

Study of wind speed attenuation at Kavaratti Island using land-based, offshore, and satellite measurements

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Abstract- The role of dense coconut palms in attenuating the wind speed at Kavaratti Island, which is located in the southeastern Arabian Sea, is examined based on land-based and offshore wind measurements (U_{10}) using anchored-buoy-mounted and satellite-borne sensors (QuikSCAT scatterometer and TMI microwave imager) during an 8-year period (2000-2007). It is found that round the year monthly-mean wind speed measurements from the Port Control Tower (PCT) located within the coconut palm farm at the Kavaratti Island are weaker by 15-61% relative to those made from the nearby offshore region. Whereas wind speed attenuation at the island is ~15-40% in the mid-June to mid-October south-west monsoon period, it is ~41-61% during the rest of the year. Wind direction measurements from all the devices overlapped, except in March-April during which the buoy measurements deviated from the other measurements by $\sim 20^\circ$. U_{10} wind speed measurements from PCT during the November 2009 tropical cyclone “Phyan” indicated approximately 50-80% attenuation relative to those from the seaward boundary of the island’s lagoon (and therefore least influenced by the coconut palms). The observed wind speed attenuation can be understood through the theory of free turbulent flow jets embodied in the boundary-layer fluid dynamics, according to which both the axial and transverse components of the efflux of flows discharged through the inter-leaves porosity (orifice) undergo increasing attenuation in the downstream direction with increasing distance from the orifice. Thus, the observed wind speed attenuation at Kavaratti Island is attributable to the decline in wind energy transmission from the seaward boundary of the coconut palm farm with distance into the farm. Just like mangrove forests function as bio-shields against forces from oceanic waves and storm-surges through their large above-ground aerial root systems and standing crop, and thereby playing a distinctive role in ameliorating the effects of catastrophies such as hurricanes, tidal bores, cyclones, and tsunamis, the present study provides an indication that densely populated coconut palms and other tall tree vegetation would function as bio-shields against the damaging effects of storms through attenuation of wind speed.

I. INTRODUCTION

Dense coastal tree and sand dune vegetation forests have iconic status as natural ecosystems that function as living dykes [1]. The protective buffering function of tree vegetation against a wide variety of storm events is well known [2], [3]. The role played by coastal tree vegetation in protecting the lives of people during the 26 December 2004 Indian Ocean

tsunami is well recognized [4]. The theme of the present study is to examine the extent of wind speed attenuation at Kavaratti Island in the Lakshadweep archipelago in the eastern Arabian Sea and the role played by dense coconut palms and the associated canopies in causing the observed attenuation.

II. DESCRIPTION OF STUDY AREA

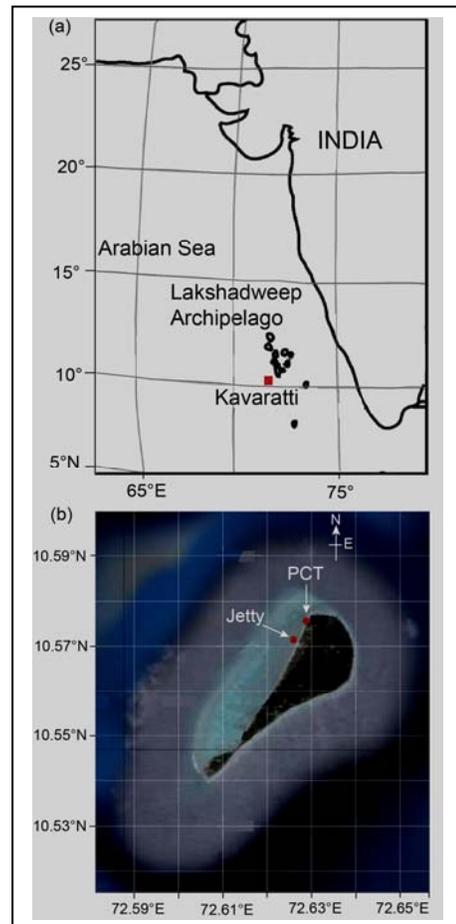


Fig. 1. Location map of wind measurements at Kavaratti Island

Kavaratti Island (Fig. 1), 4.22 km² in area, abounds primarily in dense coconut palms, interspersed by other tree vegetation (Fig. 2) and therefore provides an excellent experimental setting to examine the role of tree vegetation, particularly coconut palms, in wind speed attenuation.



