Lecture 3

Design Wind Speed

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The 21st Century Center of Excellence Program

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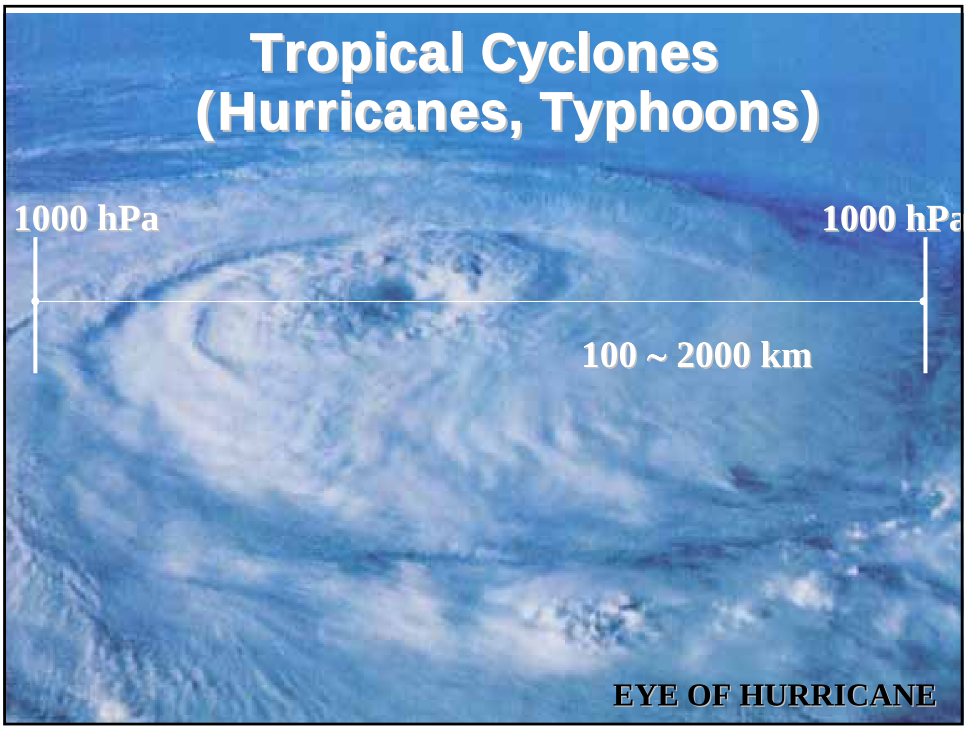
Wind Climates

- Temperature Gradient due to Differential Solar Heating

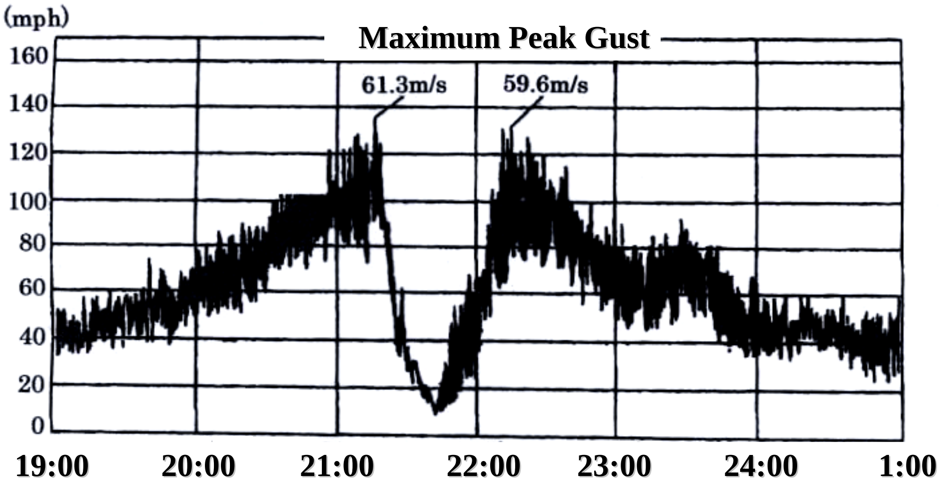
→ Density Difference
  Pressure Gradient

(Conservation of mass/momentum)

- Global Circulations (Hadley, 1973)
- Monsoons
- Frontal Depressions
- Tropical Cyclones (Hurricanes, Typhoons, Cyclones)
- Thunderstorms (Down Bursts)
- Tornadoes
- Devils
- Gravity Winds (Katabatic Winds)
- Lee Waves etc.

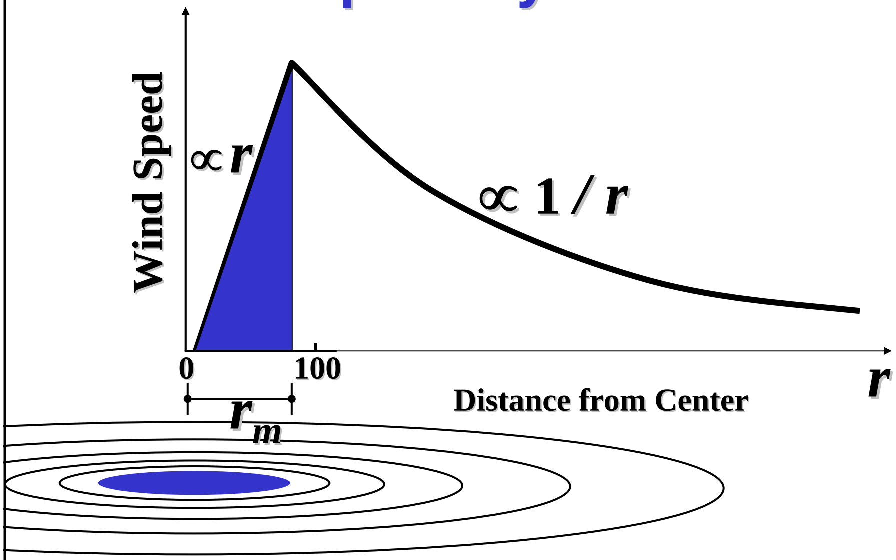


Temporal Variation of Wind Speed (Hurricane Celia, 1970)

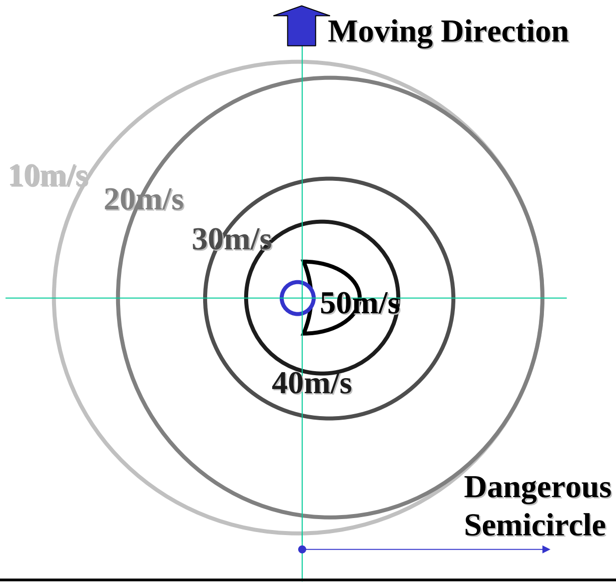


Cook, 1983

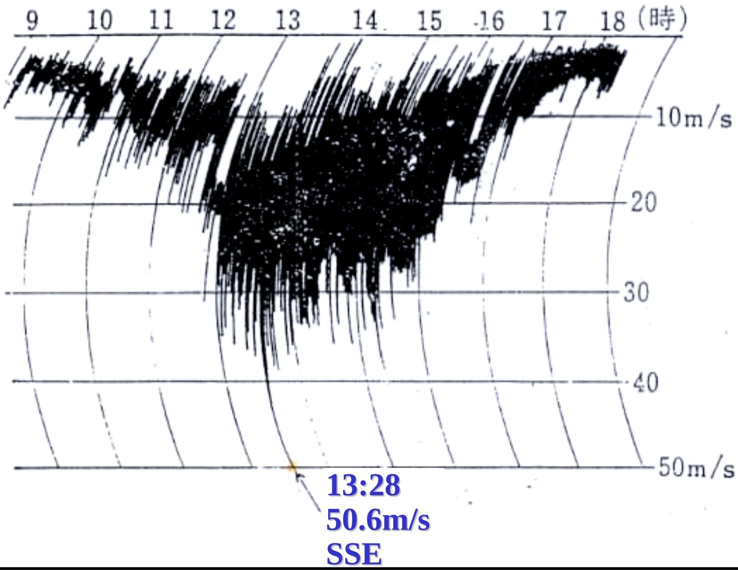
Wind Speed Distribution in Tropical Cyclones



