BUILDING AERODYNAMICS

BME GEÁT MW08

Wind in the atmosphere

* * *

The atmospheric boundary layer

MŰEGYETEM 1782

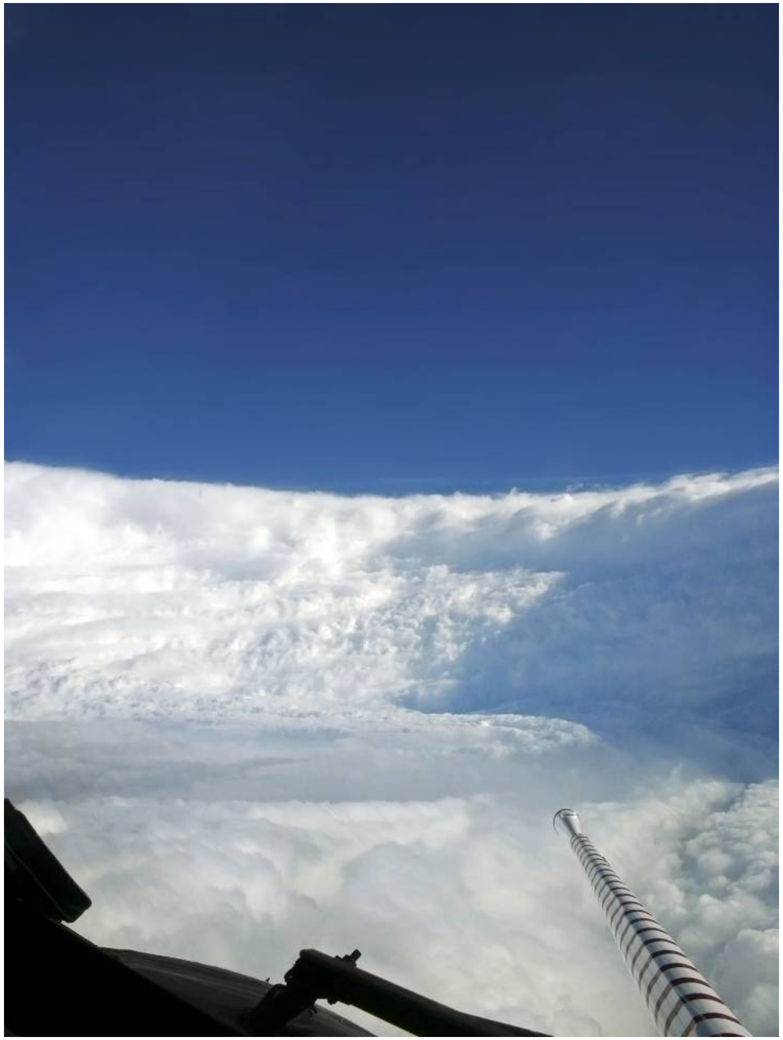
Kármán Tódor
Szélcsatorna
Laboratórium

Dr. Goricsán István, 2008
Balczó Márton, Balogh Miklós, 2009
Budapesti Műszaki és Gazdaságtudományi Egyetem, Áramlástan Tanszék

TROPICAL CYCLONES

Hurricane (Atlantic Ocean), typhoon (Indian Ocean), Cyclone (Pacific Ocean)

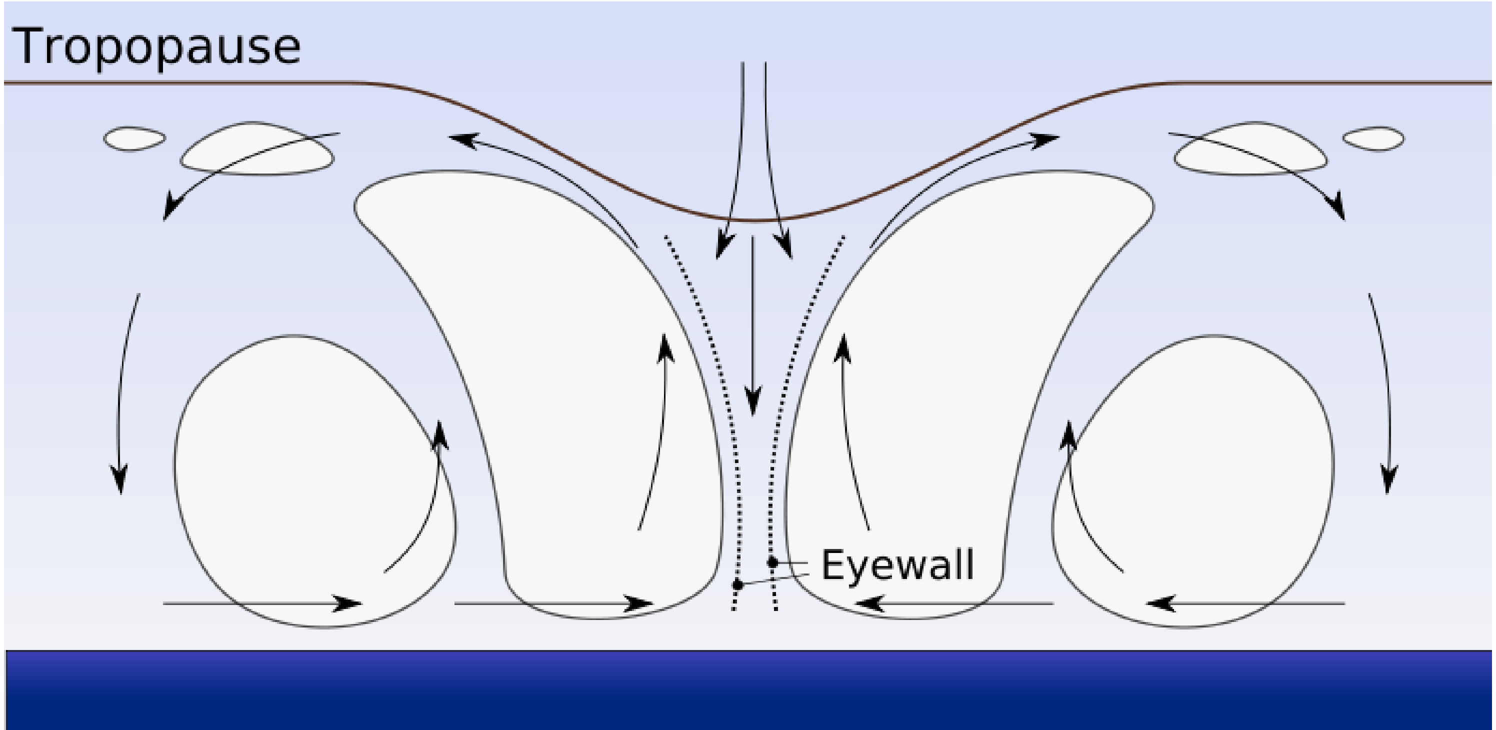
The tropical cyclone ***Catarina*** near the shore of Brazil, photographerd from the International Space Station, March 26, 2004



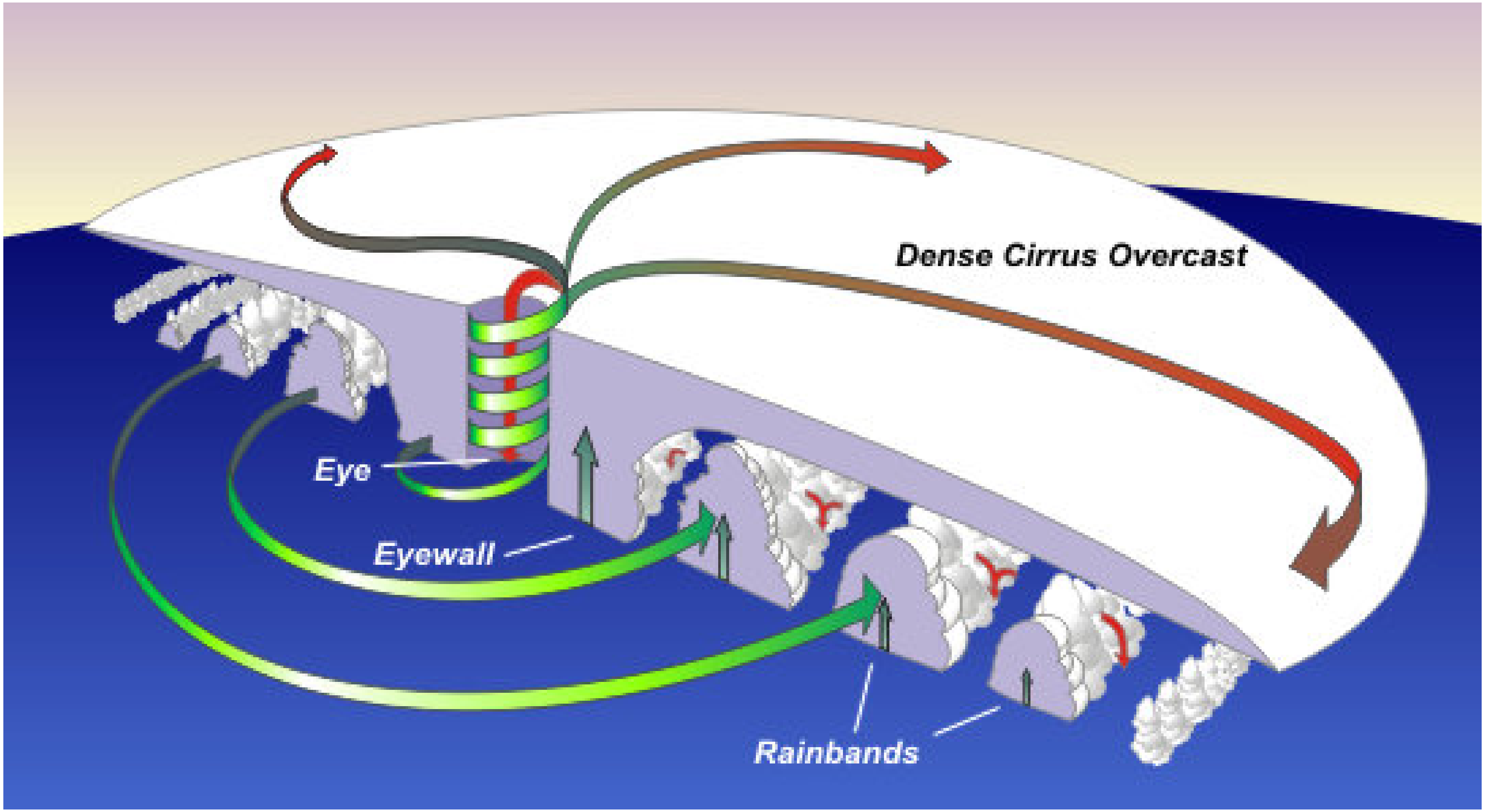
Eye of hurricane ‘Katrina’ Aug 28, 2005 photographed from an airplane.

TROPICAL CYCLONES

- From 26°C ocean temperature > very high evaporation
- Warm air transported by convection up to the tropopuse ⇨ condensation ⇨ relase of latent heat ⇨ further heating further uprise ⇨ low pressure at the sea surface ⇨ inducing strong horizontal flows to the eye (positive feedback)
- Warm dry air is entering the centre from above ⇨ the hurricane’s eye
- Pressure difference 50 - 100mbar compared to the environment
- A hurrican is a thermodynamic machine cooling the ocean and transporting heat and moisture into the higher levels of the atmosphere

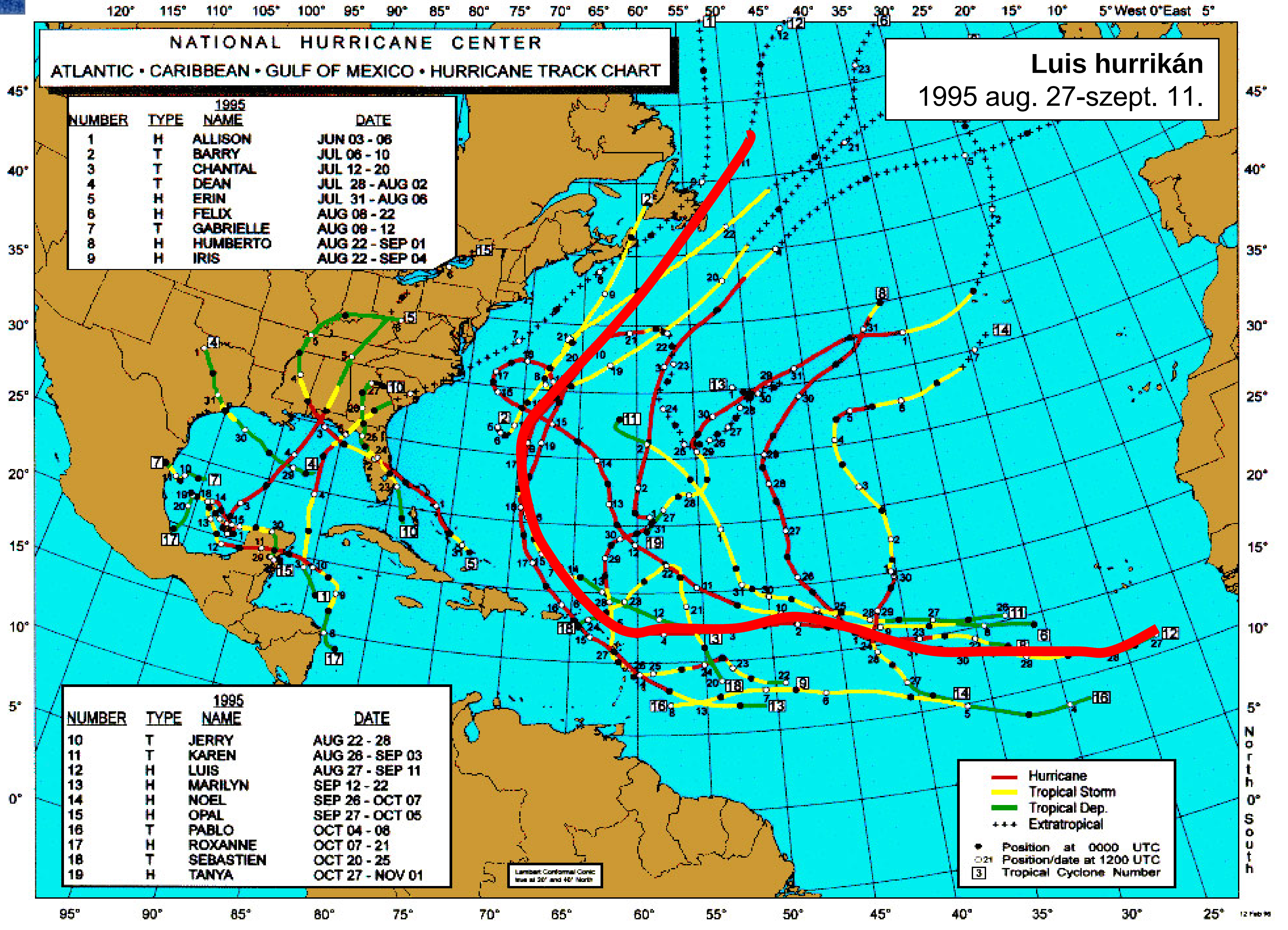


TROPICAL CYCLONES



- Eye 15-40 km diamater
- Eyewalls: max. speed 200-300 km/h. Moving velocity: 20-30km/h
- High level outflow is counter-rotating
- if reaching solid terrain, the driving force, latent heat transport is prohibited
- If heading north, gets weakes and turns into an extratropical storm.

TROPICAL CYCLONES



Luis hurrikán
1995 aug. 27-szept. 11.

NATIONAL HURRICANE CENTER

ATLANTIC • CARIBBEAN • GULF OF MEXICO • HURRICANE TRACK CHART

1995

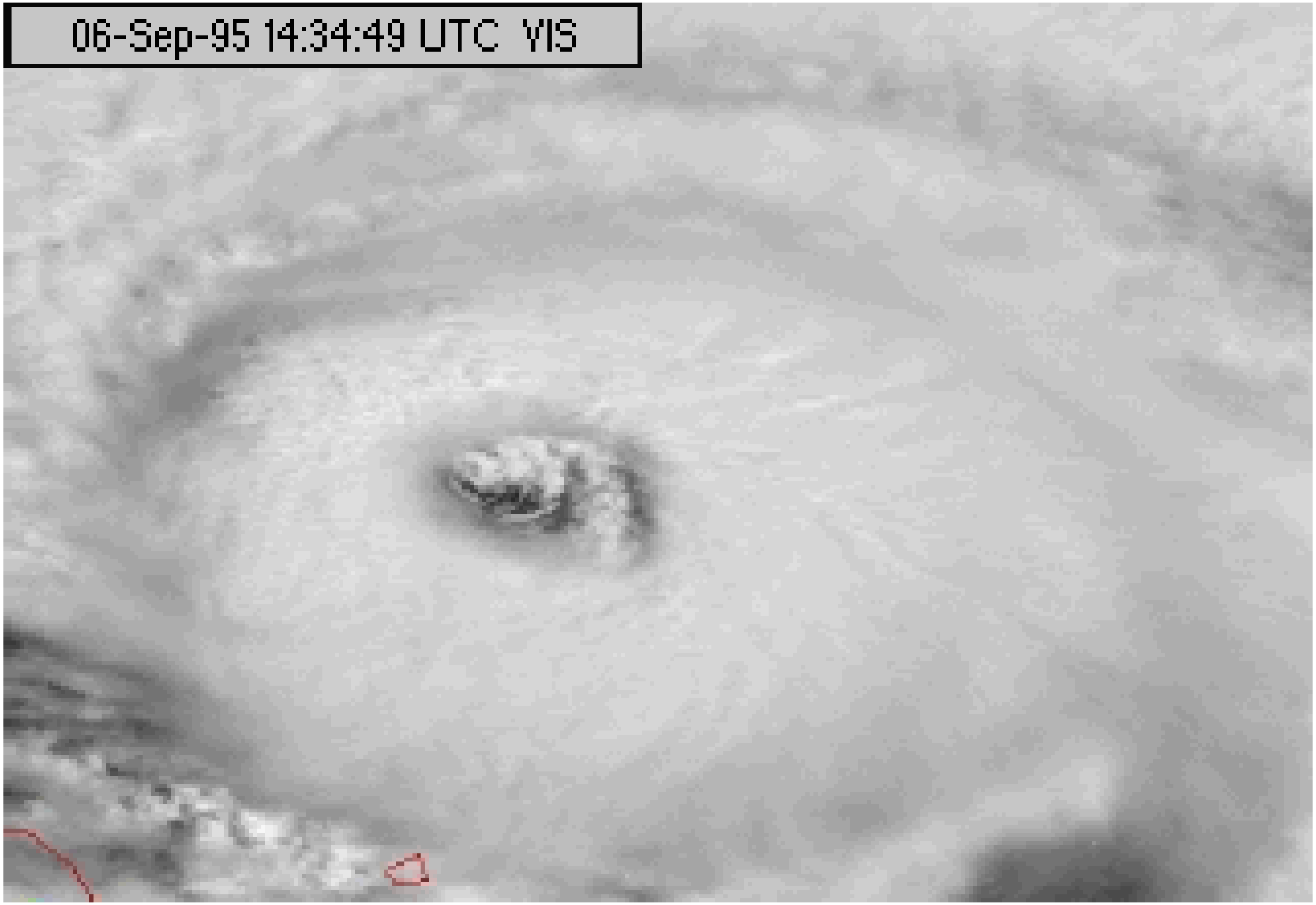
NUMBER	TYPE	NAME	DATE
1	H	ALLISON	JUN 03 - 06
2	T	BARRY	JUL 06 - 10
3	T	CHANTAL	JUL 12 - 20
4	T	DEAN	JUL 28 - AUG 02
5	H	ERIN	JUL 31 - AUG 06
6	H	FELIX	AUG 08 - 22
7	T	GABRIELLE	AUG 09 - 12
8	H	HUMBERTO	AUG 22 - SEP 01
9	H	IRIS	AUG 22 - SEP 04

1995

NUMBER	TYPE	NAME	DATE
10	T	JERRY	AUG 22 - 28
11	T	KAREN	AUG 26 - SEP 03
12	H	LUIS	AUG 27 - SEP 11
13	H	MARILYN	SEP 12 - 22
14	H	NOEL	SEP 26 - OCT 07
15	H	OPAL	SEP 27 - OCT 05
16	T	PABLO	OCT 04 - 06
17	H	ROXANNE	OCT 07 - 21
18	T	SEBASTIEN	OCT 20 - 25
19	H	TANYA	OCT 27 - NOV 01

🟥	Hurricane
🟨	Tropical Storm
🟩	Tropical Dep.
+ + +	Extratropical
●	Position at 0000 UTC
○21	Position/date at 1200 UTC
3	Tropical Cyclone Number

TROPICAL CYCLONES



90km

1 sec = 10 min

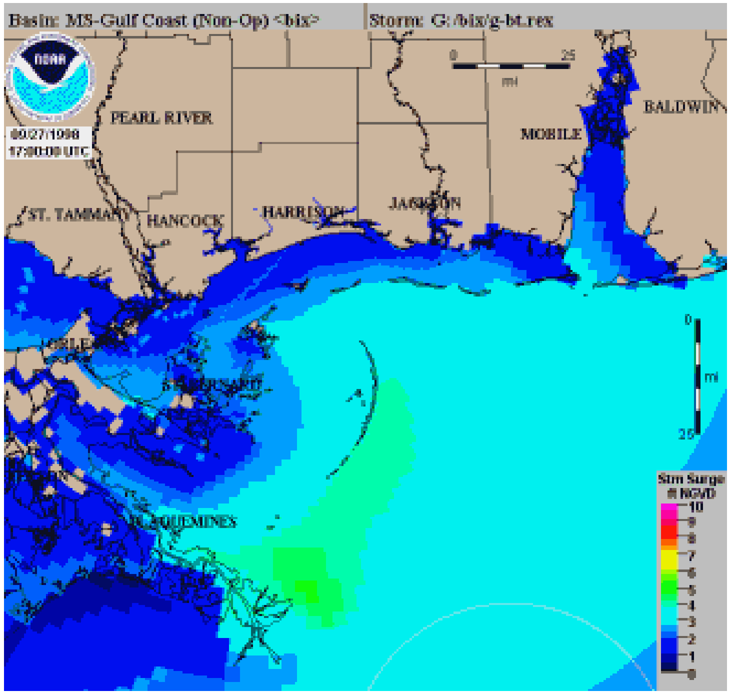
Hurrrivane Luis, Sept 1995

TROPICAL CYCLONES

The effects

- Wind damage (Épület, autók stb.)
- 15-20m waves on the shore
- Low pressure elevates water level
- High participation (300 mm/24h , Texas, 1921: 750mm!! – difficult to measure)

⇨ **floodings** (+ 5m)



National Hurricane Center (USA) szimulációja

Hurricane watch:

- Meteorological radar (from the 1950's), satellites (from the 1970's),
- Fly-in with manned or unmanned airplanes, to measure wind speed and pressures (dropsondes)
- Hurricane season: July - September
- 100 tropical lows annaually, from which 6-7 develop to hurricanes (wind higher than Beaufort 12)
- Global climate change: oceans getting hotter (T< 26 C) ⇨ higher probability!