Fig. 2. Dense coconut palms interspersed by other tree vegetation at Kavaratti Island

III. DATA AND METHODS

Wind speed attenuation at Kavaratti Island is examined based on an 8-year (2000-2007) wind measurements (U_{10}) from the island as well as those obtained from offshore anchored buoys and satellite-borne sensors. Such measurements permit reliable estimate of attenuation of wind speed at Kavaratti Island, presumably under the influence of dense coconut palms and other tree vegetation.

A. Kavaratti Island measurements using NIO-AWS

Surface meteorological measurements at this island were carried out using an autonomous weather station (AWS), designed and developed at the Indian National Institute of Oceanography (NIO) [5]. Based on operational requirements, the AWS was installed on the top terrace of the Port Control Tower (PCT) inside the coconut palms at 10 m elevation from mean sea level (MSL). The NIO-AWS provides digital data (10-minutes average of 60 samples collected at 10 seconds interval). Wind is vector-averaged. Gust (i.e., the largest wind speed amongst an ensemble of 60 samples that are measured during the 10-minute sampling span) is also recorded.

Wind measurements, which are less influenced by the luxuriant growth of coconut palms and other foliage spread over the Island, were collected from a second NIO-AWS installed near the external boundary of the lagoon, distant ~220 m from the shore at an elevation of 10 m from MSL. Intensified wind flow that occurred over Kavaratti Island in association with a strong cyclonic storm, named *Phyan*, during 9-12 November 2009 [6] provided a fortuitous opportunity to examine the wind speed records that are less influenced by the island vegetation.

B. Off island measurements from anchored-buoy

In the anchored buoy-mounted AWS, wind measurements ~24 km away from PCT are made at 3 m height from MSL at 1-s interval and averaged over 10-minutes at 3 h interval.

Wind measurements at 10 m height from MSL (i.e., U_{10}) are derived based on the power-law wind profile using the formula $U_{10m} = U_{3m} \times (10/3)^{0.128}$ in which U_{3m} is the wind measured by the buoy at 3m height from MSL [7], [8].

C. Off island measurements from QuikSCAT-scatterometer

QuikSCAT satellite-borne Ku-band scatterometer measures winds with a nominal spatial resolution of 25 km. Twice-daily observations are made at ~06 and 18 h local time for satellite's ascending and descending passes, respectively. The accuracy specified for QuikSCAT derived wind speed is better than ± 2 m/s within the range 3–30 m/s. The direction accuracy within the speed range 3–30 m/s is better than $\pm 20^\circ$. Measurements were made ~37 km away from PCT to avoid land contamination. Wind observations that fell within the 10-minutes window from the QuikSCAT measurements were used because the NIO-AWS recorded vector-averaged wind speed at 10-min interval.

D. Off island measurements from TRMM-Microwave Imager (TMI)

TMI provides only wind speed (U_{10}) and no direction. U_{10} measurements derived from 10.7 and 37 GHz channels at 12-hour interval are considered in the present study. The closest TMI cell on the sea surface is centered at ~60 km away from PCT.

IV. RESULTS

Land-based wind measurements at Kavaratti Island are examined against nearby offshore wind measurements. The geographical locations of the buoy, QuikSCAT measurement cell, and TMI measurement cell used in the present study are approximately 24 km, 37 km and 60 km, respectively, from PCT. For the purpose of comparative evaluation of wind measurements from the various devices, monthly-mean wind speeds are used so that the inferences made are least biased by short-term disturbances/scatter in the wind fields. Only those measurements which are made simultaneously have been picked for analysis. All the various in-situ and remote measurement devices used in the present study exhibit good direct correlation in wind speed and direction measurements with R^2 in the range 0.67-0.89.

