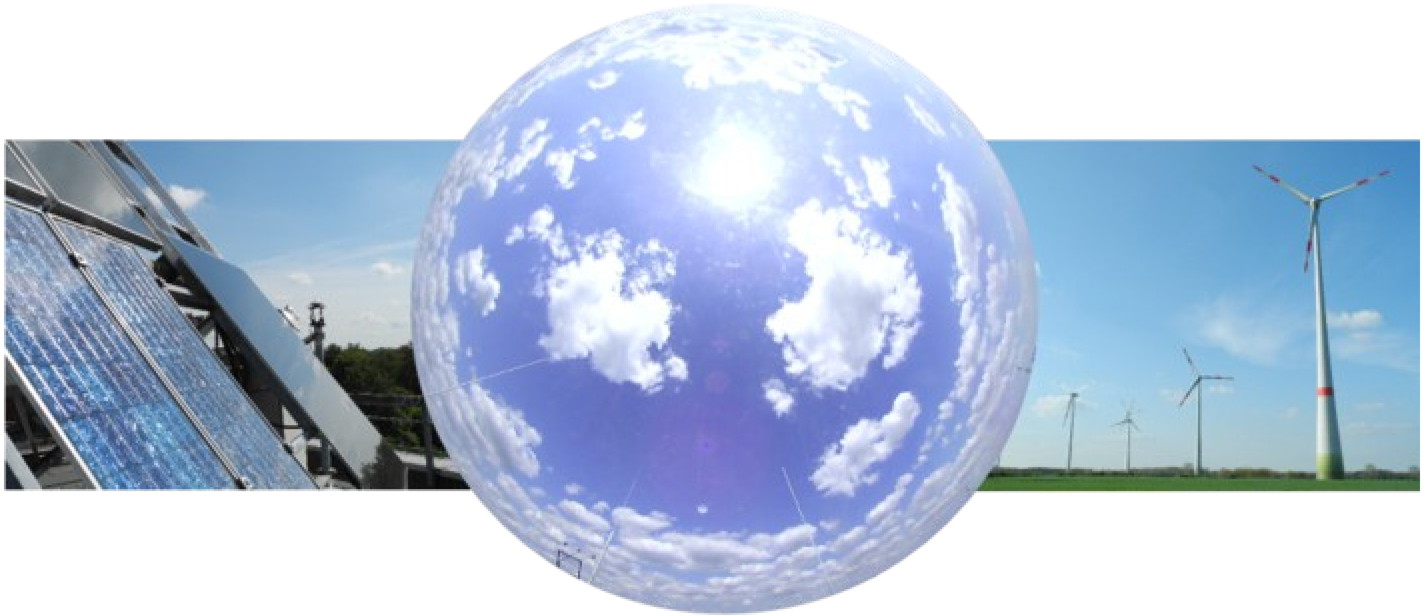
Wind Physics Measurement Project

Energy Meteorology

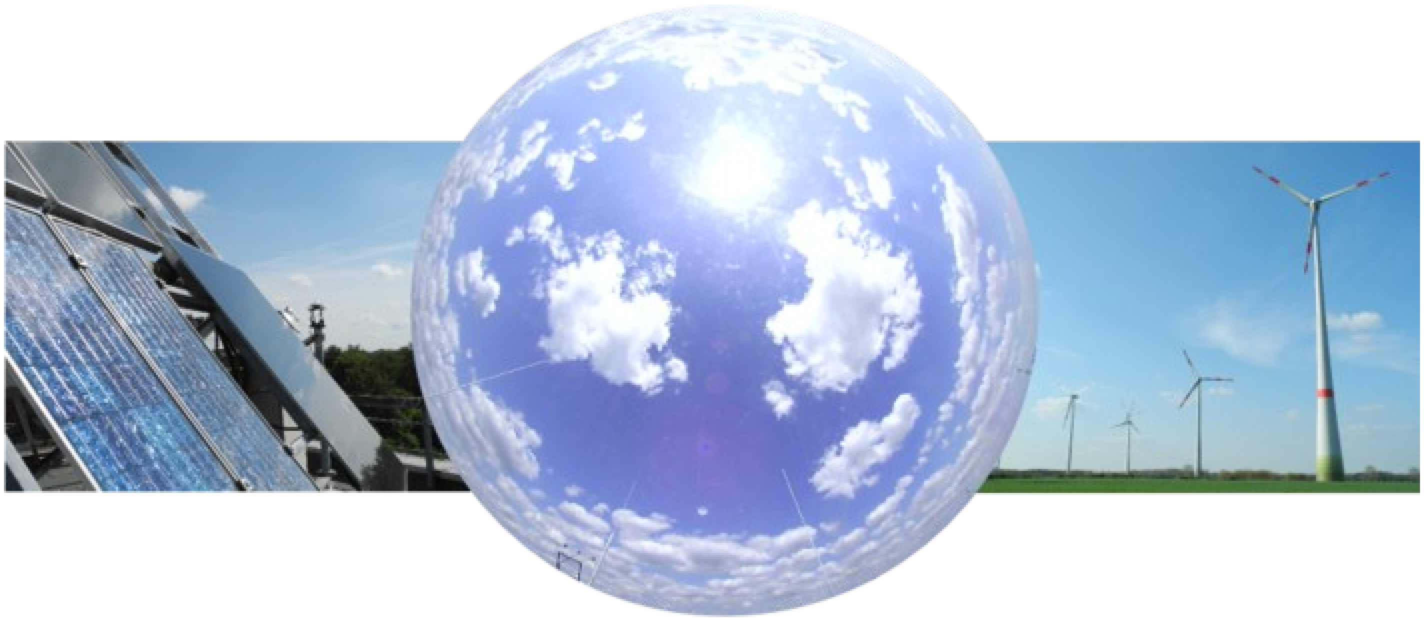


Institute of Physics
AG Wind Energy Meteorology

CARL VON OSSIETZKY universität OLDENBURG

Learning Objectives

- Overview of Meteorology and Energy Meteorology
- Physical and mathematical background
- *Get a feeling for meteorological values*



Content

I. Geographical distribution of surface winds

II. Wind regimes on different time and length scales

III. Statistical distribution of wind speed

IV. Vertical wind speed profile

V. Differences between onshore and offshore conditions

What is Meteorology?

“Meteorology is the interdisciplinary scientific study of the atmosphere“
Wikipedia

What is a meteorologist doing?

- Measurements of the state of the atmosphere in time and space
- Derivation of physical and mathematical concepts
- Application of these concepts in models

Challenges:

- Multivariate
- 4 dimensions
- Non linear
- Complex boundary conditions
- Huge scale range in space and time

What is Meteorology?

"Meteorology is the interdisciplinary scientific study of the atmosphere"

Wikipedia

What are scientific questions in classical meteorology?

- Climate Variability "Climate Change"
- Surface weather prediction
- Storm prediction
- Pollution

What is Energy Meteorology?

“Energy Meteorology … ?“

Wikipedia

“Energy Meteorology is an active field of research interfacing renewable energy and atmospheric physics by providing data and developing new methods for the characterisation of the fluctuating power output from solar and wind energy systems.” *www.uni-oldenburg.de/en/energiemeteorology*

What are scientific questions in Energy Meteorology?

- Solar Energy: Prediction and characterisation of clouds
- Wind Energy: Wind speed and wind direction at ~ 30-150m
- Prediction of conditions for ~ 20 yr
- Short term prediction for few hours and days for the energy market
- Geographical distribution of wind and radiation

Challenges:

- Few measurements at heigher heights, few measurements offshore
- $P \sim u^3$

I. Geographical Distribution of Surface Winds

The Atmosphere

- 99.9% of the Atmosphere's total mass is accumulated below a height of 50 km
- The Atmosphere has just about 0.4 % of the mass of the oceans

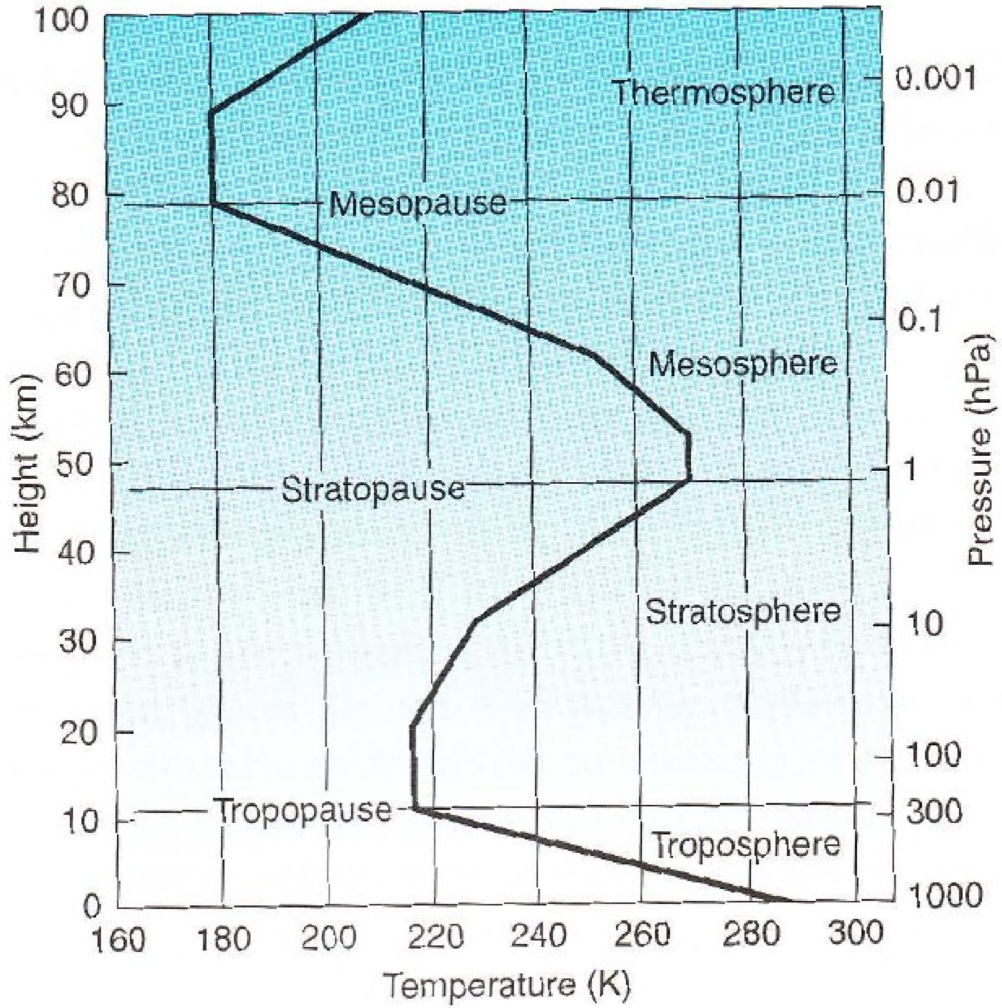
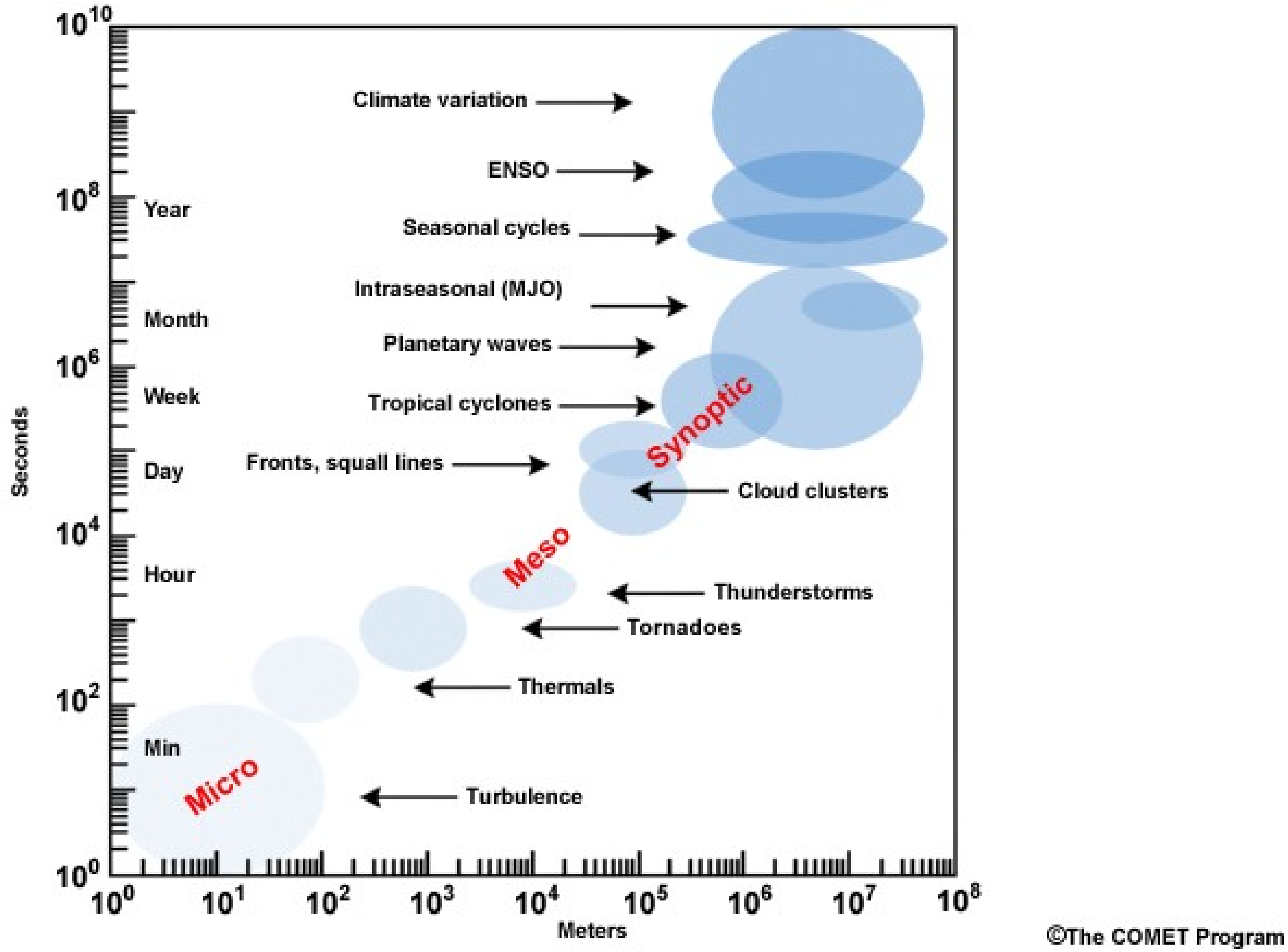


Fig. 1.9 A typical midlatitude vertical temperature profile, as represented by the U.S. Standard Atmosphere.

