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14. ABSTRACT
The stress contributed by nutrients to the coral reef ecosystem is among many problems that may be resolved using the coastal ocean observing system (COOS) being developed by various institutions. Traditional nutrient sampling has been inadequate to resolve issues on episodic nutrient fluxes in reef regions due to temporal and spatial variability. This paper illustrates sampling strategy using COOS information to identify areas that need critical investigation. The area investigated is within the Puerto Rico subdomain. Nutrient profile results from the region indicate nitrate is undetectable in the upper 50m due to high biological consumption. The strong vertical fluctuation in the upper 50m demonstrates a high anomaly in temperature and salinity and a strong cross correlation signal. High chlorophyll a concentration corresponding to seasonal high nutrient influx coincides with higher precipitation accumulation rates and apparent riverine input from the Amazon and Orinoco rivers. Non-detectability of nutrients in the upper 50m is a reflection of poor sampling frequency or the absence of a highly sensitive nutrient analysis method to capture episodic events. Thus, this paper explores the range of depths and concentrations that need to be critically investigated to determine nutrient fluxes, nutrient sources, and climatological factors that can affect nutrient delivery. It also provides insight into needed sampling rates and temporal and spatial domain choices. Finally, it demonstrates a scientific reconnaissance for a field study that is now possible with online in-situ and remote sensing observations and numerical simulation, as a consequence of IOOS in general and COOS in particular.

15. SUBJECT TERMS
nutrient fluxes; coastal reefs; oligotropic; caribbean; sampling; coos; coastal ocean observing system

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Developmental strategy for effective sampling to detect possible nutrient fluxes in oligotrophic coastal reef waters in the Caribbean

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The stress contributed by nutrients to the coral reef ecosystem is among many problems that may be resolved using the coastal ocean observing system (COOS) being developed by various institutions. Traditional nutrient sampling has been inadequate to resolve issues on episodic nutrient fluxes in reef regions due to temporal and spatial variability. This paper illustrates sampling strategy using COOS information to identify areas that need critical investigation. The area investigated is within the Puerto Rico subdomain.

Nutrient profile results from the region indicate nitrate is undetectable in the upper 50m due to high biological consumption. The strong vertical fluctuation in the upper 50m demonstrates a high anomaly in temperature and salinity and a strong cross correlation signal. High *chlorophyll a* concentration corresponding to seasonal high nutrient influx coincides with higher precipitation accumulation rates and apparent riverine input from the Amazon and Orinoco rivers. Non-detectability of nutrients in the upper 50m is a reflection of poor sampling frequency or the absence of a highly sensitive nutrient analysis method to capture episodic events. Thus, this paper explores the range of depths and concentrations that need to be critically investigated to determine nutrient fluxes, nutrient sources, and climatological factors that can affect nutrient delivery. It also provides insight into needed sampling rates and temporal and spatial domain choices. Finally, it demonstrates a scientific reconnaissance for a field study that is now possible with online *in-situ* and remote sensing observations and numerical simulations, as a consequence of IOOS in general and COOS in particular.

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INTRODUCTION

Global changes – global warming, sea level rise, drought, freshening, eutrophication and pollution – affect the susceptibility of coastal areas to natural catastrophic events (eg, hurricanes, tsunamis, floodings, harmful algal blooms and coral bleachings). These changes have been known to jeopardise the sustainability of marine and coastal systems required to support human needs. As a worldwide concern, these ushered changes in the implementation of treaties and conventions to improve observational and prediction capabilities for various ecosystems from local to global scales.[1,2] Significant growth of coastal ocean observing system planning (IOOS, GOOS, OCEAN.US, IOCARIBE, IAS-GOOS, IASNFS, CaTS) resulted from this effort to improve the level of detection, prediction and attribution of climatic changes.[3] The advent of real-time observations using various platforms, expanded coordinated observations, and co-operative efforts from federal governments, universities, industries and various agencies beyond international borders, has improved prognostic calculations of important physical, chemical and biological mechanisms in oceanic and coastal regimes.[4]

Coral reefs are one of the major ecosystems that benefit from modern observing system capability. They are highly complex in nature and known for their high productivity that serves to sustain high marine biodiversity. In contrast, any increase in coral reef community nutrient level contributes to reef stress and degradation – a paradox in coral reef ecosystems.[5] Areas of high turbidity and lower salinity correlate with regions of low or poor coral reef health or absence of coral reef regions, suggesting the ocean processes controlling nutrient transport directly affect reef health.[6] Nutrients enter reef communities from various sources and could vary with climatology.[7] The transport and distribution of nutrients can be influenced by the water circulation and frontal eddies on both local and regional scales varying from diurnal to seasonal scale. [8,9,10] Episodic surges and upwelling events commonly bring cool nutrient-rich water to oligotrophic euphotic surface zones resulting in new primary production.[11]

However, not all upwelling systems increase productivity since it depends on the nutrient availability and mixing depth[12] with macroscale, mesoscale, and microscale processes also influencing nutrient supplies.[13] Thus, determining the driving factors of nutrient loading depends on knowing nutrient sources, transports, and their distribution in time and space.

Puerto Rico (PR) is one of the islands in the Pan-Caribbean that abounds with coral reefs.[14] Corals are abundant in the insular shelf segments of PR. The narrow northern and northwestern coasts exhibit high wave action during wintertime, coincident with cold front passages from the North Atlantic to the Caribbean Antilles. In contrast, on the southern coast of PR, wave action is milder and the insular shelf wider and, thus, favourable for coral reef growth. Two islands, Mona and Desecheo (still part of PR) bounded by PR on the east and Dominican Republic on the west similarly exhibit steep platforms in the north and wider shelf margins in the south indicative of high wave energy in the former.[14] The water masses contributing to the Caribbean Sea include inflows over the sills of the Caribbean passages. Sources of these water masses include recirculated water from the North Atlantic Subtropical gyre and contributions from the South Atlantic which feed directly to the Caribbean basin and then to the southeastern Gulf of Mexico.[15] Seasonality of this wind-driven circulation is highly influenced by the dominant zonal trade winds in the Caribbean during winter months as a result of the Intertropical Convergence Zone (ITCZ) migration.[16] This induces coastal upwelling along the southern boundary of the Caribbean Sea[17] and causes weakening of pycnocline stratification of the central and northeast Caribbean Sea.[18] Also, the southern region of PR is intermittently influenced by plumes from two major rivers, the Orinoco and Amazon. Thus, water masses delivered to PR can be a mixture of these river plumes.

Long-term observations are necessary to improve parameterisations of contributions to nutrient signals in order to determine not just the coastal variation in reef regimes but also the variation in oceanic regimes. Global and coastal ocean observing systems characteristically provide long-term observations used in the data assimilation for prognostic and hindcast models. The resultant products include synoptic maps of currents, eddies, fronts, upwelling areas, temperature, salinity and chlorophyll, which are publicly available and updated regularly. The predictive capabilities of these models offer great benefit to sampling strategies. For instance, in conducting a nutrient flux study in coastal ecosystems, determining sampling sites in remote places and large-scale areas can be time-consuming and requires significant manpower and financial resources. With this mode of investigation, a wide area of potential sampling sites can be covered reducing sampling bias. This approach can provide an inexpensive scheme of assessing sampling sites for estuarine, coastal, and oceanic studies. Thus, this paper highlights the value of using numerically modelled coastal ocean observing systems products as an effective tool in improving sampling strategy for nutrient dynamics in coastal reef regions.

