# CHAPTER 3
# PROTECTION FROM WIND AND SALT SPRAY

## Thematic paper: Protective functions of coastal forests and trees against wind and salt spray

**Eugene S. Takle, T.-C. Chen and Xiaoqing Wu**[1]

*This paper provides an overview of the hazard potential presented by wind and salt spray to human settlements in coastal areas of Southeast Asia. Damage to infrastructure (such as buildings, dams, bridges and dykes) and degradation of natural systems in Southeast Asia and India due to wind and salt spray are closely linked to climatological conditions that lead to high wind in the region (Section 1.1). The mechanisms for generation of salt spray and their relation to windspeed are discussed in Section 1.3. Introducing shelterbelts and coastal forests is proposed as an environmentally attractive method for suppressing damage due to wind and sea spray. The properties of shelterbelts that define their effectiveness for reducing wind and capturing sea salt are described in Section 2 and the development of guidelines for their re-establishment in coastal areas is addressed in Section 3. There is a brief discussion on economics and social aspects of establishing coastal forests in Section 4, and Section 5 offers concluding remarks.*

## 1 Wind and salt spray damage in Asia

Section 1 gives an overview of wind and salt spray damage potential for Southeast Asia. Actual records or maps of past damage to human assets in the region are neither comprehensive nor widely available, particularly in the context of salt spray damage. Available data for assessing wind and salt spray damage *potential* in Southeast Asia are perhaps a useful surrogate and arguably more relevant for policy-making, as actual damage maps would be highly dependent on the value of coastal human assets exposed to damaging conditions. Therefore, climatological information and maps offer opportunities for assessing hazard potential in various areas as a basis for evaluating alternative strategies for types of protection and hardening of structures in order to minimize the negative impacts of such hazards.

### 1.1 Wind

#### 1.1.1 Climatology of mean wind

Traxler *et al.* (1997) provide a detailed climatology that includes wind climatology in the form of wind roses for the Southeast Asia region. The wind climatologies, including both speed and direction, for localized coastal areas within this region are strongly influenced by the northeast and southwest monsoon circulation systems, tropical cyclones, land and sea breezes, frontal systems, mesoscale convective processes and topographical features. Wind rose data provided by Traxler *et al.* (1997) are given in Figure 3.1; the major differences in windspeed and wind direction conditions among the various locations should be noted.

Of particular value for assessing potential damage due to high wind and sea spray is the frequency of direct and oblique onshore winds (separately for day and night) in the calm, weak and moderate

---

[1] Agronomy Department, Geological and Atmospheric Science Department, 3010 Agronomy Hall, Iowa State University, United States.

speed categories for each of the 16 compass directions. Evaluating the protective function of trees and shelterbelts and determining the design factors (for example, species, orientation, density, width and length) for any particular location must first start with an assessment of the magnitude of the local threat and the direction from which it arrives. The Southeast Asian and Indian coastal regions subject to wind damage from tropical cyclones, monsoon and other meteorological events can be subdivided into five general locations: Viet Nam and coastal southeast China; the east-facing Malay Peninsula coast; the west-facing Malay

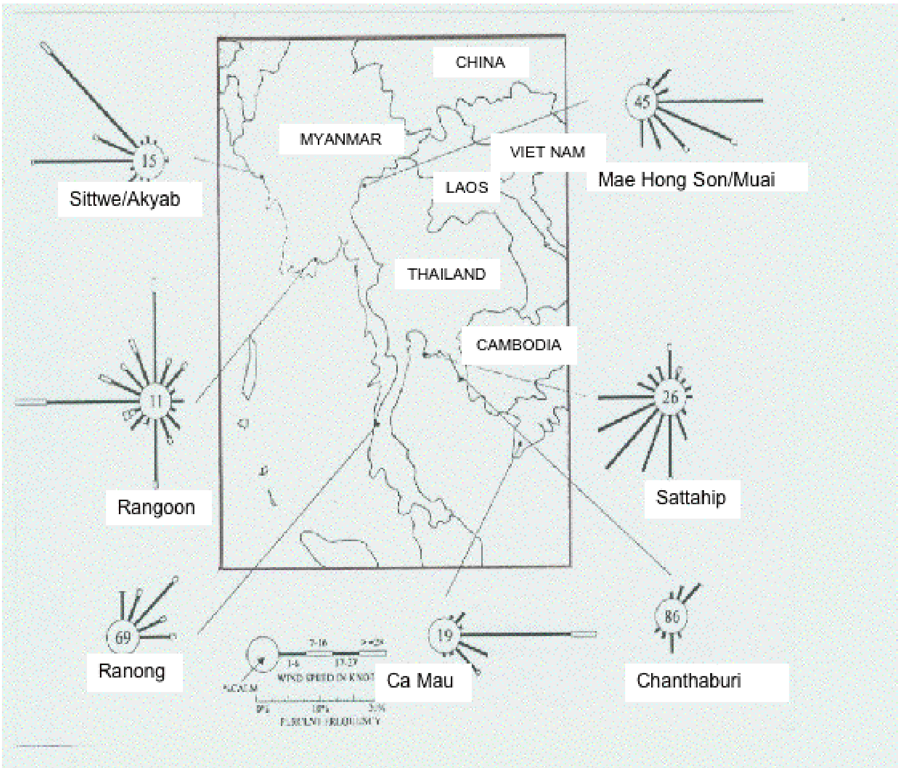


**Figure 3.1 January wind roses showing frequency of wind occurrence in various speed categories (including calm) for each compass direction (Traxler *et al.* 1997)**

Peninsula coast; India's east-facing coast; and India's west-facing coast. For each of these regions the wind roses of Traxler *et al.* (1997) allow a summary of conditions, possibly leading to damage from wind and salt spray:

- Viet Nam and coastal southeast China: Mean winds from the north and northeast (onshore) from October to March (northeast monsoon) have periods in the 17–27 nautical miles per hour (knot or kt: equivalent to 32–50 kilometres/hour) range and higher frequency of occurrence of winds in the range of 7–16 kt (13–30 kilometres/hour). The southwest monsoon period (April to September) occasionally brings strong onshore winds in the southern part of this region.

- East-facing Malay Peninsula coast: The northeast monsoon period of November to April brings strong easterly winds that can persist both day and night. Mean winds can exceed 17 kt (32 kilometres/hour) in southern Thailand. In this region, only Singapore receives moderately high winds from the southwest monsoon (May to October).

- West-facing Malay Peninsula coast: Strong south and southwest winds associated with the southwest monsoon in April to September have the potential for extended periods of sea-spray generation and possibly isolated wind damage events.

- India's east-facing coast: The summer southwest monsoon favours offshore flow in this region. The winter northeast monsoon mean wind direction is nearly parallel to the coast, thereby reducing the incidence of strong onshore flows.

- India’s west-facing coast: The southwest monsoon provides a persistent onshore flow in summer, and the northeast monsoon with offshore winds suppresses the potential for onshore salt transport in winter.

The polar frontal zone sags southward over the northern Bay of Bengal in winter, giving Bangladesh and adjacent areas primarily offshore winds of low speed. These offshore winds do not pose a threat to the coasts or inland transport of sea salt. In summer, the southwest monsoon provides flow primarily from the southwest for this region; it has persistent onshore winds with the potential for onshore flow with a high content of salt particles owing to long trajectories over a warm ocean, where waves launch bubbles that burst above the sea surface and distribute salt particles through the lower atmosphere (see Section 1.2).

### 1.1.2 Climatology of tropical cyclones

This section provides a brief discussion on the region and conditions of tropical cyclone origins and lifetimes and possible factors that could contribute to differences in occurrences from one year to the next.

