MODELLING OF SEA SURFACE CURRENT AND CIRCULATION FROM SATELLITE ALTIMETRY AND ANCILLARY DATA

NURUL HAZRINA BINTI IDRIS

UNIVERSITI TEKNOLOGI MALAYSIA

MODELLING OF SEA SURFACE CURRENT AND CIRCULATION FROM SATELLITE ALTIMETRY AND ANCILLARY DATA

NURUL HAZRINA BINTI IDRIS

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Science (Remote Sensing)

Faculty of Geoinformation Science and Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2008

ABSTRACT

Altimeter data from Jason-1 satellite are very useful in providing general and continuous information about the ocean, including sea surface currents. The main objective of study is to identify the most appropriate mathematical equation for determining sea surface current in the South China Sea. The seasonal changes of surface current during different monsoon periods in 2004 and 2005 were also identified. The equations used to derive sea surface current are geostrophic current equations, wind-driven current equations and tidal current equations. The methodology of this study involves the use of sea level height and sea surface wind speed data from Jason-1 satellite altimeter to derive geostrophic current and wind-driven current. Tidal amplitudes from co-tidal charts were used to derive tidal current. The derived surface currents were used to produce combined geostrophic and wind-driven current. Combined geostrophic and tidal current as well as total surface current which is the combination of geostrophic current, wind-driven current and tidal current were also derived. Maps of total surface current circulation pattern were produced during four monsoon periods in 2004 and 2005. Regression analysis and comparison of mean and standard deviation values with sea truth data were carried out to identify the most appropriate equation of surface current for the South China Sea. Results of the analysis indicate that total surface current speed and direction have good correlation with the sea truth data, that is 0.68 and 0.70 respectively. The analysis by comparing the mean values indicate that there are no significant difference between the means of total surface current and the means of sea truth data. The standard deviations of total surface current are smaller compared to the sea truth data values. In conclusion, altimeter data from Jason-1 satellite combined with tidal data to derive the total surface current is appropriate to determine sea surface current circulation pattern in the South China Sea.

ABSTRAK

Data altimeter dari satelit Jason-1 sangat berguna untuk memberikan maklumat berkaitan lautan secara menyeluruh dan berterusan, termasuk arus permukaan laut. Objektif utama kajian ini adalah untuk mengenalpasti persamaan matematik yang paling sesuai bagi menentukan arus permukaan laut di Laut China Selatan. Perubahan corak arus permukaan pada musim monsun yang berbeza bagi tahun 2004 dan 2005 juga dikenalpasti. Persamaan yang digunakan untuk memperolehi arus permukaan laut adalah persamaan arus *geostrophic*, persamaan arus disebabkan faktor angin dan persamaan arus pasang surut. Kaedah kajian ini melibatkan penggunaan data ketinggian aras laut dan kelajuan angin dipermukaan laut daripada altimeter satelit Jason-1 untuk memperolehi arus *geostrophic* dan arus disebabkan faktor angin. Amplitud pasang surut daripada carta *co-tidal* digunakan untuk memperolehi arus pasang surut. Arus permukaan yang telah diperolehi digunakan untuk menghasilkan gabungan arus *geostrophic* dan arus disebabkan faktor angin. Gabungan arus *geostrophic* dan arus pasang surut serta jumlah arus permukaan iaitu gabungan arus *geostrophic*, arus disebabkan faktor angin dan arus pasang surut juga dihasilkan. Peta corak jumlah arus permukaan dihasilkan bagi empat musim monsun bagi tahun 2004 dan 2005. Analisis regrasi dan perbandingan nilai purata dan sisihan piawai dengan nilai data lapangan dijalankan untuk mengenalpasti persamaan arus permukaan yang paling sesuai untuk Laut China Selatan. Hasil analisis menunjukkan bahawa kelajuan dan arah jumlah arus permukaan mempunyai hubungan korelasi yang baik dengan data lapangan iaitu 0.68 dan 0.70. Analisis perbandingan nilai purata menunjukkan tiada perbezaan yang signifikan antara purata jumlah arus permukaan dengan purata data lapangan. Nilai sisihan piawai bagi jumlah arus permukaan adalah lebih kecil berbanding nilai data lapangan. Kesimpulannya, data altimeter dari satelit Jason-1 yang digabungkan dengan data pasang surut adalah sesuai untuk menentukan corak arus permukaan laut di Laut China Selatan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

