

An Evaluation of Tides in the Caribbean

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Key words: tides, tidal constituents, Caribbean

SUMMARY

The Caribbean region lies between North and South America and encompasses the Caribbean Sea, the countries from as far south as Guyana to as far north as Bahamas and the adjacent coasts. The region comprises more than 7,000 islands, islets, reefs, and cays and has a population that exceeds 230 million. The Caribbean Sea is approximately 90 percent enclosed by insular and continental landmasses. It has a unique biodiversity and highly fragile ecosystems, including the second largest coral reef system of the world.

The countries of the Caribbean, most of which are Small Island Developing States, are highly vulnerable to the effects of climate change including sea level rise, coastal inundation and the increase in the frequency and intensity of natural disasters. These situations have created a greater need to understand the nature and pattern of the tides in the Caribbean Sea, as this will allow for more efficient protection and sustainable management strategies and support investigations into the vertical datum issues in the Caribbean.

The monitoring of tides in the Caribbean region, particularly in the southern Caribbean has left much to be desired. In 1981 a study of the tides in the Caribbean sea was carried out using data from 46 tide gauges stations, most of which are currently in a state of disrepair or no longer exist. This study uses tidal constituents derived from 19 tide gauge stations, with data sets ranging from 70 years to 2 years. The majority of the datasets used in this study is more recent than those used in (Kjerfve 1981). Six major tidal constituents were investigated and found to agree closely with those of the previous study.

1.0 INTRODUCTION

The Caribbean Sea is one of the largest salt water seas in the world and has an area of approximately 2,754,000 km². It is bounded to the south by Venezuela, Columbia, and Panama, and to the west Costa Rica, Nicaragua, Honduras, Guatemala, Belize and the Yucatan Peninsula of Mexico. The Greater Antilles Islands are to the north and the islands of the Lesser Antilles are found to the east. The islands generally form island arcs that delineate the eastern and northern edges of the Caribbean Sea. The Caribbean coastline has many gulfs and bays, including the Gulf of Gonâve, Gulf of Venezuela, Gulf of Darién, Golfo de los Mosquitos, Gulf of Paria and Gulf of Honduras. The sea's deepest point is the Cayman Trough, between the Cayman Islands and Jamaica, at 7,686 m below sea level.

The Caribbean Sea qualifies as a semi enclosed sea under the 1982 United Nations Convention on Law of the Sea (UNCLOS), which defines an enclosed or semi-enclosed sea as a gulf, basin or sea surrounded by two or more states and connected to another sea or the ocean by a narrow outlet or consisting entirely or primarily of the territorial seas and exclusive economic zones of two or more coastal states. The Caribbean is comprised entirely of Exclusive Economic Zones over which the insular and littoral states of the region exercise jurisdiction. UNCLOS 1982 also requires that states bordering such an area; cooperate with each other to coordinate the implementation of their rights and duties with respect to the protection of the marine environment.

In recent times the highly fragile ecosystems of the region have become vulnerable to the effects of climate change including sea level rise, coastal inundation and the increase in the frequency and intensity of natural disasters (Girvan 2002). These situations have created a greater need to understand the nature and pattern of the tides in the Caribbean Sea, as this will allow for more efficient protection and sustainable management strategies and support investigations into the vertical datum issues in the Caribbean coastal areas.

Tides are of particular importance as they produce strong currents and have speeds of up to 5m/s in coastal waters which can pose problems for navigation and causes the mixing of coastal waters. Tides also cause vertical displacement of the earth's crust and thus influence almost all precise geodetic measurements. As a result of tidal forces, the earth's rotation about its axis slows, increasing the length of day. Tides also influence the orbits of satellites. Accurate knowledge of tides is needed for computing the orbit of altimetric satellites and for correcting altimeter measurements of oceanic topography (Stewart 2008).