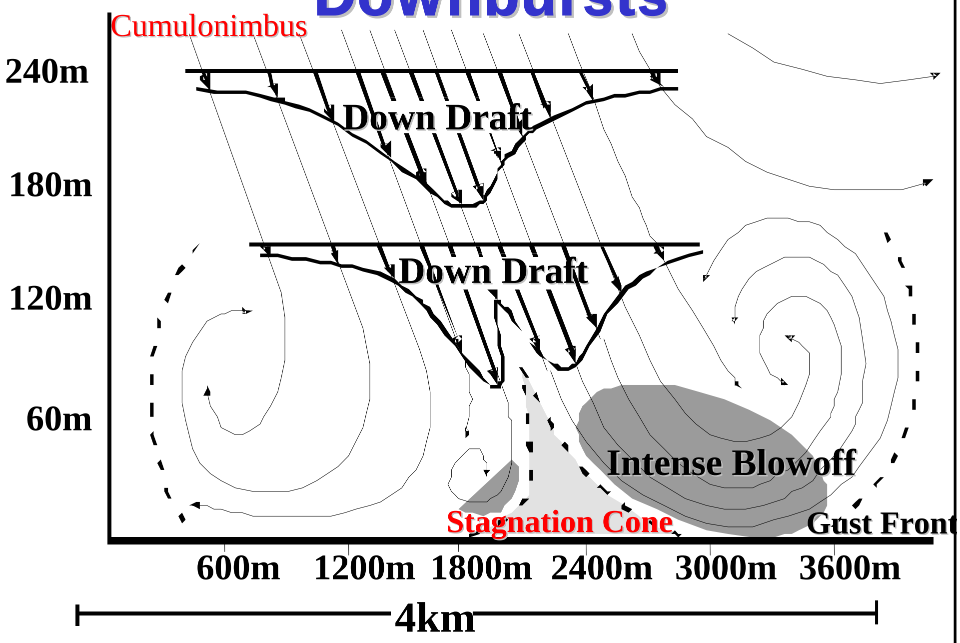
Wind Speed Distribution in Tropical Cyclones



Temporal Variation of Wind Speed (Typhoon)



Downbursts

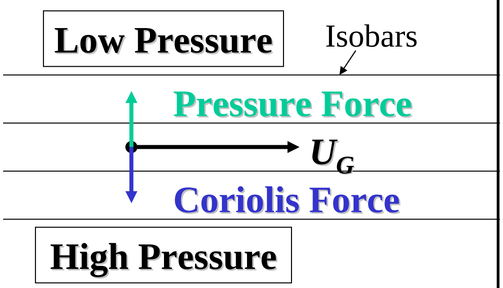


Tornadoes

Geostrophic Wind

Geostrophic Wind Speed U_G

$$-\frac{dp}{dn} + \rho_a U_G f = 0$$



ρ_a : Air Density

f : Coriolis Parameter

$= 2\Omega \sin\phi = 1.454\times10^{-4} \sin\phi$ (rad/s)

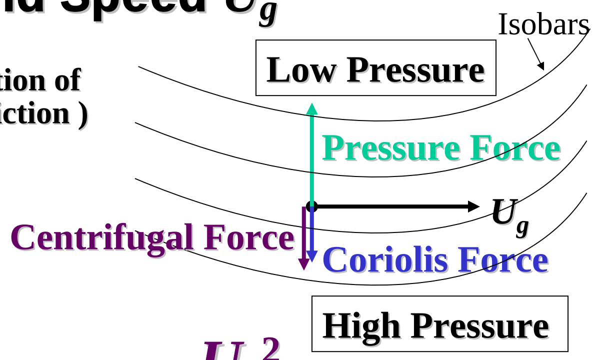
Ω : Earth's Rotational Speed

ϕ : Latitude

Gradient Wind

Gradient Wind Speed U_g

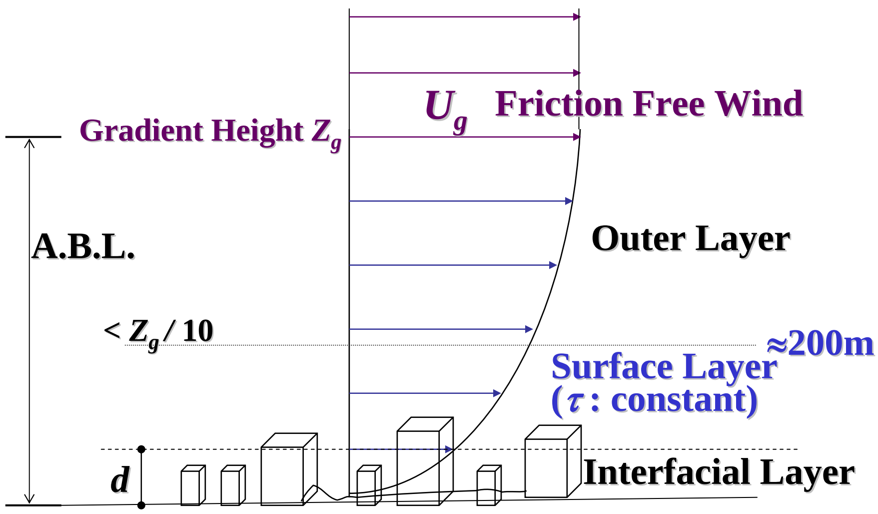
(without consideration of ground surface friction)



$$-\frac{dp}{dn}+\rho_a U_g f+\rho_a\frac{U_g^{\,2}}{r}=0$$

r : Radius of Curvature

Atmospheric Boundary Layer



d : Zero-plane displacement ≈ Average building height

Gradient Wind ($Z > Z_g$)

Pressure Gradient Force
Coriolis Force + Centrifugal Force

Outer Layer ($\approx Z_g/10 < Z < Z_g$)

- **Momentum transfer from Gradient Wind**
- **Momentum delivered to lower altitude due to Friction Effects**
  (Reynolds Stress : Turbulent Transfer)