Span Systems Inc.

Open ait theatre with tensile fabric roof
(St Augustine, Florida, USA)

Open air theatre destroyed by a hurricane
(Porthsmouth, Virginia, USA)

HURRICANE OBSERVATIONS

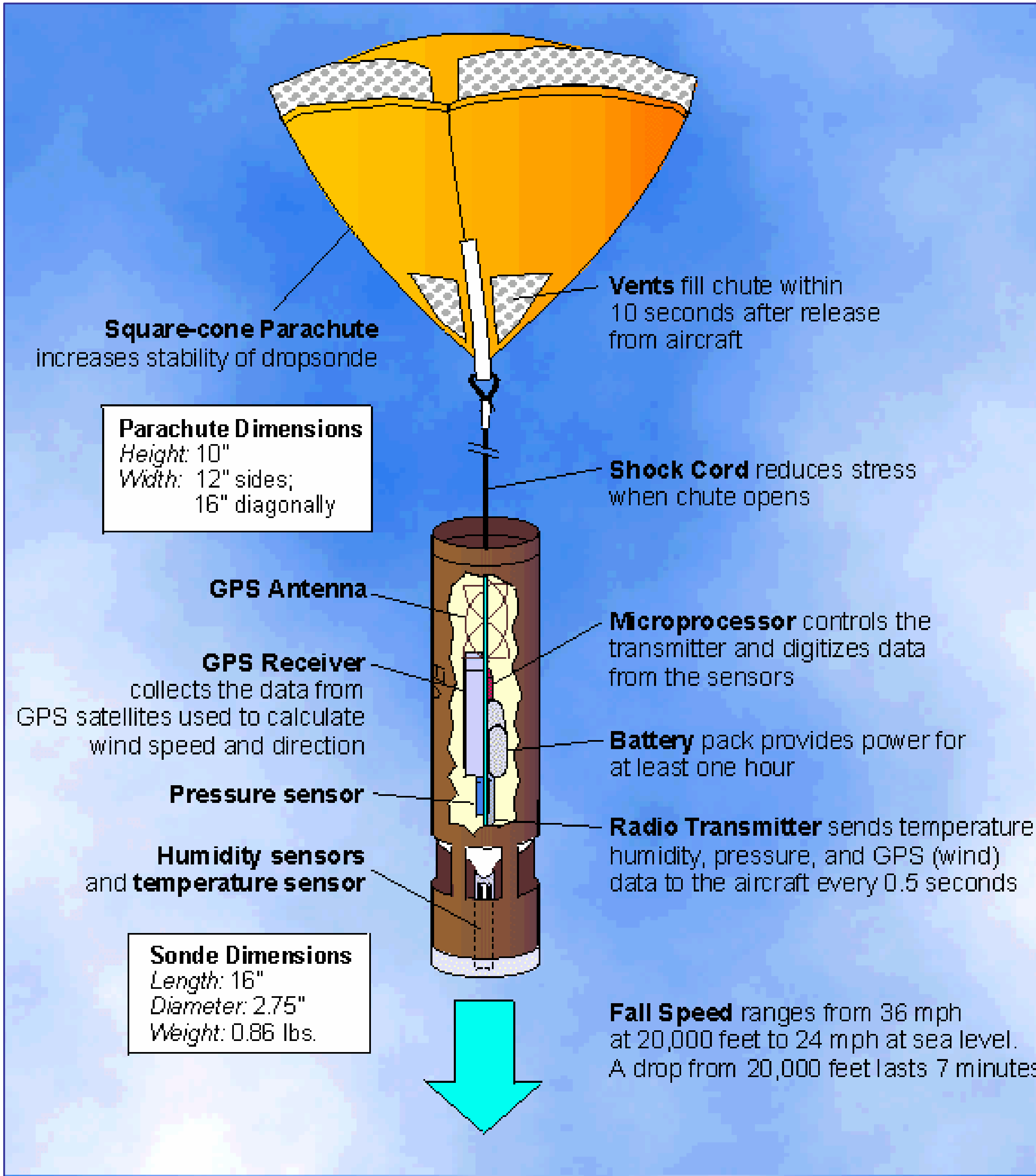
Unmanned Aerial vehicle

Dropsonde (vertical profiling)

HURRICANE OBSERVATIONS

Unmanned Aerial vehicle

Dropsonde (vertical profiling)



Square-cone Parachute increases stability of dropsonde

Parachute Dimensions
Height: 10"
Width: 12" sides;
16" diagonally

Vents fill chute within 10 seconds after release from aircraft

Shock Cord reduces stress when chute opens

GPS Antenna

GPS Receiver collects the data from GPS satellites used to calculate wind speed and direction

Pressure sensor

Humidity sensors and **temperature sensor**

Microprocessor controls the transmitter and digitizes data from the sensors

Battery pack provides power for at least one hour

Radio Transmitter sends temperature humidity, pressure, and GPS (wind) data to the aircraft every 0.5 seconds

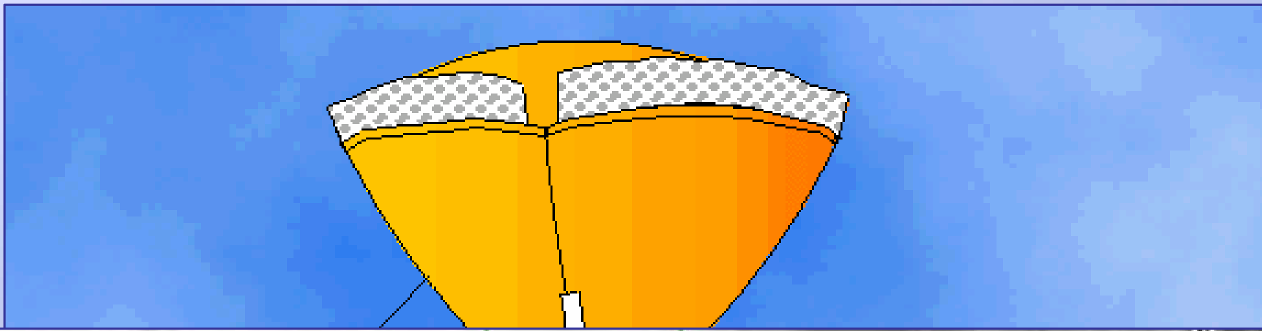
Sonde Dimensions
Length: 16"
Diameter: 2.75"
Weight: 0.86 lbs.

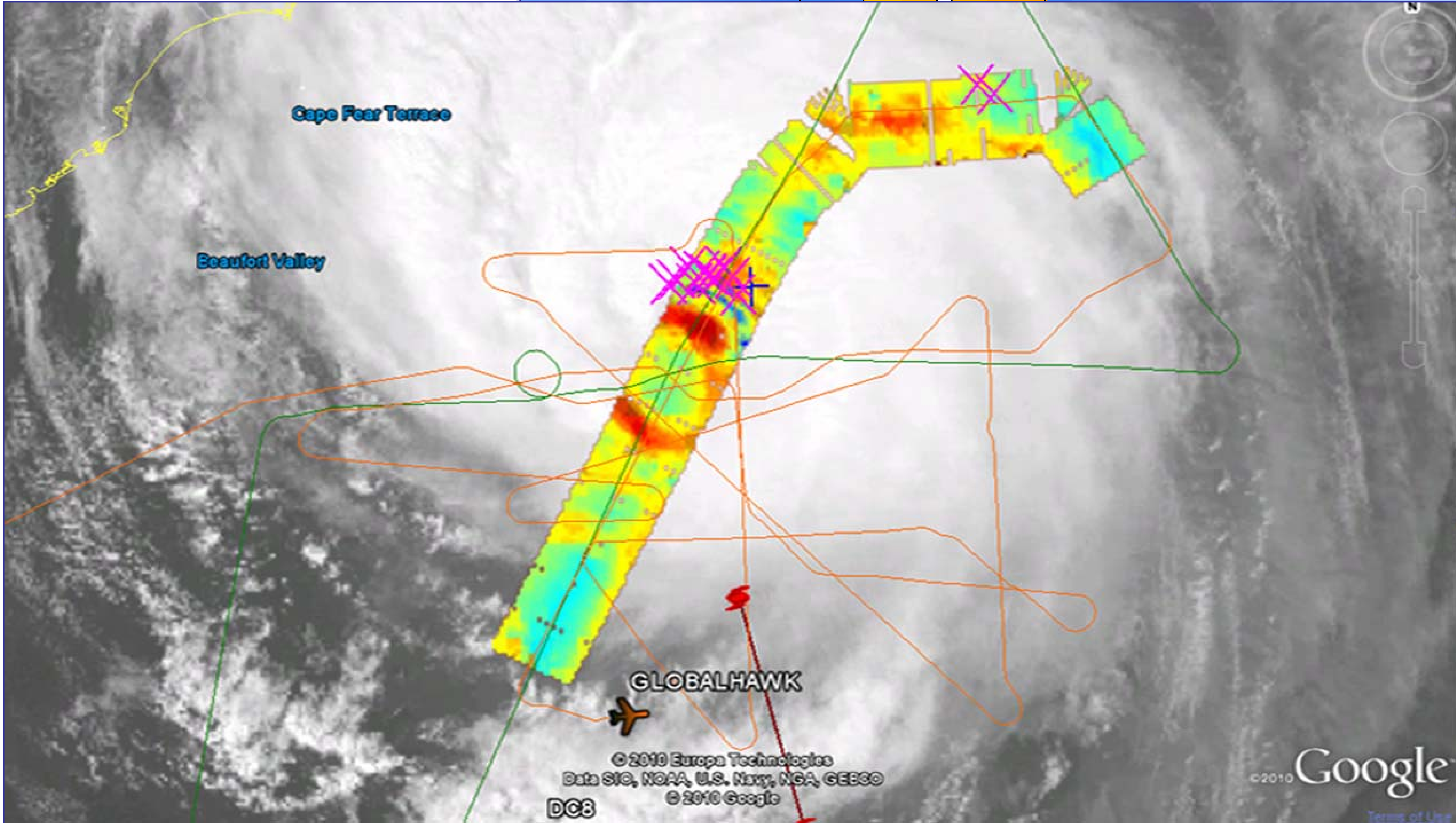
Fall Speed ranges from 36 mph at 20,000 feet to 24 mph at sea level. A drop from 20,000 feet lasts 7 minutes

HURRICANE OBSERVATIONS

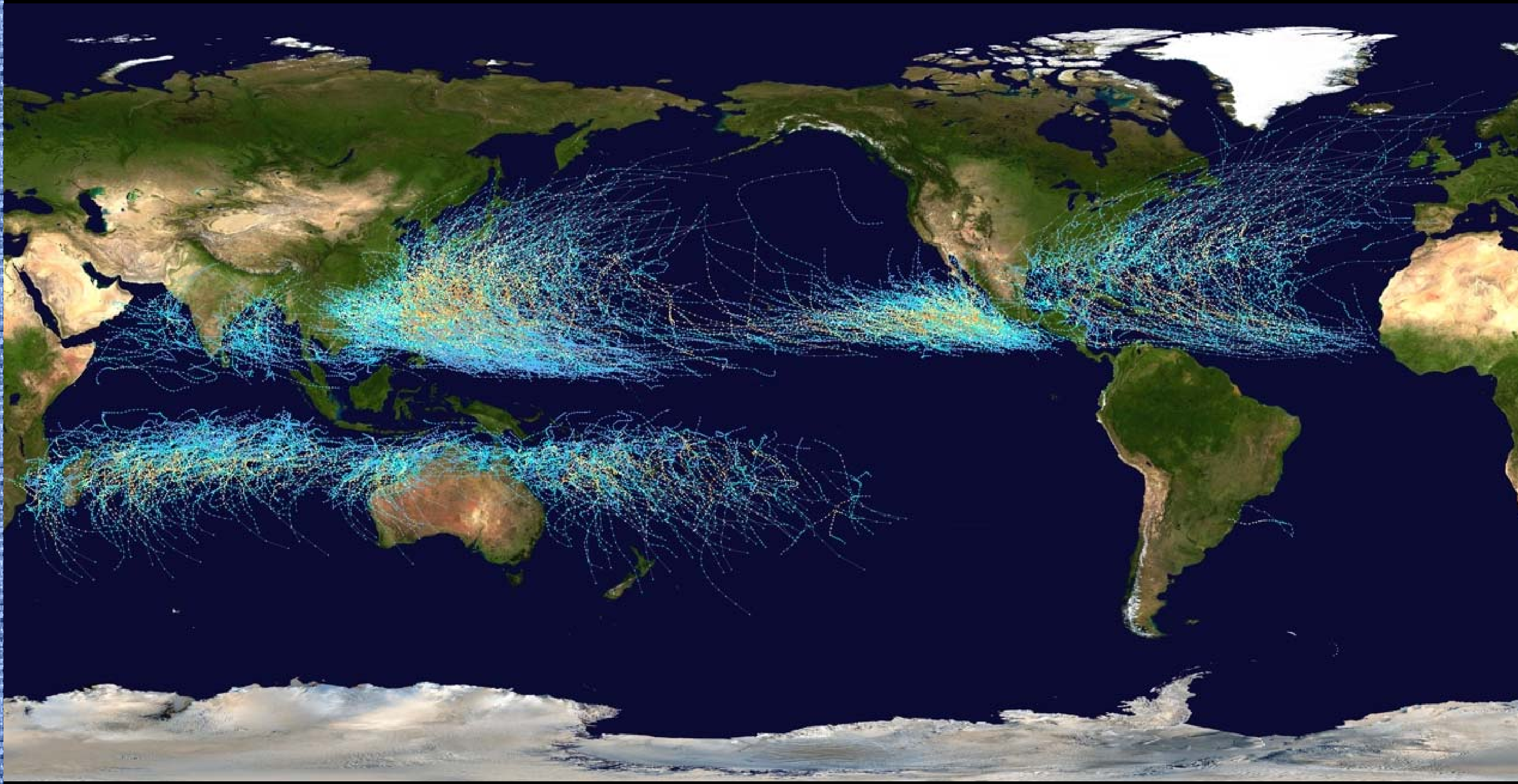
Unmanned Aerial vehicle

Dropsonde (vertical profiling)





TROPICAL CYCLONES



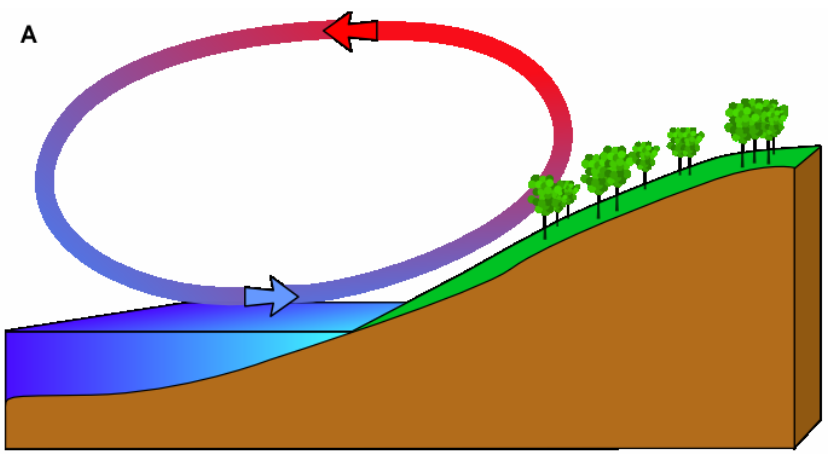
Hurricane paths 1985-2005

LOCAL WINDS

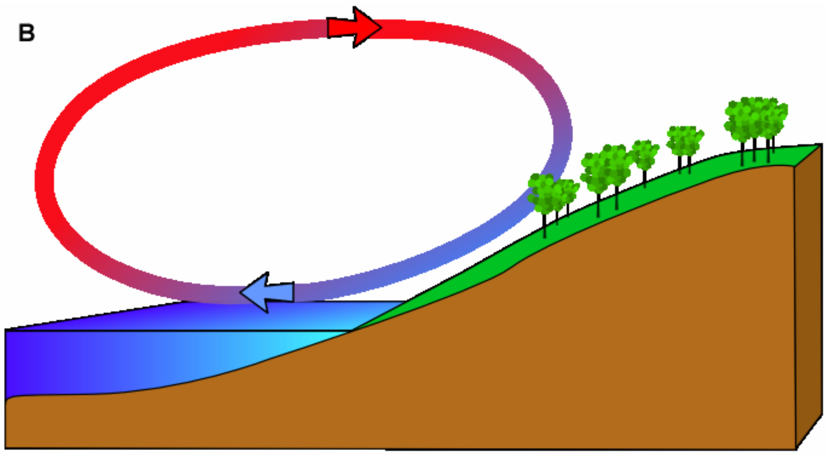
- sea winds
- Urban winds
- orographic winds

different albedo, heat capacity of surfaces and consequently varying temperature of air
⇨ daily periodocity

- Can be strengthened by other effects : e.g: bora



morning



evening

LOCAL WINDS

Orographic wind

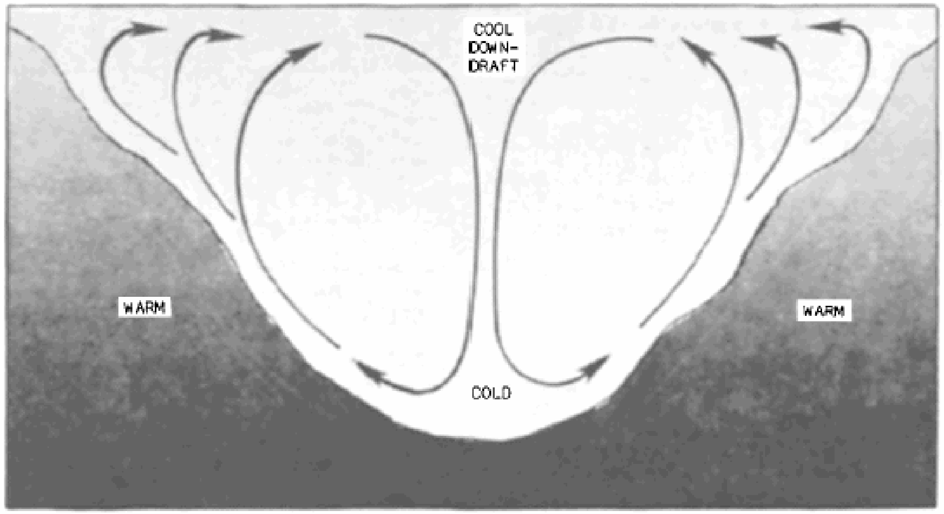
- In the morning: southern slopes ⇨ warm updraft : wind from the valley

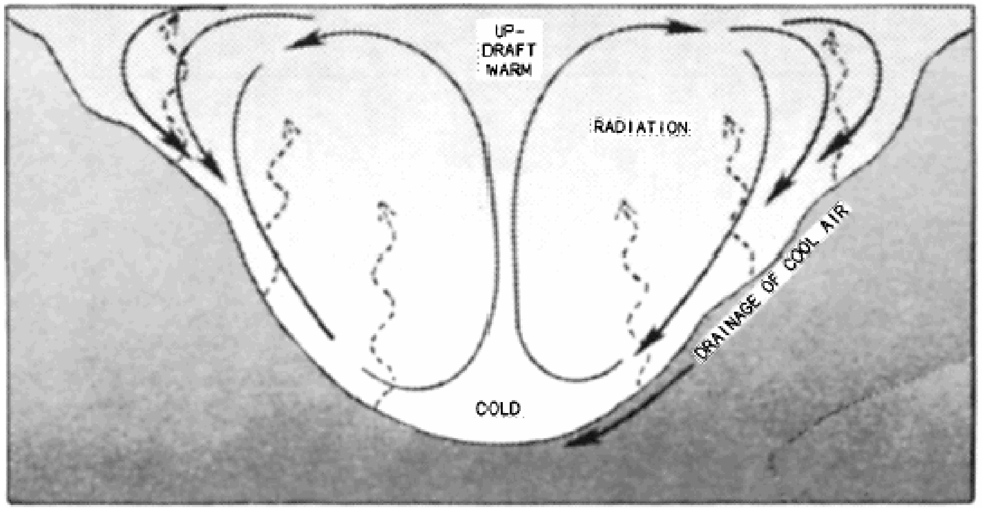
Anabatic wind

- In the late afternon: faster cooldown of slopes due to radiation (effect stronger without forest coverage) ⇨ cold downdrafts

Catabatic wind

Thin layer of wind (some meters – some 10 meters), 2-4 m/s max. speed (can be blocked by buildings)