A storm is considered to be a tropical cyclone when its sustained winds exceed 17.5 metres/second (34 kt or 63 kilometres/hour). If the sustained winds reach 33 metres/second (64 kt or 119 kilometres/hour) the system is referred to as a severe tropical cyclone (a typhoon in the western North Pacific and a hurricane in the Atlantic and eastern Pacific). McBride (1995) provides more details on the structure and evolution of tropical systems. Each year approximately 84 (±8) tropical cyclones occur throughout the world, with about two-thirds reaching the severe tropical cyclone stage (Elsberry, 1995). About five (±2) form in the North Indian Ocean, with three (±2) being severe; approximately 26 (±4) form in the western Pacific Ocean, with 16 (±4) being severe.

The occurrence and nature of tropical cyclones are best described by their interannual variation in genesis locations, population, intensity and lifetime (Chan, 1985; Dong, 1988; Wu and Lau, 1992; Chen *et al.*, 1998; Camargo and Sobel 2005; and many other sources). The Southeast Asian monsoon trough is a preferred genesis region for tropical cyclones. Consequently, any mechanism causing the interannual variation of the atmospheric circulation around the monsoon trough (such as an El Niño) may affect the tropical genesis location and frequency over the western tropical Pacific (Lighthill *et al.*, 1994). Chen *et al.* (2006) clarified the roles of these factors by using the six hour tropical cyclone/depression track records issued by the Joint Typhoon Warning Center (JTWC) (JTWC 2006) and the Japan Meteorological Agency (JMA) for the period 1979 to 2002.

The tropical cyclone intensity scale of the JMA defines cyclones in terms of their windspeeds. Figure 3.2 shows the cyclone population vs. windspeed intensity, lifetime vs. windspeed intensity, and cyclone population vs. lifetime of tropical cyclones for May to October from 1979 to 2002 (Chen *et al.*, 2006). Note that most tropical cyclones are weak and have short lifetimes and only a few can be considered super typhoons, but these will last far longer. Chen *et al.* (2006) further found that the Southeast Asian monsoon trough provides an environment favourable for the genesis of tropical cyclones. As shown in Figure 3.3, catastrophic typhoons tend to originate at lower latitudes (7.5º north ) compared to strong and very strong typhoons (12.5º north), and tropical depressions and weak typhoons (15º north). Wu *et al.* (2004) clarified the impact of the El Niño/Southern Oscillation (ENSO) on the behaviour of tropical cyclone landfall. They found that the number of tropical cyclone landfalls in Southeast Asia in the late season (September, October, November) is much reduced in El Niño years compared to normal years. However, in the late season of La Niña years, China receives significantly more landfalls.

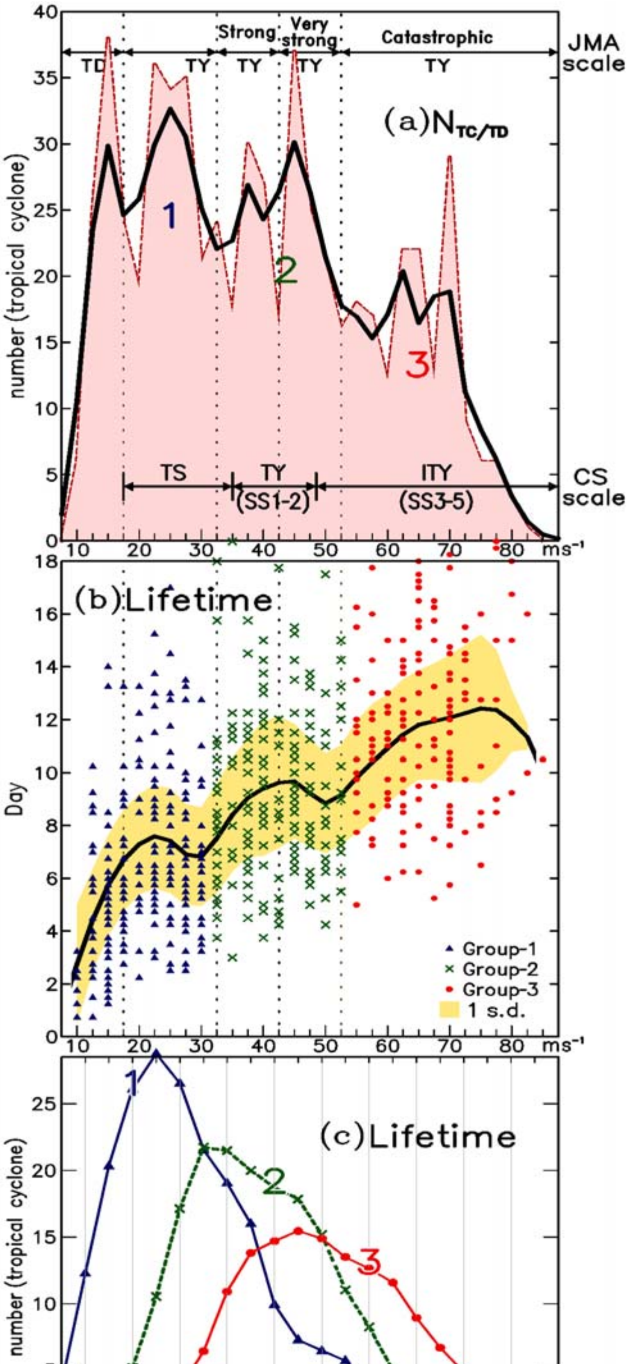


**Figure 3.2 Relationships between population, lifetime and intensity of tropical cyclones: (a) population vs. intensity superimposed with the JMA scale at the top and the Camargo–Sobel (CS) scale at the bottom and the division of three tropical cyclone groups (b) lifetime vs. intensity superimposed with populations of all three tropical cyclone groups identified in (a) and (c) accumulated population vs. lifetime for three groups of tropical cyclones. The CS scale consists of three groups: (1) TS = tropical storms, (2) TY = typhoons, (3) ITY = intense typhoons. The thick solid line in (a) is a 3-point moving average applied on the original population (dark-red dashed line)**