Through this analysis, valuable information can be obtained to assess possible mechanisms for transporting nutrient-enriched waters to coastal reef areas. Evaluation of this sophisticated technology beforehand can provide valuable inputs to an effective sampling strategy and reduce the cost and time required to obtain data of high quality. Thus, the aim of this study is to understand the temporal and spatial variability in flow patterns and the mechanisms that control the transports of nutrients to the inner shelf of PR. Properties observed will be used as potential indicators of nutrient transport mechanisms.

METHODS

The time series profile data (1993–2007) are from the Caribbean Time Series (CaTS) station (Fig 1) located 28 nautical miles south of the PR at 17°36N, 67°W, with a bottom depth of 2000m (provided by Profs Jorge Corredor and Julio Morrel from the University of Puerto Rico). A

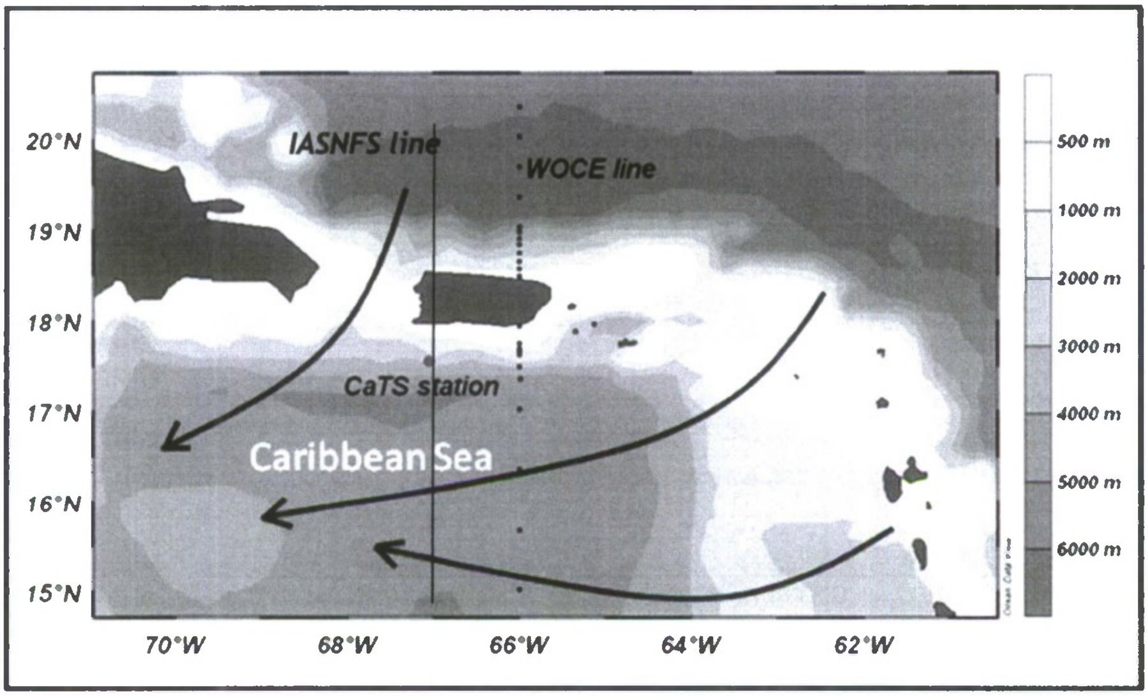

Fig 1: Bottom topography (GlobHR and GEBCO-6m) of Puerto Rico. Within the sub-domain study region (15–20°N; 60–70°W) includes the Caribbean Time Series (CaTS) station (17.6°N, 67°W), IASNFS transect line (15–20°N, 67°W) and the A-22 WOCE line (15–20°N, 66°W). Schematic representation of the surface circulation in the Caribbean observed using Acoustic Doppler Current Profiler (ADCP) transports[16]

Sea-Bird Electronics SBE19 (conductivity-temperature-depth) unit downcast was performed at a 1m interval to a standard depth of 200m to measure temperature and salinity. Water samples collected (500ml) for nutrients analyses (1998–2006) were frozen prior to analysis. Standard analytical procedures were employed for nitrate, phosphate and silicate (see[18] for detailed analyses). From this dataset, temperature and salinity anomalies were computed and cross correlated.

World Ocean Circulation Experiment (WOCE: www.woce.org) temperature, salinity and nutrient data were processed using Ocean Data View (ODV) developed by R Schlitzer (http://odv.awi.de/home.html). Line transect WOCE A-22 (see Fig 1) was located at 15–20°N, 66°W and occupied from 18–23 August 1997.

Chlorophyll a concentration acquired using MODIS (Aqua) level 2 in the Puerto Rico coastal region was obtained from the OceanColor website of NASA (http://oceancolor.gsfc.nasa.gov/). Daily images for mid-month of February and August 2005 were processed using MATLAB 6.5. Monthly mean *chlorophyll a* images with 9km resolution MODIS Aqua monthly SMI (Standard Mapped Image) products from the Ocean Biology Processing Group (OBPG) at Goddard Space Flight Center (GSFC) were acquired and processed using the GES-DISC Interactive Online Visualisation ANd aNalysis Infrastructure (Giovanni), a part of NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (http://reason.gsfc.nasa.gov/Giovanni/).

The nowcast sea surface temperature (SST), sea surface salinity (SSS), sea surface height (SSH), geostrophic velocities within the sub-domain (15–20°N, 60–70°W,) and vertical T,S profiles (15–20°N, 67°W) were obtained from the Experimental Real-Time Intra-Americas Sea Nowcast/Forecast System (http://www7320.nrlssc.navy.mil/IASNFS_WWW/today/IASNFS_crb.html). Archived data on 14 February and 18 August 2005 were provided by Dr Dong-Shan Ko, NRL).

The spatial distribution of corals in PR was obtained from the Millenium Coral Reefs Landsat Archive (http://oceancolor.gsfc.nasa.gov/cgi/landsat.pl).

The precipitation dataset was produced by the Global Precipitation Climatology Center (GPCC), GSFC. The global precipitation dataset was set on the 1x1 degree grid in its original format with a monthly temporal resolution (http://disc2.nascom.nasa.gov/Giovanni/tovas/ground.GPCC.2.shtml).

Ocean surface winds and 3B42 Precipitation were obtained by Quickscat and TRMM, respectively, and viewed using the TRMM QuikScat analysis tool (http://disc.sci.gsfc.nasa.gov/hurricane/trmm_quikscat_analysis.shtml).

RESULTS

Caribbean times series (17.6°N, 67°W)

Salinity, temperature and nutrient variability were investigated from 26 October 1993 to 12 June 2007. Seasonal high (36.6psu) and low salinity (~34.2psu) fluctuations occur in the upper 100m (Fig 2a) of the Caribbean surface water (CSW). Below this water mass, the subtropical underwater depth varies commonly between 20–30m above 125m with higher frequency during August to December. A strong vertical signature of salinity (~36.3psu) from ~60m to the surface occurred in two events during March-May 1998 and April 2005, which correspond to a strong salinity anomaly of 1.06psu (Fig 2b). The strong band of salinity anomaly in the former month (March 1998) in this region was preceded by a strong anomaly (March 1997) in the subtropical underwater mass of ~1.4psu. This observation corresponded to the wide warm band between March and December 1998 of the temperature time series plot (Fig 3c) in the upper 50m with small net seasonal temperature fluctuation within a year and preceding this year, a negative temperature anomaly of -2.2°C (Fig 2d) occurred. Mean salinity within this regime (Fig 3a) in the upper 40m is ~35.3 psu and increases sharply to 37.06psu with depth reaching its maximum at 145m and slowly relaxing back to 36.5 at 200m. A strong deviation of salinity occurs in the upper 50m which coincides with a strong salinity vertical fluctuation (Fig 3b) maximising at 25m. The same feature is observed with the