Strong Wind Condition

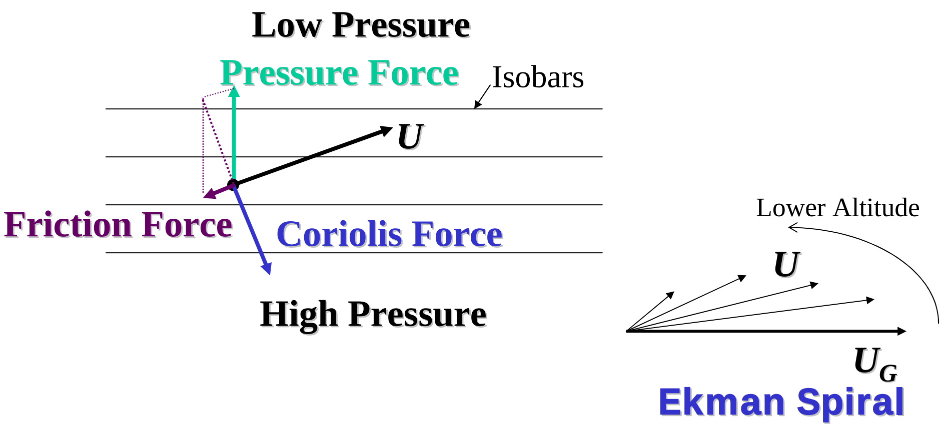
- **Sufficient mixing of air**
- **Thermally neutral condition**
  ($\partial\theta/\partial Z \approx 0$, θ: Temperature)
- **Effects of ground roughness are predominant.**
- **Shear force (Reynolds stress: $\tau = -\rho_a \overline{uw}$) increases from zero at the gradient height Z_g to a maximum at the zero-plane displacement.**
- **Surface shear stress:**
  $\tau_0 = -\rho_a \overline{uw}_{max} = \rho_a u_*^2$
  u_*: Friction velocity

cf. **Boussinesq: Kinetic Eddy Viscosity ε**

$$-\rho_a \overline{uw} = \rho_a \varepsilon \frac{dU}{dz}$$

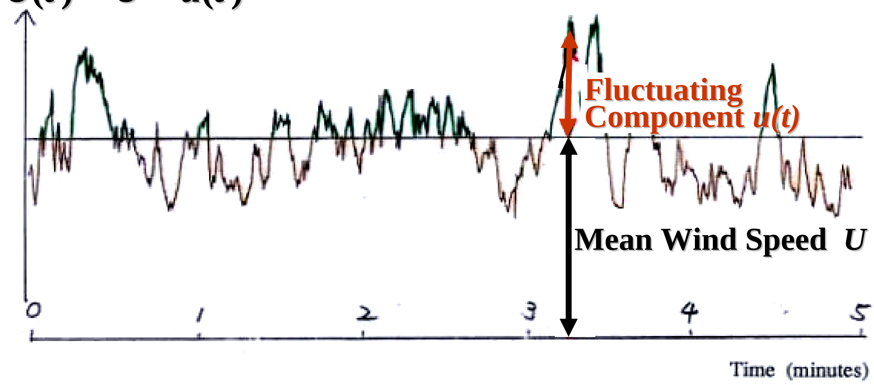
Ekman Layer

Geostrophic Balance With Friction

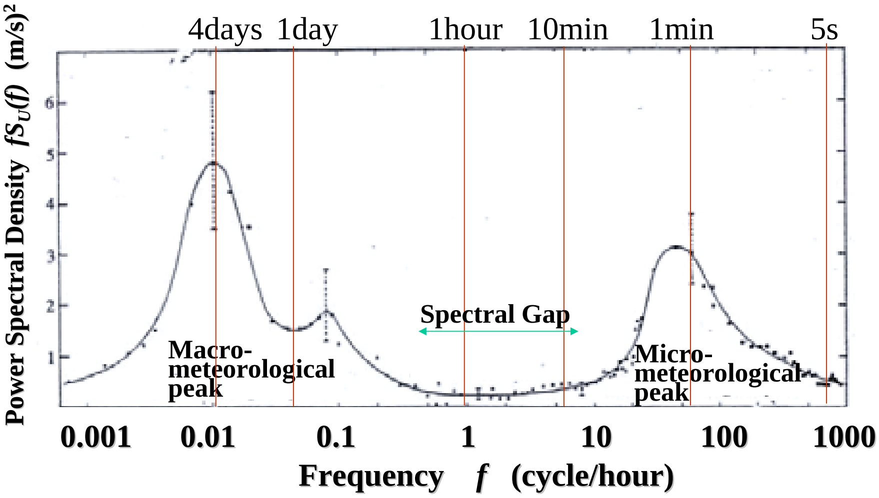


Wind Speed Fluctuation

$U(t) = U + u(t)$



Power Spectrum of Wind Speed
(van der Hoven for Brookhaven, 1957)



Long Term and Short Term Fluctuations

Averaging Time of Wind Speed

T = 10min (Japan, ISO4354, etc.) – 1hour

Long Term Fluctuation *T* > 10min – 1hour

--- Variation of Mean Wind Speed
(Design Wind Speed)

--- Static Effects on Buildings

Short Term Fluctuation *T* < 10min – 1hour

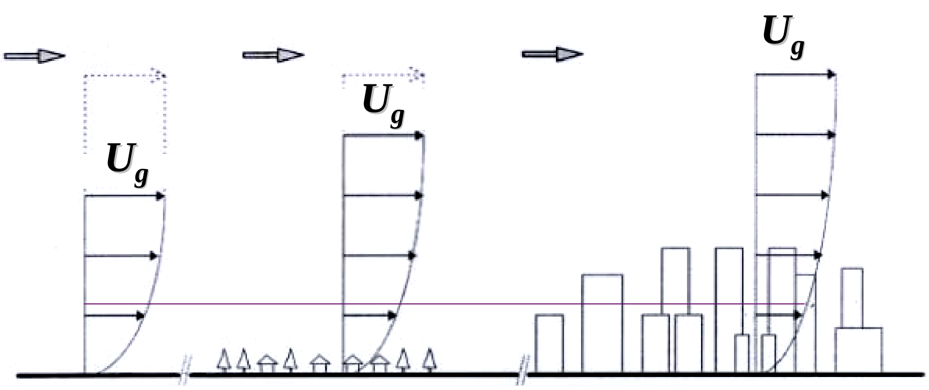
--- Turbulence or Gust

--- Dynamic Effects on Buildings

Mean Wind Speed Structure

- Geographical Location
- Ground Roughness and Height
- Topographic Effects
- Direction
- Seasonal Variation
- Return Period
- etc.

Wind Speed Profile



Wind Speed Profile
(Theoretical Approach)

- **Surface Layer**

$$U = \frac{u_*}{k}\{ \ln(\frac{Z-d}{z_0}) + A \}$$

Law of Wall (Prandtl, 1932)

- **Near Gradient Height**

$$U_g = \frac{u_*}{k}\{ \ln(\frac{u_*}{f z_0}) - B \}$$

Velocity Defect Law (Karman, 1930)

z_0 : Roughness length, u_*: Friction velocity
k : Karman constant (≈ 0.4)
f : Coriolis parameter, A, B : Empirical constants

Wind Speed Profile in Codes

- **Log Law**

$$U = \frac{u_*}{k}\ln(\frac{Z-d}{z_0})$$

- Uniform roughness & Constant τ

- **Power Law** (fully empirical)

$$U = U_r(\frac{Z-d}{Z_r})^{\alpha}$$

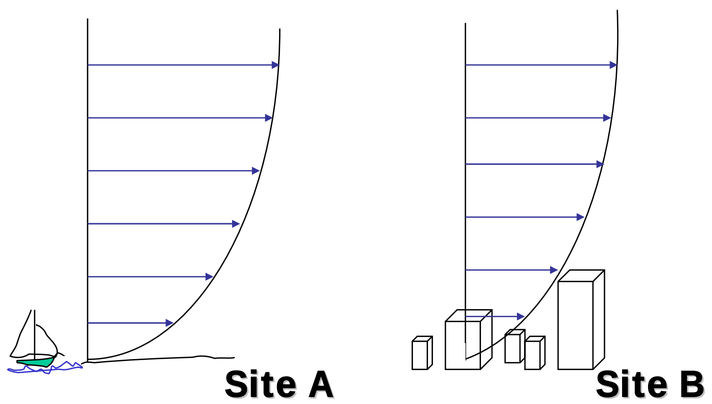
z_0 : Roughness length, u_*: Friction velocity
k : Karman constant (≈ 0.4)
d : Zero-plane displacement (0 ~ 0.75$\bar{H}$)
U_r: Wind speed at reference height Z_r
Z_r: Reference height, α : Power-law index

