



EIFER

EUROPÄISCHES INSTITUT FÜR ENERGIEFORSCHUNG
INSTITUT EUROPEEN DE RECHERCHE SUR L'ENERGIE
EUROPEAN INSTITUTE FOR ENERGY RESEARCH

Wind

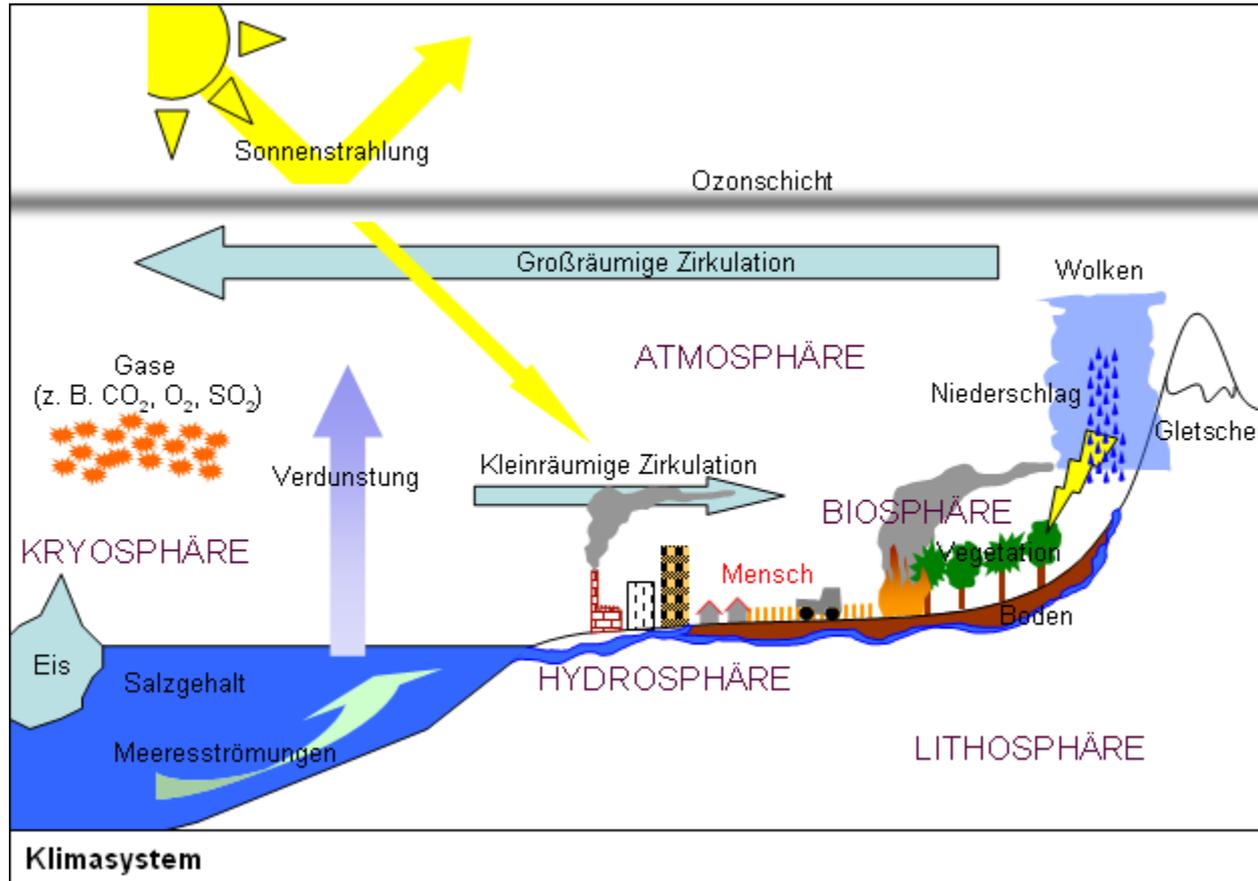
KIT

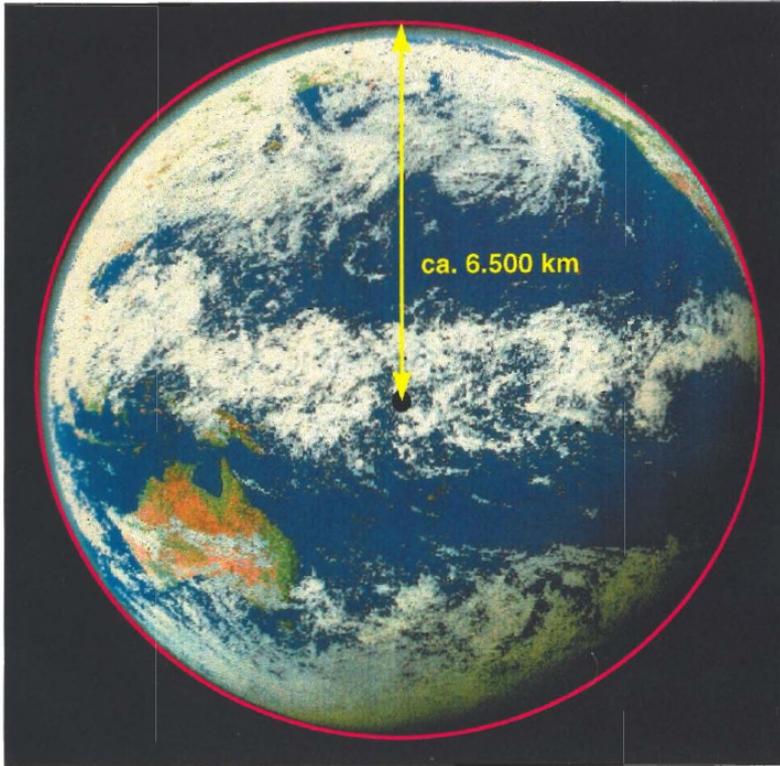


- Definitionen
- Atmosphäre
- Globales Windsystem
- Lokale Windsysteme
- Höhenprofile
- Windmessung
- Windatlanten
- Simulationen
- Geschwindigkeiten