(aus Walace and Hobbs)

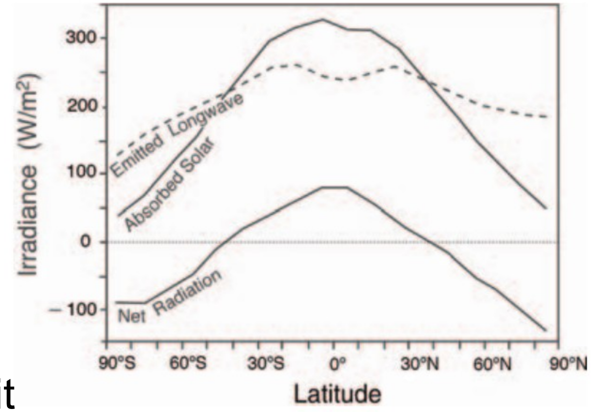
Temporal and spacial scales



[Fig: http://www.goes-r.gov/users/comet/tropical/textbook_2nd_edition/index.htm]

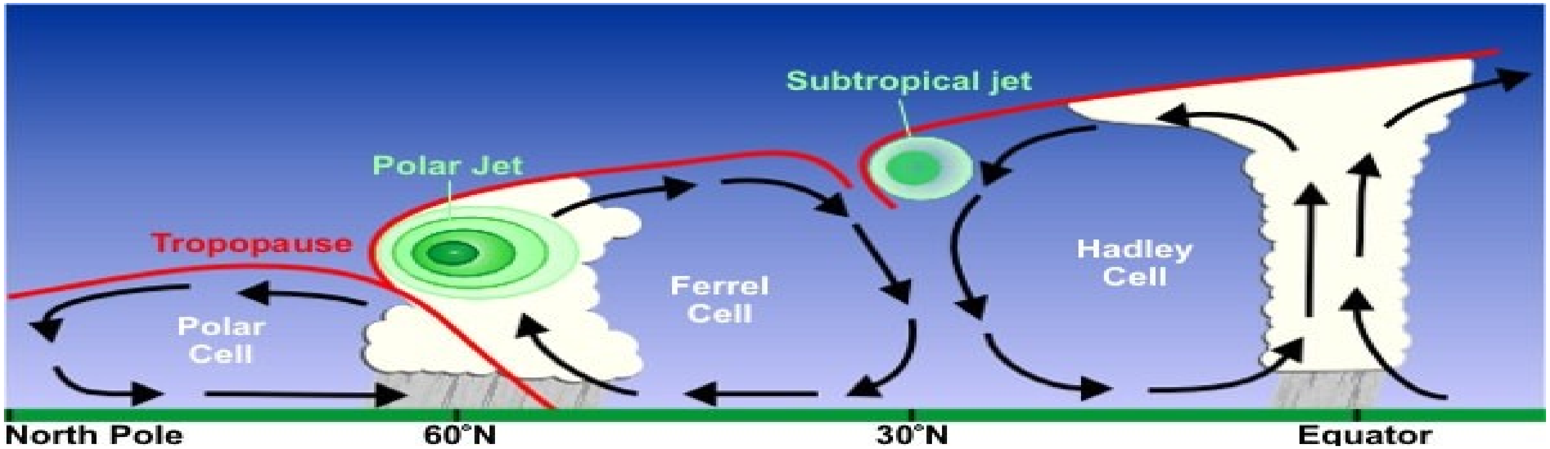
I. Geographical Distribution of Winds

- The *only* energy source on the Earth is the Sun
- Tropical belt and lower latitudes: Positive energy budget (+)
- Polar regions and higher latitudes: Negative energy budget (-)
- Global atmospheric and ocean circulation balances the surplus/deficit



[Fig.: Marshall & Plumb, 2008]

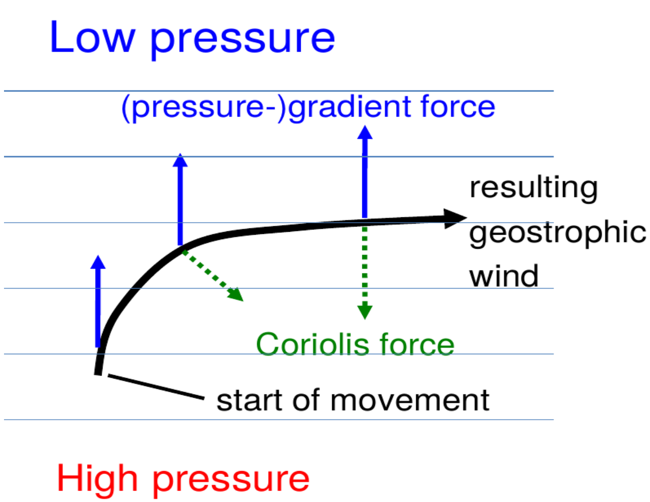
- Realized mainly by three cells: Hadley Cell (direct), Ferrel Cell (indirect) and Polar Cell (direct)
- Indirect circulation maintained by energy conversion from potential energy into kinetic energy

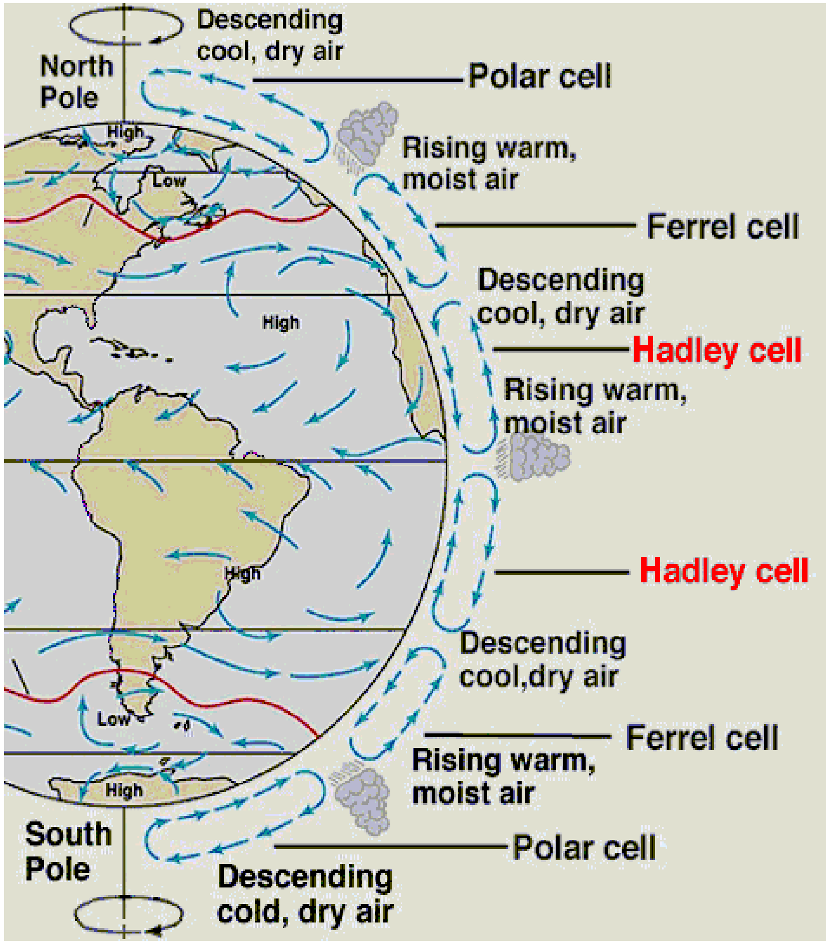


[Fig.: National Weather Service, USA]

I. Geographical Distribution of Winds

- Cells would produce meridional winds only
- Earth's rotation modifies these meridional circulation (Coriolis Force)
- Winds in Northern (Southern) hemisphere are deflected towards the right (left)
- Winds towards equator are deflected in an eastward direction, winds towards the poles are deflected in a westward direction





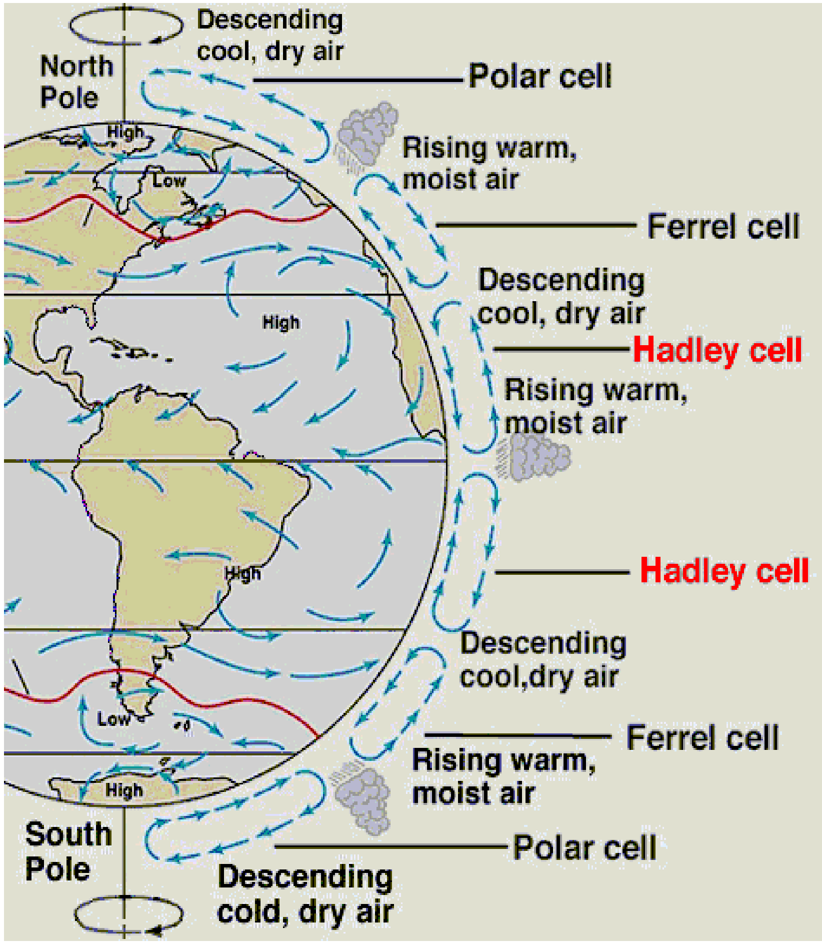
[Fig.: CALS, Arizona]

I. Geographical Distribution of Winds

- Cells would produce meridional winds only
- Earth‘s rotation modifies these meridional circulation (Coriolis Force)
- Winds in Northern (Southern) hemisphere are deflected towards the right (left)
- Winds towards equator are deflected in an eastward direction, winds towards the poles are deflected in a westward direction