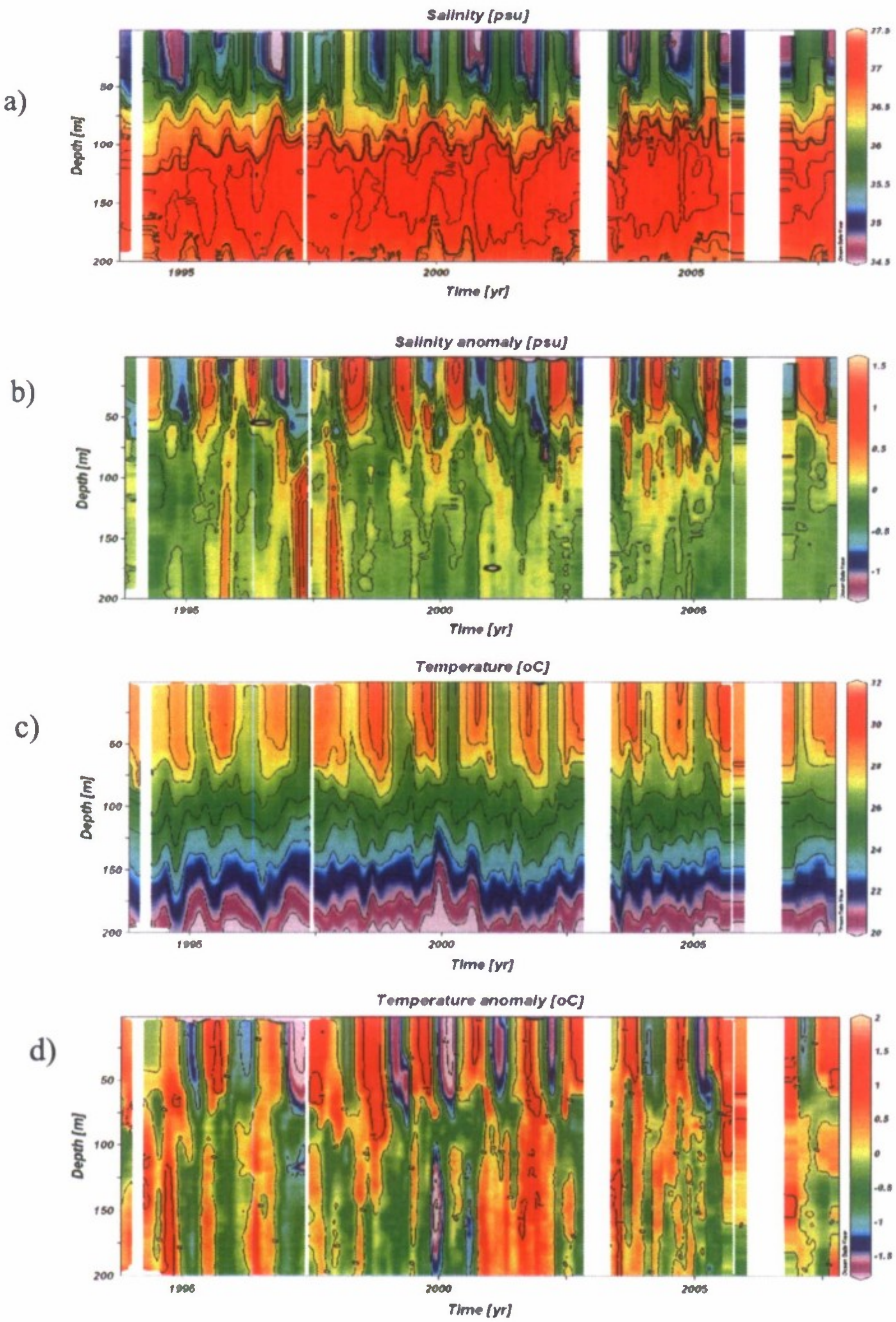

Fig 2: a) Salinity (psu) and c) Temperature (°C) time-depth series in the Caribbean Time Series (CaTS) station in Puerto Rico (17.6°N, 67°W) from 1993–2007. Bold lines marks high salinity (>36.8psu) of the subtropical underwater mass.
b) Salinity and d) Temperature anomaly (psu) series in the CaTS station in Puerto Rico from 1993–2007. Blank bands indicate no data available. [Data courtesy of Profs Jorge Corredor and Julio Morrel, UPR]

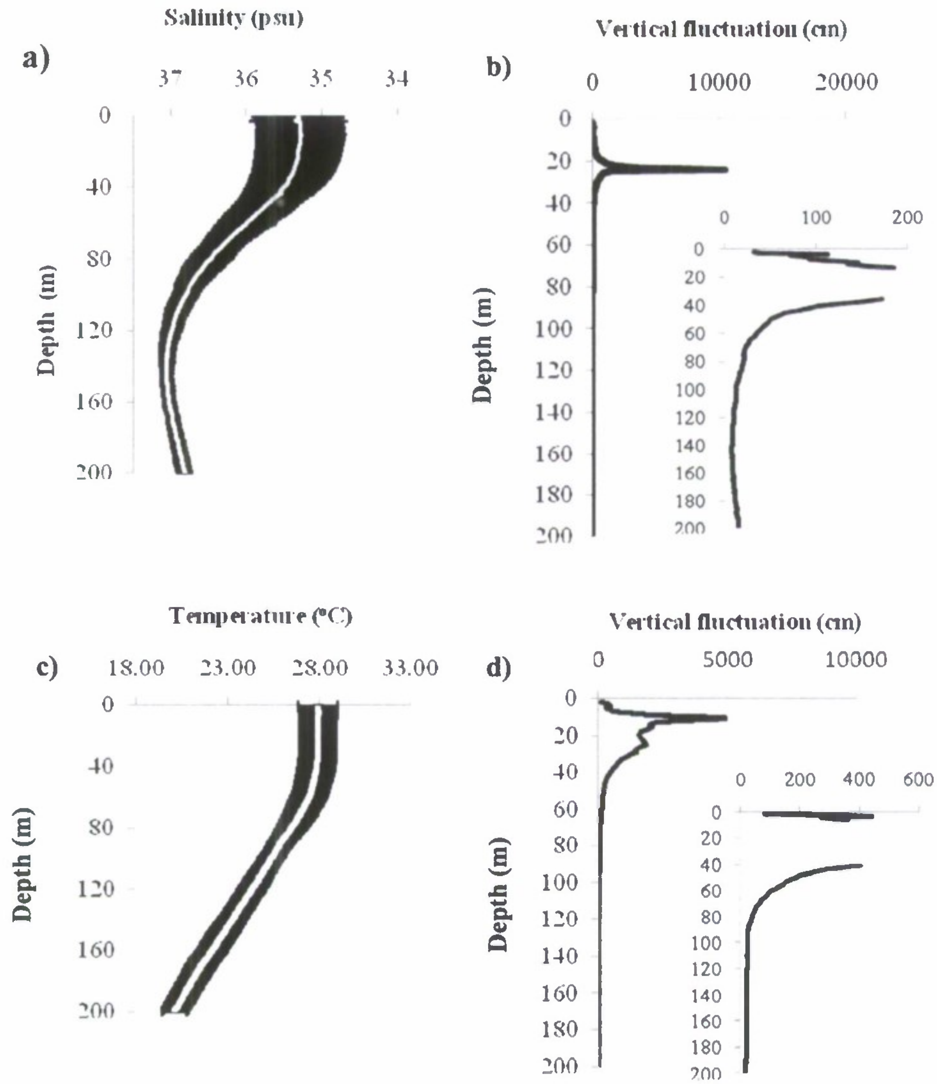

Fig 3: a) Mean salinity (psu) and c) Mean temperature in the Caribbean Time Series (CaTS) station (17.6°N, 67°W) from 2003–2007 with depth. Horizontal bars indicate standard deviation from the mean. b) Salinity and d) Temperature vertical fluctuations of the Caribbean Time Series subsurface water mass. Strong vertical fluctuation of salinity occur at 25m and decreases with depth for salinity. Strong vertical fluctuations of temperature occur at 15m and decreases with depth. Lower right plot shows vertical fluctuation profile at expanded scale after strong signal is removed

temperature profile (Fig 3c): the temperature deviates strongly in the upper 50m but linearly decreases with increasing depth below 50m.