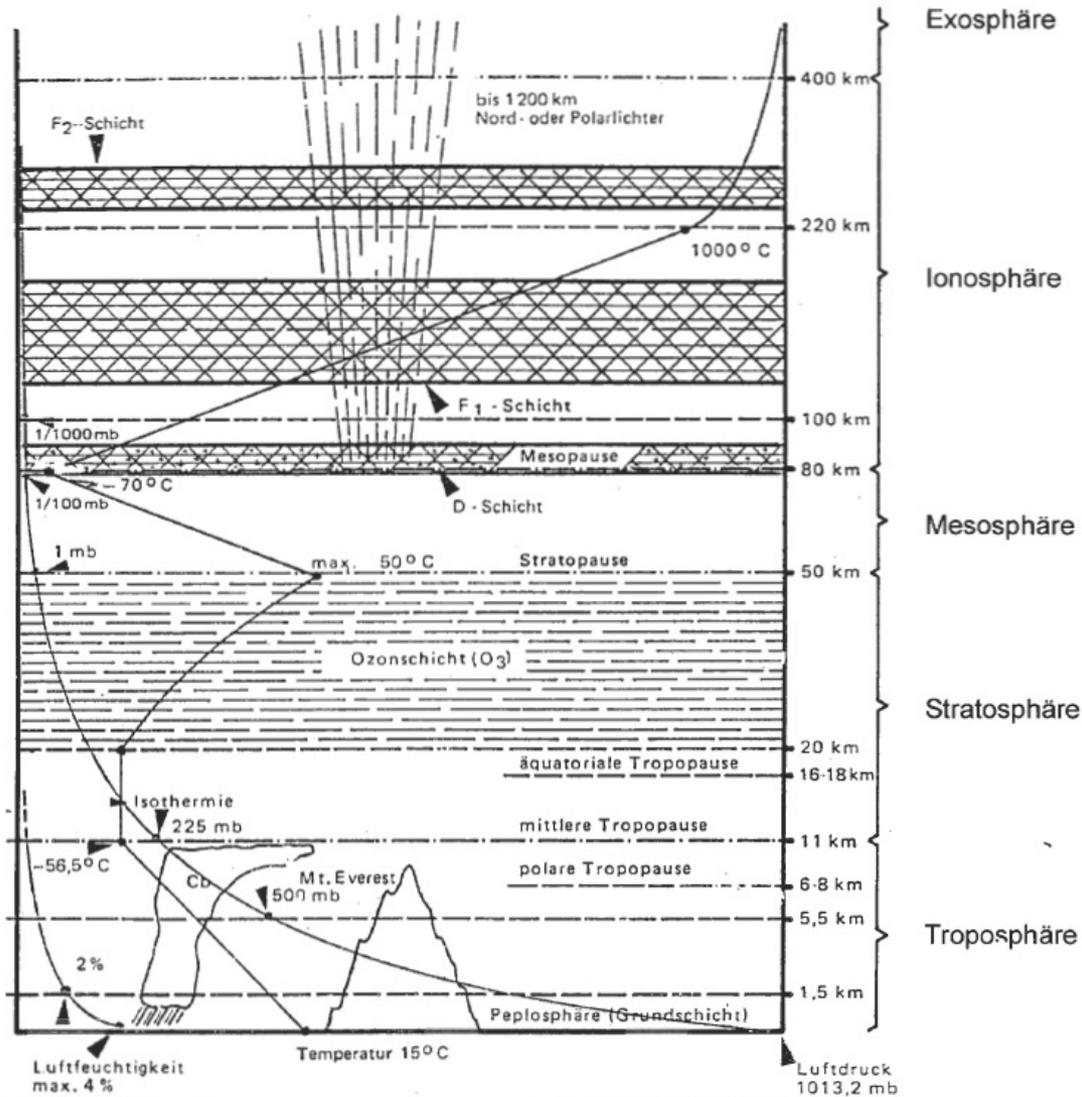
- **Wetter**
 - Momentaner Zustand der Atmosphäre (1h-1d)
- *Witterung*
 - Charakter des Wetter über mittleren Zeitraum (Woche/Jahreszeit)
- **Klima**
 - Mittlerer Zustand der Atmosphäre über längeren Zeitraum (10a+)

- Makroklima (Großklima)
 - Klimaregionen der Erde
- Mesoklima (Regional-/Lokalklima)
 - z.B. Mittelmeerraum,
 - z.B. Insel, großes Tal wie Rheinebene
- Mikroklima (Engräumiges Kleinklima)
 - Wald, Stadt, enges Tal