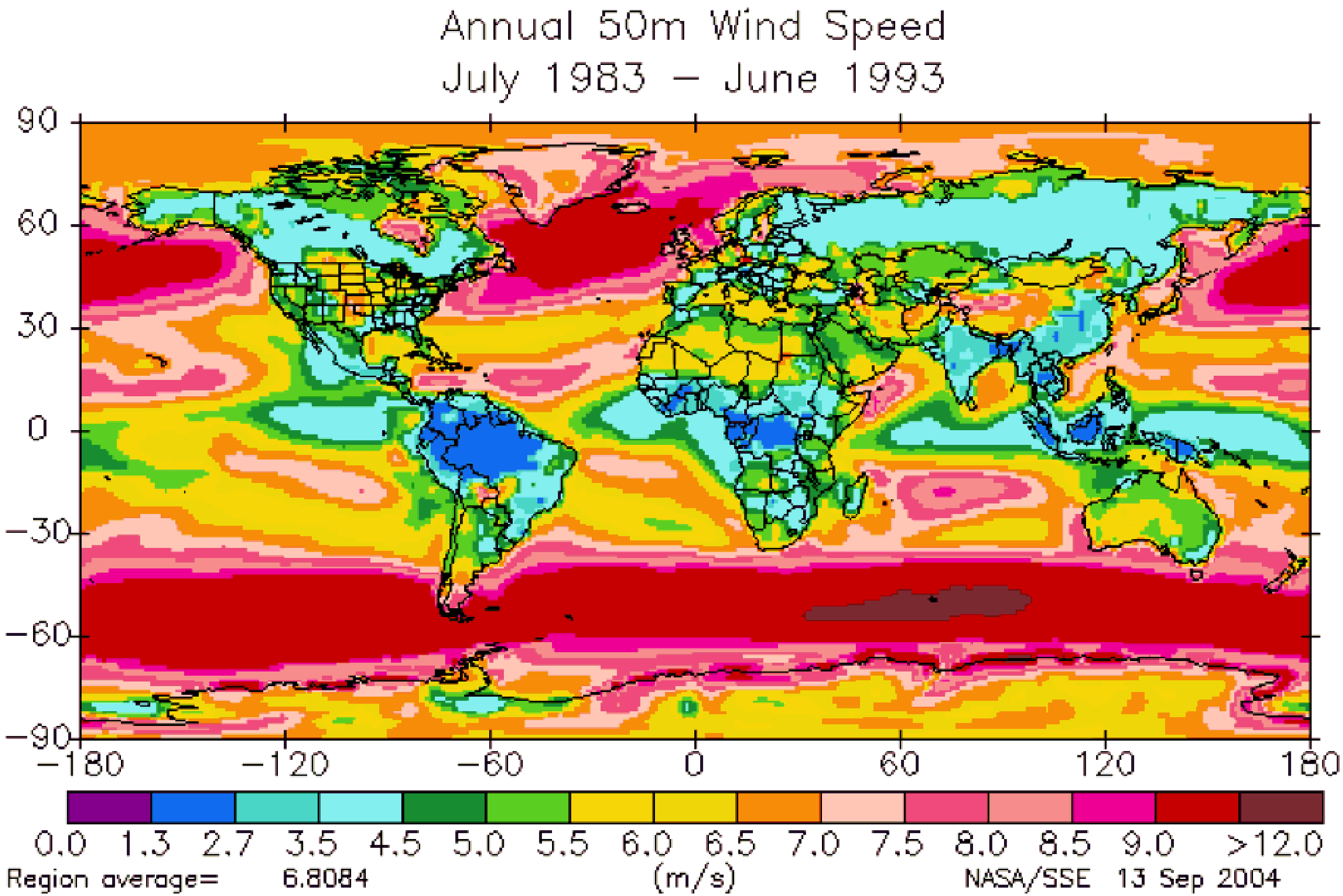
These Winds are modified by:

1. Temperature contrasts between land and sea
2. Long Mountain ridges
3. Land-Sea breeze systems (Chapter 2)
4. Mountain-Valley wind systems (Chapter 2)



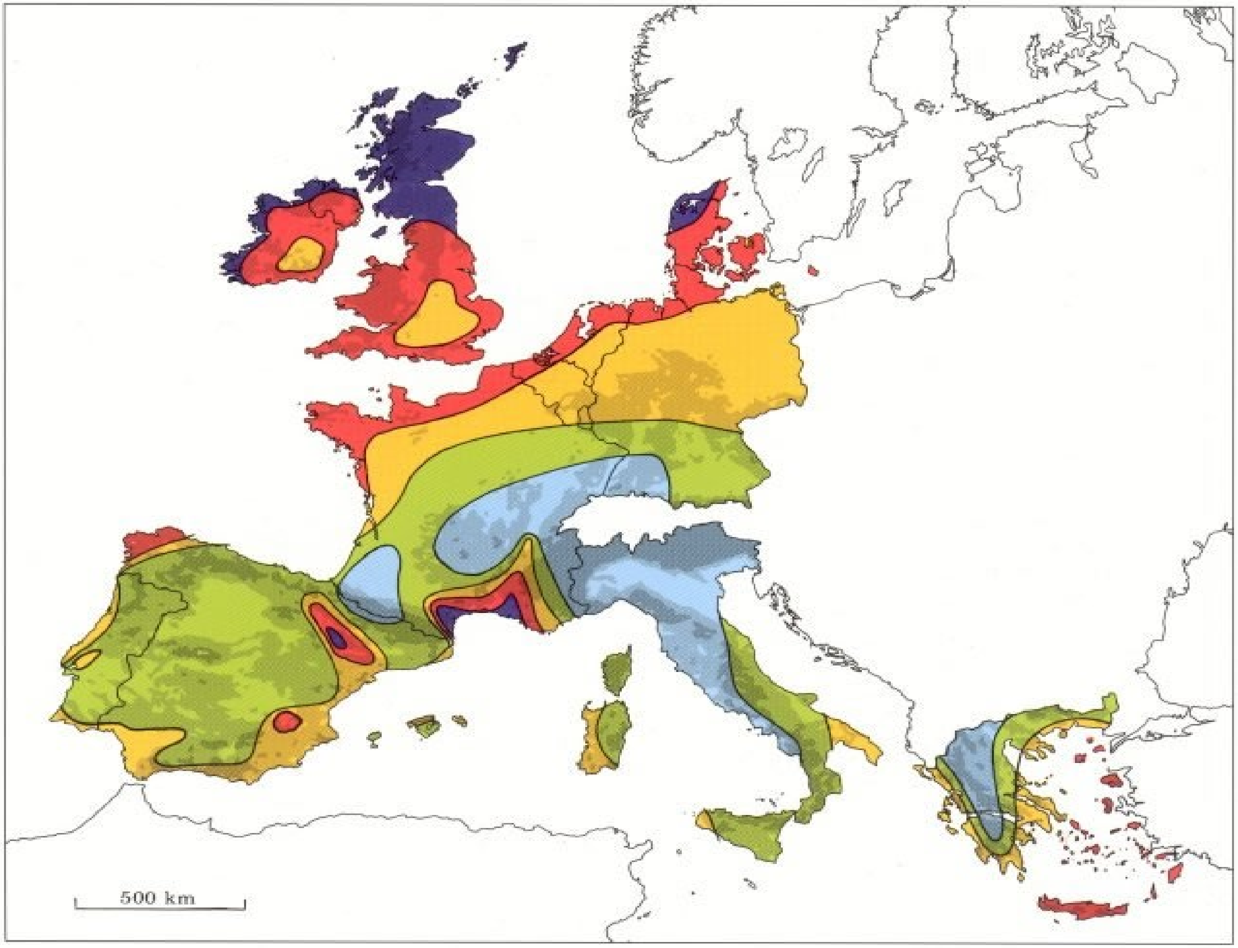
[Fig.: CALS, Arizona]

Global Distribution



[Fig: NASA Surface meteorology and Solar Energy: Methodology, 2004]

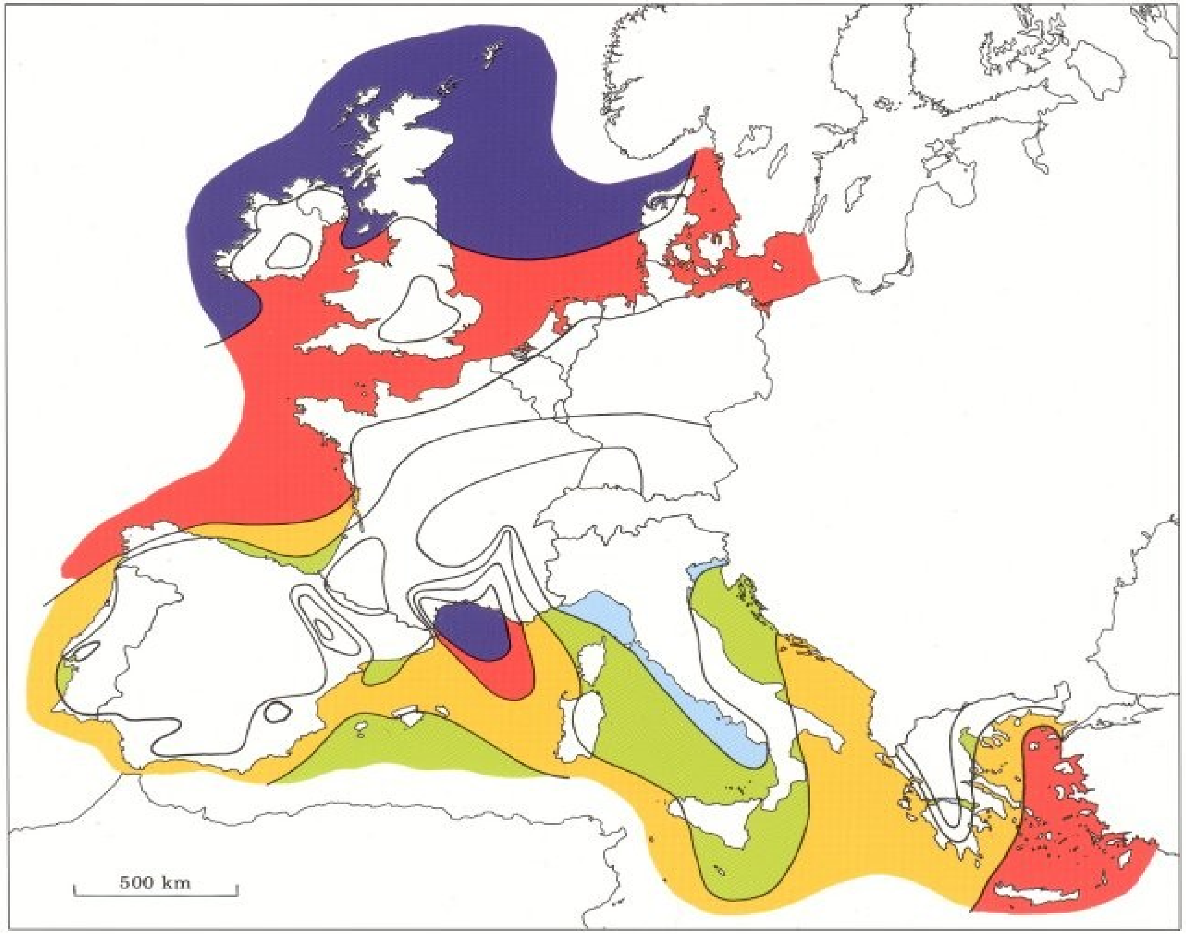
Europe Onshore



Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

[Fig.: *Risø National Laboratory,Denmark*]

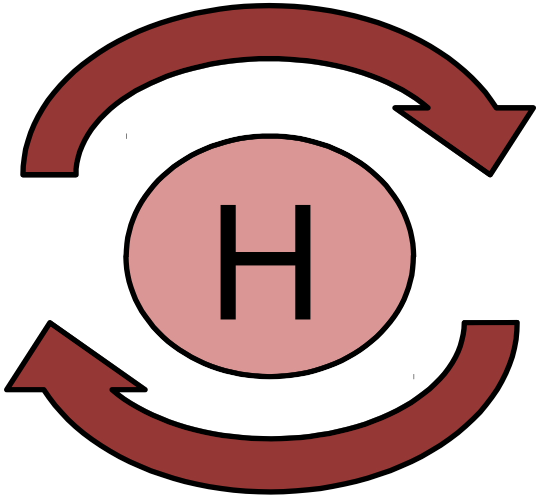
Europe Offshore



Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

[Fig.: *Risø National Laboratory,Denmark*]