- **Deaves & Harris Model** (log + polynomial)

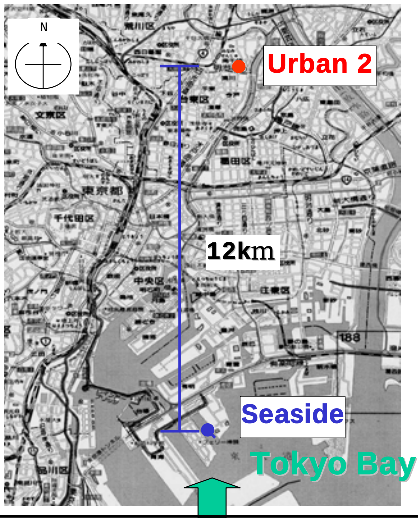
Wind Speed Profile (Field Data)

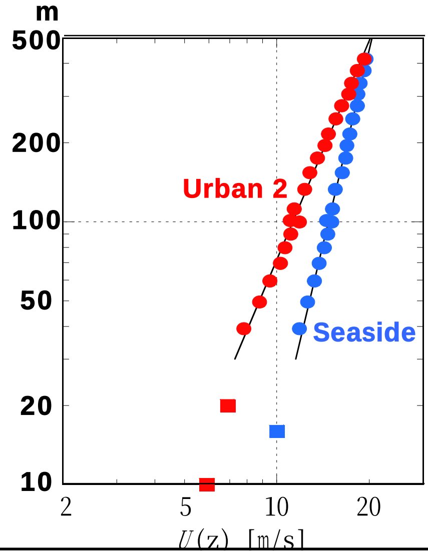
Terrain	z_0	α
sea, mudflats, snow covered flat land, etc.	0.0005m - 0.003m	0.1 - 0.13
flat open countryside, fields with crops, fences and few trees, etc. (Meteorological Standard)	0.003m - 0.2m	0.14 - 0.2
dense woodland, domestic housing, suburban area	0.2m -1m	0.2 - 0.25
city	1m -2m	0.25 - 0.3
large city center	2m - 4m	0.3 - 0.5

- **Wind speed difference between two sites with different roughnesses**

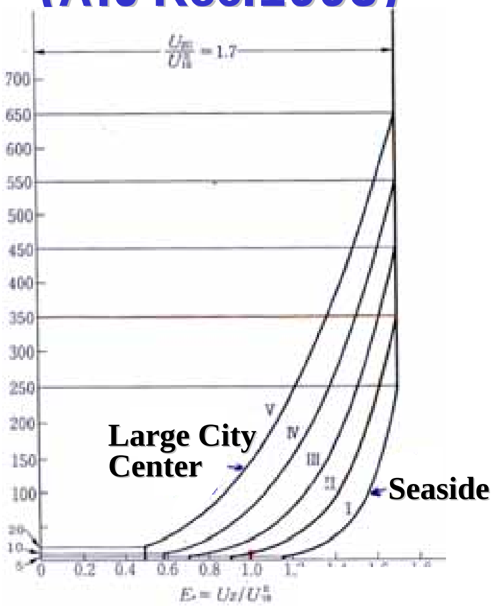


Wind Speed Profiles at Two Sites with Different Roughnesses



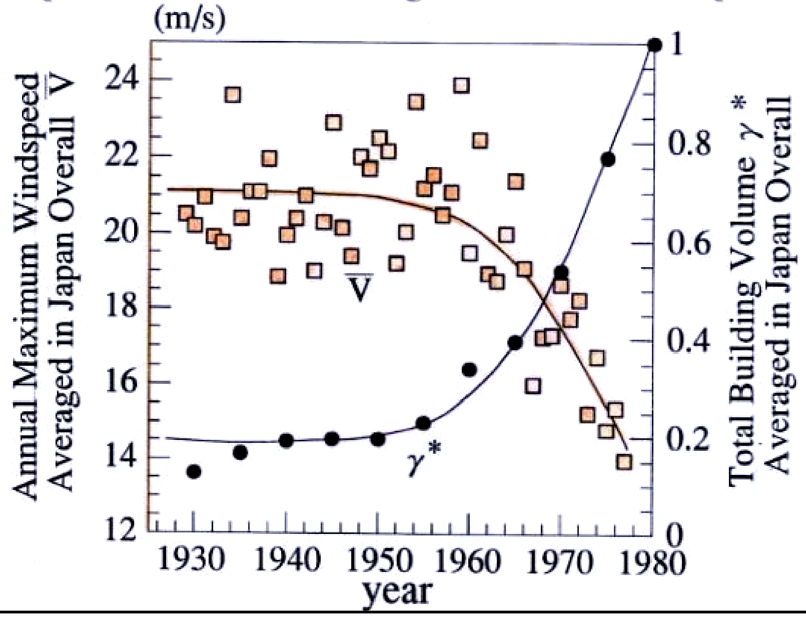


Wind Speed Profile
(AIJ Rec.1993)

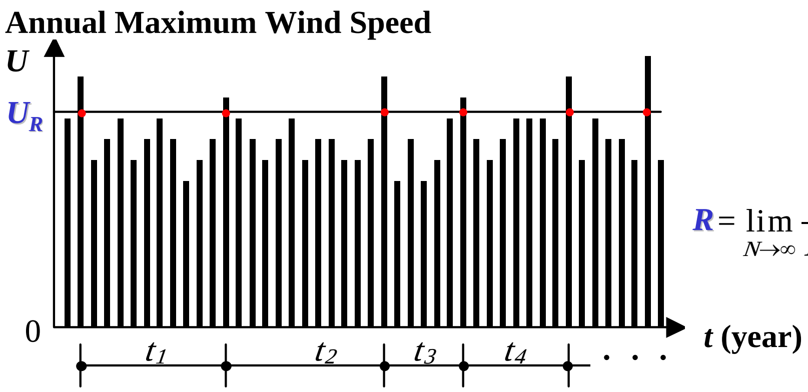


AIJ 1993

Yearly Variation of Annual Maximum Wind Speed and Building Volume in Japan



Return Period : *R*



$$R = \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{N} t_i$$

Return Period ***R*** = Mean Time Between Failure (MTBF)

Wind Speed U_R and Return Period R

Wind Speed U_R (m/s)	26	28	34	37	42	52
Return Period R (years)	5	10	50	100	500	1000

Tokyo

Annual probability of exceedence of wind speed U_R:

$$Q(U_R) = \frac{1}{R}$$

Probability of non-exceedence (CDF) of wind speed U_R :

$$P(U_R) = 1 - \frac{1}{R}$$

R-year Recurrence Wind Speed U_R

Probability of exceedence of U_R during Building's Life Time, e.g. T_L = 50 years

$$Q(U_R: T_L) = 1 - P(U_R)^{T_L} = 1 - (1 - \frac{1}{R})^{T_L}$$

R (years)	50	100	500	1000
$Q(U_R$: 50)	63.6%	39.5%	9.5%	4.9%

(T_L = 50 years)

Extreme Value Analysis

(Asymptotic Form: Cumulative Distribution Function)

