Atmospheric Phenomena for Wind Energy

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October 18, 2022
TWIND short course

TU Delft

Who am I?

- Assistant professor in the Wind Energy Section at TU Delft
- BSc, MSc and PhD from KU Leuven, Postdoc at NREL (Boulder, CO, US)

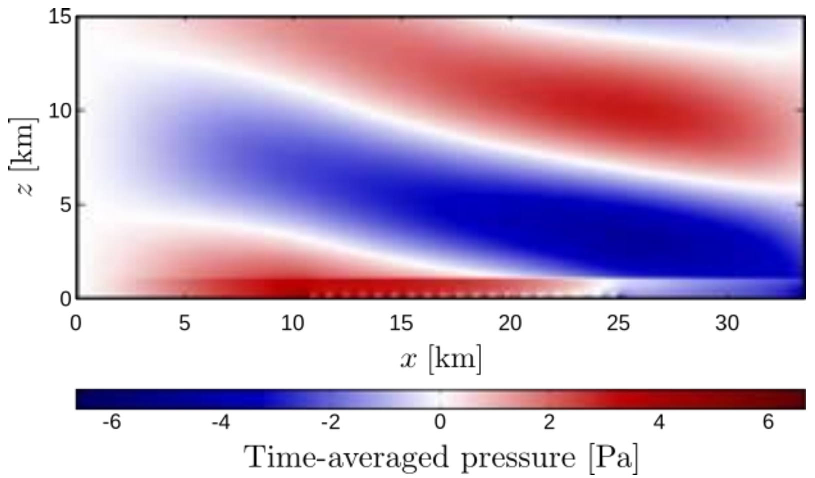
What is my research background?

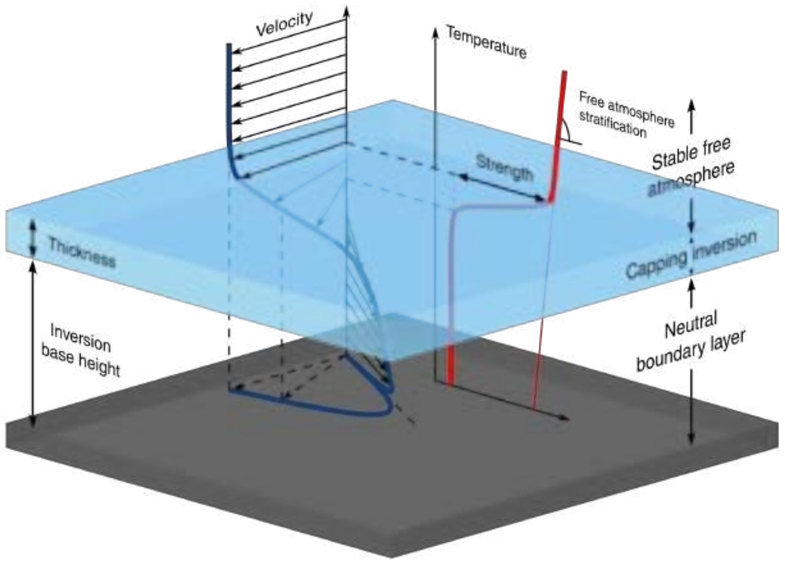
- Wind farm aerodynamics
  How does the wind flow in, above and around a wind farm?

  Topics include
  – Global blockage effect
  – Self-induced gravity waves
  – Wind-farm wakes

- Boundary-layer meteorology
  How does the atmospheric boundary layer affect wind energy?

  Topics include
  – Atmospheric stability
  – Capping inversion
  – Low-level jets





What do you know about atmospheric phenomena for wind energy?

What would you like to learn today?

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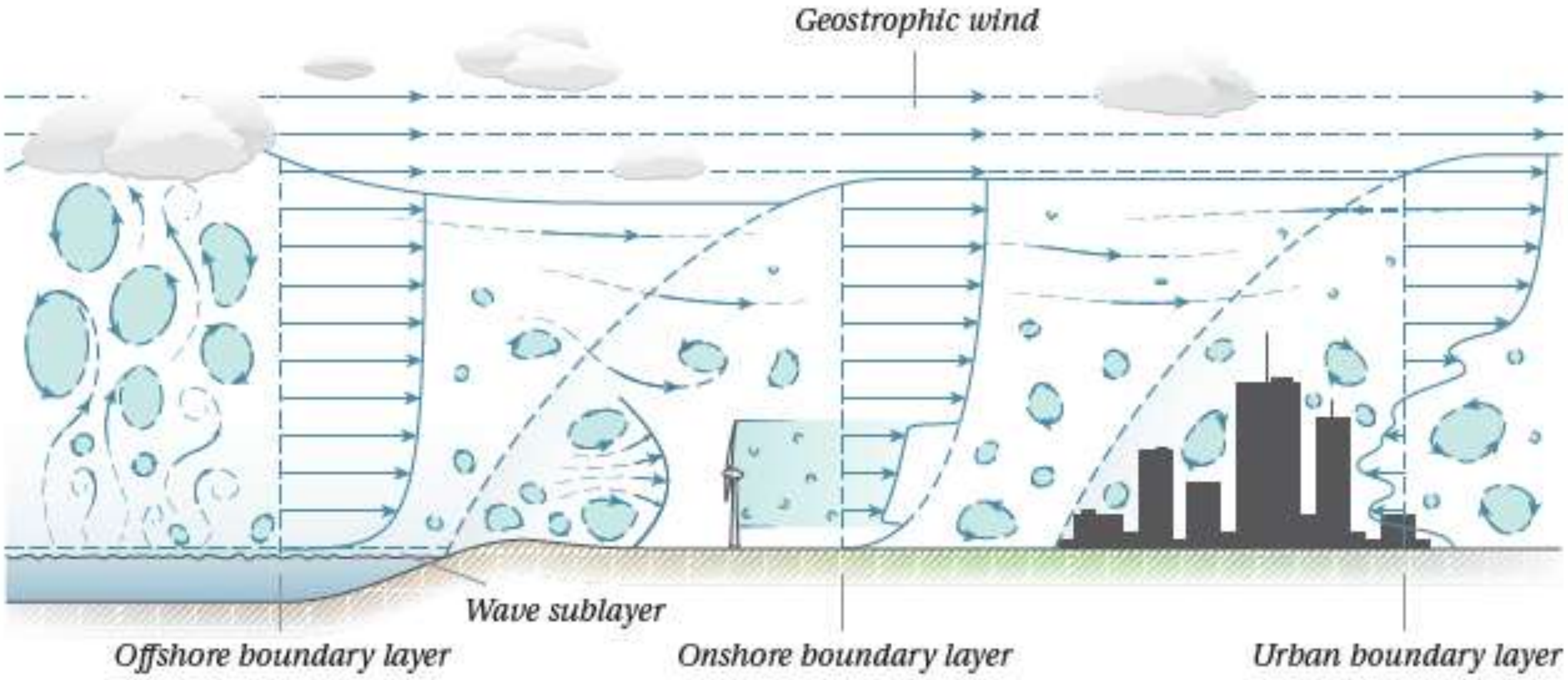
Atmospheric science: Why bother?

1) In wind energy, the inflow wind is the “fuel”



Source: Bos (2017)

2) Wind conditions drive design, operation and maintenance

Typhoon resistant wind turbines in the Akita Noshiro Offshore Wind Farm

3) Large wind farms interact with the atmosphere

Objectives of this lecture

- Give a brief introduction to atmospheric sciences for wind energy
- Explain some of the basic and widely used concepts in wind energy
- Provide relevant reference material for future study of wind energy meteorology
- Discuss any atmospheric science topics that are of interest to you

Outline

Motivation and objectives

Overview of relevant reference material

Part 1: General meteorology

Part 2: Boundary-layer meteorology

Part 3: Wind power meteorology

Take-home messages

Not covered today (at least not in detail)

- Mesoscale weather phenomena (frontal systems, thunderstorms, hurricanes, monsoons, etc.)
- Complex terrain (flow speed up, valley winds, fall winds, etc.)
- Forest and urban canopy flow
- Humidity, clouds, precipitaton
- Air-sea interaction
- Wind farm – atmospheric boundary layer interaction
- Modelling and measuring techniques
- Climate change

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Prior knowledge

- Calculus
- Thermodynamics
- Fluid mechanics
- Basics of wind energy
- A notion of turbulence

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Take-home messages

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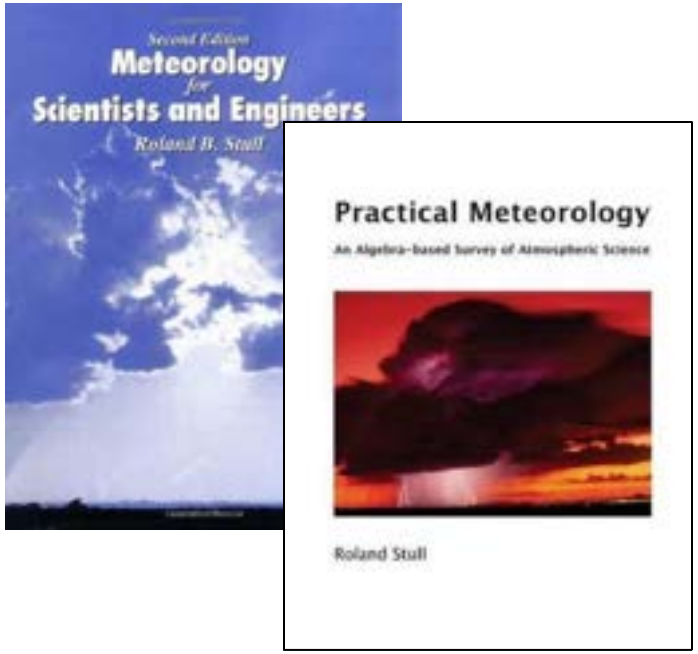
Reference material

Meteorology

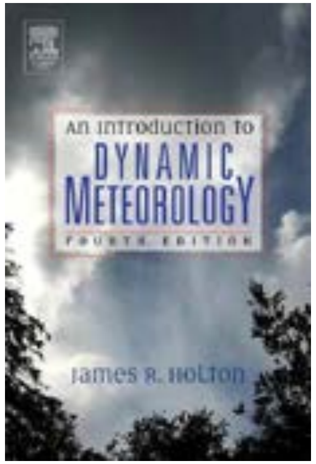


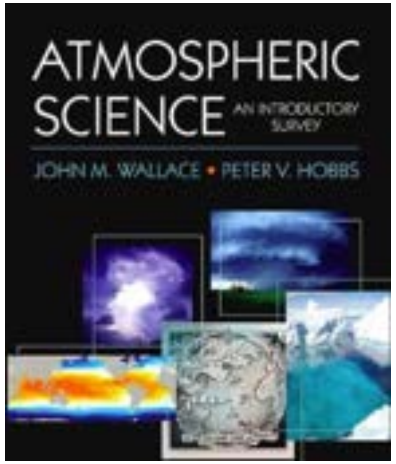
Stull – Practical Meteorology (2017)

successor of *Meteorology for Scientists and Engineers*

Available as e-book:

www.eos.ubc.ca/books/Practical_Meteorology





Holton – An introduction to dynamic meteorology (1992)

Wallace & Hobbs – Atmospheric Science (2006)

Reference material

Boundary-layer meteorology

Stull – An introduction to boundary layer meteorology (1988)

Garratt – The atmospheric boundary layer (1992)

Kaimal & Finnigan – Atmospheric boundary layer flows (1994)

Wyngaard – Turbulence in the atmosphere (2010)

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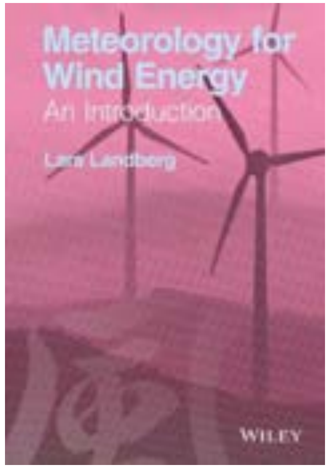
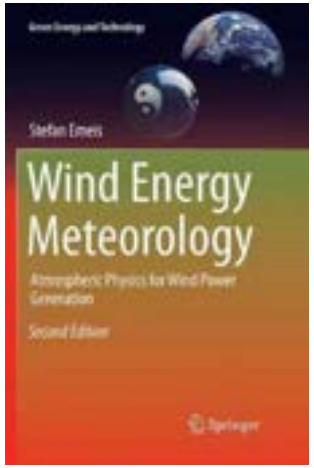
Reference material

Wind energy meteorology

Landberg – Meteorology for wind energy (2016)

Emeis – Wind energy meteorology (2018)

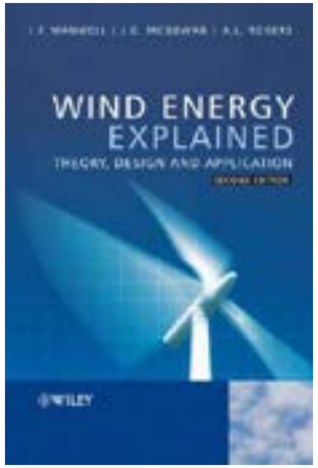


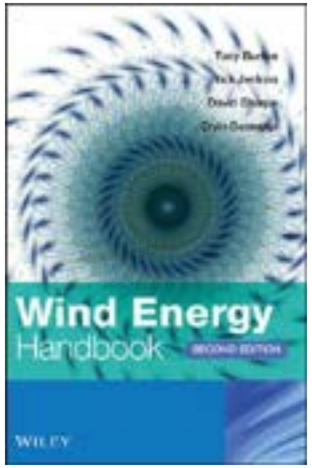


Dedicated chapters in wind energy textbooks:

Manwell et al. – Wind energy explained (2009)

Burton et al. – Wind energy handbook (2018)





Outline

Motivation and objectives

Overview of relevant reference material

Part 1: General meteorology

- What is wind?
- Why does the wind blow?
- Scales of atmospheric motion

Part 2: Boundary-layer meteorology

Part 3: Wind power meteorology

Take-home messages

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What is wind?

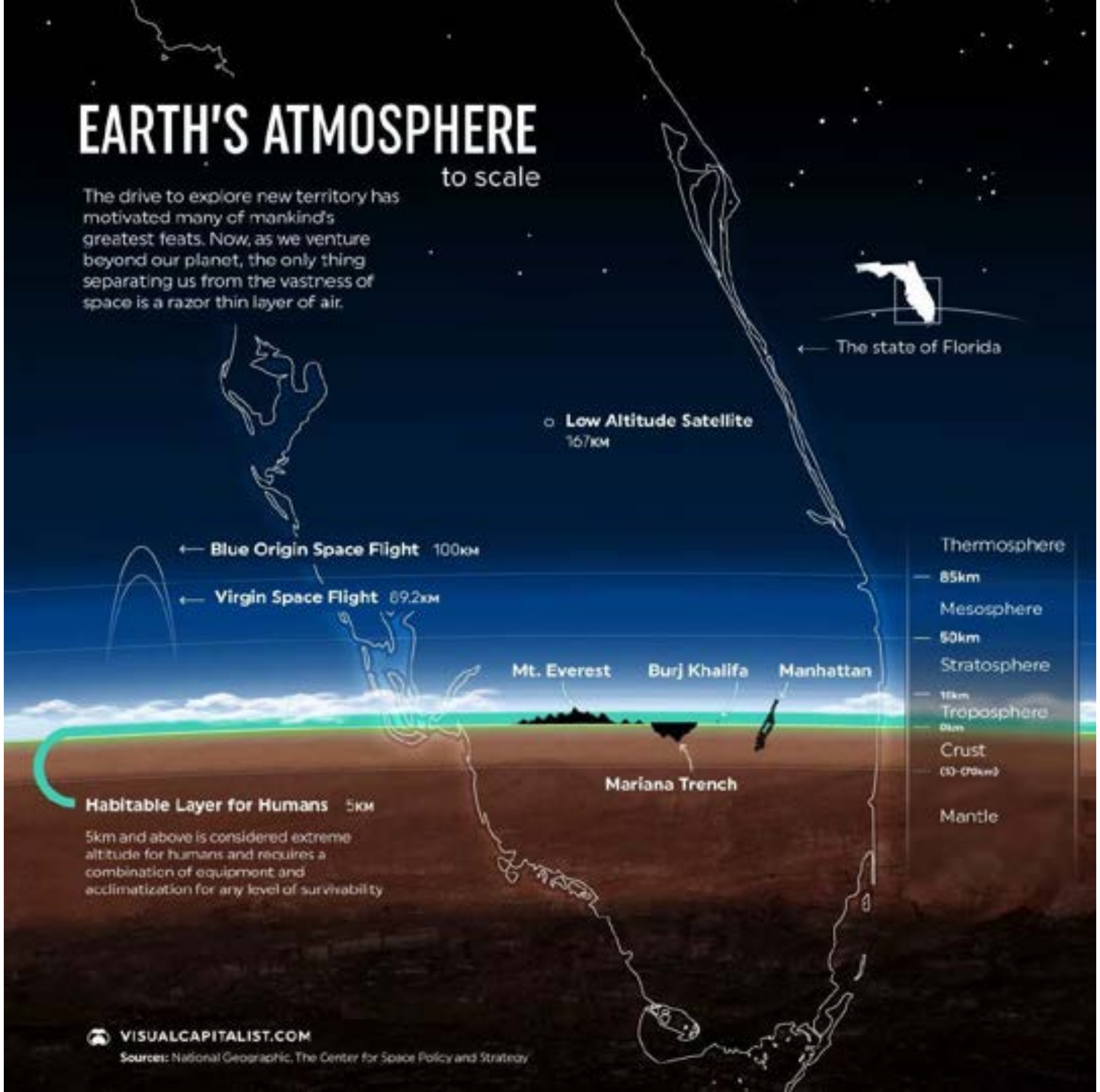
Image: *NASA/NOAA/GSFC/Suomi NPP/VIIRS/Norman Kuring*

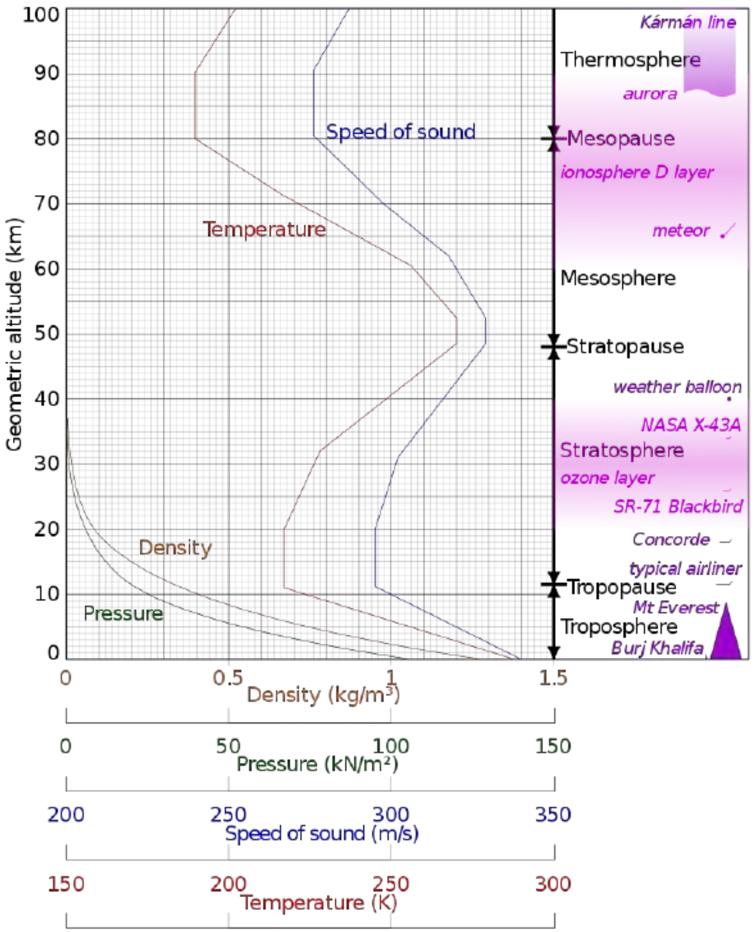
Neil deGrasse Tyson
@neiltyson

SMOOTH EARTH: If shrunk to a few inches across, Earth would feel as smooth as a billiard-hall cue ball.

7:02 PM · Apr 22, 2016 · TweetDeck

590 Retweets **9** Quote Tweets **2,356** Likes

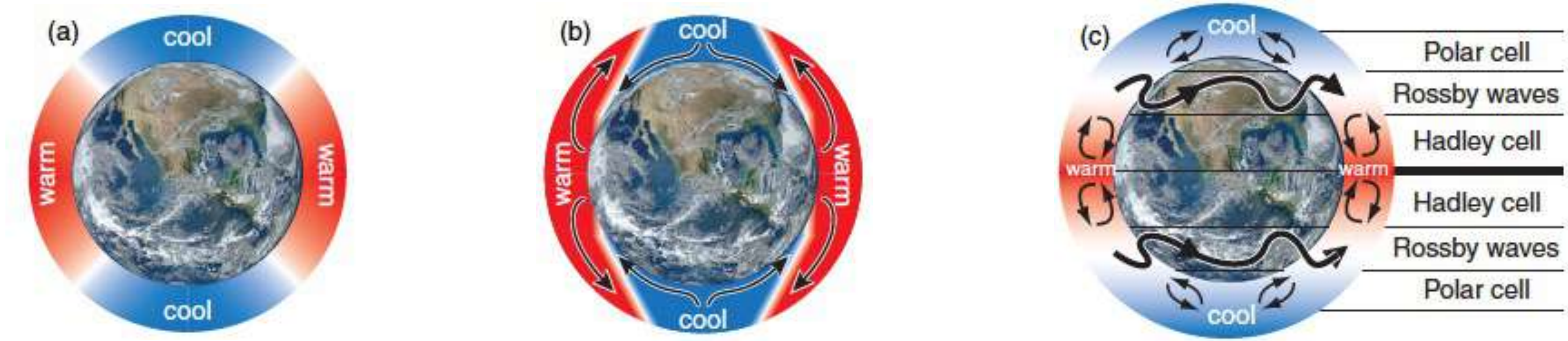




1962 US Standard Atmosphere graph of geometric altitude against air density, pressure, the speed of sound and temperature *(source: Wikipedia)*

Why does the wind blow?

The origin of wind



Radiative imbalance creates warm tropics and cold poles

Differential heating powers a global atmospheric convection system

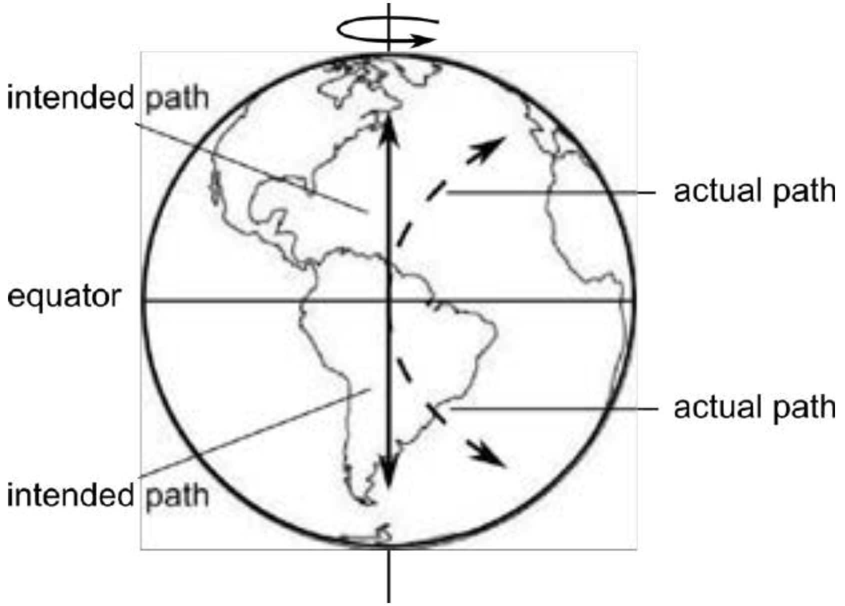
The rotation of the Earth leads to three circulation bands in each hemisphere

Source: Stull (2016)

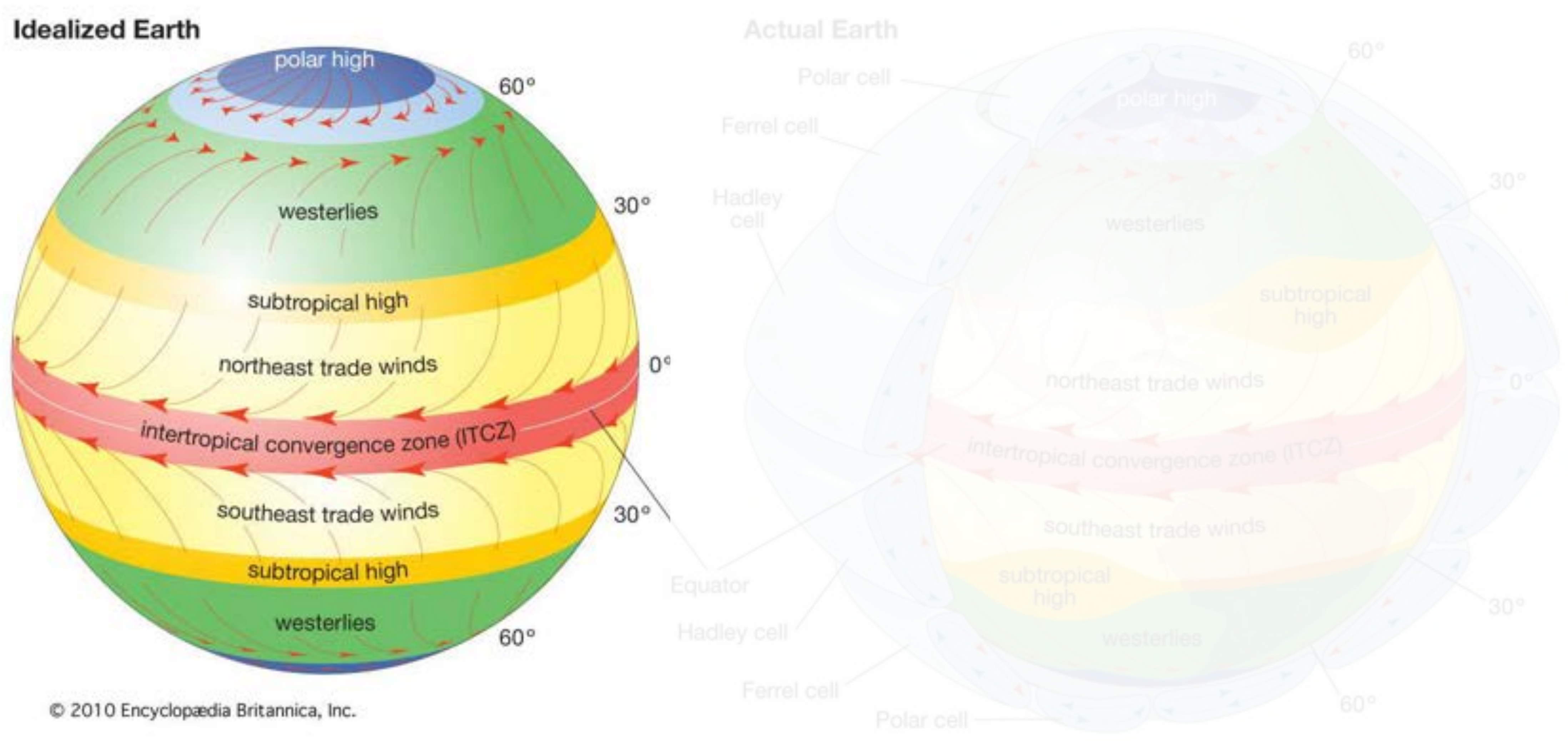
Intermezzo: Coriolis effect

- Due to Earth's rotation
- Motions are deflected to the right (northern hemisphere)
- Coriolis forces scale linear with wind speed
- Coriolis force is perpendicular to the velocity