Monthly-mean wind speed measurements indicate that whereas buoy-based AWS wind measurements (AWS_{buoy}) and QuikSCAT-based wind measurements (QS) compare reasonably well (within ± 0.4 m/s), the island PCT winds are attenuated by ~2-3 m/s (Fig. 3). The percentage attenuation of monthly-mean wind-speed measurements at Kavaratti Island relative to the nearby offshore wind speed measurements from QuikSCAT, anchored buoy-mounted AWS, and (TMI) are in the range of approximately 31-58%, 25-57%, and 15-61%, respectively (Fig. 4). Whereas the attenuation of monthly-mean wind-speed measurements at Kavaratti Island is ~15-40% in the mid-June to mid-October south-west monsoon

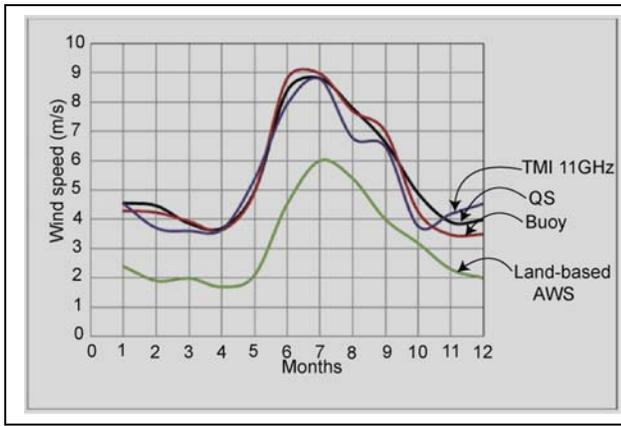


Fig. 3 Comparison of monthly-mean wind speed measurements corresponding to each of the 12 months obtained from (1) AWS at Kavaratti Island (PCT) and offshore of Kavaratti Island using (2) buoy-mounted AWS, (3) QuikSCAT satellite scatterometer, and (4) TMI; indicating attenuation of land-based wind speed measurements.

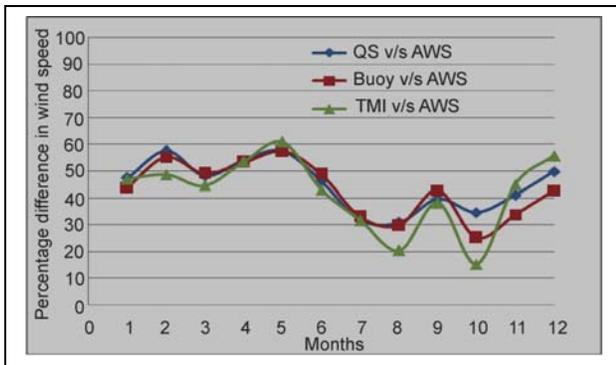


Fig. 4 Comparison of percentage under-estimation of monthly-mean wind speed measurements corresponding to each of the 12 months obtained from Kavaratti Island (PCT) relative to nearby offshore measurements using (1) QuikSCAT, (2) buoy-mounted AWS, and (3) TMI.

period (when the largest wind speed prevails), it is ~40-60% in the rest of the year (when the wind speed is relatively weaker). The relatively larger attenuation observed in association with weaker wind regime is a consequence of the inability of satellite-based remote measurements to detect smaller winds, which in-situ measurements are capable of detecting.

Comparison of combinations of wind speed ratios (QS/AWS_{land} , AWS_{buoy}/AWS_{land} , QS/AWS_{buoy}) against land-based wind speeds at Kavaratti Island (PCT) during the study period (Fig. 5) indicates that all these ratios decrease fast in the weaker wind speed band (1-2.5 m/s). However, the rate of decrease of this ratio becomes considerably slower beyond 2.5 m/s. The relative dominance of QS/AWS_{land} and

