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INVESTIGATION OF THE EFFECT OF SPACE VARYING WIND INPUT ON HYDRODYNAMIC MODELING IN MANILA BAY and LAGUNA LAKE

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ABSTRACT:

Surface water currents and waves are largely driven by wind forcing by inducing shear stress to the water surface. The circulations formed carry with it various materials and pollutants all over a large body of water like the Manila Bay and Laguna Lake. Considering the spatial and temporal variability of wind over the Bay and the Lake is essential to model the hydrodynamics of water more accurately. This study simulated bay hydrodynamics using high resolution space- and time-varying wind data from Weather Research Forecasting (WRF) as input and compared the results with using uniform-directed wind. The downscaled winds from WRF demonstrated patterns in agreement with the country's seasonal monsoon wind dynamics. Its effect on the bay hydrodynamics is more pronounced during the dry season as it changes the flow direction of water at the bay mouth. On the other hand, the hydrodynamic difference in circulation patterns for the lake was accentuated with a more defined clockwise gyre circulation during the wet season where prevailing winds are stronger. Thus, it is imperative to incorporate spatially varying wind input to accurately characterize the bay water movement. Results also showed that global weather inputs can be used in areas with scarce monitoring stations as long as they are validated.

1. INTRODUCTION

1.1. Effect of wind and surface pressure to coastal hydrodynamics

Wind is an important driver in generating surface water currents and waves especially in large bodies of water. It induces shear stresses to the water surface which creates deformation and flow. In the case of storms, atmospheric pressure gradients become more relevant in wave propagation. Thus, it is crucial to accurately depict wind stresses and mean sea level pressure as input to hydrodynamic models. (Bricheno et al., 2013). This means taking into account the spatial and temporal variability of these forcings.

Le et al. (2023) found the responses of the hydrodynamics of a lake under both spatially uniform and non-uniform wind fields to be significant. Their study used numerically downscaled wind inputs to a horizontal resolution of 333m. However, Clunies et al. (2017) study showed that water levels from spatially uniform wind were generally in better agreement with observations levels than predictions using varying wind fields with a 32-km resolution.

1.2. Weather Research Forecasting Model

The Weather Research and Forecasting (WRF) Model is a numerical weather prediction system designed for both mesoscale atmospheric research and operational forecasting applications Skamarock et al. (2008). It offers a wide range of meteorological applications across scales from tens of meters to thousands of kilometers. This allows for dynamical downscaling of coarse global atmospheric initial and boundary conditions to high resolution regional meteorological forcing data. Physical parameterization schemes determine the various assumptions by which the computations are done.

The use of this tool in the Philippines has been growing in recent years to study the effects of Urban Heat Islands (Oliveros et al., 2019), model precipitation (Acierto et al., 2015) and air pollution (Garcia et al., 2019)

1.3. The case for Manila Bay and Laguna Lake

Manila Bay is a natural harbor in the Philippines with an area of 2,000 km^2 and a coastline that is 190 km long. The National Capital Region is located at the eastern shore of the bay, the Provinces of Pampanga and Bulacan on the north, Bataan on the west, and Cavite on the south. Natural habitats such as mangroves, mudflats, seagrass and corals are found within the bay as well.

Laguna Lake, on the other hand, is the largest lake in the Philippines has a surface area of 900km^2 and an average depth of 2.5 meters. It has natural brackish waters brought by its interaction with Manila Bay through the tidally affected Pasig River from the west side.

The high socio-economic and environmental importance of Manila Bay and Laguna Lake has warranted extensive research of their hydrodynamics. However, the current distribution of local weather stations is insufficient to have a good representation of the spatial variability of meteorological information within the bay. This study aims to compare the performance of its hydrodynamic models which uses spatially uniform wind inputs to that of downscaled WRF space- and time-varying wind fields.