Figure 1 Showing map of the Caribbean

2.0 TIDES

The word tide is the generic term used to describe the shallow water waves which results in the vertical displacement of the sea level as a function of astronomical argument; the combined effects of the gravitational forces of the moon and the sun and the rotation of the earth. (Stewart 2008)

The dynamic theory of tides is built on the concept of a harmonic analysis of the components that compose real world tides. The moon and the sun generate their own tides within the earth's ocean. These tides vary with the distance of these astronomical bodies from the earth as the orbits of the moon around the earth and the earth around the sun are not perfectly circular. These tides are considered to be constituents of the overall tide. Constructive and destructive interference of these tides occur periodically, accounting for the spring and neap tides (Davis and Dalrymple 2011). These constituents are further discussed in section 2.2.

2.1 Types of tides

There are three main types of astronomical tides; diurnal tides, semi-diurnal tides and mixed tides. A *diurnal tide* has one occurrence of high water and one of low water each lunar day¹. These tides generally occur in locations when the moon is farthest from the equator.

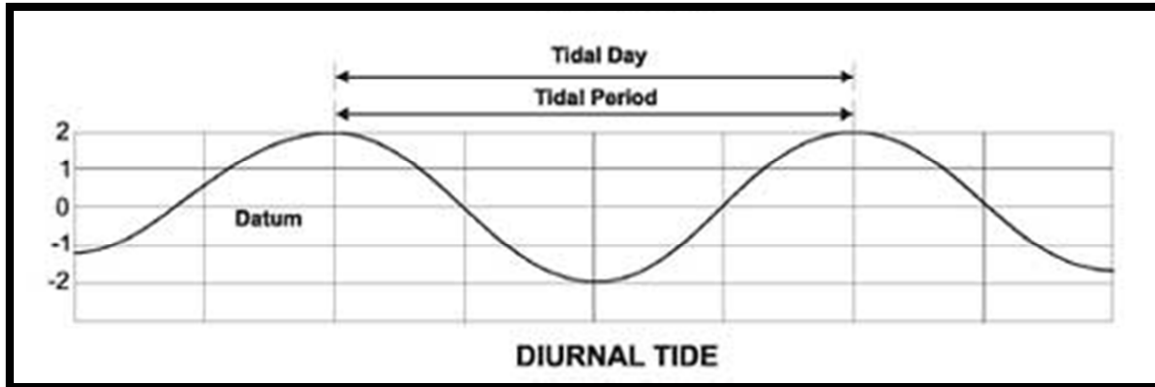


Figure 2 Diagram of a diurnal tide

A *semi-diurnal tide* has two occurrences of equal high water and two of equal low water in each lunar day. These tides usually occur when the moon is directly over the equator. This is the most common type of tidal pattern found around the world.

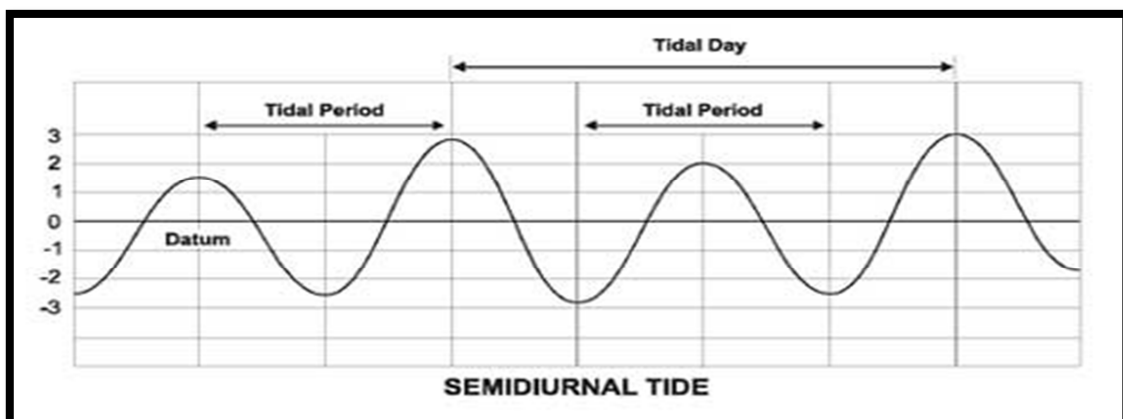


Figure 3 Diagram of semi-diurnal tide

¹ A lunar day is the period of time it takes the moon to make a complete rotation on its axis with respect to the sun; equivalently, it is the time it takes the Moon to make one complete orbit around the Earth and come back to the same phase, this amounts to twenty four hours and fifty minutes.

