tropical cyclone CI numbers and trajectory. Contradicting to tropical cyclone tracking, the intensity estimates have not shown significant progress for over a decade (Rappaport *et al.*, 2009). There is no reduction of intensity forecast error has been recorded for the past 30 years, mainly due to the low accuracy U_{10} estimation in tropical cyclone (DeMaria *et al.*, 2014). The higher atmospheric level measurement from optical images has little relevance to oceanography for which the U_{10} that interacts with the ocean's surface. This is problematic to the spaceborne optical measurement which primarily covered with expansive cloud shield leading to masking important data within and beneath the cloud top layer and inheriting the different types of errors particularly from unfavorable weather condition. Kotal *et al.* (2019) have shown that misestimation of tropical cyclone intensity from cloud tracking corresponds to the U_{10} error of 10 to 15 ms^{-1} (20 to 30-kt). This is unacceptable considering the difference in RMW extent thresholds used by the agency to classify tropical cyclone strength from initial stage (30-kt) to early mature stage (50-kt) that must be lower than the abovementioned errors. Thus, it is very important to have a robust objective method which defines the "true wind" by a reflected tracer representing the situation at the sea surface level to be adopted to achieve more accurate tropical cyclone wind analysis.

The fact that microwave sensors are nearly weather independent and having strong ocean interaction in signal thus considered as the alternative in tropical cyclone U_{10} measurement. Microwave radiometer such as WindSat and AMSR-2 on board of Coriolis and GCOM-W satellite respectively has demonstrated that the brightness temperature (T_B) can retrieve tropical ocean surface U_{10} (Kim and Lyzenga, 2008; Yao *et al.*, 2015; Hong *et al.*, 2015). A study conducted by Yin *et al.* (2017) has successfully developed an algorithm to retrieve wind speed above 20 ms^{-1} by using 6.8- and 10.7-GHz brightness temperature at great accuracy. However, Yang *et al.* (2014b) have reported that microwave radiometer resolution of 50 km x 70 km is often much coarser to present the fine-scale tropical cyclone structures thus determine the storm's eye and the RMW. Hence, it is best to have higher spatial-resolution and active microwave measurement to retrieve dynamic tropical cyclone wind speed.

On the other hand, the backscatter signal emitted by an active microwave sensor has direct contact with the ocean surface roughness that was in equilibrium induced to the wind. Undeniable strength of daily radar scatterometer observation to operationally measure the ocean surface wind at speed of 1.5 ms^{-1} and 20° directional accuracy has proved to be the vital element in estimating the TC intensity (Quilfen *et al.*, 2007; Liu and Tang, 2016). Take MetOp-A and MetOp-B scatterometer for instance, retrieving wind speed with nominal 12.5 km spatial resolution with the developed model function has consistently underestimated wind speed above 30 ms^{-1} (Fore *et al.*, 2012; Stiles *et al.*, 2014; Alsweiss *et al.*, 2014), hence necessary calibration had been considered (Chou *et al.*, 2013). Great attention on satellite scatterometer shows promising progress in tropical cyclone wind speed study and similar efforts should also be applied to the altimeter and radiometer which can offer more accurate wind speed inside this extreme event.

The polar orbiting altimeter has taken little attention in TC study because of the information in narrow instantaneous field of view (IFOV) was limited to represent larger storm extent. Yet, the altimeter satellite such as Jason-2 and Jason-3 (Jasons) has higher along-track resolution to allow fine-scale tropical cyclone U_{10} profile presentation. Instead of few studies are working on resolving the outer-core of low-to-moderate U_{10} (Quilfen *et al.*, 2006; Carrère *et al.*, 2009), limited study focused on inner-core of higher U_{10} profile estimation. Motivated by the remarkable altimeter derived high U_{10} algorithm developed by Young (1993), the later developed algorithms have surprisingly estimated winds up to 50 ms^{-1} (Gu *et al.*, 2011; Quilfen *et al.*, 2011; Qin *et al.*, 2014) but the rain contamination to the signal was not accounted. Furthermore, the altimeter derived U_{10} variable is accompanied by an extra sea state condition information at 5 to 10 km along-track spatial resolution can be beneficial in investigating extreme dynamic variation (Quilfen *et al.*, 2006; Li *et al.*, 2018).