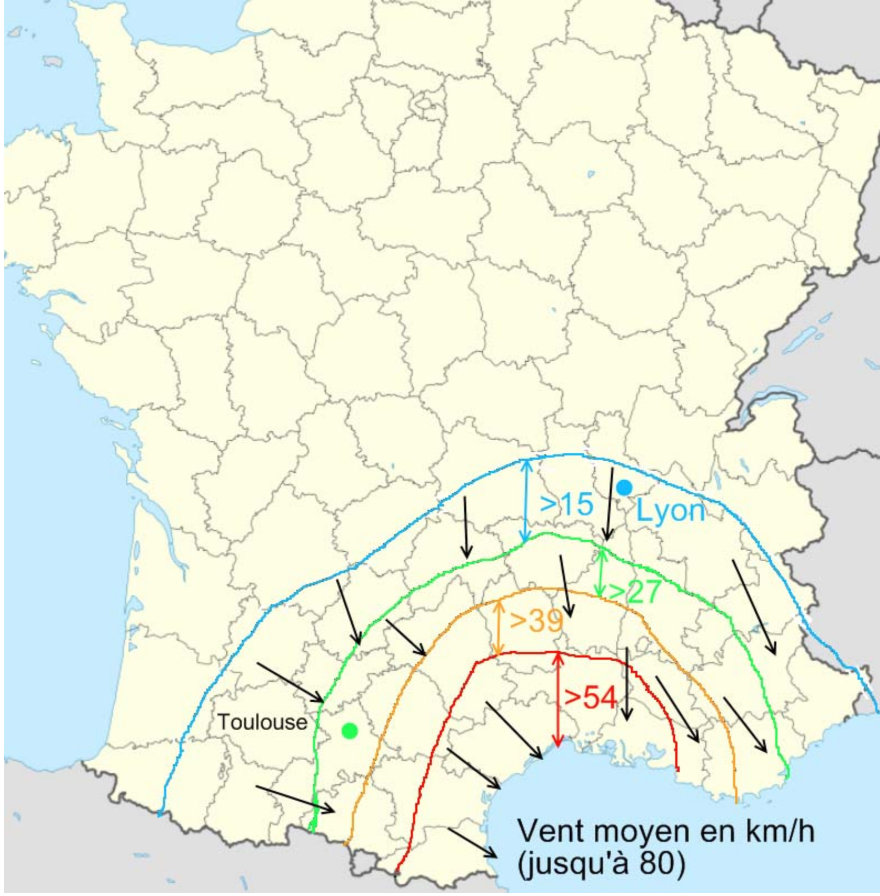
http://www.tpub.com/weather2/3-23.htm

REGIONAL WINDS

Desert winds:

Cyclones generated above desert areas (high T) and modified by local effects

Scirocco:	Mediterranean sea
Samum:	Palestine
Khamsin,	
haboob:	Egypt (causing transport of sand to the Alps - blood rain)
Brickfielder:	Australia (very dry hot wind)
Pampero:	Argentina

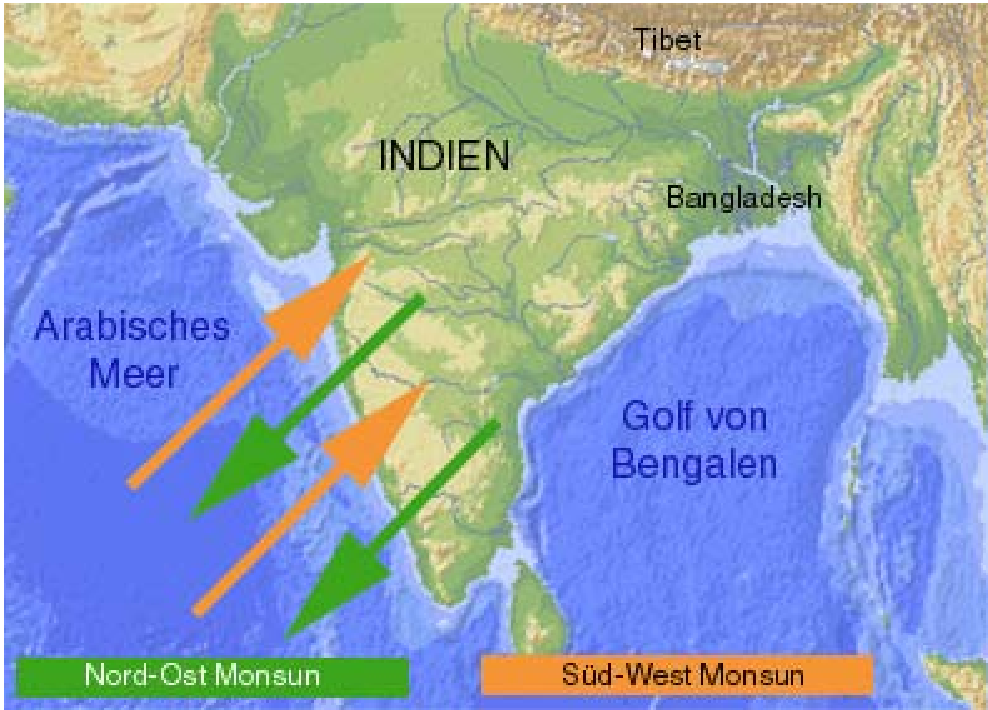


Mistral:	catabatic wind strengthened by orographic effects in the valley of the Rhone river. (Bay of Biscaya, Western Franc: anticyclonic = high pressure, Gulf of Genova: low pressure)
Buran:	eastern Asian cyclone, snow storm
Bora:	High speed wind at the NE shore of Adriatic Sea coming from the mountains (up to 200km/h wind speed, and 14 days of endurance)

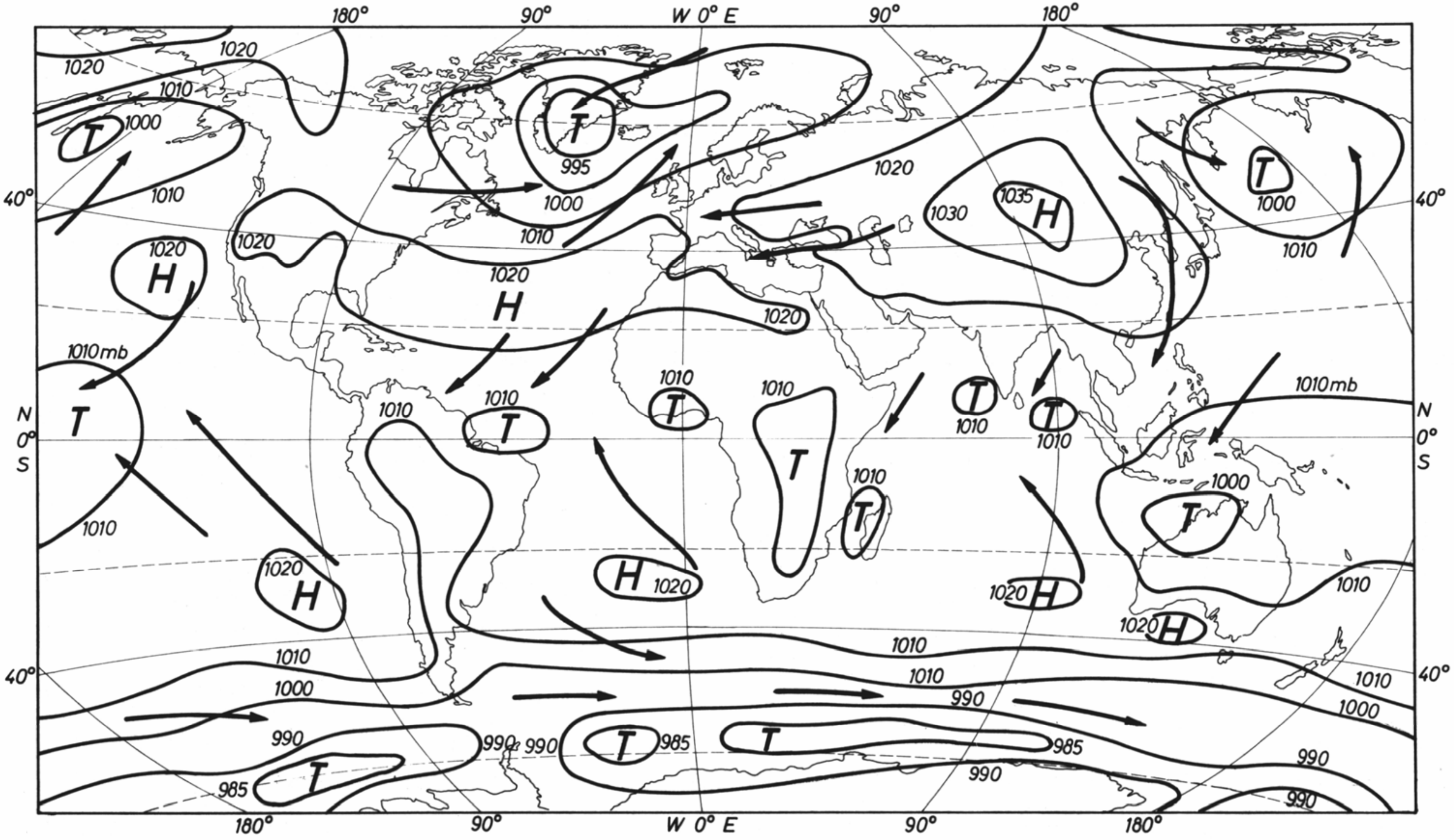
WINDS MODIFYING THE PLANETARY CIRCULATION

Monsoon (- circulation)

- Seasonal reversing wind with annual changes of wind direction 2x a year (min. 120°)
- cause: ITCZ and asymmetric heating of land and sea
- Low pressure areas above desert areas in summer (Indus-plain, Tibetian highlands, Siberia) ⇨ ITCZ is moved towards the north
- Southeast trade winds turn to southwest (Coriolis force!) and transport moist air to the land.
- In winter: cold dry winds from northeast (intensified trade wind)
- Orographic effects: pld. Himalaya
- Monsoon:
  - North-Australia
  - West Africa
  - India
  - East-Asia
  - Gulf of Mexico (weak)

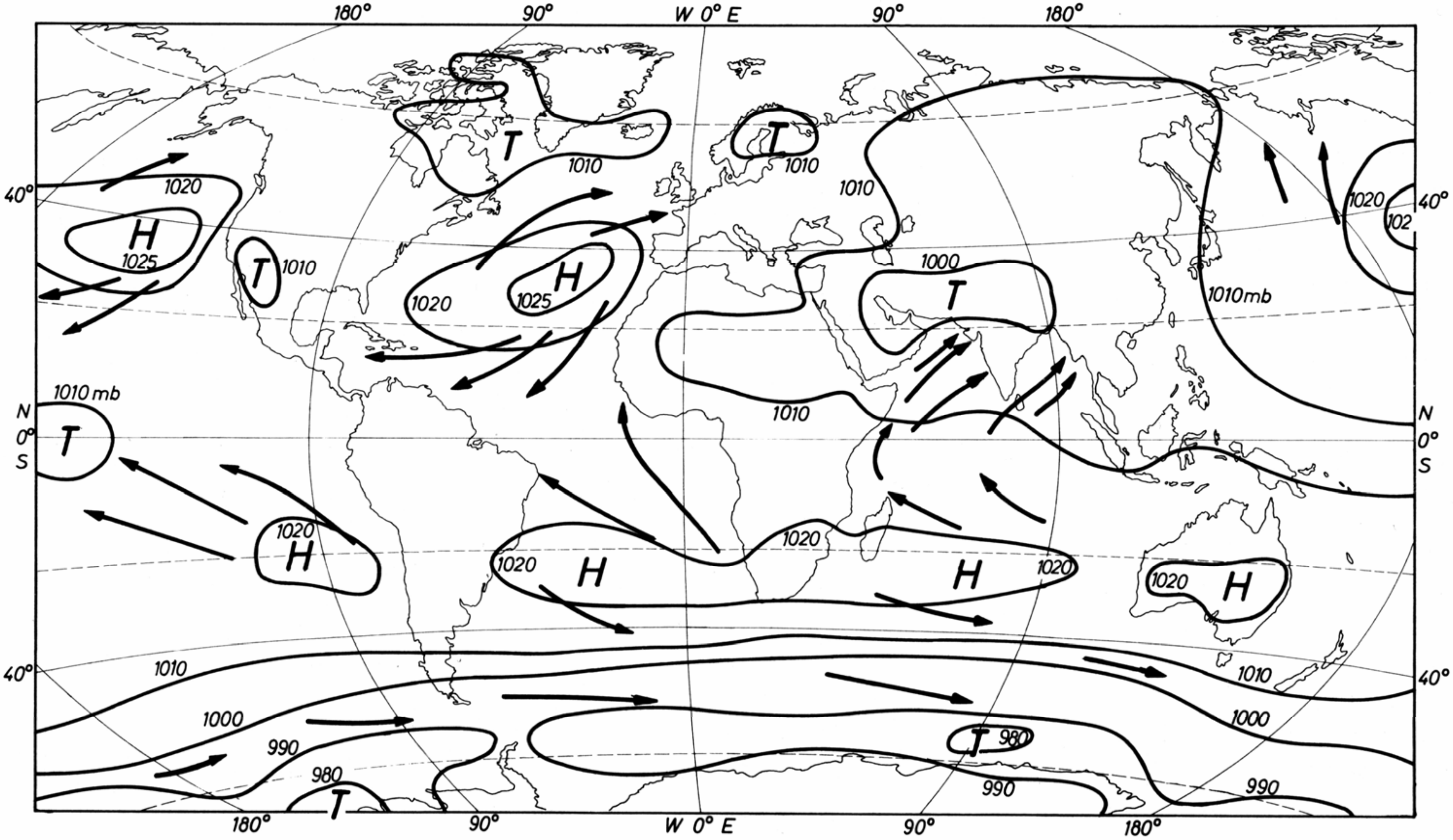


GLOBAL ATMOSPHERIC CIRCULATION - SUMMARY



Surface wind directions ans pressure in **January** (Weischet, 1977)
T: low pressure; H: high pressure

GLOBAL ATMOSPHERIC CIRCULATION - SUMMARY



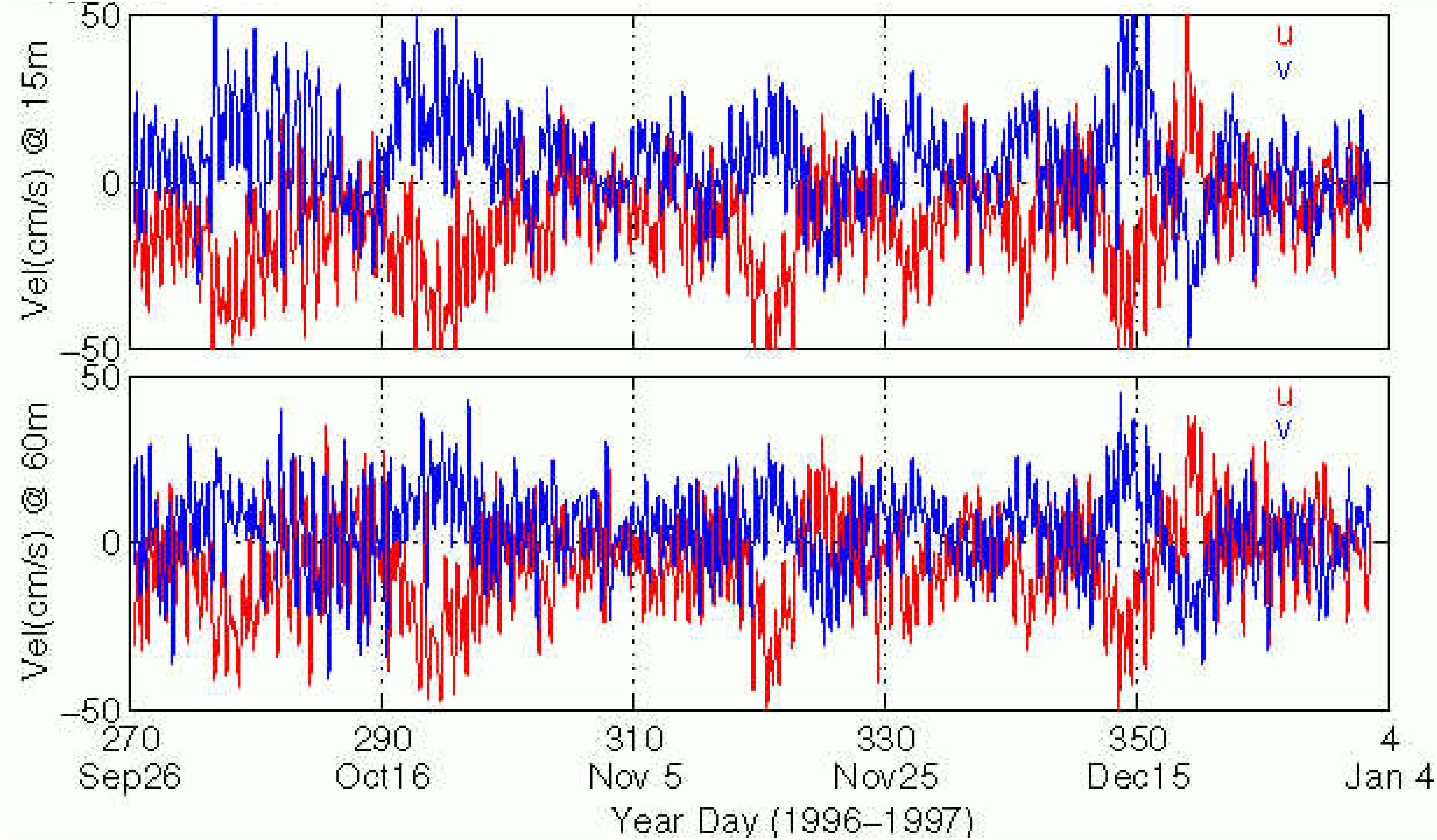
Surface wind directions ans pressure in **July** (Weischet, 1977)
T: low pressure; H: high pressure

WIND SPEED FLUCTUATIONS

High temporal variability of wind speed and direction

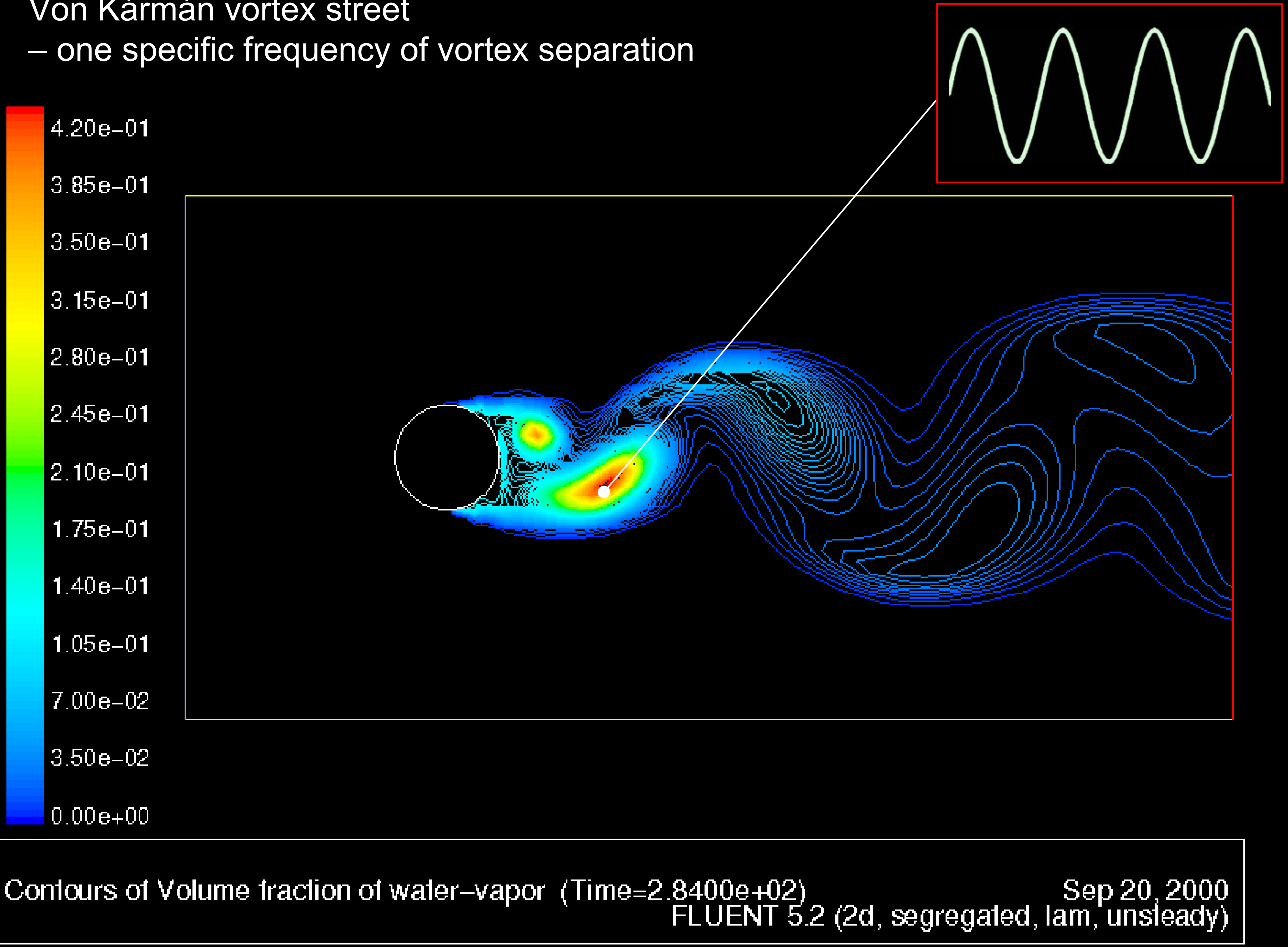
$$\underline{V}(\underline{r},t)=\begin{bmatrix}u\\v\\w\end{bmatrix}(\underline{r},t)$$

- Wind observations in a fixed observation point:



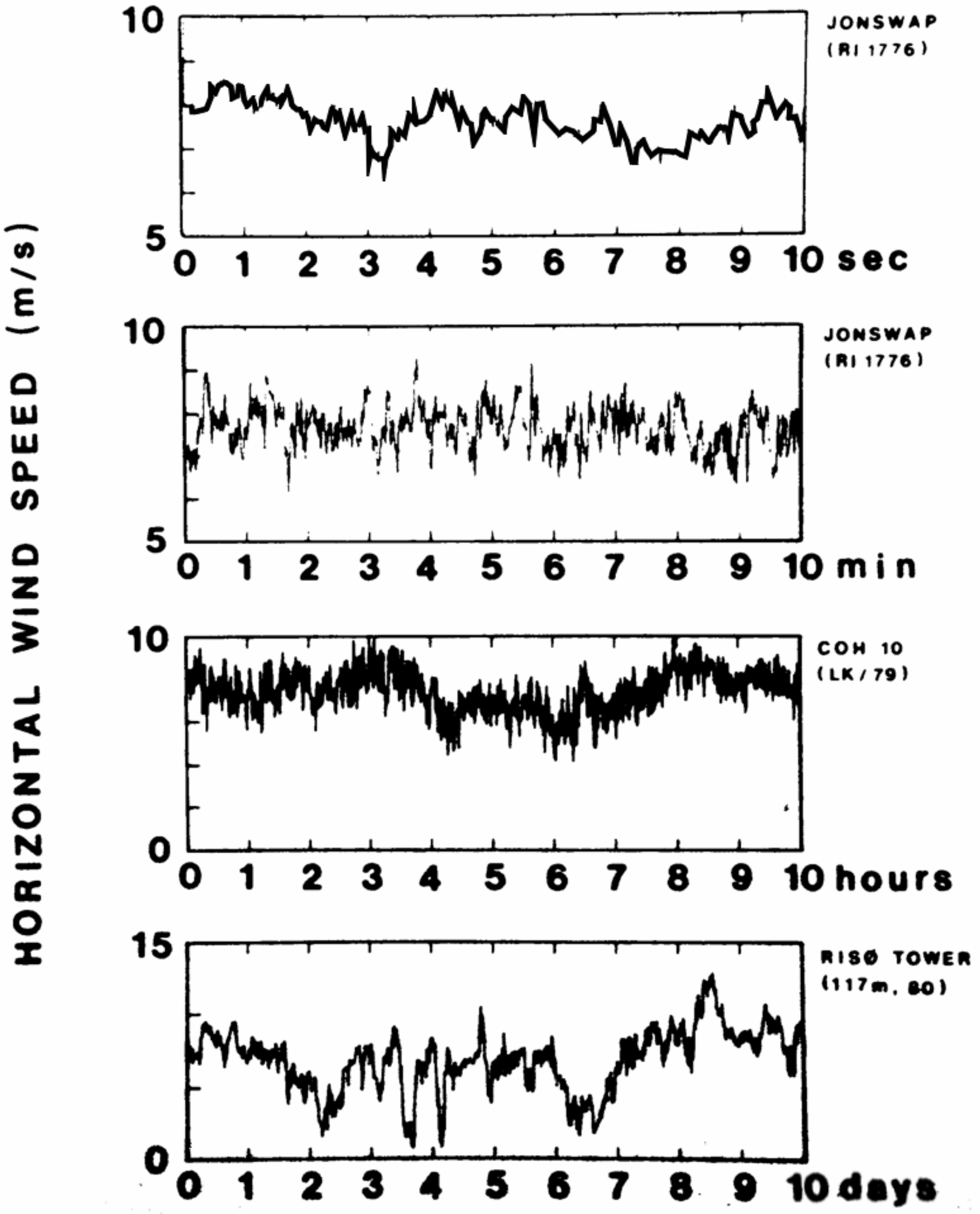
EXAMPLE OF STRUCTURES CAUSING WIND FLUCTUATIONS

- Von Kármán vortex street
  – one specific frequency of vortex separation



Forrás: Dr. Kristóf Gergely

ATMOSPHERIC TURBULENCE



- Mixture of frequencies
- Signalling the pass of vortices of different size
- Max. freq: some Hz (T = 0.1s)

► spectral analysis useful

FREQUENCY ANALYSIS OF SIGNALS

Transformation from time domain to frequency domain:

$$f(t) \Rightarrow F(\omega)$$

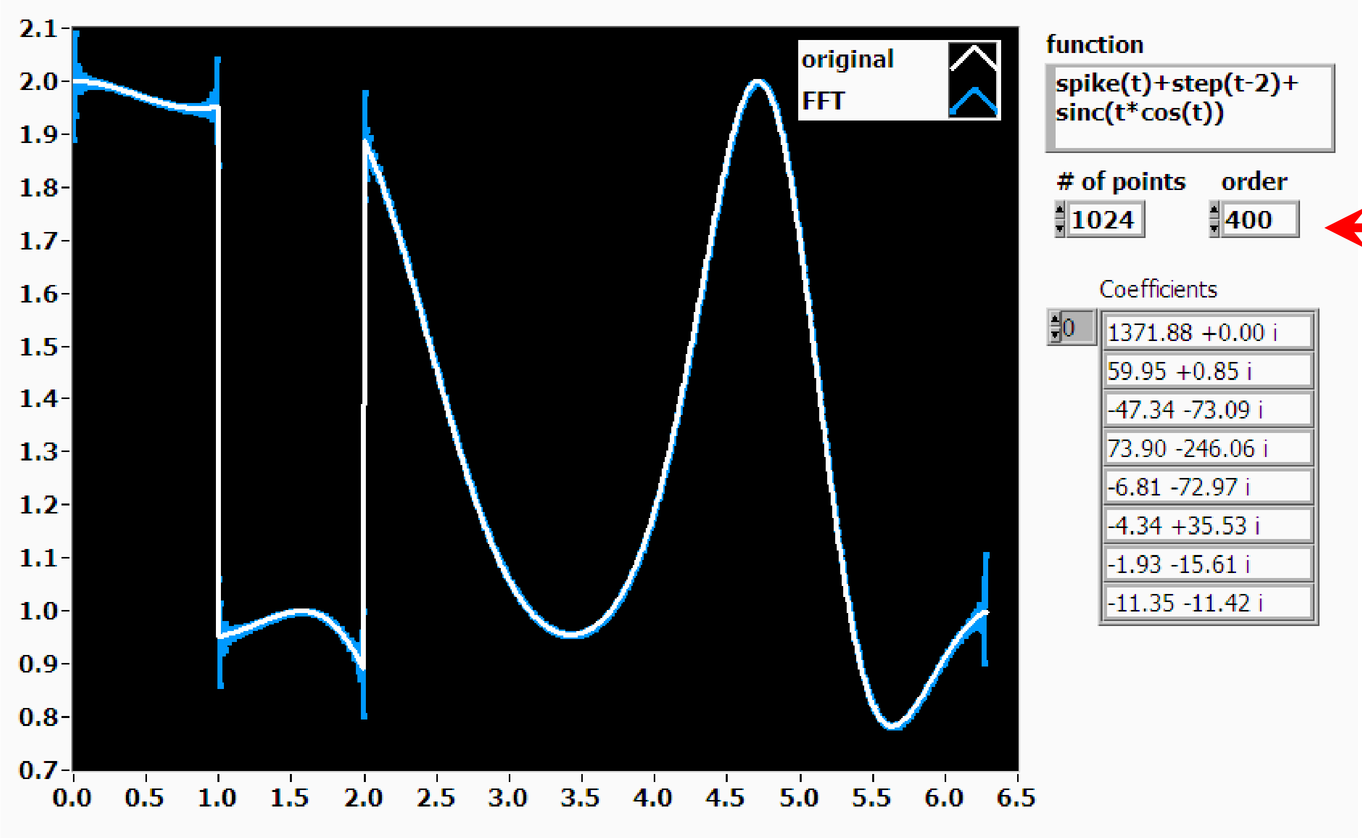
Euler formula: $e^{2\pi i\theta} = \cos(2\pi\theta) + i \cdot \sin(2\pi\theta)$

Fourier-transformation:

$$F(\omega) = \int_{-\infty}^{+\infty} f(t) \cdot e^{-2\pi i\omega t}\, dt$$

Conversion to time domain:

$$f(t) = \int_{-\infty}^{+\infty} F(\omega) \cdot e^{2\pi i\omega t}\, d\omega$$



function
spike(t)+step(t-2)+sinc(t*cos(t))

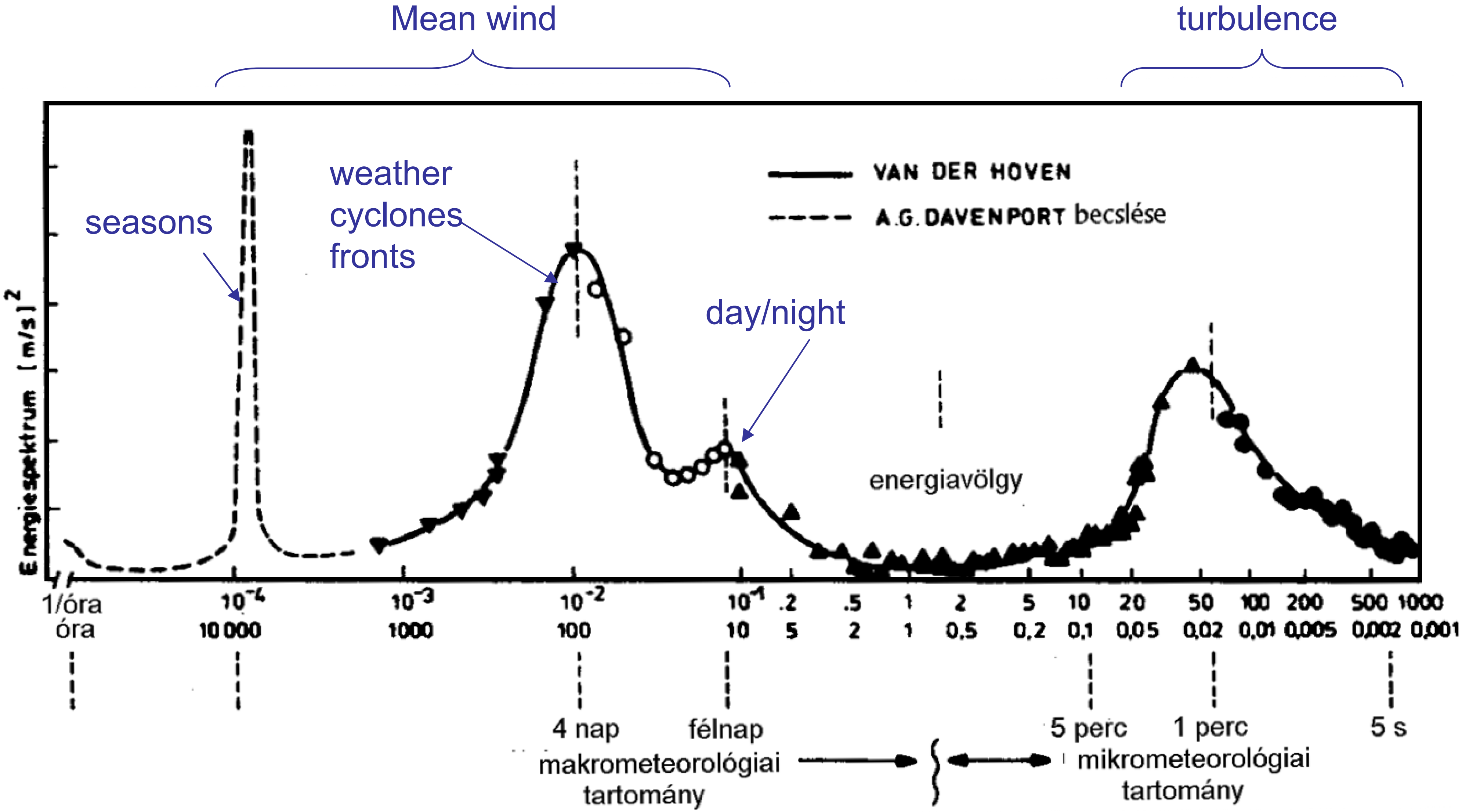
\# of points: 1024
order: 400

Coefficients
0
1371.88 +0.00 i
59.95 +0.85 i
-47.34 -73.09 i
73.90 -246.06 i
-6.81 -72.97 i
-4.34 +35.53 i
-1.93 -15.61 i
-11.35 -11.42 i

F(ω) complex function: amplitude and phase

Az ampl. squared: powers spectrum

WIND POWER SPECTRUM



- shows the contribution of met. Scales to the wind genesis
- right section of the plotis important when addressing building aerodynamics

DESCRIPTION OF TURBULENT FLOWS

$$\underline{V}(\underline{r},t) = u(\underline{r},t)\cdot \underline{i} + v(\underline{r},t)\cdot \underline{j} + w(\underline{r},t)\cdot \underline{k}$$

Mean wind:

$$\overline{u(\underline{r},t)} = \overline{u(\underline{r})} = \frac{1}{T}\int_0^T u(\underline{r},t)dt$$

Similarly :

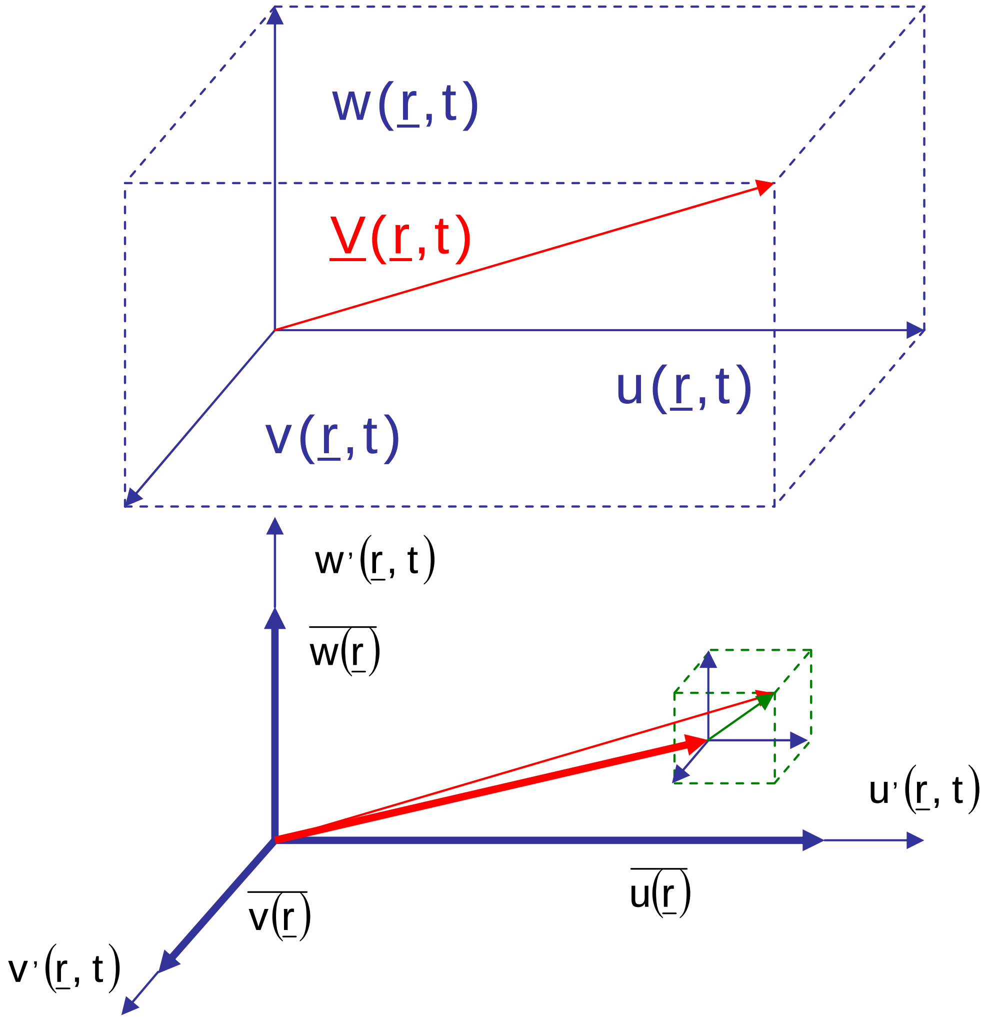
$\overline{v(\underline{r})}$ $\overline{w(\underline{r})}$

Velocity fluctuation:

$$u'(\underline{r},t) = u(\underline{r},t) - \overline{u(\underline{r})}$$

Similarly:

$v'(\underline{r},t)$ $w'(\underline{r},t)$



DESCRIPTION OF TURBULENT FLOWS

Temporal average of fluctuations:

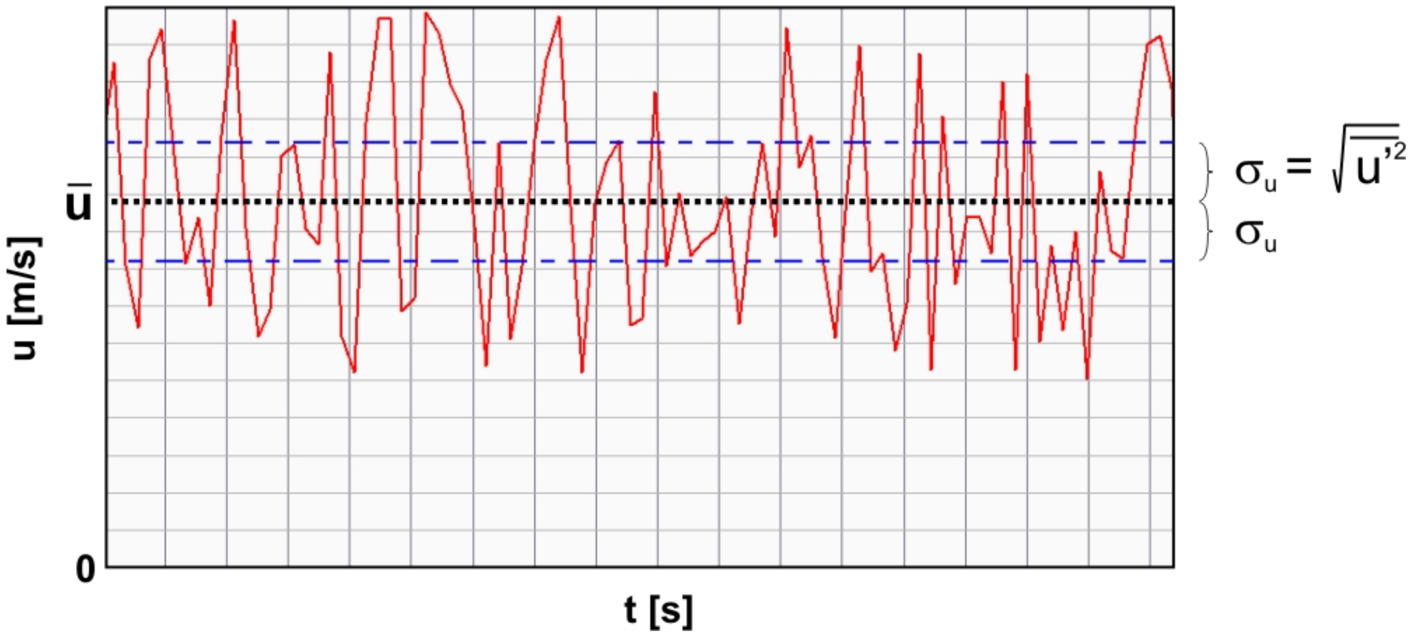
$$\overline{u'(\underline{r})} = \frac{1}{T}\int_0^T u'(\underline{r},t)\,dt = 0$$

$$\overline{v'(\underline{r})} = 0 \qquad \overline{w'(\underline{r})} = 0$$

Root mean square of fluctuations:

$$\overline{u'^2(\underline{r},t)} = \frac{1}{T}\int_0^T u'^2(\underline{r},t)\,dt = \frac{1}{T}\int_0^T \left(u(\underline{r},t) - \overline{u(\underline{r})}\right)^2 dt = \sigma_u{}^2(\underline{r})$$

Root mean square of fluctuations = squared deviation of velocity



DEFINITION OF TURBULENCE INTENSITY

$$\sigma_u, \sigma_v, \sigma_w \; [m/s]$$

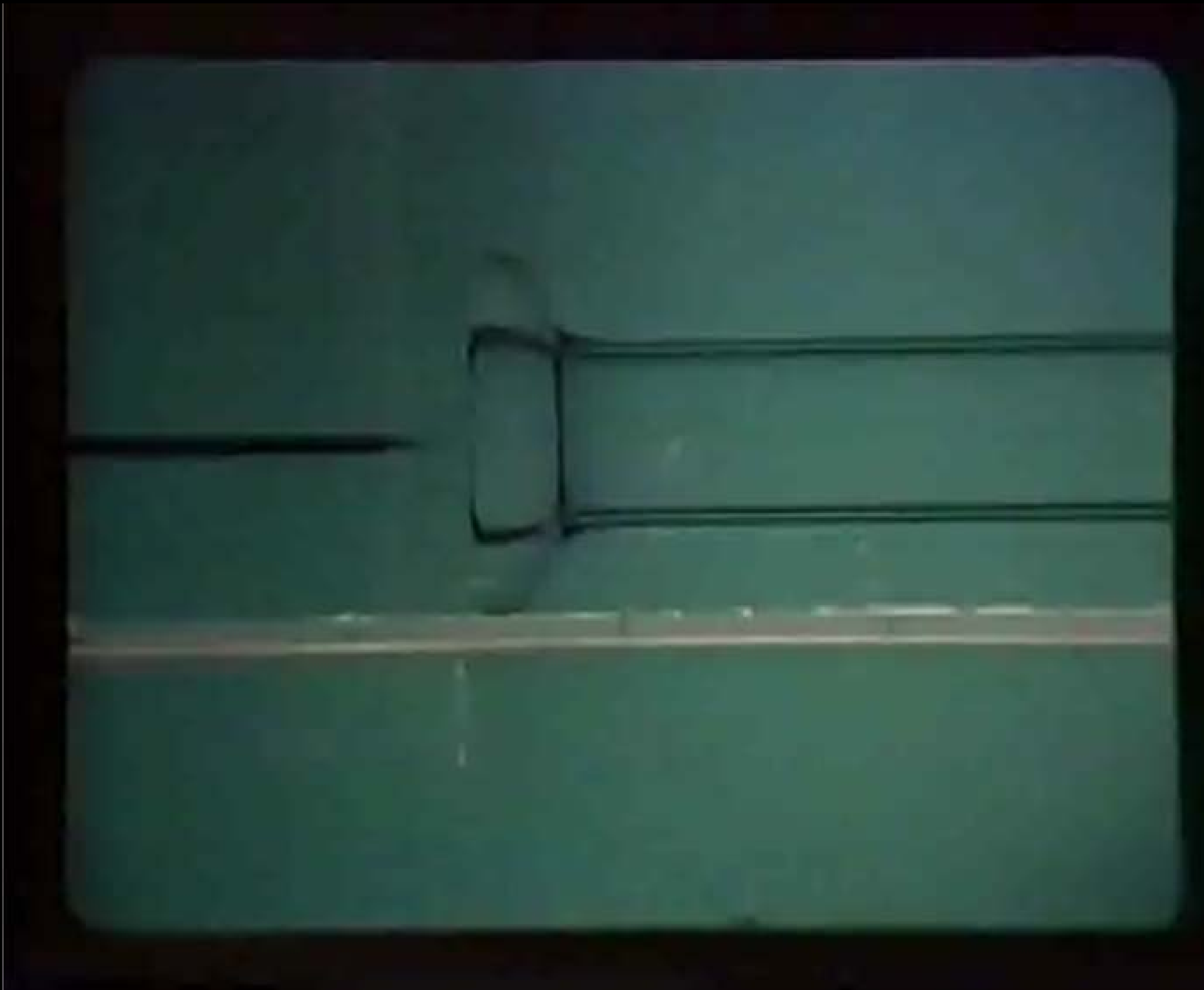
Quotient of stnadard deviation and mean wind velocity [-]

$$T_u = \frac{\sigma_u}{\bar{u}}$$

$$T_v = \frac{\sigma_v}{\bar{u}}$$

$$T_w = \frac{\sigma_w}{\bar{u}}$$

- Laminar flows: very low turbulence intensity
- Growing flow velocity: high turbulence (shown by stronger mixing)