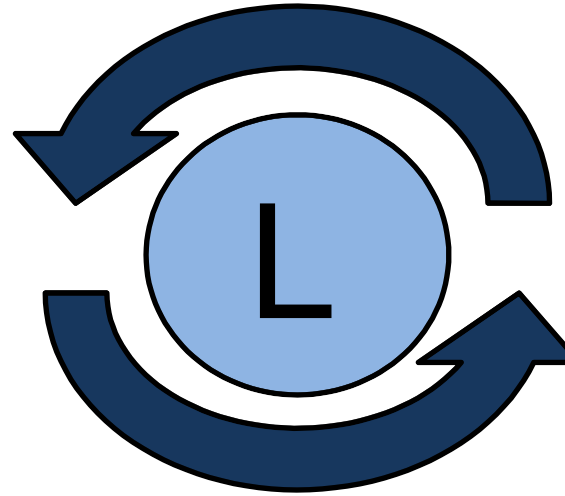
High/Low Pressure Systems



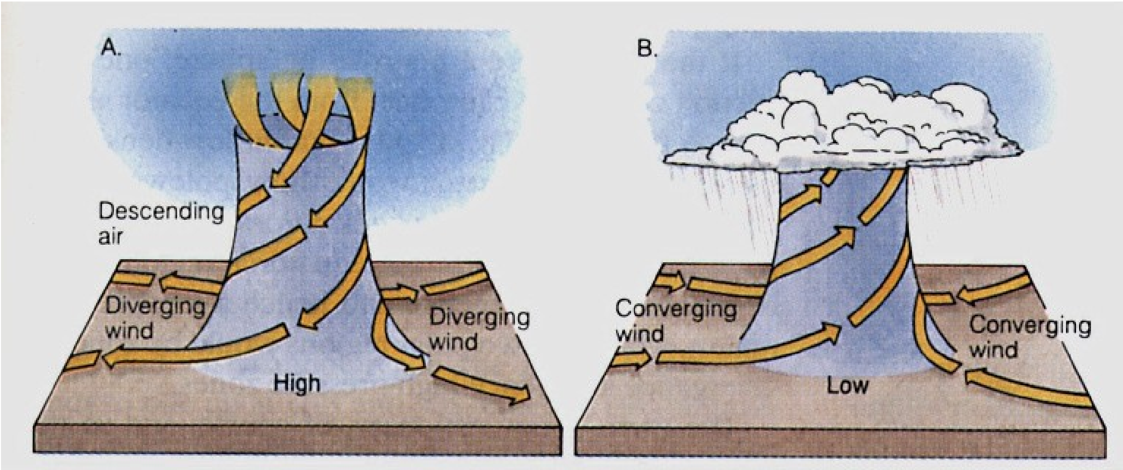
anti-cyclonic

Northern Hemisphere

- Clockwise (anti-cyclonic) rotation around high pressure system
- Anti-clockwise (cyclonic) rotation around low pressure system
- Downdraft during high pressure conditions, updraft under low pressure conditions

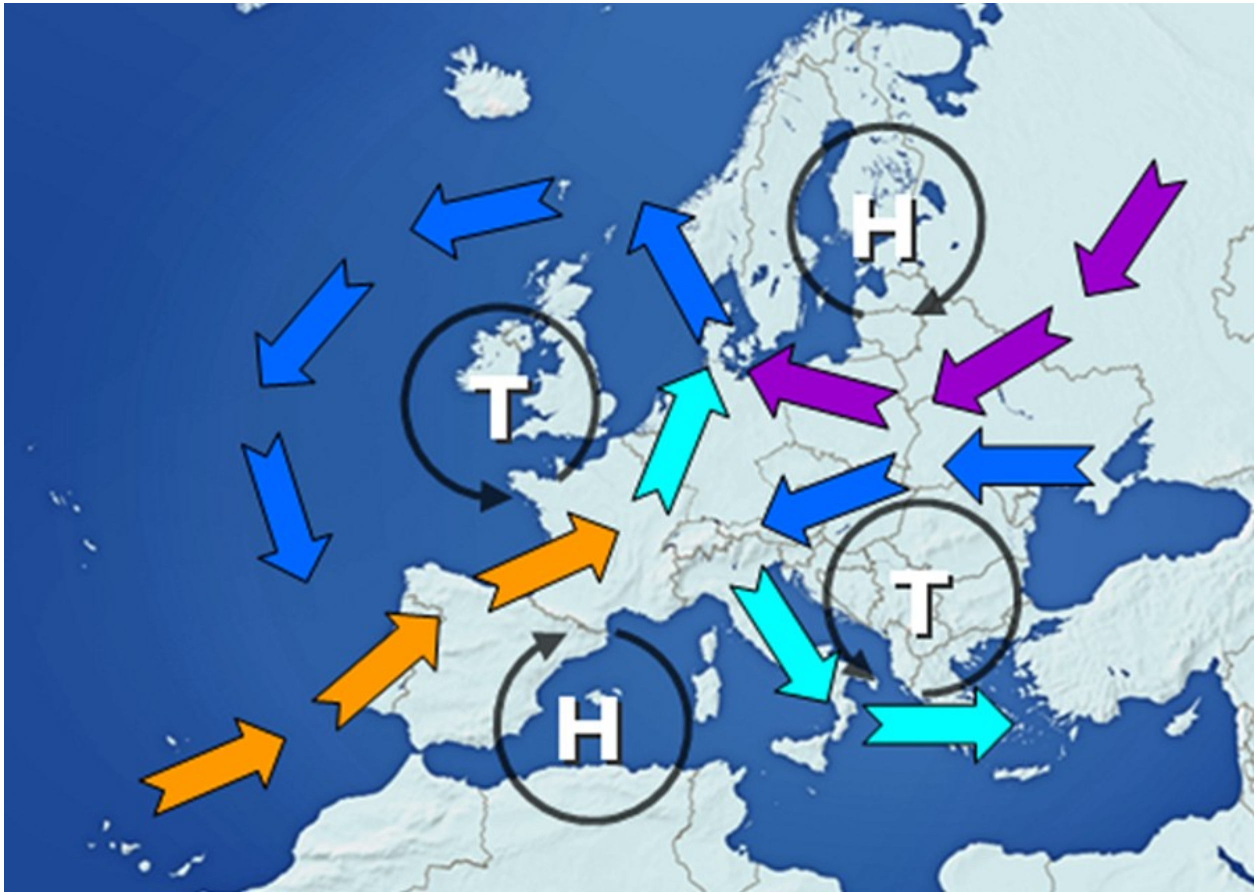


cyclonic



[Fig.: coastguardwx.com]

Typical Weather Pattern over Europe



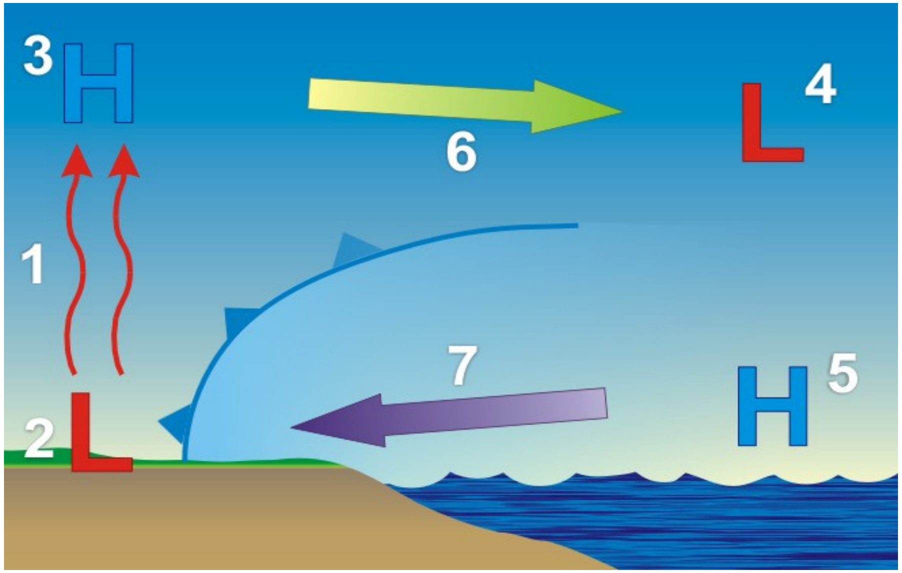
Warm air advection [Fig.: Meteomedia]

II. Wind Regimes on Different Time and Length Scales

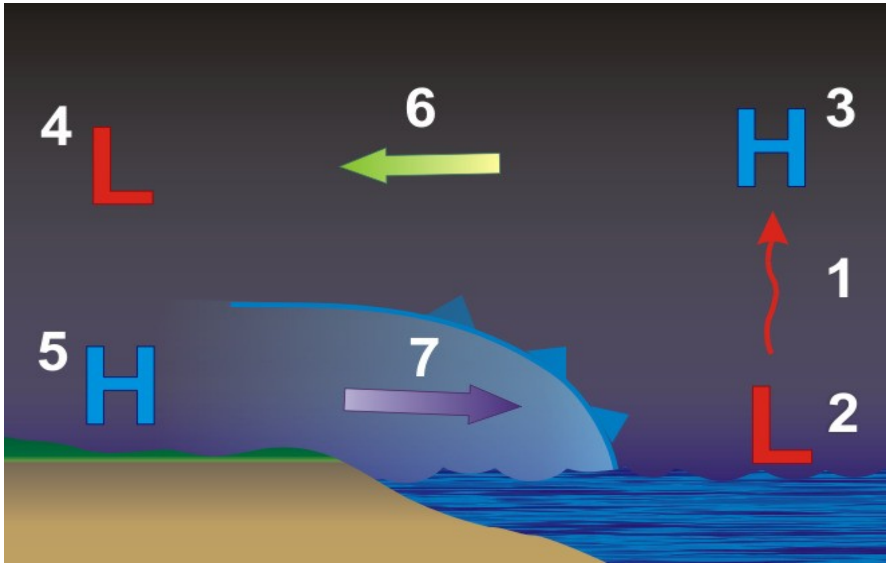
Thermally induced local wind systems

- Wind can be driven by different local thermal conditions
- One example is the **<u>land and sea - breeze system</u>**
- Induced by different heat capacity of water and land cover

Sea/lake breeze (during the day)



Land breeze (during the night)

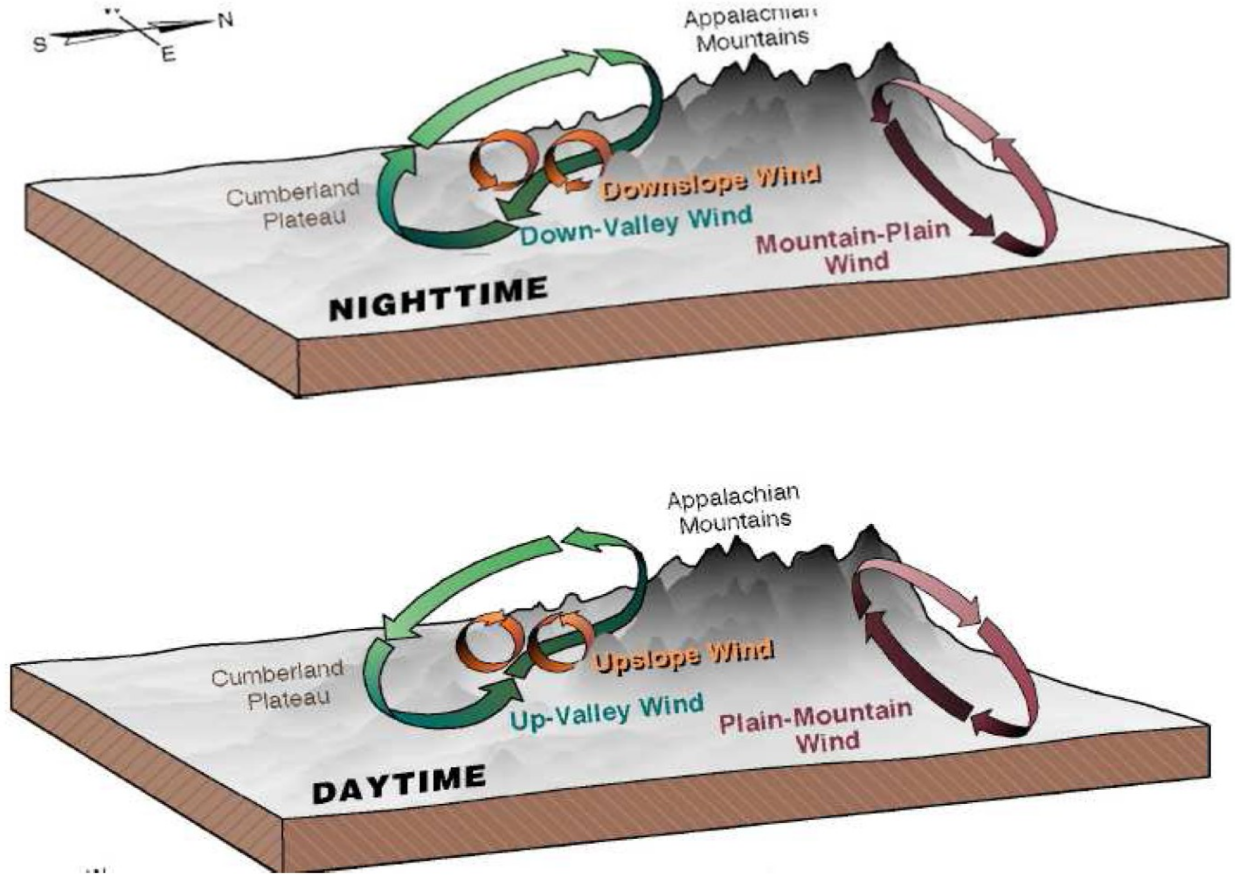


[Fig.: oceanservice.noaa.gov]