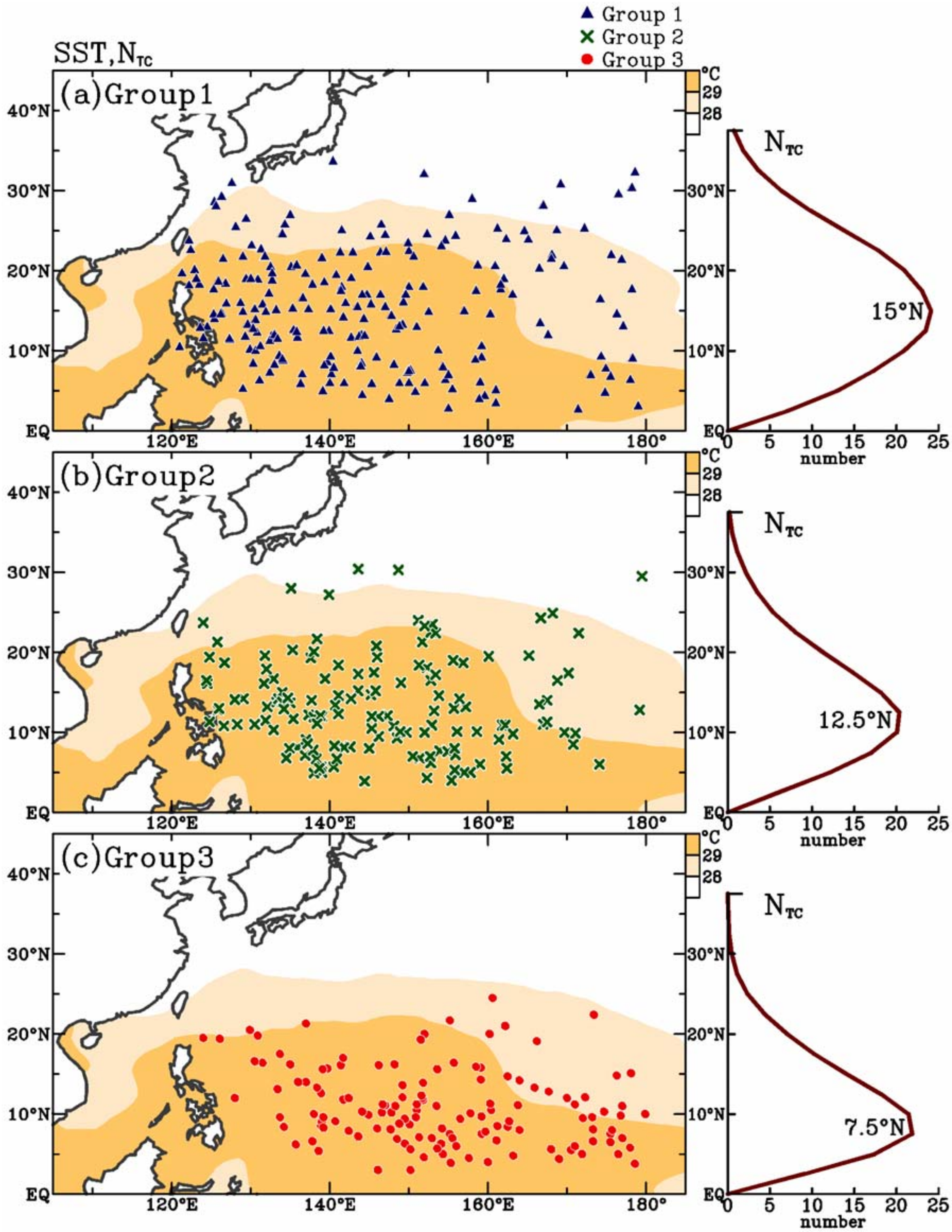


**Figure 3.3 Genesis locations of tropical cyclones (marked by different colour symbols) and accumulated tropical cyclone population within a 2.5° latitudinal zone (indicated by the thick brown line in the right side of each panel): (a) Group 1, (b) Group 2, (c) Group 3. The monsoon trough is denoted by a black thick-dashed line. Colour symbols of genesis locations in each group of tropical cyclones follow those used in Figure 3.2b**

### 1.1.3 Tropical cyclone winds at landfall in the Western Pacific and Indian Ocean

From Figure 3.4 and Figure 3.5 we can create a brief survey of frequency of occurrence and maximum expected windspeeds for tropical cyclones at time of landfall for various parts of Southeast Asia and India (Table 3.1). Note that Figure 3.4 gives the number of occurrences per year for each 1° latitude by 1° longitude box. As this paper focuses on coastal regions, we have made an approximate conversion of these graphical data to occurrence per year per 100 kilometres of coastline, as reported in Table 3.1.

### 1.1.4 Wind-induced damage in Southeast Asia and India

The frequency of wind damage in Southeast Asia and India is directly related to the frequency and intensity of winds at landfall of tropical cyclones and to the magnitude of short-term winds produced by frontal systems and local storms. For a tropical cyclone at landfall, a particular coastal location could experience high and gusty winds for periods of 12 or more hours. High winds from frontal systems may last for six to 12 hours, whereas winds generated by local storms, while temporarily very strong, typically last less than one hour.

The source and duration of winds has significant influence on the amount and nature of wind damage in the coastal area. A local storm, for instance, does not induce a storm surge in the coastal ocean and produces only short-term forces on trees and structures. In contrast, frontal systems, and more especially tropical cyclones, can produce sustained high winds with accompanying turbulent gusts that provide more modes of failure in both trees and buildings. One such mode is commonly observed when power lines “gallop” wildly in a strong and turbulent wind, finally acquiring sufficient energy from the turbulent atmospheric motions to break loose from supporting poles or pull down entire lines of poles. A similar “rocking” motion induced in trees or buildings is more likely to lead to structural failure if the force is sustained over long periods.

Damage paths created by high winds also vary with storm type. Tropical cyclones can cut wide swaths of damage with widths in the order of 100 kilometres and lengths of 1 000 kilometres. Damage paths from frontal systems are about an order of magnitude smaller and localized storms another smaller order of magnitude.

Hossain and Singh (2006) provide a graphical depiction of storm risk in India, Sri Lanka and Bangladesh(Figure 3.6) that takes into account the historical spatial distribution of density of tropical storm intensity. It is noteworthy that when the spatial distribution of human population at risk is factored in, regions such as the northern part of the east coast of India and Bangladesh rise in importance despite the fact that tropical cyclones, as depicted in Figure 3.4, have a lower frequency of occurrence in these regions.

Evaluation of the vulnerability of the east coast of India (Mascarenhan, 2004) from over a century (1891–2000) of cyclone data revealed that of the cyclones that formed in the Bay of Bengal, Andhra Pradesh received 32 percent, Orissa 27 percent, Tamil Nadu 26 percent and West Bengal 15 percent. The number of severe cyclones affecting these states over this period included 55 in Tamil Nadu, 69 in Andhra Pradesh, 58 in Orissa and 33 in West Bengal.

## 1.2 Increase in tropical cyclone intensity due to global warming

Sea surface temperatures are widely known to influence tropical storm and typhoon intensity. A large fraction of the energy trapped near the Earth's surface by increased concentrations of atmospheric greenhouse gases contributes to the heating of global ocean surface waters. Emanuel (2005) reported that the strength of tropical cyclones has more than doubled for the Atlantic region in the last 30 years and nearly doubled for the Western Pacific region. Webster *et al.* (2005) found a large increase in the number and proportion of tropical cyclones that reach categories 4 and 5 on the Saffir–Simpson scale of 1 to 5. This change is most pronounced in the North Pacific, Indian and Southwest Pacific oceans, with the least change in the North Atlantic Ocean. They find no long-term global trend in the number of storms or number of storm days.