Also, coincident to this deviation is a strong vertical temperature fluctuation that occurs strongly above 50m with a maximum value at 11m but starts to stabilise below this depth. The strong vertical fluctuation (Fig 3d) corresponds to a sudden shift in mean temperature from ~28°C at 25m and suggests a strong heating and cooling process in the mixed layer. The 11m strong vertical temperature fluctuation is indicative of an internal wave. A cross correlation function between temperature and salinity (Fig 4) shows strong negative correlation in the upper 50m and at depths below 70–120m indicative of warm, salty or cool, fresh anomalies. The seasonal mixed layer occurs in the upper 60m depth. The strong positive correlation below 60m corresponds to cool, salty or fresh and warm anomalies. The derived sigma-θ in the upper 50m (with strong vertical temperature and salinity fluctuation) varies from 21.5 to 22.5kg/m^3.

A characteristic profile (Fig 5; Table 1) of depth, salinity, temperature and potential density of detectable concentration from 0.1µmol/kg to 2.0µmol/kg for nitrate and 0.1µmol/kg to 0.5 µmol/kg for phosphate is determined at the CaTS station. In the upper ~60m, the nitrate concentration is not detectable. Nitrate with 0.1µmol/kg concentration is detected at ~60m and starts to increase with depth. A different property is exhibited at ~88m for nitrate concentration of 0.5µmol/kg. Temperature and potential density vary along with the increase in nitrate concentration while salinity exhibits similarity starting with 1.0µmol/kg to 2.0µmol/kg. On the other hand, phosphate concentration does not vary with depth and does not exhibit any characteristic water mass that is coincident to any specific concentration (Table 1b). Silicate is at its maximum in the upper 50m (Fig 5d) with a concentration of 3.92µmol/kg. Increase in concentration starts from January 1998 to September 2002 and occurs on February 2005. Silicate is minimum with a minimum concentration of about 1.2µmol/kg between 90–200m and a high salinity of ~37psu and mean temperature of 23.5°C. A water mass

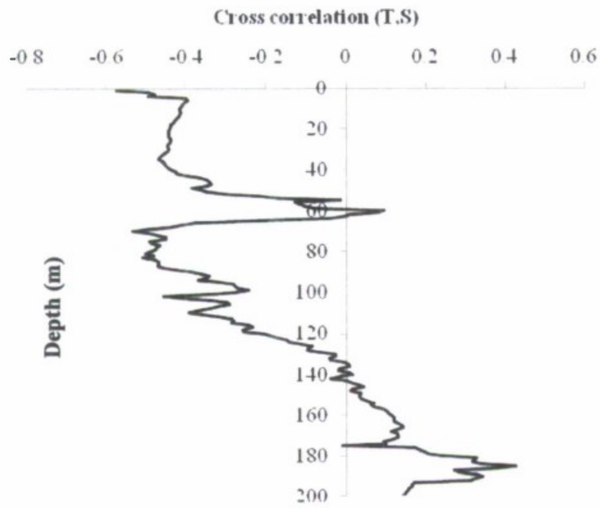

Fig 4: Cross-correlation function between temperature and salinity in the upper 200m of the Caribbean Time Series (CaTS) station (17.6°N, 67°W). The high correlation band occurs in the upper 50m and starts to decrease below this depth with low correlation at 60m. The negative high correlation band continued below 70m with low correlation at 135m. Below 140m, temperature and salinity exhibit positive correlation bands

with this concentration occurred at 50m from July to September 2004.

The chlorophyll maximum at a concentration ~1.3mg/m^3, fluctuates between the 70–120m from 1994–1999 based on the CaTS dataset.[18] From the spatially averaged surface chlorophyll time series, the surface chlorophyll concentration ranges from 0.08 to 0.25mg/m^3 (Fig 6). In this sub-domain integrated time-series, peaks of chlorophyll occur during June and July which also coincides with peaks in the CaTS dataset.

WOCE line transect along 66°W, 15–20°N (Aug 1997)

A strong plume of nitrate ~6μmol/kg at 170m is present south of PR and reaches to 60m with 0.1μmol/kg (Fig 7a). The 0.1μmol/kg concentration of nitrate can reach up to 50m south of PR while it is lower in the north to around 100m. A low salinity with depth profile from 15–17°N indicates possible influence of riverine waters. This low salinity feature coincides with the high salinity band from 15°N to 18°N of the IASNFS meridional vertical salinity transect (Fig 8). A strong signal of nitrate ~1.0μmol/kg at 100m coincides with the CATS time series nitrate signal (Fig 5a). However, nitrate and phosphate in mixed layer are limited due to their low levels. These nutrient levels, however, are in contrast to the high silicate concentration at the same depth (Fig 7c). The silicate concentration (>1.75μmol/kg) coincides well with the low salinity from 36.0 to 35.5psu and density at 22.5 and 23kg/m^3.

IASNFS meridional vertical transect along 67°W, 15–20°N (Februry 2005 and August 2005)

Seasonal variation occurs in the IASNFS meridional transects along 15–20°N, 67°W (Fig 8). The zonal velocity in February (Fig 8.1c) flows entirely westward with maximum speeds of 35cm/s located above 50m off the northern and southern coasts of PR. In August (Fig 8.2c), an eastward flow (blue) predominates in the south than in the north boundaries of PR with a maximum eastward speed of 70cm/s. Trade winds occur during February while August shifts the wind pattern to the west (Fig 9.1b & 9.2b). The cyclonic (15–18°N, 68.5–70.0°W) and anticyclonic (15–18°N, 66–68°W) current structures at this position (Fig 9.2a) results in a northward jet located 68.7°W. This prominent cyclonic eddy feature is coincident with the higher chlorophyll concentration in August than February for both in time-series monthly chlorophyll concentration at the CaTS station {*Chlorophyll a* (mg/m^3) = [CaTS station] 0.094 (Feb 2005); 0.118 (Aug 2005) and the integrated surface chlorophyll concentration within the sub-domain [sub-domain] 0.100 (Feb 2005); 0.112 (Aug 2005)}.

The cyclonic and anticyclonic eddy system forms the northward jet structure and coastal upwelling system off PR which brings nutrients to the surface and mixed layer, feeding phytoplankton growth. The presence of this eddy is also confirmed by the daily and mean monthly surface chlorophyll data between those months whereby high values of chlorophyll in the southwestern region of PR is apparent in August, compared to the same location in February (Fig 10). Further confirmation of the anticyclonic feature is manifested in the IASNFS surface maximum which has a surface elevation of ~44cm (Fig 11.2a). The strong low salinity fluctuation and the surface salinity (<34psu) inflow (Fig 11c) coming from the southeastern region indicated freshwater contribution to the PR region either by precipitation and contribution from two major rivers, the Orinoco and Amazon. Contribution of low salinity water from the Amazon is pronounced during August 2005 (Fig 11.2c).