- **Fisher-Tippett Type I (Gumbel Distribution)**

  CDF: $P(U) = \exp[-\exp\{-a(U-b)\}]$

  $1/a$: dispersion, b : mode

- **Fisher-Tippett Type II (Frechet Distribution)**

  CDF: $P(U) = \exp\{-(\frac{c}{U-\varepsilon})^{\gamma}\}$

  - having lower limit : ε

- **Fisher-Tippett Type III (Weibull Distribution)**

  CDF: $P(U) = \exp\{-(\frac{U-w}{v-w})^{\gamma}\}$

  - having upper limit : w

Gumbel Distribution

CDF: $P(U_R) = \exp[-\exp\{-a(U_R-b)\}]$

$1/a$: dispersion, b : mode

- **Cumulative Distribution Function of R-year Recurrence Wind Speed U_R**

  $$P(U_R) = 1 - \frac{1}{R}$$

- **R-year Recurrence Wind Speed Based on Gumbel Distribution**

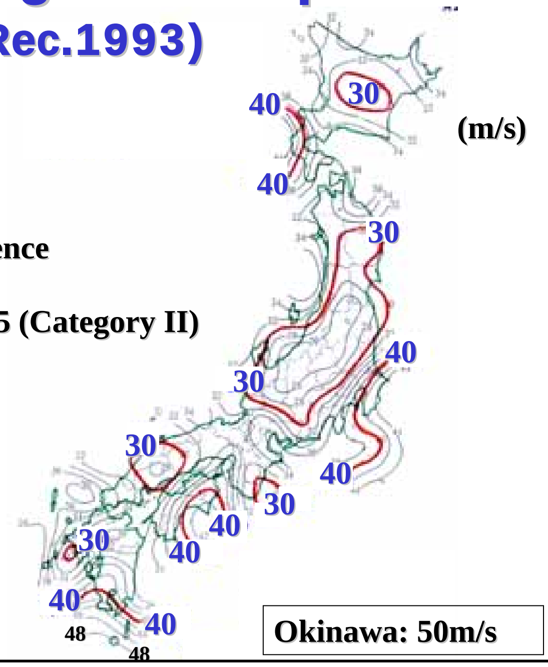
  $$U_R = -\frac{1}{a}\ln\{-\ln(1-\frac{1}{R})\} + b$$

- **Modified *Jensen-Franck Method* (Cook, 1982) (Individual Storms, Gumbel, Threshold)**

Basic Design Wind Speed in Japan

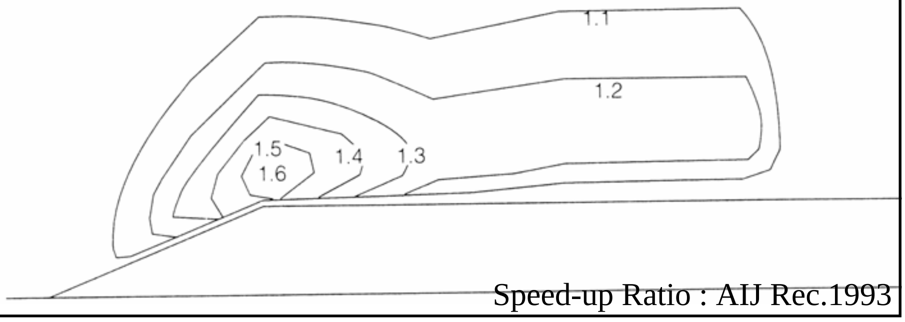
(AIJ Rec.1993)

- 100-year Recurrence
- 10-min Mean
- Z =10m, α = 0.15 (Category II)



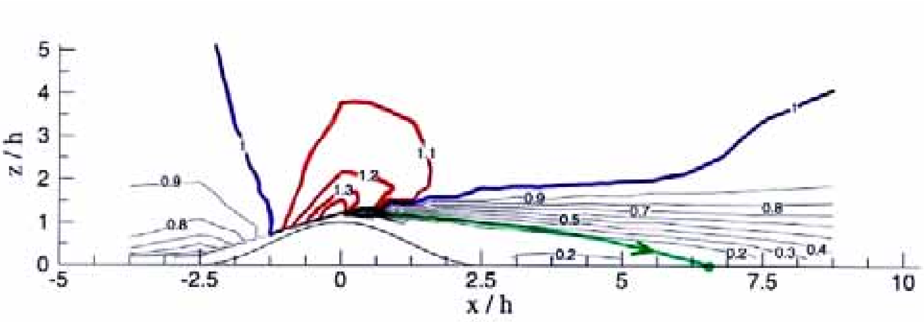
Topographic Effects

- Escarpments
- Cliffs
- Ridges
- Hills
- Valleys
  - Speed-up Ratio (Mean Wind Speed)
  - Turbulence



Speed-up Ratio : AIJ Rec.1993

Topographic Effects

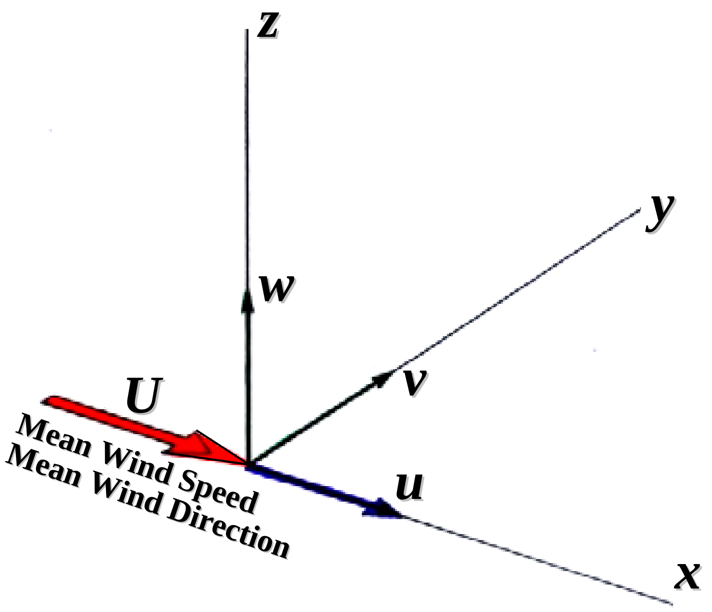


Fluctuating Wind Speed Structure

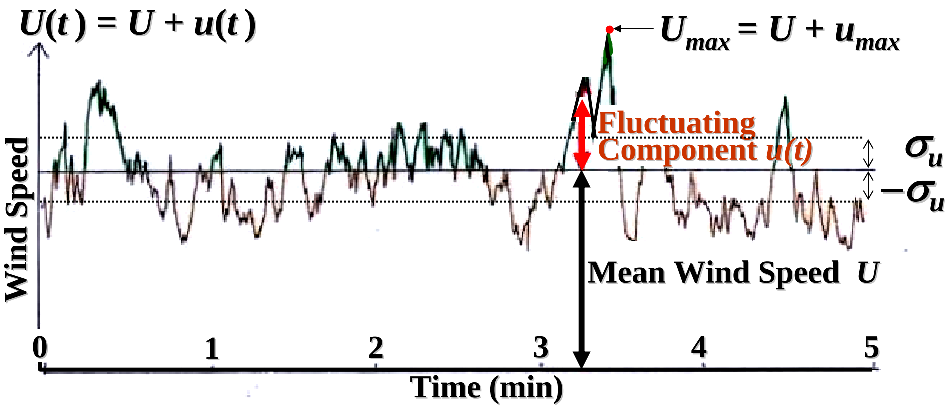
- Gust Factor / Peak Factor
- Power Spectrum
- Spatial- / Temporal- Correlation

  Taylor's Hypothesis of Frozen Turbulence
- Turbulence Intensity
- Turbulence Scale