c	-	Speed of Light
t	-	Time
H	-	Orbital Height
H_d	-	Dynamic Sea Surface Height
SSH	-	Sea Surface Height Relative to the Ellipsoid
H_g	-	Geoid Undulation
H_t	-	Tidal Height
H_a	-	Ocean Surface Response to Atmospheric Pressure Loading
h	-	Sea Level Height Relative to the Geoid
V_0	-	Wind-driven Current at the Sea Surface
D_E	-	Ekman Depth
A_v	-	Vertical Eddy Viscosity
f	-	Coriolis Force
C_d	-	Drag Coefficient on the Sea Surface
U_{10}	-	Wind Speed 10 meters Above the Sea Surface
u_g	-	Zonal Component of Geostrophic Current
v_g	-	Meridional Component of Geostrophic Current
V_g	-	Velocity Amplitude of Geostrophic Current
u_e	-	Zonal Component of Wind-driven Current
v_e	-	Meridional Component of Wind-driven Current
V_e	-	Velocity Amplitude of Wind-driven Current
u_t	-	Zonal Component of Tidal Current
v_t	-	Meridional Component of Tidal Current
V_t	-	Velocity Amplitude of Tidal Current
R	-	Earth Radius

z	-	Water Level
g	-	Gravitational Acceleration
x	-	Local East Coordinate
y	-	Local North Coordinate
k	-	Von Karman Constant
τ	-	Wind Stress
θ	-	Surface Current Direction in Degree
Ω	-	Earth Rotation Rate
φ	-	Latitude in Radian
λ	-	Longitude in Radian
ρ	-	Water Density
ρ_a	-	Air Density
u	-	Frictional Velocity
η	-	Tidal Amplitude

LIST OF ABBREVIATIONS

ADCP	: Acoustics Doppler Current Profilers
AVISO	: Archiving, Validation, and Interpretation of Satellite Data in Oceanography
CNES	: Centre National d'Etudes Spatiales
DUACS	: Data Unification and Altimeter Combination System
ECMWF	: European Centre of Medium-Range Weather Forecasts
GC	: Geostrophic Current
GDR	: Geophysical Data Records
G+T	: Combined Geostrophic and Tidal Current
G+W	: Combined Geostrophic and Wind-driven Current
G+W+T	: Total Surface Current
JODC	: Japanese Organization Data Centre
NASA	: National Aeronautics and Space Administration
NE	: North-east Monsoon
SCS	: South China Sea
SLA	: Sea Level Anomaly
SW	: South-west Monsoon
TC	: Tidal Current
TIN	: Triangle Irregular Network
TOLEX	: Tokyo-Ogosawara Line Experiment
WC	: Wind-driven Current

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Remote sensing technology is a valuable source of environmental information about the atmosphere, continents as well as oceans. The oceans cover three quarters of our planet and the study of their properties is important in understanding the ocean environment (Duxbury et al., 2002). Even though the ocean surface is generally quasi homogeneous in composition, its dynamic nature makes global remote sensing a critical tool in understanding and monitoring its behavior.

The satellite altimeter mission started in 1973 when SKYLAB was successfully launched. Then, in April 1975, GEOS-3 was launched and continued by SEASAT in 1978. Many interesting and useful results about the ocean circulation have been obtained from these missions. However, the data from these missions were not sufficiently accurate to address many aspects of large scale ocean circulation because none of the missions were specifically designed and conducted for studying ocean circulation. As a result in 1992, TOPEX/ Poseidon was launched to be useful for studying ocean circulation, especially at the gyre and basin scales (Fu et al., 1994). Numerous improvements have been made to TOPEX/ Poseidon including specially designed satellite, sensor suite, satellite tracking systems, orbit configuration as well as the development of an optimal gravity model for precision orbit determination and a dedicated ground system for mission operations (Emery and Thomson, 2001).