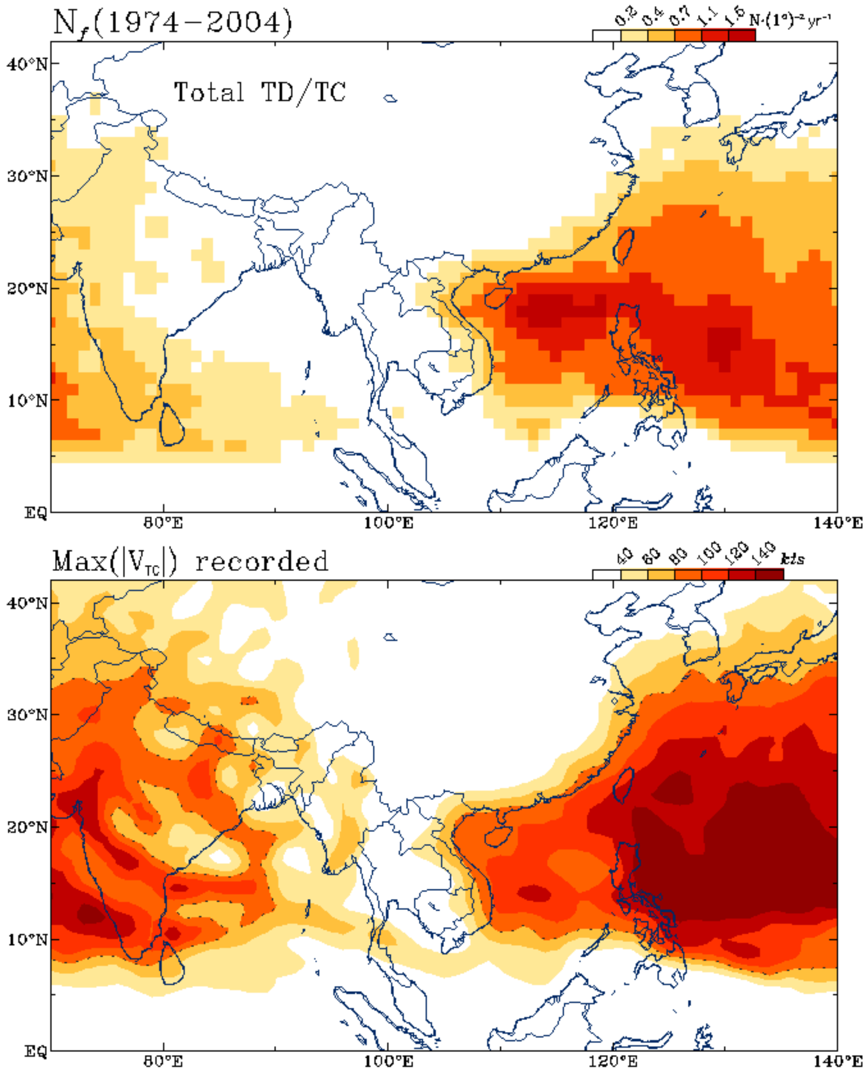


**Figure 3.4 Upper figure — frequency of tropical cyclones from 1974 to 2004 in number of occurrences per year for each 1° latitude by 1° longitude box. Indochina, South China, Taiwan Province of China and the Philippines are most likely to have tropical cyclone landfall. Lower figure — maximum windspeed of typhoons ever recorded in the period 1974 to 2004. The coastlines of Viet Nam, China and much of India may receive 80 kt winds, while Taiwan Province of China, the Philippines and a small portion of India may encounter winds of about 120 kts**

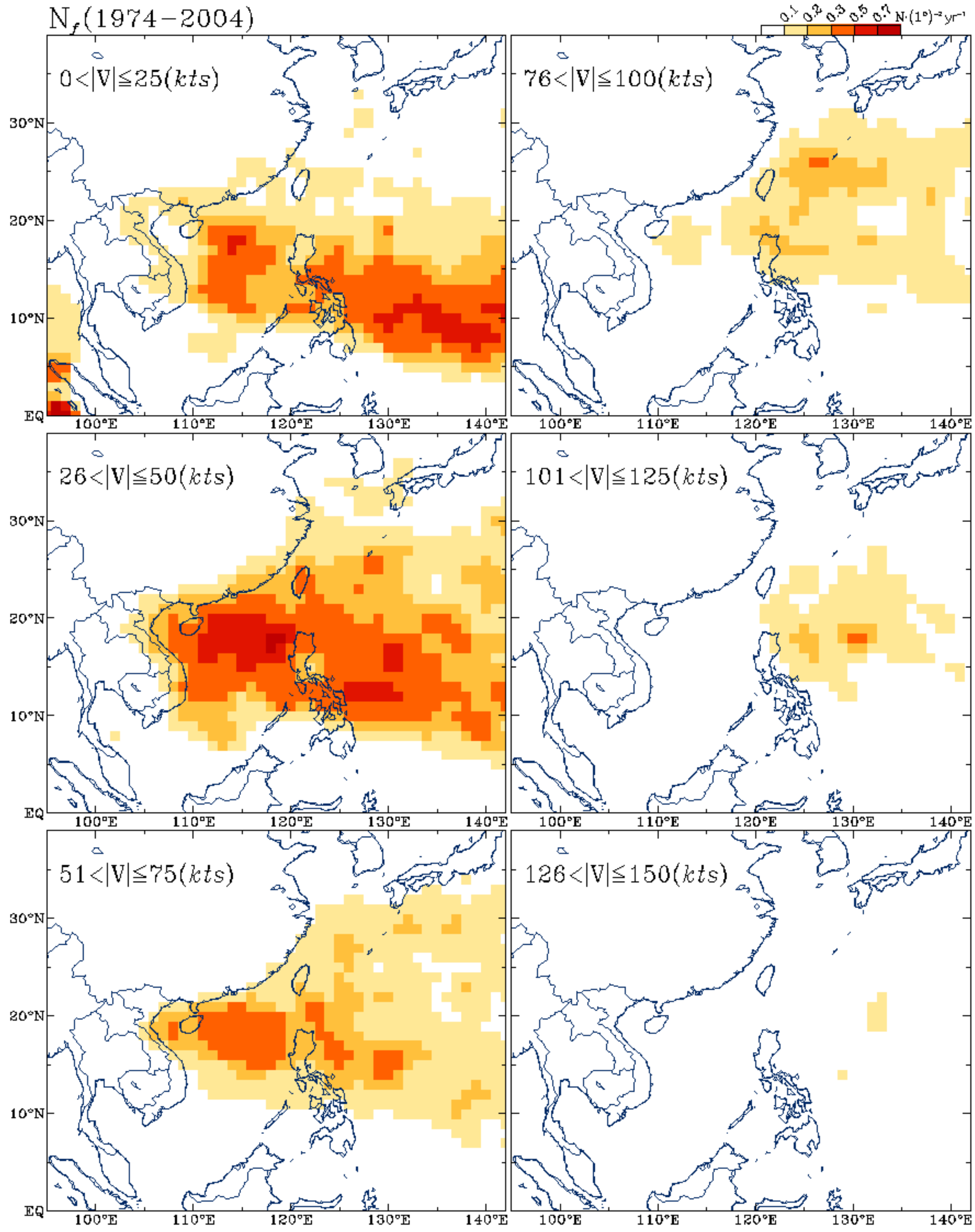


**Figure 3.5 Frequency of tropical cyclones with windspeed within the range given in the upper lefthand corner; the most frequent windspeed of typhoons for coastlines around the South China Sea is between 25 and 50 kts, while most of the typhoons that strike Indochina and China have an intensity under 100 kts**

**Table 3.1 Tropical cyclone landfalls per year and winds at landfall in the Western Pacific and Indian Ocean for 1974 to 2004. Annual number of landfalls is given in landfalls per 100 km of coastline. Maximum windspeed is the approximate maximum windspeed recorded in each country listed over the period 1974 to 2004**

| Country/area | Windspeed range (kts) | Annual no. of landfall | Maximum windspeed (kts) | Total annual no. of landfalls | Notes |
|---|---|---|---|---|---|
| China | 0–25<br>26–50<br>51–75<br>76–100<br>101–125 | 0.0–0.1<br>0.1–0.2<br>0. 07<br>0.0<br>0.0 | 80 | 0.17–0.37 | Hainan has 0.7 to 1.1 per year per 100 km |
| Taiwan Province of China | 0–25<br>26–50<br>51–75<br>76–100<br>101–125 | 0.1<br>0.3–0.5<br>0.2<br>0.1–0.2<br>0.0 | 120 | 0.7–1.0 | |
| Viet Nam | 0–25<br>26–50<br>51–75<br>76–100<br>101–125 | 0.1–0.2<br>0.2–0.3<br>0.0–0.2<br>0.0<br>0.0 | 80–100 | 0.3–0.7 | Few landfalls in the south<br>Max. winds in the west |
| The Philippines | 0–25<br>26–50<br>51–75<br>76–100<br>101–125 | 0.2–0.3<br>0.2–0.4<br>0.0–0.3<br>0.0–0.2<br>0.0–0.1 | 80–140 | 0.4–1.3 | Few landfalls in the south<br>Extreme winds in the northern half |
| Cambodia | | | < 40 | < 0.2 | |
| Thailand | | | 60-80 | < 0.2 | |
| Malaysia | | | < 60 | < 0.2 | |
| Indonesia | | | < 40 | < 0.2 | |
| Myanmar | | | 40–60 | < 0.2 | |
| Bangladesh | | | 60 | < 0.2 | |
| Sri Lanka | | | 50–110 | 0.4–0.7 | |
| The Maldives | | | 40–80 | 0.6–0.7 | |
| India | | | | | |
| Coastal NE | | | 100 | < 0.2 | |
| Coastal SE | | | 80–100 | 0.2–0.6 | |
| Coastal NW | | | 90–130 | 0.3–0.4 | |
| Coastal SW | | | 100–140 | 0.4–0.6 | |