Wind Speed Components



Temporal Variation of Wind Speed



Turbulence Intensity I_u

$$I_u = \frac{\sigma_u}{U} \quad , \qquad \sigma_u^2 = \int_{-\infty}^{\infty} S_u(f)\,df$$

Gust Factor and Peak factor

- **Gust Factor: G_U**

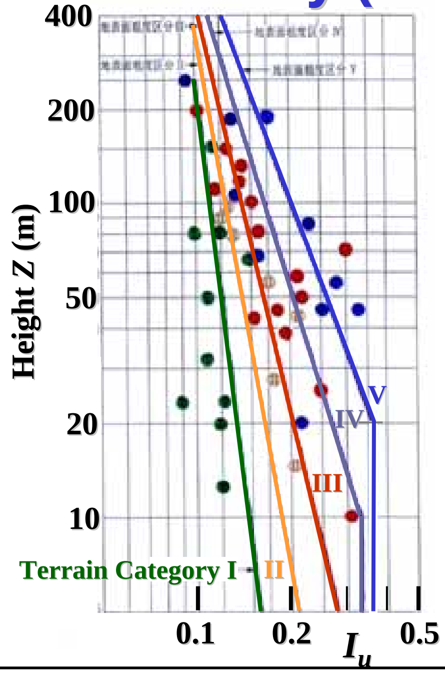
$$G_U = \frac{U_{max}}{U} = \frac{U + u_{max}}{U}$$

- **Peak Factor: g_U**

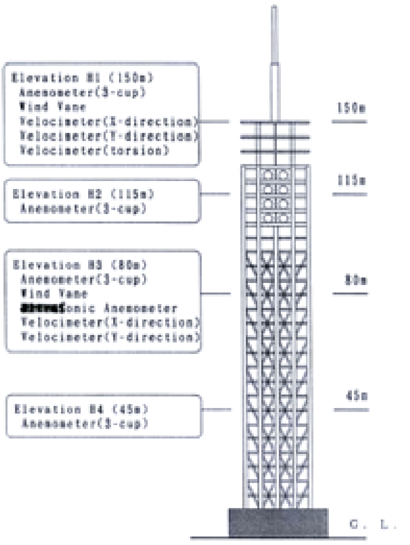
$$g_U = \frac{u_{max}}{\sigma_u}$$

- $G_U = 1 + \dfrac{u_{max}}{U} = 1 + g_U \dfrac{\sigma_u}{U} = 1 + g_U I_U$

Turbulence Intensity (AIJ Rec.1993)

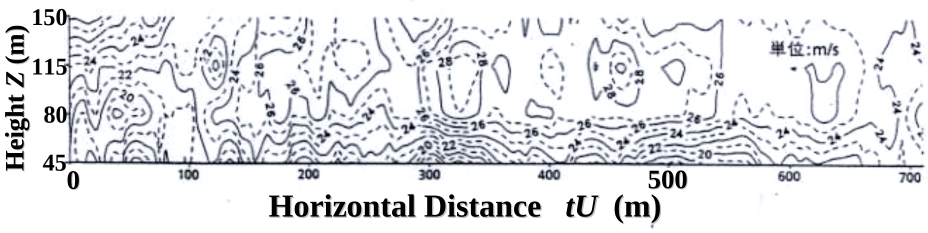


Wind Speed Measurement

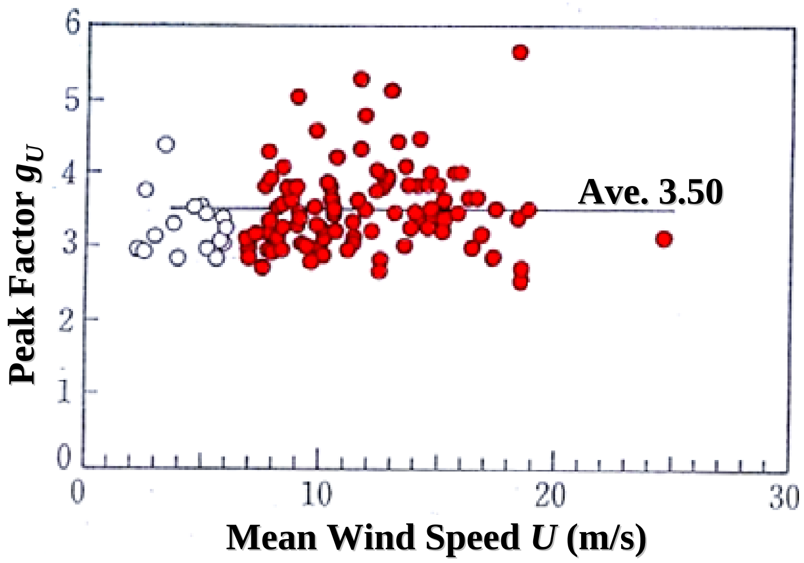


A sketch of Communication Tower & Elevation of Wind Observation

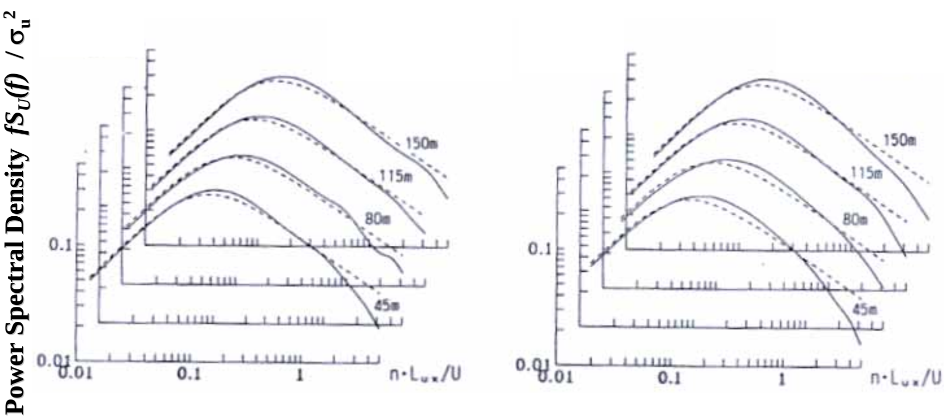
Spatial & Temporal Variations of Wind Speed