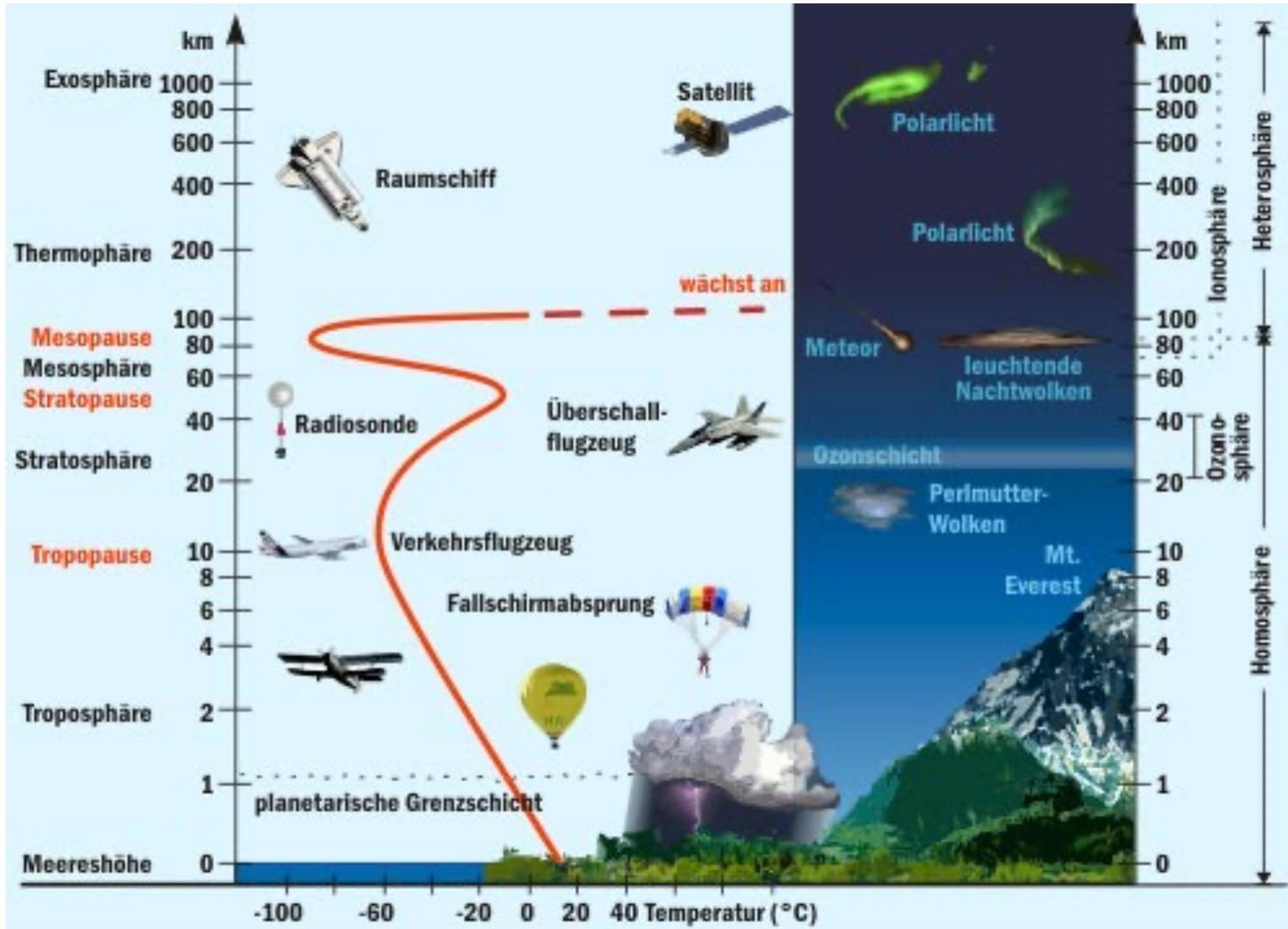




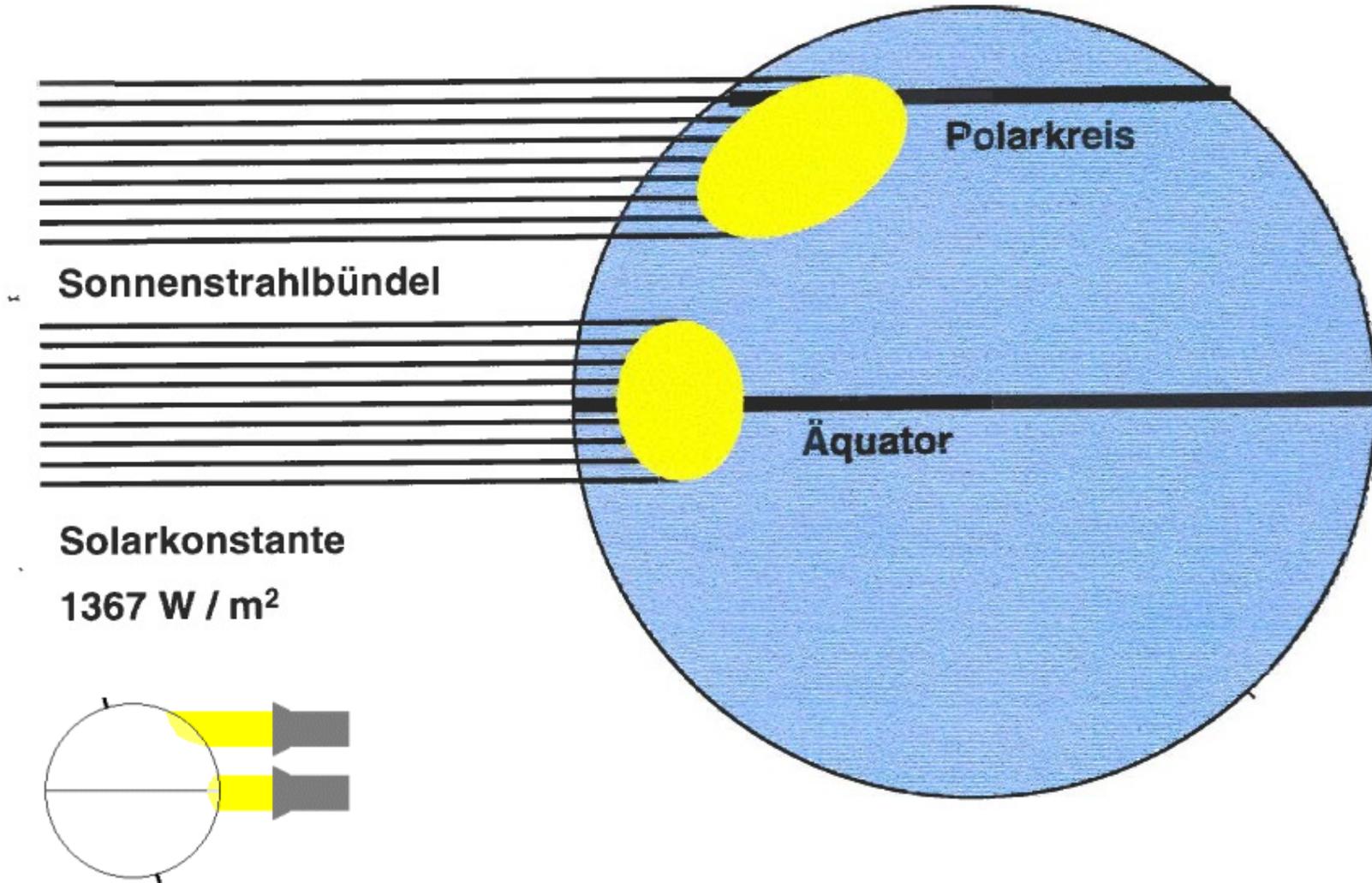
Die Schichten der Atmosphäre