Thermally induced local wind systems

Orographically-induced wind systems

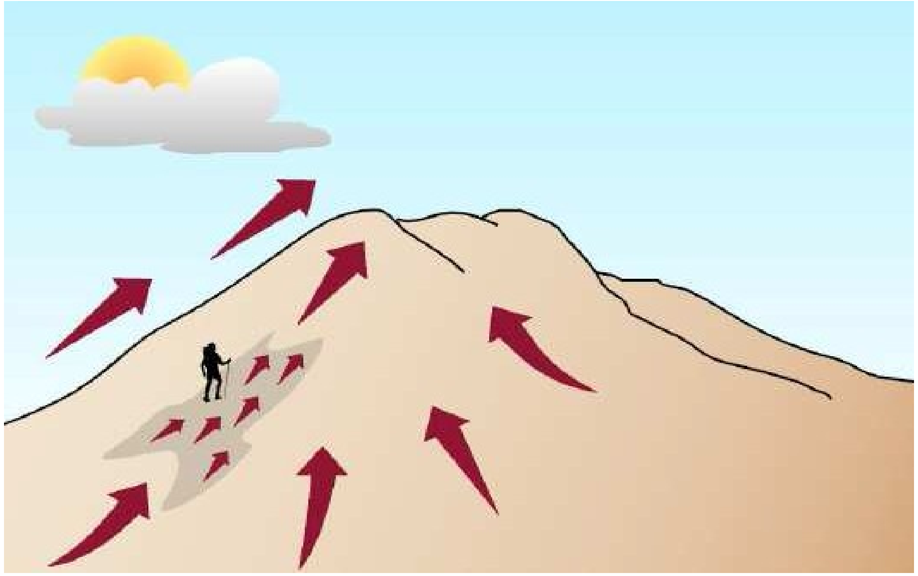
- Can be observed in complex terrain
- Mixture of Slope Winds, Valley Winds and Plain-Mountain Winds



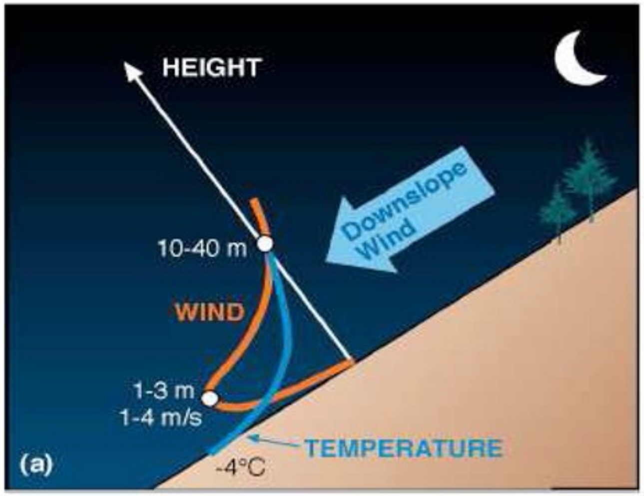
[Fig.: Whiteman, 2000]

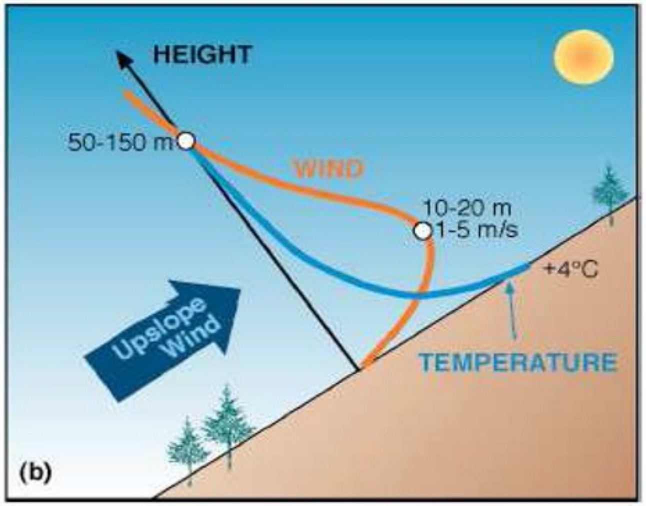
Slope Wind

- Upslope winds develop a few minutes after sunrise
- Generated by different heating of slopes and adjacent air



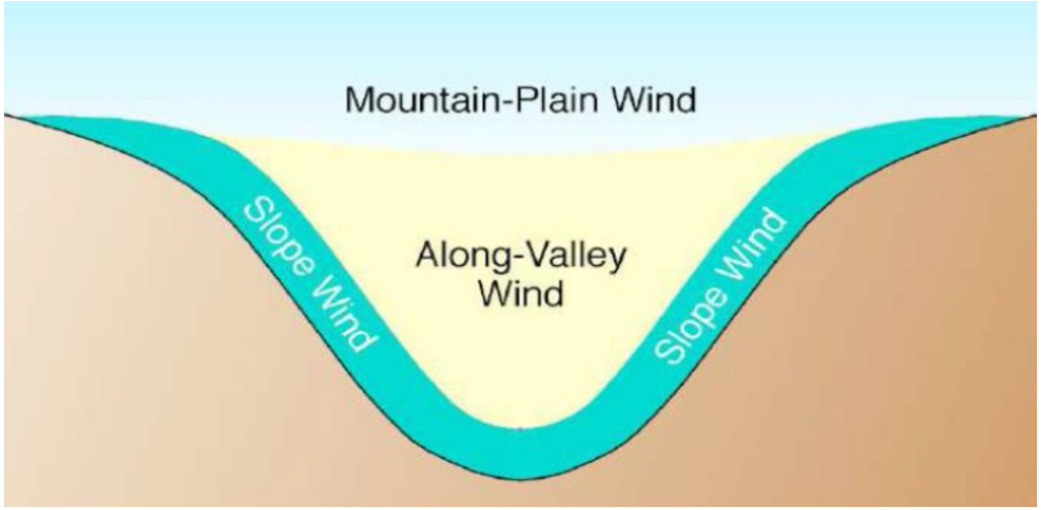
[Fig.: Whiteman, 2000]





Three-dimensional view

- Slope Winds only exist directly above the surface
- Valley Winds often fill the entire valley (several 100 m depth)!!!



[Fig.: Whiteman, 2000]

Slope Winds	Different heating of slopes and adjacent air
(Along-)Valley Wind	Different heating of air along a valley
Mountain-Plain Wind	Different heating of mountain and plain

What is the Time Scale of Typical Variations?

- Wind speed most often changes on the synoptic scale or turbulent scale
- Does not change much in the mesoscale

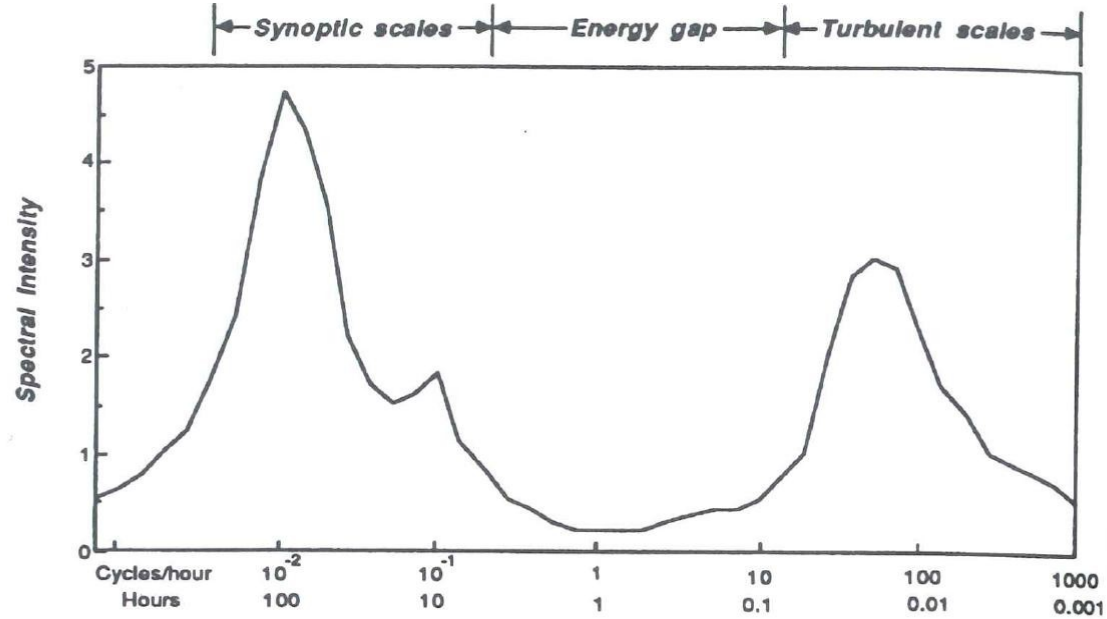
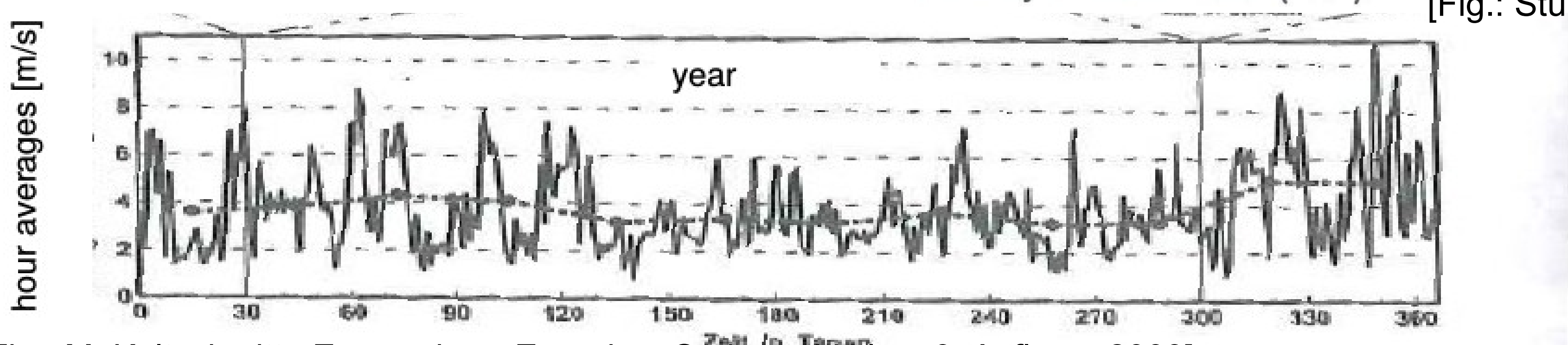


Fig. 2.2 Schematic spectrum of wind speed near the ground estimated from a study of Van der Hoven (1957).

[Fig.: Stull (1988)]

➡ ***"spectral gap"***

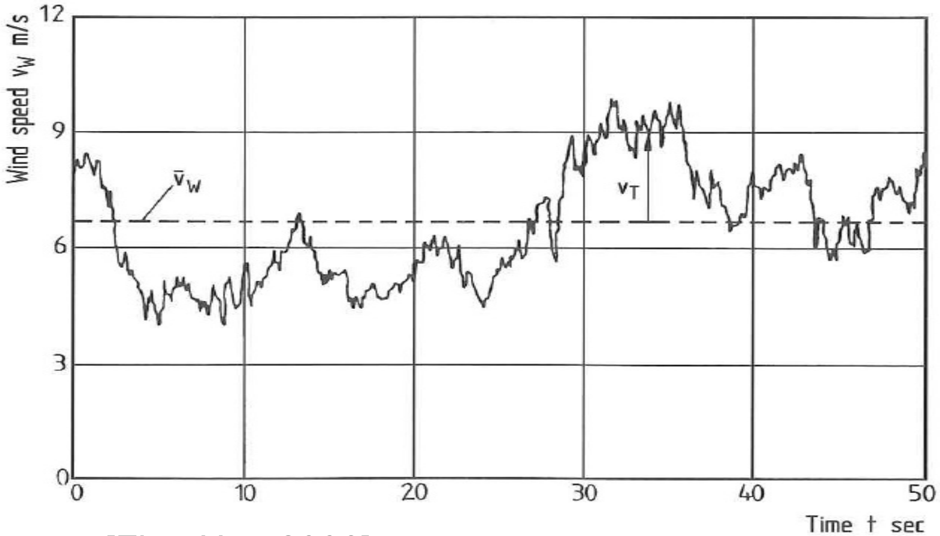


[Fig.: M. Kaltschmitt.: Erneuerbare Energien; Springer-Verlag; 3. Auflage; 2003]