TURBULENT KINETIC ENERGY

Kinetic energy of an elementar mass:

$$\frac{E(t)}{m} = \frac{1}{2}\left|\underline{V}(t)\right|^2$$

Average kinetic energy:

$$\frac{\overline{E(t)}}{m} = \frac{1}{2}\overline{\left|\underline{V}(t)\right|^2}$$

$$\frac{\overline{E(t)}}{m} = \frac{1}{2}\overline{\left(u^2 + v^2 + w^2\right)} =$$

$$\boxed{\overline{u}(\underline{r})^2 + \sigma_u{}^2(\underline{r}) = \overline{u^2}(\underline{r})}$$

$$\frac{1}{2}\left(\overline{u}^2 + \sigma_u{}^2 + \overline{v}^2 + \sigma_v{}^2 + \overline{w}^2 + \sigma_w{}^2\right)$$

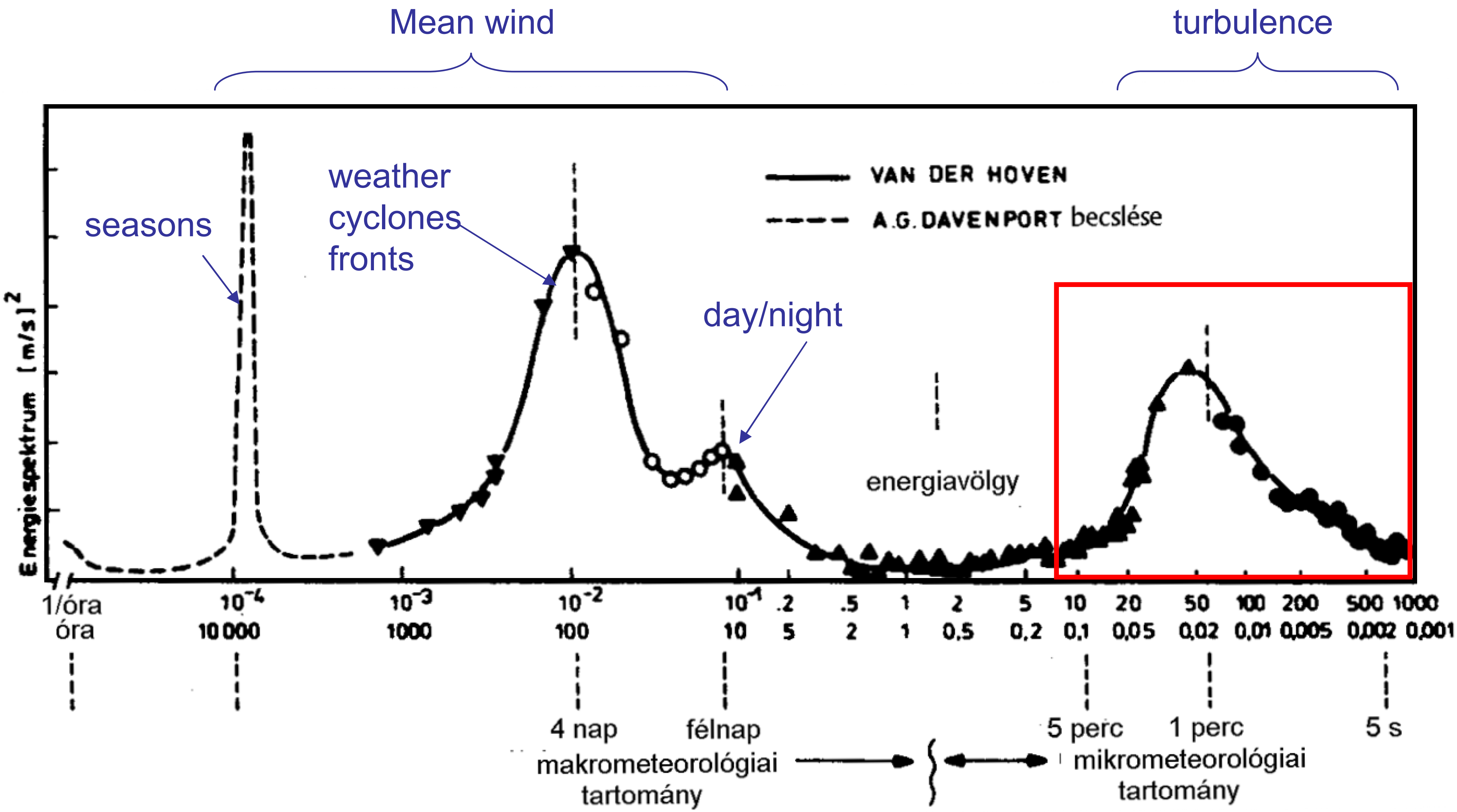
Kinetic energy of the mean flow:

Kinetic energy of fluctutations (turbulent kinetic energy, TKE):

$$\frac{E_{össz}}{m} = \frac{E_{átlag}}{m} = \frac{1}{2}\left(\overline{u}^2 + \overline{v}^2 + \overline{w}^2\right) + \frac{TKE}{m} = \frac{1}{2}\left(\sigma_u{}^2 + \sigma_v{}^2 + \sigma_w{}^2\right)$$

The total kinetic energy of the turbulent flow is larger than that of a laminar flow with the same mean wind velocity!

TURBULENT KINETIC ENERGY


Mean wind

turbulence

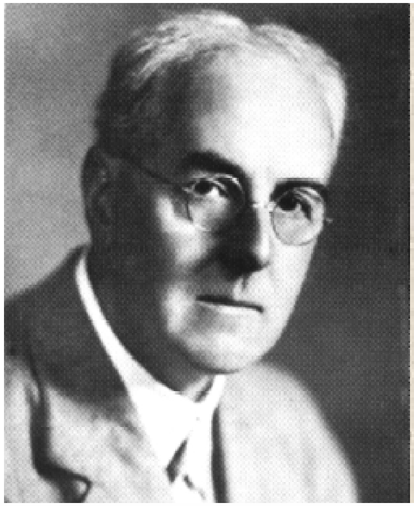
seasons

weather
cyclones
fronts

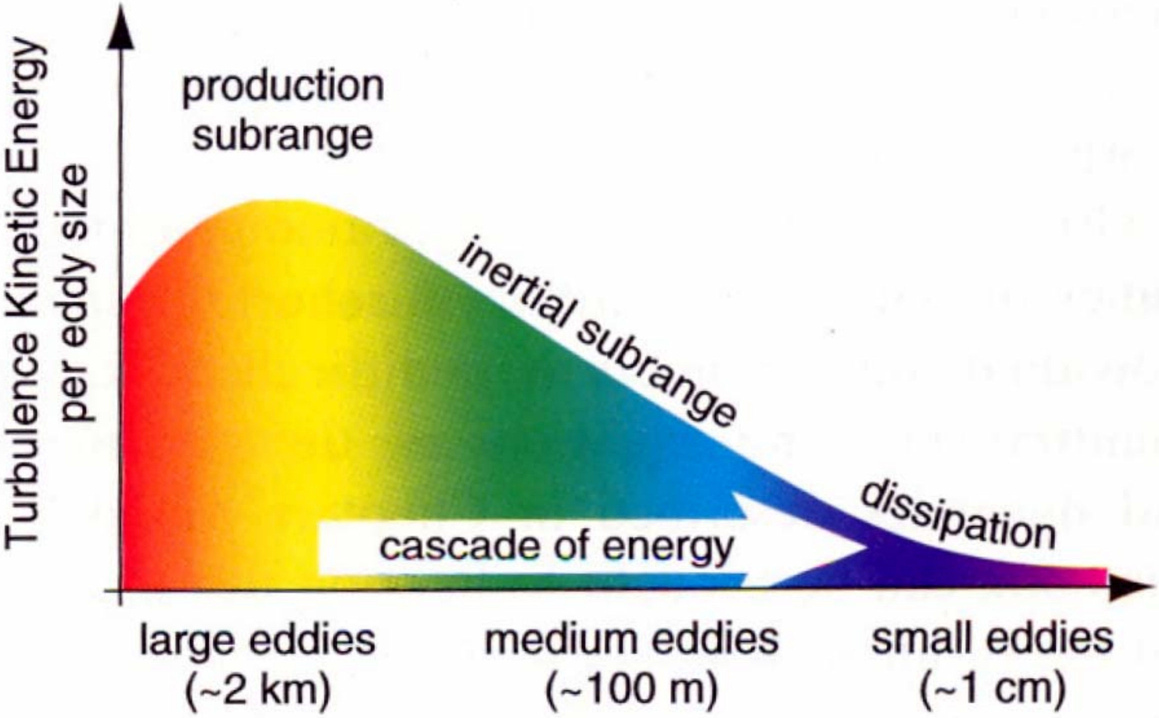
day/night

- Area below the curve ~ TKE
- Distribution of TKE by frequency / vortex size

TURBULENT KINETIC ENERGY SPECTRUM



Big whorls have little whorls
That feed on their velocity,
And little whorls have lesser whorls
And so on to viscosity.
(Lewis F. Richardson[*]*, 1922)*



Large vortices in the atmosphere fall a part to smaller ones.
At the end, smallest vortices dissipate their kinetic energy to heat. (because real flows are viscous)
The spectrum of winf is formed by this mechanism to a typical shape.

Turbulent energy cascade

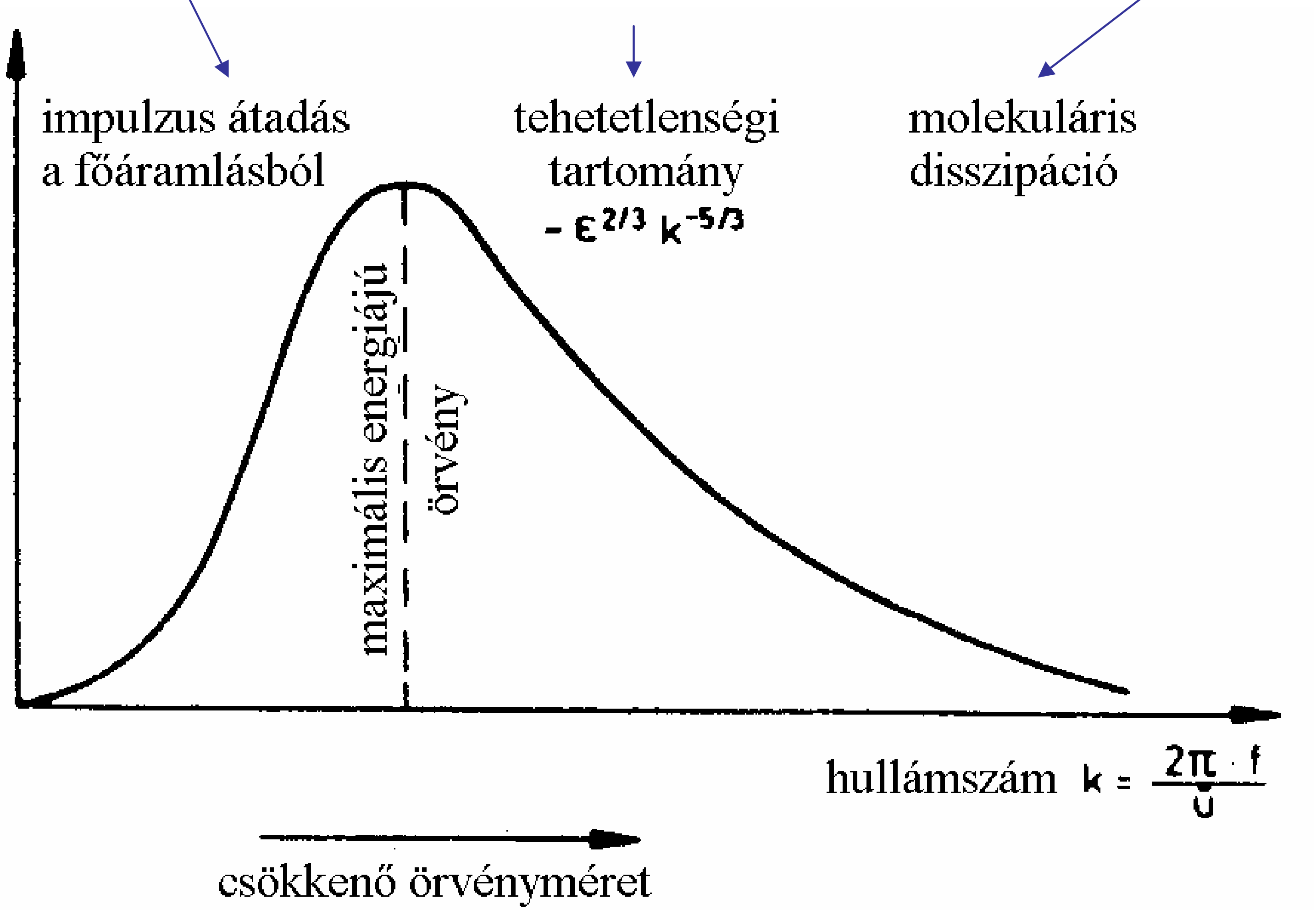
**English mathematician, physicist, meteorologist (1881-1953), who created the concept of numerical weather prediction*

TURBULENS KINETIKUS ENERGIA SPEKTRÁLIS MEGOSZLÁSA

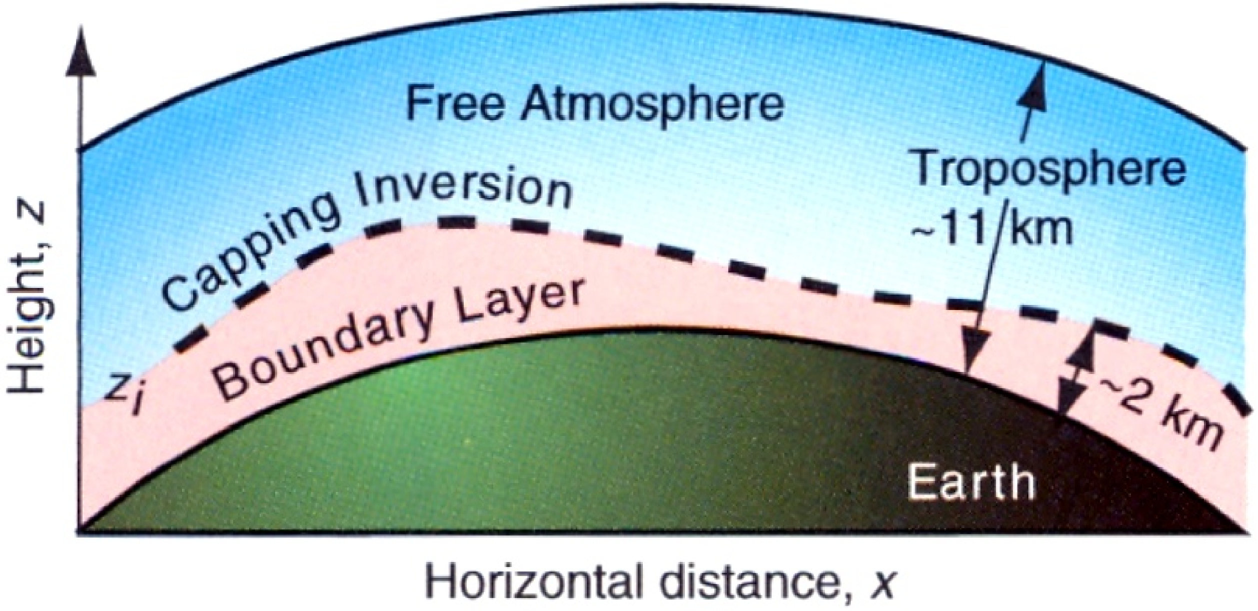
Momentum transport from the mean flow: vortices are developed on the edges of flow obstacles

Inertial domain: a energy of large structures passed to smaller flow structures

Molecular dissipation: kinetic energy turns into heat



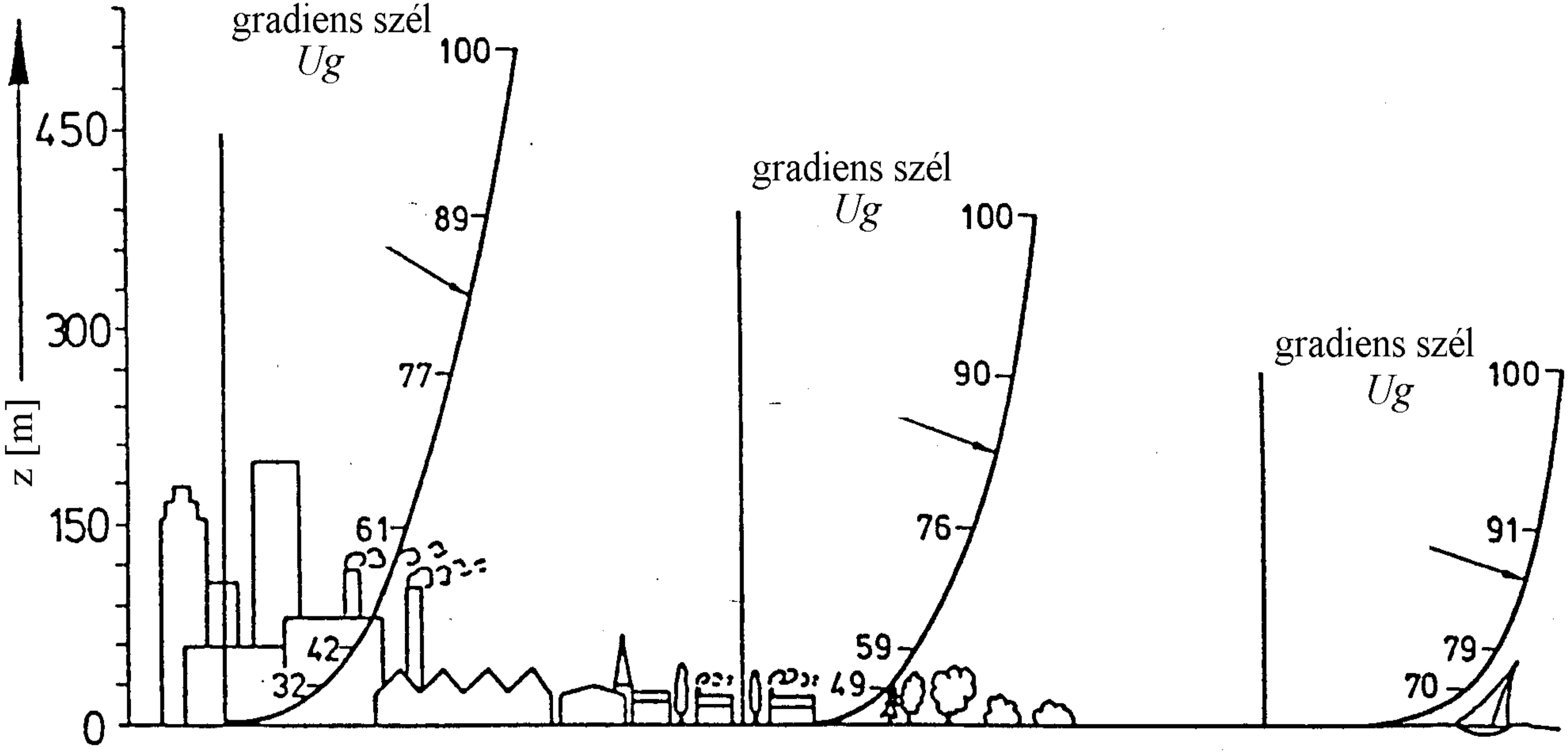
THE ATMOSPHERIC BOUNDARY LAYER



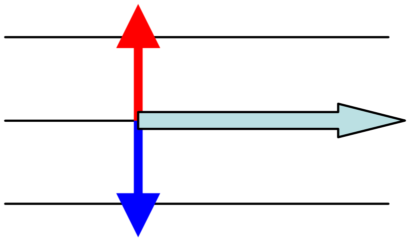
The planetary boundary layer (PBL), also known as the atmospheric boundary layer (ABL), is the lowest part of the atmosphere and its behavior is directly influenced by its contact with a planetary surface. Heat, momentum and moisture transport between earth and atosphere occurs in the ABL. Flow in the ABL is mostly turbulent, transport is done by turbulent vortices (turbulent diffusion).

THE ATMOSPHERIC BOUNDARY LAYER

- Driving force: free atmosphere, gestrophic or cyclonic winds
- On the surface : velocity = 0
- Thermal convection
- Surface roughness and elevation has major influence on its shape and thickness
- Thickness can vary in time (– time scale ≤ 1day)
- 3D flow – **w** cannot be neglected



EKMAN LAYER

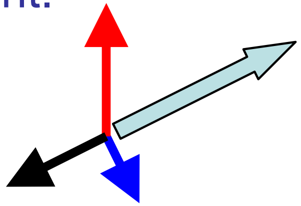


Geostrophic wind,

acting forces: Coriolis and pressure gradient force,
flow || isobars

$$fV_g - \frac{1}{\rho}\frac{\partial p}{\partial n} = 0$$

- Friction on the surface ⇨ $V < V_g$
- Coriolis-force smaller ⇨ wind direction deflected towards the pressure gradient.