Mann and Emanuel (2006) concluded that anthropogenic factors are the dominant cause of these trends. As atmospheric greenhouse gas concentrations are certain to increase over the next 50 years, it is prudent to factor an increase in tropical cyclone intensity into the planning of long-term changes in coastal management to avert damage from wind and sea spray. Mascarenhan (2004) pointed out that Bay of Bengal temperatures have been rising since 1951 and pose enhanced vulnerability of the east coast of India to cyclones of higher windspeeds and greater storm surges.

### 1.3 Salt spray

Excessive salt in terrestrial environments can lead to accelerated corrosion of human assets, salinization of agricultural soils, elevated water stress, leaf or needle necrosis and growth inhibition of plants that have low salt tolerance. Onshore movement of salt due to sea spray (as opposed to the transport of dry aerosols) directly impacts only the coastal region. However, dry aerosols may be transported further inland and contribute to the salinization of soils in agricultural areas far from the coast. Therefore, introduction of coastal vegetation that improves capture of sea salt aerosols (in addition to sea spray) in the coastal environment reduces the movement of salt further inland.

Maps of actual damage due to the onshore movement of salt are not readily available. However, effective coastal planning to minimize future damage due to salt spray begins with an evaluation of the *hazard potential,* which is best understood by recognizing the physical factors, climatological conditions and geographical locations that produce salt spray.

### 1.3.1 Movement and deposition of sea salt in the coastal environment

Bursting bubbles at the ocean surface eject droplets of saltwater into the marine atmosphere with a typical radii of 0.5 to 5 μm for film droplets and 3 to 50 μm for jet droplets (Zhang *et al.*, 2005). A second source of droplets is the forceful separation of water droplets of >20 μm (called spume droplets) at the top of waves caused by sufficiently strong winds (Mueller and Veron, 2005; Zhang *et al.*, 2005).

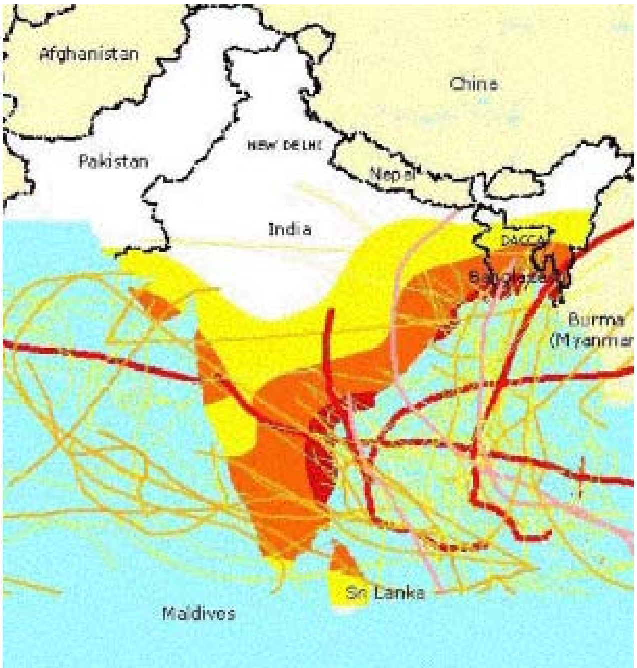


**Figure 3.6 Regions of high (red), medium (orange) and low (yellow) risk to human populations from tropical storms for India and Bangladesh (Hossain and Singh, 2006). Lines indicate paths of tropical cyclones for the period 1971 to 1999**

Piazzola *et al.* (2002) analysed the relationship of spray–droplet generation to windspeed. They state that periods with windspeeds in excess of 10 metres/second are associated with direct production of large aerosols extracted by the airflow at the crest of the waves. For instance, a 20 metres/second wind generates five times as many droplets as a 10 metres/second (36 kilometres/hour) wind, and a 30 metres/second (108 kilometres/hour) wind generates 13 times as many. This underscores the importance of knowing offshore windspeeds for estimating spray–droplet generation hazards.

Offshore convective storms, monsoonal winds and tropical cyclones can produce enhanced windspeeds that generate droplets of diameters ranging from 1 to 1 000 μm. After evaporation of these droplets, the remaining salt particles typically are in the size range of 0.1 to 30 μm and are dispersed throughout the lower kilometres of the atmosphere and moved by the ambient wind. The fate (settling back to the ocean surface or dispersion throughout the marine atmospheric boundary layer) of both droplets and salt particles depends on their fall velocity (which depends on their size) and the atmospheric turbulence throughout the boundary layer (the vertical component of turbulence counteracts gravitational settling). Owing to gravity, large droplets (with large fall velocity values) will settle back to the ocean surface more quickly than smaller droplets, which are more likely to remain airborne due to turbulent upward motions.

The source and duration of winds has significant influence on inland transport of salt owing to sea spray and dry salt particles. Tropical cyclones with long paths over a warm ocean roughen the ocean surface through breaking waves that launch high numbers of salt-laden droplets into the lower atmosphere. Strong upward motions in the cyclone carry these droplets to heights several kilometres above the surface. As a result, the tropical cyclone creates a large airborne volume of sea salt in both droplets and dry aerosol particles (residual of evaporated droplets). Neither frontal systems nor local storms have the capacity to load the atmosphere with salt in the manner accomplished by the tropical cyclone.

Being very soluble, salt particles will be readily dissolved by interaction with raindrops or fog droplets. Rain has a tendency to clear the air of salt particles. The rainfall climatology of Traxler *et al.* (1997) provides details on the spatial variability of rainfall amounts throughout Southeast Asia, which is useful in determining regions of high salt deposition to the surface owing to frequent washout by rain.

Salt-laden air, fog droplets and raindrops moving onshore near the surface will encounter vegetation and will deposit salt upon contact with solid surfaces (Figure 3.7). For onshore wind directions this means that the seaward edge of the shelterbelt or forest will be most highly impacted, capturing disproportionately high amounts of salt in solution that will drip to the soil surface and enhance soil salinity. Salt particles not associated with fog or rain will be captured by wetted vegetation as the ambient air moves through the forested region. Turbulent motions above the canopy will bring down air from aloft with higher salt particle concentrations, thereby providing for continued salt deposition as the air traverses inland from the coast. The drier the vegetation and the lower the humidity of the ambient air, the further the transport of salt particles inland will be. Absence of rain events also will allow further inland penetration of airborne salt.