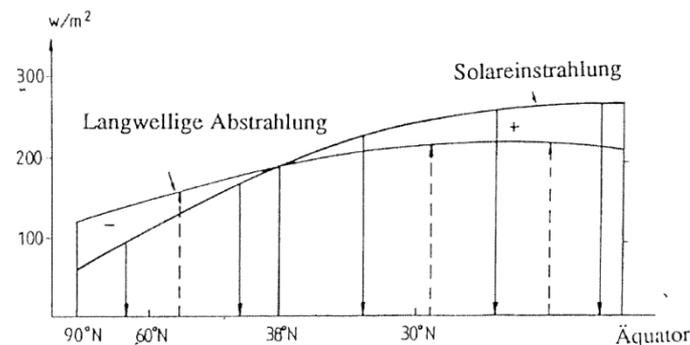
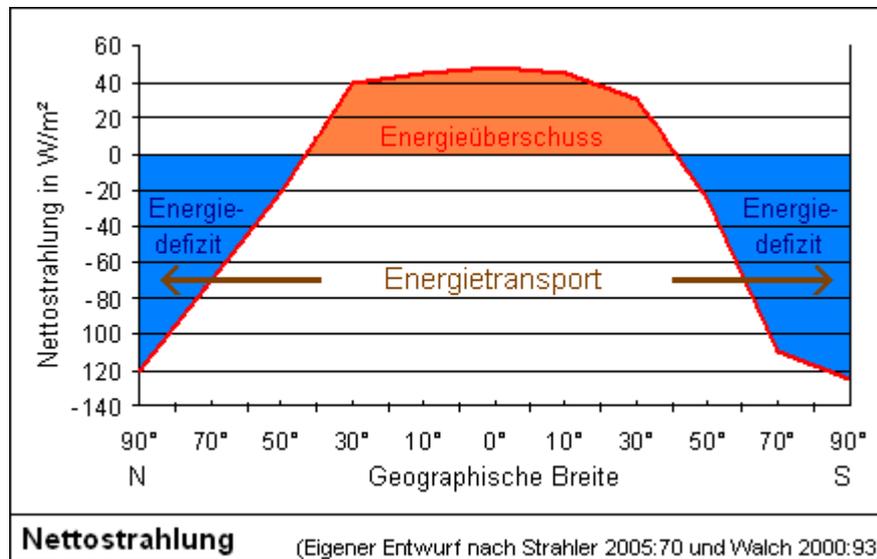
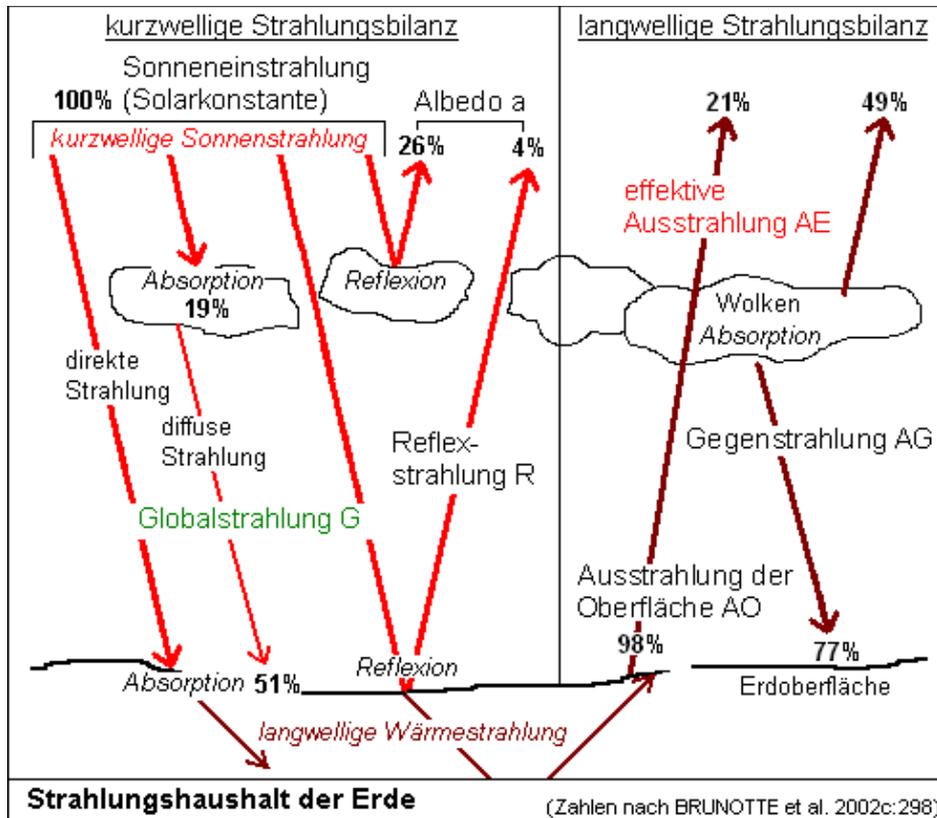