Peak Factor of Wind Speed

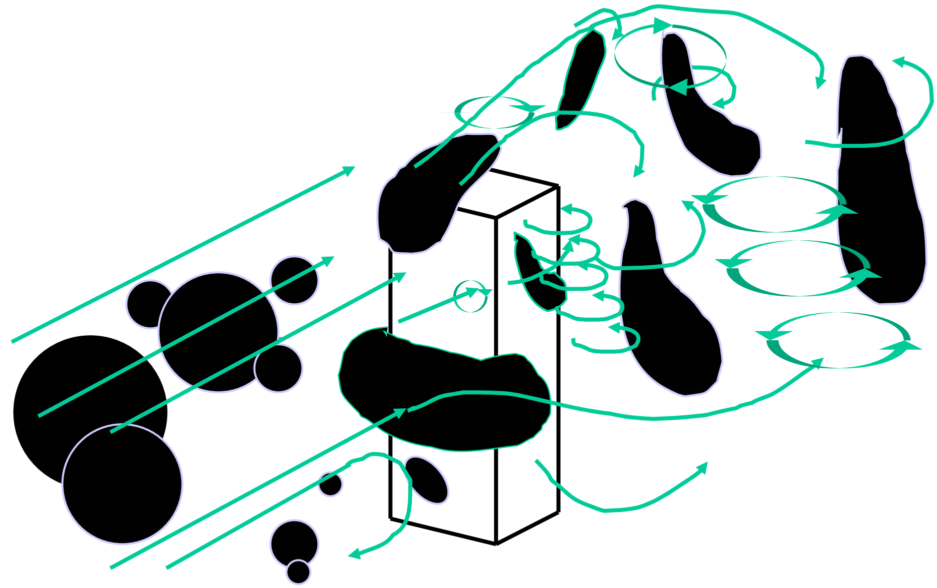


Power Spectrum of Wind Speed



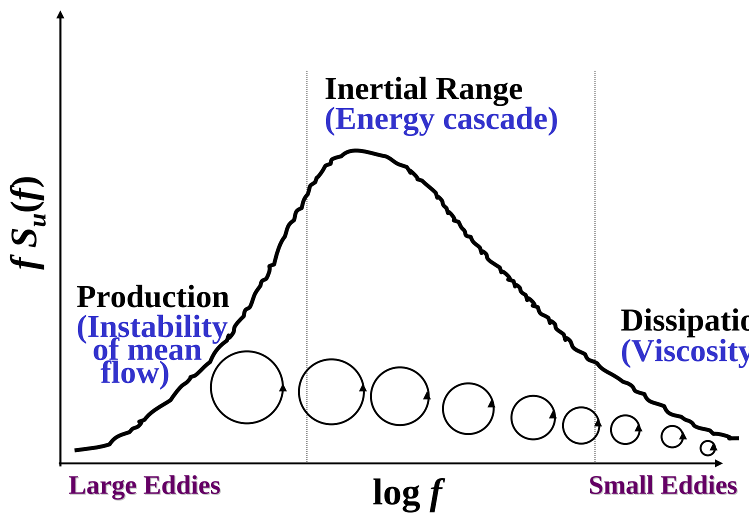
Typhoon

Frontal Depression



Schematic view of turbulence

Turbulence Spectrum



Cook, 1983

Power Spectrum of Wind Speed
(Fichtl-McVehill Model)

$$\frac{f\,S_u(f)}{\sigma_u^{\,2}} = \frac{4\,f^*}{(1 + a\,f^{*\beta})^{\frac{5}{3\beta}}}$$

Gamma Function

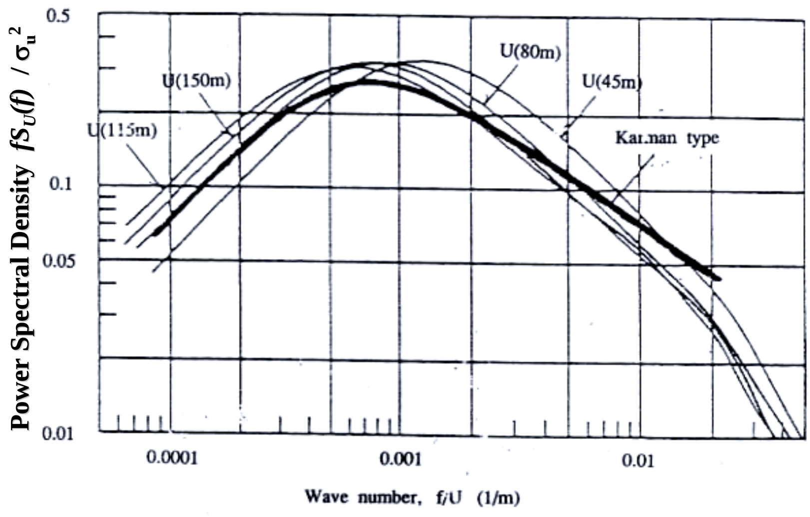
$$f^* = \frac{f\,L_{ux}}{U}, \quad a = 1.5\frac{4^{\beta}}{b^{\beta}}, \quad b = \frac{1.5^{(1/\beta)}\beta\,\Gamma(5/3\beta)}{\Gamma(1/\beta)\,\Gamma(2/3\beta)}$$

$\beta = 1$ (Kaimal Spectrum)
$\beta = 5/3$ (Panofsky Spectrum)
$\beta = 2$ (Karman Spectrum)

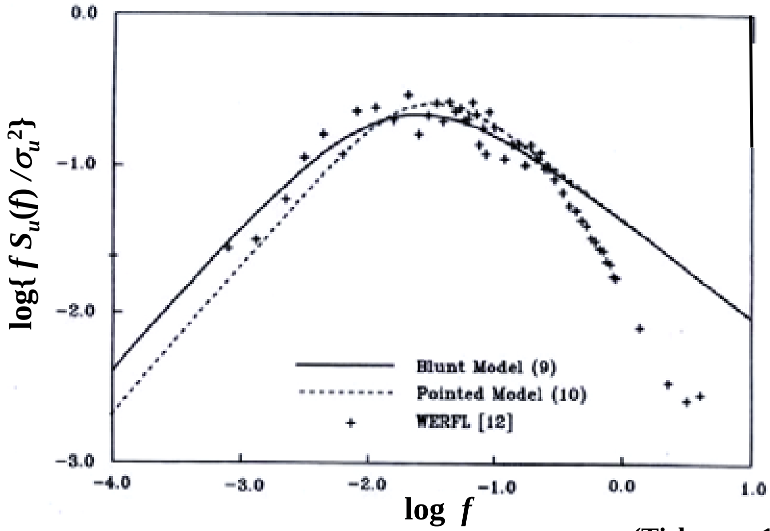
$$f \to \infty \qquad S_u(f) \propto f^{-\frac{5}{3}}$$

(Kolmogorov's Hypothesis of Local Isotropy,
Power of –5/3 Law in Inertial Subrange)

Power Spectrum of Wind Speed



Power Spectrum of Wind Speed (TTU)



(Tieleman, 1995)

Power Spectrum of Wind Speed

(Tieleman,1995)

$$\frac{f\,S_u(f)}{u_*^2} = \frac{A\,f^{*\gamma}}{(C + B\,f^{*\alpha})^{\beta}}$$

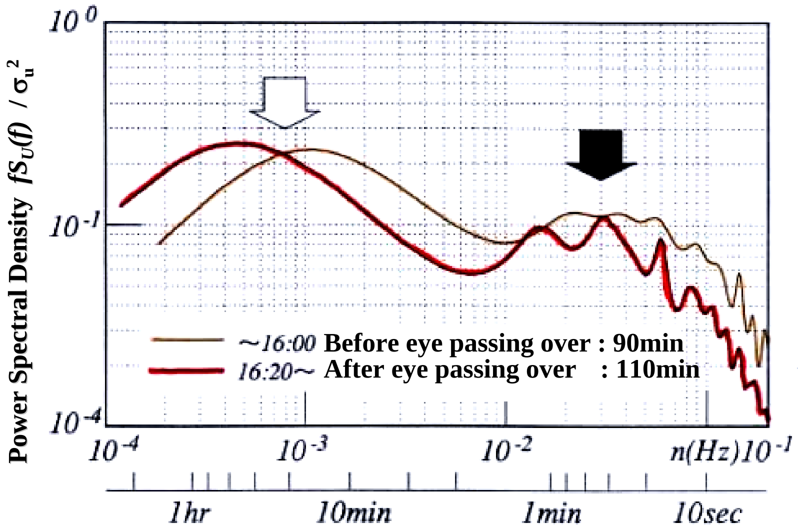
$$f^* = \frac{f\,Z}{U}$$

Z = Height

$\alpha = 1,\quad \beta = 5/3,\quad \gamma = 1$ (Blunt Model)

$\alpha = 5/3,\quad \beta = 1,\quad \gamma = 1$ (Pointed Model)

Power Spectrum of Wind Speed (Typhoon 9119)