After TOPEX/Poseidon mission ended, Jason-1 satellite altimeter was launched on 7 December 2001 as a follow on mission to the highly successful TOPEX/ Poseidon mission. Jason-1 is jointly conducted by the French Space Agency, "*Centre National d'Etudes Spatiales*" (CNES), and the United States National Aeronautics and Space Administration (NASA). The main goal of this mission is to measure the sea surface topography and to study the global circulation from space. The information given by the satellite altimeter includes sea surface height, surface wind speed, geoid, significant wave height and others. This provides an extended continuous time series of high accuracy measurement of the ocean topography from which the scientist can determine the general circulation of the ocean and understand its role in the Earth's climate. The characteristics of Jason-1 satellite are illustrated in Table 1.1.

Table 1.1: Characteristics of Jason-1 satellite altimetry.

Parameter	Value
Pulse duration	105.6 μs
Transmission frequencies	13.575 GHz (Ku-band), 5.3 GHz (C-band)
Antenna bandwidth	1.2 m
Mean altitude	1336 km
Inclination	66 degrees
Cycle duration	9.9 days

(Source: Kramer, 2002)

The major goal of altimeter missions is to understand the spatial and temporal characteristics of the changes in the ocean surface. A radar altimeter satellite is capable to measure the sea surface elevation, from which surface geostrophic current circulation can be inferred and measured globally for long time period. Besides, it is also capable to observe the ocean topography, globally and frequently, with high spatial resolution at short time intervals (Fu and Cazenave, 2001).

Space-based mapping systems like radar altimetry provide synoptic measurements of the Earth's ocean. The vast ocean surface is systematically mapped from orbiting platforms yielding data consistency, coverage and temporal continuity which are not available from any other methods. The capability of radar altimetry to provide accurate information of ocean properties has been proved (Challenor et al., 1996) whereby accuracy of each measurement of the ocean properties can achieve up to 4 centimeter (Fu and Cazenave, 2001). Generally, satellite altimeter observations of sea level, coupled with knowledge of the marine geoid (the gravitational equipotential closest to the time averaged sea surface height), therefore provide global information on the ocean surface velocity. Besides measurement of sea level, radar altimetry also observed the strength of the returned signal based on the small scale roughness of the sea surface. This provides the magnitude of surface wind speed (without direction), which is valuable for estimating the wind-driven surface current velocities (Digby et al., 2000).

Sea surface current is defined as a horizontal movement of current at the sea surface. There are many factors driving the surface current i.e. density gradient, Coriolis force, wind forcing and tidal forces (Digby et al., 2000). Basically, density gradient and Coriolis force generate the geostrophic current, wind-forcing generates the wind-driven current and tidal forces generate the tidal current (Yanagi, 1999). These currents are the main component of water flow in the coastal sea.

The South China Sea has been identified as one of the coastal seas in the world (Yanagi, 1999). It is a semi-closed ocean which is located near the equatorial region (small effect of Coriolis force) and also situated at the doldrums area (area of weak and variable winds). As a result, the effects of wind, Coriolis force as well as tide in this region are small.

Geostrophic current can be estimated directly from satellite altimetry data. Geostrophy is the term used to describe the situation when there is equilibrium between the horizontal pressure gradient forces in the ocean and the Coriolis force. The Coriolis force is an inertial force which tends to deflect the moving particles because of the Earth's rotation (Robinson, 2004). In this study, geostrophic current will be derived from Jason-1 satellite altimetry data. Since the surface current is a function of Coriolis force, wind forcing and tidal forces, the geostrophic current will be combined with the wind-driven surface current and the tidal current. Analysis will be carried out to identify the suitable mathematical equation of surface current in the South China Sea.

1.2 Problem Statement

The South China Sea is one of the coastal oceans in the world. Normally, sea surface current in the coastal seas are induced by three major factors i.e. density and Coriolis force, winds as well as tides (Yanagi, 1999). However, these factors are minor in the South China Sea because of its position in the equatorial region and the doldrums area (Knauss, 1978). Basically, the effect of Coriolis force in the equatorial region and the wind effect in the doldrums area are very small. On the other hand, the bottom topography of the South China Sea can be divided into the deep water basin and continental shelf. The tidal effects in the deep basin are very small. This study will investigate and identify the most suitable mathematical equation to estimate the sea surface currents in the South China Sea.

In order to minimize cost and duration of ship journey, normally commercial ship routing systems and shipmasters will incorporate some surface current data to control their routes. Therefore, study and knowledge about the seasonal variation and pattern of surface currents is very important.