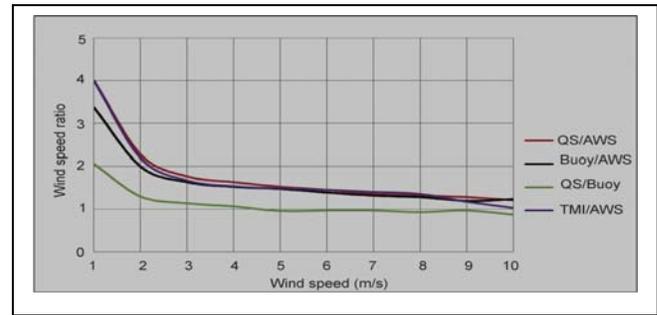


Fig. 5 Comparison of combinations of wind speed ratios against land-based wind speeds at Kavaratti Island (PCT), indicating attenuation of land-based wind speed measurements.

AWS_{buoy}/AWS_{land} over QS/AWS_{buoy} is noteworthy. These results also indicate attenuation of land-based wind measurements, with dominant attenuation occurring in the weaker wind speed band (1 - 2.5 m/s) and much reduced attenuation beyond 2.5 m/s. Near-unity value for QS/AWS_{buoy} beyond 3 m/s indicates excellent match between QuikSCAT-based and buoy-based wind speed measurements beyond 3 m/s. However, this feature deteriorates faster towards lower wind speeds. The offshore to onshore wind speed ratio decreases with increasing wind speed. The ratio varies from ~2-4 in case of light winds (1-4 m/s) to ~1 for AWS winds >4m/sec. Fig. 6 shows inter-comparison of wind direction measured from Kavaratti Island (PCT) using NIO-AWS, with the offshore buoy measurements, and QuikSCAT scatterometer measurements (QS).

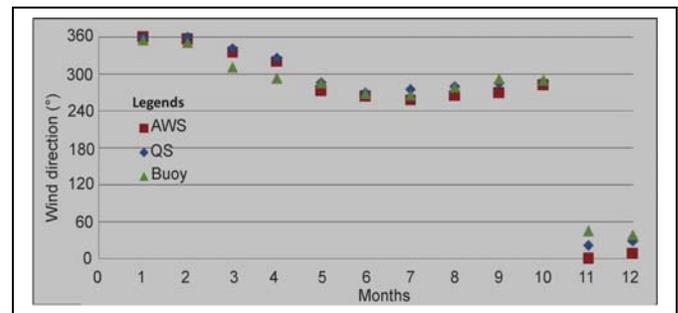


Fig. 6 Inter-comparison of wind direction measured from Kavaratti Island (PCT) with those made from offshore of Kavaratti Island using buoy-mounted AWS, and QuikSCAT scatterometer (QS).

Polar- and stick-plots of wind flows over Kavaratti Island recorded by the two NIO-AWS installations (one at the lagoon and the other at PCT) during the passage of tropical cyclonic storm *Phyan* in November 2009 reveals a clear indication of the wind attenuation at PCT (Figs 7 and 8). Ratio of wind speed measurements from the island's lagoon and the PCT (Fig. 9) reveals that the former is generally twice the latter, thereby indicating ~50% attenuation in the wind measurements from PCT. However, during the cyclone this ratio shot up to ~5, corresponding to 80% attenuation in the

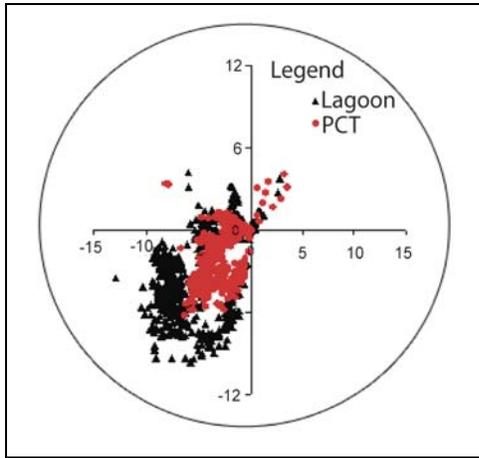


Fig. 7 Polar plot of wind flows over Kavaratti Island during the passage of tropical cyclonic storm *Phyan* in November 2009, recorded by NIO-AWS installations at the lagoon and PCT at Kavaratti Island.