2. METHODOLOGY

2.1. WRF Model Setup

WRF v.3.9.1 was used to simulate meteorological inputs for this study. The model was configured with 3 one-way nested domains as shown in Figure 1. It has a horizontal grid resolution of 9 km, 3 km, and 1 km and grid spacing of 100x100, 101x101,

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and 121x101, respectively, where result from innermost domain (D3) will be used. The number of vertical layers is 50 with 16 levels below 1 km. WRF produces an hourly instantaneous data from 2017-2019, where the first 16 hours output is discarded and is treated as the model spin-up time. Initial and boundary condition used to drive WRF model were taken from NCEP GDAS/FNL Operational Model Global which has a spatial resolution of 0.25° and a temporal resolution of 6 hours. Table 1 presents the rest of the parameters used for microphysics and cumulus physics which were based on related literatures mentioned in Section 1.2.

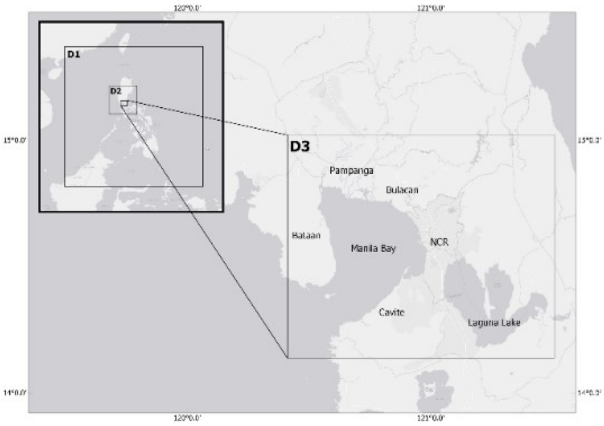

Figure 1. WRF simulation domains

WRF Model	
WRF Dynamical Solver	ARW
Domains	3
Nesting	Two-way, triply nested
Resolution	Domain 1: 25 km Domain 2: 5 km Domain 3: 1 km
Map Projection	Mercator
Temporal Resolution of Output Files	1-hour interval
Land Use	MODIS 2015
Initial Meteorological Data	NCEP FNL Operational Model Global Tropospheric Analyses Spatial Resolution = 1^{O} Temporal Resolution = 6 hours
Vertical Levels	30 with a top of 50 hPa.
Simulation Period	1200 UTC on 01 January 2017 1200 UTC on 01 January 2020
Microphysics	Purdue Lin Scheme
Cumulus Parameterization	Kain-Fritsch
Surface layer	Eta surface layer scheme
Land-surface model	Noah
Planetary boundary layer	Yonsei University (YSU) planetary boundary
Longwave radiation scheme	Rapid radiative transfer model (RRTM) longwaye
Shortwave radiation scheme	MM5 (Dudhia) shortwave

Table 1. WRF Parameterization

2.2. Hydrodynamic Modeling

The hydrodynamics of the integrated Manila Bay – Pasig River – Laguna Lake system was investigated by modelling using DELFT3D. Figure 2 shows the hydrodynamic modelling grid for the integrated model. The tide-influenced offshore dynamics at the mouth of Manila Bay served as the boundary condition. Other inputs to the model are the meteorological data (precipitation, evaporation, heat flux) which are time-series datasets derived from nearby local weather stations, and initial condition values (salinity, temperature, water level). The bed roughness (n=0.05 for Pasig River, n=0.03 elsewhere), water viscosity (1 m^2/s), and diffusivity (10 m^2/s affect the discharge capacity of Pasig River, the rate at which Laguna Lake is being drained by the river, and the mixing potential of the water in the system. These parameters were adjusted to calibrate the Manila Bay model.

Having discharge values assigned at watershed outlets resulting from a well-calibrated hydrologic model also helped in developing the hydrodynamic model. A hydrologic model of the Manila Bay area was developed with the help of the Soil and Water Assessment Tool (SWAT) and using secondary meteorological and topographic data from local weather stations and government offices.

Wind vectors were derived from the Weather Research and Forecasting (WRF) model to consider temporal and spatial difference across the model domain.

Residual flows or tidally averaged flows were computed from hydrodynamic results by averaging two weeks of current velocity vectors for the entire model domain. This was done with the help post-processing tool (QUICKPLOT) of the Delft3D software.

For the integrated Manila Bay – Pasig River – Laguna Lake system, the water level at Laguna Lake is indicative of the water balance at the Lake, including its exchange of water with Manila Bay through Pasig River. The simulated water levels at Laguna Lake showed a good correlation with the actual observed water levels, with a root-mean-square-error value of 0.2 and an R-squared value of 0.87 for the 3-yr simulation (2017-2019).