On the other hand, traditional methods for mapping ocean circulation patterns employ current meters; drifts float and direct temperature measurements. In addition to being expensive, these methods are hampered by the difficulty of obtaining simultaneous data over broad expanses of water. In addition, it is not possible to visualize the changes and patterns of the physical state of the ocean.

These problems can be overcome by satellite remote sensing systems that provide instantaneous information of circulation patterns over very large areas. Besides that, through remote sensing, current changes can be monitored continuously in a cost effective manner.

1.3 Objectives

The main objectives of this study are:

a) To examine and analyse suitable equations for determination of sea surface currents in the South China Sea area.

b) To determine the seasonal changes of sea surface current from satellite altimetry data.

c) To map sea surface current circulation pattern over the South China Sea during different monsoon periods.

1.4 Scope of study

The scope of the study are:

1) Equations of geostrophic current, wind-driven current (Chung et al., 2000) and tidal current (Al-Rabeh et al., 1990) are used to derive the total surface current. These equations were used because the dominant factors driving the sea surface current in the coastal sea are the density gradient, wind forcing and tidal forces.

2) Regression analysis and comparison of the mean and standard deviation of the derived surface current with the sea truth data is carried out to determine the most suitable equations of surface current for the South China Sea.

3) The data utilized in this study are sea level anomaly and wind speed data derived from Jason-1 satellite altimetry. Sea level anomaly data are used to model the geostrophic current whereas wind speed data are used to model the wind-driven surface current. On the other hand, data from co-tidal chart and tide tables were utilized to model the tidal current. Tidal data from satellite altimeter which is derived using global ocean tide model is not used in this study because it is not valid to be used in the shallow sea.

4) In order to validate the derived surface current, sea truth data are used. It was obtained from related agencies such as Malaysian

Meteorological Service, Japanese Organization Data Centre and Coriolis Data Centre.

5) Analysis was carried out to determine the variability of the surface current over four monsoon periods in 2004 and 2005. The seasons include inter monsoon periods of April, inter monsoon periods of October, north-east monsoon and south-west monsoon.

1.5 Significance of the study

This study is important to understand the characteristics of water circulation in the South China Sea. The suitable equations for determination of sea surface currents in the South China Sea area were examined to accurately model the sea surface current circulation pattern. As a result, patterns and effects of climate cycles such as El-Nino and La-Nina can be monitored precisely. Hence, the prediction and mitigation of disastrous effects of floods and drought can be made.

Accurate knowledge of ocean circulation pattern is also useful for marine operations. As for commercial shipping, the map can be used to determine the optimum routes and as for the offshore oil operations, it can be used to identify areas with minimum impacts from strong currents. For fishing industry, the information of currents is important to identify the possible places of higher fish concentrations and also to determine locations of target species.

1.6 Study Area

This study was carried out over the southern part of the South China Sea region covering from latitude 2^0 to 15^0 north and longitude 100^0 to 120^0 east. Basically, the southern part of the South China Sea occupies an area of 1.7×10^6 km^2 from 0^0 north to 15^0 north and from 100^0 east to 120^0 east. In this study, the area within 0^0 to 2^0 north is not considered because the ocean characteristic within this region is unique whereby the Coriolis force is zero.

The South China Sea is a large marginal sea situated at the western side of the tropical Pacific as shown in Figure 1.1. It is a semi-closed ocean basin surrounded by South China, the Philippines, Borneo Island, Indo-China Peninsula and Peninsular Malaysia. This water body connects with the East China Sea, the Pacific and the Indian Ocean through the Taiwan Straits, the Luzon Straits and the Straits of Malacca respectively (Chung et al., 2000).

The climate of the South China Sea belongs to the tropical monsoon type. During south-west monsoon (May, June, July, August and September), the southwesterly winds with an average wind speed of 6 meter per second dominate. In north-east monsoon (November, December, January, February and March), the wind direction reverses; northeasterly winds with an average speed of 9 meter per second prevail over the whole region (Pohlmann, 1987; Shaw and Chao, 1994; Metzger and Hurlburt, 1996).