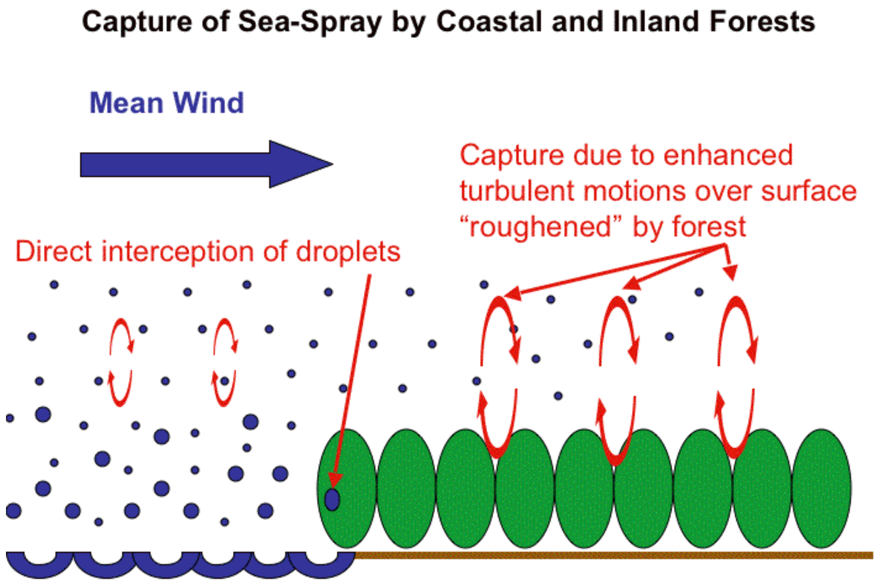


**Figure 3.7 Sketch of mechanisms for capture of sea-spray and sea-salt particles by coastal and inland forests. Large droplets generated by breaking waves, particularly in the coastal zone, are indicated by large blue dots. Smaller droplets with low gravitational settling velocity are indicated by small blue dots. The "rough" surface created by the forest increases the size of turbulent eddies and brings more small droplets and salt particles into contact with the vegetation, where they can be captured and prevented from travelling further inland**

### 1.3.2 Onshore flux of sea salt in Southeast Asia and India

Few studies have been carried out to assess the magnitude of onshore wind-blown salt intrusion in Southeast Asia and India. A technical memorandum issued by the World Meteorological Organization in 2003 (Das *et al.*, 2003) included a brief assessment of agricultural damage due to wind-blown salt from sea spray and cited only one 50-year-old publication by Tamate (1956) from Japan on reducing airborne salt movement by the use of shelterbelts. Airborne salt concentrations in the lee of shelterbelts were measured to be 12 percent lower than on the windward side. Sequeira and Kelkar (1978) measured the sea salt content of rainwater at ten coastal and inland stations in India during the entire monsoon period of 1975 and estimated that four million tonnes of sea salt are likely to be transported annually into the country by monsoon winds. Rainwater near the coast had concentrations of sodium from 400 to 1 000 percent that of seawater. This is consistent with previous paragraphs that describe how air parcels with long trajectories over the ocean are continually supplied with droplets, which evaporate leaving salt particles that continually increase the salt loading of the parcel. Onshore moving air parcels very near the surface will interact with coastal forests, which provide some opportunity for salt to be extracted from the air. However, salt particles distributed throughout the lowest two kilometres of the atmosphere will have high salt content. These salt particles, high in the atmosphere, cannot be captured by coastal vegetation but will be washed out by rainfall further inland.

Spray movement onshore can be expected when offshore winds are sufficiently strong to generate sea spray by the previously mentioned mechanisms, which generally require speeds in excess of 10 metres/second for the generation of large salt aerosols (Piazzola *et al.*, 2002). Localized damage potential can be estimated by the frequency of winds exceeding this threshold.

Damage to growing plants caused by salt from sea spray can be attributed to higher water stress and leaf or needle necrosis, as well as inhibition of growth (Griffiths and Orians, 2004) depending on the species. Differential responses to salt by different species can lead to gradations in the ecosystem community structure in the near coastal zone. Some species (for example, pines) are vulnerable to "salt-pruning" on their ocean-facing sides. When combined with a persistent or prevailing wind from the ocean, salt-pruning may cause a tree to become "flagged," with growth only occurring on the side of the tree protected from the salt spray (Storm Center Communications, 2006). If the coastal area has high levels of wastewater returned to the ocean, high concentrations of surfactants could be passed on to the spray droplets generated by waves breaking in the near-shore environment. Spray droplets containing surfactants counteract the natural low wetability (Rettori *et al.*, 2005) and absorption of leaf surfaces of halophytes such as mangroves and Norfolk Island Pines, thereby allowing excessive amounts of salt spray to penetrate into the leaf through open stomata (leaf pores) (Allen, 2006). Rettori *et al.* (2005) reported that coastal vegetation damage in Italy is generated by this effect.

Intense rainfall can reduce salt accumulation problems by washing salt from vegetation and leaching salt from the soil. Regions receiving in excess of 50 centimetres of rain per year have fewer problems with salt accumulation in the soil (Appleton *et al.*, 2003).

## 2 Use of forests and trees for suppressing damage

Research on the characteristics and sheltering effectiveness of coastal shelterbelts and forests is quite limited. Recent review papers on shelterbelt modelling (Wang *et al.*, 2001) and worldwide applications of shelterbelts (Brandle *et al.*, 2000) make no mention of coastal applications. Zhu *et al.* (2003) provide a model for winds *within* a coastal forest canopy, but do not address the sheltering function beyond the confines of the forest.

However, the fluid dynamics of flow through vegetation barriers are based on universal laws of physics, so simulating flow through a coastal shelterbelt is no different than simulating flow through agricultural shelterbelts, provided that the characteristics of the coastal vegetation (see Section 2.1 below) are specified. Windbreaks consisting of shelterbelts (one or two rows of trees) and forest belts (multiple rows) are commonly used at inland locations as natural barriers to reduce windspeed, modify the microclimates of small regions and suppress the movement of snow, pollen, dust, sand and odours. They are most widely used in agriculture in regions of high windspeed such as Australia, New Zealand, the Russian Federation, China and the Great Plains of the United States. Therefore, the methods used and results derived from studies of agricultural shelterbelts can be applied to coastal shelterbelts and forests as well. In this section we discuss the knowledge base on shelterbelt design and application as it has been established through research on agricultural shelterbelts. In Section 3 we apply the qualitative results of these agricultural applications to the design of coastal shelterbelts and forests.

Windbreaks substantially reduce windspeed on the windward side for a horizontal distance of 2–5 H, where H is the height of the barrier (Figure 3.8). A much larger region of reduced windspeed, typically extending from approximately 10 H downwind to 30 H downwind, is created in the lee of the barrier, with the sheltering effectiveness near the barrier being determined by the incident angle of the wind to the shelterbelt (Wang and Takle, 1996a). Some very limited windspeed reduction as far as 60 H downwind has been reported (Caborn, 1957; 1971), but the biological or practical significance is considered to be quite limited (Brandle *et al.*, 2000). However, as will be shown in Section 2.3, the impact of even minor wind reduction can have a disproportionately high impact on particle deposition, even though windspeed reduction might be considered minor.