A plume of low salinity water extends northwestward from the southeastern region of the Caribbean which also corresponds to the high accumulated rain rate per month (Feb 2005 = ~26.189mm; Aug 2005 = ~155.65mm). The seasonal and annual accumulated rain rate (mm) within the sub-domain region (15–20°N, 60–70°W) was produced by the Global Precipitation Climatology Center (GPCC), GSFC, set on the 1x1 degree grid with monthly temporal resolution. Seasonal increase in the accumulated rain rate starting June in the sub-domain corresponds to a decrease in salinity on October 1997 in the region. The strong positive decadal salinity anomaly on October 1997, derived from 10–60m 1995–2005 datasets in the Caribbean Time Series (CaTS) station in Puerto Rico (17.6°N, 67°W) from 1995–2005, coincided with the low annual accumulated rain region, suggesting a seasonal trend. Similar observation is apparent with temperature variability in seasonal and annual cycles. However, a strong negative salinity anomaly occurred in 2001 in the same month which suggest variation

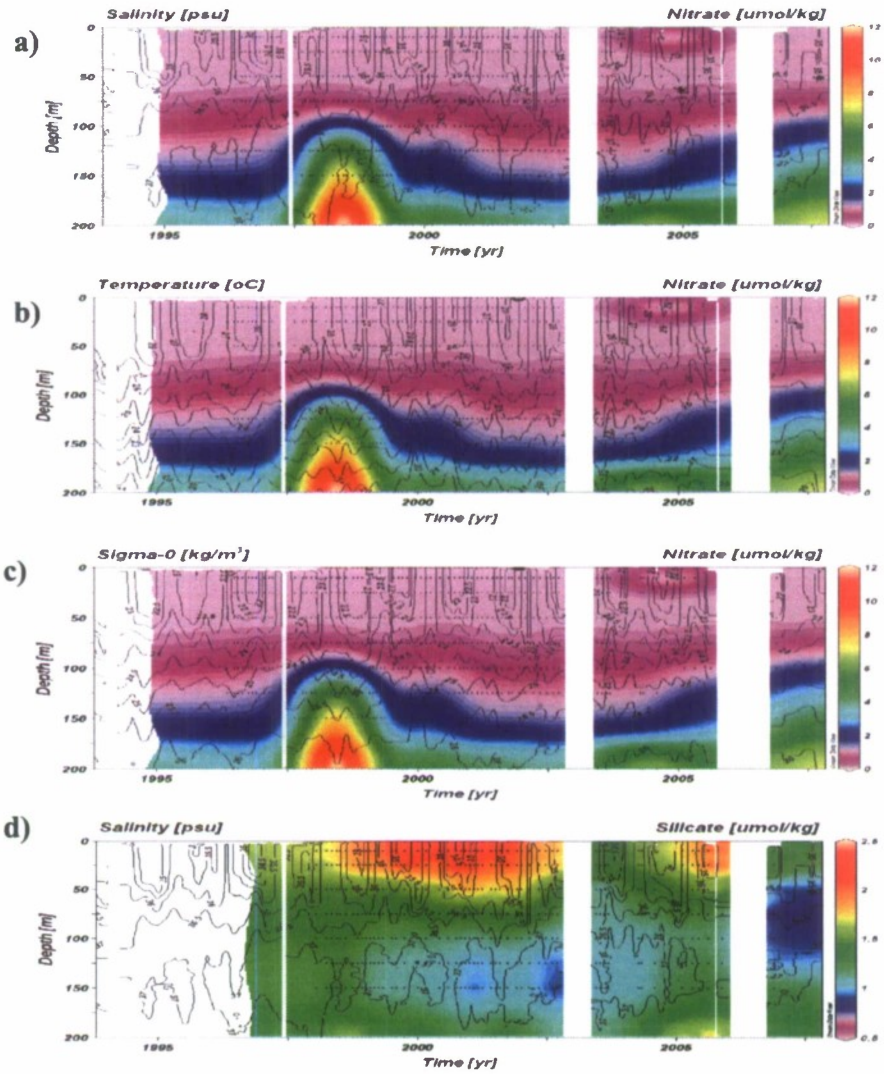

Fig 5: Nitrate (µmol/kg) time-depth plot from the Caribbean Time Series (CaTS) station (17.6°N, 67°W) overlaid with a) Temperature (°C), b) Salinity (psu) and c) Sigma-θ (µmol/kg) plots. d) Silicate (µmol/kg) Caribbean Time Series (CaTS) profile overlaid with salinity (psu). High concentration of silicate (1.75µmol/kg) occurs in the upper 50m except during the mid-2003 and mid- and low concentration of silicate 2006 (1.25µmol/kg) occurs from 70 to 170m. Blank spaces indicate no data available. [Data courtesy of Profs Jorge Corredor and Julio Morrel, UPR]

a) Nitrate (µmol/kg)	Depth (m)	Salinity (psu)	Temperature (°C)	Sigma-θ (kg/m³)
0.1	60.9 ± 4.2	35.945 ± 0.310	27.268 ± 0.818	23.348 ± 0.379
0.4	87.8 ± 7.3	36.736 ± 0.256	25.998 ± 0.824	24.351 ± 0.414
0.9	13.8 ± 11.7	37.08 ± 0.319	24.509 ± 0.805	25.002 ± 0.345
1.5	124.2 ± 21.8	36.944 ± 0.323	24.312 ± 1.330	25.027 ± 0.641
2.0	147.1 ± 21.5	37.01 ± 0.085	22.604 ± 1.044	25.580 ± 0.333
b) Phosphate (µmol/kg)				
0.1	79.2 ± 49.7	36.353 ± 0.710	26.195 ± 1.963	23.988 ± 0.1.091
0.2	114.4 ± 39.9	36.74 ± 0.481	24.75 ± 1.848	24.7307 ± 0.903
0.3	59.6 ± 24.9	36.388 ± 0.360	26.306 ± 1.198	23.9831 ± 0.618
0.4	55.5 ± 23.4	36.142 ± 0.400	27.645 ± 1.188	23.3723 ± 0.557
0.5	42.6 ± 23.0	35.863 ± 0.513	27.475 ± 1.425	23.2139 ± 0.678

Table 1: Depth (m), salinity (psu), temperature (°C) and density classes for a) nitrate (µmol/kg) and b) phosphate (µmol/kg) concentration of the Caribbean Time Series (CaTS) from 1995–2007 (n=10, mean ± SD)

can occur in the same period or season. Thus, diurnal, seasonal, and decadal scale variability of temperature and salinity effect nutrient distribution in a given time period in a sub-domain.