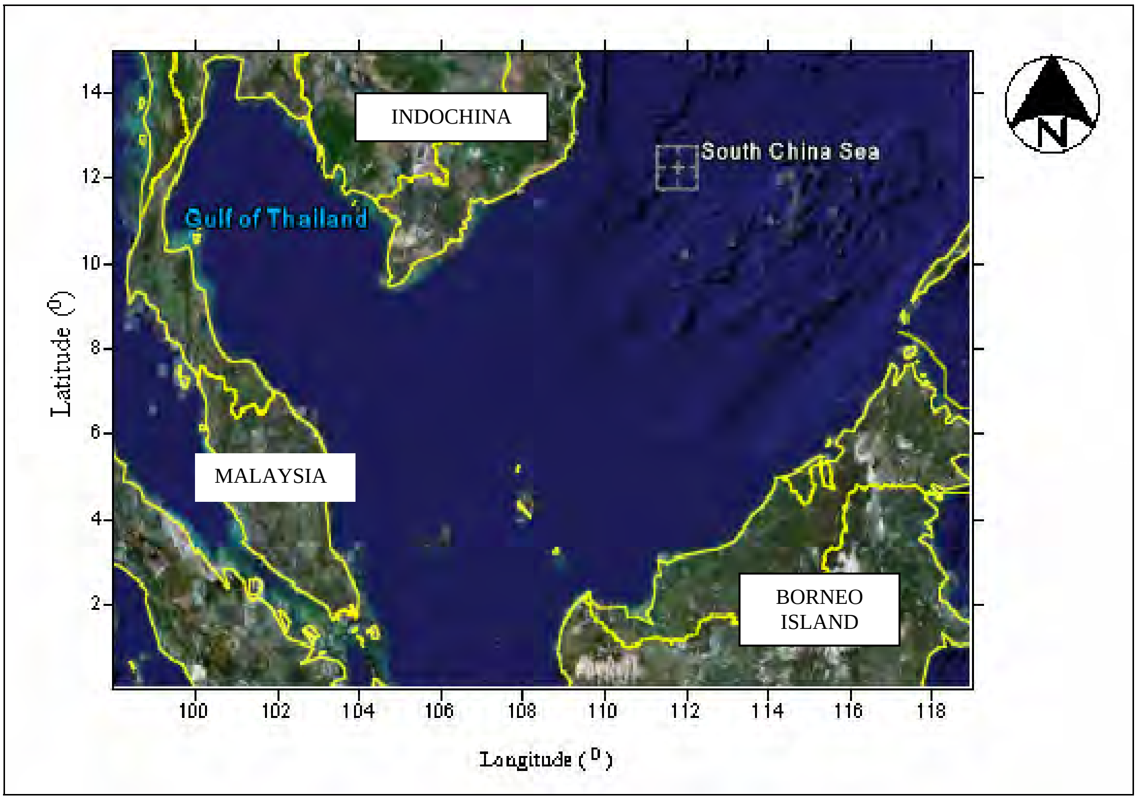

Figure 1.1: The South China Sea region.

REFERENCES

Al-Rabeh, A. H., Gunay, N., and Cekirge, H. M. (1990). A Hydrodynamic Model for Wind-driven and Tidal Circulation in the Arabian Gulf. *Journal of Applied Mathematical Modelling*, August 1990, 14 : 410 – 419.

Aviso and Podaac User Handbook. (2003). Smm-Mu-M5-Op-13184-Cn, Edition 2.0, April 2003.

Burrough, P. A (1986). Principles of Geographical Information Systems for Land Resources Assessment. Clarendon Press, Oxford.

Camerlengo, A., and Demmler, M. I. (1996). Wind-driven Circulation of Peninsular Malaysia's Eastern Continental Shelf. *Scientia Marina*, 61 (2):203-211.

Challenor, P.G., Read, J.F., Pollard, R.T., and Tokmakian, R.T. (1996). Measuring Surface Currents in Drake Passage from Altimetry and Hydrography. Journal of Physical Oceanography, 26: 2748-2758.

Cheong, H. F., Shankar, N. J., and Chan, C. T. (1992). Numerical Modelling of Tidal Motion in the Southern Waters of Singapore. Partridge, P.W. (eds.) Computer Modelling of Seas and Coastal Regions. Computational Mechanics Publications and Elsevier Applied Science. Pp 175-193.

Chu, P. C., Edmons, N. L., and Fan, C. (1999). Dynamical Mechanisms for the South China Sea Seasonal Circulation and Thermohaline Variabilities. *Journal of Physical Oceanography*, 29: 2971 – 2989.