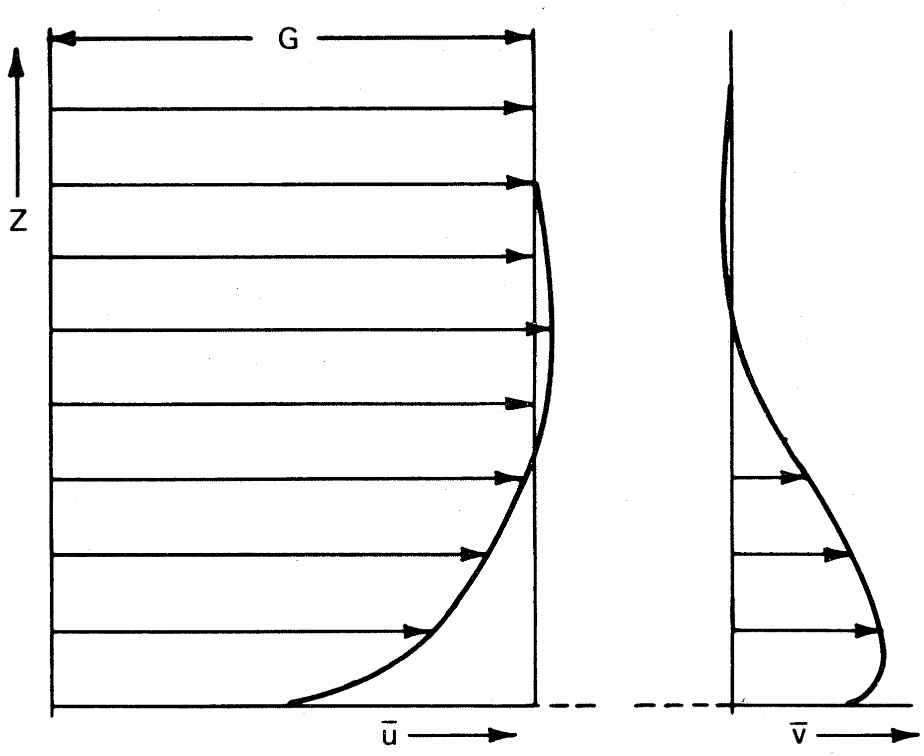


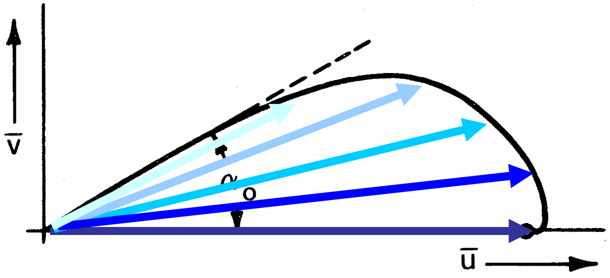
- Max.deflection : 45°

Momentum equations:

X :
$$\frac{1}{\rho}\frac{\partial p}{\partial n} = fU + \frac{\partial\left(\overline{v'w'}\right)}{\partial z}$$

Y :
$$0 = fV + \frac{\partial\left(\overline{u'w'}\right)}{\partial z}$$

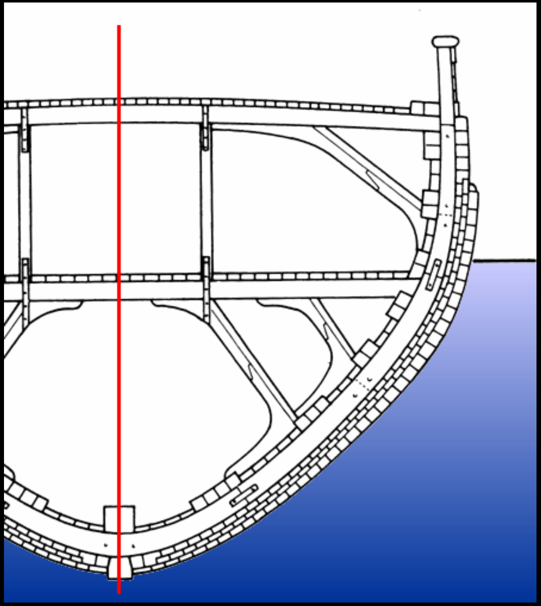




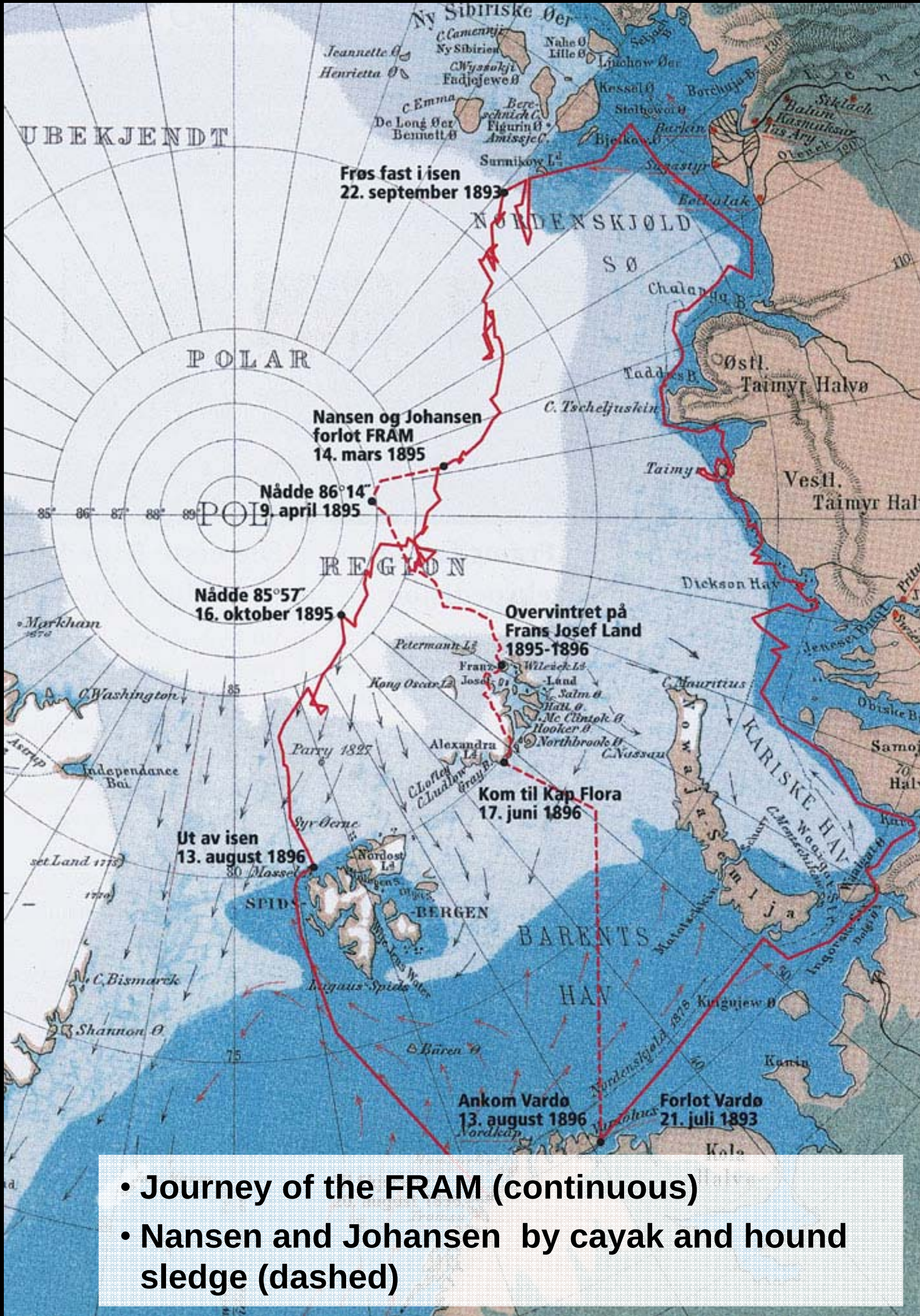
FRIDTJOF NANSEN’S EXPEDITION WITH FRAM (1893-1896)

The ‘Fram’ in the ice

Nansen (1861-1930)

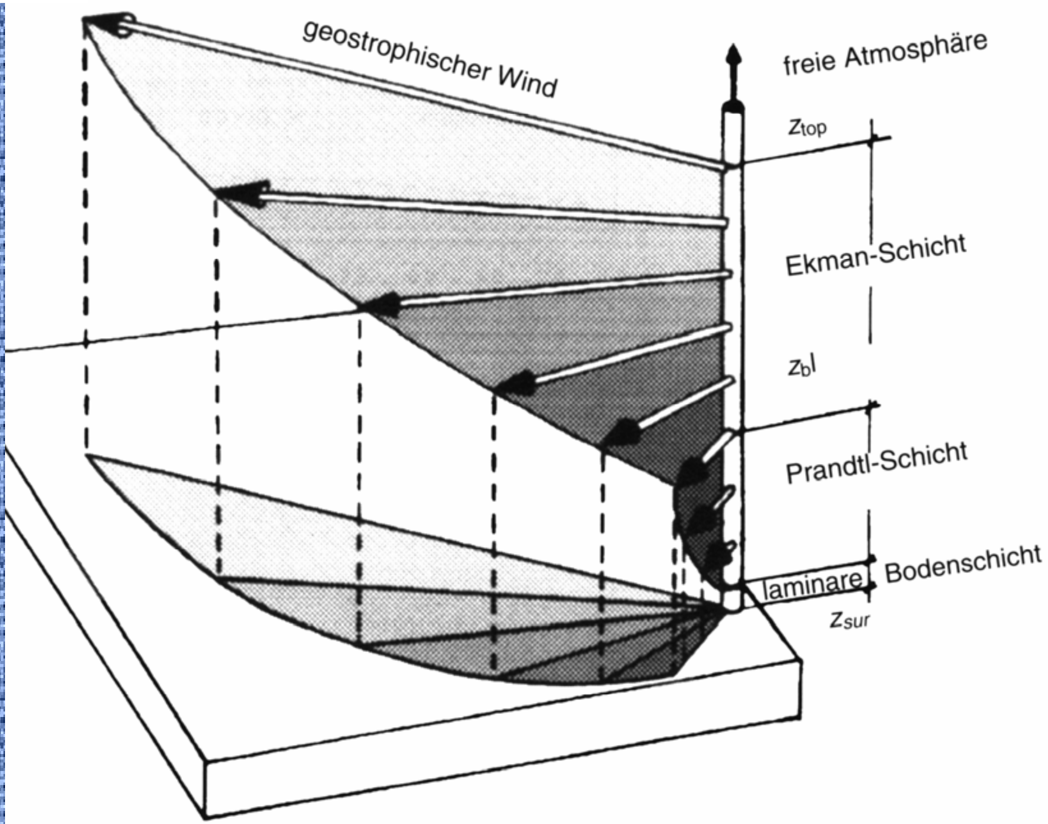


‘Fram’s cross-section

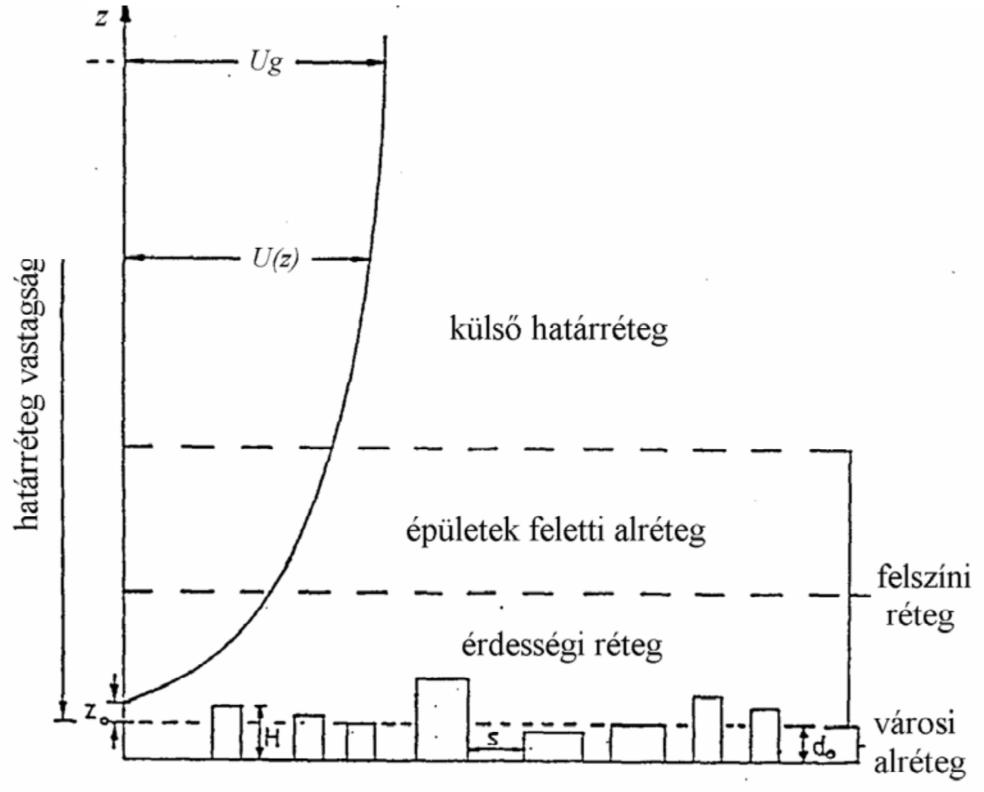


- Journey of the FRAM (continuous)
- Nansen and Johansen by cayak and hound sledge (dashed)

EKMAN-SPIRAL, SUBLAYERS

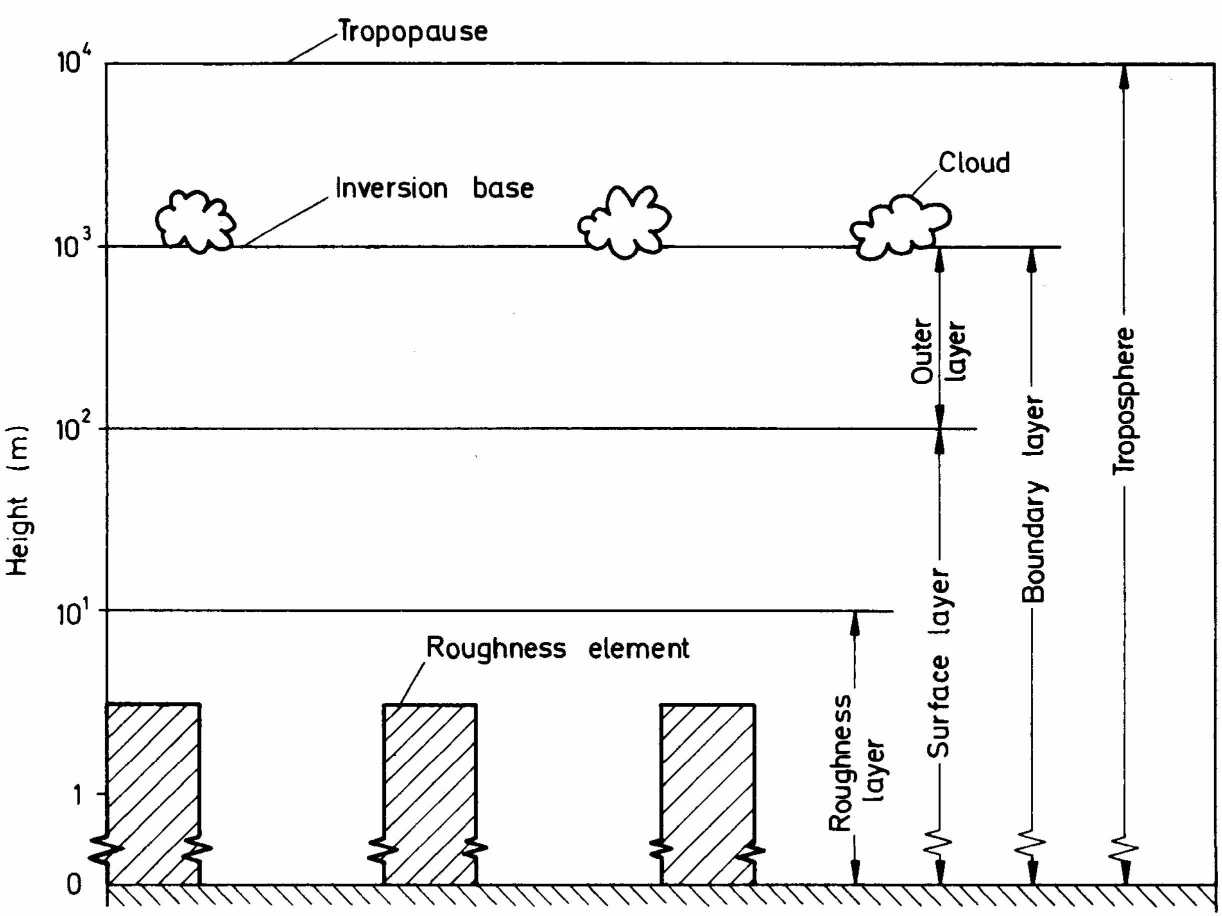


Surface layer (Prandtl layer)



BOUNDARY LAYER STRUCTURE ABOVE ROUGH TERRAIN

boundary layer thickness ~ 10% of troposphere width,
~ 1 km, but can vary between 200 m - 5 km



Surface layer: wind speed, temperature change with height.

Turbulence induced by surface roughness / obstacles and thermal convection

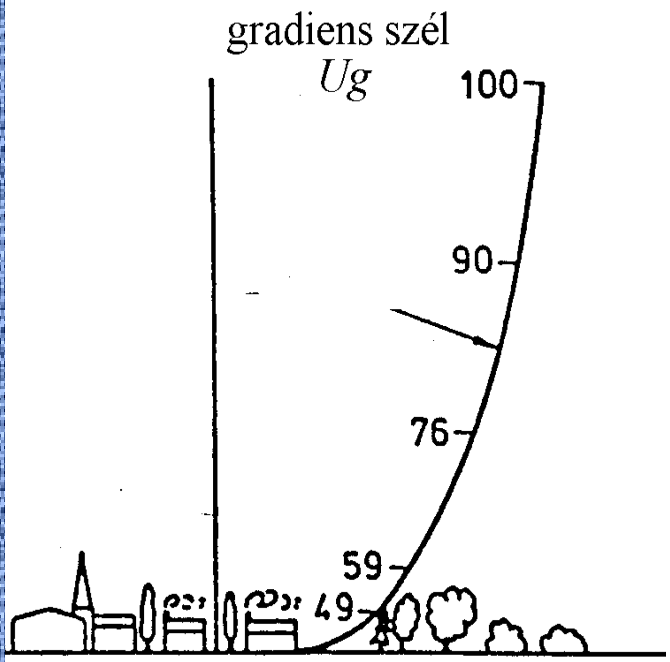
constant flux of mass heat etc.

Wind direction approximately constant

Typical height: 50 m, can vary between 5-200 m

roughness or canopy layer: wind speed influenced strongly by buildings, groves trees: chaotic (3D) dominance of turbulent movement.

LOGARITHMIC BOUNDARY LAYER PROFILE



- Turbulent momentum exchange between layers:

$$\frac{\tau}{\rho} = \overline{u'w'} = K_M \frac{\partial \overline{u}}{\partial z}$$

- K-theory: shear stsess proportianal to the gradient of the mean wind profile
- Turbulent vortices cause an additional viscosity (turbulent viscosity)

$$K_M >> \nu$$

- K_M not constant, and can be determined using **turbulence models**

☐ τ constant in the surface layer

$$\frac{\tau}{\rho} = \overline{u'w'} = \left(u^*\right)^2 = \text{áll.}$$

u* - friction velocity

(fictitious quantity with velocity dimension)

$$K_M = \kappa \cdot u^* \cdot z$$

Simple assumption: Km ⇨0 at the surface

κ – Kármán-constant = 0.41

$$\frac{u^*}{\kappa z} = \frac{\partial \overline{u}}{\partial z}$$

$$\overline{u}(z) = \frac{u^*}{\kappa} \cdot \ln(z) + K$$

LOGARITHMIC BOUNDARY LAYER PROFILE

$$\bar{u}(z) = \frac{u^*}{\kappa} \cdot \ln\left(\frac{z}{z_0}\right)$$

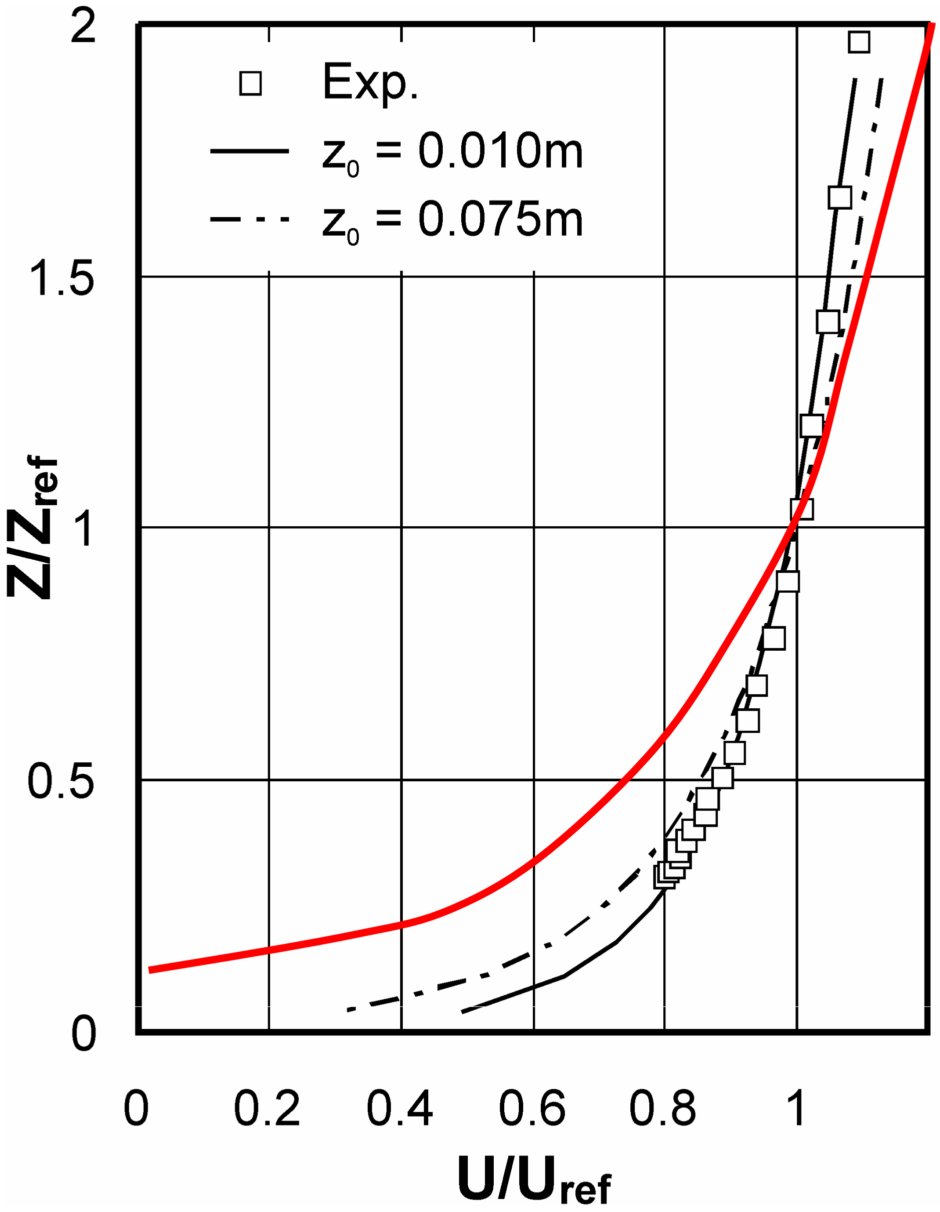
z_0 – roughness length

$$\frac{\bar{u}(z)}{u^*} = \frac{1}{\kappa} \cdot \ln\left(\frac{z - d_0}{z_0}\right)$$

d_0 – displacement height

(if the whole boundary layer is shifted upwards)