III. Statistical Distribution of Wind Speeds

Fluctuation of Wind Speed

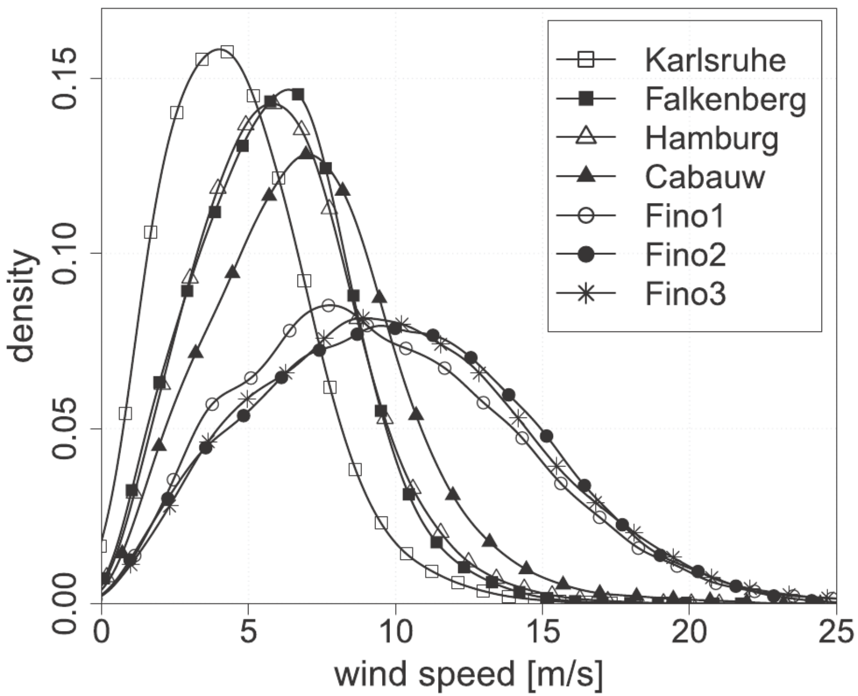
- Atmospheric wind speeds and wind directions change from second to second (or even millisecond to millisecond).
- In meteorology and wind energy utilisation **wind speed and wind direction are commonly averaged over 10 minutes (600 s).**
- Advantage of 10 minutes averages: <u>smaller amount of data, wind speed changes most relevant for the power output of wind farms are captured</u>



[Fig.: Hau 2006]

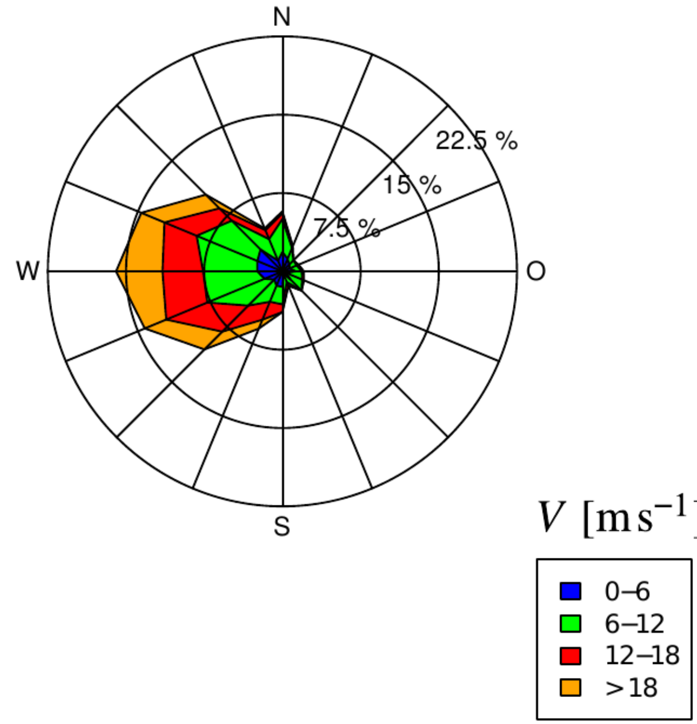
Frequency distributions

Empirical wind speed distribution



Source: Junk et al, 2014

wind rose: wind speed and direction distribution



Weibull distribution of wind speed

The frequency distribution of a measured wind regime (10 min averages) can often be approximated by a Weibull distribution:

$$p(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} \exp\left(-\left(\frac{v}{A}\right)^{k}\right)$$

Weibull factors:

A - Scaling parameter [m/s]: proportional to $\overline{v}$

k - Shape parameter [-]: (here: $1 < k < 4$), $k = 2$ Rayleigh-distribution

Relation between $\overline{v}$, σ_v, k and A :

$$\overline{v} = \mathrm{A} \cdot \Gamma\left(1 + \frac{1}{k}\right)$$

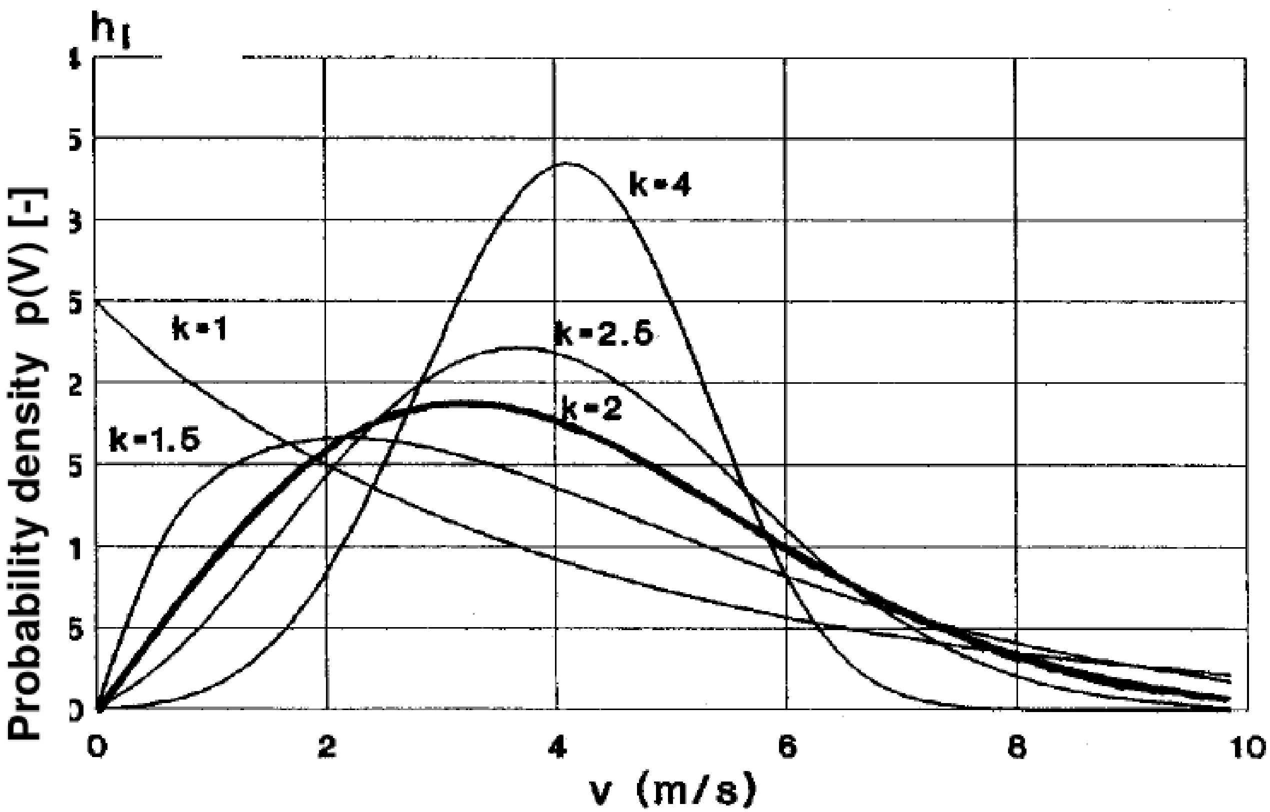
$$\sigma_v{}^2 = A^2 \cdot \left[\Gamma\left(1 + \frac{2}{k}\right) - \left(\Gamma\left(1 + \frac{1}{k}\right)\right)^2\right]$$

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt$$

Weibull distribution of mean wind speed

Example:

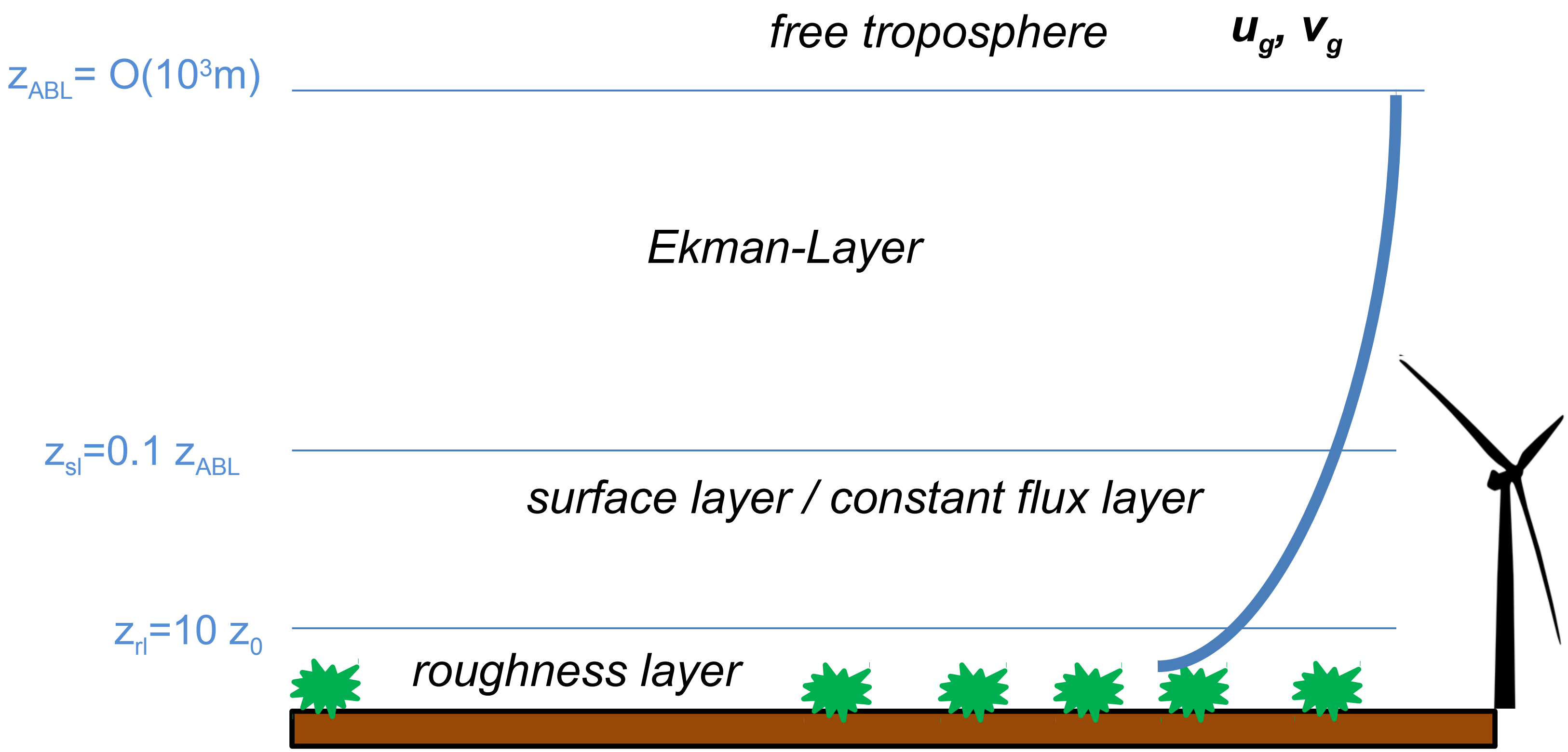
Different wind speed distributions for same annual average wind speed V_{ave} = 4 m/s



[Fig.: Gasch]

IV. The Vertical Wind Speed Profile

The Vertical Wind Profile (in the ABL)



Governing Equations

- Navier Stokes equations (momentum budget equations):

$$\frac{\partial u}{\partial t} + \vec{v}\nabla u + \frac{1}{\rho}\frac{\partial p}{\partial x} \qquad - fv + f^{*}w \mp v\frac{|\vec{v}|}{r} + F_x = 0$$

$$\frac{\partial v}{\partial t} + \vec{v}\nabla v + \frac{1}{\rho}\frac{\partial p}{\partial y} \qquad + fu \qquad \pm u\frac{|\vec{v}|}{r} + F_y = 0$$

$$\frac{\partial w}{\partial t} + \vec{v}\nabla w + \frac{1}{\rho}\frac{\partial p}{\partial z} - g - f^{*}u \qquad + F_z = 0$$

1. 2. 3. 4. 5. 6. 7.