Die atmosphärische Schichtung



Unterschiedliche Einstrahlung

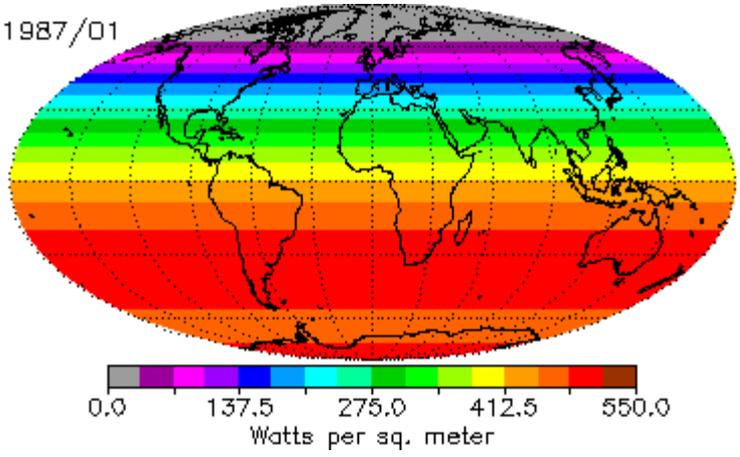




Strahlungsbilanz

Einstrahlung & Erwärmung

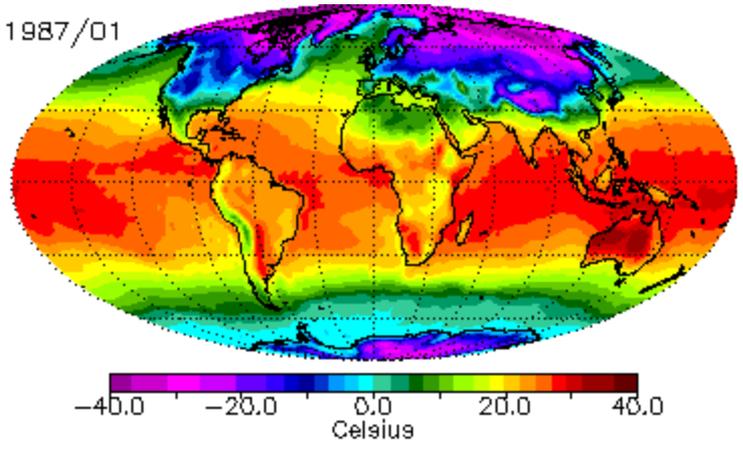
1987/01



Einstrahlung

Erwärmung

1987/01



Eigenschaften der Luft

Dichte der Luft bei verschiedenen Temperaturen
und einem Druck von 1013 mbar :

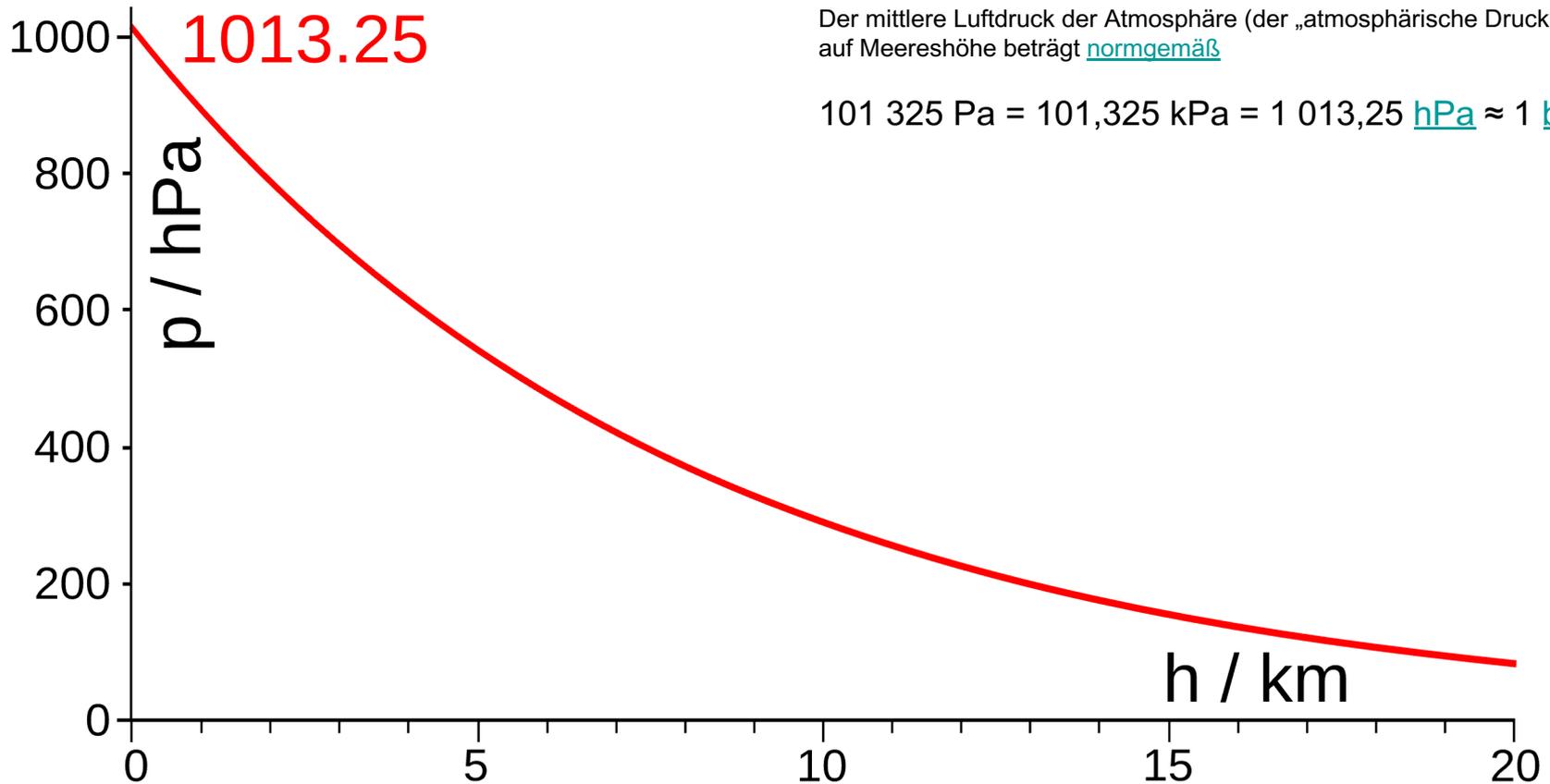
| Temperatur | Dichte |
|------------|-----------------------|
| 0°C | 1293 g/m ³ |
| 10°C | 1247 g/m ³ |
| 20°C | 1205 g/m ³ |