Chung, R. H., Zheng, Q, Soong, Y.S., Nan, J. K., and Jian, H. H. (2000). Seasonal Variability of Sea Surface Height in the South China Sea Observed With TOPEX/Poseidon Altimeter Data. *Journal of Geophysical Research*, 105(C6): 13,981-13,990.

Condie, S. A. (1991). Separation and Recirculation of the North Brazil Current. *Journal of Marine Science*, 49: 1-19.

Digby, S., Antczak, T., Leben, R., Born, G., Barth, S., Cheney, R., Foley, D., Goni, G. J., Jacobs, G., and Shay, N. (2000). Altimeter Data for Operational Use in the Marine Environment. Oceans '99. Mts/IEEE. Pp 605 – 613.

Duxbury, A. B., Duxbury, A. C., and Sverdrup, K. A. (2002). Fundamentals of Oceanography. Fourth Edition. Mc Graw Hill Publisher.

Emery, W. J., and Thomson, R. E. (2001). Data Analysis Methods in Physical Oceanography: Second and Revised Edition. Elsevier Science Publisher.

Fang, G., Yue, K. K., Yu, K., and Zhu, Y. (1999). Numerical Simulation of Principal Tidal Constituents in the South China Sea, Gulf of Tonkin and Gulf of Thailand. *Journal of Continental Shelf Research*. 19: 845-869.

Fang, W. D., Guo, Z. X., and Huang, Y. T. (1997). Observation and Study on the Circulation in the Southern South China Sea. *Chinese Science Bulletin*, 42(21): 2264–2271.

Fang, W. D. (1997). Structures of Summer Circulation in Southern South China Sea. *Nanhai Studia Marina Sinica*, 12: 217–223.

Fang, W. D., and Fang, G. H. (1998). The Recent Progress in the Study of the Southern South China Sea Circulation. Advance in Earth Science.13(2):166-172.

Fu, Lee Leung, and Cazenave, A. (2001). Satellite Altimetry and Earth Sciences. A Handbook of Techniques and Applications. International Geophysics Series, Academic Press Publisher.

Fu, Lee Leung., Christensen, E. J., and Yamarone Jr., C. A. (1994). TOPEX/ Poseidon Mission Overview. *Journal of Geophysical Research*, 99(C12):24, 369- 24,381.

Gary, S.E., Lagerloef, Gary,T. M., Roger, B. L., and Niiler, P. P. (1999). Tropical Pacific Near Surface Currents Estimated from Altimeter, Wind, and Drifter Data. *Journal of Geophysical Research*, 104(C10):23,313 – 23,326.

Honda, T., and Mitsuyasu, H. (1980). Experimental Study on the Influence of Wind to the Sea Surface. Proc. 27th Coastal Engineering in Japan, Pp 90-93.

Hu, J., Kawamura, H., Hong, H., and Qi, Y. (2000). A Review on the Currents in the South China Sea: Seasonal Circulation, South China Sea Warm Current and Kuroshio Intrusion. *Journal of Oceanography*, 56: 607-624.

Hwang, C., and Chen, S. A. (2000). Fourier and Wavelet Analyses of TOPEX/ Poseidon Derived Sea Level Anomaly over the South China Sea: A Contribution to the South China Sea Monsoon Experiment. *Journal of Geophysical Research*, 105(C12): 28,785-28,804.

Jianbo, H., Jie, Z., Jungang, Y., and Junmin, M. (2005). Imaging Ability Research of Shallow Underwater Bottom Topography by SAR in Chinese Coastal Sea. *Proceedings of Dragon Symposium*, Santorini, Greece.

Knauss, J. A. (1978). Introduction to Physical Oceanography. New Jersey: Prentice Hall, Inc. Englewood Cliffs, 07632.

Kramer, H. J. (2002). Observation of the Earth and Its Environment. Survey of Missions and Sensors. 4th Edition. Springer.

Kwok, Y. K., Wu, L., and Pan. H. (1995). Second Order Accurate Scheme for Numerical Simulation of Shallow Water Flows. *Proceedings of the First Asian Computational Fluid Dynamics Conference*. Pp 16- 19.

Lemoine, F. G. (1998). The Development of the Joint NASA GSFC and NIMA Geopotential Model EGM96."NASA/TP-1998-206861. Pp 575.