Mixed tides have two unequal occurrences of high and low water in each lunar day. This means that the two high water occurrences do not reach the same level and/or the two low water occurrences do not reach the same level. These tides are generally present when the moon is extremely far north or extremely far south of the equator.

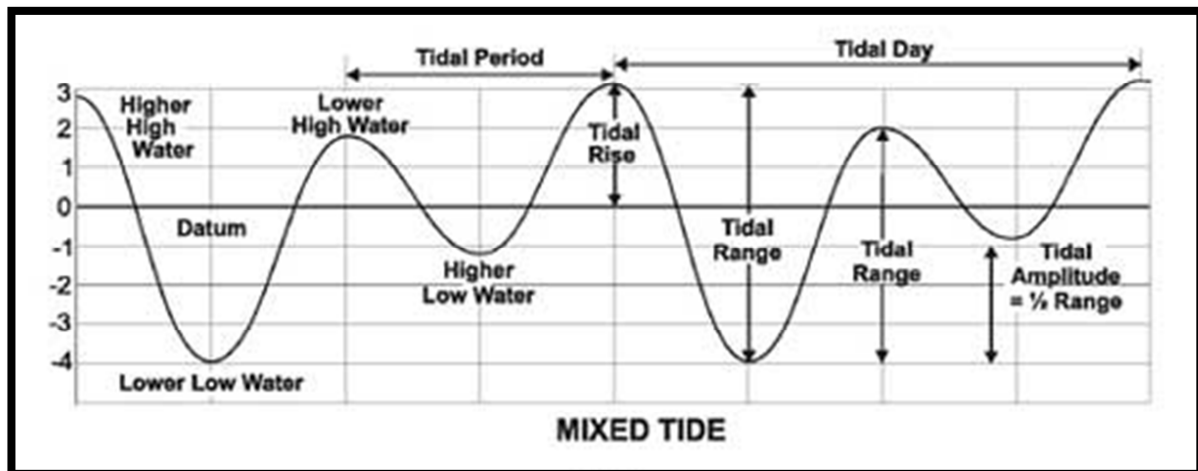


Figure 4 Diagram of mixed tide

2.2 Tidal constituents

Each tidal constituent is defined by its period in mean solar hours or alternatively by speed in degrees per mean solar hour. Table 1 shows six major tidal constituents used to describe tides.

Table 1 Description of some major tidal constituents (Defant 1961)

TIDAL CONSTITUENT (DARWINIAN)	PERIOD (SOLAR HOURS)	SPEED (DEGREES/HOUR)	NATURE
M ₂	12.42	28.984	Semi-diurnal
S ₂	12.00	30	Semi-diurnal
N ₂	12.66	28.439	Semi-diurnal
K ₁	23.93	15.041	Diurnal
O ₁	25.82	13.943	Diurnal

P_1	24.07	14.958	Diurnal
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Semi diurnal tides have two occurrences in one lunar day as indicated by subscript in the Darwinian symbol. The principal lunar semi diurnal constituent (M_2) is the largest and most significant in most locations. This constituent alone would give the tide if the sun could be neglected, and if the moon orbited in a perfect circle in the plane of the earth's equator. The principal solar semi diurnal constituent (S_2) would give the solar tide if the sun was always in the earth's equatorial plane and the earth's orbit was a perfect circle. The larger lunar elliptic semi diurnal constituent (N_2) involves the non-circularity of the moon's orbit. During the month the moon's orbit is an ellipse, and the tides are higher when it is near its perigee and lower when it is near its apogee (M. P. M. Reddy 2002).

The luni-solar declinational diurnal constituent (K_1), the principal lunar declinational diurnal constituent (O_1) and the principal solar diurnal constituents (P_1) all have one occurrence in a lunar day. They take into account the inclination of the earth's equatorial plane with respect to the plane of the moon's orbit (M. P. M. Reddy 2002).