Most altimeters have dual frequency radar and additional radiometer onboard allowing comprehensive information on atmospheric response (Quartly, 1997; Tournadre *et al.*, 2009; Ali *et al.*, 2015). Such information could enhance understanding on atmospheric related parameters and thus improve the accuracy of estimated U_{10}. To develop all-inclusive algorithm to fit with all altimeter missions is not a straightforward task particularly where different satellite mission provides various number of additional parameters at different frequencies. However, no study has established the fundamental basis of incorporating all these parameters to estimate U_{10} even in a single altimeter mission. Most studies solely focus on development of new model based on collocated higher U_{10} reference regardless of critical analysis about the complementation of onboard radiometric parameters (Quilfen *et al.*, 2010; Qin *et al.*, 2014). Therefore, this study motivates assessment of altimeter derived parameters for exploiting their advantages in U_{10} estimation inside tropical cyclone environment.

1.3 Problem Statements

The limitation of the optical images from Geostationary Meteorological Satellite (GMS) is their inability to provide information on the situation occurring beneath the cloud cover. The DT tracks cloud patterns and features at higher altitude to estimate the U10 which has led to major uncertainty in classifying the tropical cyclone intensity (Emanuel and Zhang, 2016). Although satellite altimeters can provide global U_{10} measurement at accuracy of 1.5 ms^{-1} (Ribal and Young, 2019), the application was only limited to a neutral atmospheric condition. Studies reported that the inverse physical and empirical relationship between the Jasons Ku-band backscatter to U_{10} can only hold for measurement up to 20 ms^{-1} because of the models were designed only for normal atmospheric stability and rain-free environment (Abdalla, 2012; Ribal and Young, 2019). The models are however unreliable during off-normal condition such as in the tropical cyclone, where the U10 accuracy is significantly reduced due to complex atmospheric interaction (Chavas *et al.*, 2017). For that reason, some studies suggested to explore conditions that significantly impaired the altimeter signal and remarkably undermined the accuracy of U_{10} product especially at the speed greater than 20 ms^{-1} (Zhao and Toba, 2003; Young *et al.*, 2017). Estimating U_{10} in such extreme environment of tropical cyclone is exceptionally difficult considering rapid variation in low-to-high regimes with additional signal attenuation from various rain rate episodes (Carrère *et al.*, 2009).

Tropical cyclone permits complex ocean-atmospheric relation and thus physical correlations established in normal condition were no longer valid. Operational models commonly developed from Ku-band related parameters were not providing inadequate information of the real tropical cyclone. For instance, the increasing U_{10} induces saturation state at 15 ms^{-1} despite higher sea state roughness is available (Gourrion *et al.*, 2002; Abdalla, 2012) and the additional rain contamination superimposed in the backscatter is almost unconsidered and left without correction (Young, 1993; Quilfen *et al.*, 2011). Thus, this has led the existing Jasons U_{10} algorithms to become unreliable. Although Ku-band backscatter shows great sensitivity to higher U_{10}, other frequency lower than Ku-band was suggested to be less affected by the rain (Quartly, 2015).

The U_{10} estimation should fully utilize the advantage of dual frequency altimeter data to deal with complex ocean-atmosphere conditions and leverage the limitation provided by the single Ku-band estimation model. Several other surpluses including the ocean geophysical and backscatter related parameters simultaneously observed by multiple sensors onboard have potential to describe this complex TC environment. Yet, integrating those multiple parameters is not straightforward because of the complex multi-relationship established between them (Ali *et al.*, 2015). There is no clear justification and immature physical relations between each parameter in emulating the tropical cyclone environment. Poor understanding of the relationship between remotely sensed ocean parameters and U_{10} in this environment has led to 5 to 14% uncertainty (Powell, 2010). Thus, the comprehensive understanding about parameters relationship to U_{10} is needed before a new model can be developed.