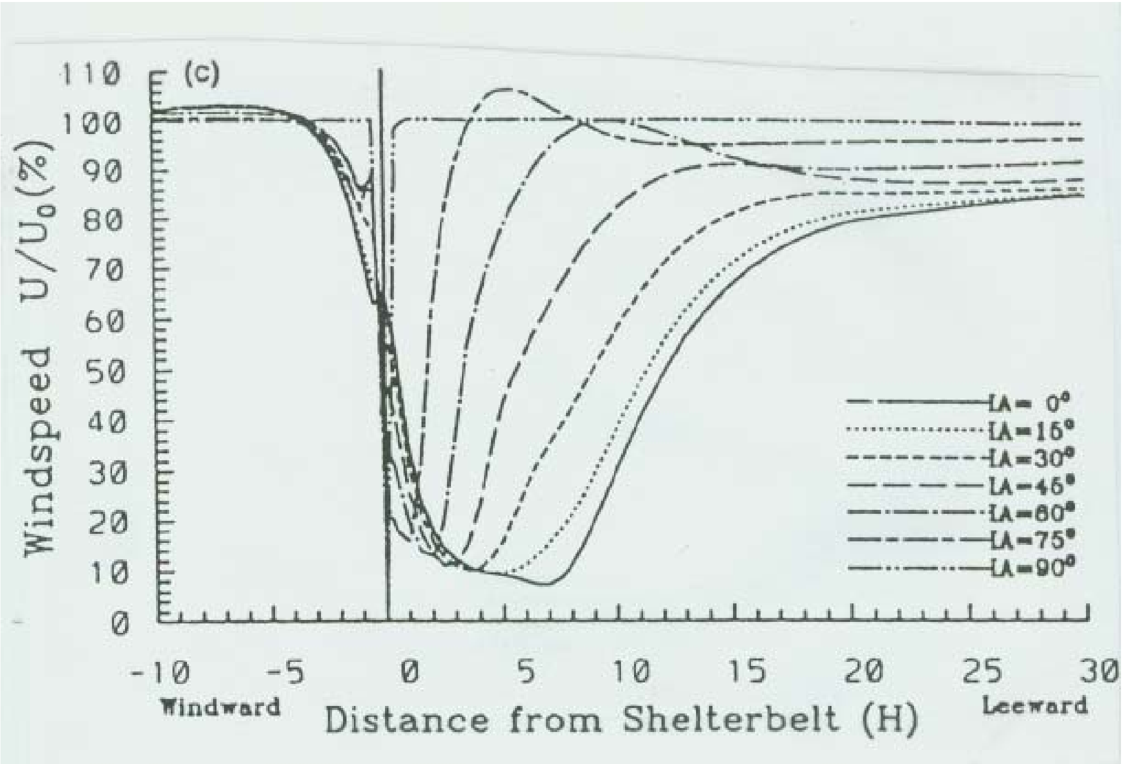


**Figure 3.8 Percentage reduction in windspeed (U) upwind and downwind of a shelterbelt of width 1 H for various attack angles (IA) of the wind. Wind perpendicular to the belt has IA = 0$^o$, and wind parallel to the belt has IA = 90$^o$. The solid vertical line marks the downwind edge of the shelter**

### 2.1 Design factors for windbreaks

Brandle *et al.* (2000) list seven features that determine the effectiveness of a windbreak: height; density; orientation; length; width; continuity or uniformity; and cross-sectional shape. These factors determine the overall size and characteristics of the protected zone. Each will be briefly described.

#### 2.1.1 Height

Windbreak height (H) is the most important factor determining the downwind extent of the sheltered region and usually is employed as the measure of its length. In shelterbelts with species of various heights used throughout the belt, the average height of the tallest species usually is taken to represent H. In plantings with distinct regions of short and tall species, multiple heights may need to be specified (see Section 2.1.5). The protected distance is measured from the most leeward row of trees in the windbreak.

### 2.1.2 Density

Windbreak density is related to the total windbreak volume that is occupied by solid vegetation. The fraction of unoccupied volume of a windbreak, or porosity, is sometimes used to describe the shelter. With these definitions, the sum of the density and porosity is 1.0 (or 100 if expressed as percent). Although simple to define, these factors are difficult to specify for a given shelterbelt.

Wind flows through the open portion of the shelterbelt, so a shelter of higher density allows less air to flow through and forces more air over its top. Figure 3.9 shows that wind passing over the top of the shelter ultimately re-establishes flow patterns similar to those upwind of the shelter. The length of the protected region depends on the shelterbelt density. A solid barrier forces all air to flow up and over its top, creating a downward flow behind the barrier that allows for only a short protected area. On the other hand, a very porous vegetative barrier does little to slow the wind and is not very effective for sheltering purposes. Shelters of "intermediate" density are most effective because they create the largest region of protection. Brandle *et al.* (2000) indicate that multiple-row shelters (2–4 rows) that include conifers can provide this intermediate density. Early studies of shelterbelts referred to three density classes as "loose", "medium" and "dense," which could be approximated, respectively, by a single row of deciduous, a multiple-row (2–4) that includes conifers and a solid wall or many rows of conifers.

Figure 3.10 demonstrates the influence of density (expressed as porosity) on the lateral leeward extent of the sheltered region and the windspeed reduction owing to the shelter. U is windspeed in the lee of the shelter and $U_o$ is the speed at the same location if there were no shelter. This figure shows that very porous shelters are only marginally effective in reducing windspeed. Nearly solid barriers (see porosity equalling 10 percent), by contrast, sharply reduce the windspeed immediately behind the shelter but allow the windspeed to recover to its undisturbed value more quickly, thereby limiting the leeward extent of the sheltered region. A shelter of porosity equalling 50 percent reduces the windspeed to 40 percent of its undisturbed value and creates a protected region of greater length than the shelter of porosity equalling 10 percent.

For numerical models that simulate the detailed characteristics of the flow field through and around the shelter, a more practical measure is the surface area per unit volume (A) of the shelter (Wang and Takle, 1995a). In a physical sense, it is the drag force created by individual plant parts that extracts momentum and energy from the moving air, so the surface area of these plant parts is highly relevant to determining the mechanical influence of the barrier on the flow. Many tree species consist mostly of open space with a shell of leaves or needles at the outer boundary, in which case A is a function of location within the shelterbelt. Some shelterbelts using tall tree species have been deliberately pruned to create open space near the ground to allow modest low-level air penetration in exchange for a longer protected distance. Seasonal changes in the vegetation surface area, such as for deciduous trees, will change A and hence, the sheltering function throughout the year. Leaf-area index (LAI), a biophysical parameter frequently used to describe stands of trees and crops, is sometimes used as a measure of surface area per unit volume of the shelter.

Optical porosity (how dense a shelter "looks") is frequently used to describe a shelter, but this is somewhat misleading because air can easily penetrate a barrier even though light does not easily pass through it.

The density of the shelter, and particularly the presence of gaps in forest belts, also influences how well the trees can survive high winds (Quine, 2003). The processes of gap formation and expansion are related to the spatial and temporal variability in occurrence of strong winds. Once a gap forms it can expand at lower windspeed than that required to form new gaps (Quine, 2003).