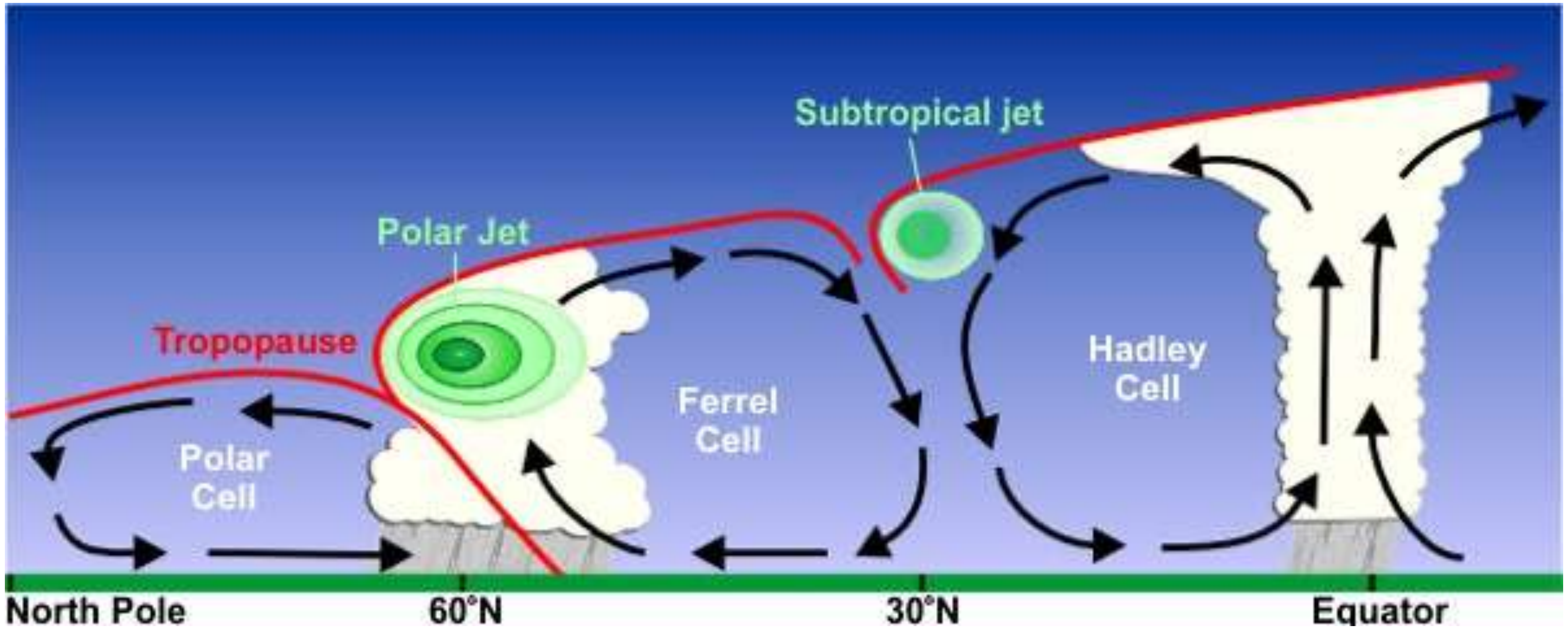
$$F_C = -2\rho\Omega \times u$$

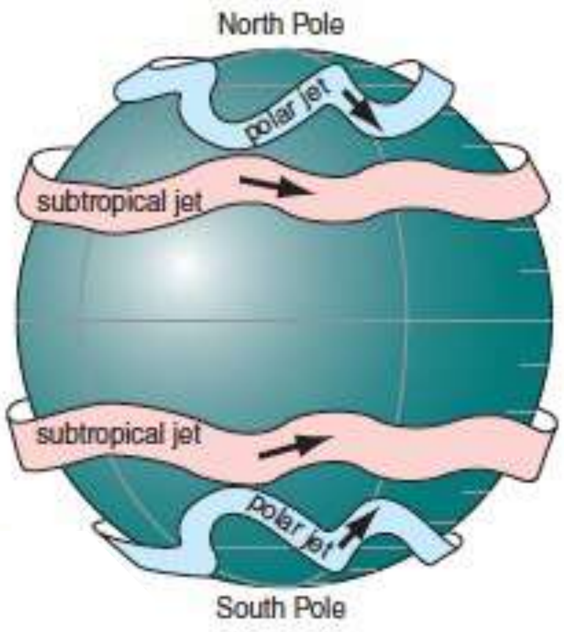


Three-band global circulation



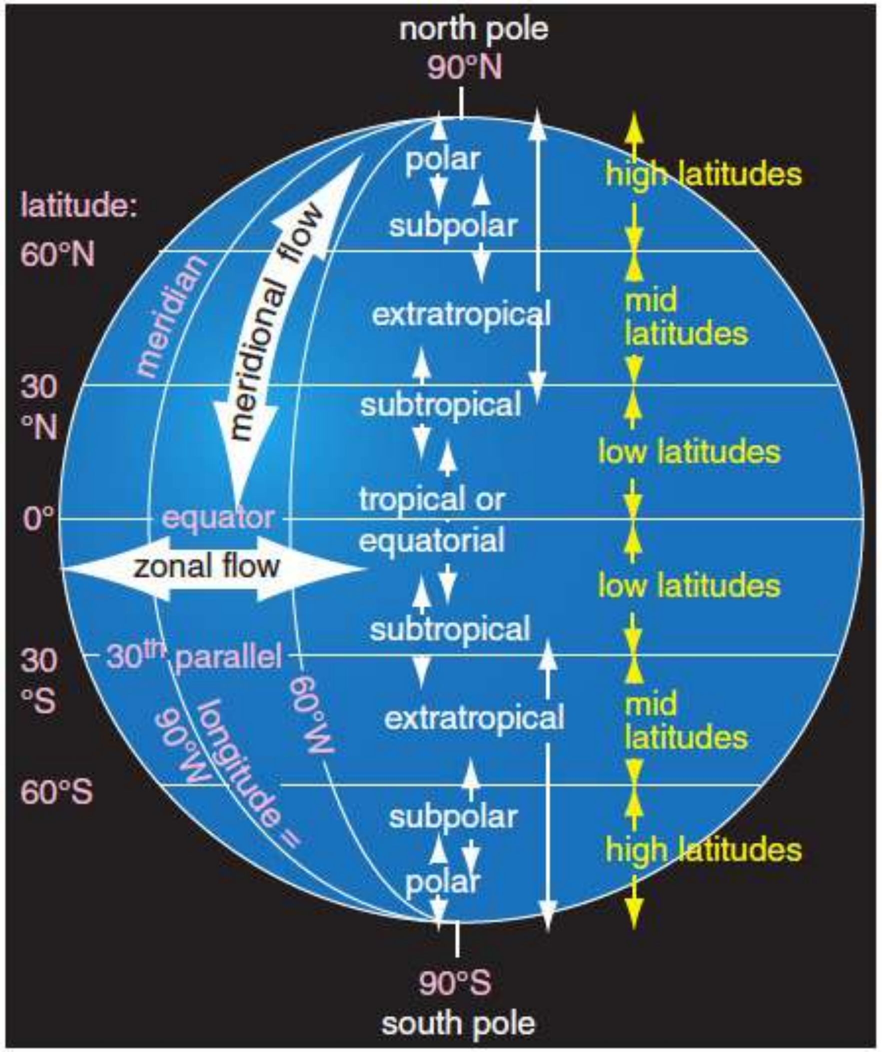
Jet streams

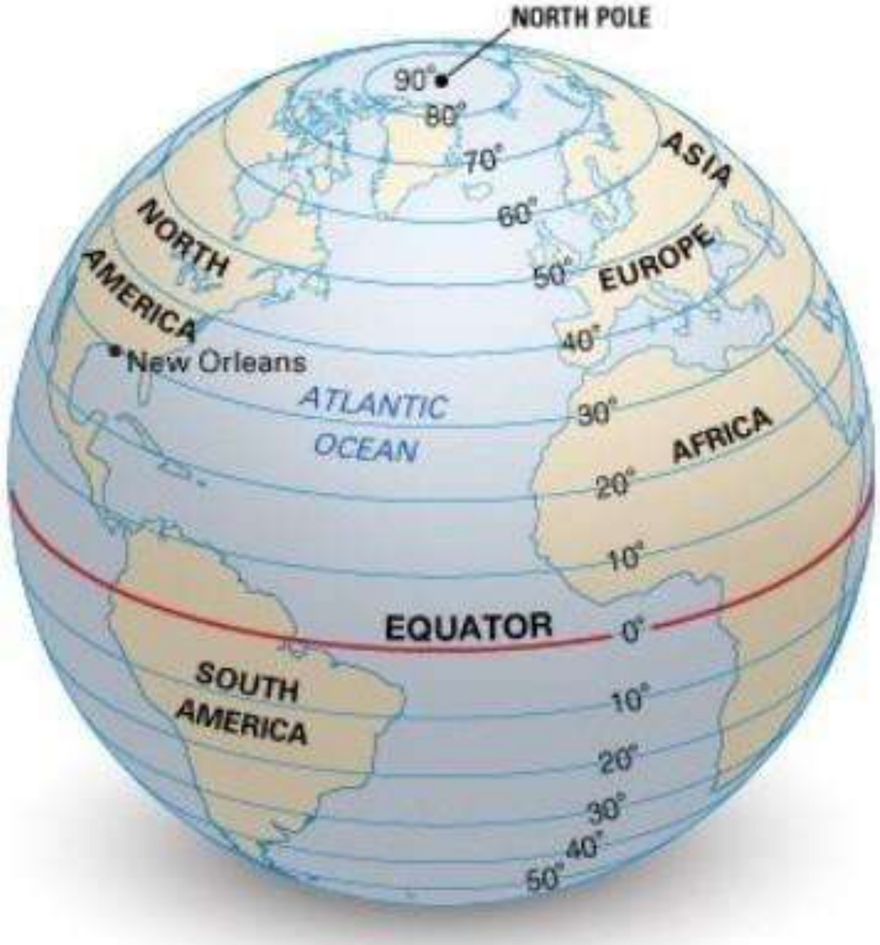




Source: Stull (2016)

Some key terms





Source: Stull (2016)

Scales of atmospheric motion

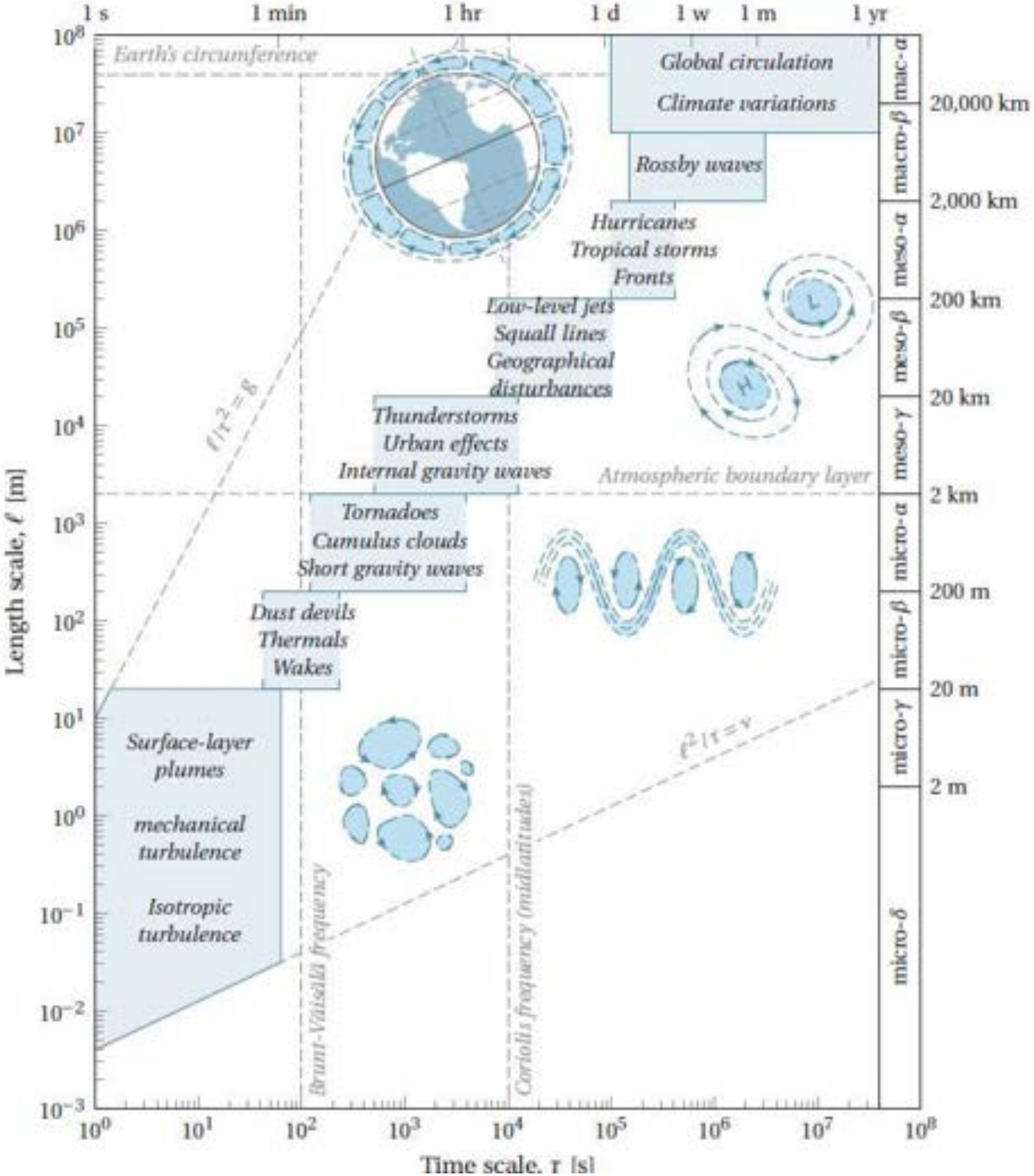
anisotropic ↑ … ↓ *isotropic*

Horizontal Size	Scale: Designation	Scale: Name	
40,000 km	macro α	planetary scale	
4,000 km	macro β	synoptic scale*	
700 km	meso α	mesoscale**	
300 km	meso β	mesoscale**	
30 km	meso γ	mesoscale**	
3 km	micro α	microscale***	boundary-layer turbulence
300 m	micro β	microscale***	surface-layer turbulence
30 m	micro γ	microscale***	inertial subrange turbulence
3 m	micro δ	microscale***	inertial subrange turbulence
300 mm	micro δ	microscale***	fine-scale turbulence
30 mm	micro δ	microscale***	fine-scale turbulence
3 mm	viscous	dissipation subrange	
0.3 µm	molecular	mean-free path between molec.	
0.003 µm	molecular	molecule sizes	
0			

global winds

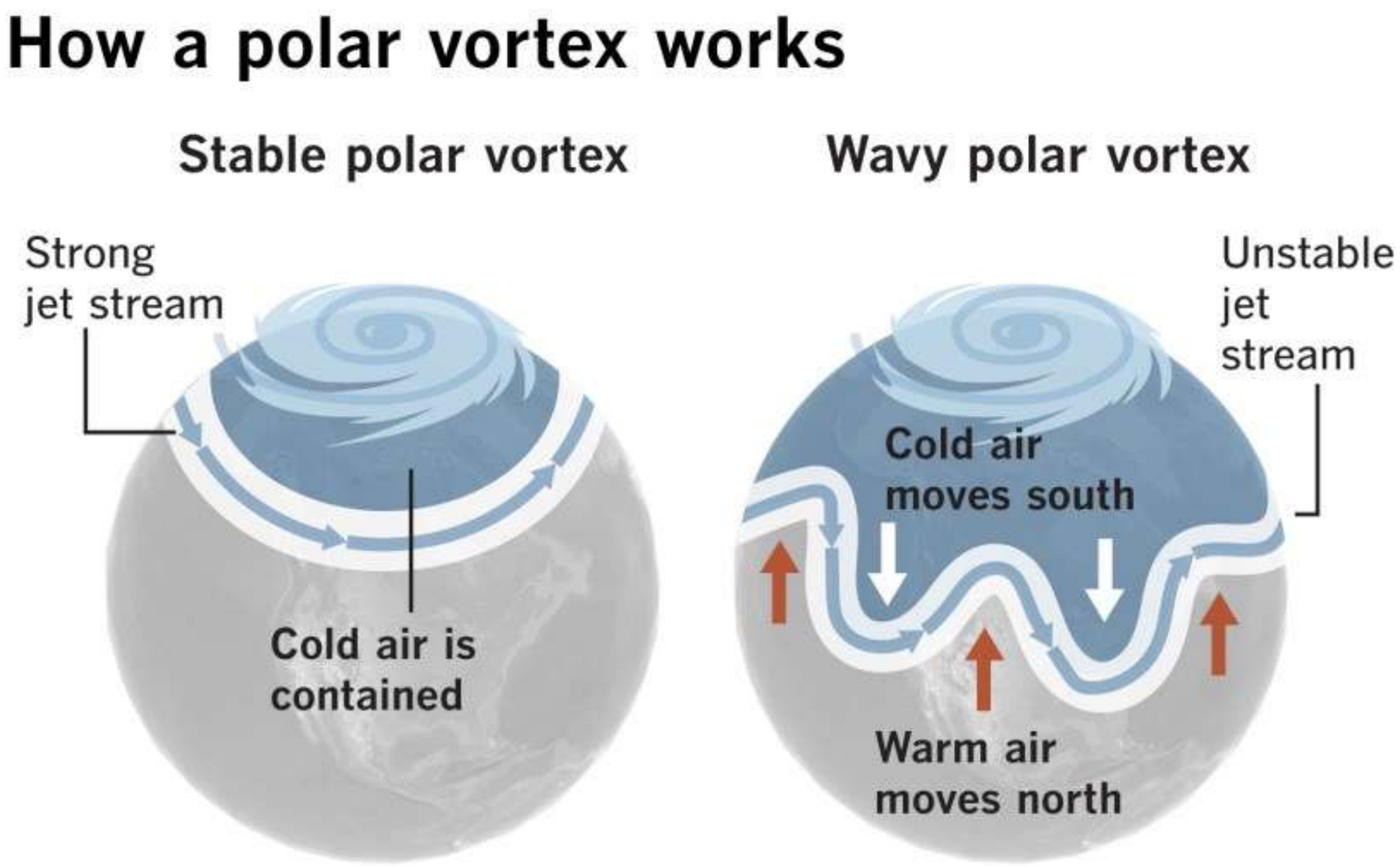
local winds

Source: Stull (2016)



Source: Bos (2017)

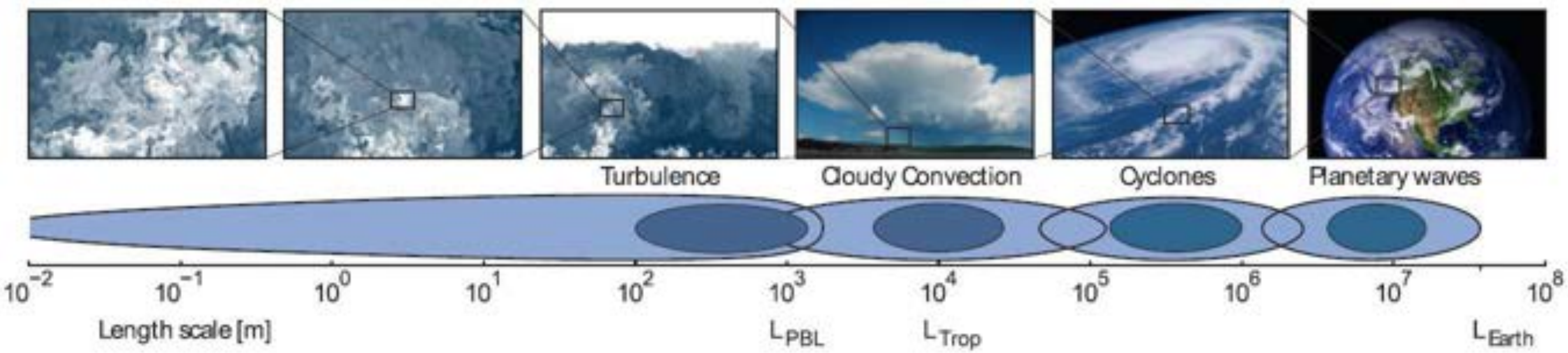
Example of planetary scale motions



NOAA

See also https://earth.nullschool.net/

Multi-scale nature of atmospheric motions



Source: Schalkwijk et al. (2015)

Outline

Motivation and objectives

Overview of relevant reference material

Part 1: General meteorology

Part 2: Boundary-layer meteorology

"*The physics-based approach"*

- The atmospheric boundary layer
- Vertical structure of the lower troposphere (free atmosphere, surface layer, Ekman layer)
- Atmospheric stability
- Selected topics of interest

Part 3: Wind power meteorology

Take-home messages

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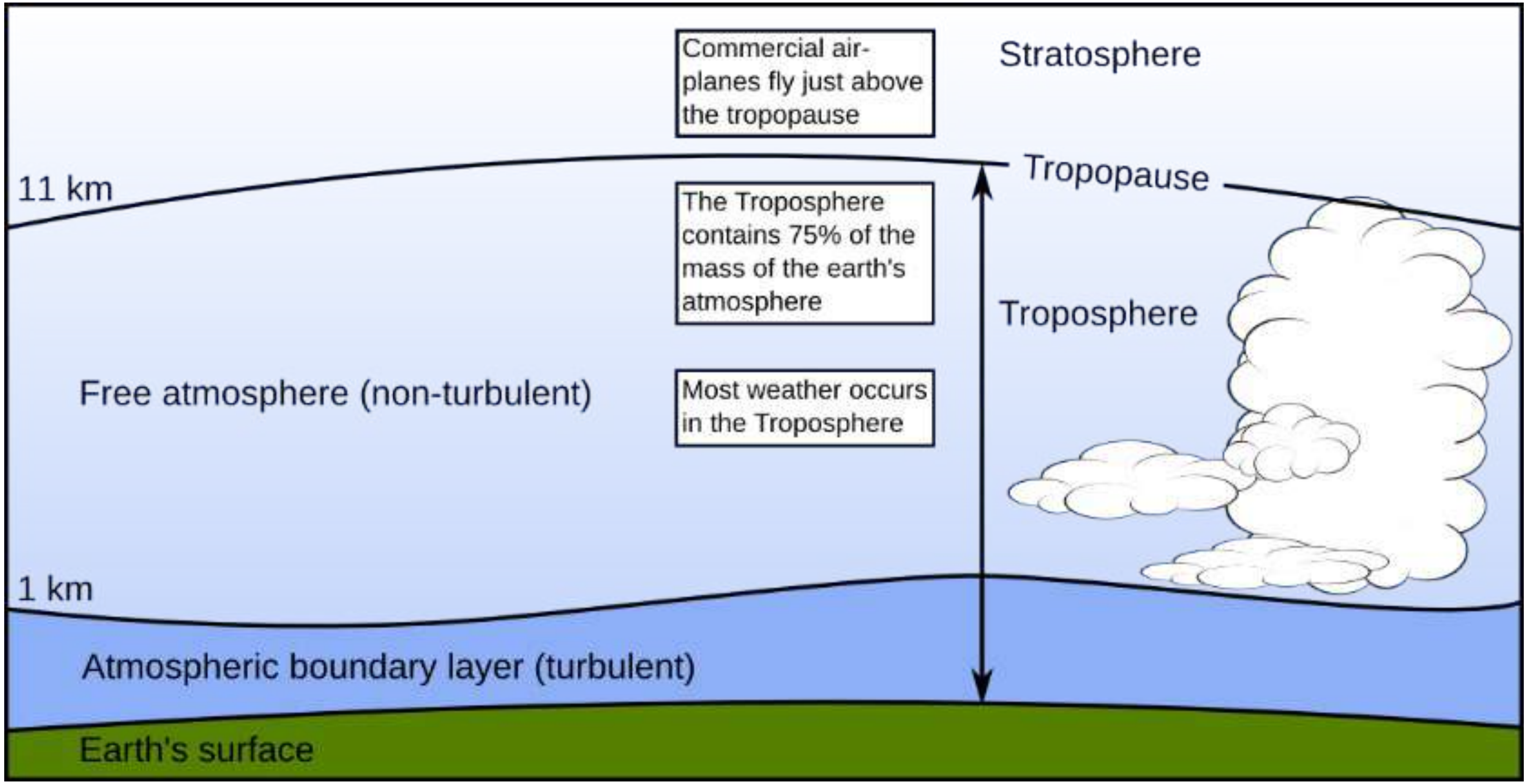
Atmospheric Boundary Layer (ABL)

also called the planetary boundary layer (PBL)

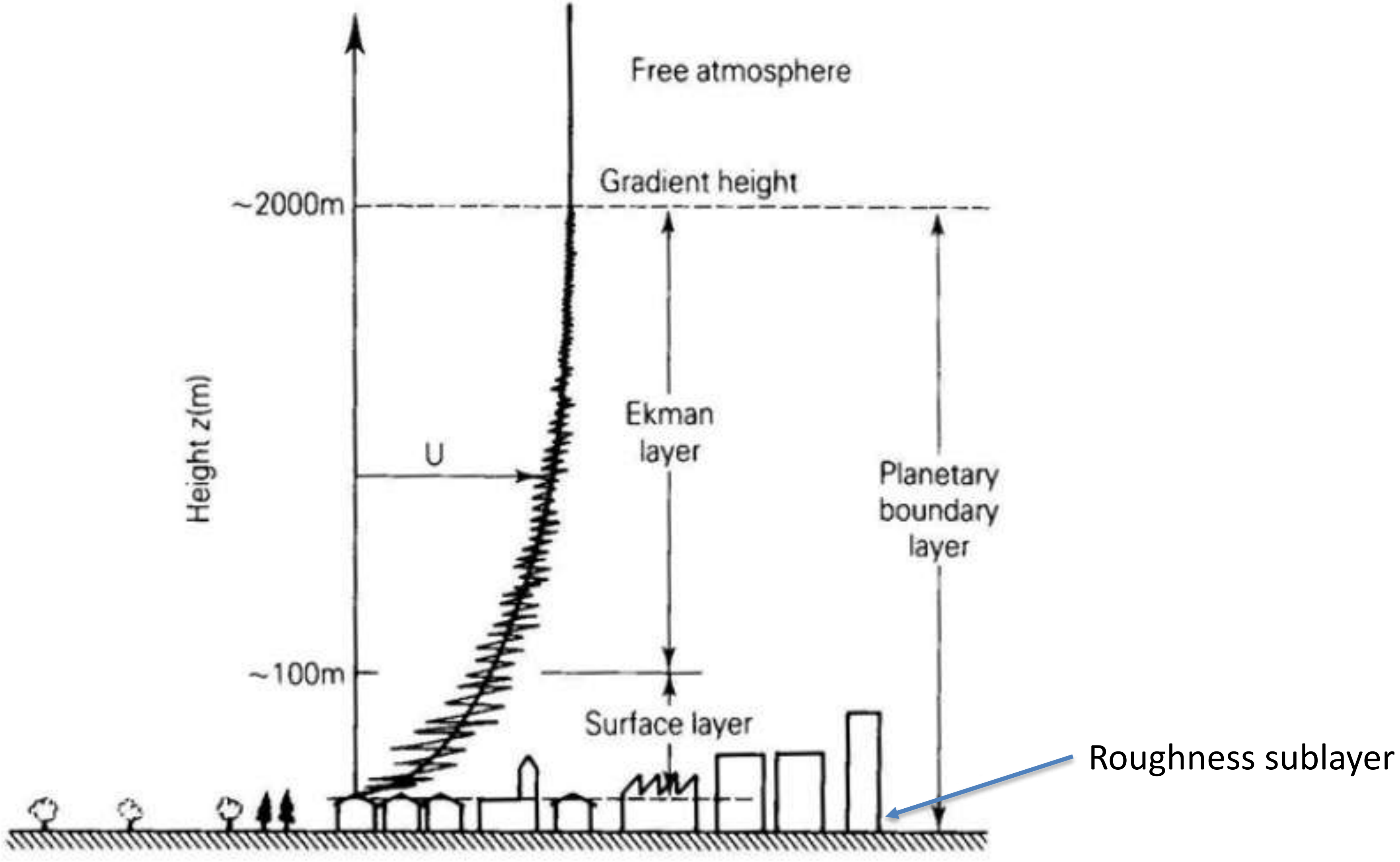


"… that part of the troposphere that is directly influenced by the presence of the earth's surface, and responds to surface forcings with a timescale of about an hour or less."
Stull (1988)