DISCUSSION

In the marine environment, nitrogen and phosphorus are considered to be limited in supply, while silicon is limited only to siliceous organisms, thus may not be important in

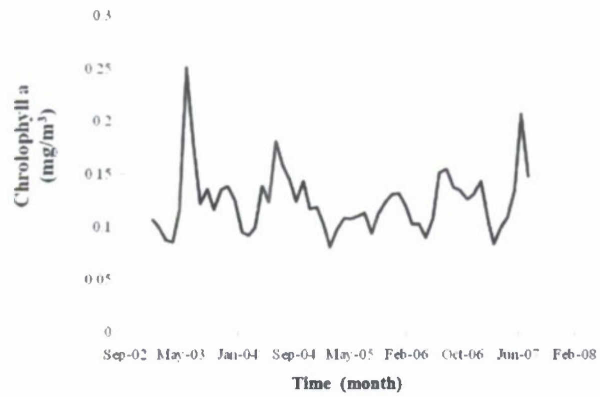

Fig 6: Integrated chlorophyll concentration (mg/m^3) from 2002 to 2007 within the sub-domain (15–20°N, 60–70°W) based on monthly mean *chlorophyll a* images with 9km spatial resolution MODIS Aqua monthly SMI (Standard Mapped Image) products from the Ocean Biology Processing Group (OBPG), GFSC

coral reef systems.[19] Inorganic nutrients (ie, nitrate and phosphate) in the mixed layer of the CaTs and the WOCE datasets are depleted. The depletion of these nutrients leads to a restriction in driving primary production,[20] thus resulting in high levels of silicate in the upper 50m. The biological removal of silicate is likely insignificant due to its constant supply from the Amazon and Orinoco.[20,21]

The delivery of nutrients to reef systems in PR is through vertical displacements associated with the passage of cyclonic and anticyclonic eddies[22] that correspond to high biological uptake indicated by high chlorophyll concentration on the offshore coastal reef. These eddies increase chlorophyll concentration which implies nutrient transport comes from below as presumably supplied from Amazon and Orinoco inflows. Based on coastal zone colour scanner (CZCS) images, river discharge is among the factors that control pigment abundance in the Caribbean Sea through supply of nutrients from riverine outflows and upwelling systems.[23] From a simple mixing model, 60% of the freshwater in the Caribbean is from the Amazon[20] and

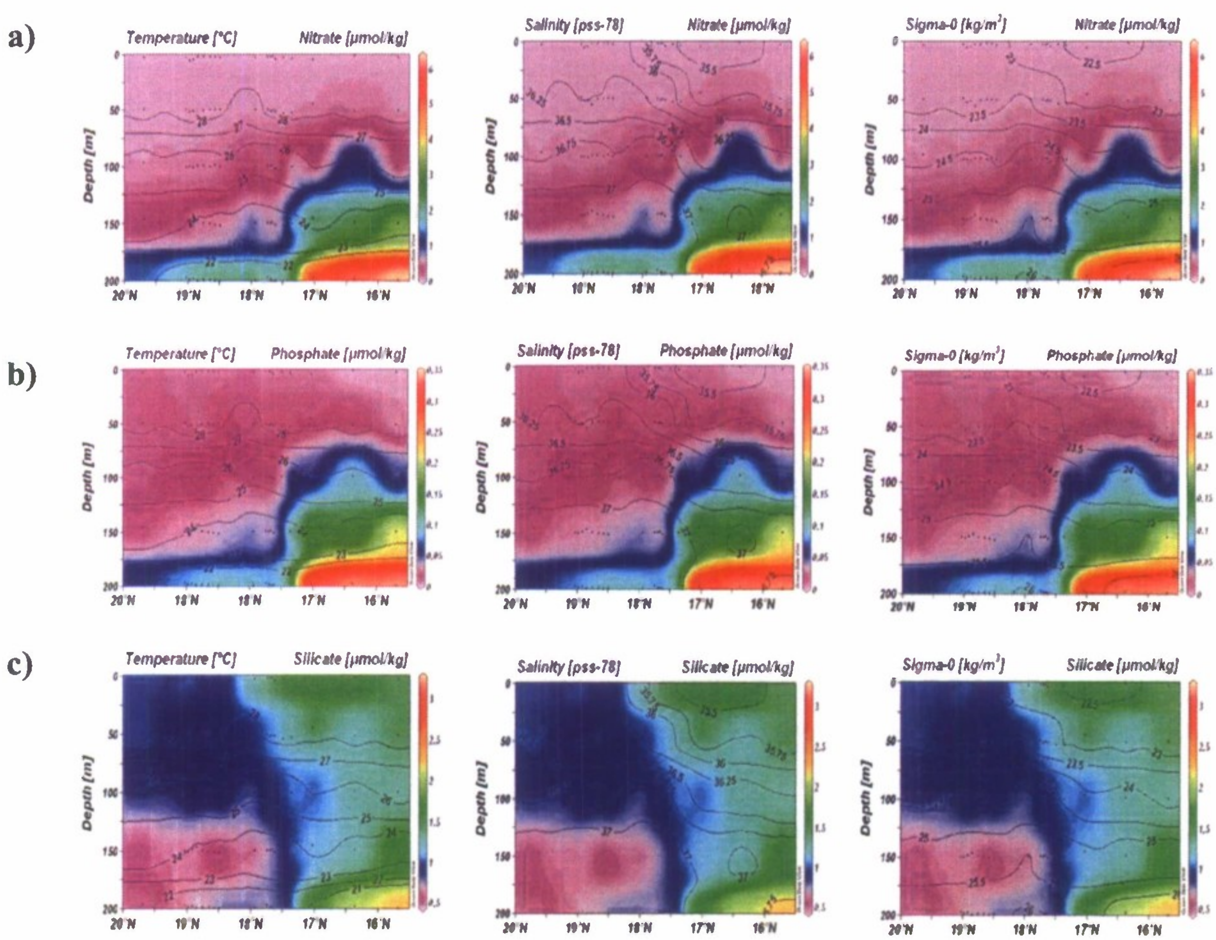

Fig 7: a) Nitrate (µmol/kg), b) Phosphate (µmol/kg) and c) Silicate (µmol/kg) transect overlaid temperature (°C), salinity (psu), and sigma-0 (µmol/kg) plots from World Ocean Circulation Experiment (WOCE) A-22 meridional transect (15–20°N, 66°W) in August 1997

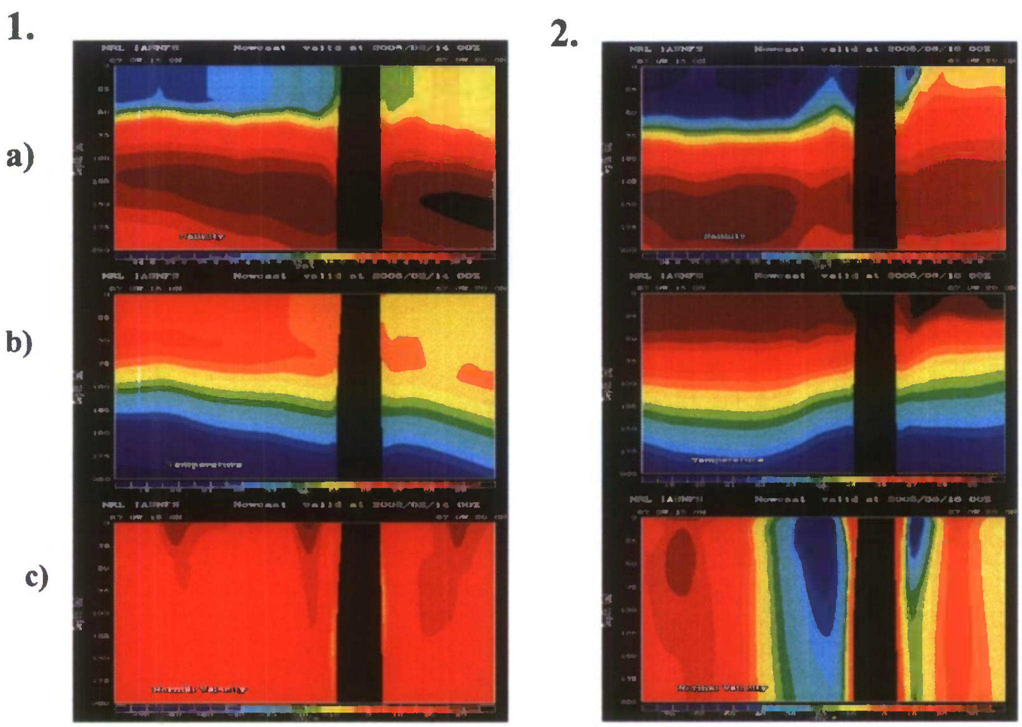

Fig 8: Meridional transects of a) Salinity (ppt), b) Temperature (°C) and c) Zonal velocity (cm/s) from the Experimental Real-Time Intra-Americas Sea Nowcast/Forecast System (IASNFS) along 15–20°N, 67°W for 1) February and 2) August 2005. [Data courtesy of Dr D-S Ko, NRL]