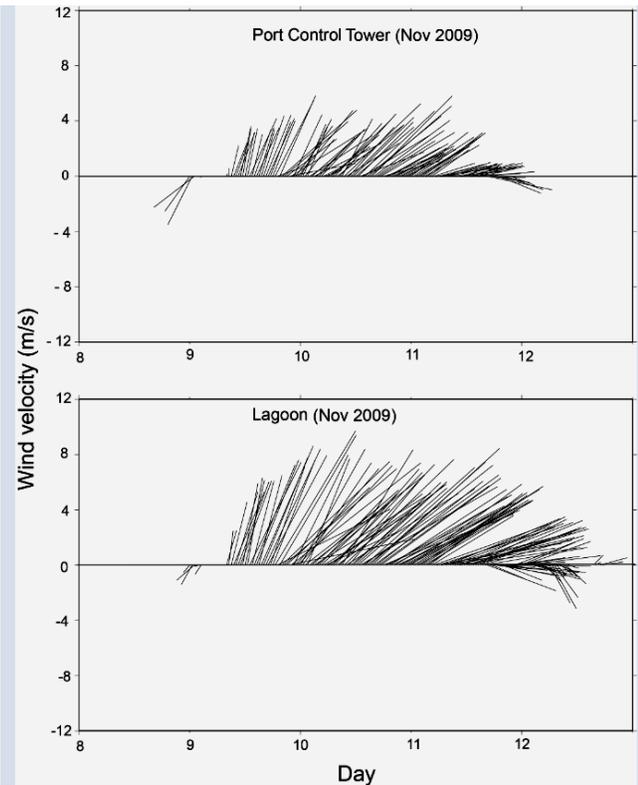


Fig. 8 Stick plot of wind flows at Kavaratti Island during the passage of tropical cyclonic storm *Phyan* in November 2009, measured at PCT (located among tree vegetation) and at the island's lagoon (located away from tree vegetation), indicating wind speed attenuation by tree vegetation.

PCT measurements. For a short while during the cyclone, this ratio dropped to <1 , thereby indicating amplification during a small interval of the cyclone. Comparison of percentage

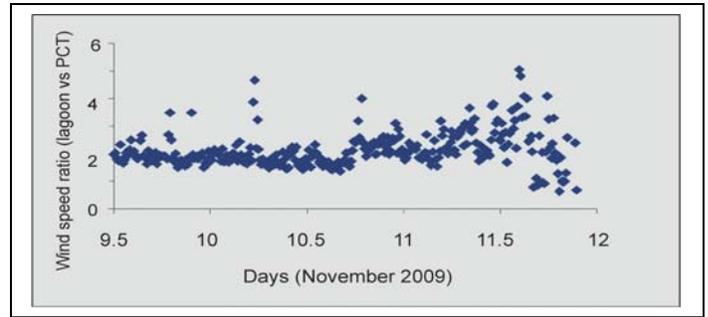


Fig. 9 Ratio of U_{10} wind speeds measured from Kavaratti island's lagoon and those from PCT (inside coconut palms) during tropical cyclone *Phyan*. Only wind speeds ≥ 1 m/s are used to estimate the ratio.

attenuation of PCT wind speeds relative to the lagoon wind speeds indicate that stabilized attenuation happens for lagoon wind speeds exceeding 2.5 m/s (Fig. 10). Wind speed ratio (lagoon/PCT) versus lagoon wind speed does not indicate a clear relationship between them (Fig. 11).