Atmospheric Boundary Layer (ABL)

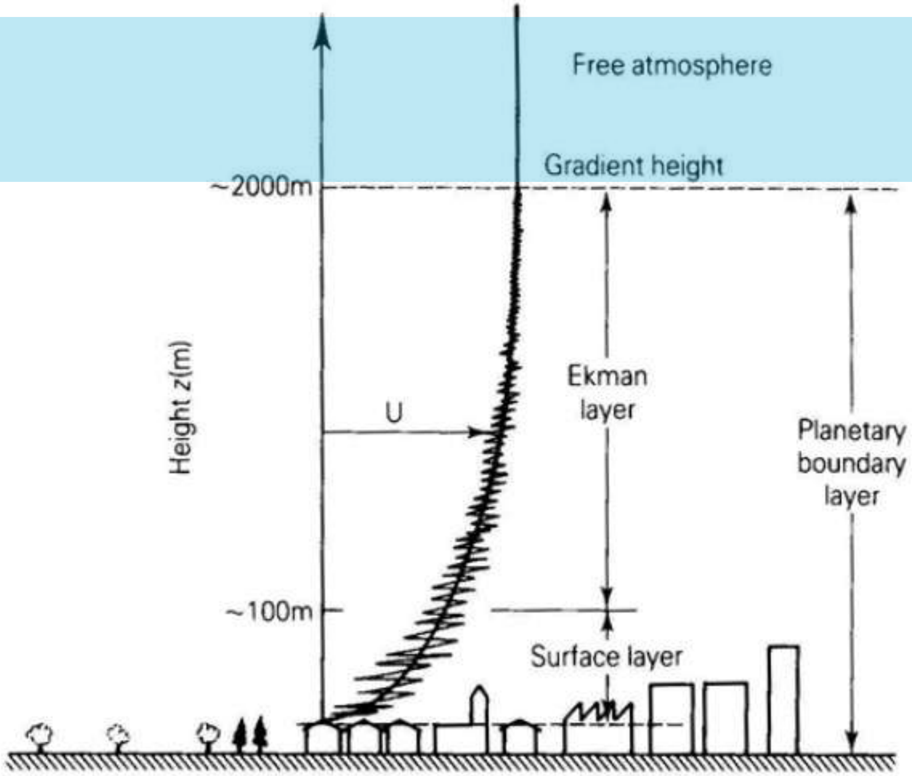
Planetary boundary layer over Berlin at night. Light pollution is easily scattered off of aerosols (suspended small particles) below the planetary boundary layer, but not so easily scattered in the clean air above.
Photo by Ralf Steikert, http://userpage.fu-berlin.de/~kyba/images/night_boundary_layer.html

Vertical structure of the lower troposphere



Source: Tavner et al. (2006)

Free atmosphere



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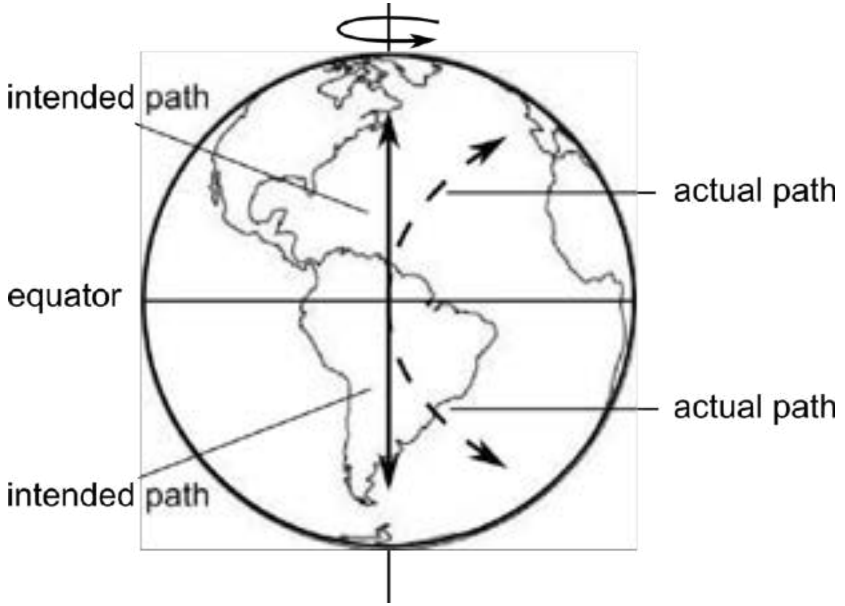


Geostrophic balance

Balance between pressure gradient and Coriolis force
(horizontally homogeneous, no friction, steady state)

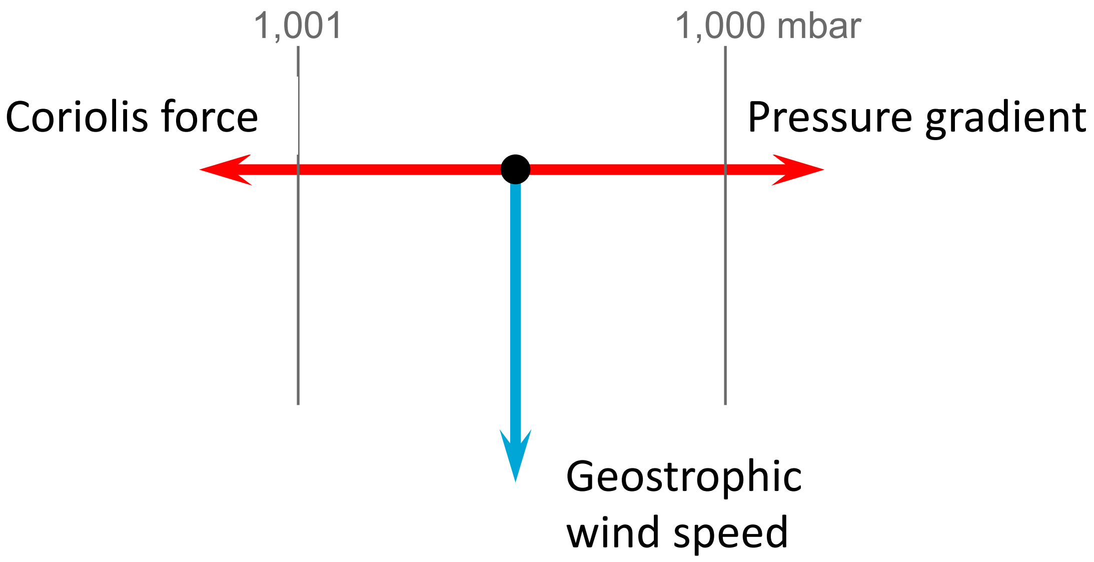
$$0 = -\frac{1}{\rho}\frac{\partial P}{\partial x} + f_c V_g$$
$$0 = -\frac{1}{\rho}\frac{\partial P}{\partial y} - f_c U_g$$

with Coriolis parameter $f_c = 2\Omega \sin\phi$

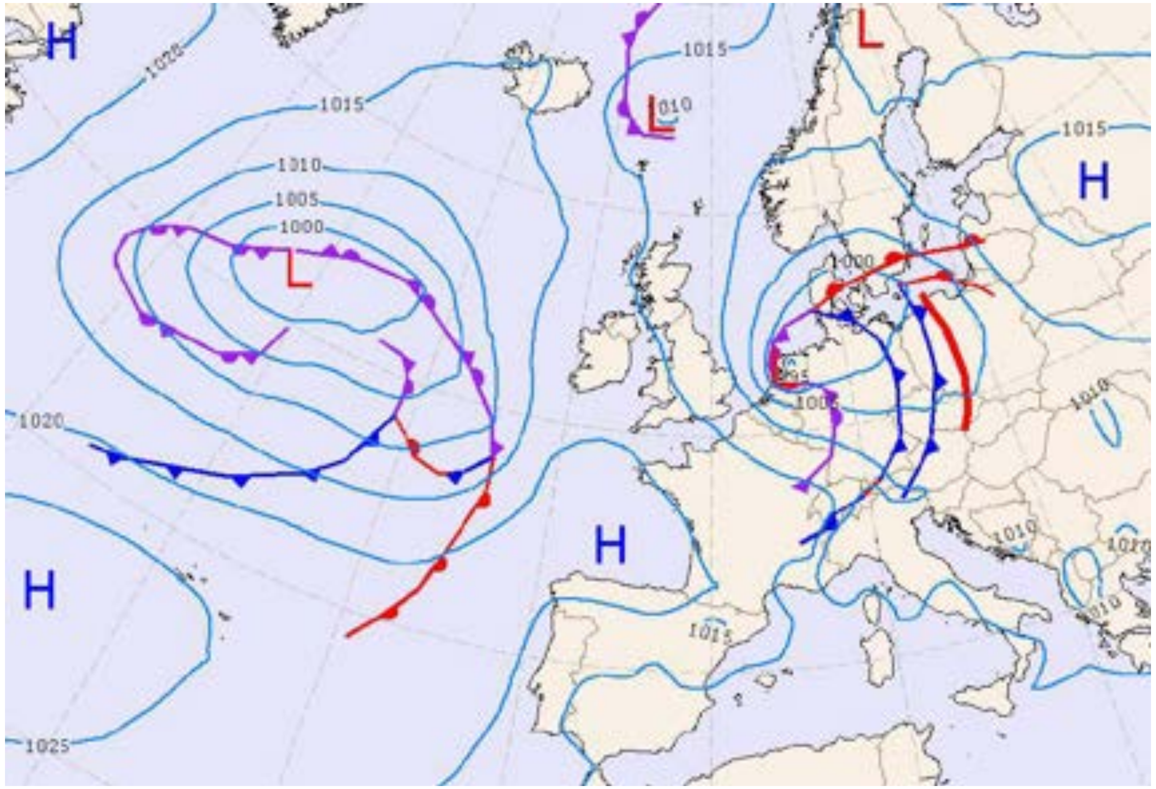
Geostrophic wind speed:

$$U_g = -\frac{1}{\rho f_c}\frac{\partial P}{\partial y}, \quad V_g = +\frac{1}{\rho f_c}\frac{\partial P}{\partial x}$$

Wind parallel to isobars



Geostrophic wind

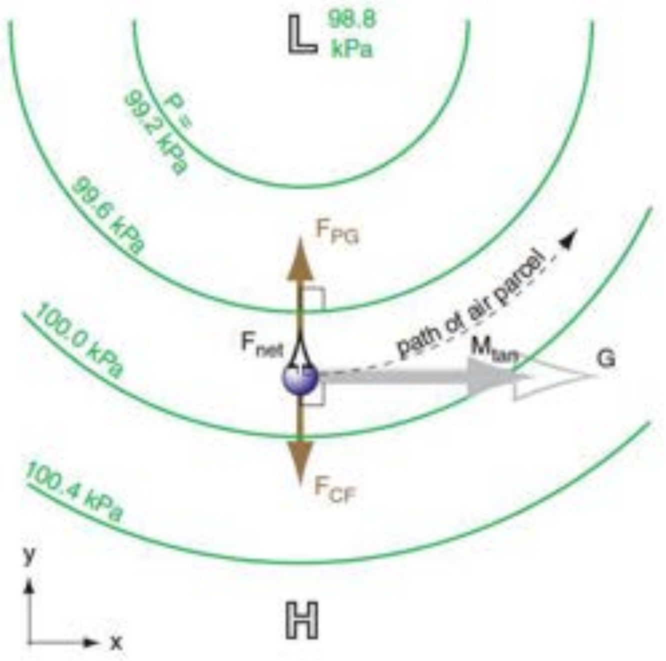


Isobars during a storm on 25 July 2015 (KNMI / WOW-NL)

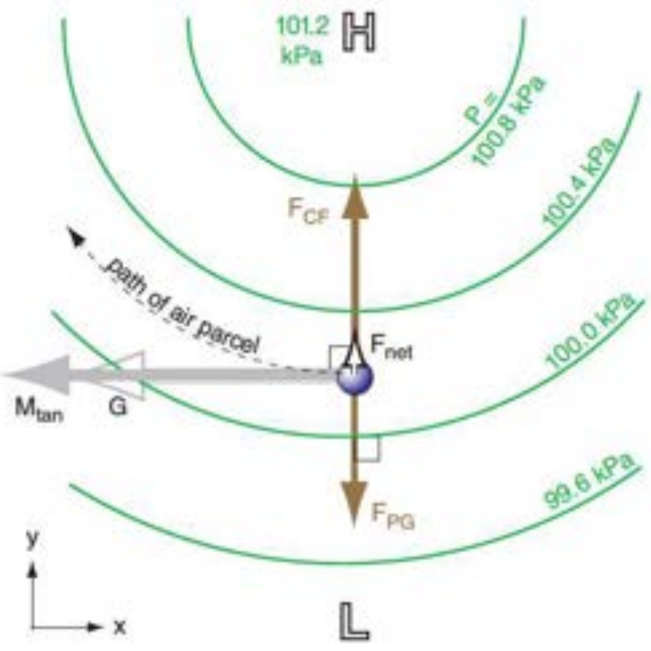
Gradient winds around L or H

Balance between pressure gradient, Coriolis force and centrifugal force

Low pressure system (cyclone)
Counterclockwise rotation in
northern hemisphere



High pressure system (anticyclone)
Clockwise rotation in
northern hemisphere



Source: Stull (2016)

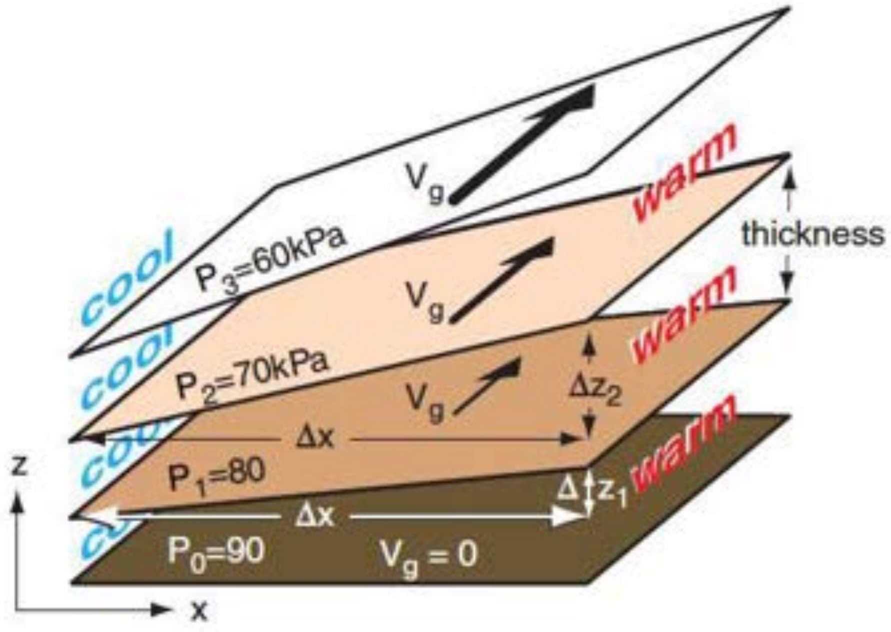
Thermal wind effect

Horizontal temperature gradients cause changes of the geostrophic wind with height

$$\frac{\partial U_g}{\partial z} \approx -\frac{g}{f_c T}\frac{\partial T}{\partial y}$$
$$\frac{\partial V_g}{\partial z} \approx +\frac{g}{f_c T}\frac{\partial T}{\partial x}$$

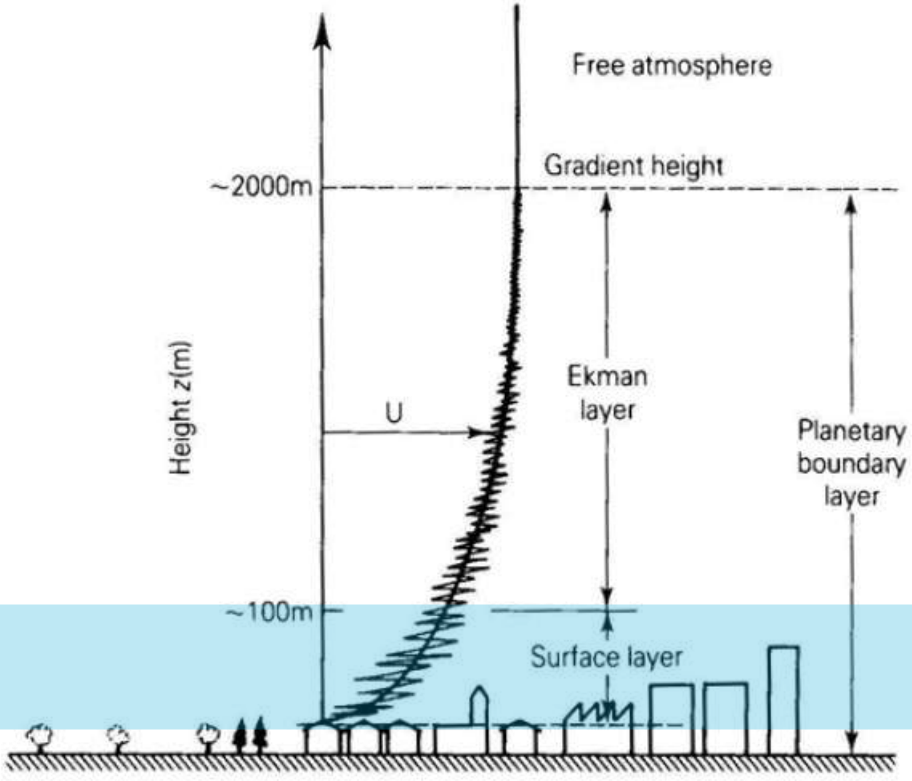
Barotropic conditions: $U_g, V_g = cst$

Baroclinic conditions: $U_g, V_g = f(z)$



Source: Stull (2016)

Surface layer



also called Prandtl layer or constant-stress layer

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Logarithmic wind profile

Wind stress at the ground $\tau_0 = \rho u_*^2$ with u_* defined as the friction velocity

Assume constant-stress layer, so $\tau = \rho u_*^2 = \rho \nu_t \frac{\partial u}{\partial z}$ throughout the surface layer, with ν_t an eddy-viscosity

Mixing length assumption (Prandtl) yields $\nu_t = \kappa u_* z$ with $\kappa = 0.4$ the von Kármán constant

Hence,

$$\frac{\partial u}{\partial z} = \frac{u_*}{\kappa z} \quad \Rightarrow \quad u(z) = \frac{u_*}{\kappa} \ln(z/z_0)$$

with z_0 the surface roughness length, dependent on the surface coverage

Alternative: Power law

Empirical description of the vertical wind profile:

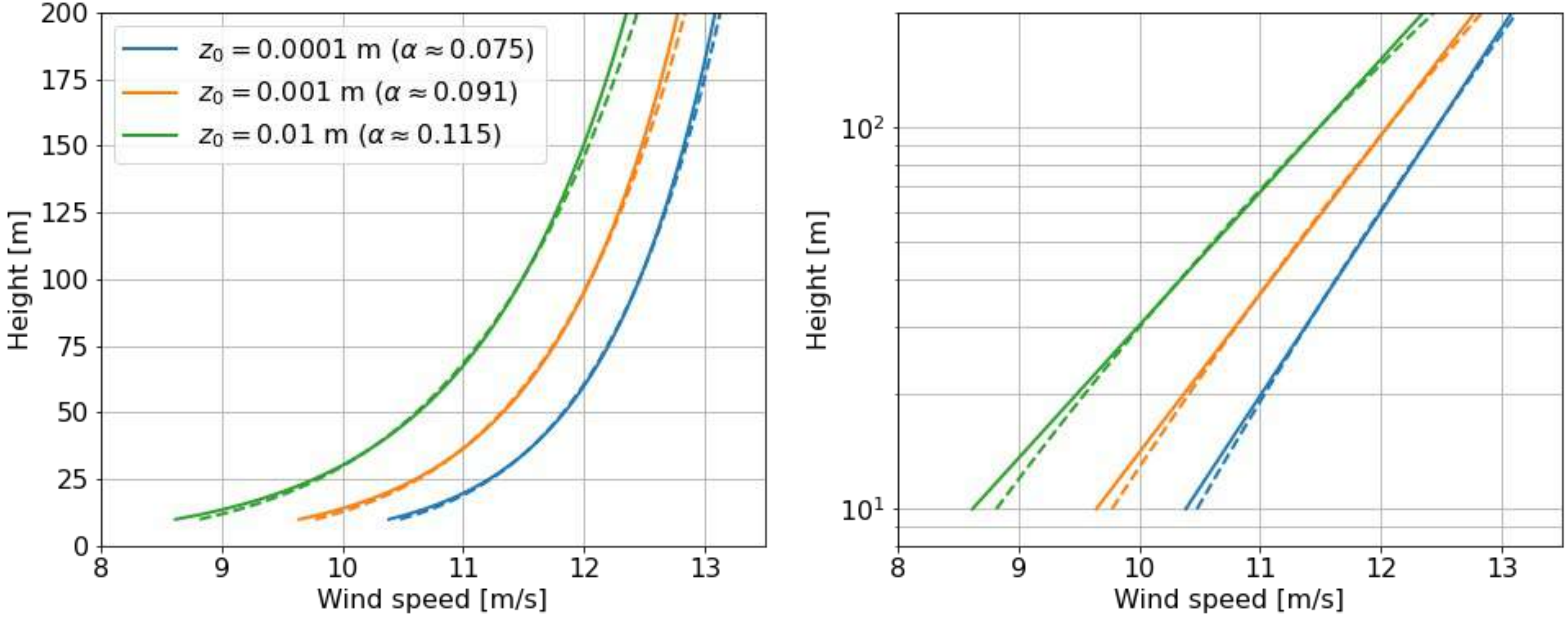
$$u(z) = u(z_{\text{ref}}) \left(\frac{z}{z_{\text{ref}}} \right)^{\alpha}$$

with α the shear exponent

Typical Roughness Lengths

Type of terrain	$z_0(m)$	α
Mud Flats, Ice	10^{-5} to $3x10^{-5}$	
Calm Sea	$2x10^{-4}$ to $3x10^{-4}$	
Sand	$2x10^{-4}$ to 10^{-3}	0.01
Mown Grass	0.001 to 0.01	
Low Grass	0.01 to 0.04	0.13
Fallow Field	0.02 to 0.03	
High Grass	0.04 to 0.1	0.19
Forest and Woodland	0.1 to 1	
Built up area, Suburb	1 to 2	0.32
City	1 to 4	

Vertical wind profile



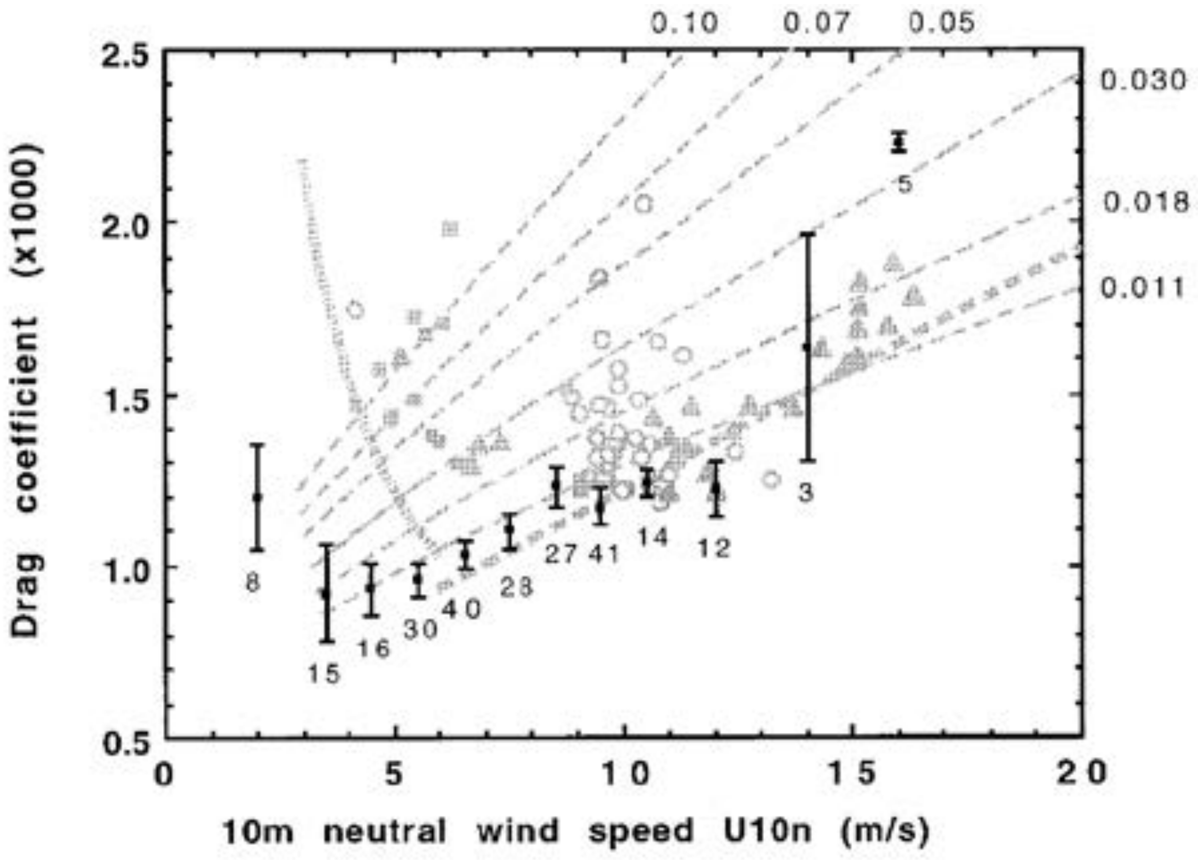
Full lines: Logarithmic profile
Dashed lines: Power profiles