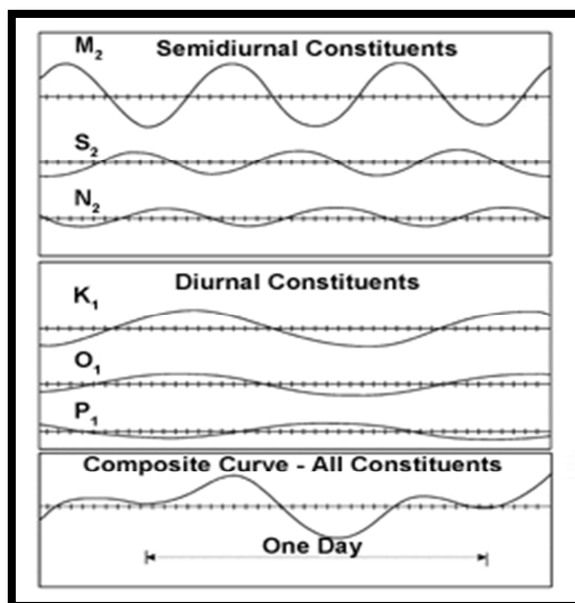


Figure 5 Showing examples of the major tidal constituents

The extended tidal measurements at a given point (usually a port) would result in a dataset that is a combination of these constituents for the given time period. The relative intensity of each of these constituents along any coastline can be derived from the extended tidal data by harmonic analysis.

2.2.1 Form number

The form number (F) also called the amplitude ratio, is used to determine the best description of the tide in an area. (Defant 1961).

$$\text{Equation 1} \quad F = (K1 + O1)/(M2 + S2)$$

Where K1, O1 M2 and S2 are primary tidal constituents discussed in section 2.1.

The value of F found using the tidal constituents derived from the tide gauges in a certain area determines whether the tide is diurnal, semi diurnal, mixed primarily semi diurnal or mixed primarily diurnal (Kjerfve 1981). For

$F < 0.25$	the tide is described as semi-diurnal
$0.25 \leq F < 1.5$	the tide is mixed primarily semi-diurnal tide
$1.5 \leq F < 3$	the tide is mixed primarily diurnal tide
$F \geq 3$	the tide is diurnal

2.3 Deriving tidal constituents

Tidal measurements are characteristic sinusoidal oscillations and can be broken down into its constituents which are usually represented by cosine functions. Tidal constituents are all of the form

$$\text{Equation 2} \quad f(t) = H \cos(at + \varphi).$$

H= amplitude of the constituent
a= the speed of the constituent (degrees/hour)
 φ = the phase of the constituent (degrees)

The speed (a) of each constituent is constant the sums and differences of small integral multiples of 5 basic astronomical speeds, which are:

T	the rotation of the Earth on its axis, with respect to the Sun, 15 degrees/hour
h	the rotation of the Earth about the sun, .04106864 degrees/hour
s	the rotation of the Moon about the Earth, .54901653 degrees/hour
p	the precession of the Moon's perigee, .00464183 degrees/hour
N	the precession of the plane of the Moon's orbit, -.00220641 degrees/hour.

Table 2 Derivation of the speed of the tidal constituents

Tidal constituent	Speed combinations	Speed (degree/hour)
M2	$2T - 2s + 2h$	28.9841
S2	2T	30
K1	T + h	15.041
O1	T - 2s + h	13.942

Tidal analysis is done to obtain the amplitude and phase of each tidal constituent. There are two main methods of tidal analysis, the response method and the harmonic analysis method of least squares (HAMELS).

The response method calculates the spectral admittance between the major tidal constituents and the tidal potential at each tide station. While this method requires only a few months of data, it only works if the wave propagates as a linear wave and data gaps pose a problem for this technique. Though the HAMELS method requires longer data sets for higher accuracies, it is simple and can be used to give a good estimate of the amplitude and phase for any set of tidal constituents with known period.