Among all parameters studied, the best parameter combination in developing a new U_{10} model is uncertain. The parameters might contain redundant information, if worse, can degrade the quality of the model when unnecessary higher dimensions are considered (Jiang *et al.*, 2020; Wang *et al.*, 2020). When decided, incorporating those parameters into a single model is another issue. Not all parameters showing a similar perfect linear trend to the U_{10}. Studies suggested that even the principal backscatter could modify itself to an exponential form when considering wider U_{10} range (>20 ms^{-1}) (Quilfen *et al.*, 2011). Radiometric quasi-linear connections to the U_{10} and additional inter-parameter relationships among the inputs are another troublesome aspect need to be reviewed (Bushair and Gairola, 2019; Varma *et al.*, 2020). To contemplate these concerns, a comprehensive and intelligent technique is required to integrate all possible complex relationships. Furthermore, in a real tropical cyclone, the attributes of U_{10} and all parameters are unique and vary drastically to different event and hourly period interval (McTaggart-Cowan *et al.*, 2007). A developed model should be smart enough to sensitively identify slight variations and adjusting itself by compromising all the combined parameters in inversing the tropical cyclone U_{10}. Although the conventional regression technique is easy (Barhmi *et al.*, 2019; Casella, 2019), fitting those parameters to a single line model equation might appear to be improper. More advanced computational technique is required when considering complex conditions. In contrast to the conventional regression, the developed model should also meet model generalization and robustness criteria when dealing with rain contamination in high U_{10} condition and when applying to unique and independent tropical cyclone scenario.

The model should provide continuous depiction of sensible U_{10} approximation pattern especially in the region close to the tropical cyclone centre and consequently feasible to study wind characters from altimeter fine-scale resolution. Currently the cloud images, however, give no indication about the real condition at sea surface level, thus neglecting sea state information to be accounted for lifecycle analysis (Zeng *et al.*, 2010). The scatterometer with nominal spatial resolution of 25 x 25 km^2 experienced U_{10} underestimation in all tropical cyclone areas and the largest difference was found at near the eyewall section (Chou *et al.*, 2013). Higher Jasons along-track resolution can offer finer scale of near the tropical cyclone centre where very dynamic ocean-atmospheric conditions are always exist (Scharroo *et al.*, 2005). With existing operational U_{10} product despair specifically inside the rain and high U_{10} range, no convincing attempt has been made. Therefore, it is recommended that continuous work needs to be done in exploiting active microwave observation such as Jason-2 and Jason-3 altimeters, in estimating and establishing complex ocean-atmosphere relationships with more accurate tropical cyclone wind characters.

1.3.1 Research Questions

Based on the abovementioned problem statements, four research questions are designed.

(i) What is the limitation of the current operational satellite altimeter and scatterometer product in representing the U_{10} inside the tropical cyclone conditions??

(ii) To what extent the simultaneous satellite altimeter and radiometer derived ocean parameters can emulate the real U_{10} relationships in a complex tropical cyclone condition?

(iii) Which combination of satellite altimeter and radiometer related parameters performed at best with more intelligent regression technique for highly accurate tropical cyclone U_{10} derivation?

(iv) How the improved U_{10} estimates help in deducing instantaneous tropical cyclone wind characters?

1.3.2 Aim and Objectives

This study aims to analyse multiple altimeter ocean-related parameters and numerically estimate highly accurate U_{10} for describing the tropical cyclone wind characteristics. Therefore, to achieve the aim, four main specific objectives are designed.

(i) To assess the quality of operational U_{10} products measured from MetOps scatterometer and Jasons altimeter in tropical cyclone environment.

(ii) To establish the relationships between altimeter and radiometer derived ocean parameters to the U_{10} in the tropical cyclone condition.

(iii) To develop and validate the new U_{10} estimation model from Jason-2 and Jason-3 altimeter measurements using machine learning regression techniques.

(iv) To derive the tropical cyclone wind characters from the new U_{10} model and compare their pattern agreement to the verified best track report.