Offshore surface roughness

$$C_{D10n} = \frac{u_*^2}{U_{10}^2} = \frac{\kappa^2}{[\ln(10\,m/z_0)]^2}$$

At sea, z_0 depends on

- Wave height
- Fetch
- Wave age

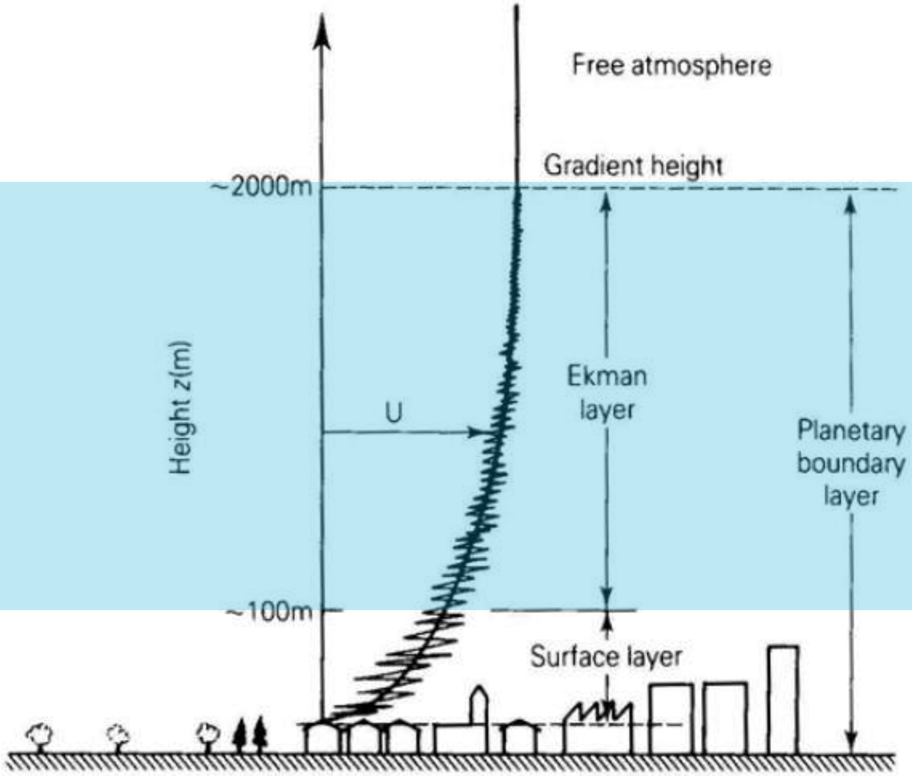


Charnock relation

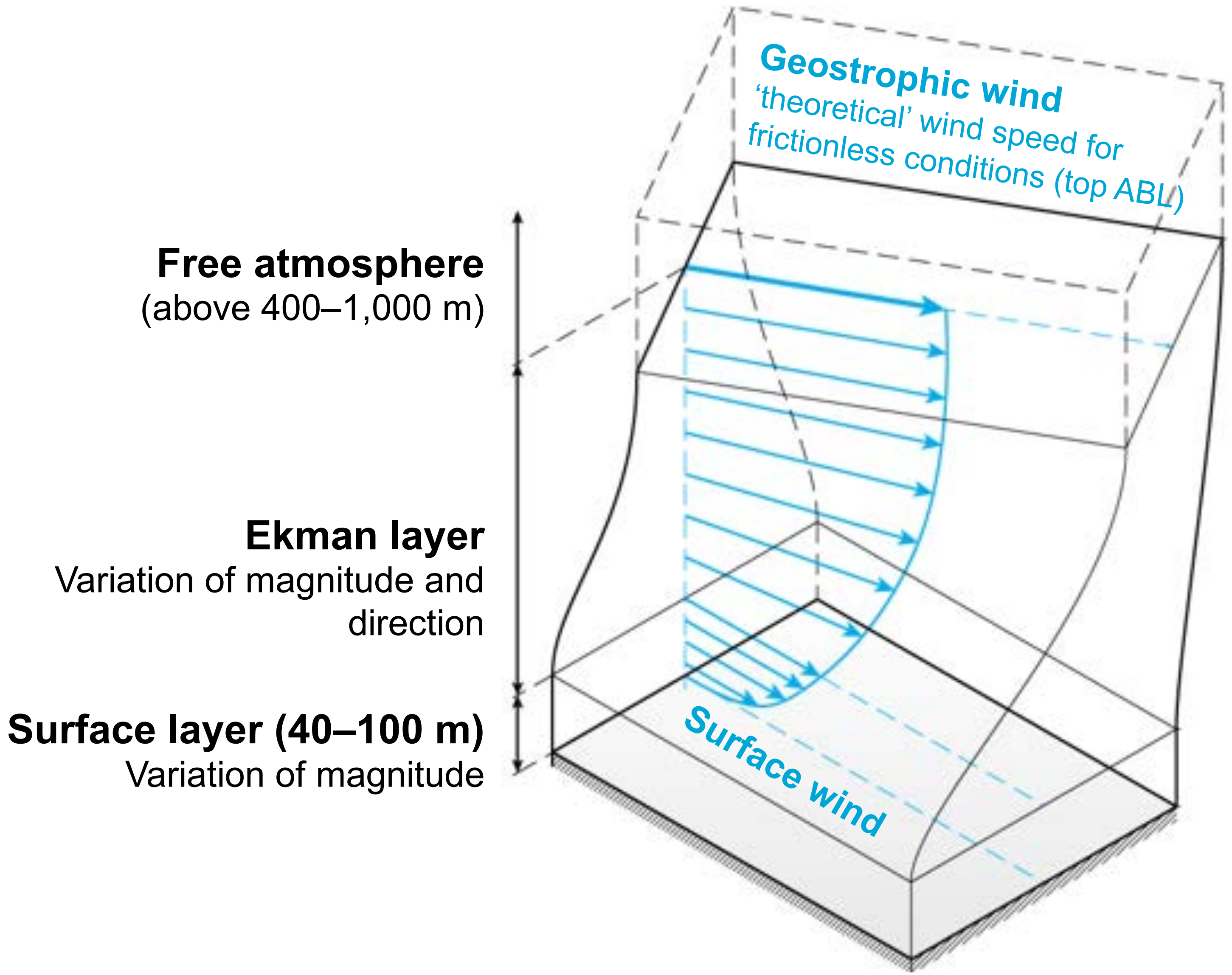
$$z_{0,\text{Charnock}} = \alpha \frac{u_*^2}{g}$$

Source: Taylor and Yelland (2001)

Ekman layer



Free atmosphere
Gradient height
~2000m
Height z(m)
U
Ekman
layer
Planetary
boundary
layer
~100m
Surface layer

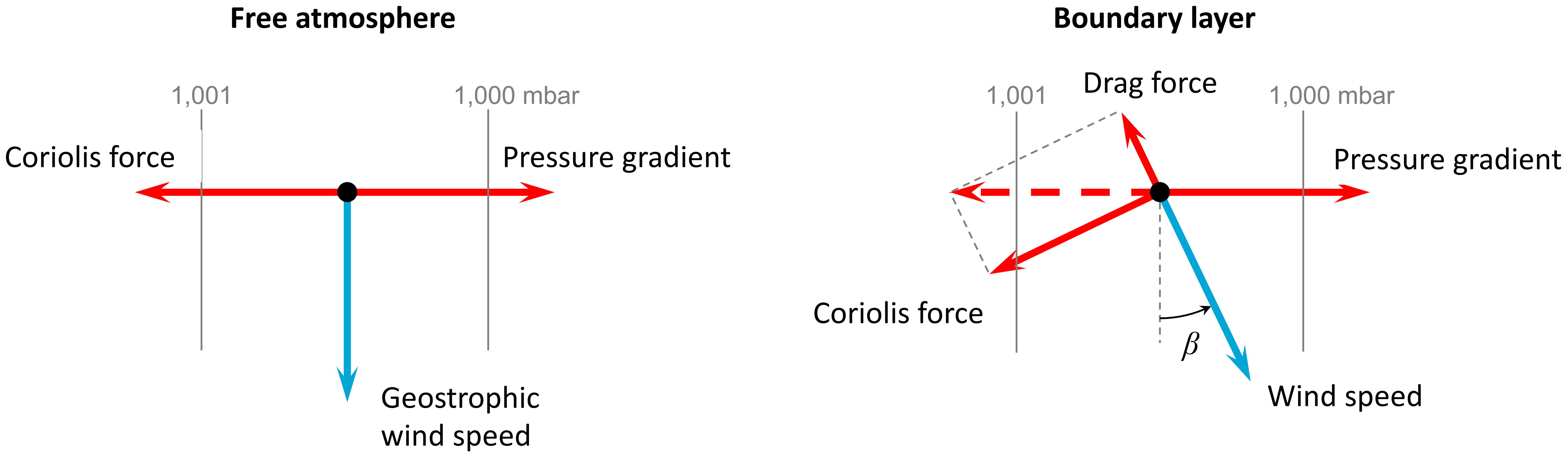


Ekman layer equations
(steady state, horizontally homogeneous)

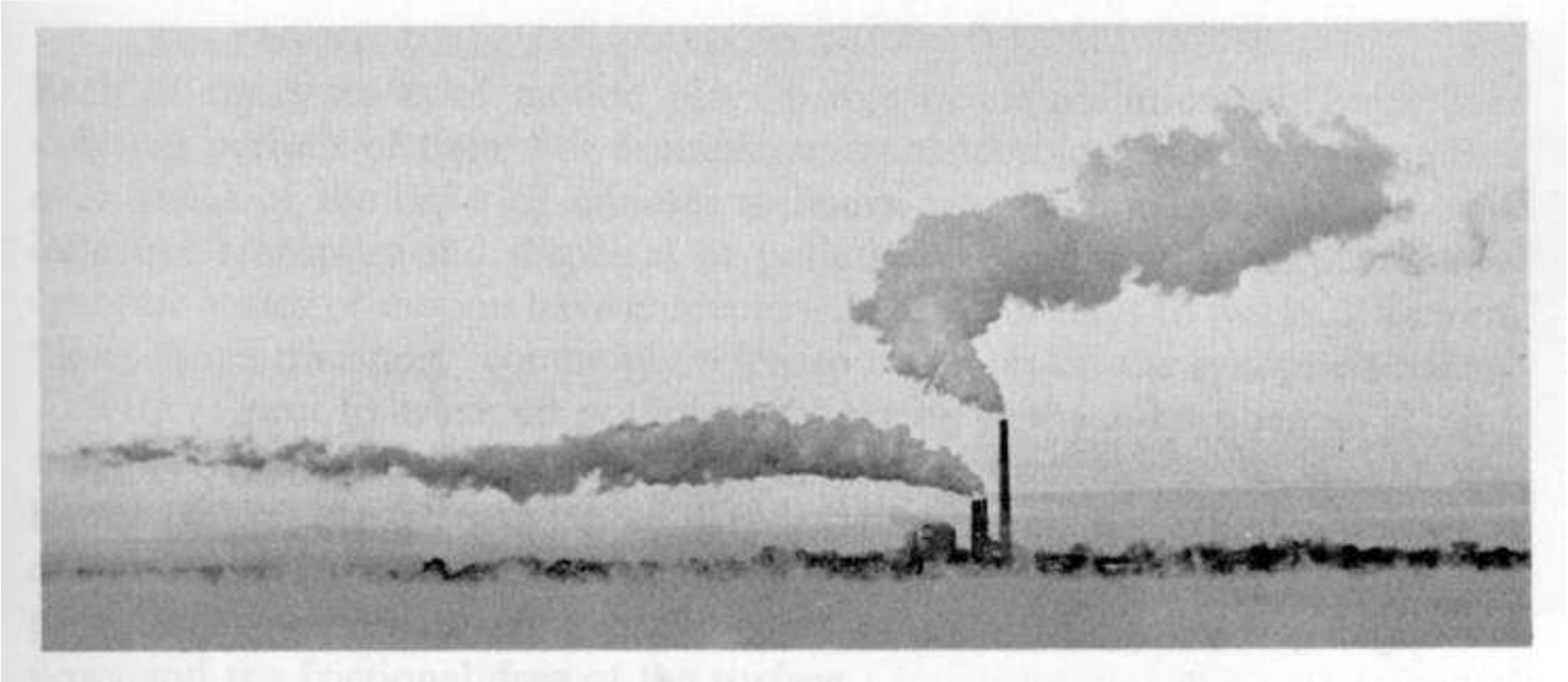
$$-f_c v + \frac{1}{\rho}\frac{\partial p}{\partial x} - \frac{\partial}{\partial z}\left(\nu_t \frac{\partial u}{\partial z}\right) = 0$$

$$f_c u + \frac{1}{\rho}\frac{\partial p}{\partial y} - \frac{\partial}{\partial z}\left(\nu_t \frac{\partial v}{\partial z}\right) = 0$$

Geostrophic departure in the Ekman layer



ABL Wind field is NOT uni-directional



Stacks in Salem, Massachusetts. Photo by: Ralph Turcotte, Beverly Times

Geostrophic drag law

also called resistance laws or Rossby number similarity theory

Asymptotic matching of the surface layer and the Ekman layer yields

$$G = \frac{u_*}{\kappa}\sqrt{\left(\ln\left(\frac{u_*}{f_c z_0}\right) - A\right)^2 + B^2}$$

$$\sin\alpha = -\frac{B u_*}{\kappa G}$$

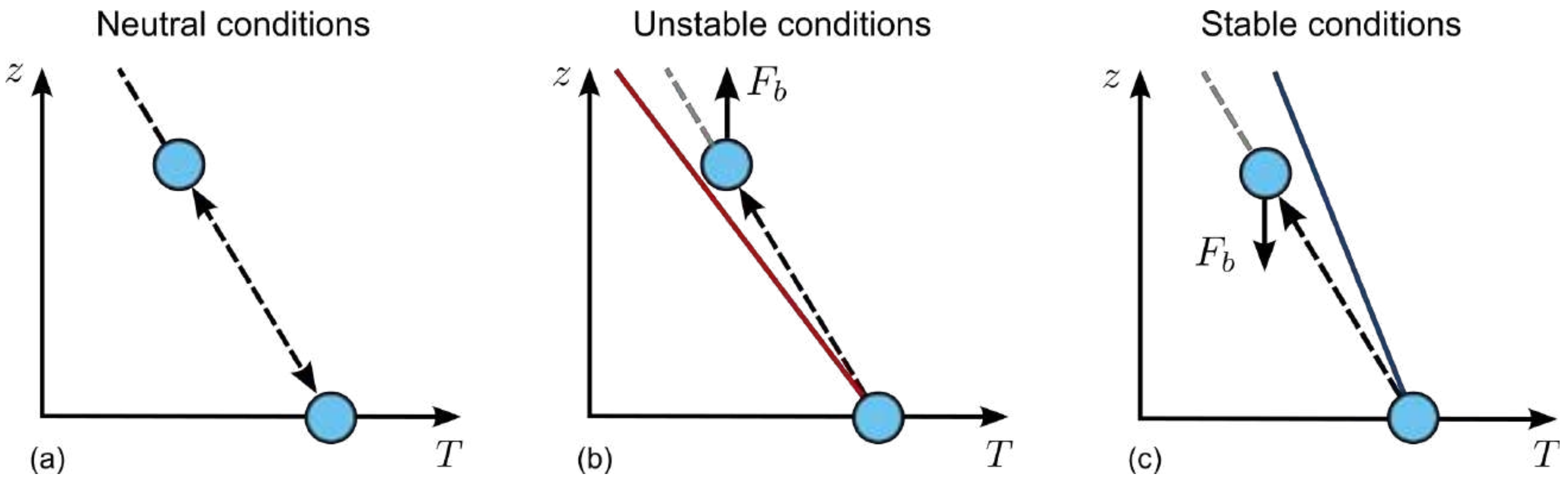
with

G the magnitude of geostrophic wind speed
α the angle between the near-surface winds and the geostrophic wind
$A = 1.8$ an empirical constant
$B = 4.5$ an empirical constant

Atmospheric stability

Thermal stability

Adiabatic lapse rate $$\Gamma_d = -\frac{g}{C_p} = -9.8\ \mathrm{K/km}$$



$$\frac{\mathrm{d}T}{\mathrm{d}z} = -\frac{g}{C_p}$$

Motions are unaffected

$$\frac{\mathrm{d}T}{\mathrm{d}z} < -\frac{g}{C_p}$$

Motions are enhanced

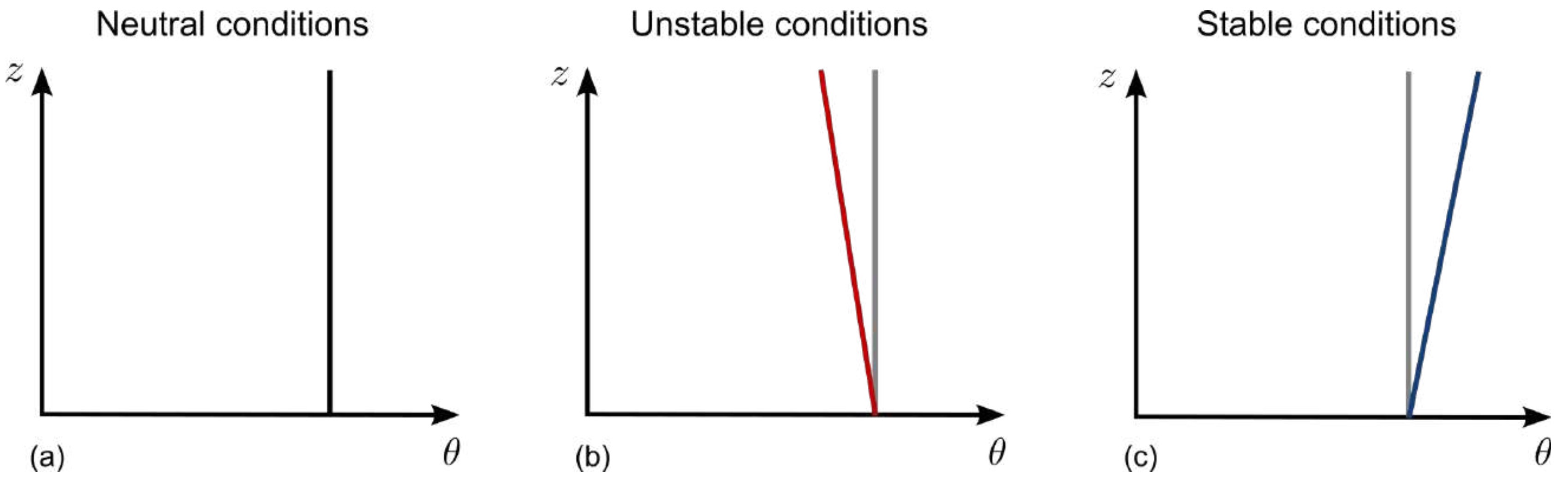
$$\frac{\mathrm{d}T}{\mathrm{d}z} > -\frac{g}{C_p}$$

Motions are suppressed

Potential temperature

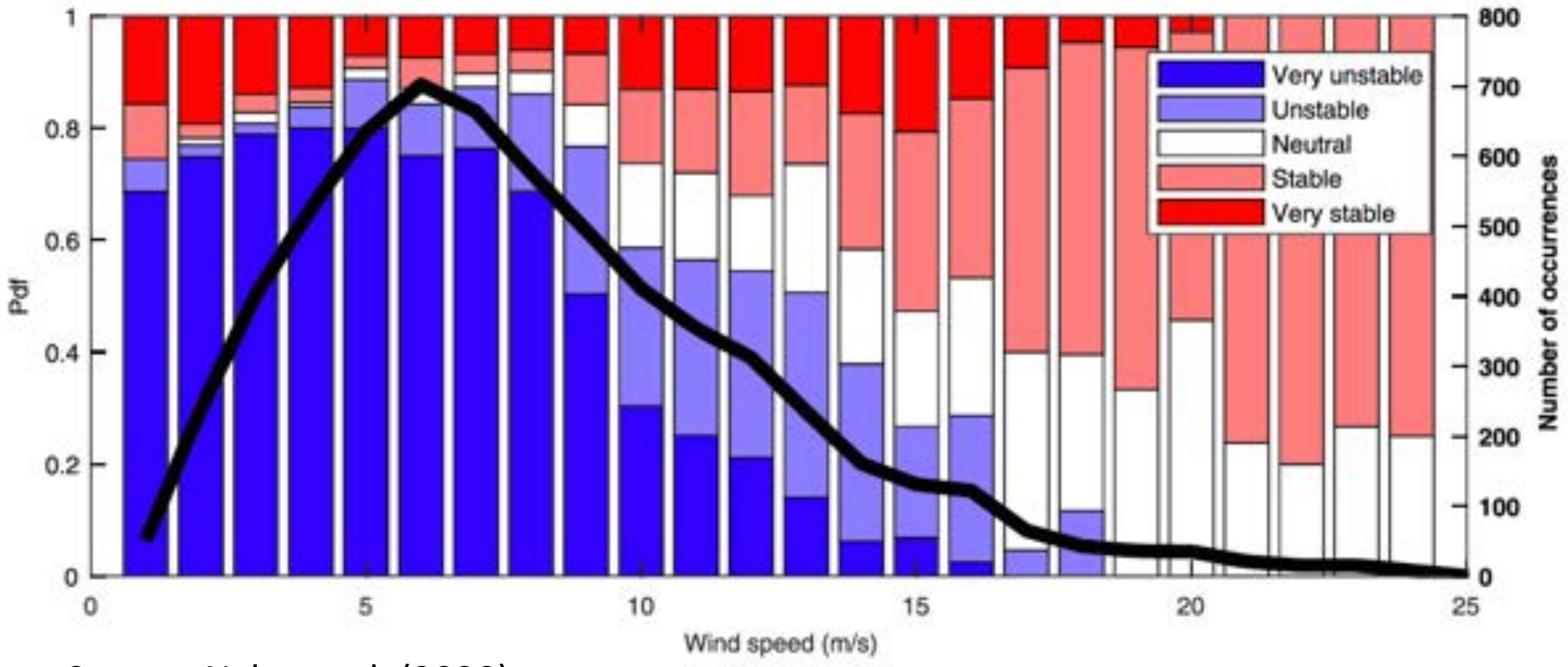
= temperature an air parcel with pressure p would attain if adiabatically brought to a reference pressure p_0

$$\theta = T\left(\frac{p_0}{p}\right)^{R/C_p}$$



$$\frac{d\theta}{dz} = 0 \qquad \frac{d\theta}{dz} < 0 \qquad \frac{d\theta}{dz} > 0$$

Stable, neutral and unstable conditions



Source: Nybø et al. (2020)

Example: Stability distribution at FINO-1

Stable conditions

- Over land at night (clear skies)
- Warm air advected over cold surface

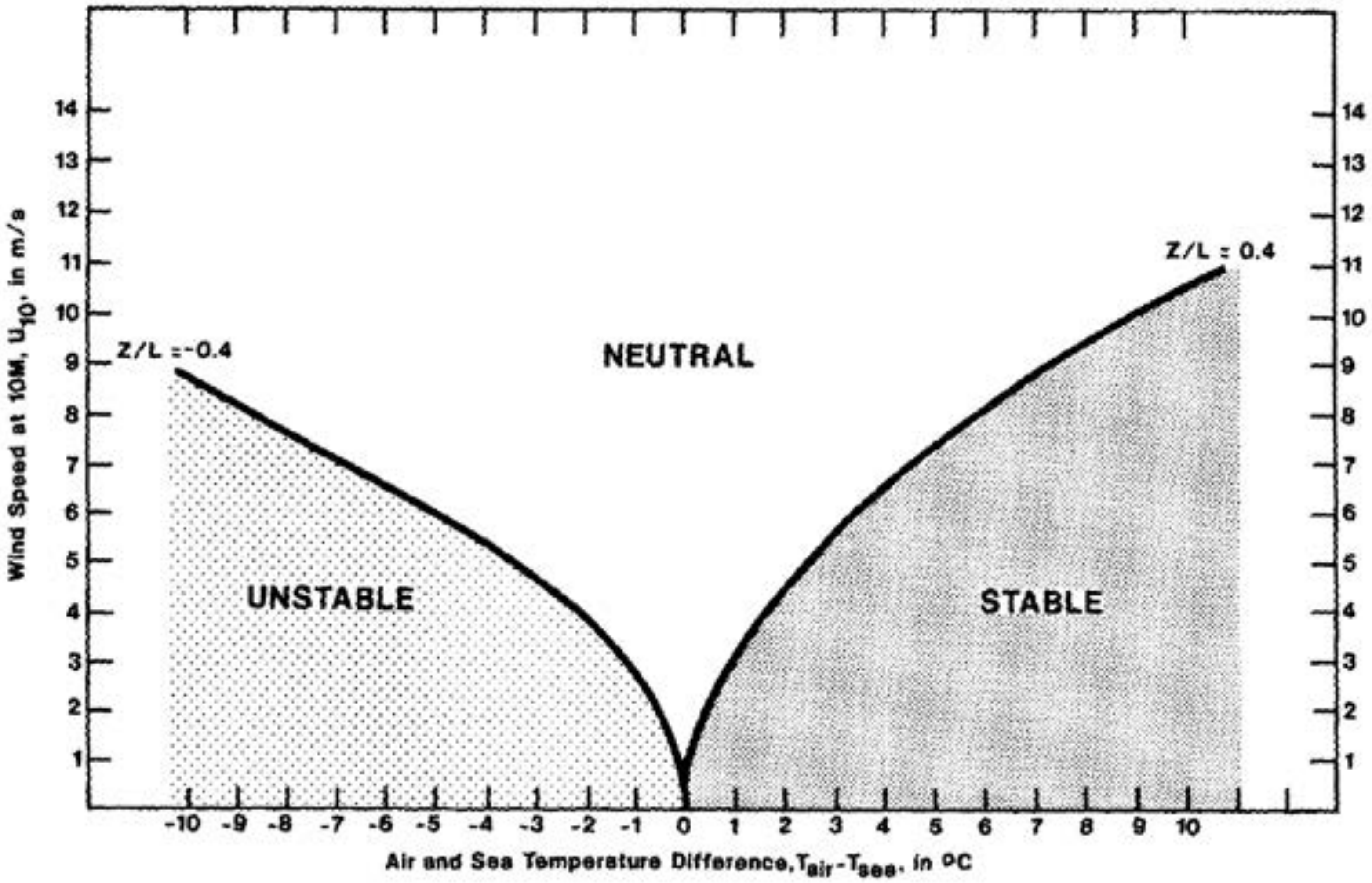
Neutral conditions

- Strong winds & overcast conditions
- Short transition period after sunset

Unstable conditions

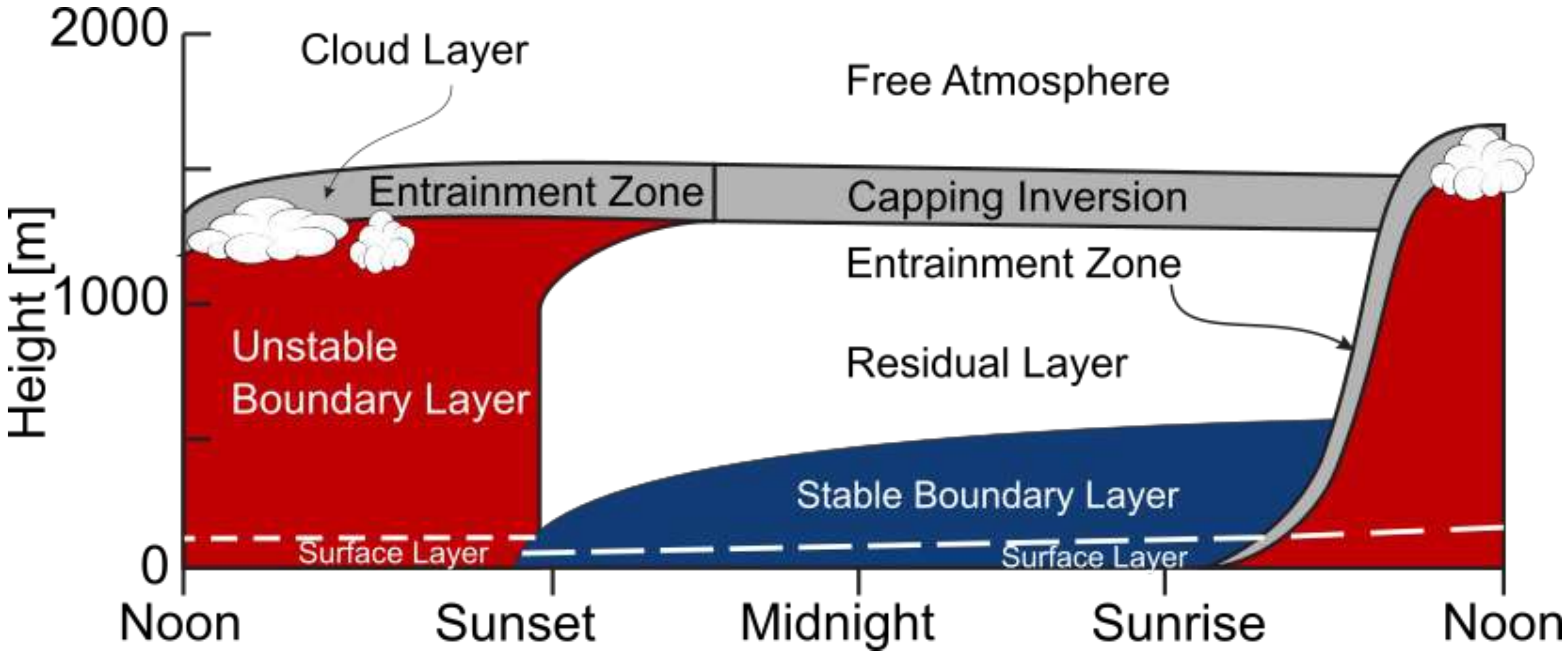
- Over land during daytime
- Cold air advected over warm surface

Atmospheric stability offshore



Source: Hsu et al. (1994)