The hydrodynamic simulation results were validated using Project MapABLE's Sentinel-3-derived images of the distribution of chlorophyll-a and total suspended matter across Manila Bay.

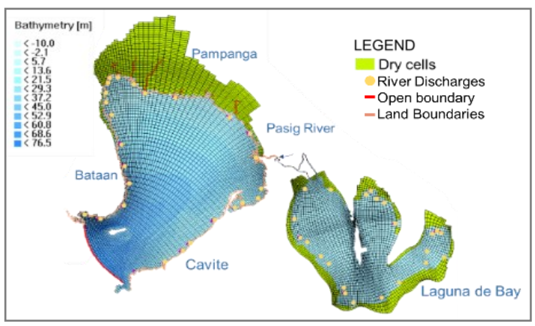

Figure 2. Hydrodynamic modeling grid.

3. RESULTS AND DISCUSSION

3.1. Wind Vectors

This section discusses the wind speed and direction data extracted at 10 meters above the surface with a temporal resolution of 15 minutes. Wind was given priority since it is a major forcing for the hydrodynamic model. Figure 3 shows the mean monthly wind velocity in domain 3. The color gradient indicates the magnitude of the wind, faster winds are on the red side of the color spectrum while those in the blue side

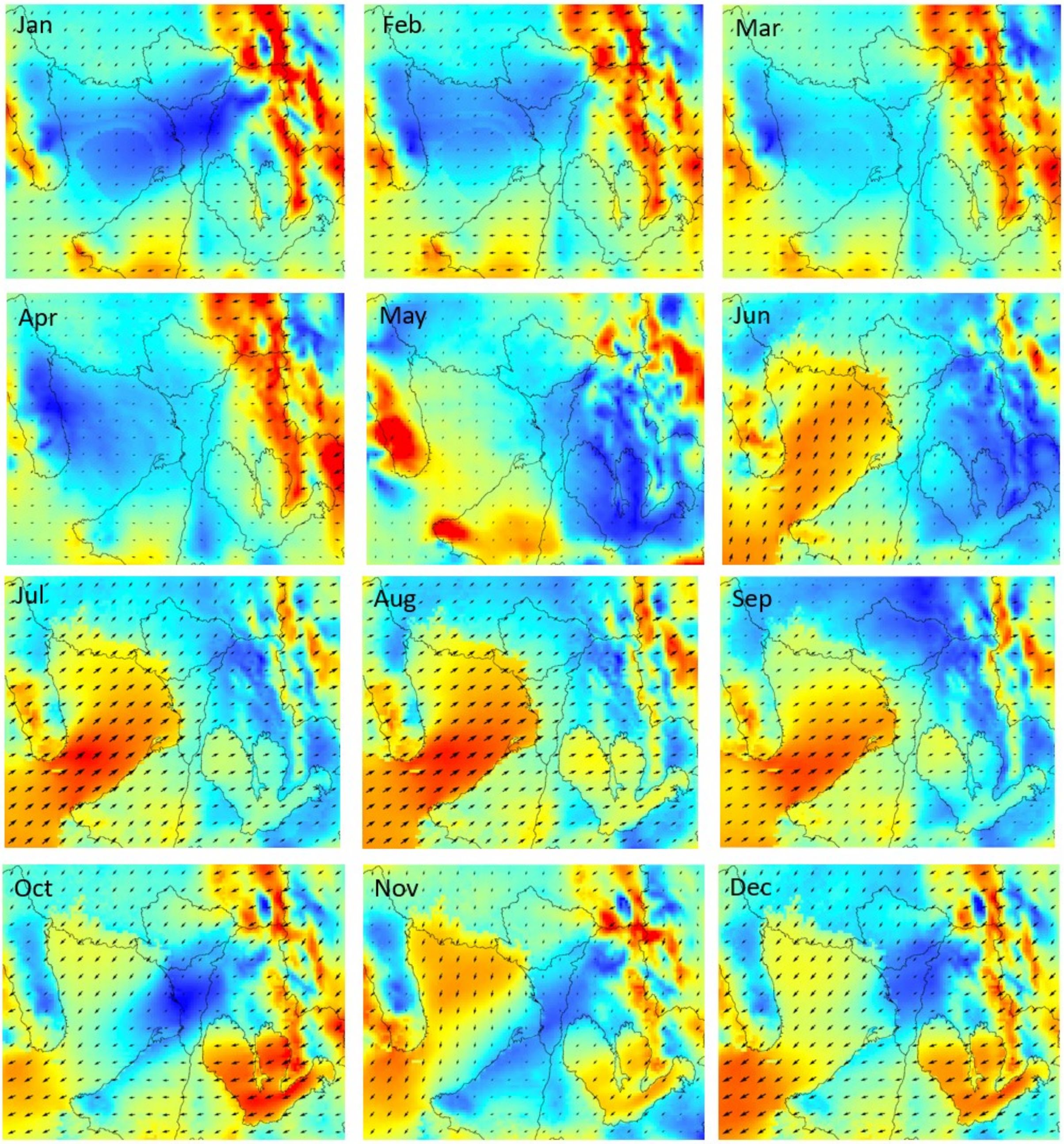

Figure 3. Mean Monthly Wind Velocity from WRF