1.4 Scope of Study

Tropical cyclone events that reached at least tropical storm intensity occurred in 2015 to 2018 globally were used for this study. As this study is not intended to explore the climate variability of the tropical cyclone phenomenon globally, these 4-year observations are considered sufficient to comprehend the technical aspect of altimeter satellite in modelling tropical cyclone U_{10} within the diverse geographical influences of natural phenomena. Furthermore there are several most intense tropical cyclone events recorded within this period such as Hurricane Maria 2017 and Typhoon Mangkhut 2018 that directly hit Caribbean's countries and the Philippines to the wider South China Sea's countries respectively. Despite that all ocean's basins were considered, this study committed to demonstrate and extensively discuss the tropical cyclone events within the regions of the Pacific and Atlantic oceans. It is important to note that this study only investigates tropical cyclone with at least 30-km distance from land. The observation involved isolates this criterion to preserve good quality of ocean-atmospheric interactions by discard land contamination to the altimetric signal and various land structure led to complex atmospheric interaction.

As the most intense tropical cyclone category is called Typhoon in Northwest Pacific and Hurricane in Northeast Pacific and Atlantic, these are the top three regions that actively hit by the tropical cyclone accordingly. Thus, more details discussion and examples will be focused on these regions The annual reports released by the JMA (JMA, 2017, 2018) shows that Northwest Pacific has the highest concentration of tropical cyclone activity with 26 and 27 of tropical storm (TS) intensity or higher observed in 2016 and 2017 respectively, exceeding the climatological normal frequency of 25.6. For Northeast Pacific (Kimberlain, 2017) and Atlantic (Beven, 2017), the occurrences of tropical storm strength reported by NHC in 2016 was 21 and 15 in comparison to their climatological normal frequency of 15 and 12 respectively. A study reported that typhoons could occur in any season, unlike hurricanes which happen almost entirely from June to November. However, both typhoons and hurricanes take place most frequently in the late summer and during the fall seasons where heat energy budget stored at maximum inside the earth's ocean (Pun *et al.*, 2011; D'ASARO *et al.*, 2011). This study includes all events developed within the global main basins at the latitude of 0° to 45°N/S with their intensity category officially published by the tropical cyclone warning centre (TCWC). However, a major discussion highlighted the events that have been investigated thoroughly by the scientific community with at least sustained significantly in the typhoon/hurricane category.

The advantage of the polar-orbiting satellite altimeter is its global coverage which includes all ocean basins covering all active tropical cyclone regions and events. As most of the altimeter satellite is now operating at the same dual Ku/C frequency band, this study only focuses on the most discussed altimeter derived parameters from Jason-2 and Jason-3 missions (Jasons) to develop the fundamental understanding. High quality ocean's data assurance enables Jasons to be used extensively as benchmark for wider altimeter's application fields even to extreme events such as tsunami (Gower, 2005), extreme waves (Woo and Park, 2021), extreme wind (Li *et al.*, 2017), and tropical cyclone (Quilfen *et al.*, 2006). This study presumed that the basic knowledge unfolding through this study can be used as the underlying foundation for other altimeter satellites.

The operational U_{10} product was initially assessed for its applicability and compared along with the developed models. The Level-1B of research quality Geophysical Data Record (GDR) products for Jason-2 and Jason-3, that contain quality assured derived ocean parameters were used as a core dataset. At this level, the dataset is presented in geolocation along track swath, corrected systematic error, calibrated measurements to all their predecessor mission programs, and has been converted to sensor units such as backscatter in decibel (dB) and brightness temperature in Kelvin (K). The random error existed is anticipated caused by the complex atmospheric interactions inside the tropical cyclone, in which, this is the core data investigate throughout this study.

Level-2 ocean surface wind vector data products from MetOp-A and MetOp-B scatterometers (MetOps) were used only to validate all Jasons's derived parameters observed in the tropical cyclone environment. Dataset at this level has been processed into geophysical product, but retaining its Level-1 spatio-temporal resolutions, with several corrections imposed such as atmospheric emission and attenuation caused by water vapor. Many studies demonstrated this product exhibits high wind vector quality even in extreme tropical cyclone environment (Zabolotskikh *et al.*, 2014a; Tamizi *et al.*, 2020). This dataset was first calibrated following Chou *et al.* (2013) to the dropwindsonde measurement inside the tropical cyclone before it was used as the reference in building the U_{10} model. Apart from the altimetric dual-frequency backscatter, this study also assessed the dual-frequency significant waves height, radiometric brightness temperatures and its derived water content in relation to tropical cyclone U_{10} with reference from calibrated MetOps. These parameters are anticipated to play a significant contribution in providing enough information to emulate the real complex tropical cyclone environment, much needed in developing the U_{10} model process. Even the HWind (considered as the best quality of U_{10} in TC) is available only for several TC cases, this data was limited and only used as a trend validation to the developed Jasons U_{10} models.