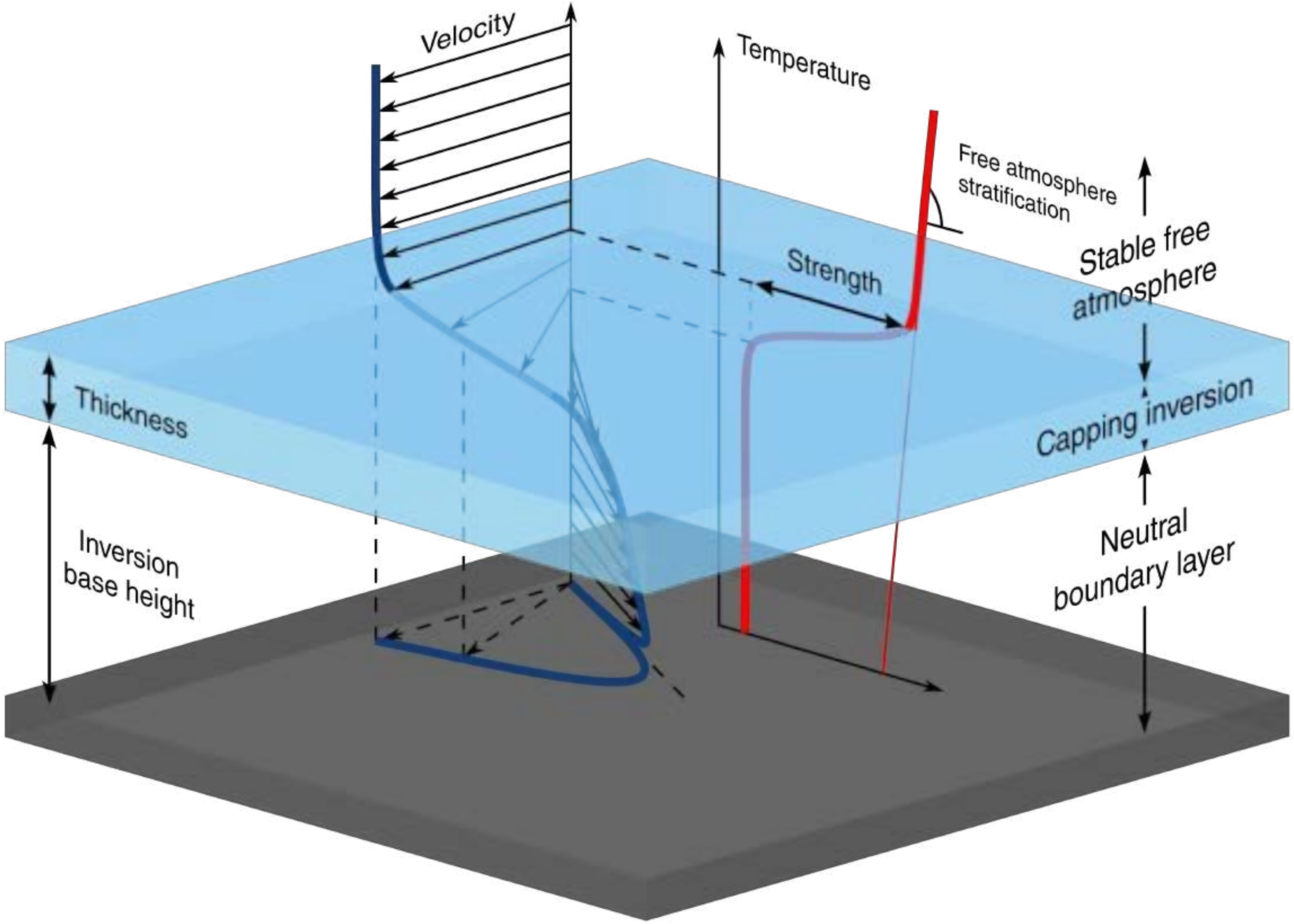
Diurnal cycle



Unstable boundary layer is also called the Convective Boundary Layer (CBL)

Source: Adapted from Stull (1988)

Different "types" of stability



Free atmosphere stratification
Always stably stratified

Capping inversion/Inversion layer
very stable layer at the top of the ABL

Surface layer stability
neutral, stable or unstable

Source: Allaerts (2016)

Atmospheric stability metrics: Obukhov length

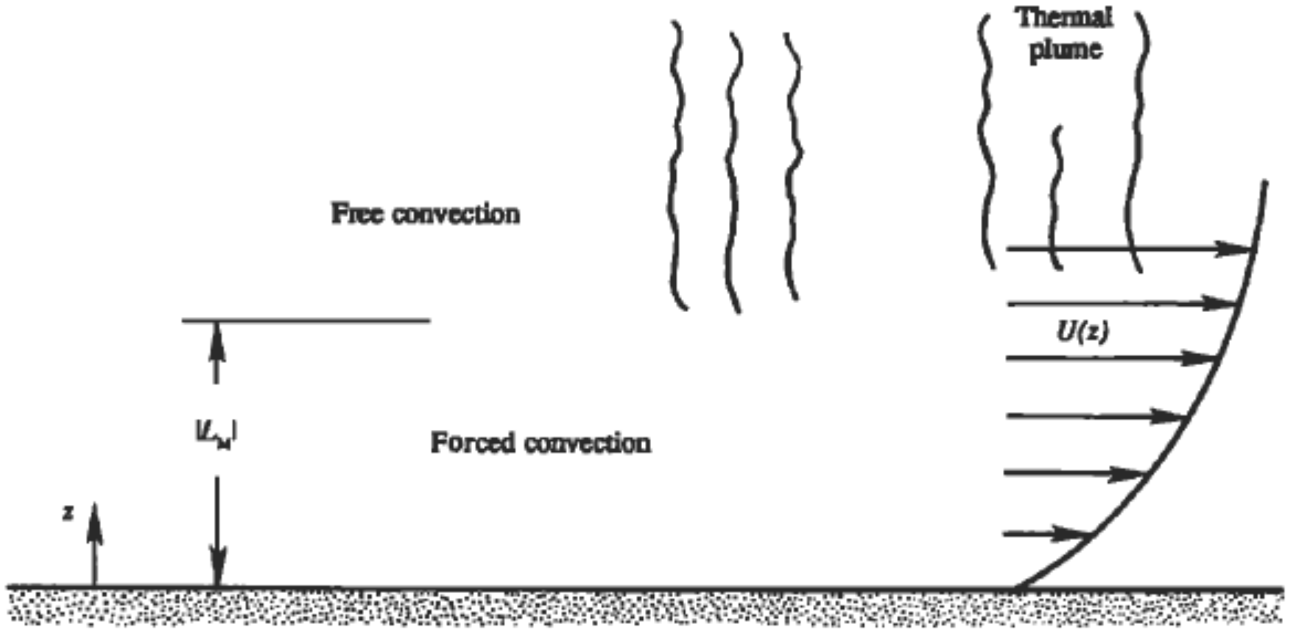
$$L = -\frac{u_*^3}{\kappa g \alpha \overline{w'\theta'}}$$

with
u_* friction velocity
$\overline{w'\theta'}$ kinematic heat flux
κ von Karman constant
g gravitational acceleration
α thermal expansion coefficient
cfr. $\rho = \rho_0[1 - \alpha(T - T_0)]$

Interpretation:

$$\frac{z}{L} = \zeta \sim \frac{\text{buoyant destruction}}{\text{shear production}}$$

$z \ll |L|$: shear production dominates (mechanical turbulence)
$z \gg |L|$: buoyant destruction/production dominates



Source: Kundu et al. (2002)

Atmospheric stability metrics: Richardson number

gradient Richardson number

$$Ri = \frac{\frac{g}{\theta_0}\frac{\partial \theta}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$$

flux Richardson number

$$R_f = \frac{\frac{g}{\theta_0}\overline{w'\theta'}}{\overline{u_i' u_j'}\frac{\partial \overline{u}_i}{\partial x_j}}$$

bulk Richardson number

$$R_B = \frac{\frac{g}{\theta_0}\Delta\theta\Delta z}{(\Delta u)^2 + (\Delta v)^2}$$

Empirical relation between Ri and L:

- unstable conditions: $\frac{z}{L} = Ri$
- stable conditions: $\frac{z}{L} = \frac{Ri}{1-5Ri}$

Monin-Obukhov similarity theory

Velocity gradient in the surface layer depends on stability

$$\frac{\kappa z}{u_*}\frac{dU}{dz} = \Phi(\zeta)$$

Universal function from experimental data

$\zeta > 0$: $\Phi(\zeta) = 1 + \beta\zeta$

$\zeta < 0$: $\Phi(\zeta) = (1 - \gamma\zeta)^{-1/4}$

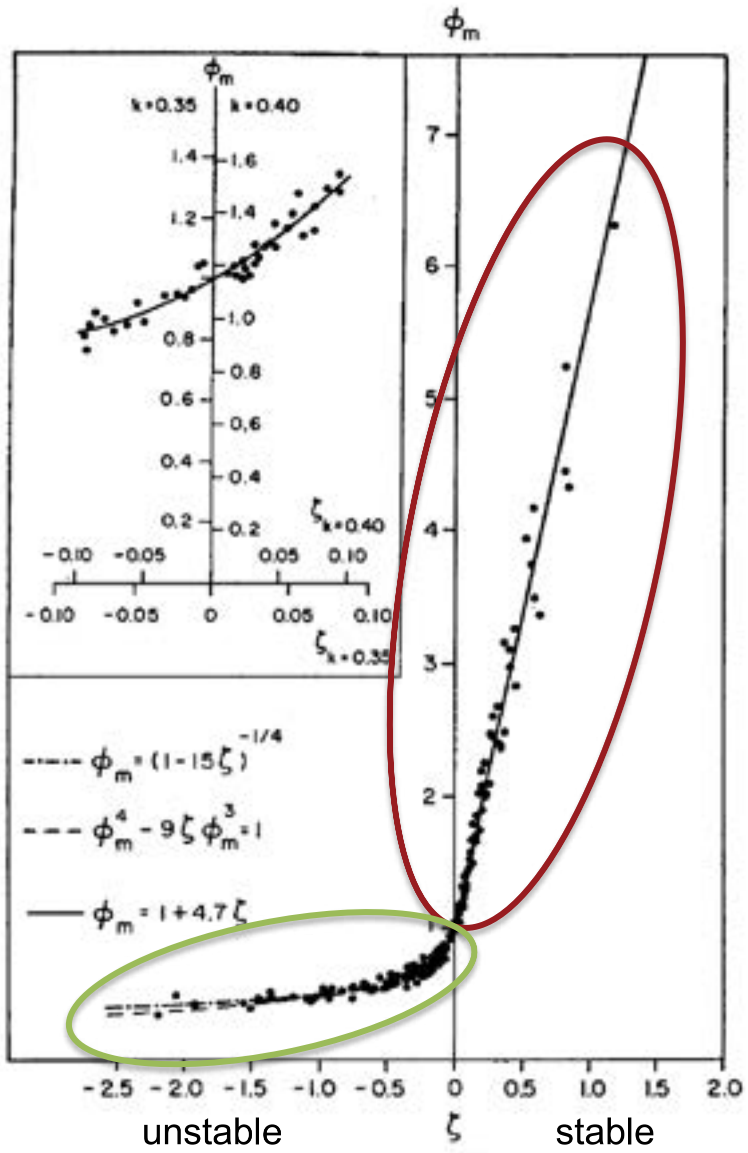
with empirical constant $\beta \approx 4.7, \gamma \approx 15$

Integration leads to an expression for the wind profile:

$$\rightarrow \; U(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \Psi\left(\frac{z}{L}\right) + \Psi\left(\frac{z_0}{L}\right)\right]$$

where

$$\Psi(\zeta) = \int_{\zeta_0}^{\zeta} \frac{1 - \Phi(x)}{x}\,\mathrm{d}x$$



Source: Businger et al. (1971)

Monin-Obukhov similarity theory

$$U(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) - \Psi\left(\frac{z}{L}\right) + \Psi\left(\frac{z_0}{L}\right)\right]$$

with stability correction functions

$\zeta = 0$: $\quad \Psi(\zeta) = 0$

$\zeta > 0$: $\quad \Psi(\zeta) = -\beta\zeta$

$\zeta < 0$: $\quad \Psi(\zeta) = 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2\tan^{-1}x + \frac{\pi}{2}, \qquad x = (1-\gamma\zeta)^{-1/4}$

with empirical constant $\beta \approx 4.7, \gamma \approx 15$

Similar expressions can be found for the temperature

$\zeta = 0$: $\quad \Phi(\zeta) = 1$

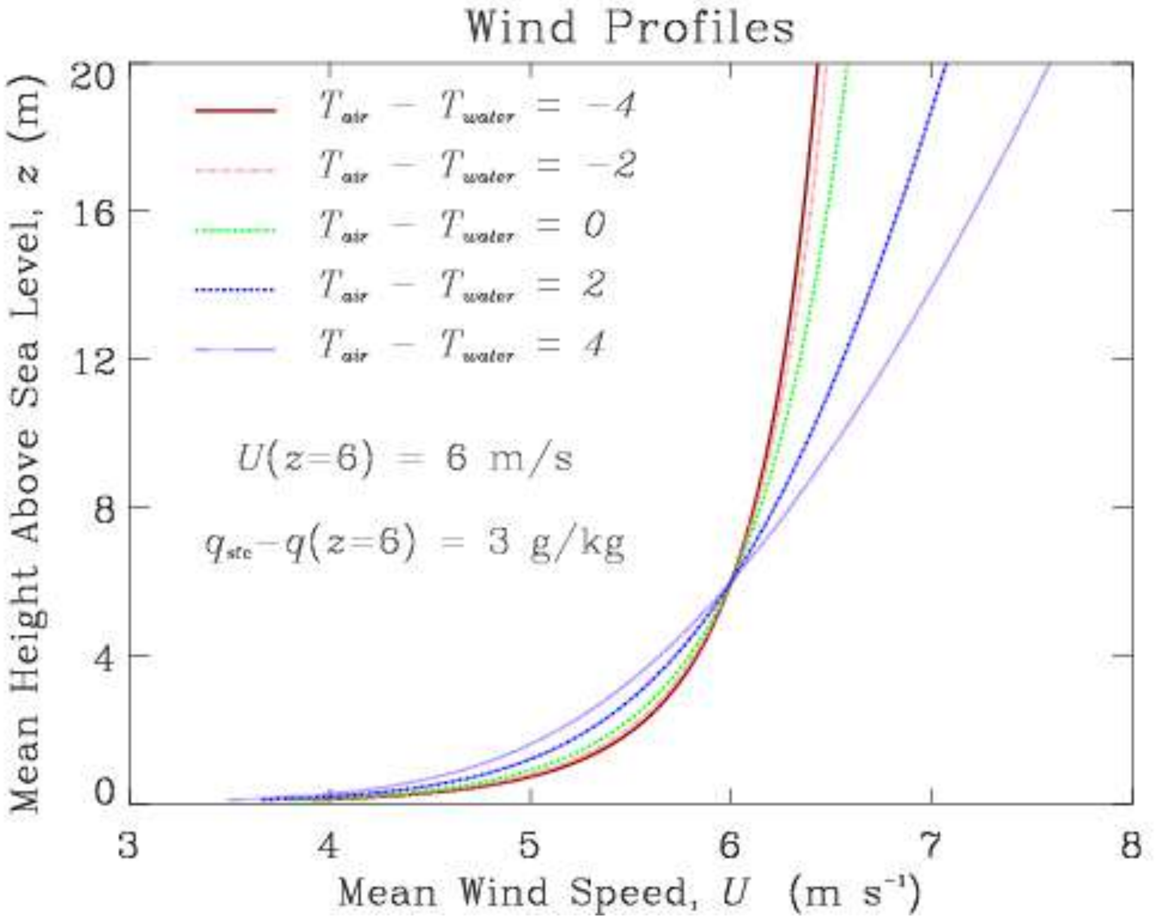
$\zeta > 0$: $\quad \Phi(\zeta) = 1 + \beta\zeta$

$\zeta < 0$: $\quad \Phi(\zeta) = (1-\gamma\zeta)^{-1/4}$

and

$$\Psi(\zeta) = \int_{\zeta_0}^{\zeta} \frac{1-\Phi(x)}{x}\,\mathrm{d}x$$

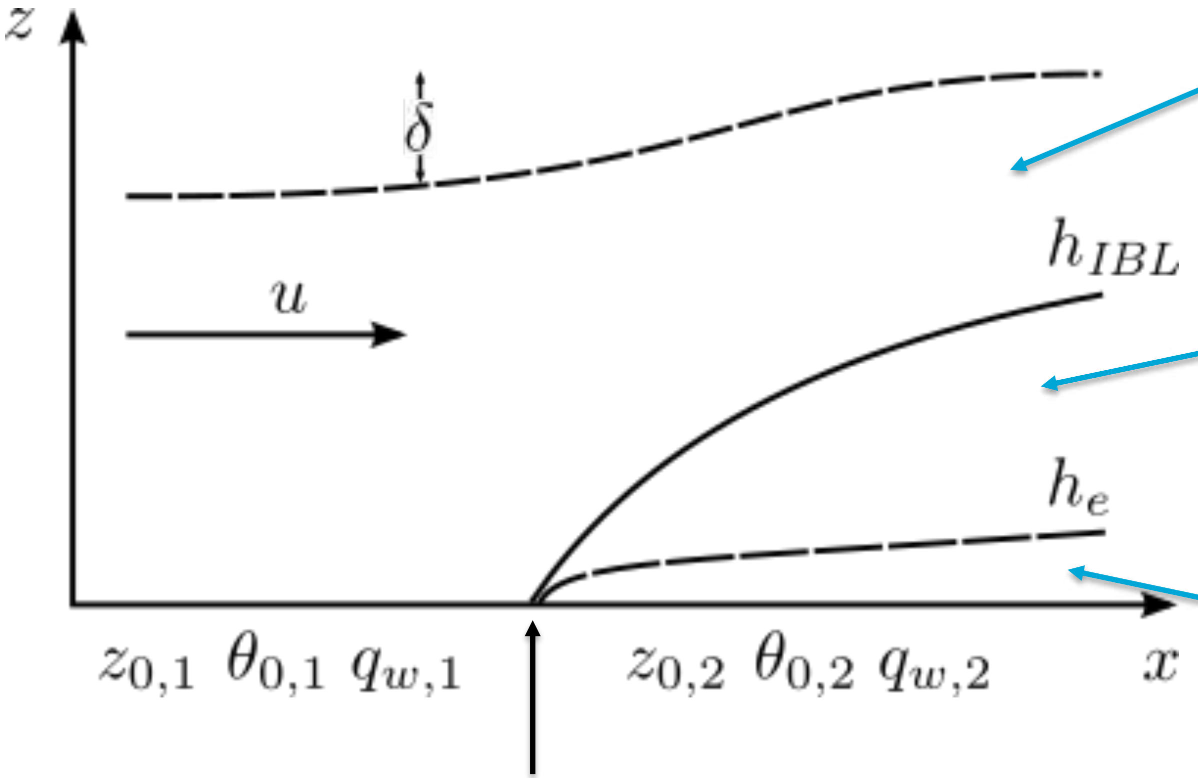
Influence of thermal effects on wind shear



Selected topics of interest

TU Delft

Internal boundary layer (IBL) theory



Discontinuity in surface conditions, e.g., land-sea transition

Free stream: Flow is characteristic of the upstream conditions (except for a displacement δ of the outer flow field)

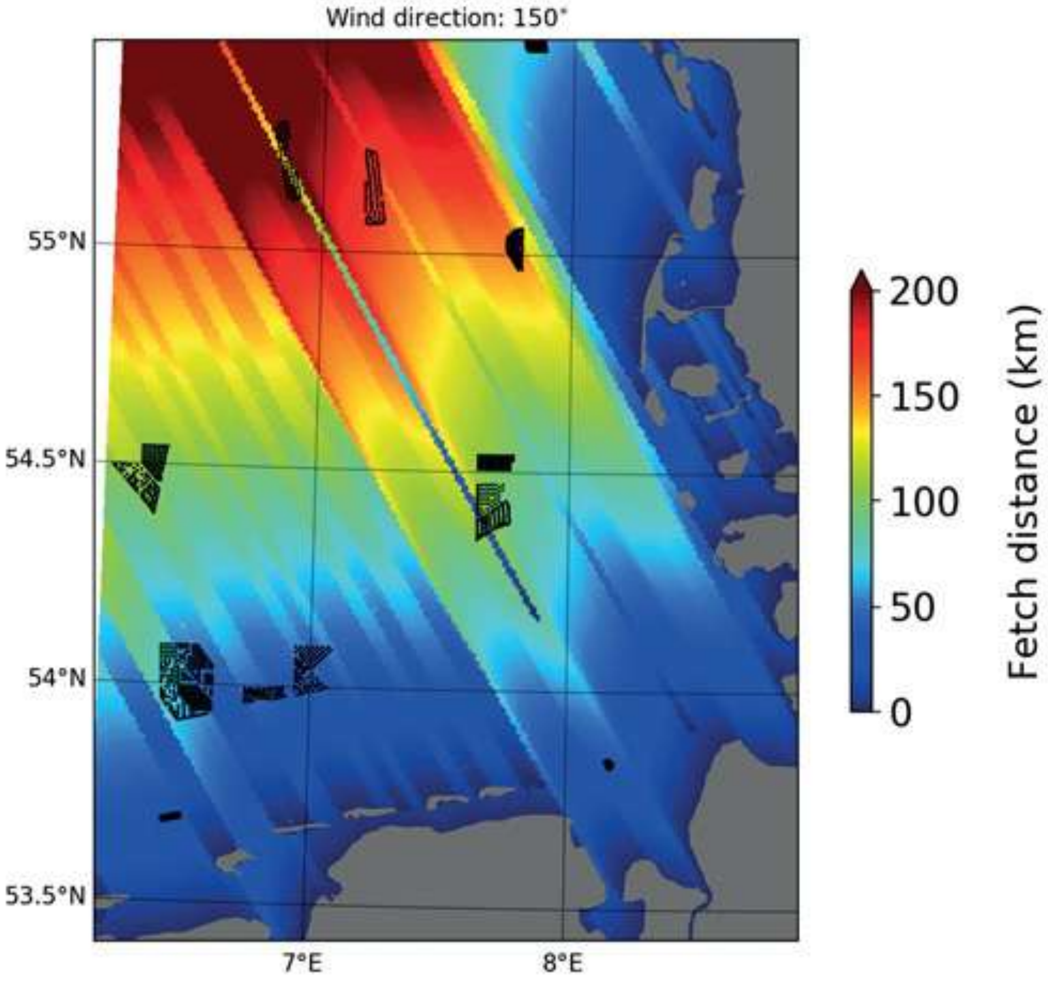
Internal boundary layer: Region where the velocity and turbulent stress are significantly affected by the change in surface conditions

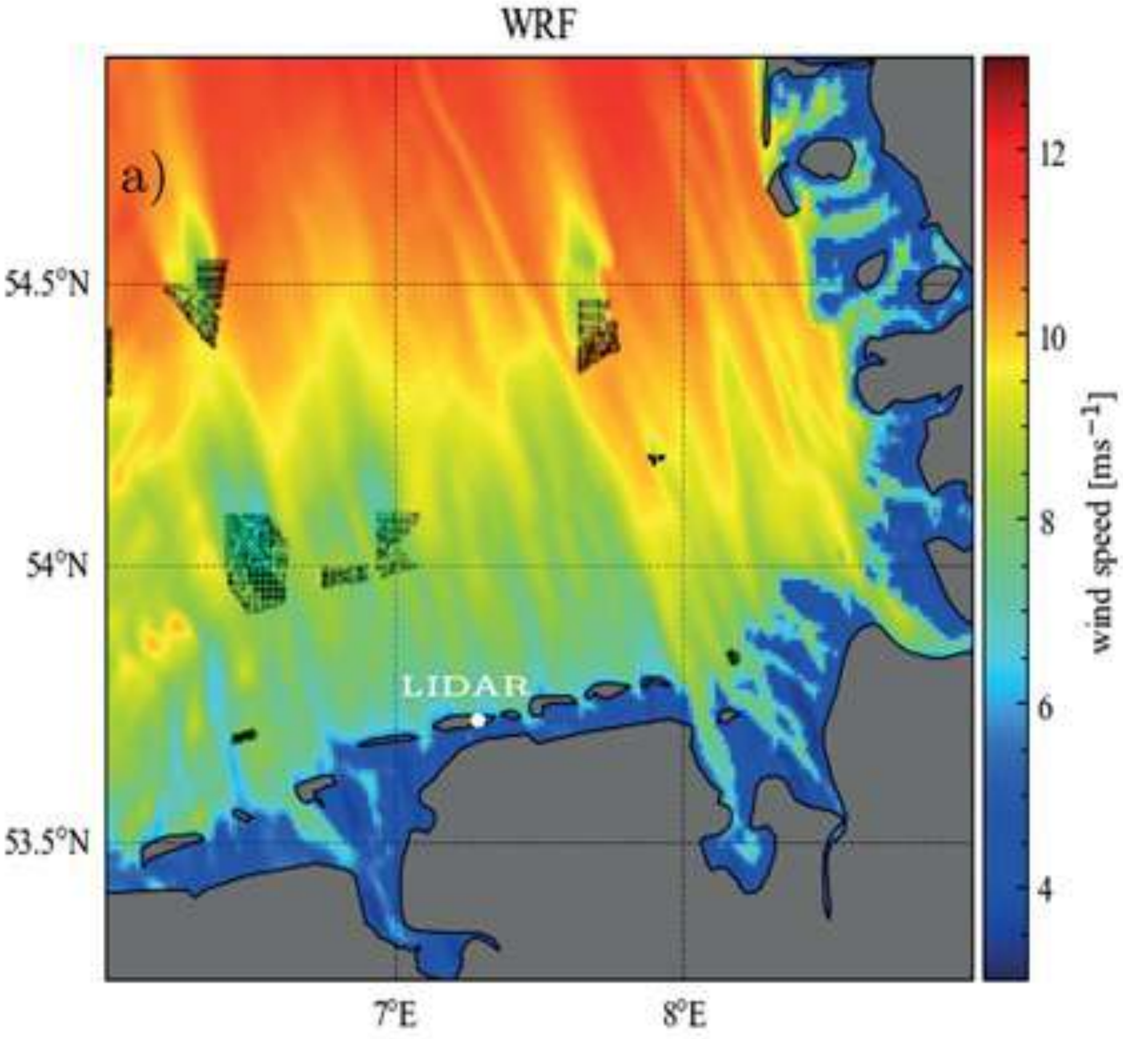
Equilibrium layer: Wind profile has completely adjusted to the local surface conditions

$$\frac{h_{ibl}(x)}{z_{0,2}} \sim \left(\frac{x}{z_{0,2}}\right)^{0.8}$$

Source: Garratt (1990)