1. Inertial/storage term
2. Interaction between the three wind components
3. Pressure force
4. Influence of earths gravitation
5. Coriolis force (earths rotation)
6. Centrifugal force (upper sign: flow around lows, lower sign: flow around highs)
7. Frictional forces

Geostrophic Wind

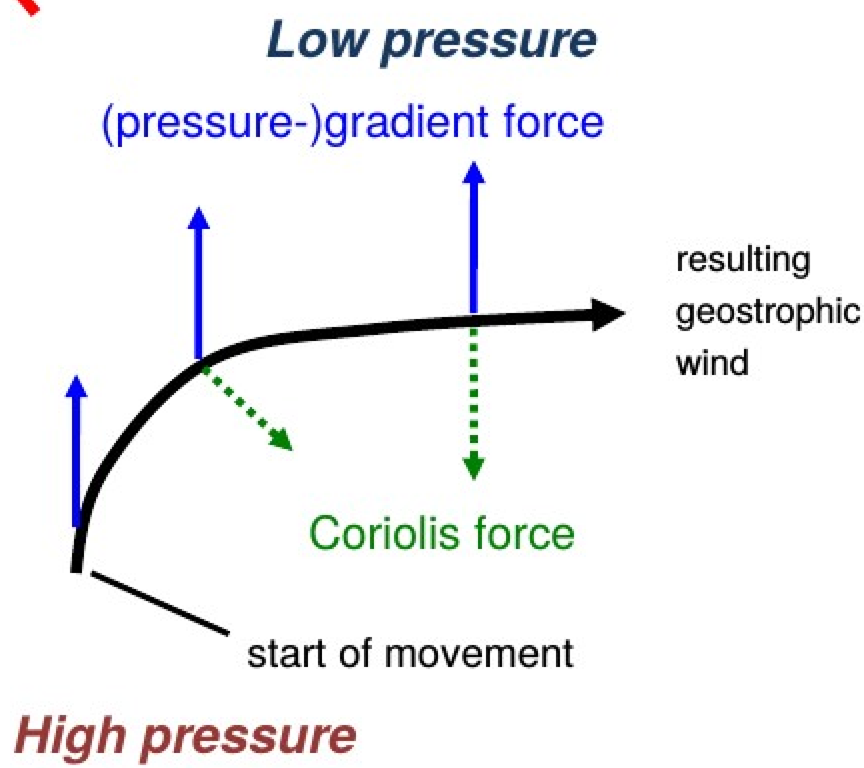
$$\cancel{\frac{\partial u}{\partial t}} + \cancel{\vec{v}\nabla u} + \frac{1}{\rho}\frac{\partial p}{\partial x} \quad - fv + \cancel{f^{*}w} \mp \cancel{v\frac{|\vec{v}|}{r}} + \cancel{F_x} = 0$$

$$\cancel{\frac{\partial v}{\partial t}} + \cancel{\vec{v}\nabla v} + \frac{1}{\rho}\frac{\partial p}{\partial y} \quad + fu \quad \pm \cancel{u\frac{|\vec{v}|}{r}} + \cancel{F_y} = 0$$

Above the ABL (atmospheric boundary layer):

- Stationarity
- No frictional forces
- Large scale winds
- Small horizontal gradients

$$u_g = -\frac{1}{\rho f}\frac{\partial p}{\partial y} \qquad v_g = \frac{1}{\rho f}\frac{\partial p}{\partial x}$$



Geostrophic wind blows parallel to isobars on constant height surfaces

Ekman Layer

$$\cancel{\frac{\partial u}{\partial t}} + \cancel{\vec{v}\nabla u} + \frac{1}{\rho}\frac{\partial p}{\partial x} \qquad - fv + \cancel{f^{*}w} \mp \cancel{v\frac{|\vec{v}|}{r}} + F_x = 0 \qquad F_x = \frac{\partial}{\partial z}\left(K_m \frac{\partial u}{\partial z}\right)$$

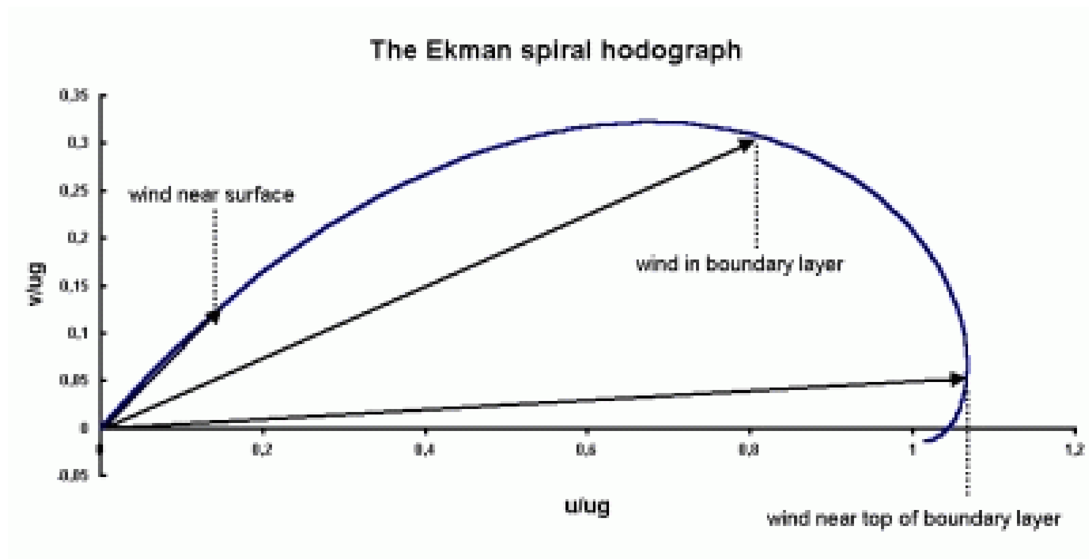
$$\cancel{\frac{\partial v}{\partial t}} + \cancel{\vec{v}\nabla v} + \frac{1}{\rho}\frac{\partial p}{\partial y} \qquad + fu \qquad \pm \cancel{u\frac{|\vec{v}|}{r}} + F_y = 0 \qquad F_y = \frac{\partial}{\partial z}\left(K_m \frac{\partial y}{\partial z}\right)$$

In the Ekman layer :

- Stationarity
- Frictional forces
- Coriolis force
- Pressure force

$$f\left(v_g - v\right) - \frac{\partial\left(K_m \frac{\partial u}{\partial z}\right)}{\partial z} = 0$$

$$-f\left(u_g - u\right) - \frac{\partial\left(K_m \frac{\partial v}{\partial z}\right)}{\partial z} = 0$$



[Fig.: zamg.ac.at]

Solution of differential equation describes
Ekman spiral (turning of the wind with height)

Surface Layer / Prandtl Layer

$$\cancel{\frac{\partial u}{\partial t}} + \cancel{\vec{v}\nabla u} + \cancel{\frac{1}{\rho}\frac{\partial p}{\partial x}} - \cancel{fv} + \cancel{f^{*}w} \mp \cancel{v\frac{|\vec{v}|}{r}} + F_x = 0$$

$$\cancel{\frac{\partial v}{\partial t}} + \cancel{\vec{v}\nabla v} + \cancel{\frac{1}{\rho}\frac{\partial p}{\partial y}} + \cancel{fu} \pm \cancel{u\frac{|\vec{v}|}{r}} + F_y = 0$$

The Surface Layer:

- lowest 10% of ABL (! Wind Energy !)
- no turning of the wind anymore
- strongly influenced by the ground
- horizontal homogeneity

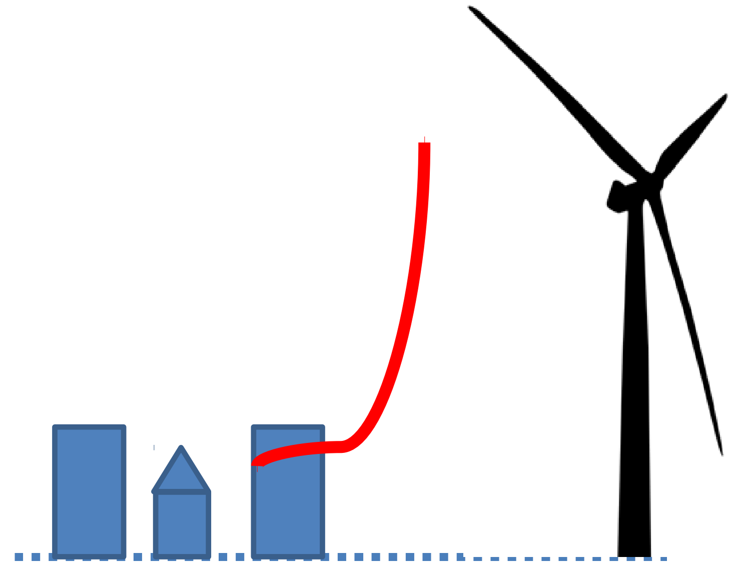
$$K_m \frac{\partial u}{\partial z} = const. = u_*^2$$

$$u_*^2 = \sqrt{\left(\overline{u'w'}\right)^2 + \left(\overline{v'w'}\right)^2}$$

“Surface Stress“

or

“Vertical Flux of horizontal momentum“



Fluxes from Sonic-Measurements

The logarithmic wind speed profile

$$K_m \frac{\partial u}{\partial z} = const. = u_*^2$$

- Vertical momentum exchange coefficient proportional to mixing length $l = \kappa z$

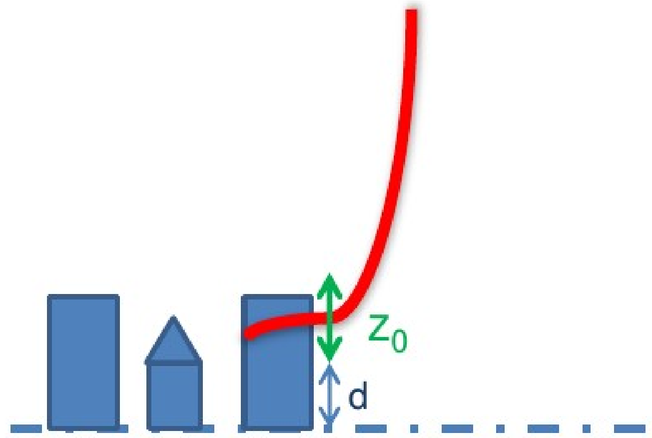
$$K_m = l u_*$$

- Equation for the Prandtl layer:

$$\frac{\partial u}{\partial z} = \frac{u_*}{l} = \frac{u_*}{\kappa z}$$

- Integration with respect to u gives:

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z-d}{z_0}\right)$$



surface type	z_0 [m]	u_* [m/s]
water	$10^{-6} - 10^{-4}$	0.2
Grass	0.01-0.05	0.3
shrubs	0.1-0.2	0.35
forests	0.5	0.4

[Tab.: Emeis (2001)]

with: *frictional velocity u_*,*
roughness length z_0,
displacement height d (usually 2/3 of obstacle height)

Vertical Wind Profile

- Logarithmic wind profile $$u(z) = \frac{u_*}{\kappa} \ln \left(\frac{z-d}{z_0}\right)$$
- Empirical power law $$u(z) = u(z_r) \left(\frac{z}{z_r}\right)^\alpha$$

surface type	z_0[m]	u_* [m/s]	α
water	$10^{-6} - 10^{-3}$	0.2	0.11
Grass	0.01-0.05	0.3	0.16
shrubs	0.1-0.2	0.35	0.20
forests	0.5	0.4	0.28

[Tab.: Emeis (2001)]

The empirical power law fit works well for slightly stable and slightly rough surfaces, a realistic fit for unstable stratifications is not possible!

Vertical Profiles – Atmospheric Stability

Logarithmic Wind Profile $u(z) = \frac{u_*}{\kappa}\left(\ln\left(\frac{z-d}{z_0}\right) - \Psi_m\left(\frac{z}{L_*}\right)\right)$, $L_* = \frac{\theta_v}{\kappa g}\frac{{u_*}^3}{\overline{\theta'_v w'}}$

Empirical Funktion Ψ is a function of the Obhukov Length.