The conventional regression technique was applied to give simple indication about the relationship of altimetry parameter and only used for pre-assessment. The primary focus is on several machine learning (ML) approaches in developing the tropical cyclone U_{10} model. The complex multi-relation parameters that existed are anticipated to provide an ill-posed solution to the conventional technique, thus more advanced non-parametric modelling was considered. These include the implementation of Artificial Neural Network (ANN), Support Vector Machine (SVM), and Gaussian Process Regression (GPR). This study not intended to delve thoroughly into each ML hyperparameter setup in computer analysis perspective, but more focus on the algorithm comparison based on the interaction of altimetry parameters towards complex tropical cyclone condition. The applicability and unique advantage of the derived tropical cyclone characters from the Jasons' U_{10} profile is the major highlight. For this study, the estimated characters of the tropical cyclone center location, maximum sustained wind, storm's radius and the radial extend of tropical cyclone size are anticipated and is one of the novel altimeter U_{10} studies for tropical cyclone ever conducted. To compare the estimated tropical cyclone characters, the best-track (TCBT) reports from different tropical cyclone warning agency (e.g., NHC, JMA) are used for validation (Kruk *et al.*, 2010).

In managing a huge amount of numeric data and conducting complex computation scientific study, MATLAB language environment is embarked as the main processing platform. MATLAB is a programming platform that employs matrix-based language to allow most expression and computational mathematics. All non-imaging remote sensing data contains a large matrix dataset that can be easily handled in the MATLAB environment makes this processing software the core element as this study progresses. This study also implemented the Machine Learning and Deep Learning Toolbox developed by MathWorks purposely for the MATLAB environment. All the machine learning processing frameworks used were computationally stable with high quality guaranteed and thus left for further exploration on their multiple techniques comparison in developing the best tropical cyclone U_{10} model. Finally, all figures presented in this study were primarily produced by the MATLAB software.

1.5 Significance of the Study

Monitoring tropical cyclones is a major application of weather satellites. Almost all operational centres worldwide depend on remote sensing satellite observations for monitoring and predicting tropical cyclone trajectory and strength intensity. The work on monitoring this extremely disastrous event has involved many satellite platforms with different characteristics consideration: type of sensor, spatial resolution and orbital parameter (e.g., altitude, inclination and swath). Focusing on the open-ocean state, this study is anticipated to prove the concept of estimating a wide range of U_{10} at near sea surface level under undesirably extreme tropical cyclone conditions, which no other satellites can provide except altimeter and scatterometer. Therefore, the finding can provide sea surface information that is always negligence and absent in satellite optical data with expansive clouds images. The already available missions can now provide an objectively estimated and more reliable U_{10}, which is at best acquired by flying aircraft. All regions now could utilize this product despite spending high costs and embracing dangerous risks from aircraft missions, which for long become the golden fortune only for NHC, U.S. Besides, the established product should also be considered as the replacement for aircraft observations incorporated into HWind U_{10} analysis (which considered as in-situ U_{10} observation in tropical cyclone) that later will be available to not only NHC's region, but all tropical cyclone events globally.

The polar-orbiting satellite acquisition scheme of microwave sensors allows this processing framework to be implemented consistently at all regions once established. Unlike images from geostationary satellites, the analysis framework was developed and only applicable at regional level. With the similar polar-orbiting acquisition technique, future satellite missions have committed to launch multi-sensors of microwave radiometer, scatterometer and altimeter installed on the same platform such as Hai-Yang series (from HY-2A to HY-2H). The successor of Jason series mission called Sentinel-6 having almost similar sensors specification (cooperation between NASA and EUMETSAT), was launched in November 2020 and is expected to operate at least until 2032 (Scharroo *et al.*, 2016; Donlon *et al.*, 2021). This study could provide basic fundamental knowledge of the sensors' applicability in extreme environment to be ventured over the next decade.