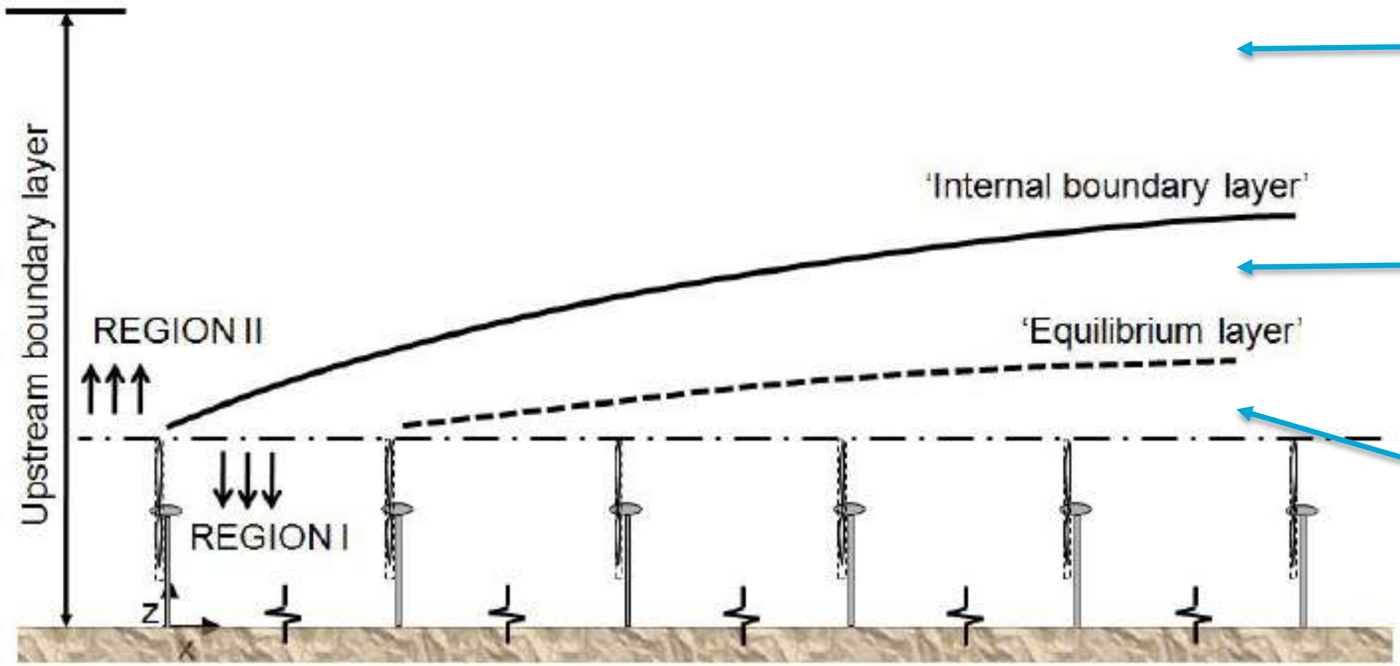
IBL example: Coastal effects





Source: Schulz-StellenFleth et al. (2022)

Wind-farm internal boundary layer



"Free stream": Air flow is not (yet) affected by the wind farm

Internal boundary layer: Wind slows down and turbulent stress increases

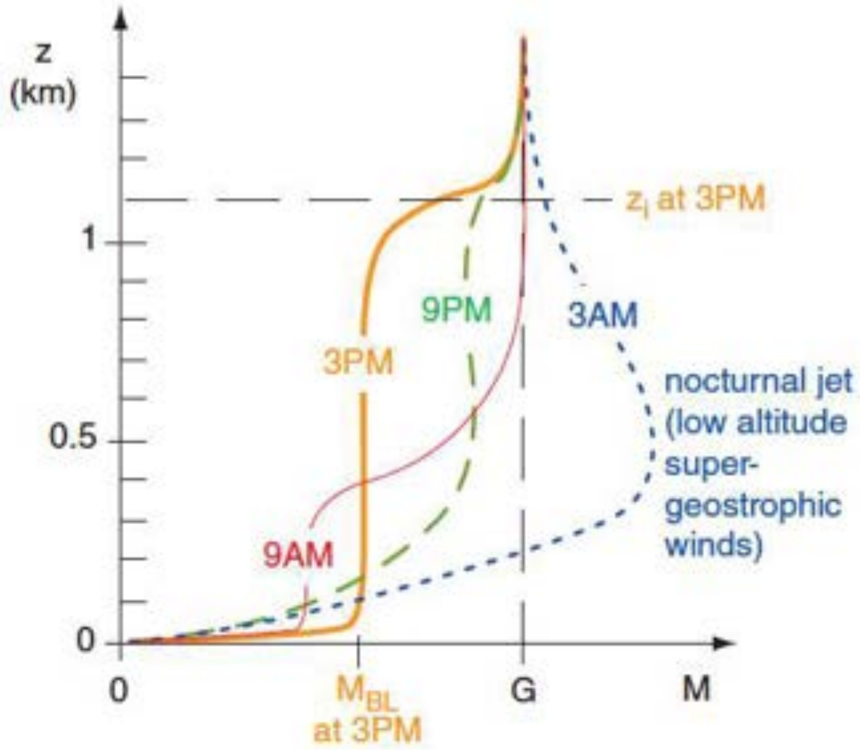
Equilibrium layer: Fully developed wind-farm flow regime

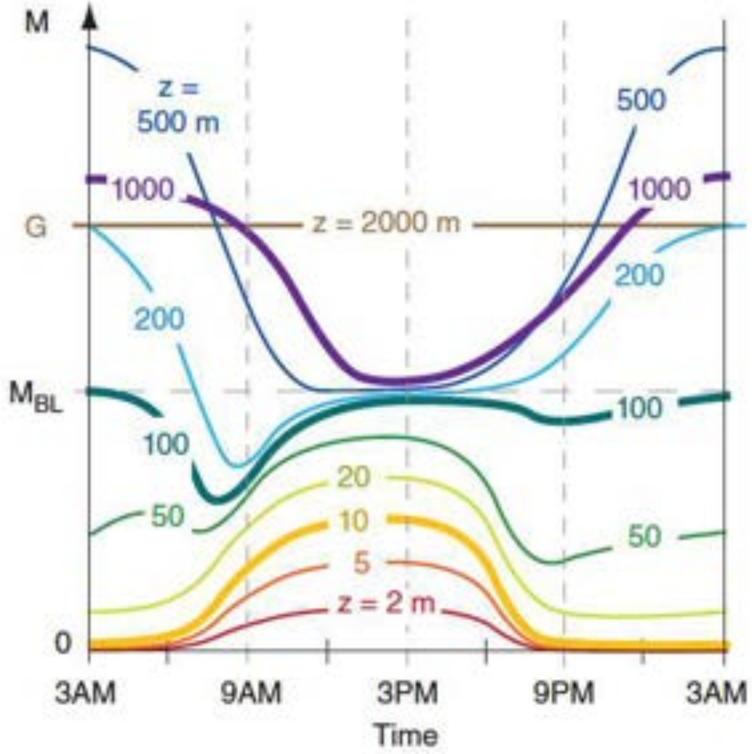
From a large-scale perspective, a wind farm can be treated as a special case of roughness transition.

Source: Chamorro and Porté-Agel (2011)

Low-level jet

= supergeostrophic wind speed at low altitudes, occurs often at night over land





Source: Stull (2016)

Low-level jet

The Blackadar (1957) model
Starting from dynamic Ekman layer equations

$$\frac{\partial U}{\partial t} = f_c V + \frac{\partial \tau_{xz}}{\partial z}$$

$$\frac{\partial V}{\partial t} = f_c (G - U) + \frac{\partial \tau_{yz}}{\partial z}$$

Friction disappears at sunset

$$\frac{\partial^2 U}{\partial t^2} = f_c^2 (G - U)$$

$$U = G + V_0 \sin(f_c t) + (U_0 - G)\cos(f_c t)$$

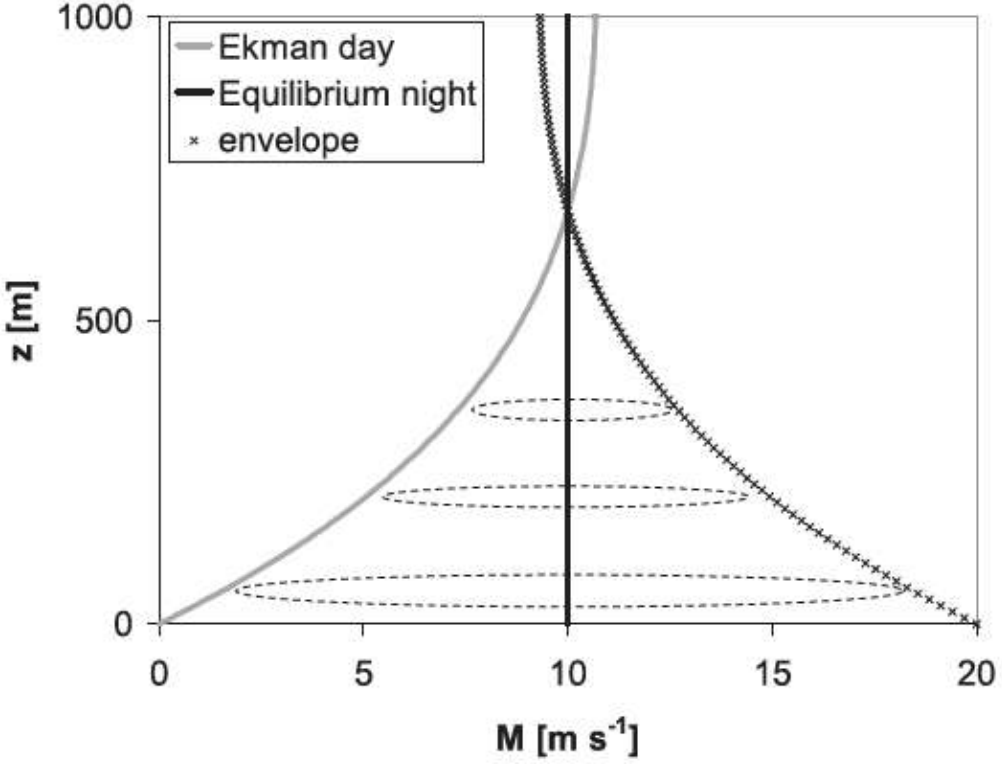
$$V = V_0 \cos(f_c t) - (U_0 - G)\sin(f_c t)$$

Undamped inertial oscillation about the geostrophic wind with period $2\pi / f_c$

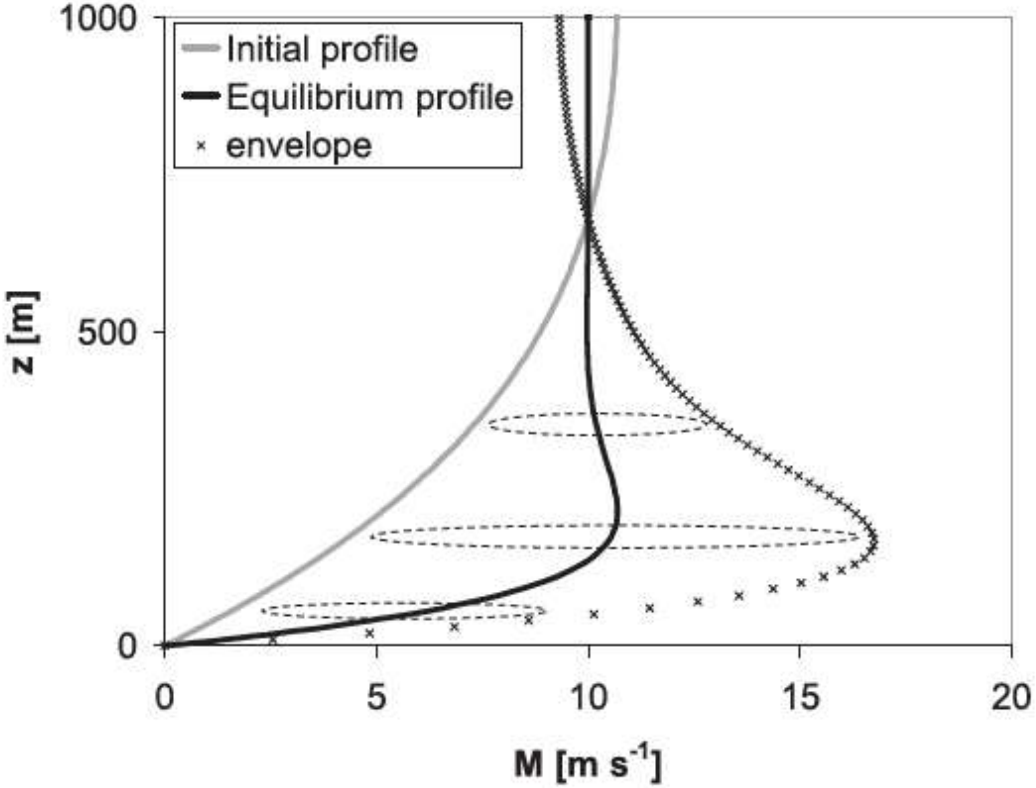
e.g. $f_c = 10^{-4} s^{-1}$ yields an inertial period of about 17h

Low-level jet

Blackadar (1957) model



More realistic model



Source: van de Wiel et al. (2010)

Flow over a hill

Flow regimes:

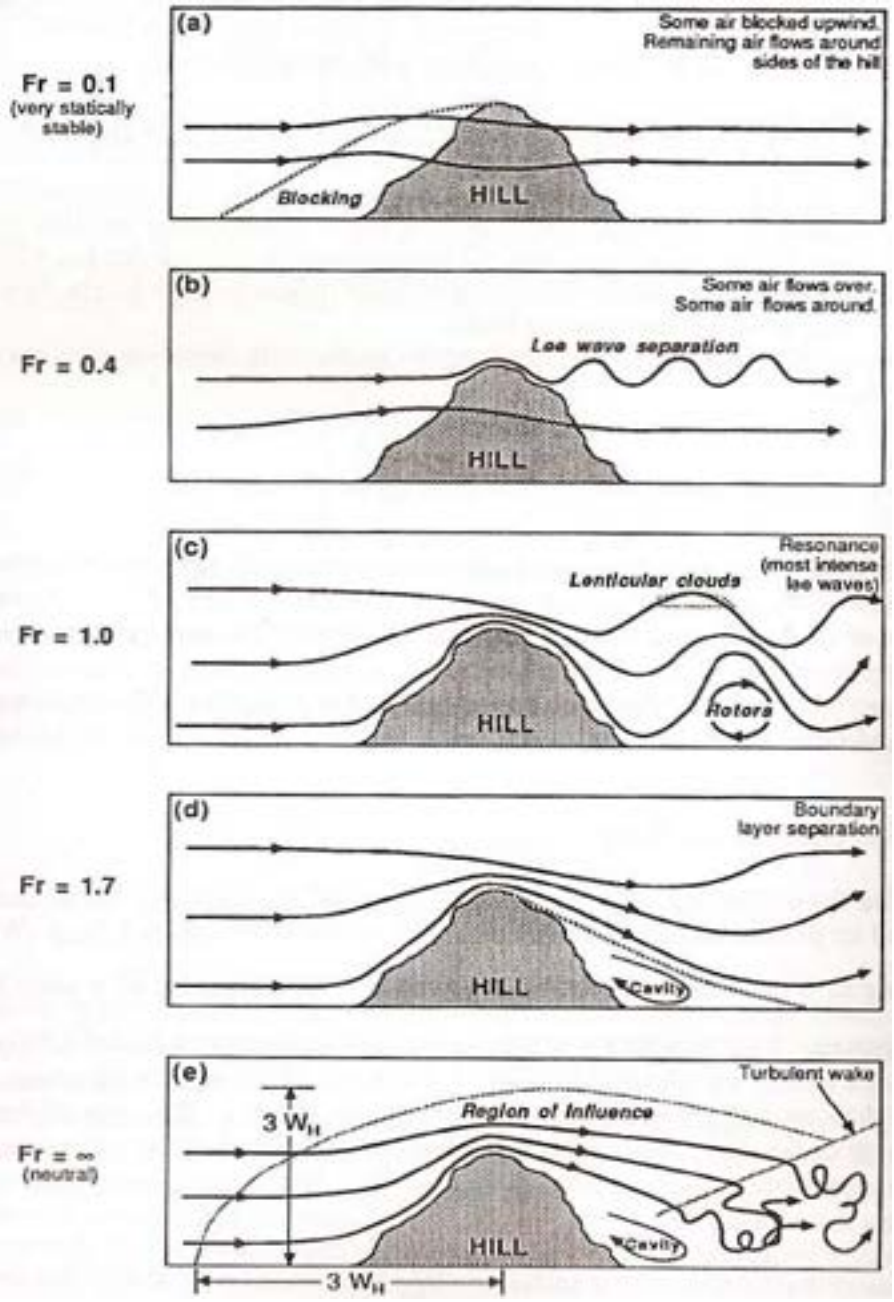
- Fr<< 1, blockage upstream, flow goes round rather than above mountain
- Fr ~ 1, wave resonance above ridge, strong downslope winds, and turbulent rotors in the lee
- Fr >> 1 , neutral flow, little blockage, flow goes above ridge, separated cavity type flow in the lee

Froude number

$$Fr = \frac{U}{N\,W}$$

Brunt Väisälä frequency

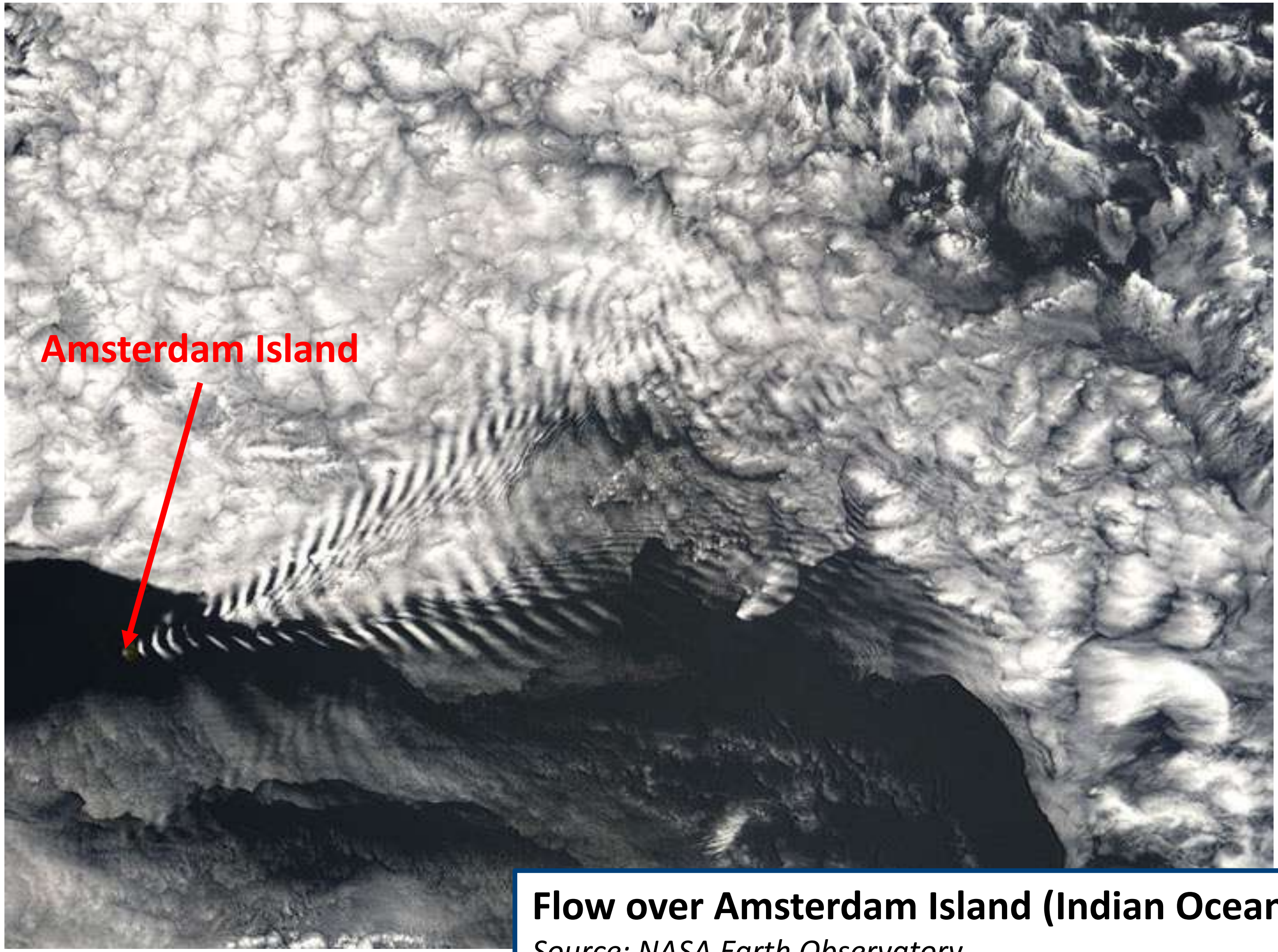
$$N = \sqrt{\frac{g}{\theta_0}\frac{\partial \theta}{\partial z}}$$



Increasing stability

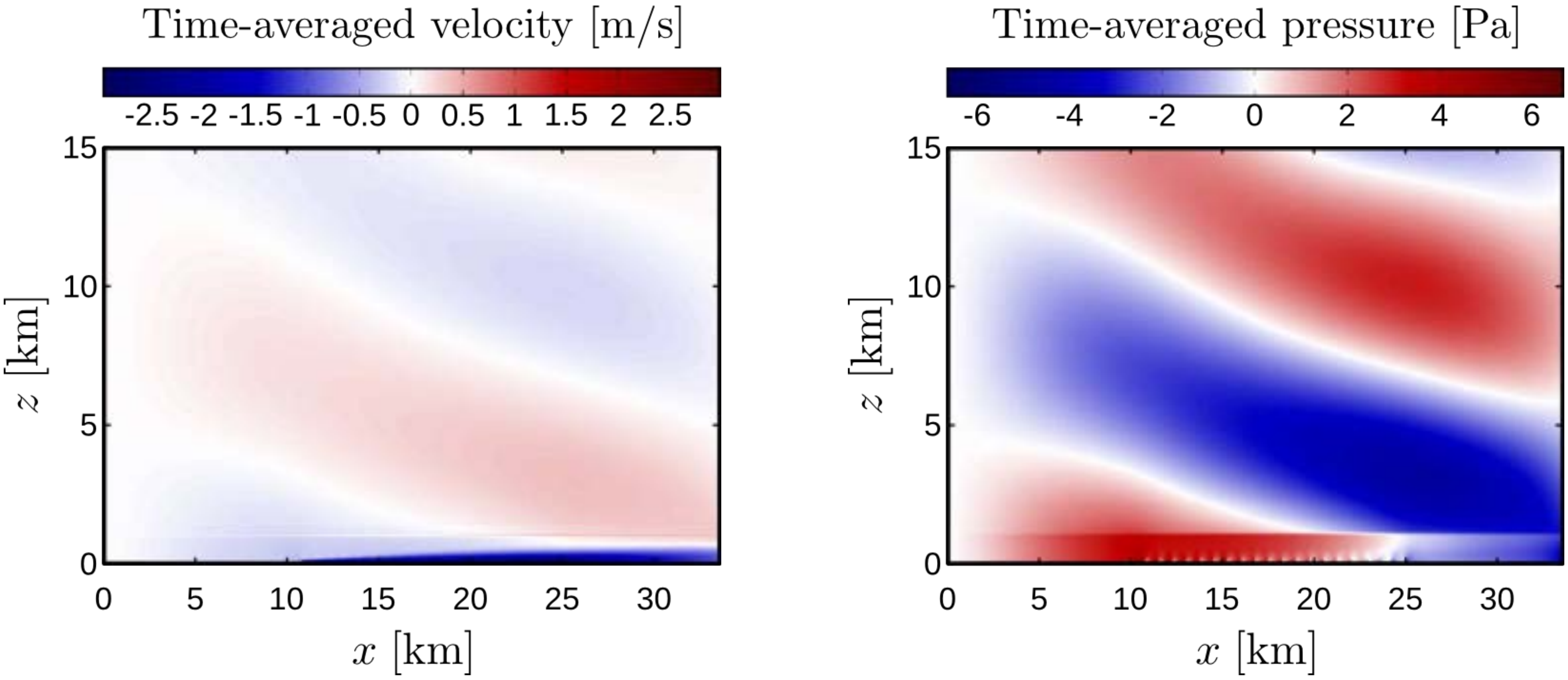
Source: Stull (1988)

Atmospheric gravity waves



Flow over Amsterdam Island (Indian Ocean)
Source: NASA Earth Observatory

Wind-farm-induced atmospheric gravity waves



Source: Allaerts (2016)

Outline

TU Delft

The importance of meteorological aspects

How much energy will my wind farm produce in 20+ years (business plan)?

How should I design the turbine to avoid failure due wind loads?

- Mean wind speed
- Frequency distribution
- Wind rose

- Turbulence
- Shear
- Extremes

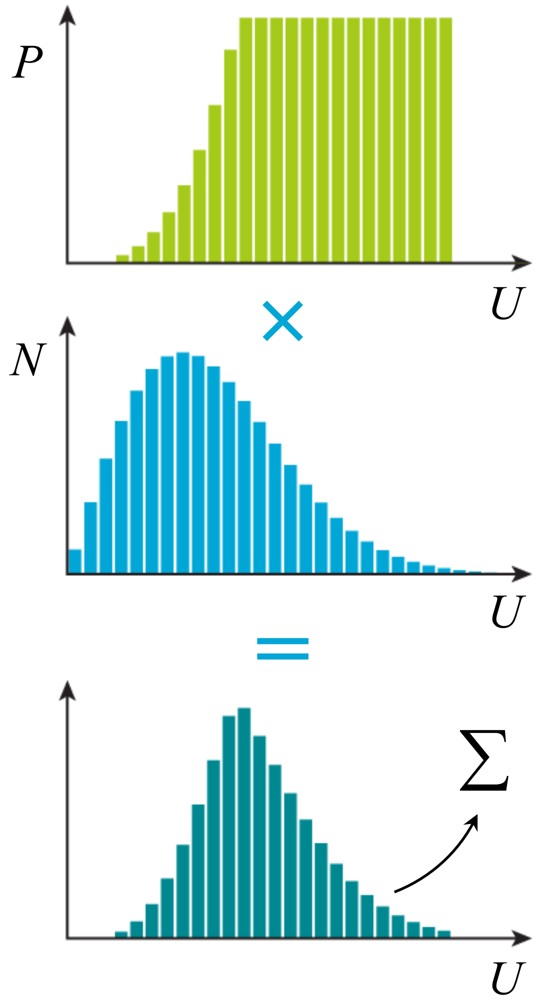
- Velocity deficit
- Thrust coefficient

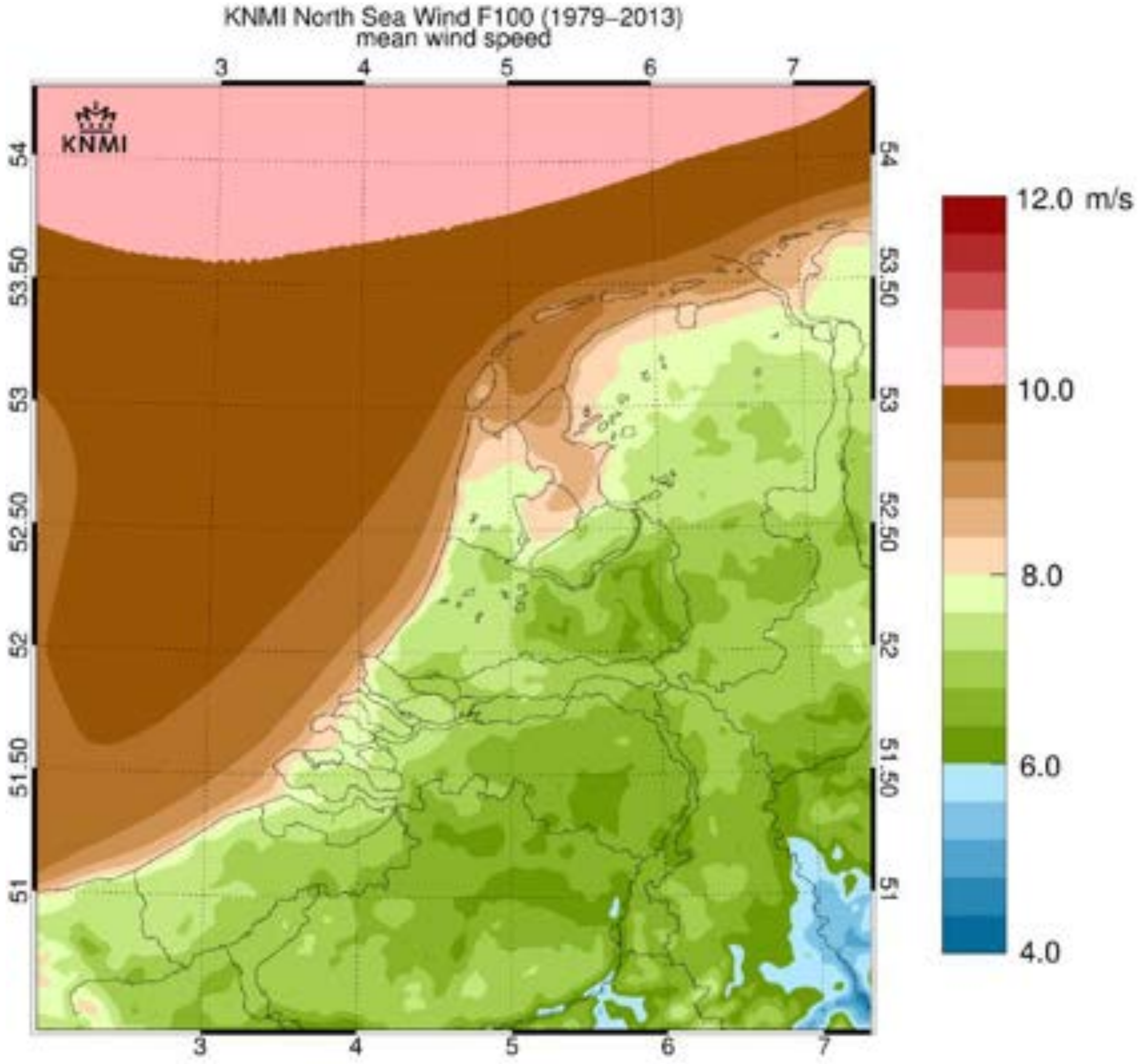
- Weather window
- Waves
- Decision system

- LiDAR
- Wind turbine interaction
- Control system

Why wind power meteorology?