Wasserdampfgehalt der Luft bei verschiedenen
relativen Feuchtigkeiten und Temperaturen:

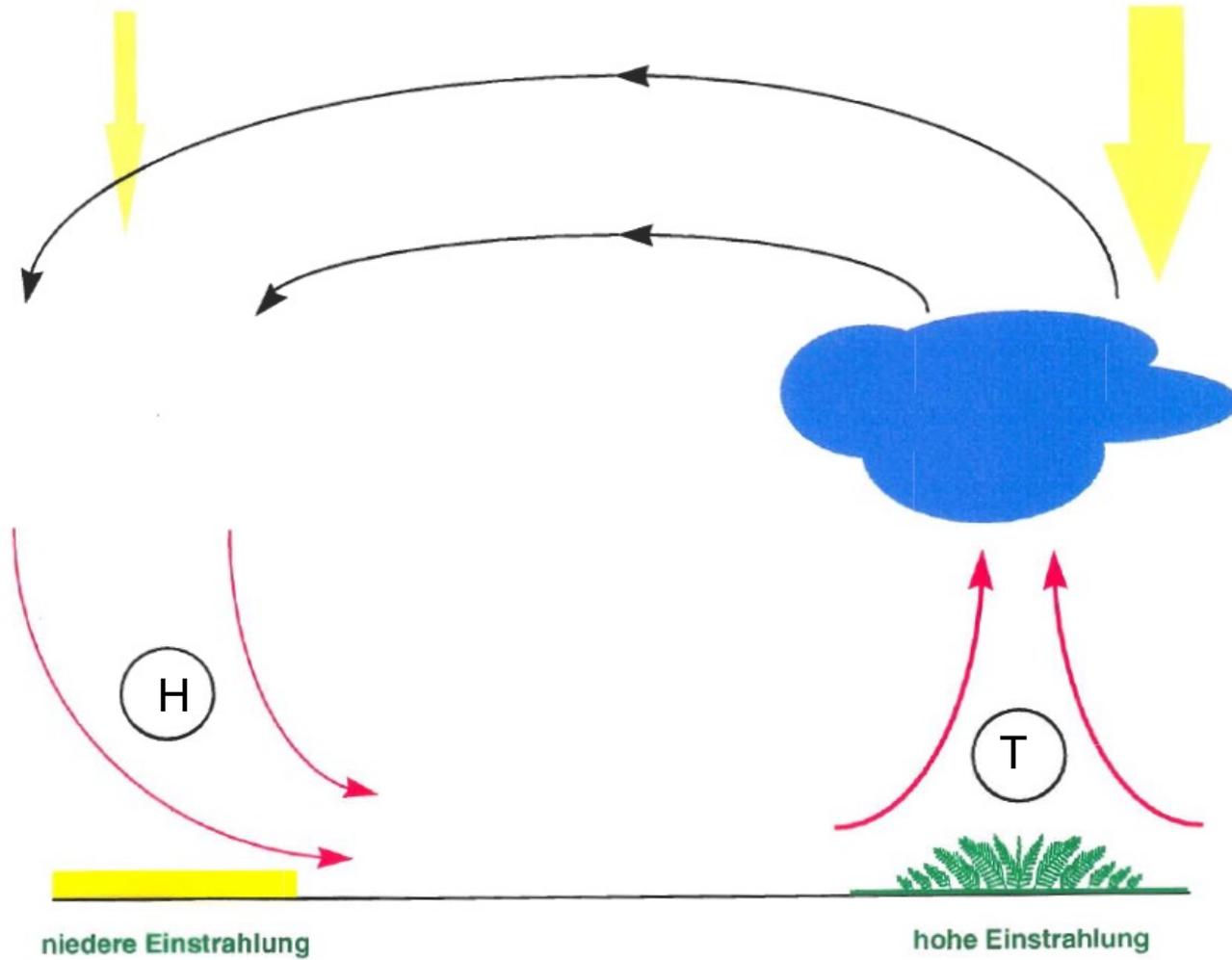
| Dampfgehalt | 30,4 g/m ³ | 17,2 g/m ³ | 9,4 g/m ³ | 4,9 g/m ³ |
|-------------|-----------------------|-----------------------|----------------------|----------------------|
| Temperatur | | | | |
| 0°C | | | | 100 % |
| 10°C | | | 100 % | 50 % |
| 20°C | | 100 % | 52 % | 26 % |
| 30°C | 100 % | 55 % | 29 % | 14 % |