3.0 RESULTS

Tidal data is difficult to obtain in the Caribbean region. The tide stations in the Caribbean are described to be in various states of disrepair with the majority of them no longer collecting data (Von Hillebrandt-Andrade 2009). Tidal data is however collected by private companies. For this study we were unable to procure any tidal dataset with the quality required for the determination of tidal constituents. The derived tidal constituents used in this study were obtained from Dr. Keith Miller, 2012, via personal correspondence. A description of the tidal datasets he used is shown in table 3.

Table 3 Showing tide gauge metadata

Country	Location of tide gauge	Data periods (s) (years)	Amount of data (%)
Honduras	Puerto Cortes	1948-1968	99
	Puerto Castilla	1955-1967	78
Belize	Belize City	1964-1967	78
Jamaica	Port Royal	1965-1968	100
Cuba	Guantanamo Bay	1937-1948	74
		1995-1997	48

	Gibara	1985-1992	100
Puerto Rico	Magueyes	1985-2001	100
	San Juan	1985-2001	95
St Croix	Limetree Bay	1982-2001	88
St Thomas	Charlotte Amalie	1978-2001	85
Guadeloupe	Point a Pitre	1991-1998	95
Martinique	Fort de France	1976-1979	21
		1983-1985	79
Barbados	Bridgetown	1968-1970	41
		1990-1991	61
		1993-1996	34
Trinidad	Port of Spain	1984-1992	79
	Point Fortin	1987-1992	84
Venezuela	La Guaira	1985-1994	97
Colombia	Cartagena	1951-1993	88
		1994-2000	79
Panama	Cristobal	1907-1978	99
		1981-1997	95
Coata Rica	Puerto Limon	1970-1971	77
		1972-1974	61
		1976-1981	66

Source: Miller 2012(personal correspondence)

Table 4 Showing amplitude and phase of the semi diurnal constituents for the Caribbean

Country	Location of tide gauge	M2		S2		N2	
		h (mm)	ϕ (degrees)	h (mm)	ϕ (degrees)	h (mm)	ϕ (degrees)
Honduras	Puerto Cortes	60.8	80.7	22.8	28.5	22.4	6.0
	Puerto Castilla	75.2	80.9	39.6	39.6	26.0	9.3
Belize	Belize City	70.4	11.8	27.9	63.4	27.3	39.2
Jamaica	Port Royal	46.0	81.4	21.0	33.8	18.9	25.2
Cuba	Guantanamo Bay	137.9	31.8	40.6	44.5	33.0	321.1
	Gibara	267.2	3.7	44.8	36.0	65.1	287.7
Puerto Rico	Magueyes	7.5	22.6	9.9	8.8	2.7	34.9

	San Juan	155.2	14.6	20.7	48.6	37.0	295.0
St Croix	Limetree Bay	12.9	323.4	6.4	7.1	-	-
St Thomas	Charlotte Amalie	41.4	18.2	8.9	10.1	8.8	311.0
Guadeloupe	Point a Pitre	86.9	218.8	32.4	244.5	20.4	147.7
Martinique	Fort de France	60.6	201.8	14.0	250.6	16.1	118.5
Barbados	Bridgetown	110.3	320.6	78.5	247.9	19.2	12.2
Trinidad	Port of Spain	297.9	225.5	95.9	261.4	63.0	151.5
	Point Fortin	417.4	230.5	131.1	267.6	86.4	153.9
Venezuela	La Guaira	45.0	150.2	5.9	145.9	14.6	75.1
Colombia	Cartagena	74.2	130.5	16.2	47.6	26.1	67.5
Panama	Cristobal	82.4	158.9	13.5	357.5	26.2	60.5
Coata Rica	Puerto Limon	83.9	171.8	15.3	329.5	25.1	64.6

Source: Miller 2012(personal correspondence)

Table 5 Showing amplitude and phase of the diurnal tidal constituents in the Caribbean