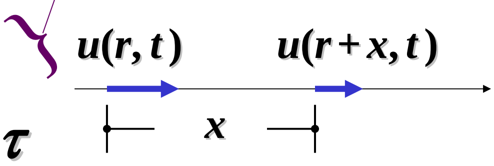
Turbulence Scale

Taylor's Hypothesis of Frozen Turbulence

- **Average Scale of Fluctuation**

$$L_{ux} \equiv \int_0^{\infty} R_{uu}(x)\mathrm{d}x$$

$$= U\int_0^{\infty} R_{uu}(\tau)\mathrm{d}\tau$$



$R_{uu}(x)$: Spatial Correlation Coefficient of $u(t)$

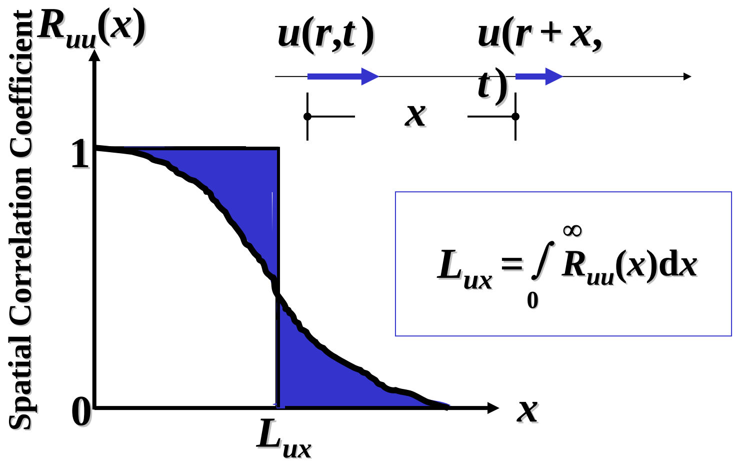
$$= \overline{u(r,t)u(r+x,t)}/\sigma_u^2$$

$R_{uu}(\tau)$: Auto-correlation Coefficient of $u(t)$

$$= \overline{u(r,t)u(r,t+\tau)}/\sigma_u^2$$

Turbulence Scale

- **Average Scale of Fluctuation**



Turbulence Scale

- **Wiener-Khintchine Relation**

$$S_u(f)/\sigma_u^2 = \int_{-\infty}^{\infty} R_{uu}(\tau)\exp(-i\,2\pi f\tau)\mathrm{d}\tau$$

$$S_u(0)/\sigma_u^2 = 2\int_0^{\infty} R_{uu}(\tau)\mathrm{d}\tau = 2L_{ux}/U$$

- **Turbulence Scale**

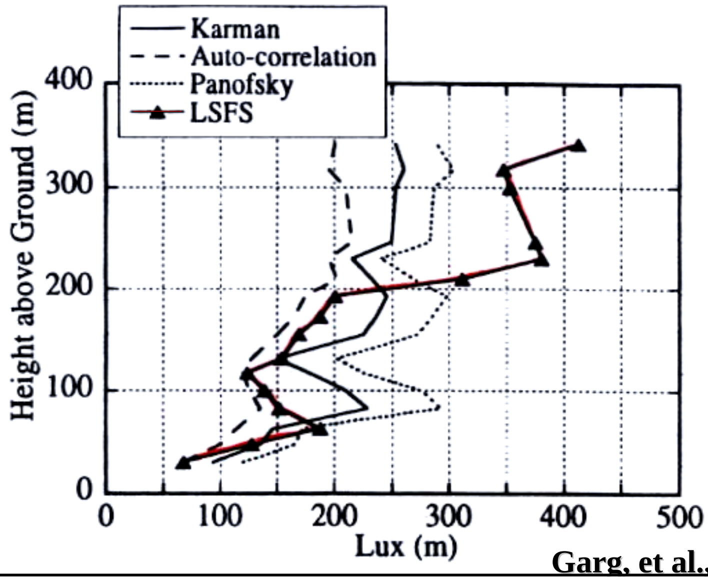
$$L_{ux} = US_u(0)/2\sigma_u^2$$

- **Isotropic Turbulence Field**

$$L_{ux} = 2L_{uy} = 2L_{uz}$$

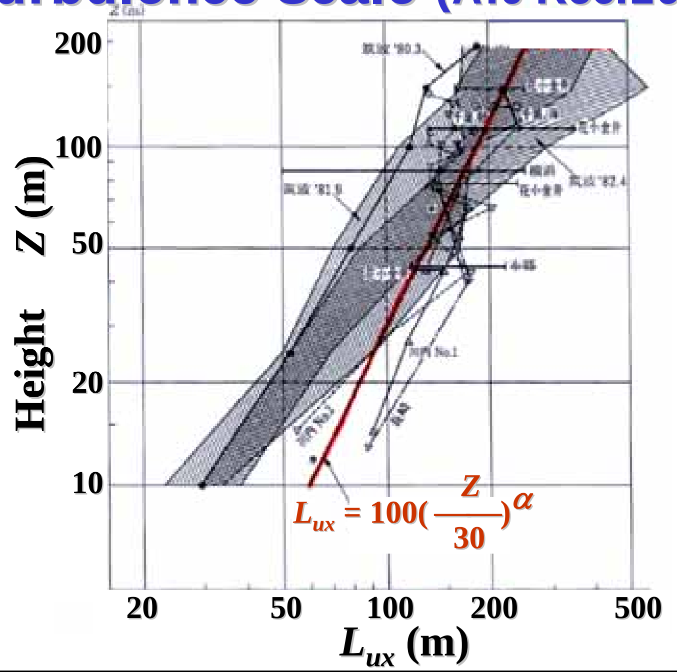
(Near Ground: $L_{ux} \approx 3L_{uz}$)

Turbulence Scale (TTU)

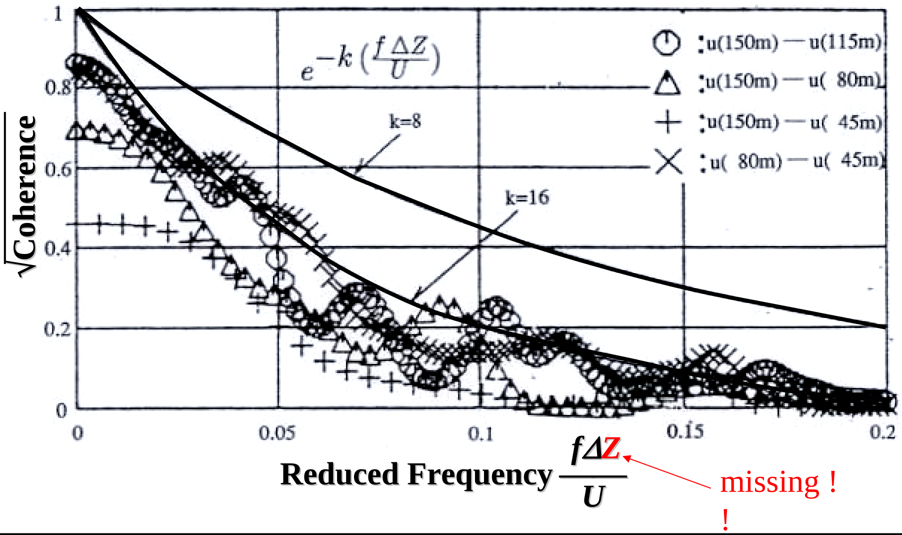


Garg, et al., 1995

Turbulence Scale (AIJ Rec.1993)



Correlation of Wind Speed (Root Coherence)



Correlation of Wind Speed (Root Coherence)

$$\sqrt{\text{Coherence}} \approx \exp\left(-\frac{\sqrt{k_y^2 y^2 + k_z^2 z^2}}{\sqrt{U_1 U_2}} f\right)$$