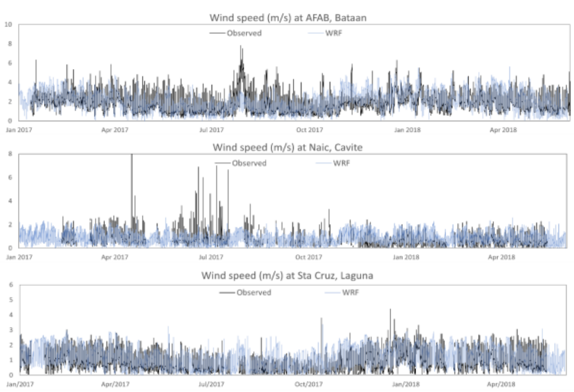

Figure 4. Wind speed validation at (a) Freeport Area of Bataan (b) Naic Campus, Cavite (c) Sta Cruz, Laguna

Stations	MAE	RMSE
AFAB, Bataan	0.92723	0.00295
Naic, Cavite	0.65548	0.00387
Sta. Cruz, Laguna	0.67798	0.01043

Table 2. Summary of Statistical Parameters

indicate slower winds. The arrows shows the direction of the wind at a point.

Variation of wind speed and direction is evident over space and time. Results agree with the country's wind dynamics which is generally governed by the Southwest Monsoon (Habagat) from June to October and the Northeast Monsoon (Amihan) from November to May. Manila Bay have faster winds from June to September, while Laguna Lake during October to December. Monsoon transition occur on May causing northward winds. Strong winds can also be observed at the eastern boundary of