COUNTRY	LOCATION OF TIDE GAUGE	K1		O1		P1	
		h(mm)	ϕ (degrees)	h (mm)	Φ (degree)	h (mm)	ϕ (degrees)
Honduras	Puerto Cortes	29.5	260.7	24.6	334.5	7.3	300.4
	Puerto Castilla	27.3	265.2	24.5	336.0	7.5	296.1
Belize	Belize City	20.9	279.6	28.0	0.6	5.3	339.7
Jamaica	Port Royal	67.3	228.2	47.8	244.0	20.8	248.6
Cuba	Guantanamo Bay	66.6	210.0	30.7	218.4	20.2	230.6
	Gibara	82.6	194.6	56.9	212.9	22.8	217.5
Puerto Rico	Magueyes	79.7	223.3	53.7	231.0	24.2	245.4
	San Juan	87.0	218.1	74.9	231.0	27.2	239.7
St Croix	Limetree Bay	83.0	226.7	63.3	232.7	25.9	248.5
St Thomas	Charlotte	80.8	220.7	60.8	226.7	25.4	244.0

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10/15

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	Amalie						
Guadeloupe	Point a Pitre	73.3	220.2	59.1	227.4	23.6	242.0
Martinique	Fort de France	84.2	228.8	62.7	233.5	26.3	248.6
Barbados	Bridgetown	78.9	222.3	20.6	120.6	28.1	253.6
Trinidad	Port of Spain	95.1	234.7	71.8	239.9	30.5	255.5
	Point Fortin	106.3	234.4	80.7	238.3	32.7	253.7
Venezuela	La Guaira	96.9	228.4	67.9	236.7	30.0	251.0
Colombia	Cartagena	97.3	230.8	58.4	245.1	29.6	252.6
Panama	Cristobal	101.2	230.7	60.9	243.9	30.8	252.2
Coata Rica	Puerto Limon	100.5	228.8	60.8	242.1	30.5	248.0

Source: Miller 2012(personal correspondence)

Table 6 Showing tide type at each tide station

Amplitude	F= (K1+O1)/(M2+S2)	Type of Tide
Jamaica	1.72	Mixed primarily diurnal
Puerto Rico (Magueyes)	7.67	Diurnal
Puerto Rico (San Juan)	0.92	Mixed primarily semi diurnal
St. Thomas	2.82	Mixed primarily diurnal
St. Croix	7.56	Diurnal
Cuba (Gibara)	0.45	Mixed primarily semi diurnal
Cuba (Guantanamo)	0.56	Mixed primarily semi diurnal
Honduras (Puerto Castillas)	0.45	Mixed primarily semi diurnal
Honduras (Puerto Cortes)	0.51	Mixed primarily semi diurnal
Belize	0.44	Mixed primarily semi diurnal
Costa Rica	1.63	Mixed primarily diurnal
Panama	1.73	Mixed primarily diurnal
Colombia	1.72	Mixed primarily diurnal
Venezuela	3.24	Diurnal
Trinidad (Port of Spain)	0.42	Mixed primarily semi diurnal
Trinidad (Point Fortin)	0.34	Mixed primarily semi diurnal
Barbados	0.53	Mixed primarily semi diurnal
Martinique	1.97	Mixed primarily diurnal
Guadeloupe	1.11	Mixed primarily semi diurnal

4.0 ANALYSIS OF TIDES IN THE CARIBBEAN

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11/15

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M₂

The M₂ amplitude for most of the Caribbean Sea does not exceed 100mm. The exceptions are at Cuba, Puerto Rico and Barbados where the values range from 200mm. A possible explanation is that the tide stations were influenced by the Atlantic Ocean tides. At Trinidad the M₂ amplitude was considerably higher than anywhere in the Caribbean exceeding 400mm at one point. (Kjerfve 1981) had similar results about the M₂ constituent.

S₂

For the majority of the Caribbean the S₂ amplitude is less than 50mm. The exceptions are at Barbados and Trinidad at the south east corner of the Caribbean Sea, where the S₂ amplitude ranges from 70mm to 140mm. While the same exception at Trinidad was noted in (Kjerfve 1981), the S₂ amplitudes were lower ranging from 20mm to 50mm and were described as uniform throughout the Caribbean.