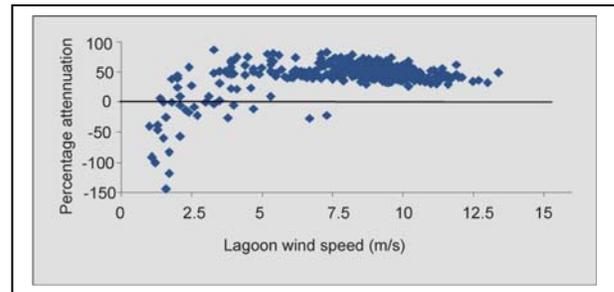


Fig. 10 Percentage attenuation of PCT wind speeds relative to lagoon wind speeds

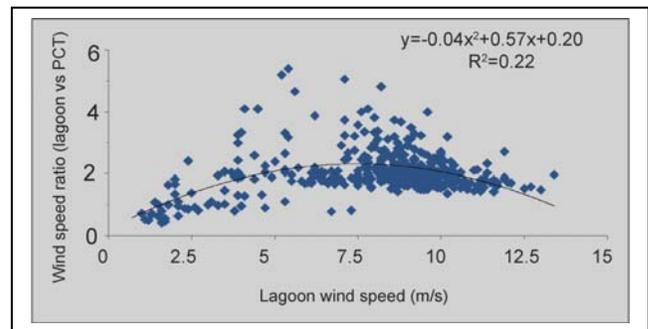


Fig. 11 Relationship between wind speed ratio (lagoon/PCT) and the lagoon wind speed

V. DISCUSSION OF RESULTS

Large protrusions on islands have been found to modify/influence the nearby wind field in varying degrees. For example, South Georgia Island in the South Atlantic Ocean is found to act as a barrier to the surface winds. QuikSCAT images reveal that winds blocked by the

mountains in this island produces a long "shadow region" of low winds on the downwind side of the island stretching over hundreds of kilometers [9]. On the other hand, excellent agreement between wind measurements from a weather station in Macquarie Island (approximately 34 km long, 5 km wide, with an area of $\sim 128 \text{ km}^2$) in the southern Pacific Ocean (where strong westerly winds prevail) and QuikSCAT were reported. The comparison showed negligible bias (-0.02 m/s). One of the reasons for such an excellent agreement between land-based and satellite-derived wind measurements was attributed to the absence of trees on this island.

A. Influence of dense tree vegetation

Wind speed attenuation capacity of different vegetation types has been found to differ from one type of vegetation to another, primarily because of differences in canopy shape, leaf density, stem size, etc. Wind speed attenuation within a canopy is intimately linked to the tree structure, trunks, and foliages. The complex arrays of leaves, branches and other components of a canopy of vegetation form a complicated lower boundary for atmospheric airflows (i.e., winds). Winds penetrating through tree vegetation and the associated foliages are subject to substantial energy loss. Consequently, the mean wind speeds within a forest canopy are considerably lower than those over bare soil with short vegetation [10]. An overview of the wide variety of numerical models used to describe canopy flow is given in [11]. The analytical models for air flow within plant canopies described in the literature equate the canopy to a two-dimensional distribution of infinitesimal momentum sinks corresponding to the canopy surface. Mathematical models for the flow of air through vegetation (i.e., canopy flow models) have either been based on empirical relationships or solutions of the equations of motion using a technique for closure, essentially utilizing the conventional eddy viscosity or mixing-length hypothesis in order to parameterize the transport of momentum directly. However, canopy flow models that are constructed based on the later method were only partially successful because of some short-comings in the model [12; 13; and 14].

Aerodynamic factors play an important role in attenuating wind speeds and the forces exerted by the winds inside and in the immediate neighborhood of the conglomeration of tree vegetation [15]. Atmospheric airflow in canopy structures tends to be strongly complex, three-dimensional, inhomogeneous, and turbulent. Accurate prediction of the pattern of airflow through a canopy is difficult due to the species-specific complexity in the structure of vegetation elements and the complex process of air momentum transport within the canopy. The complexity of airflow dynamics is compounded by the spatial variability of the canopy elements, particularly interplant spacing. However, the general agreement among researchers is that there is an overall reduction of air velocity through the canopy due to flow resistance by the canopy elements and that the extent of reduction depends primarily on canopy density and architecture. Like any solid obstacle, the tree acts as an eddy generator and therefore the maximum turbulence appears

behind the tree with a magnitude which far exceeds the undisturbed level [16]. The general agreement on the sensitivity of airflow velocity to the canopy density and architecture has been corroborated in several recent studies (e.g., [17] and [18]). Coconut palms are unique in structure in terms of cylindrical trunks of uniform diameter and absence of side-branches. In the case of such a structure, the amount of obstruction caused to the wind energy transmission remains constant with distance upwards from the forest floor until the canopy is reached (bottom friction caused by the land-floor is neglected). Thus, the coconut palm canopy consisting of numerous dense leaves can be considered as a porous media.