Abkühlung →

Eigenschaften der Luft II

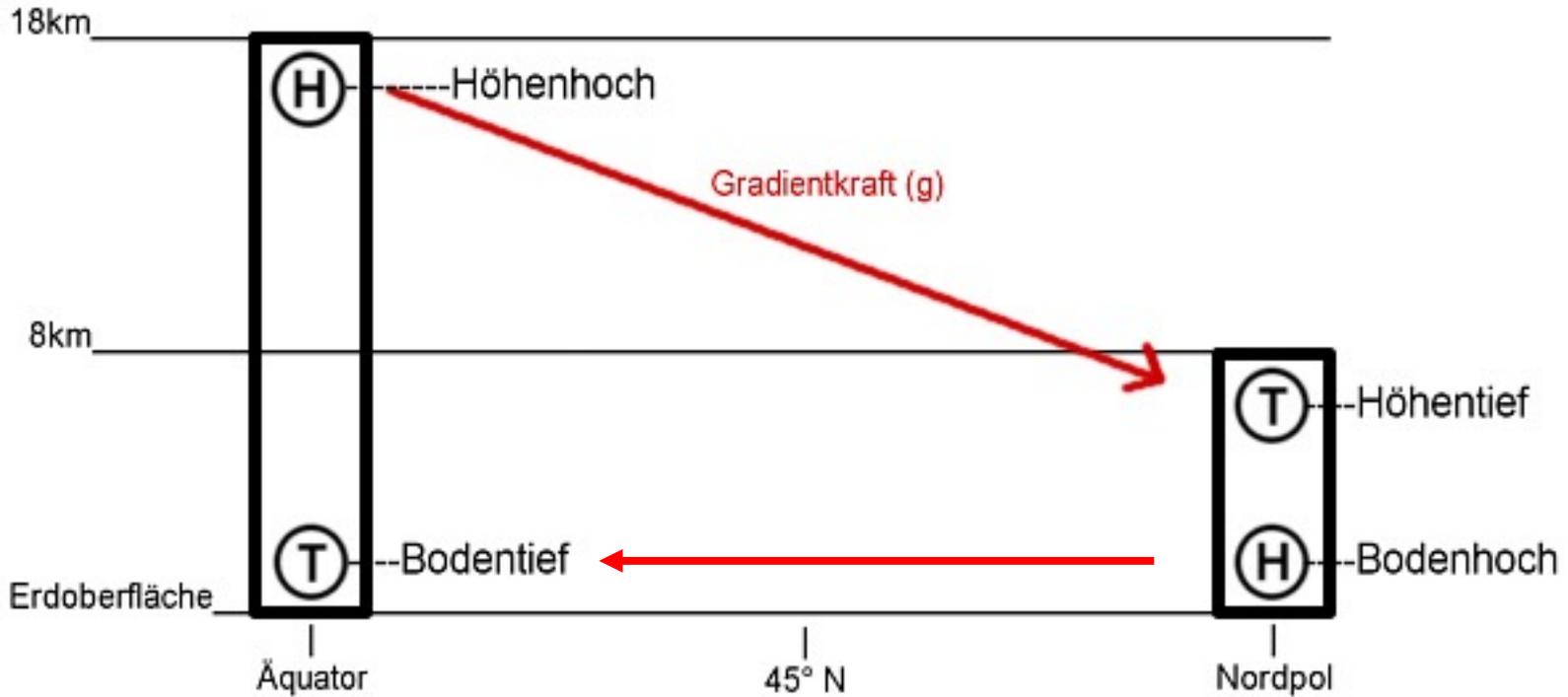


Einstrahlungsbedingte Zirkulation



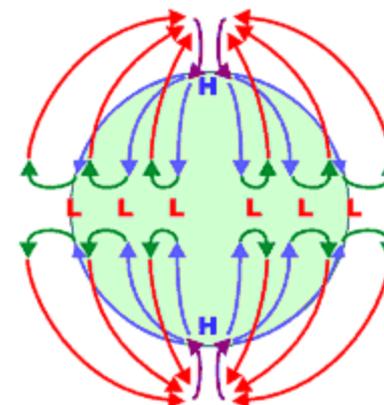
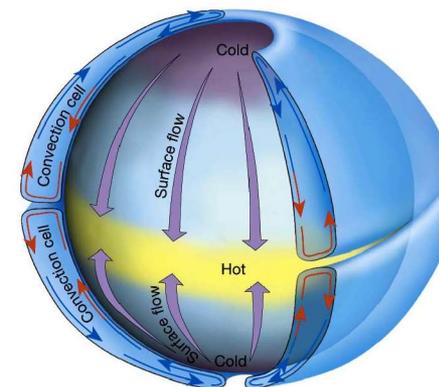
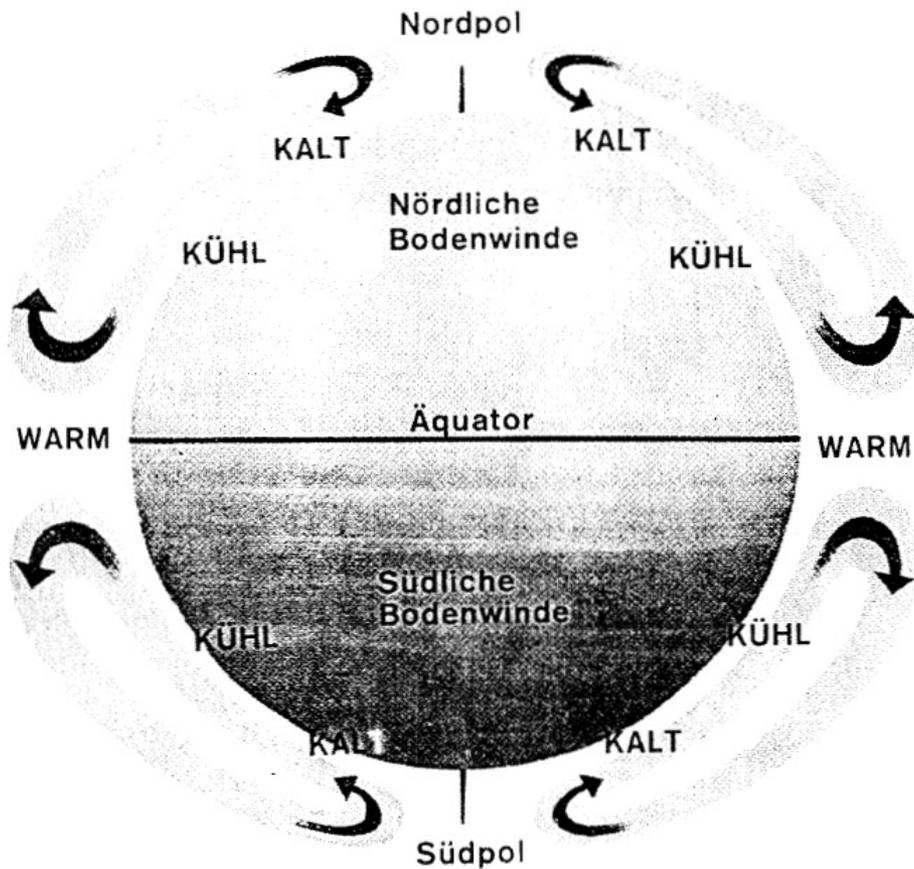
Wind als Gradientenkraft