N₂

The N₂ constituent ranges between 20mm and 40mm for most of the stations. The anomalies are again at Trinidad where it is considerably higher, rising to just under 90mm. Some smaller values were recorded at St. Thomas and Puerto Rico 8.8mm and 2.7mm respectively. (Kjerfve 1981) agrees closely with these results.

K₁

The K₁ amplitudes are relatively low in the north western region of the Caribbean Sea. Honduras, Belize, Jamaica and Cuba experience K₁ amplitudes ranging from 20mm to 70mm. Towards the eastern region of the Sea, the amplitudes increase gradually from 80mm to just over 100mm, the higher values were recorded in the south eastern region. This is corroborated by the (Kjerfve 1981) study.

O₁

The amplitude of the O₁ constituent was relatively uniform for most of the Sea with a range from 50mm to 80mm. Lower amplitudes were recorded in the western Caribbean Sea and another anomaly was 20mm at Barbados. In the previous study, the O₁ amplitudes agreed closely with the K₁ values and were generally uniform for the region.

P₁

The P₁ amplitudes were the lowest of all the constituents investigated. The values ranged from 7mm to 32mm, with values gradually increasing towards the south of the Caribbean Sea. These findings are also in agreement with those of (Kjerfve 1981).

5.0 CONCLUSION

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The tides of the Caribbean Sea can be described as mostly mixed; with some areas experiencing mixed primarily semi diurnal tides and others experiencing mixed primarily diurnal tides. A small region also experiences diurnal tides. Two studies, three decades apart, were carried out investigating the tidal constituents of the Caribbean Sea and the results agreed for the most part. The main variation between the two studies is that higher constituent amplitudes were generally noted in this study compared to (Kjerfve 1981). This study, though not as extensive as the last, had the advantage of including data from the Gulf of Paria. Both studies recorded constituent amplitudes that were considerably higher the south eastern Caribbean Sea than the rest of the Caribbean, and this additional information in the Gulf of Paria can be used to investigate this anomaly.

BIOGRAPHICAL NOTES

Ms Cassandra Nanlal holds a B.Sc, first class honours, in Geomatics from the University of the West Indies. She is currently an MPhil in Surveying and Land Information at the University of the West Indies. Her research interests include vertical separation modelling in the and tidal monitoring.

Dr. Dexter Davis holds a B.Sc. in Land Surveying from the University of the West Indies and a Ph.D. in Surveying Science from the University of Newcastle upon Tyne. He is currently a lecturer in the field of geodesy GNSS and geodetic surveying and is also Programme Coordinator of the B.Sc. of the Geomatics Engineering Programme in the Department of Geomatics Engineering and Land Management, University of the West Indies. He is a member of the Institute of Surveyors of Trinidad and Tobago as well as the ASPRS. His current research interests include geomatic techniques for hazard monitoring and mapping, including sea level rise and earthquake monitoring.

Dr. Michael Sutherland holds an M.Sc.E. and Ph.D. in Geomatics Engineering from the University of New Brunswick, Canada specializing in land information management and GIS. He is currently a lecturer, and the Programme Coordinator of the B.Sc. in Land Management Programme in the Department of Geomatics Engineering and Land Management, University of the West Indies, St. Augustine, Trinidad and Tobago. He previously held post-doctoral positions at the University of Ottawa and Dalhousie University, Canada where he did GIS research in relation to multi-criteria decision analysis supporting socioeconomic and environmental phenomena. He is a member of the Canadian Institute of Geomatics and the Institute of Surveyors of Trinidad and Tobago, and is an elected member of the Royal Institution of Chartered Surveyors. He is also an Associate of the Canadian Fisheries, Oceans, and Aquaculture Management (C-FOAM) research group, Telfer School of Management, University of Ottawa, Canada. In 2011 Michael was appointed as an Honourary Fellow, Sir Arthur Lewis Institute of Social and Economic Studies, University of the West Indies, St. Augustine, Trinidad and Tobago. In 2012 he was appointed Adjunct Professor in the Department of Geodesy and Geomatics Engineering, University of New Brunswick, Canada.

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13/15

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Michael is currently Chair (2011-2014) of Commission 4 (Hydrography), International Federation of Surveyors.

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