- d_0+ ln z_0 at $U/U_{ref} = 0$

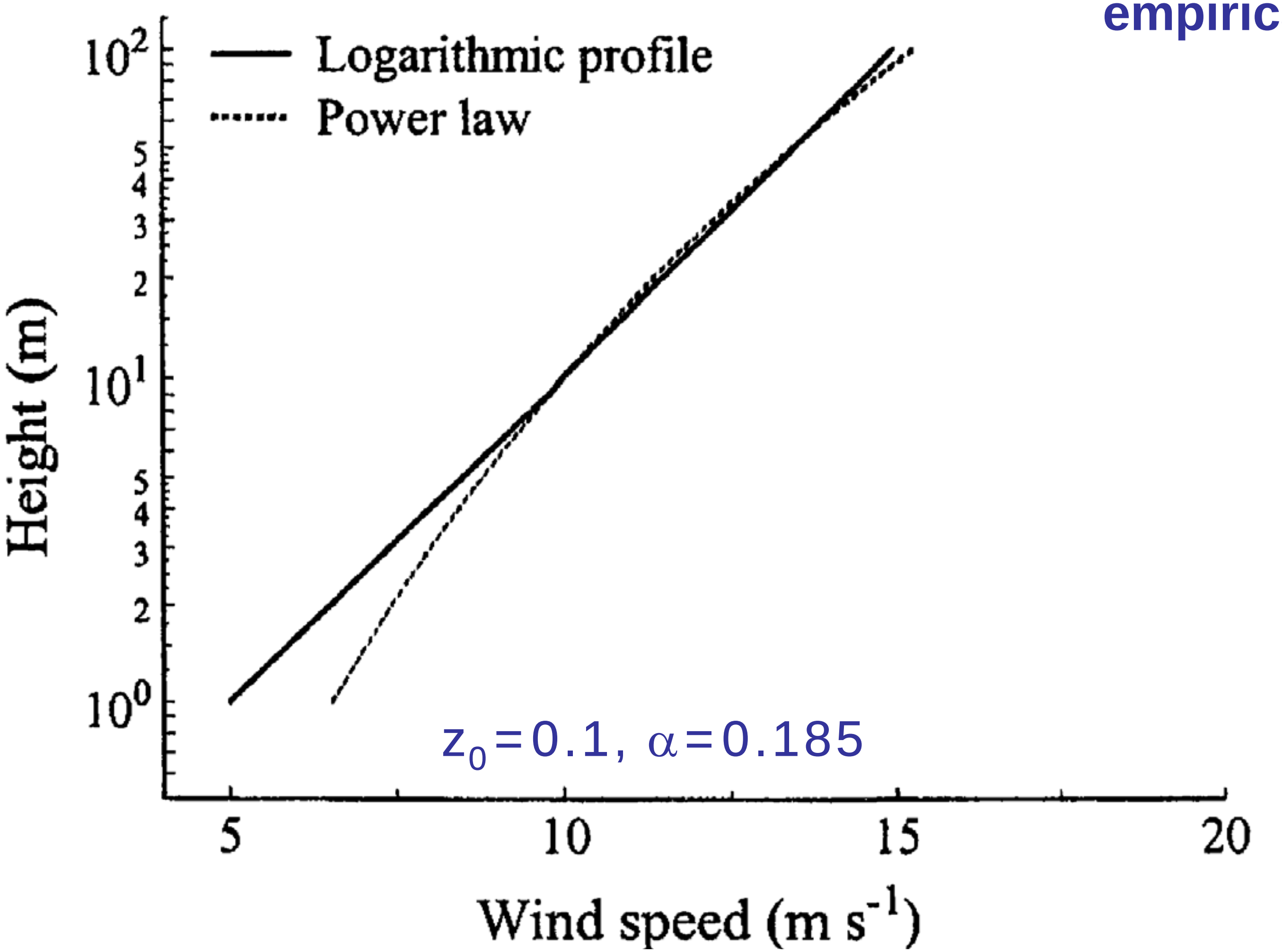


LOG-LAW AND POWER LAW WIND PROFILES

$$\frac{\overline{u}(z)}{u_*} = \frac{1}{\kappa}\cdot\ln\left(\frac{z-d_0}{z_0}\right)$$

$$\frac{\overline{u}(z)}{u_{ref}} = \left(\frac{z-d_0}{z_{ref}-d_0}\right)^{\alpha}$$

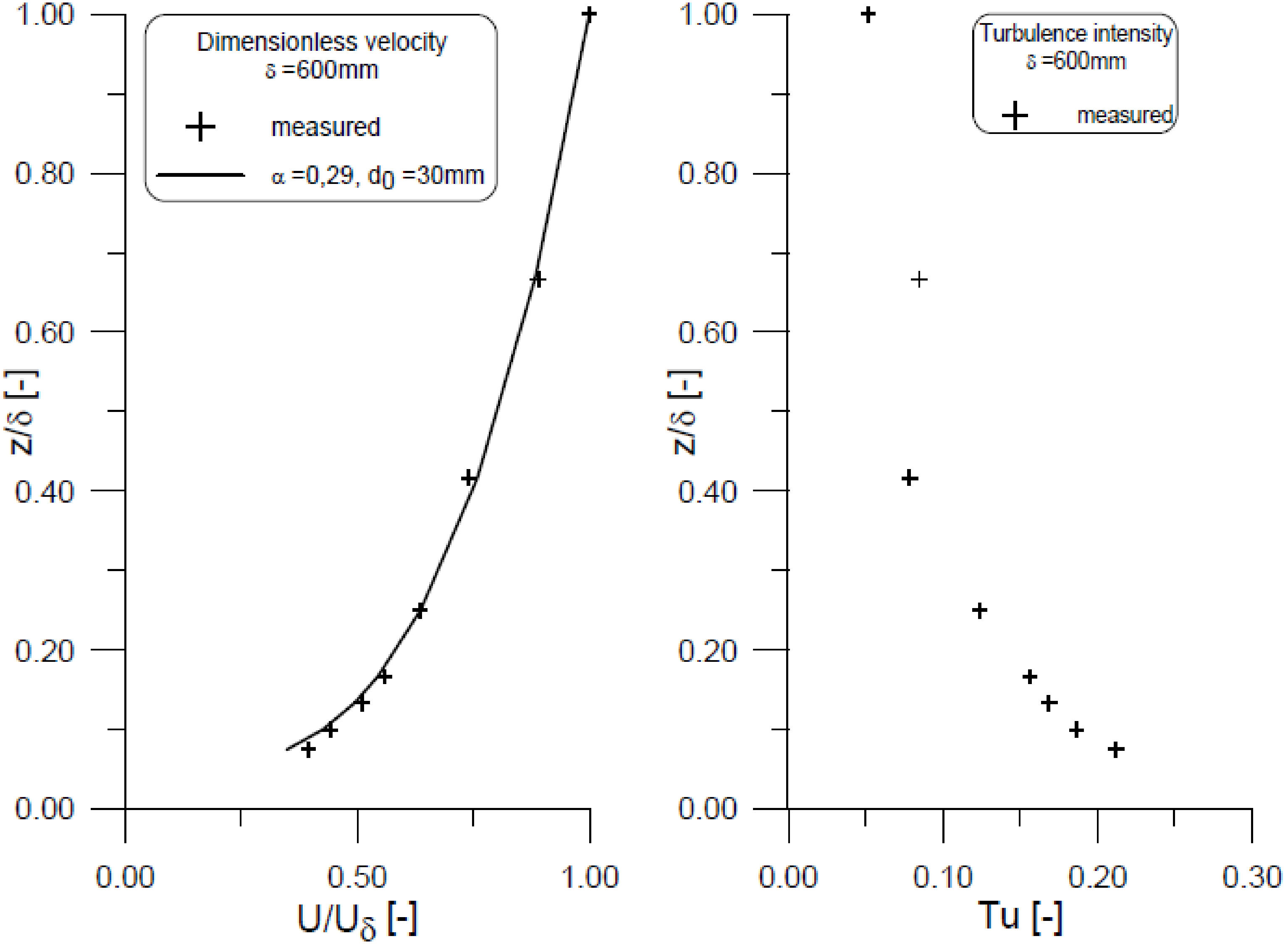
empirical power function



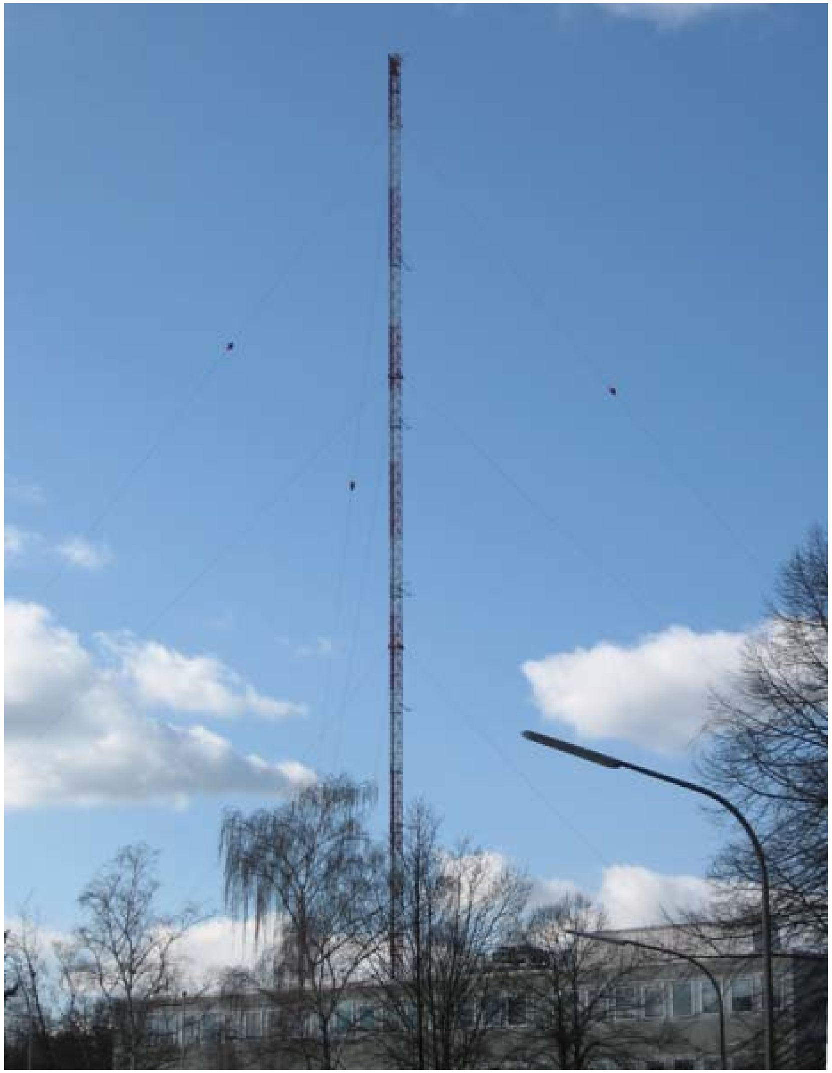
$z_0=0.1,\ \alpha=0.185$

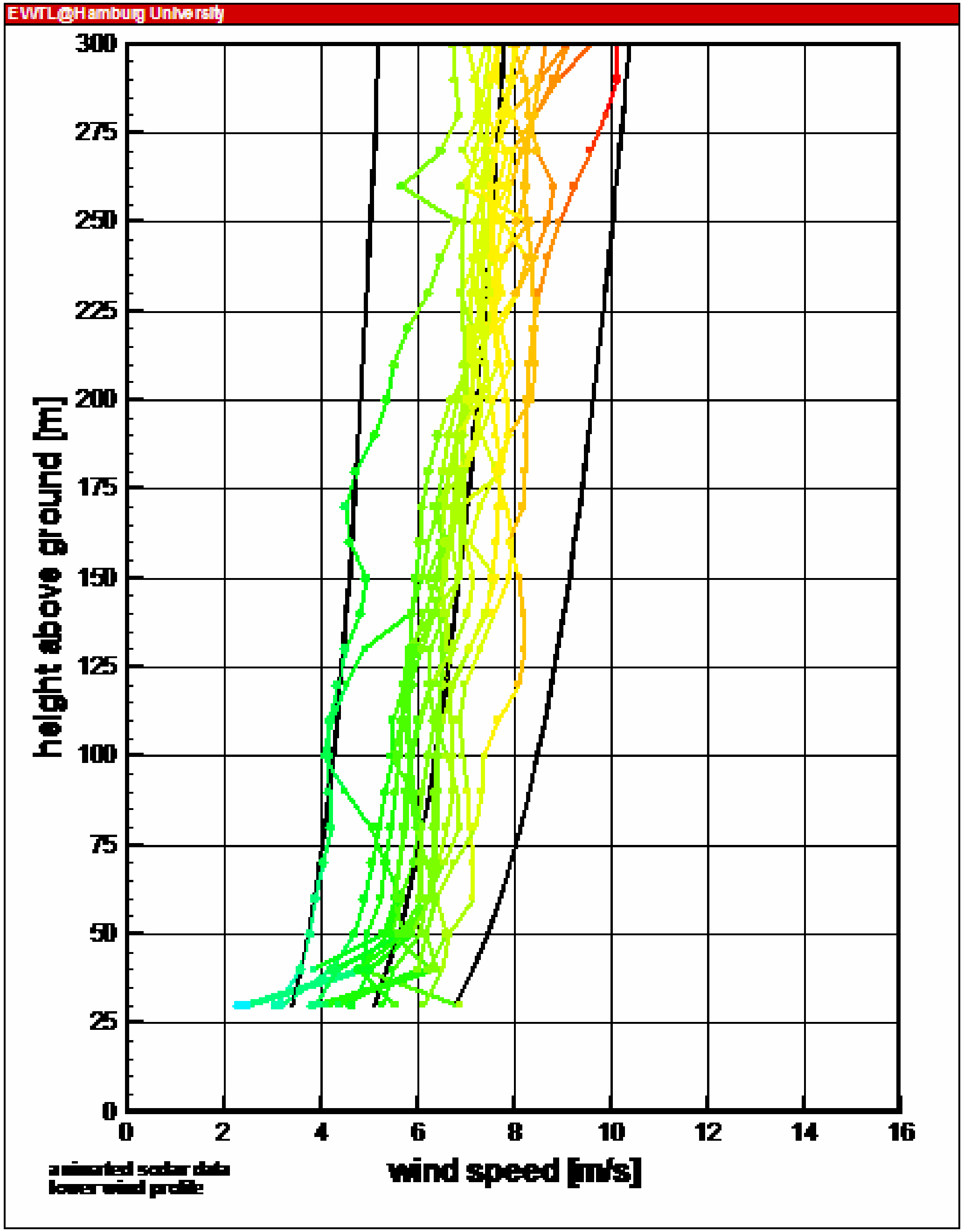
LOG-LAW AND POWER LAW WIND PROFILES

- Power law wind profiles measured in wind tunnel

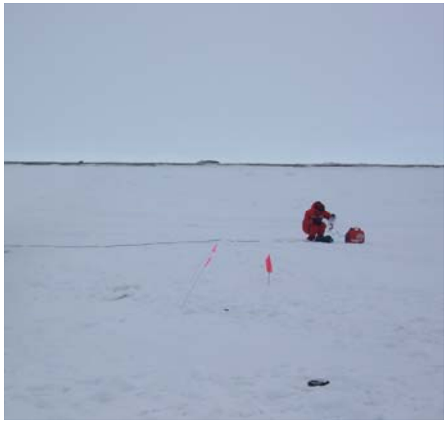


WIND PROFILES FROM ON-SITE MEASUREMENTS





PROFILE PARAMETERS



Forrás: http://www.gi.alaska.edu/~heike/Barrow2005/h_chargingADV.jpg

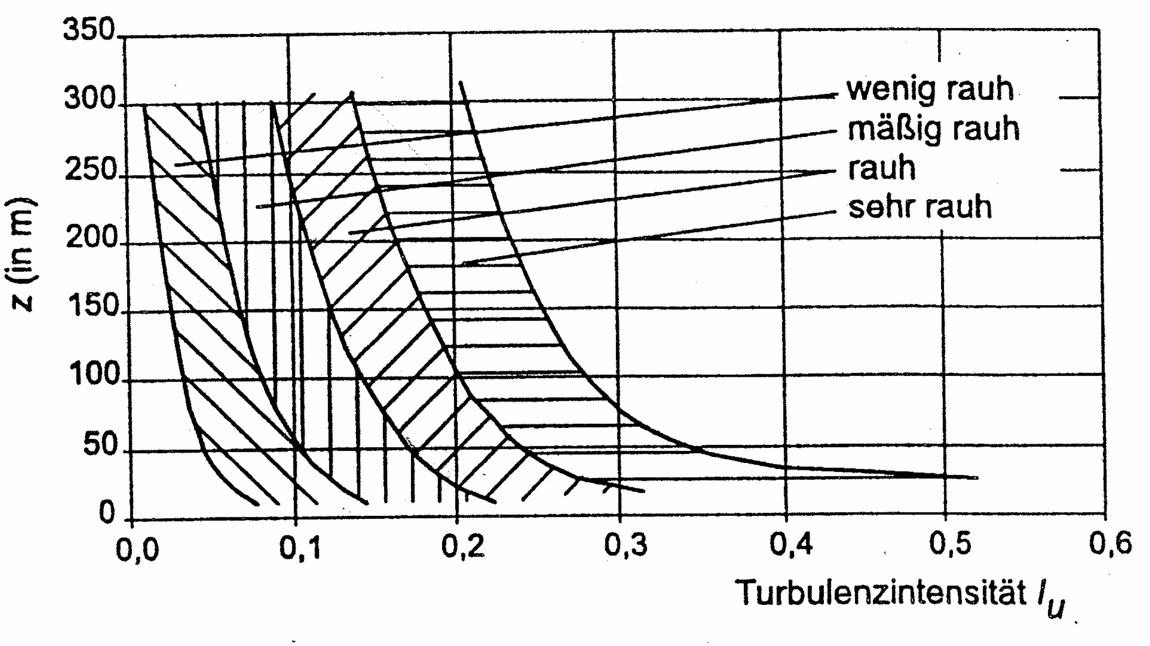
Forrás: http://earthobservatory.nasa.gov/Laboratory/Biome/Images/picgrassland.jpg

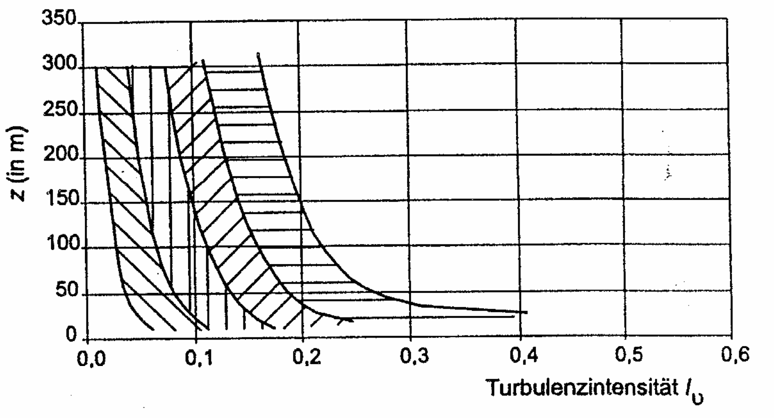
Forrás: http://www.aerometrex.com.au/AdelaideMetro/Suburban_Adelaide.jpg

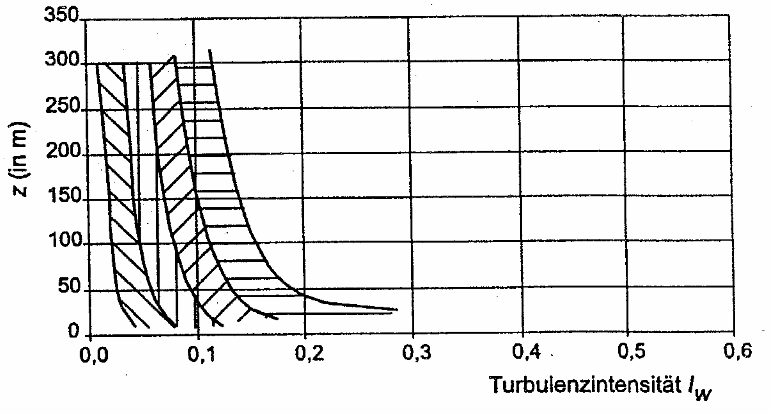
Forrás: http://www.usatravel.hu/fckep/Image/Missouri/.thumb_Kansas_City.jpg

Surface category	***smooth***	***medium***	***rough***	***very rough***
description	Ice, snow, calm water	Farmland, grass	Suburban area, groves	Forests, urban area
z_0 [m]	$10^{-5} – 5{\cdot}10^{-3}$	$5{\cdot}10^{-3} – 10^{-1}$	0.1 – 0.5	0.5 - 2
a [-]	0.08 – 0.12	0.12 – 0.18	0.18 – 0.24	0.24 – 0.4
d_0 [m]	≈0	≈0	$\approx 0.75{\cdot}h$	$\approx 0.75{\cdot}h$