– *Energy production*





KNMI North Sea Wind Atlas

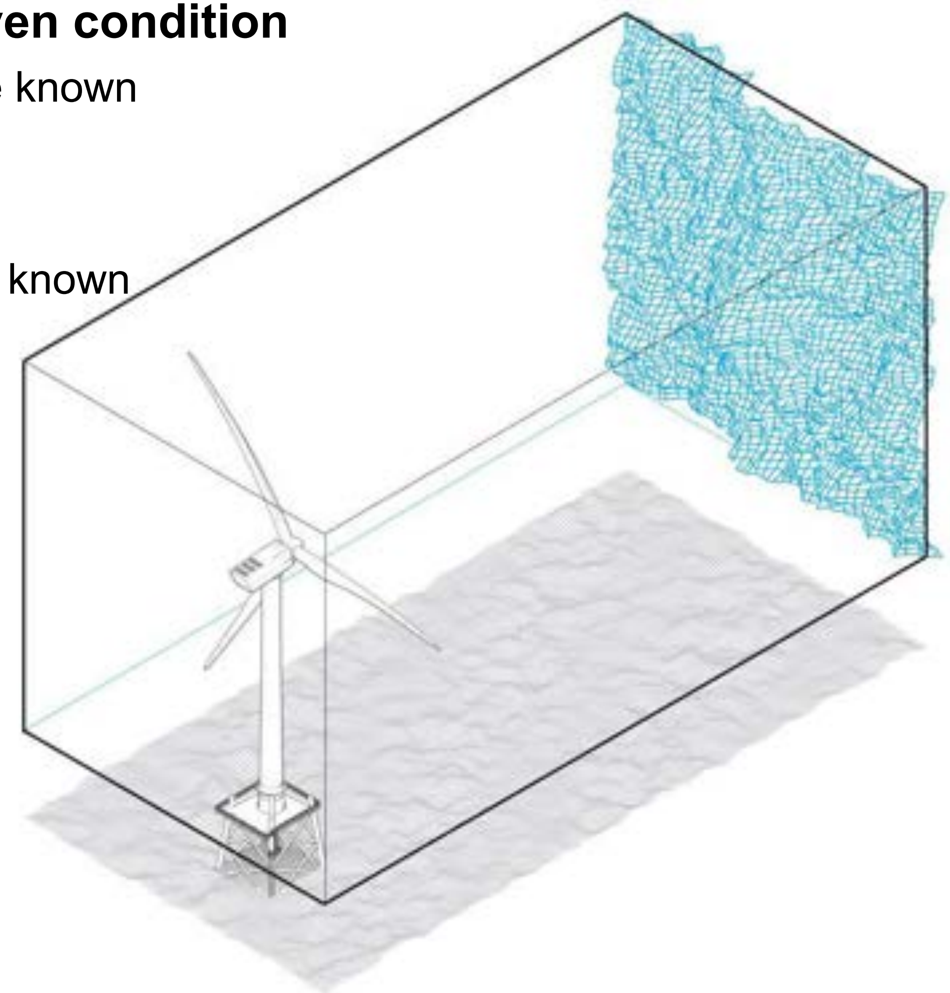
Why wind power meteorology?
– *Design*

Generate turbulent wind field / random sea for given condition

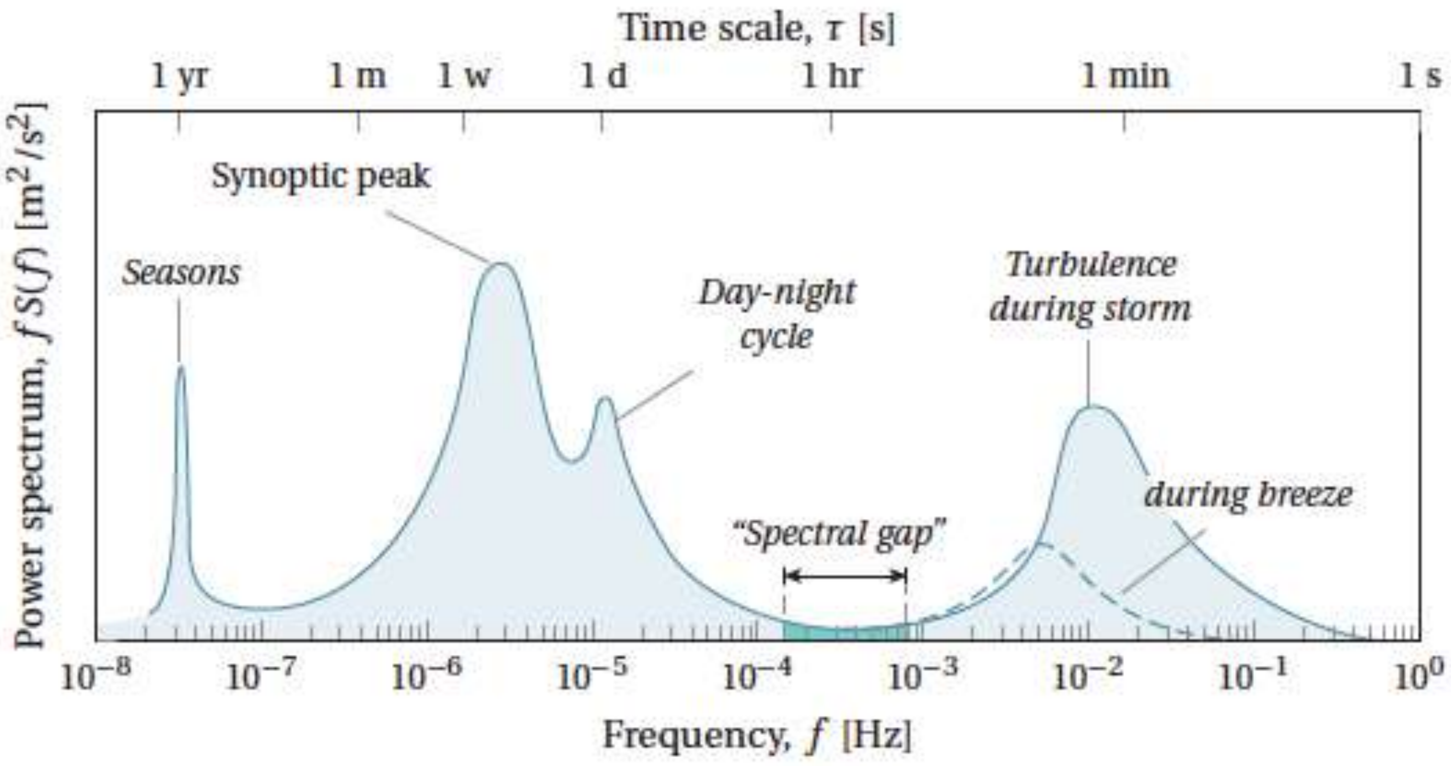
- Short-term characteristics of wind and waves have to be known

How often does a certain condition occur?

- Long-term characteristics of wind and waves have to be known



Temporal variability of wind



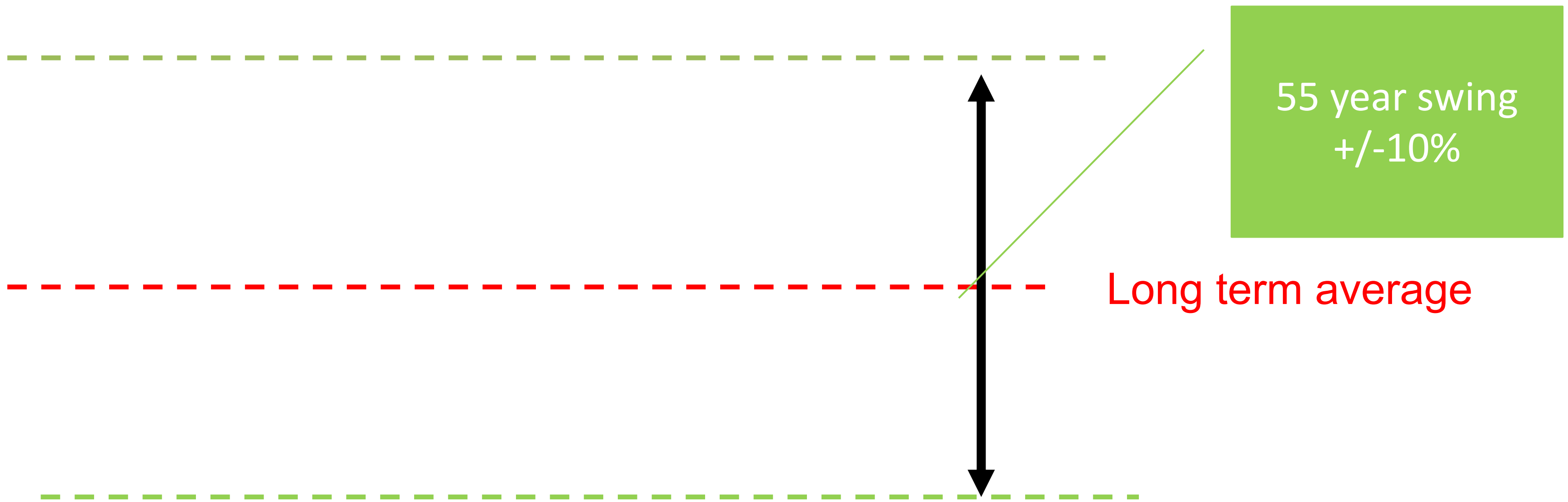
van der Hoven spectrum (1957)

Categories of wind speed variations:

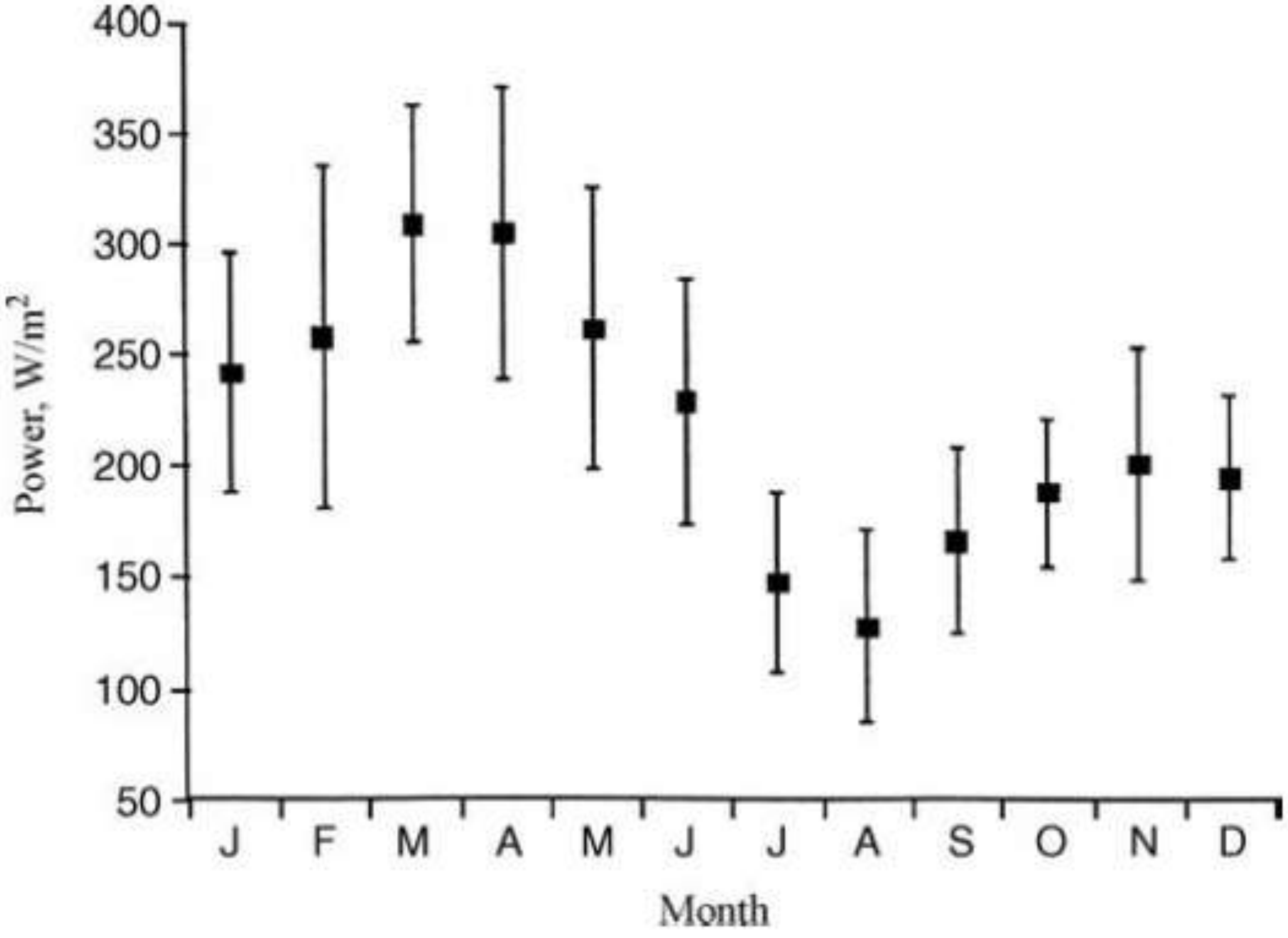
- Inter-annual
- Annual (seasonal/monthly)
- Diurnal
- Short term (gusts and turbulence)

Figure source: Bos (2017)

Inter-annual variability (UK Example)

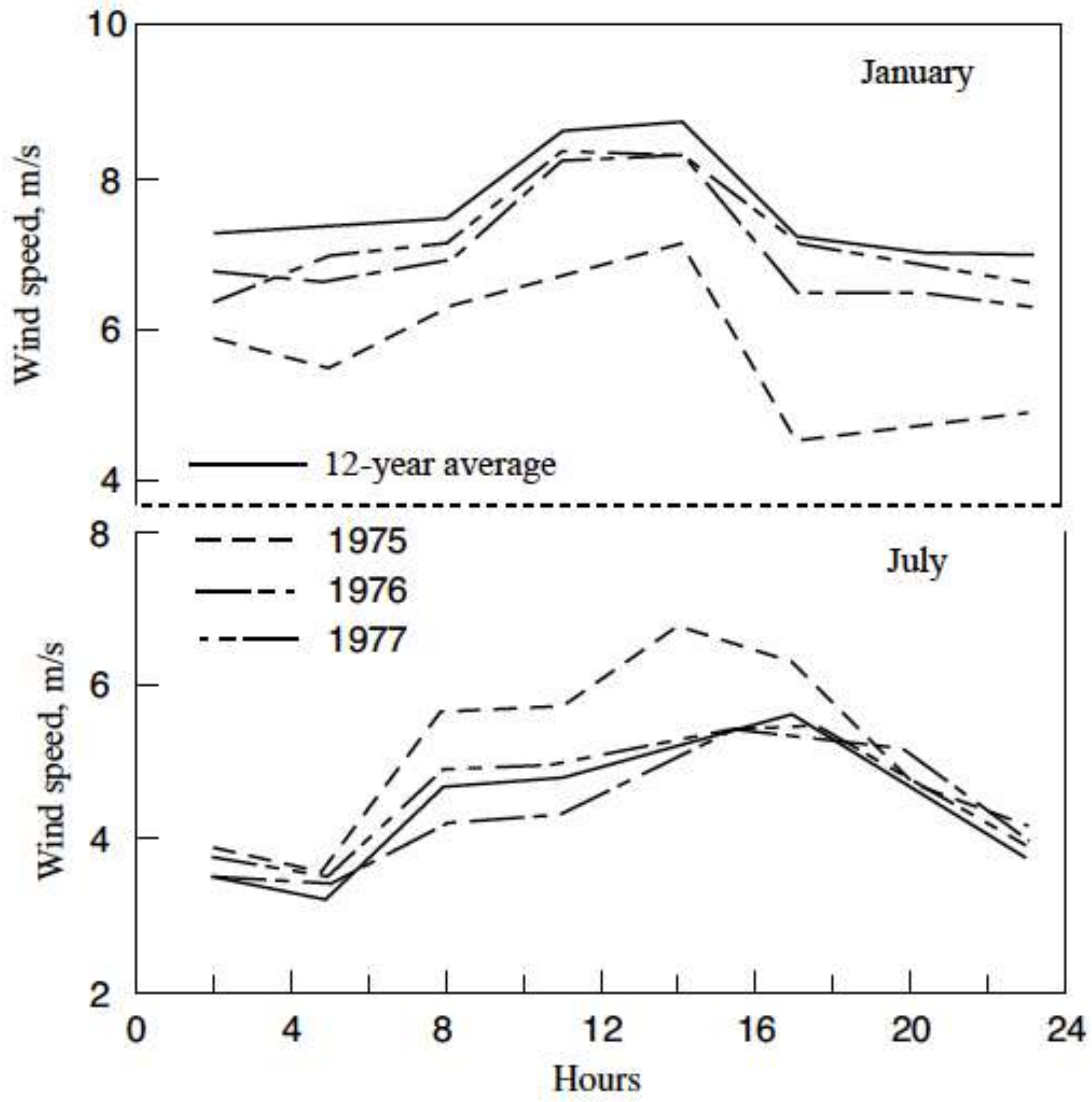


Annual variability (Amarillo, Texas)



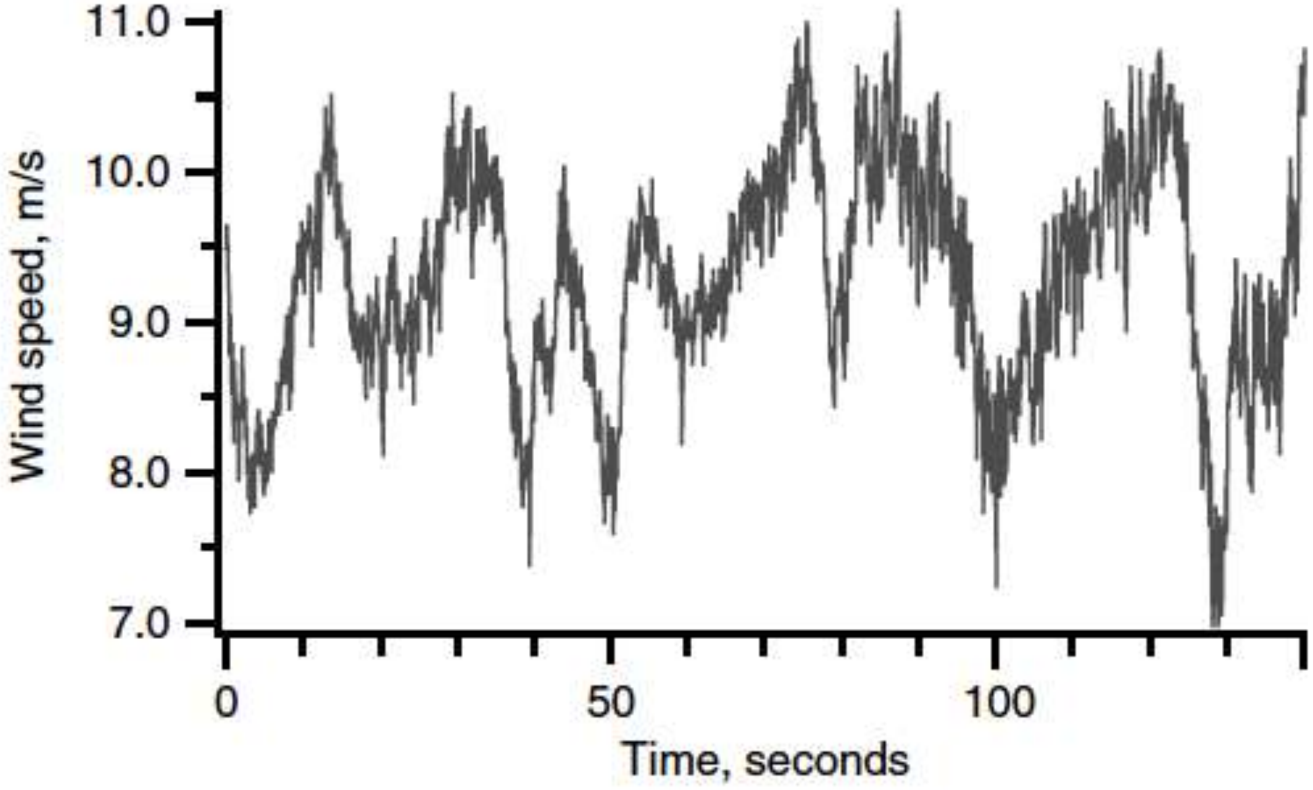
Source: Manwell et al. (2009)

Diurnal variability (Casper, Wyoming)



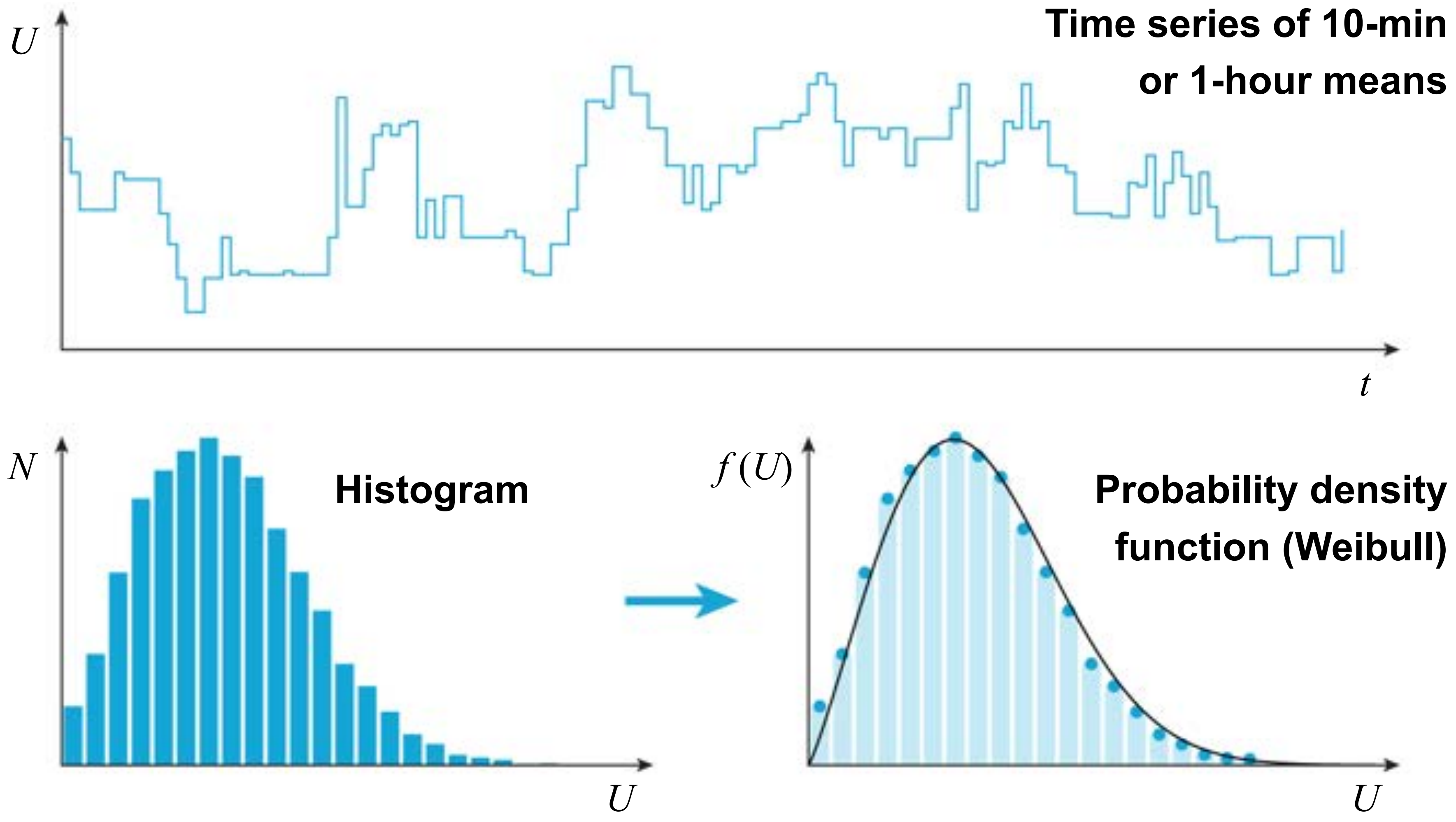
Source: Manwell et al. (2009)

Short-term variability

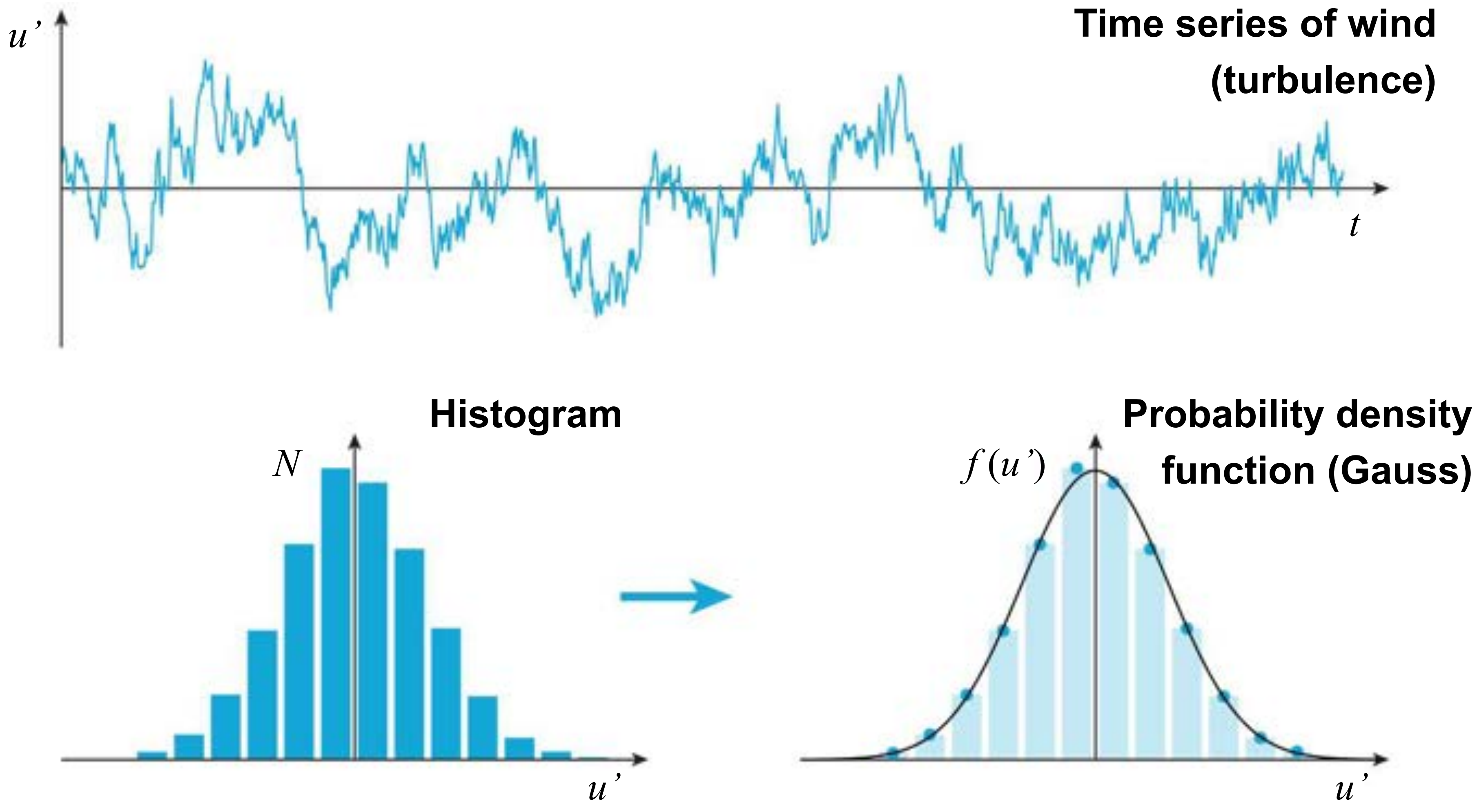


Source: Manwell et al. (2009)