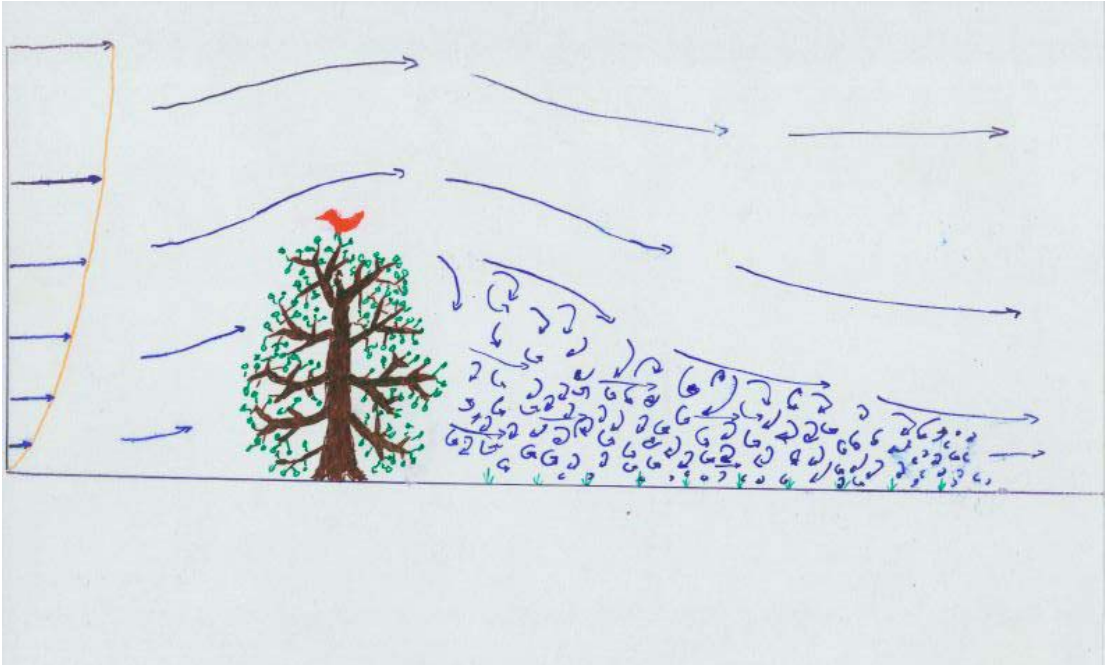

**Figure 3.9 Creation of small-scale turbulence in the wake of a shelter and recovery of the undisturbed flow downwind**

### 2.1.3 Orientation

The maximum downwind protected distance of a shelterbelt is achieved when the belt is oriented perpendicular to the wind. For winds oblique to the shelter, the protected zone is restricted to a region close the leeward edge of the shelter (see Figure 3.8). Wind directions oblique to the shelter at high angle of incidence (nearly parallel to the shelter) can create recirculation vorticies in the lee that can locally *increase* surface windspeeds over those in unprotected areas (Wang and Takle, 1996a).

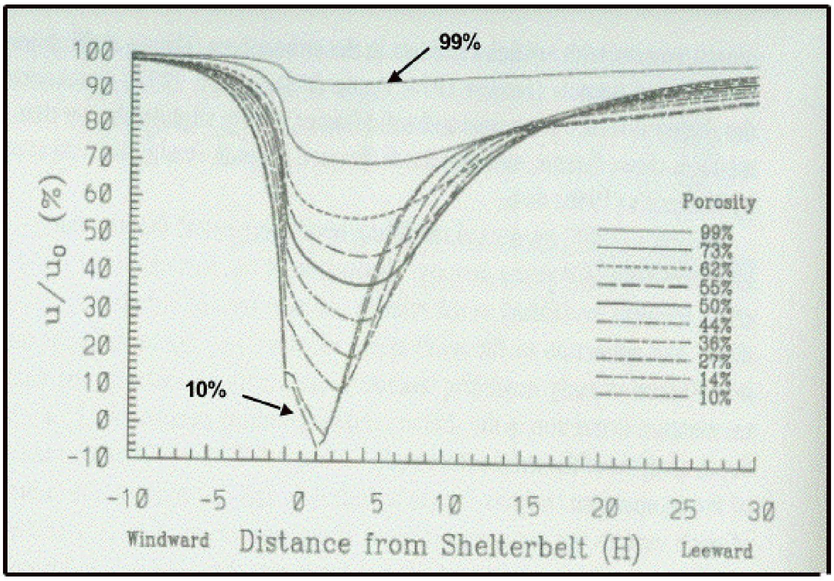


**Figure 3.10 Windspeed reduction behind shelters of width 1 H with porosities ranging from 10 to 90%**

### 2.1.4 Length

The length of a shelterbelt or forest belt is the lateral extent of the barrier in the direction most nearly perpendicular to the wind at the time of high wind occurrences (see Figure 3.11). Wind flow around the lateral edges of a shelterbelt reduces the effectiveness of wind reduction in the protected zone, but increases the lateral influence of the barrier in ways that can increase particle deposition (see Section 2.3.). The length of a shelterbelt should be much greater than H.

### 2.1.5 Width

The width (or thickness) of the shelterbelt is the distance perpendicular to the length (see Figure 3.11) and, together with the density, determines the magnitude of the windspeed reduction. Both observations (Read, 1964) and numerical models (Wang and Takle, 1996b) showed that narrow shelterbelts consisting of two to three rows of trees can create nearly as large a protected zone as much wider belts. As can be seen in Figure 3.12 (Wang *et al.*, 2001) a shelter of width 0.1 H has nearly the same magnitude of windspeed reduction as a shelter 100 times as wide and has a sheltered zone that extends further in the leeward direction. This is an important factor for applications of shelters in locations such as agricultural areas, where it is desirable to remove only minimal land area for planting shelterbelts. For the combined purposes of reducing windspeed, increasing salt deposition and reducing storm surge in coastal areas, however, wider shelters may be more advantageous as will be discussed in later sections.

### 2.1.6 Continuity

Continuity, or uniformity, of the shelter is an indicator of whether there may be localized regions of reduced shelter effect. Gaps in windbreaks tend to compress the flow and create localized jets in the near lee that can have adverse effects in the protected area.

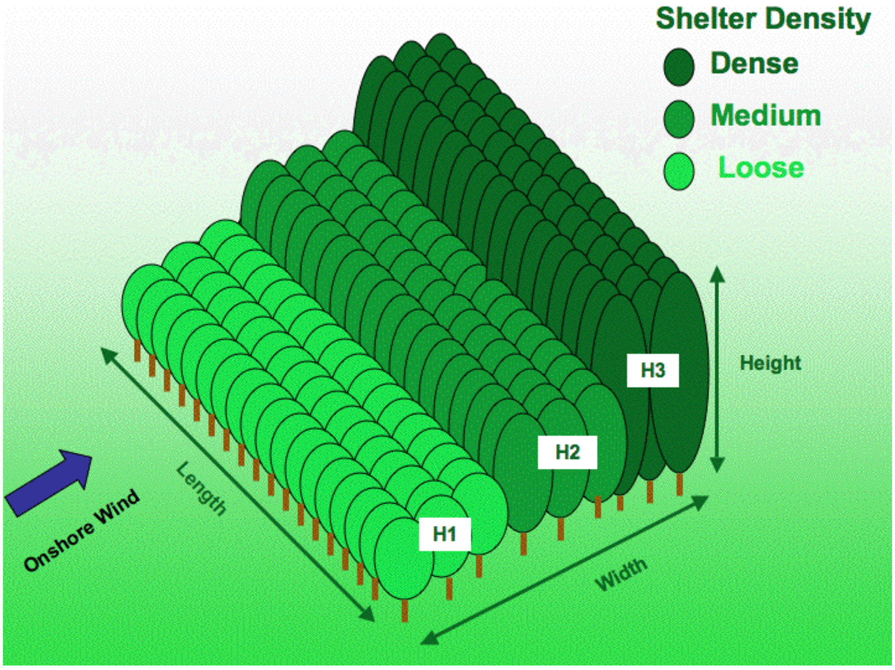


**Figure 3.11 Sketch of a nine-row shelterbelt using three different species with different heights and different densities**

Further downwind, the effect of these gaps is simply to proportionately reduce the wind-sheltering efficiency of the entire belt. Gaps may have less negative impacts on particle deposition (see Section 2.3).