TURBULENCE INTENSITY IN THE ATMOSPHERIC BOUNDARY LAYER







$$\sigma_u = 2{,}45 \div 2{,}5 \cdot u_*$$

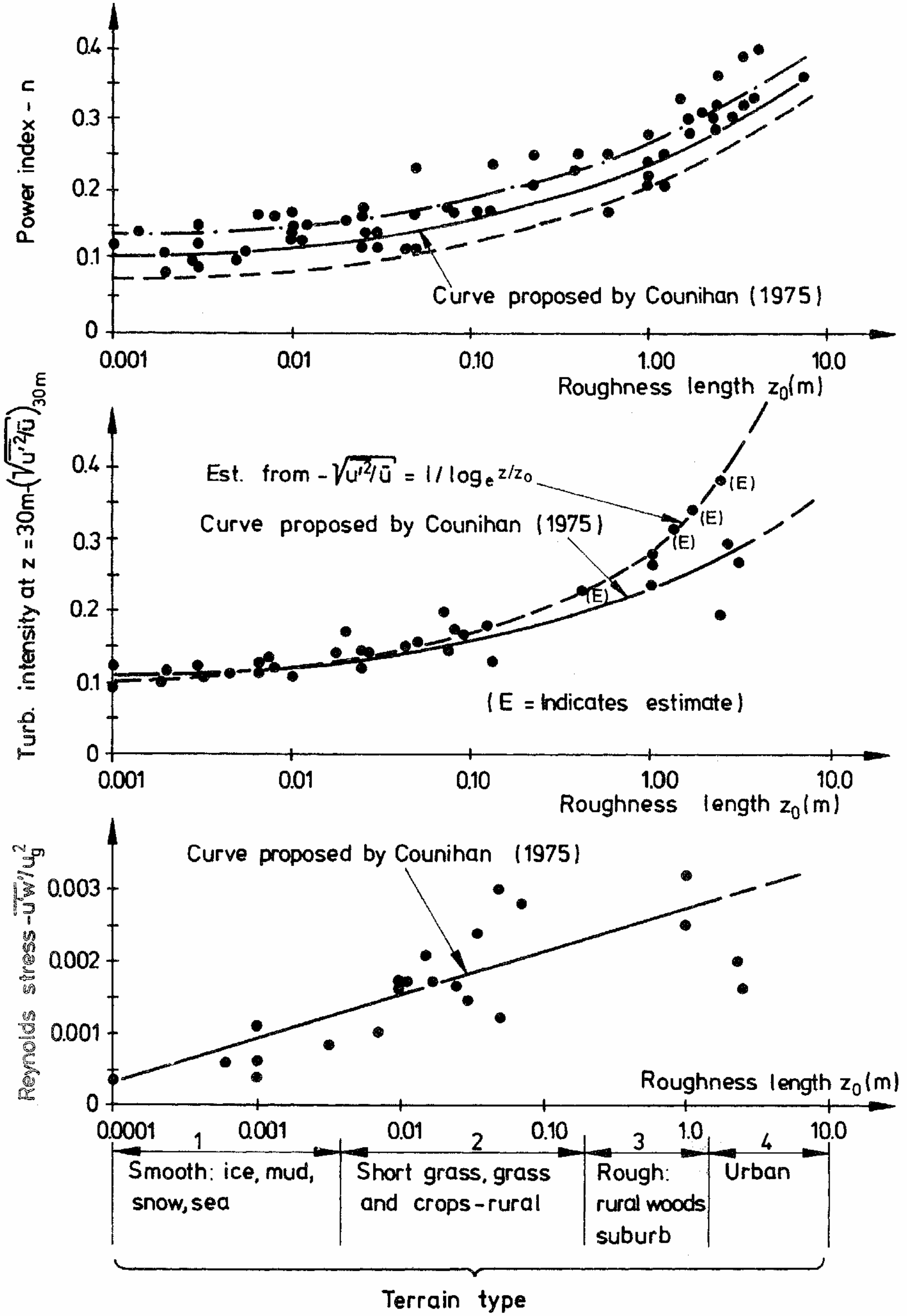
$$\sigma_v = 2{,}2 \cdot u_*$$

$$T_u : T_v : T_w = 1 : 0.8 : 0.5$$

$$\sigma_w = 1{,}25 \cdot u_*$$

ATMOSPHERIC TURBULENCE IS ANISOTROPIC!

PROFILE PARAMETERS



a. Exponent in power law for mean velocity distribution

b. Turbulent intensity at z = 30 m

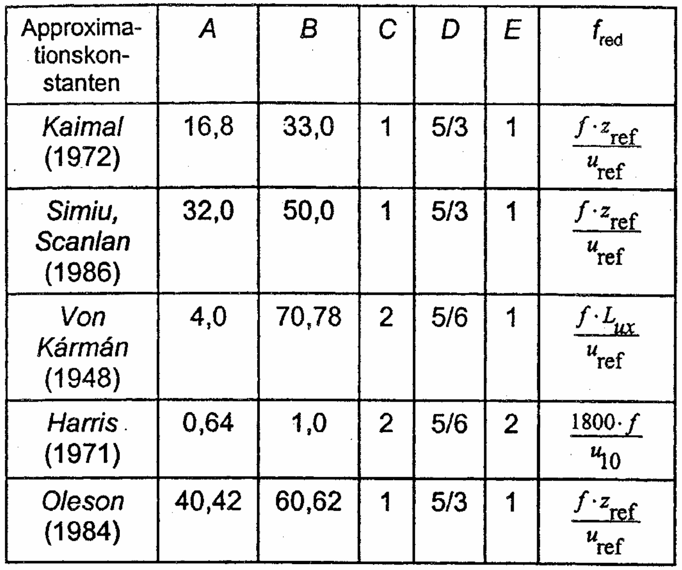
c. Turbulent shear stress

$$\frac{\bar{u}(z)}{u_{ref}} = \left(\frac{z - d_0}{z_{ref} - d_0}\right)^{\alpha}$$

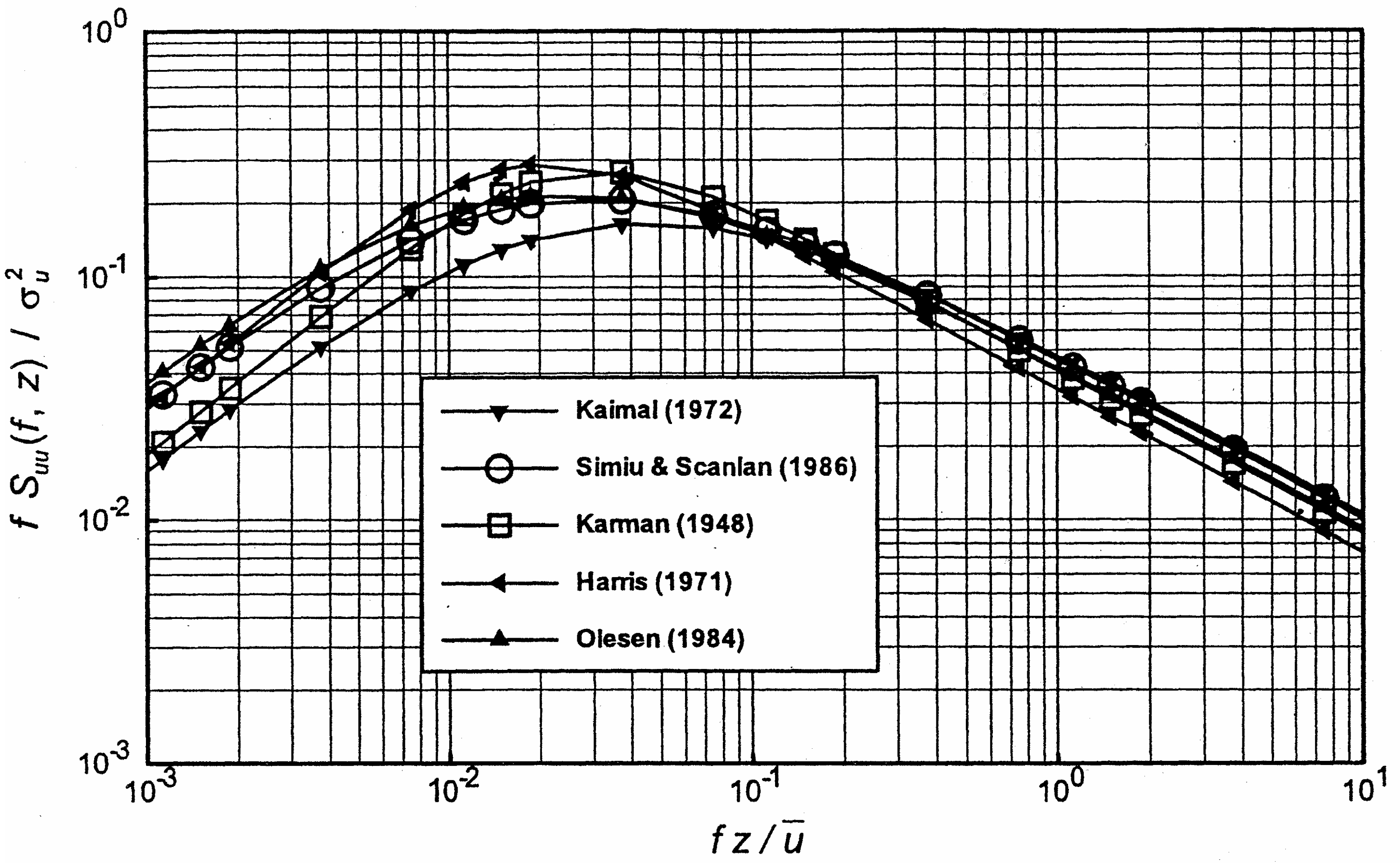
$$T_u = \frac{\sigma_u}{\bar{u}}$$

WIND SPECTRA

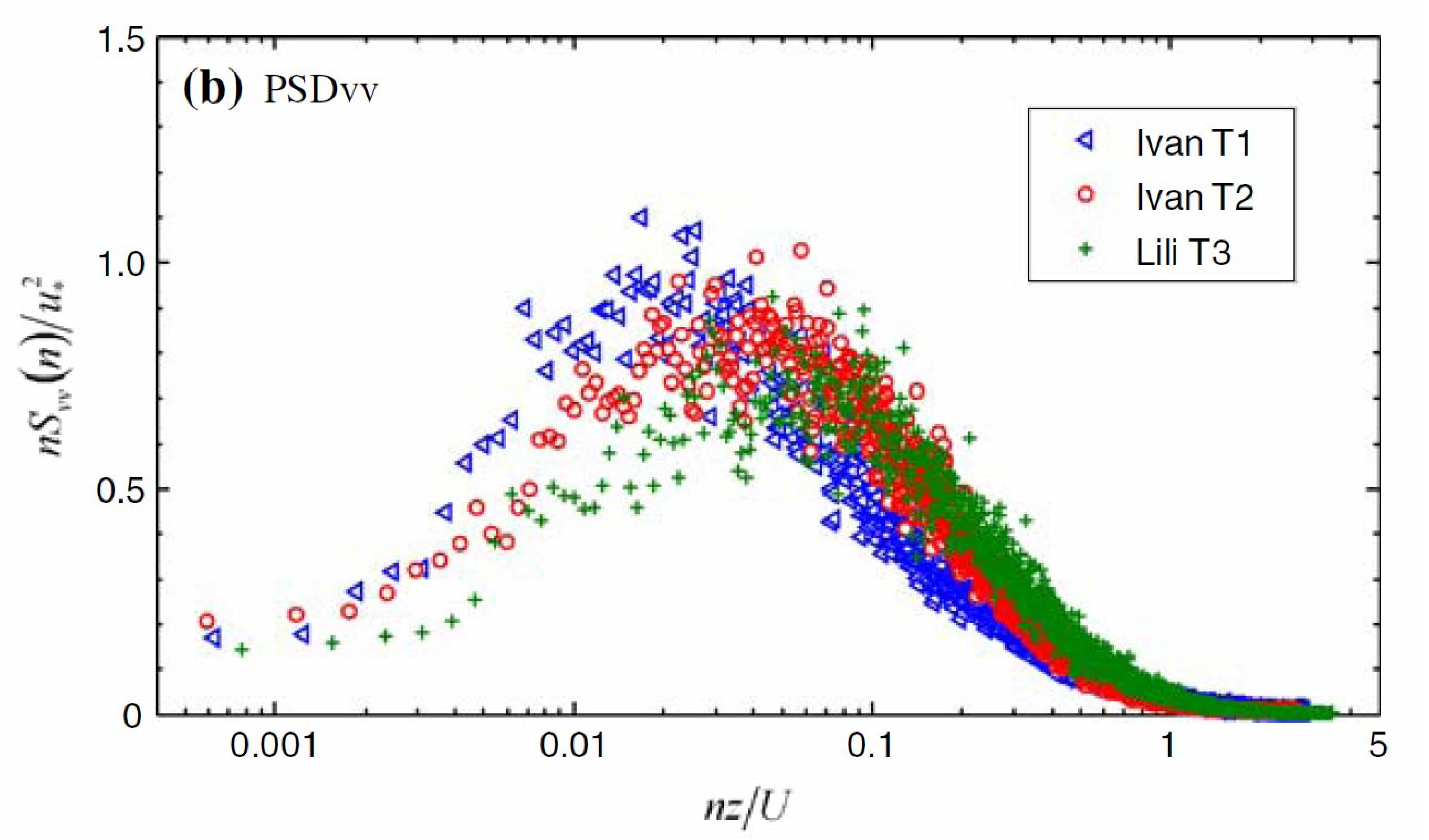
$$\frac{f\cdot S_{uu}(f,z)}{\sigma_u^2(z)}=\frac{A\cdot f_{red}}{\left(E+B\cdot f_{red}^{C}\right)^{D}}$$



Approximationskonstanten	*A*	*B*	*C*	*D*	*E*	f_{red}
Kaimal (1972)	16,8	33,0	1	5/3	1	$\frac{f\cdot z_{ref}}{u_{ref}}$
Simiu, Scanlan (1986)	32,0	50,0	1	5/3	1	$\frac{f\cdot z_{ref}}{u_{ref}}$
Von Kármán (1948)	4,0	70,78	2	5/6	1	$\frac{f\cdot L_{ux}}{u_{ref}}$
Harris (1971)	0,64	1,0	2	5/6	2	$\frac{1800\cdot f}{u_{10}}$
Oleson (1984)	40,42	60,62	1	5/3	1	$\frac{f\cdot z_{ref}}{u_{ref}}$

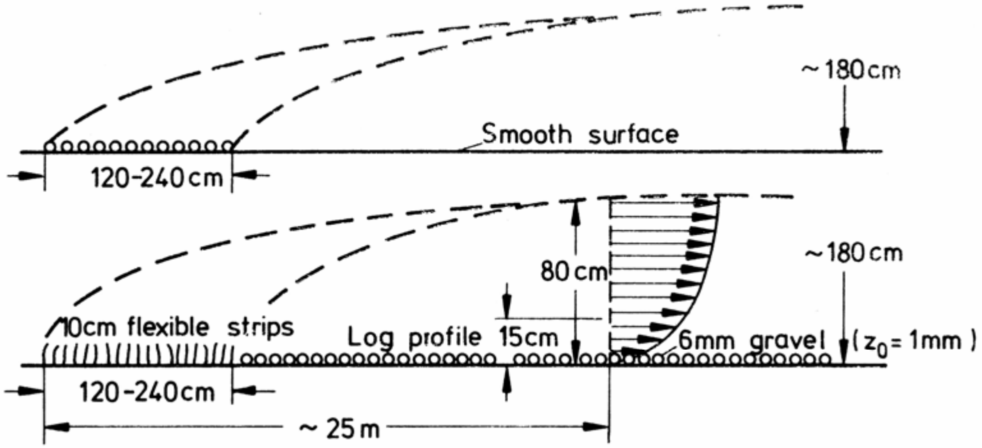


WIND SPECTRA

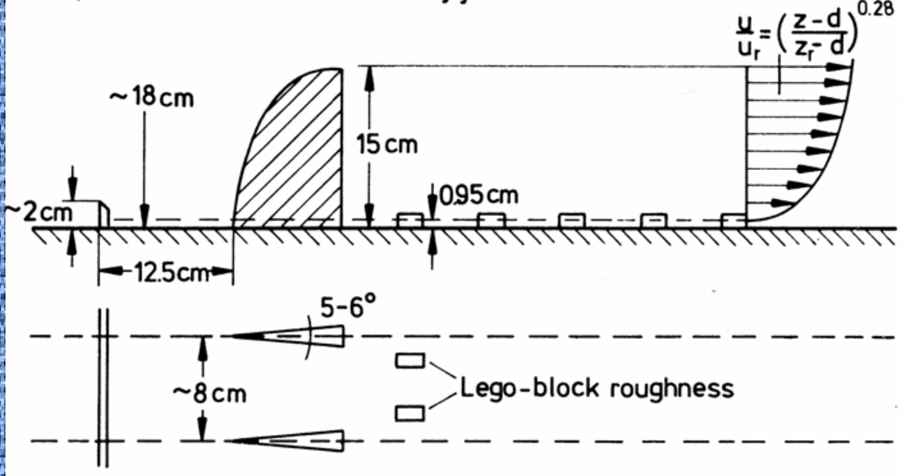


Forrás: Yu et al (2008): HurricaneWind Power Spectra, Cospectra, and Integral Length Scales

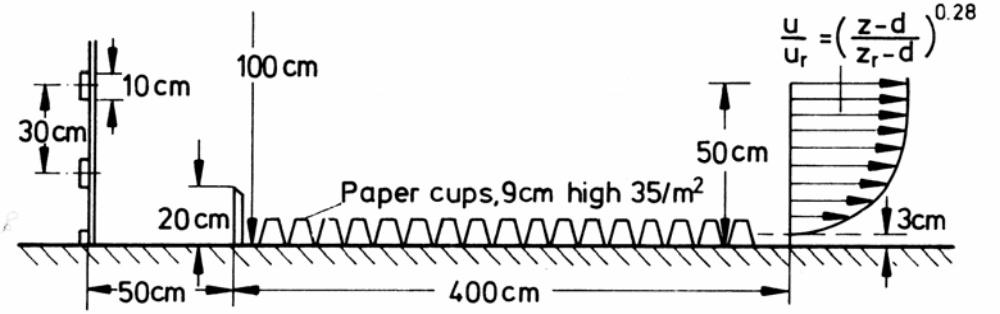
BOUNDARY LAYER GENERATION IN WIND TUNNELS



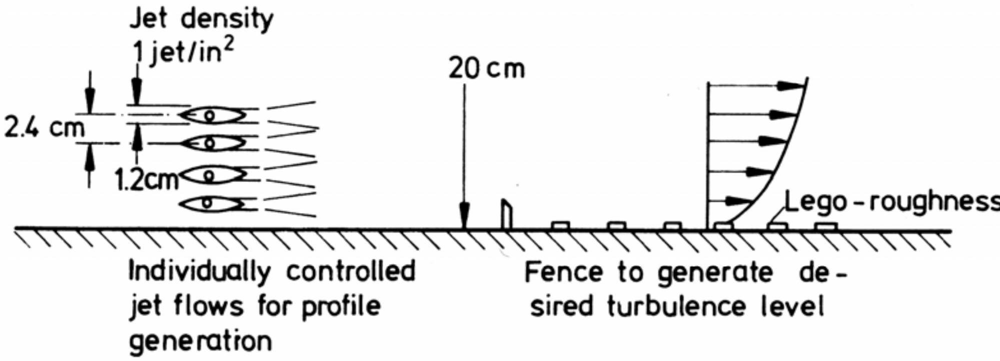
a. Boundary layer generation along test section floor (Colorado State University, 1963)



b. Boundary layer generation with vortex generators (Counihan,1971



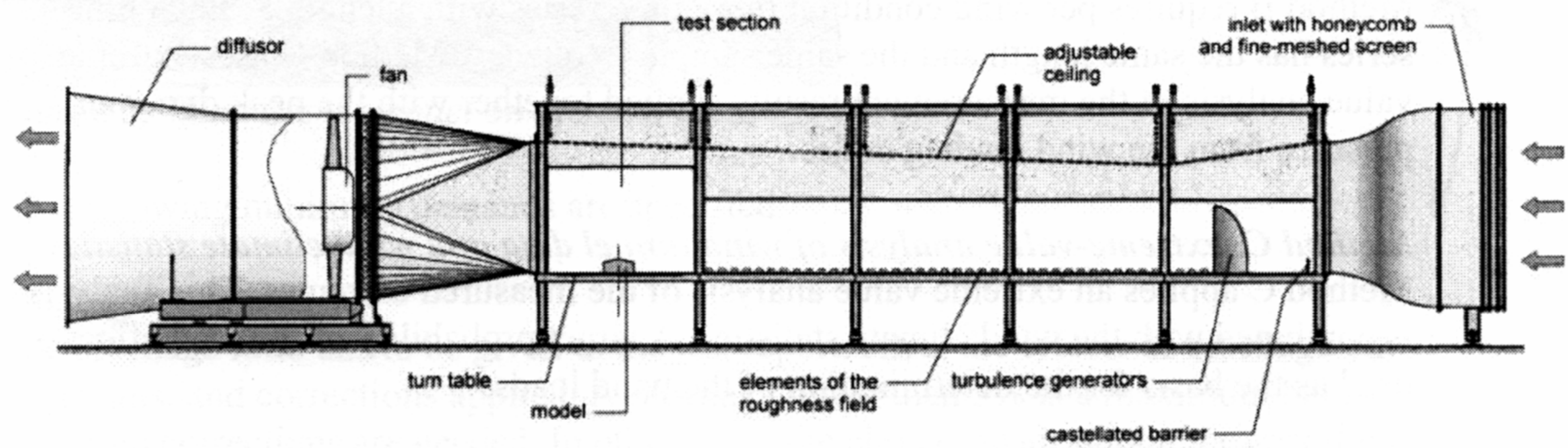
c. Boundary layer generation with fence (Cook, 1973)



d. Boundary layer generation with jets (Teunissen, 1974)

ábra: E. J. Plate. Engineering Meteorology (1982)

BOUNDARY LAYER GENERATION IN WIND TUNNELS



Open section wind tunnel of the Ruhr University in Bochum, Germany

1. Confuser
2. Turbulence generators
3. Roughness elements
4. Adjustable roof
5. Flow preparation section
6. Measurement section - model on turntable
7. Fan
8. Diffuser

BOUNDARY LAYER GENERATION IN WIND TUNNELS

test section	closed
preparation section length [m]	5 or 7
measurement section length [m]	2
measurement section width [m]	2.2
measurement section height [m]	1.4
max. wind speed [m/s]	22
inlet turbulece intensity [%]	0.5