B. Explanation based on boundary-layer fluid dynamics

In Kavaratti Island, the majority of trees consist of coconut palms. As indicated in the preceding discussion, a coconut palm can be represented as a structure consisting of a thin column (the trunk) and numerous porous leaves. Because the leaves are considerably larger in volume than the trunk, in the present study we consider only the leaves and attempt to shed some light on the practical issue of achieving a reasonably good insight into the observed attenuation of wind speed, based on the concepts from boundary-layer theory in aerodynamics. In this attempt, it is assumed for simplicity that the thickly populated coconut palms and other foliages of various heights and spatial separation (consisting of numerous leaves and trunks, separated by a multiplicity of inter-foliage spaces in between, can be broadly approximated to an array of vertically oriented flat thin perforated sheets stacked parallel to each other at suitable inter-sheet separations (Fig. 12). The

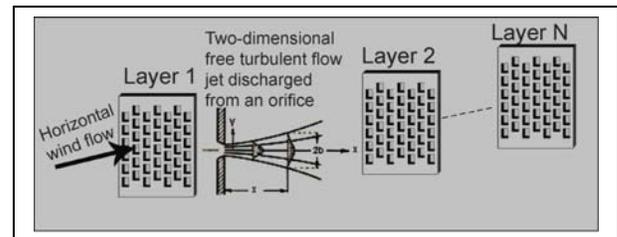


Fig. 12 Arrays of orifices on stacks of perforated sheets, aerodynamically resembling thickly populated foliages with numerous empty spaces in between.

perforations on the sheets (i.e., porosity) are considered to be analogous to the inter-foliage spaces, which function as the constricted pathways for the wind to flow through the foliages. In this analogy, each perforation resembles a nozzle/orifice and the wind flow discharged from the orifices of such a stack of perforated sheets can be considered to be streams of free turbulent flows. The flow is termed "free" because it is not confined by solid walls. Disregarding very small velocity of flow, the jet becomes completely turbulent at a short distance from the point of discharge. Owing to turbulence, the emerging jet becomes partly mixed with the surrounding air mass. Particles of air from the surroundings are carried

away by the jet in a downstream direction such that the jet spreads out with a decrease in velocity. Problems in free turbulent flow are of a boundary layer nature (*i.e.*, the region of space in which a solution is being sought does not extend far in a transverse direction, as compared with the main direction of flow, and that the transverse gradients are large, as compared with the gradient in the main direction of flow). Consequently, it is permissible to analyze such problems with the aid of boundary-layer equations in fluid dynamics. Denoting the centre-line velocity and the width of the jet at a fixed characteristic distance s from the orifice by U_s and b_s , respectively, the centre-line velocity U in terms of axial distance x from the orifice for the problem of free turbulent flow is given by the expression [19]:

$$U = U_s \left(\frac{x}{s} \right)^{\frac{1}{2}} \quad (1)$$

$$b = b_s \left(\frac{x}{s} \right) \quad (2)$$

From equations (1) and (2), the decrease in the centre-line velocity is directly proportional to $x^{-1/2}$ (where x is the axial distance from the orifice) and the rate of increase in the width of the jet is directly proportional to x . As the free turbulent jet flow discharged from the orifice is two-dimensional in nature (as against a *parallel* flow, which is one-dimensional), it has axial velocity component, u , and transverse velocity component, v . The values of u and v at axial distance x from the orifice are given in [19] as below:

$$u = \frac{\sqrt{3}}{2} \sqrt{\frac{K\sigma}{x}} \left(1 - \tanh^2 \eta \right) \quad (3)$$