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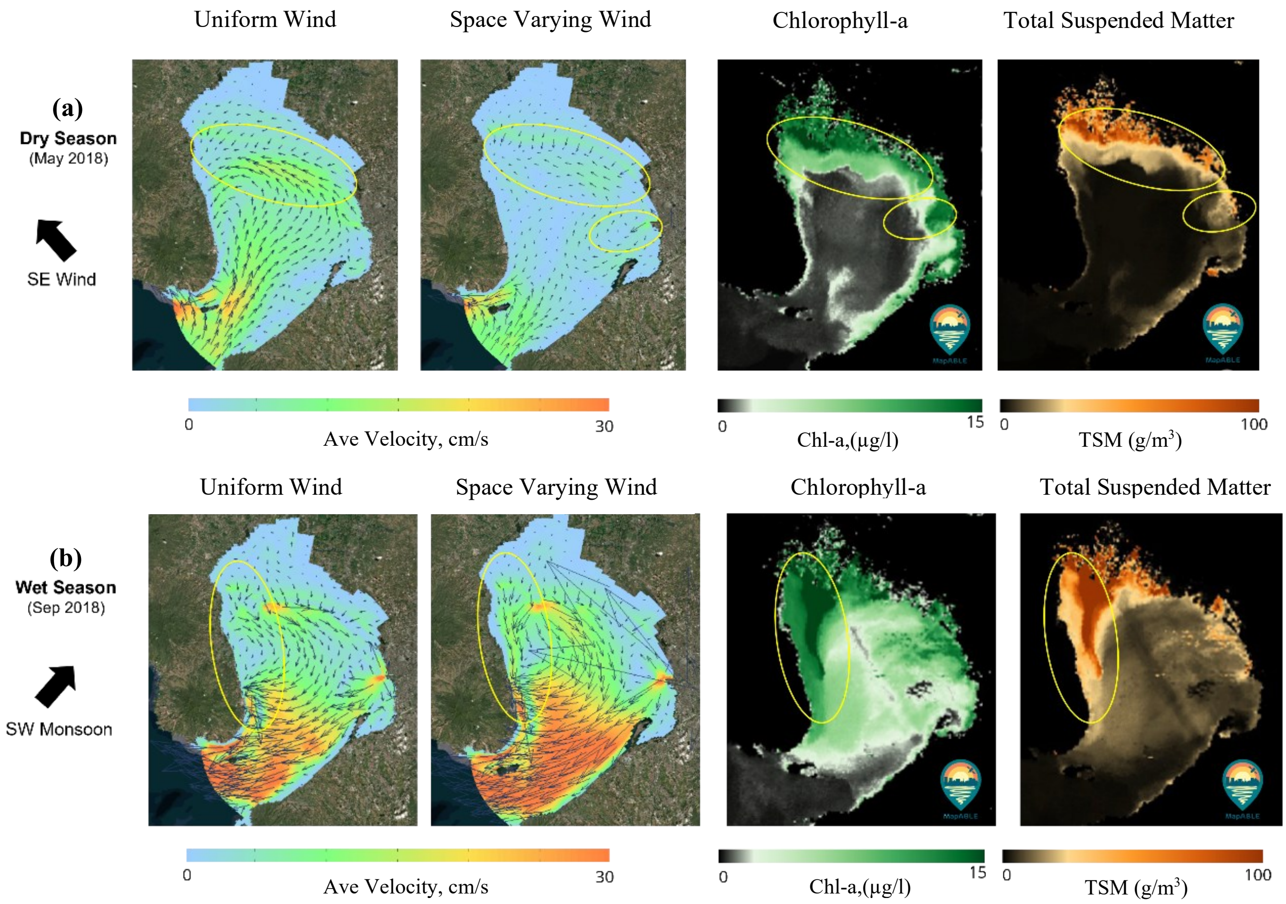

Figure 5. Near Surface Flow Velocity for (a) Dry Season and (b) Wet Season in Manila Bay with Satellite Image Validation

the watershed where the Sierra Madre is located. Mountains affects wind flow in a phenomenon known as orographic effect.

These data were further validated with field data using the following monitoring stations: Freeport Area of Bataan (FAB), Naic Campus Cavite, and Sta. Cruz Laguna. It was observed that wind speeds from WRF have significant deviations from observed wind speed. It was hypothesized that this is due to the difference in elevation at which data was collected. Simulated winds were extrapolated to the height of their respective stations to eliminate this variable. The Power Law was used for conservative yet reasonable estimates (Peterson & Hennessey, 1978).

$$\frac{v_2}{v_1} = \left(\frac{z_2}{z_1}\right)^{\alpha} \quad (1)$$

where v_1 = velocity in meters per second at height z_1
v_2 = velocity at height z_2
α = wind shear

The results now show a good correlation between the simulated and observed wind data as shown in Figure 4. The statistical parameters used for the analysis are the Mean Square Error (MSE) and the Root Mean Square Error (RMSE) are presented in Table 2.

The model captures the general trend of the observed data in all monitoring stations. However, it fails to simulate sudden peaks in the actual wind observations as seen in August 2017 at FAB Station and between April and July 2017 at Naic Station.

3.2. Effect on near-surface flows

The space varying wind generated from WRF was applied to the hydrodynamic model as wind forcing. Prior to this, only uniform prevailing wind was used as model input. A comparison between the simulated flows from the two setups was made to assess the influence of space varying wind to Manila Bay and Laguna Lake hydrodynamics.