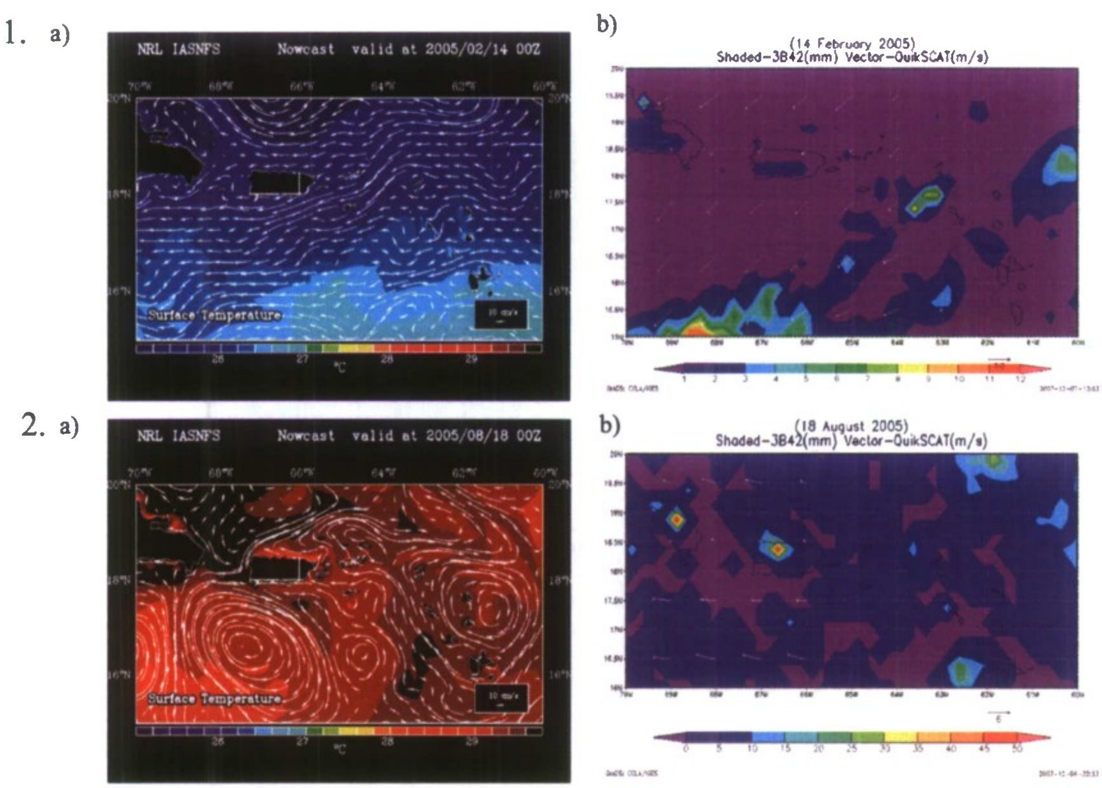

Fig 9: 1a, 2a) Sea surface temperature (°C) overlaid with sea surface velocity fields (cm/s) from IASNFS within the sub-domain (15–20°N, 60–70°W). 1b, 2b) Ocean surface winds and rain rate obtained by Quickscat and TRMM, respectively. Top maps during February 2005 and bottom maps during August 2005

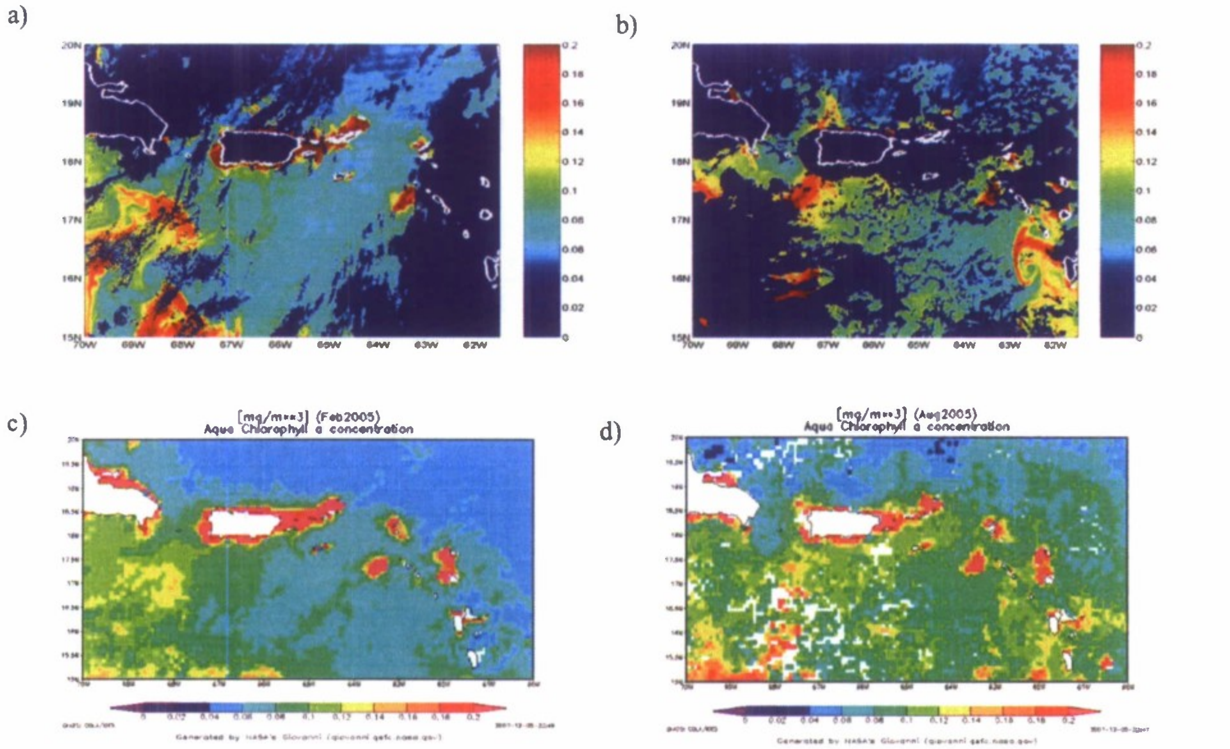

Fig 10: a-b) Daily (Ocean Color website of NASA acquired using MODIS Aqua level 2) and c-d) Mean monthly *chlorophyll a* concentrations (mg/m^3) during February and August 2005 within the sub-domain 15–20°N, 60–70°W (monthly mean *chlorophyll a* images with 9km spatial resolution MODIS Aqua monthly SMI (Standard Mapped Image) products from the Ocean Biology Processing Group (OBPG), GSFC

its influence at PR is strong during boreal winter and spring, while influence from the Orinoco is all year round.[24] The westward flows of surface currents intensified by Trade Winds during summertime in the vicinity of Caribbean coasts,[25] could play a key role in producing nutrients from the Amazon and Orinoco rivers. Additionally the jets formed from the opposing mesoscale eddies may concentrate the nutrients from these rivers and provide an episodic pulse of nutrients to the outer reefs of PR. However, the zonal wind stress associated with ITCZ (Inter-Tropical Convergence Zone) varies with season directly affecting coastal and open ocean upwelling and flow directions along the southern coasts.[22] Thus, seasonally wind patterns can vary nutrient supply to PR.