Madsen, O. S. (1977). A Realistic Model of the Wind-induced Ekman Boundary Layer. *Journal of Physical Oceanography*, 7: 248-255.

Martins, C. S., Hamann, M., And Fiuza, A. F. G. (2002). Surface Circulation in the Eastern North Atlantic, from Drifters and Altimetry. *Journal of Geophysical Research*, 107(C12): 10, 1-10, 21.

Matsuura, H. (2002). Observed Variations of Upper Ocean Zonal Currents in the Western Equatorial Pacific and their Relation to the Local Wind. *Journal of Geophysical Research*, 107(C12): 301 - 315.

Metzger, E.J., and Hurlburt, H.E. (1996). Coupled Dynamics of the South China Sea, the Sulu Sea, and the Pacific Ocean. *Journal Geophysical Research*, 101: 12,331–12,352.

Morimote, A., Matsuda, T. (2005). The Application of Altimetry Data to the Asian Marginal Seas. *Geoscience and Remote Sensing Symposium, 2005. IGARSS'05 Proceedings,* IEEE International, 8: 5432 – 5435.

Naoto, E., and Hanawa, K. (1995). Comparison of Surface Currents Variations Observed by TOPEX Altimeter with TOLEX-ADCP Data. *Journal of Oceanography*, 51: 351 - 362.

Nurul Hazrina Idris and Mohd Ibrahim (2007). Sea Surface Current Circulation Pattern in the South China Sea Derived from Satellite Altimetry. *Proceedings of the 28th Asian Conference on Remote Sensing*, Kuala Lumpur, November 2007.

Perrie, W., Tang, C. L., Hu, Y., and Detracy, B. M. (2003). The Impact of Waves on the Surface Currents. *Journal of Physical Oceanography*, 33: 2126-2130.

Pohlmann, T. (Ed (1987)). A Three Dimensional Circulation Model of the South China Sea, In Three Dimensional Models of Marine and Estuarine Dynamics. New York: Elsevier Sci. Pp 245-265.

Rio, M. H., and Hernandez, F. (2003). High Frequency Response of Wind-driven Currents Measured by Drifting Buoys and Altimetry over the World Ocean. *Journal of Geophysical Research*, 10(39):1-19.

Robinson, I. S. (2004). Measuring the Oceans from Space. Principles and Methods of Satellite Oceanography. Springer and Praxis Publishing, Chichester, UK.

Shaw, P.P., and Chao, S. Y. (1994) Surface Circulation in the South China Sea. *Journal of Deep Sea Research*, Part I, 41. Pp 1663-1683.

Shaw, P. P., Chao, S. Y., and Fu, L. L. (1999). Sea Surface Height Variations in the South China Sea from Satellite Altimetry. *Oceanologica Acta*, 22(1): 1–17.

Snidvongs, A. (1999). Geostrophic Current, Divergence and Convergence in the South China Sea, Area II: Sabah, Sarawak and Brunei Darussalam. *Proceedings of the 1st Technical Seminar on Marine Fishery Resources Survey in the South China Sea, Area II, West Coast of Sabah, Sarawak and Brunei Darussalam*, December 1998. Pp 23 – 31.

Steward, H. R. (2005). Introduction to Physical Oceanography.
Available: 9 January 2006
http://Oceanworld.Tamu.Edu/Resources/Ocng_Textbook/Contents.Html

Witter, D. L and Chelton, D. B. (1991). A Geosat Wind Speed Algorithm and a Method for Altimeter Wind Speed Algorithm Development. *Journal of Geophysical Research*, 96: 8853-8860.

Wunsch, C. and Gaposchkin, E.M. (1980). On using Satellite Altimetry to Determine the General Circulation of the Ocean with Application to Geoid Improvement. *Rev. Geophys*, 18: 725-745.

Yanagi, T. (1999). Coastal Oceanography. Terra Scientific Publishing Company, Tokyo and Kluwer Academic Publishers, Dordrecht, London, Boston.

Yanagi, T., Morimoto, A., and Ichikawa, K. (1997). Seasonal Variation in Surface Circulation of the East China Sea and the Yellow Sea Derived from Satellite Altimetric Data. *Journal of Continental Shelf Research*, 17(6): 655-664.