3.2.1. Manila Bay: Flow velocity was averaged over two tidal cycles or fourteen (14) days, as shown in Figure 5 to show the general current pattern in the Bay. This is also known as Residual Current Flow Analysis. During the dry season, both cases show that water enters the bay at the Cavite side of the bay mouth, while flushes out at the Bataan side. A counterclockwise circulation can be observed, however, flows generated with space varying wind input were slower compared to that with uniform wind input. The currents at the shallower areas in the north of the bay move with the prevailing SE winds.

A clockwise circulation flushing out of Manila Bay is seen during the wet season. The flow direction tends to be opposite of the prevailing wind which is coming from the southwest. Discharges from Pampanga River in the north and Pasig River in the east contributed to this current pattern that has higher magnitudes going as high as 30 cm/s. In this case, space varying wind generated stronger flows than that of uniform wind.

These flows have the capacity to move materials in the Bay. Another way to validate our results is to look at satellite images of water quality parameters and see if their movement patterns match that of the residual flows. We used wet season and dry

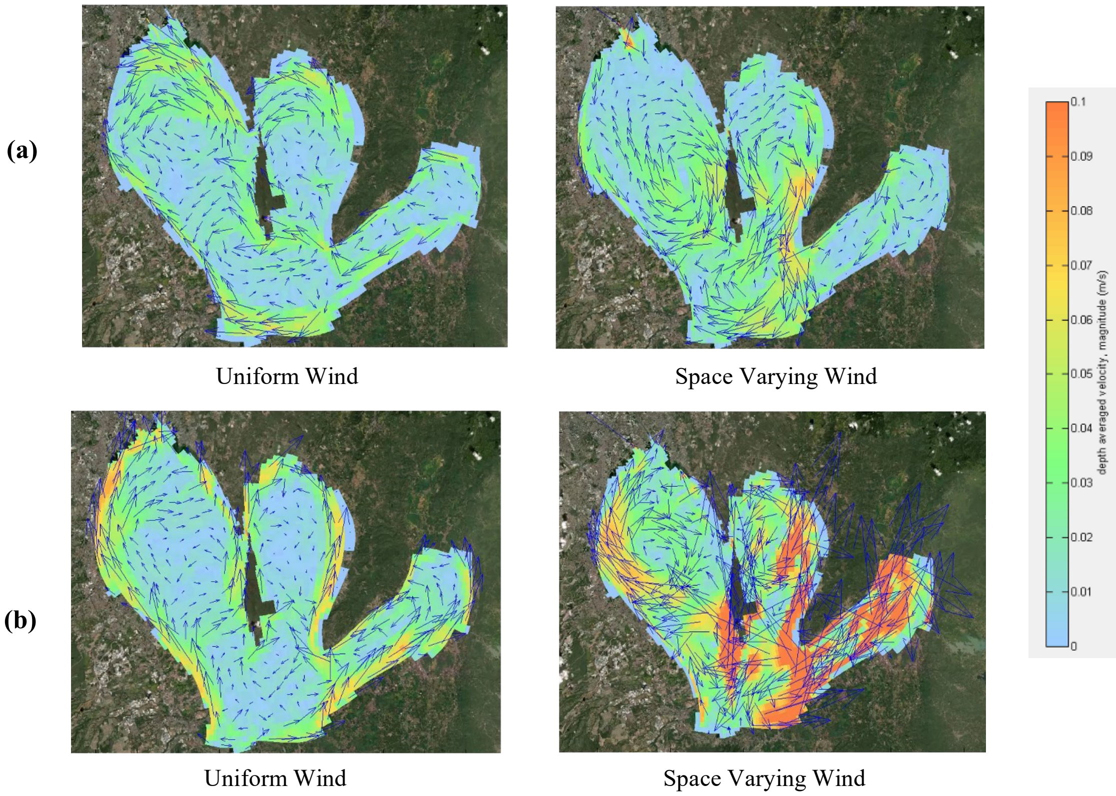

Figure 6. Near Surface Flow Velocity for (a) Dry Season and (b) Wet Season in Laguna Lake

season distributions for chlorophyll and total suspended matter generated by Project MapABLE through remote sensing as shown in Figure 5.