Basic wind statistics
– Long-term variability

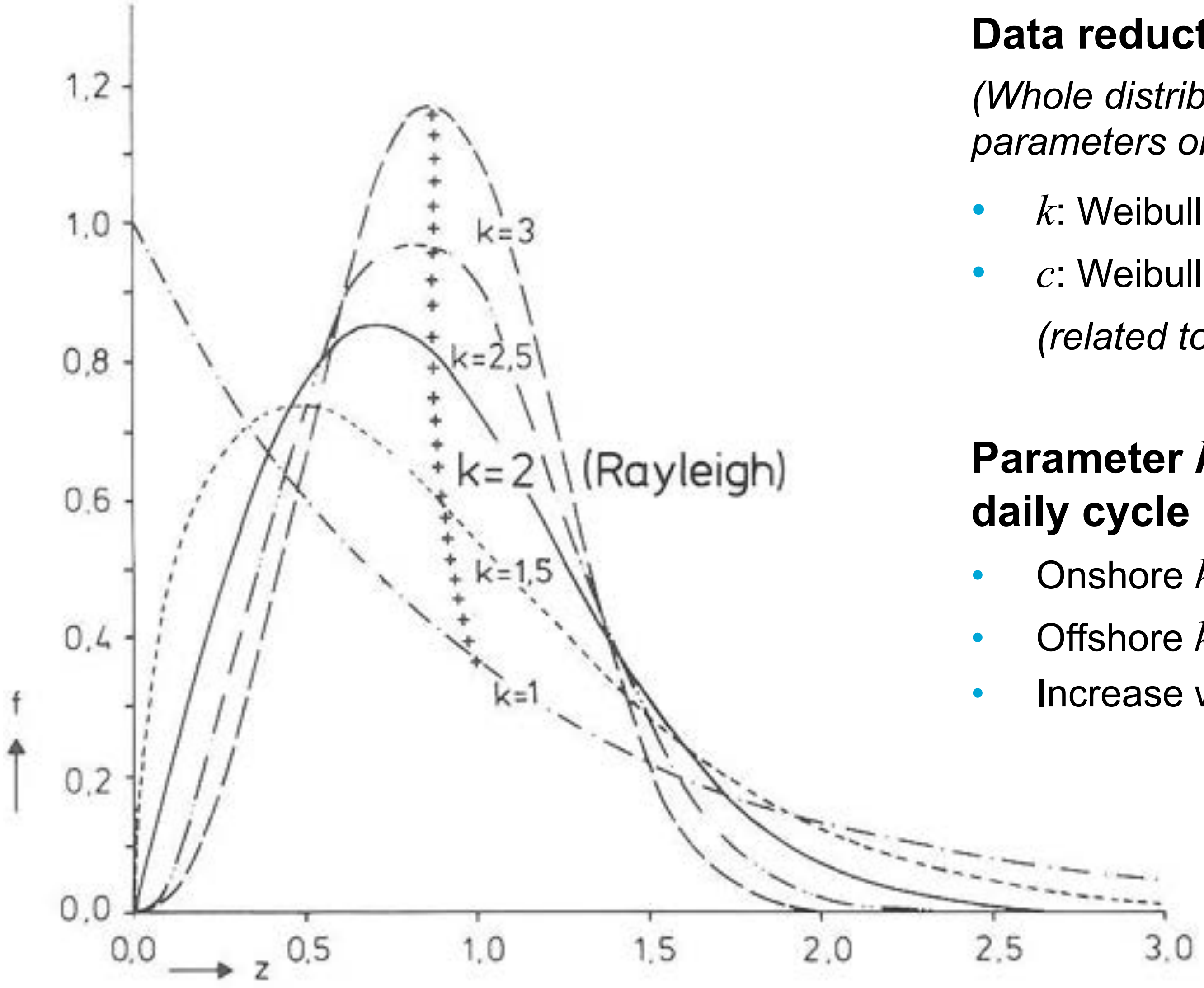


Basic wind statistics
– *Short-term variability*



Long-term wind statistics for wind resource assessment

Weibull distribution



Data reduction

(Whole distribution is given by 2 parameters only)

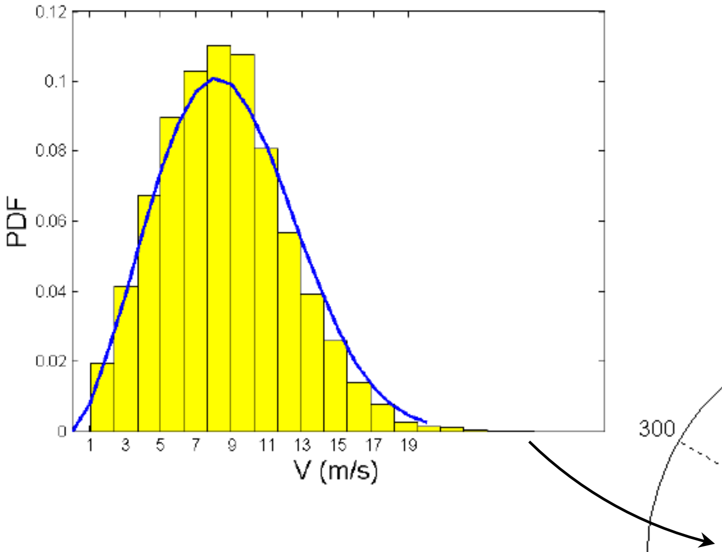
- k: Weibull shape parameter
- c: Weibull scale parameter

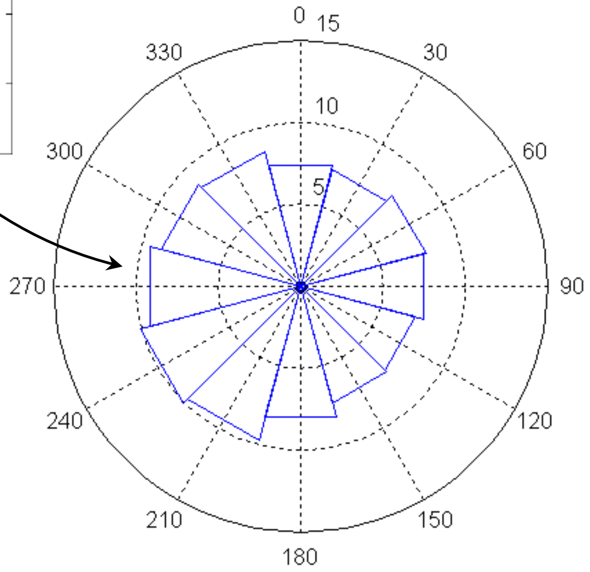
  (related to U_{mean})

Parameter k depends on daily cycle

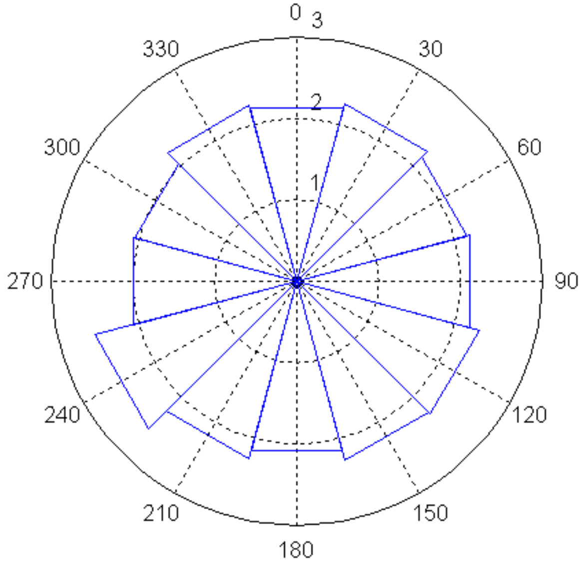
- Onshore $k \sim 1.8$
- Offshore $k \sim 2.2$
- Increase with height

Weibull distribution
– *Fit for each wind direction sector*



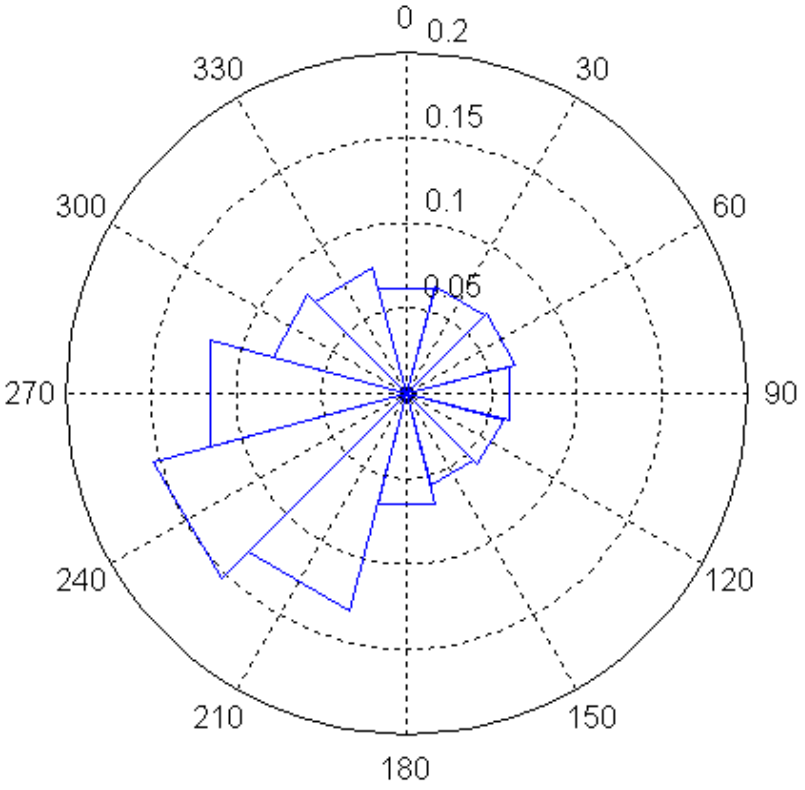


Weibull scale parameter (c)



Weibull shape parameter (k)

Weibull distribution
– *Wind rose*



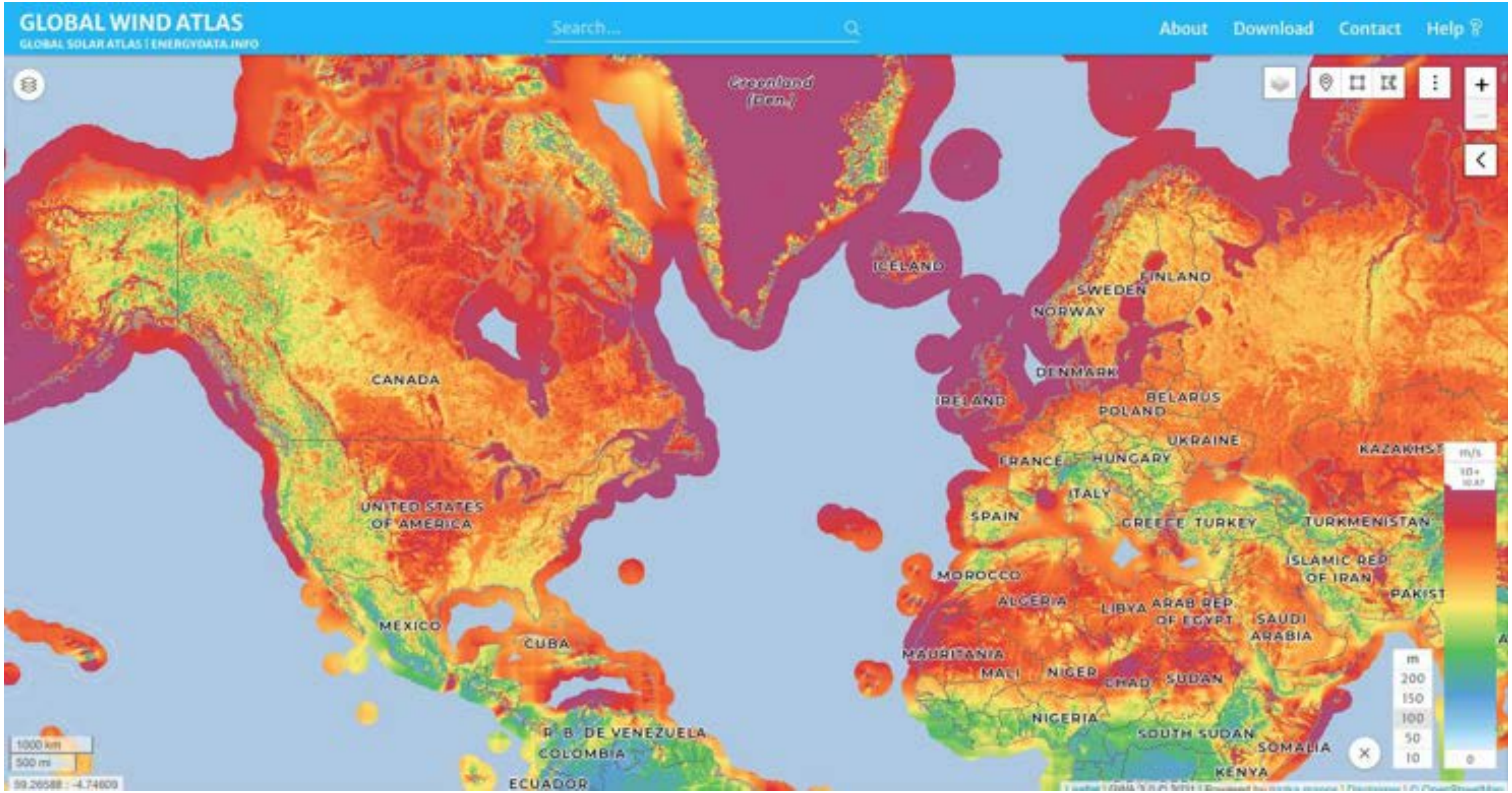
Frequency of occurrences

How to obtain wind statistics for a given location?

Two basic options

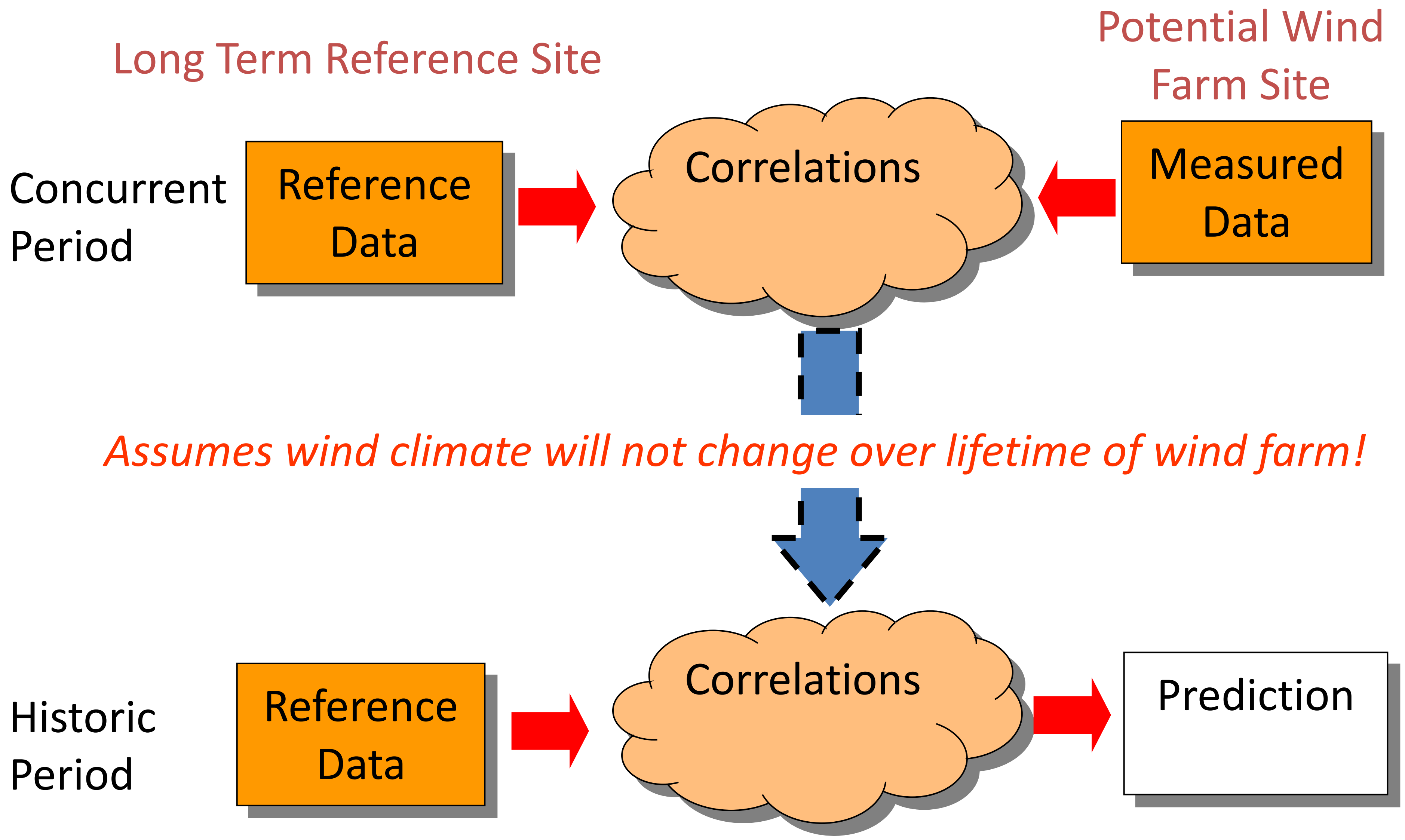
	Use existing data from other site	Perform local measurements
Problem	Other site not representative	Not possible to measure long enough to obtain long term statistics
Solution	Use of correction methods (terrain, obstacles)	Correlate with other site which has reliable long term statistics
	Windatlas correction methods (e.g. WA!P)	**"Measure Correlate Predict"**

Long term wind statistics: Wind atlas



Source: https://globalwindatlas.info/

Measure-Correlate-Predict



Reanalysis projects

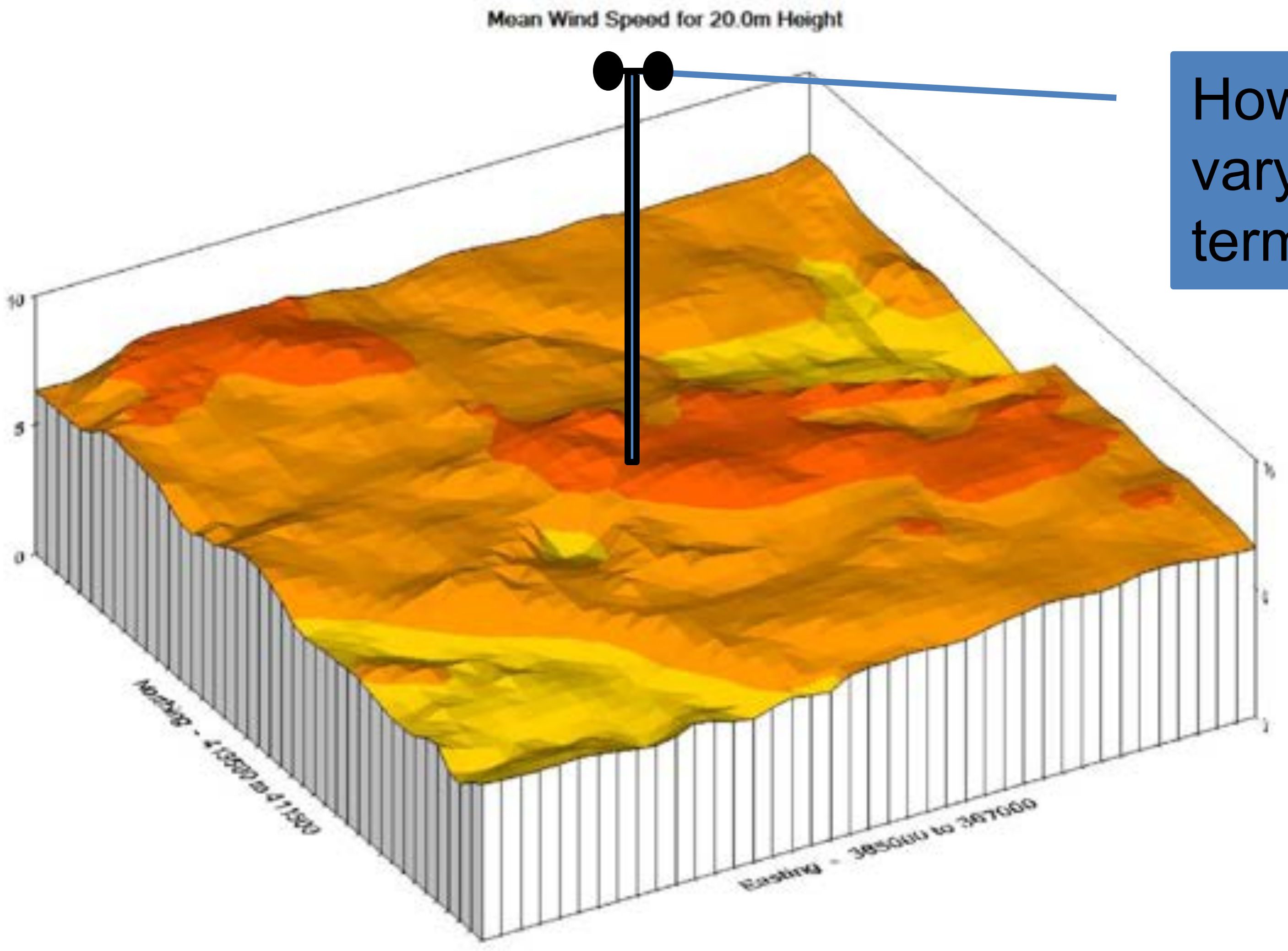
By (inter)national centers: NCEP/NCAR, ECMWF

- Collection of all kind of data (*weather stations, radiosondes, aircraft, ships, buoys, ...*); not restricted to routine weather forecast
- One (state-of-the-art) method; avoid apparant jumps in weather due to other NWP model

  ↓

- Homogeneous data sets covering a long period (from 1899!) and global scale; suitable for climate studies
- Resolution 2.5° to 5° (100–200 km); 6 or 12 hourly
- Can provide initial and boundary conditions meso scale models
- MERRA, ERA Interim, ….

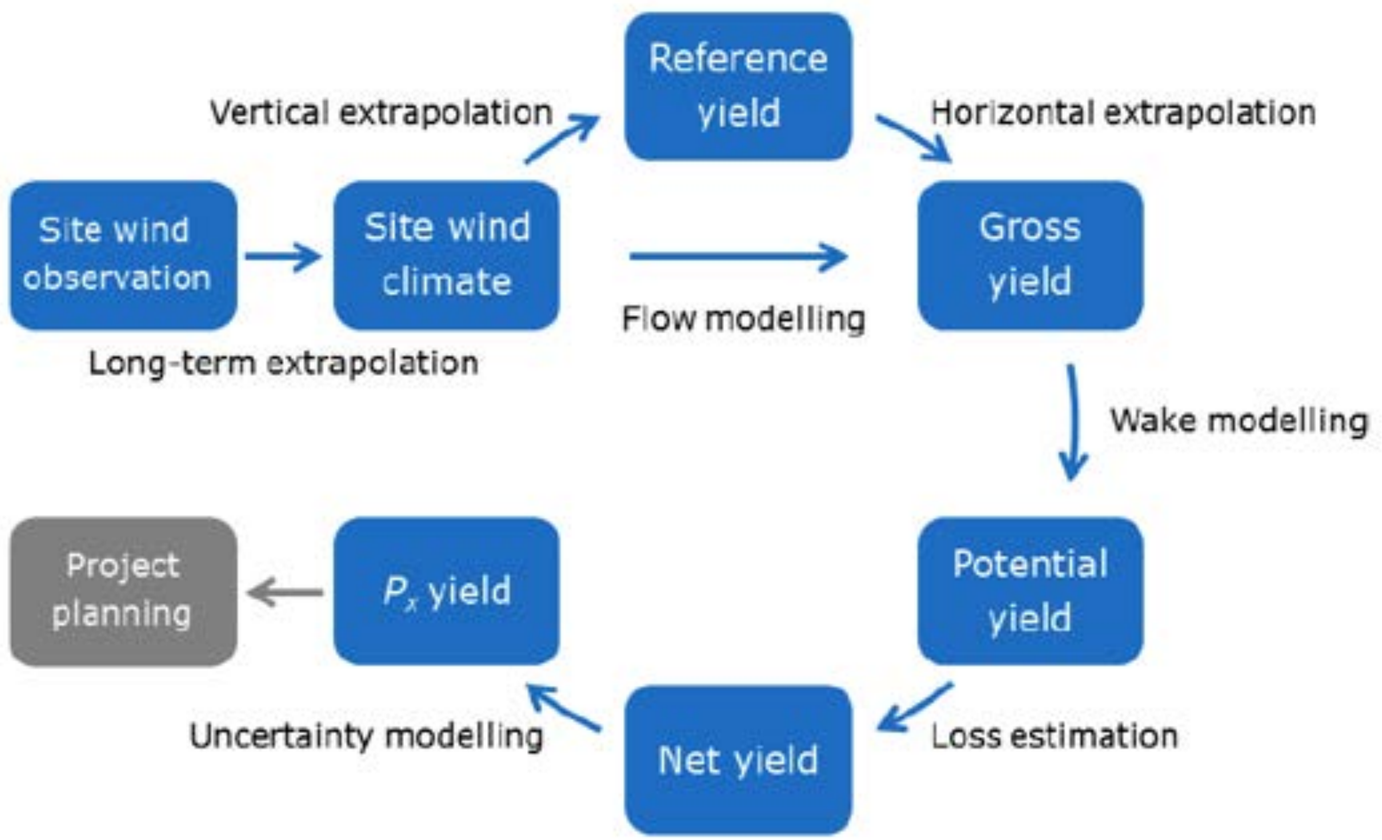
We Have a Long Term Wind Distribution: Now What?



How does wind speed vary around the long-term reference point?

m/s

Steps in wind resource and energy yield assessment procedure



Vertical extrapolation
- Logarithmic profile
- Power law
- More sophisticated?

Horizontal extrapolation
- Mass-consistent models
- Linearised models
- CFD models

Source: Mortensen et al. (2015)

Questions?

Take-home messages

- Atmospheric science is fun and very relevant to wind energy
- The wind resource is a complex phenomenon covering a wide range of temporal and spatial scales
- There is more to the atmospheric boundary layer than just the logarithmic wind profile and the Weibull distribution
- If you want to learn more, read one of the books under reference material

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