$$v = \frac{\sqrt{3}}{4} \sqrt{\frac{K}{x\sigma}} \left\{ 2\eta \left(1 - \tanh^2 \eta \right) - \tanh \eta \right\} \quad (4)$$

$$\eta = \sigma \frac{y}{x} \quad (5)$$

In equations (3), (4), and (5), σ (an empirical constant) = 7.67 and K is the kinematic momentum, given by:

$$K = \frac{4}{3} U_s^2 \left(\frac{s}{\sigma} \right) \quad (6)$$

In eq. (6), U_s is the centre-line velocity at a fixed characteristic distance s from the orifice. From equations (3) and (4) it is quite evident that both axial and transverse velocities decrease

with increasing axial distance from the orifice. When the notion of perforated sheet is used to understand the airflow velocity reduction within a vegetation canopy qualitatively, the foliage density can be represented by the inter-sheet separations (lesser separation indicates denser foliage density). In this case, the output velocity of the preceding array becomes the input velocity of the proceeding array. It is obvious that the wind speed will undergo more and more attenuation with increasing width and density of the greenbelt. In References [20] and [21], Joseph et al., conducted a series of flow flume experiments with perforated sheets of different porosity at various flow speeds, for the purpose of minimizing the flow-induced dynamic pressure at the inlet of a pressure transducer by reducing the flow speed at and in the vicinity of the pressure inlet, and found that the arrays of perforations on the sheet have the capacity to effectively reduce the flow speed at its downstream direction. In Reference [22], N'Guettia et al., carried out wind speed profile measurements within and above a cassava field and found that wind velocity reduction within and above the canopy are significant and often larger than 50 percent. The maximum reduction from the leading edge depends on the leaf area index, the measuring height within the canopy, and the maximum wind speed in the free air. Based on the physical insight and clarity provided by the well-established theoretical foundations encompassed in the boundary-layer theory in fluid dynamics addressed above, together with experimental results, it can be reasonably argued that the numerous arrays of naturally present orifices formed by a multiplicity of inter-foliage spaces present within the island vegetation are responsible for the observed under-estimation of wind speed at Kavaratti Island. The results of the measurements carried out in the present study corroborate the observations in [22].

Porosity in the greenbelt has been found to be valuable not only for attenuating wind speed but also in attenuating wave height, water current velocity, and wave pressure. For example, simulation experiments in a hydraulic channel in which the experimental target greenbelt was represented by different kinds of porous media (porous sheet, cement block dike, rubble mound) with different porosity indicated that the wave height, current velocity, and wave pressure rapidly decreases through the porous barriers and these parameters become considerably smaller in the backside of the greenbelt [23]. It was also found that the reflection from the porous barriers may cause tiny influence to the variation of current velocity. It has been inferred that the natural disaster reduction effect of greenbelt barrier is approximately represented by the averaged porous rate in the total mass of greenbelt frame.

VI. CONCLUSIONS

Long-term measurements reported in the present study indicates that the wind speed attenuation mechanism in porous barriers represented by dense greenbelt allows reduction of the damaging effects of strong winds (*e.g.*, from storms). It is inferred that the observed wind speed attenuation by greenbelt is akin to the experimentally observed tsunami/storm-surge

reduction in porous barriers. This study as well as extensive experiments in hydraulic channels and through numerical simulations carried out by several researchers over a period of time indicate that the greenbelt prevention method is applicable to a sustainable natural disaster (oceanogenic and meteorological) reduction system in the tropical coastal zones and islands alternative to man-made engineering systems. It is therefore worth examining what future role should coastal tree vegetation forests play in coastal zone management and protection. It is hoped that the present study offers disaster managers and policy-makers one of the options that can be promoted for mitigation of the effects of storms. Tree vegetations are healthy ecosystems, and preserving them would bring about human well-being in various ways, prevention of drying out a region, reducing/arresting flooding, and so on. We propose that, wherever feasible, the greenbelt natural barrier system composed of trees with enough stability against the large forces associated with oceanic and surface meteorological events should be preferred against man-made artificial hard barriers such as coastal dikes and detached breakwaters because of cost-effectiveness and a variety of ecological considerations.

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