L_* describes height in which thermally produced turbulence is balanced by mechanically produced turbulence

$z/L_* >> 0$ *– unstable stratification, buoyancy production of turbulence dominates over shear production, positive heat flux (directed upward)*

$z/L_* \approx 0$ *–neutral stratification, shear production of turbulence dominates over bouyancy production/destruction, heat flux negligible*

$z/L_* \ll 0$ *– stably stratified, bouyancy destruction of turbulence dominates over shear production, negative heat flux (directed downward)*

Ψ_m - Correction Functions

- The correction functions for the logarithmic wind speed profile need to be derived empirically and can become quite complex
- Example: For positive values of $\frac{z}{L_*}$ (stable stratification) the correction functions for the logarithmic wind profiles are [after: Businger 1971, Dyer 1974, Holtslag 1988]

$$\Psi_m\left(\frac{z}{L_*}\right) = \begin{cases} -\dfrac{az}{L_*} & for\ 0 < \dfrac{z}{L_*} \leq 0.5 \\ \dfrac{Az}{L_*} + B\left(\dfrac{z}{L_*} - \dfrac{C}{D}\right) & \\ \exp\left(-\dfrac{Dz}{L_*}\right) + \dfrac{BC}{D} & for\ 0.5 \leq \dfrac{z}{L_*} \leq 7 \end{cases}$$

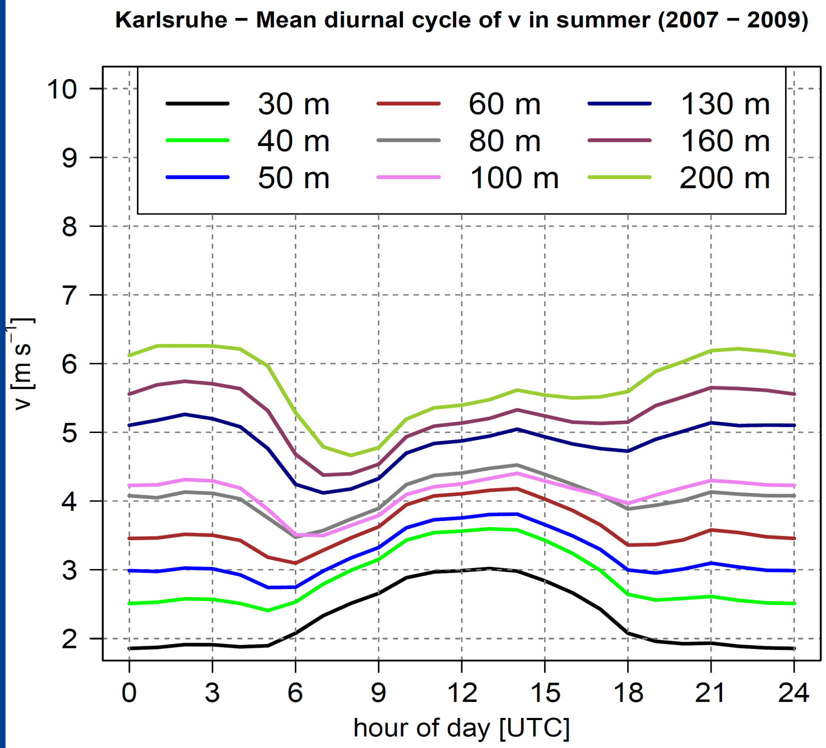
$$\boxed{L_* = \frac{\theta_v}{\kappa g} \frac{u_*^{\ 3}}{\overline{\theta'_v w'}}}$$

with: a=5, A=1, B=2/3, C=5, D=0.35

[Further Reading: Foken, 2006: 50 years of the Monin Obukhov similarity theory, 119: 431-447, Boundary Layer Meteorology]

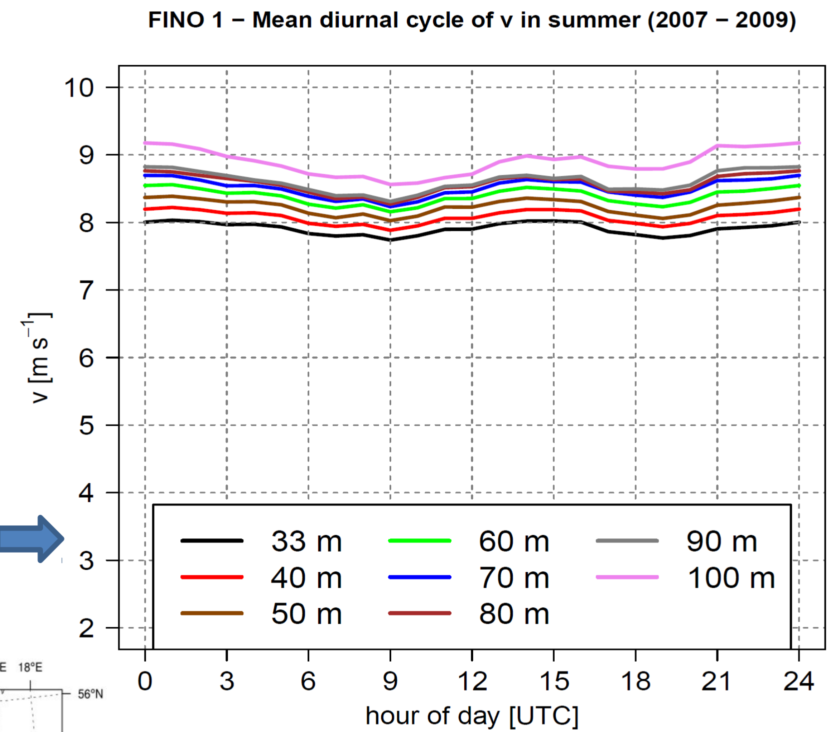
V. Differences between Onshore and Offshore Conditions

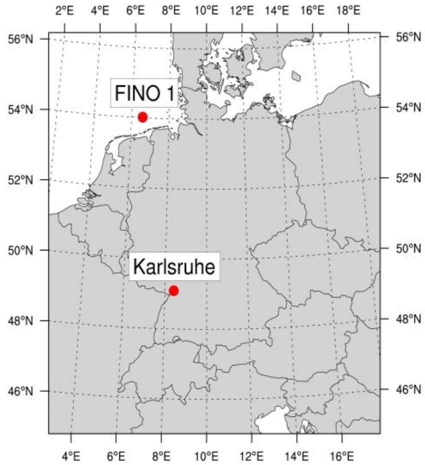
Onshore vs. Offshore diurnal cycles of wind speed



Onshore

Offshore





Onshore vs. Offshore Conditions

Wind Speed:
Onshore: Lower, diurnal variation, variation with height (in general)

Offshore: Higher, more constant in height and time (in general)

Atmospheric Stability:
Onshore: stable stratifications during night, unstable during the day

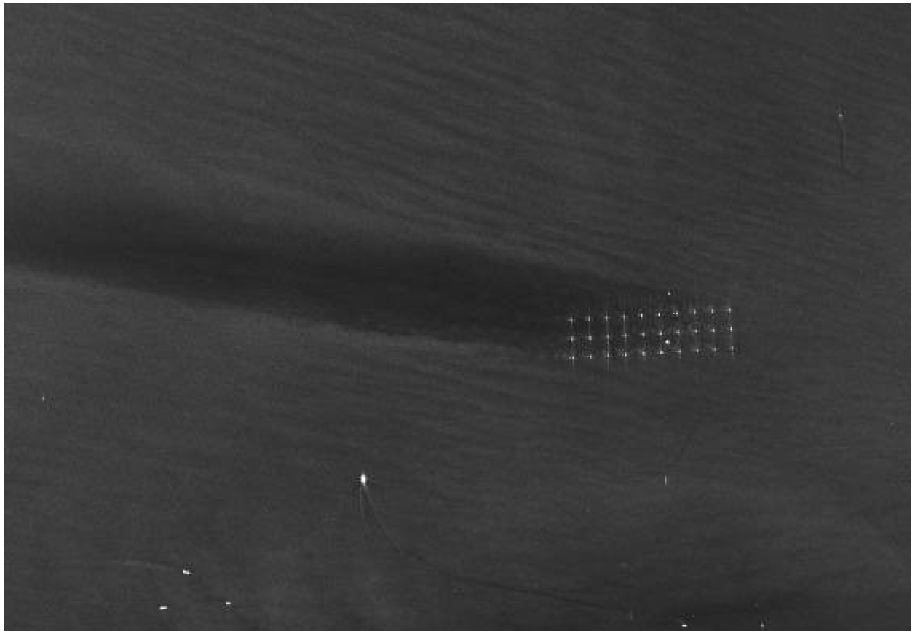
Offshore: stable stratification in early summer, unstable stratification in early winter
advection is very important!

Roughness Lengths z_0:
Onshore: depending on obstacle height O(10^{-1}-10^{1}) [m], dependent on wind direction,
changing very slowly (growth of vegetation)

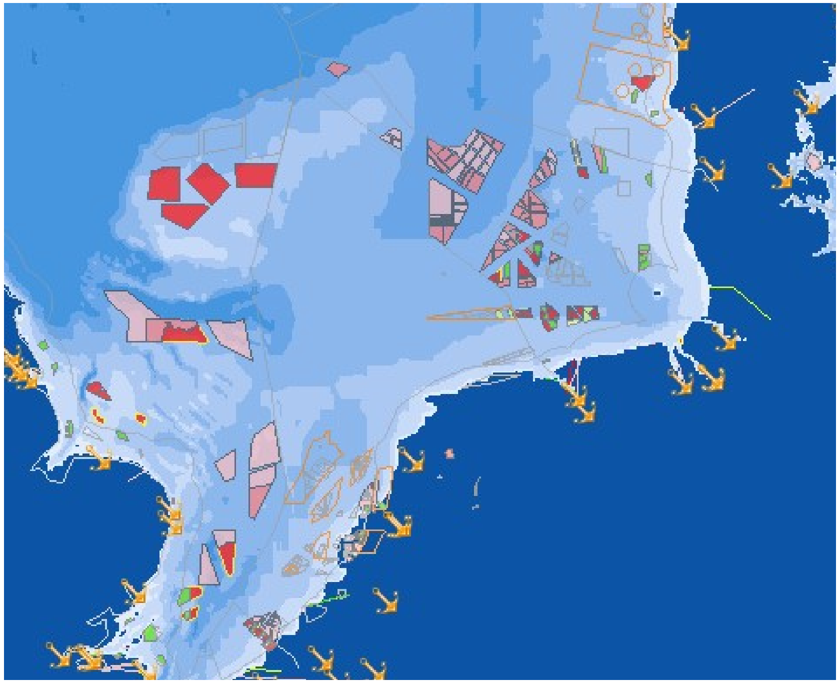
Offshore: depending on wave height O(10^{-5}-10^{-3}) [m], dependent on wind speed,
changing with change of weather patterns $z_0 = a_c \frac{{u_*}^2}{g}$ *(Charnock Formula)*

Onshore vs. Offshore: wind farm wakes

- Large wind farms will become important sinks of mean kinetic energy and sources of turbulent kinetic energy
- The influence on downwind wind turbines is not sufficiently quantified
- Measurements with lidar, SAR and modelling with meso-scale models



[Fig.: TerraSAR-X]



[Fig.: www.4coffshore.com]

Further Reading

[1] Emeis (2013): Wind Energy Meteorology, Springer, 196pp.

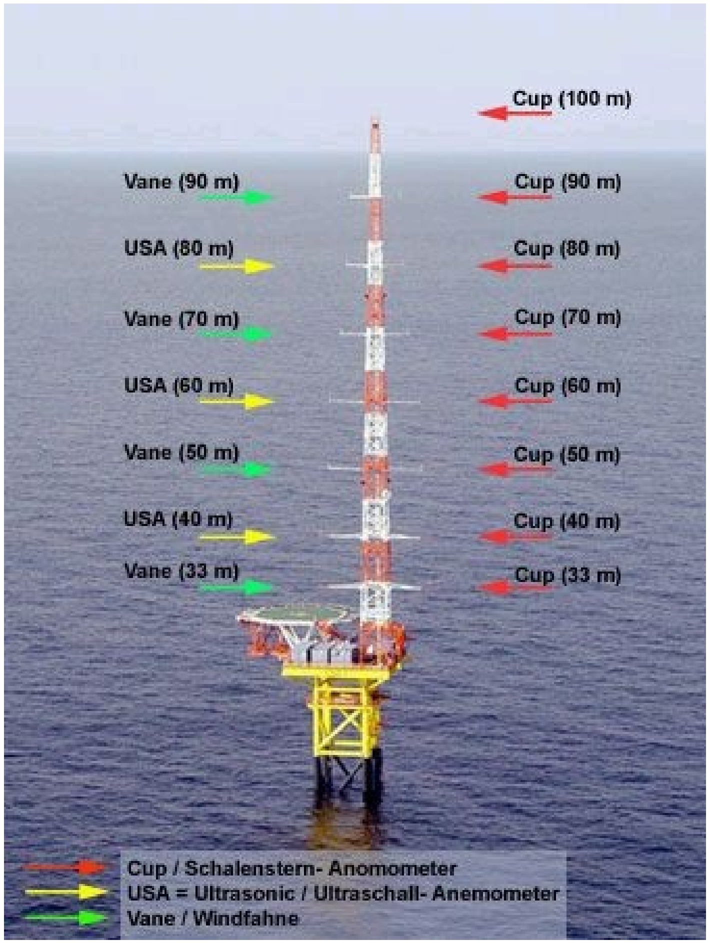
[2] Stull (1988): An Introduction to Boundary Layer Meteorology, Kluwer Academic Publishers, 666pp.

[3] Foken (2008): Micrometeorology, Springer, 326pp.

[4] Holton (2004): An Introduction to Dynamic Meteorology, Elsevier, 535pp.

FINO – Research Platforms

Forschungsplattformen **I**n **N**ord und **O**stsee
(Research Platforms in the North and Baltic Sea)



[Fig.: imk-ifu.fzk.de]

[Fig.: marinetraffic.com]

Lukas Vollmer
V02 206
lukas.vollmer@uni-oldenburg.de