High silicate values and low salinity values reflect intrusion of Amazon and Orinoco river outflow carried into the Caribbean.[20] Frequent riverine water intrusions cause high vertical fluctuations in the upper 50m of the CaTS station. Shear-induced turbulence controls the vertical transport of nutrients into the surface.[26] This transport is unstable and occurs at a short-time scale.[27] Among identified possible natural sources of nutrients are upwelling,[28,29] anticyclonic eddy pumping,[30,31] biological nitrogen fixation,[32] atmospheric deposition,[33] shelf sediment disturbance,[34] sewage discharge,[35] and river[36] and terrestrial run-off.[37] Apart from strong biological assimilation in the upper 50m of the mixed layer, these suites of nutrients can be easily mixed and diluted through turbulent transport to nearby water masses,[28] thereby making it difficult to distinguish impacts from various sources.

Traditional low resolution nutrient surveys conducted on an annual, seasonal or even weekly schedule in a discrete sampling scheme may not detect some of these critical, anomalous, episodic events that may occur between sampling times. Internal waves or tidal fluctuations for instance, an important net nutrient source for subsurface corals, cannot be captured with a low sampling frequency (eg, less than hourly).[9,38] These physical and chemical processes can vary with space and time at various scales and errors associated with under-sampling can be considerable.[39] Thus, the need for a high resolution (less than an hour monitoring) nutrient sampling and measurement is required to document such tidal, diurnal and seasonal variations in reef systems. Since the upper 50m of the Caribbean has rapid vertical changes (particularly in the region of concern in this study) sampling has to be highly frequent within this depth.

Another important consideration is the spatial sampling. Irregular or non-equidistant sampling can be more effective and statistically sound than an equidistant and uniform sampling. This nutrient sampling strategy also important in eliminating bias[40] attributed to nutrient sources since different regions can have different nutrient potential sources and mechanism of delivery.

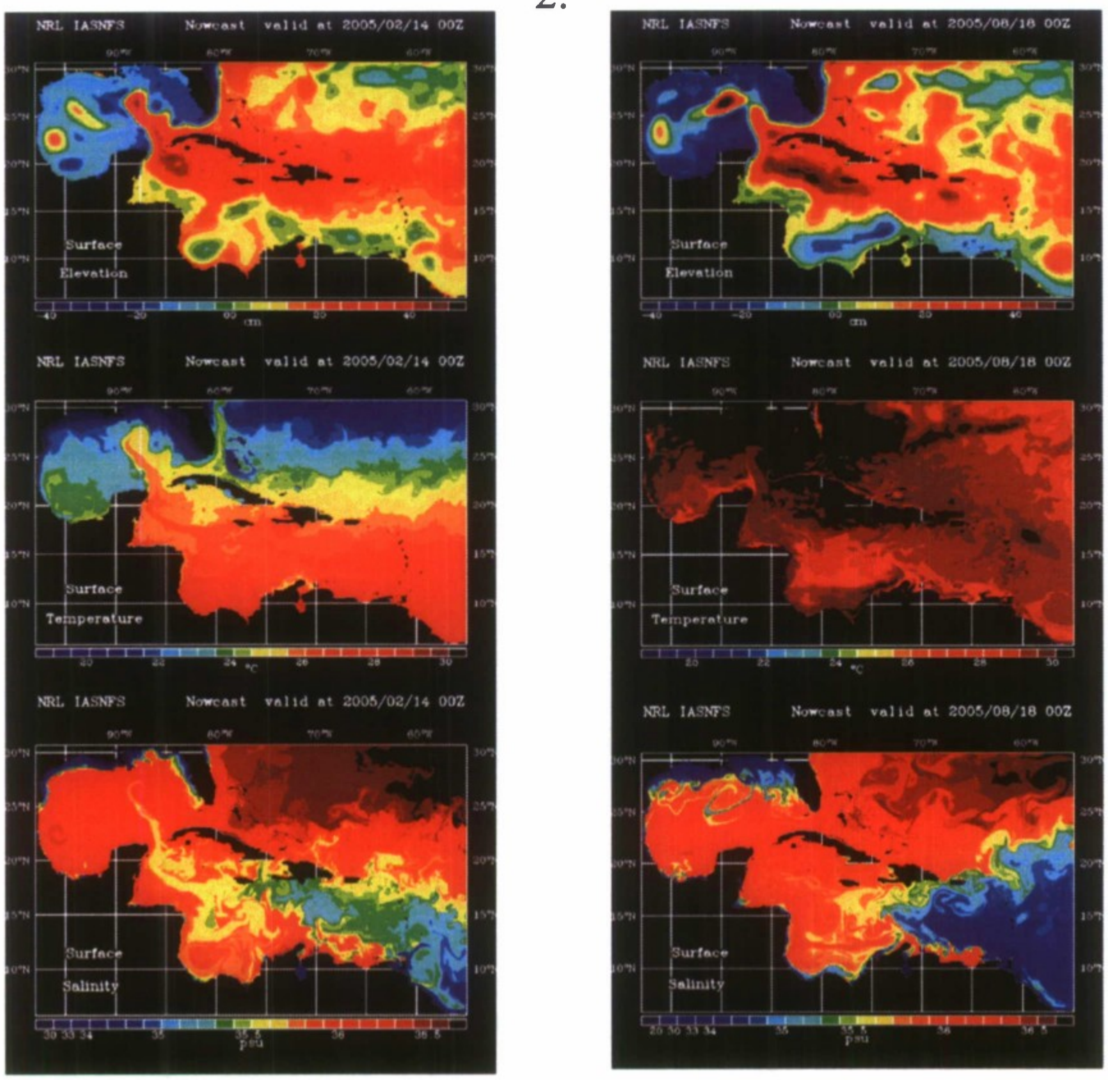

Fig 11: a) Sea surface height (SSH, cm), b) Sea surface temperature (SST, °C), c) Sea surface salinity (SSS, psu) which covers the sub-domain (15–20°N, 60–70°W) was obtained from the Experimental Real-Time Intra-Americas Sea Nowcast/Forecast System (IASNFS) from 1) February and 2) August 2005

CONCLUSION AND RECOMMENDATION

The predominant mechanism of nutrient delivery to PR, particularly at the CaTS station, is either via the wind-driven upwelling system or the meridional jet formed from two opposing eddies. The strong vertical fluctuation in the upper 50m demonstrates high anomaly in temperature and salinity and a strong negative correlation signal indicative of possible high variability in the vertical and horizontal nutrient advection to the euphotic zone. These vertical depth and the location jets and eddies observed in the Caribbean would be an area of interest to do high frequency sampling (eg, temperature, salinity, nutrient, and chlorophyll profiles).

These mechanisms and processes observed in the Caribbean are made possible from IOOS and COOS related information that are now readily available online. A new level of planning can now be employed to have a reconnaissance survey of a research site without significant manpower and financial requirement. More importantly, prior knowledge of the region of interest can provide important sampling strategy that can reduce sampling bias and aliasing.

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