Besides, the scenario of increasing tropical cyclone intensity under future climate change poses the coastal population and environment to be more vulnerable towards this deadly disaster (Moon *et al.*, 2019). The near real-time intensity estimates from the satellites play a vital element for all tropical cyclone warning centers in advising the public, government and emergency response team. This study is projected to provide complementary TCBT information of the tropical cyclone size and characters based on the estimates Jasons U_{10} and support the agencies to better consult the response team of the incoming tropical cyclone hazard. False and inaccurate alarms can result in thousands of dollars and hundreds of man-hours wasted in needless storm preparation if overestimated, or on the other hand, can lead to unexpected storm impacts due to an unanticipated landfall and jeopardizing lives. Thus, improved accuracy of U_{10} retrieval to estimate tropical cyclone characters can reduce needless evacuation and increase the confidence in the advance warning system.

As climate change is now a global concern, the tropical cyclone with greater intensity becoming the new emerging risk to several regions such as the South China Sea (Chen *et al.*, 2017, 2019a; Shao *et al.*, 2019). The tail-wind effect with heavy orographic rain is occasionally felt by the north Sabah, east coast of peninsular Malaysia, and along the Titiwangsa Mountain range when the tropical cyclone paths move into their offshore stretch (Tan *et al.*, 2011). This can trigger several cascading multi-hazard consequences, such as landslides and debris flows, as well as to the wider water pollution, sanitation services and health sectors if the affected city is not resilient enough to this new emerging risk (Wdowinski *et al.*, 2017; Purwar *et al.*, 2020). Hence, this study aims to extend its contribution to the Sustainable Development Goal (SDG), a strategic plan of the United Nation (UN) Development Program (UNDP) for a better and more sustainable future for all. The technical guideline of handling more accurate U_{10} in tropical cyclone from long historic altimeter data record is expected to provide additional information to environmentalist, climatologist and government's policy makers to engage the challenges outlined in SDG Goal 13: Climate action, as demonstrated in several studies (Burby, 2006; Sharma and Patwardhan, 2008; Barbier, 2015). The more accurate tropical cyclone information is also anticipated to help agencies analyze the human impact of geophysical disasters, which are 91% climate-related that have killed more than 1.3 million people and left 4.4 billion injured over the past two decades (Nations, 2015). Besides, this study is foreseen to work together in Sendai Framework for Disaster Risk Reduction (DRR) 2015 – 2030 under the Priorities for Action: Priority 1 – Understanding disaster risk (UNISDR, 2015). This study provides science-based information to the agency in understanding and managing the exposure and vulnerability of humans and assets towards DRR caused by the tropical cyclone.

1.6 Brief of Thesis Structure

This thesis consists of five main chapters. Chapter 1 is an introduction that provides a background of the proposed study along with motivation, problem statements, objectives, research questions, scopes and significances of this study. Chapter 2 will cover the literature review of the related topics and emphasize the application and current limitation of polar-orbiting altimeter satellites for U_{10} estimation in tropical cyclone conditions. The discussion also includes the physical understanding of selected parameters concerning U_{10} inside tropical cyclone and a previous attempt at machine learning applications. Chapter 3 will discuss in detail the proposed methodology which will be used in this study including, satellites data descriptions, events selection, data filtering, data quality control, data pre-processing, and theoretical machine learning frameworks. All selected results, analysis and discussion are put together in Chapter 4, while Chapter 5 overlay the conclusions and recommendations of the study.

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1. Sharoni, S., & Reba, M. M. (2021, February). Multi-Parameter Neural Network for Altimeter Tropical Cyclone Wind Speed Estimation. In IOP Conference Series: Earth and Environmental Science (Vol. 682, No. 1, p. 012020). IOP Publishing.

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1. Sharoni, S., Reba, M. N. M., & Hashim, M. Challenges and Possibility of Satellite Altimeter Derived Sea Level Anomaly for Tropical Cyclone Identification in the South China Sea: A Preliminary Review.
2. Sharoni, S., & Reba, M. N. M. Altimeter Wind Speed Estimation in Tropical Cyclone.