There is a limited extent of dispersion of suspended matter during the dry season which are concentrated at the NW part of the bay. It's worth noting that with WRF winds, flows were slower which might have caused the limited dispersion. Materials from the east side of the bay are dispersed to the SW direction, following the flow pattern of residual currents.

Both TSM and Chl-a are more dispersed during the wet months, and concentrations from Pampanga spread further to the south. If you look a bit closer at the average flows, the uniform-wind-induced circulation was not able to capture the flows that could have allowed this southward dispersion to happen.

3.2.2. Laguna Lake: Shallow water currents and waves are primarily driven by wind. In Figure 6, space varying wind generated faster moving flows with a clockwise gyre circulation compared to that of uniform wind which had a counterclockwise pattern. The stronger flows for uniform wind are evident along the lakeshores while space varying winds allow at the middle of the Lake.

The difference in circulation patterns was accentuated during the wet season where prevailing winds are stronger. Faster moving currents with speeds ranging between 8 to 10 cm/s were prevalent in the middle and east lake embayment.

Bed shear is an interesting parameter that describes the hydrodynamics of lake. Higher magnitudes of bed shear stress causes resuspension of sediments or nutrients from the bottom of the lake, which ultimately mixes with near surface water due to horizontal and vertical water movement. Increased bed shear stress can be observed at multiple river outlets around the lake, especially at the Pasig River mouth, in both wind profiles and season. The west and central bays bed shear stresses increased when space varying wind was applied for the dry season (Figure 7). During the wet season, the central and east bay have higher bed shear stress with space varying wind input.

Incorporating spatially varying wind input improved characterization of the lake water movement. Global weather models should be considered in areas where monitoring stations are scarce as long as they are validated. The synthetic space varying wind input increases the model's capacity for decision support in the resource management of the Manila Bay and Laguna Lake.

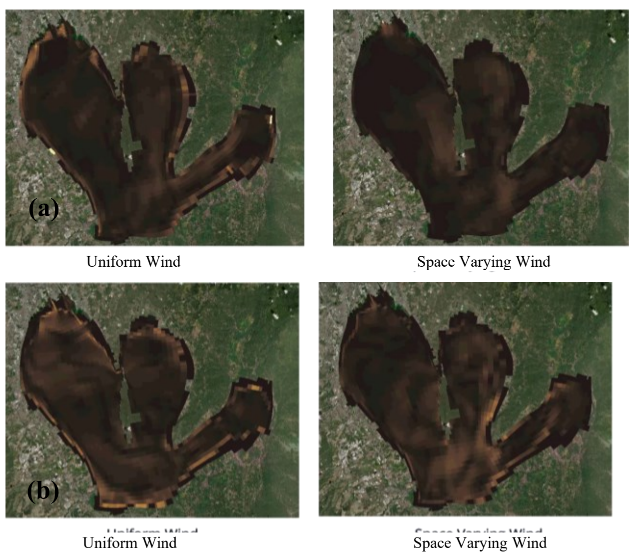

Figure 7. Bed Shear Stress for (a) Dry Season and (b) Wet Season in Laguna Lake

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4. SUMMARY AND CONCLUSIONS

The study investigated the use of space varying wind field as input to the hydrodynamic models of Manila Bay and Laguna Lake and compared to results that employ spatially uniform wind. The Weather Research Forecasting (WRF) Model was used to downscale global wind inputs to 1km resolution. Delft3D was applied to model lake and bay hydrodynamics for the period 2017-2019. Space varying winds demonstrated patterns in agreement with the country's seasonal monsoon wind dynamics. Results showed that applying spatially varying wind significantly affected the hydrodynamic circulations in Manila Bay and Laguna Lake. Stronger flows and more pronounced circulation patterns were produced for the Wet Season, especially for Laguna Lake where wind forcing is considered as a primary driver. Results for Manila Bay were validated using three monitoring stations and satellite images of Chlorophyll and Total Suspended Matter by Project MapABLE. Bed shear stress in Laguna Lake was described and showed more mixing in central and east bays for space-varying wind. It is imperative to incorporate spatially varying wind input to accurately characterize the water movement in the Bay and the Lake. Downscaled global weather models can fill the gaps of wind monitoring and improve a hydrodynamic model's capacity for decision support in the management of Manila Bay and Laguna Lake.

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