Gradientenkraft \equiv Druckgradientenkraft

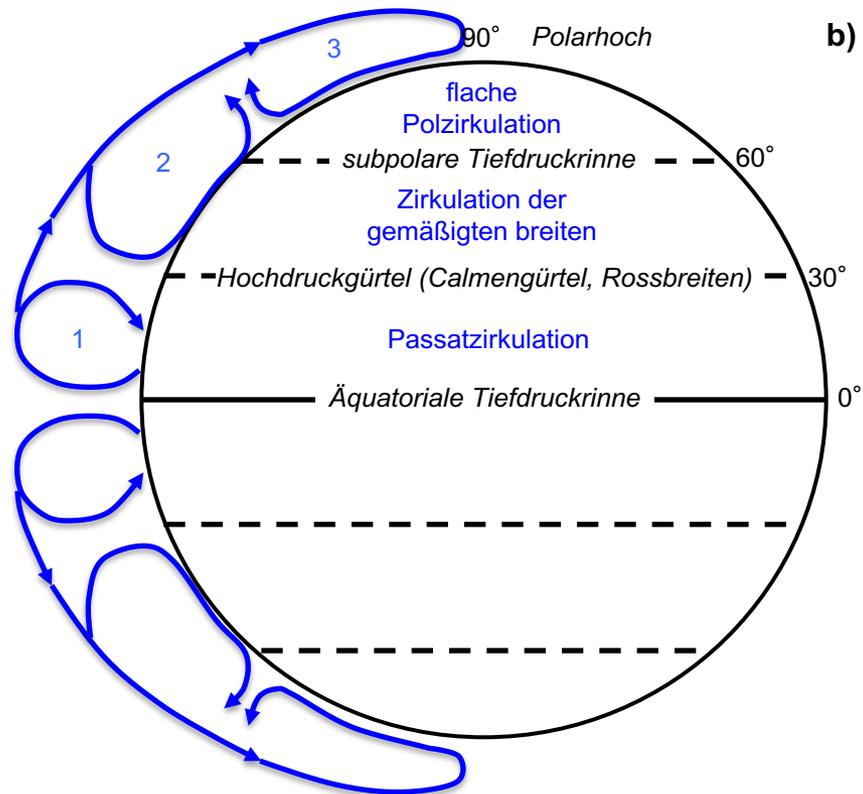
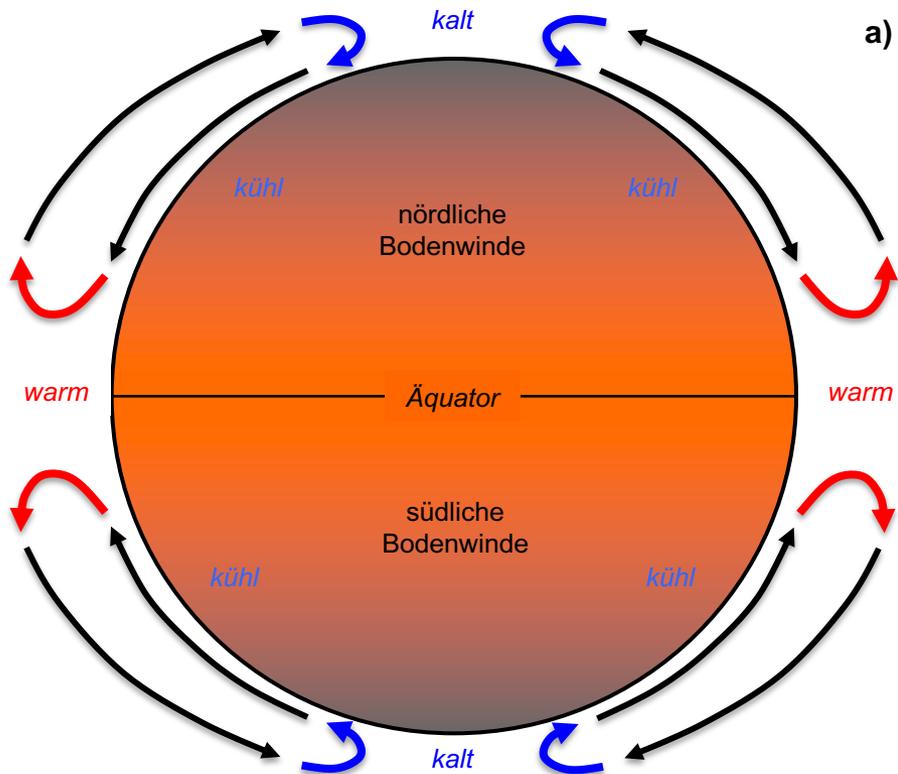


Ausgleichsströmung zwischen Hoch- und Tiefdruckgebiet

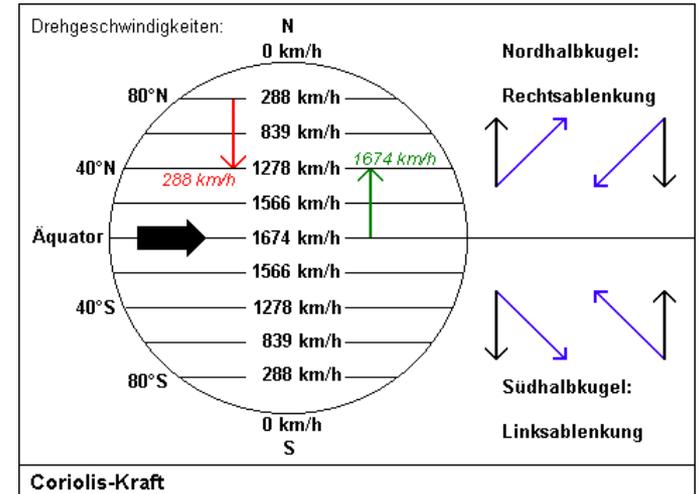
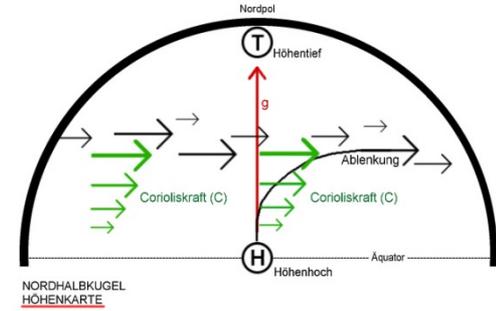
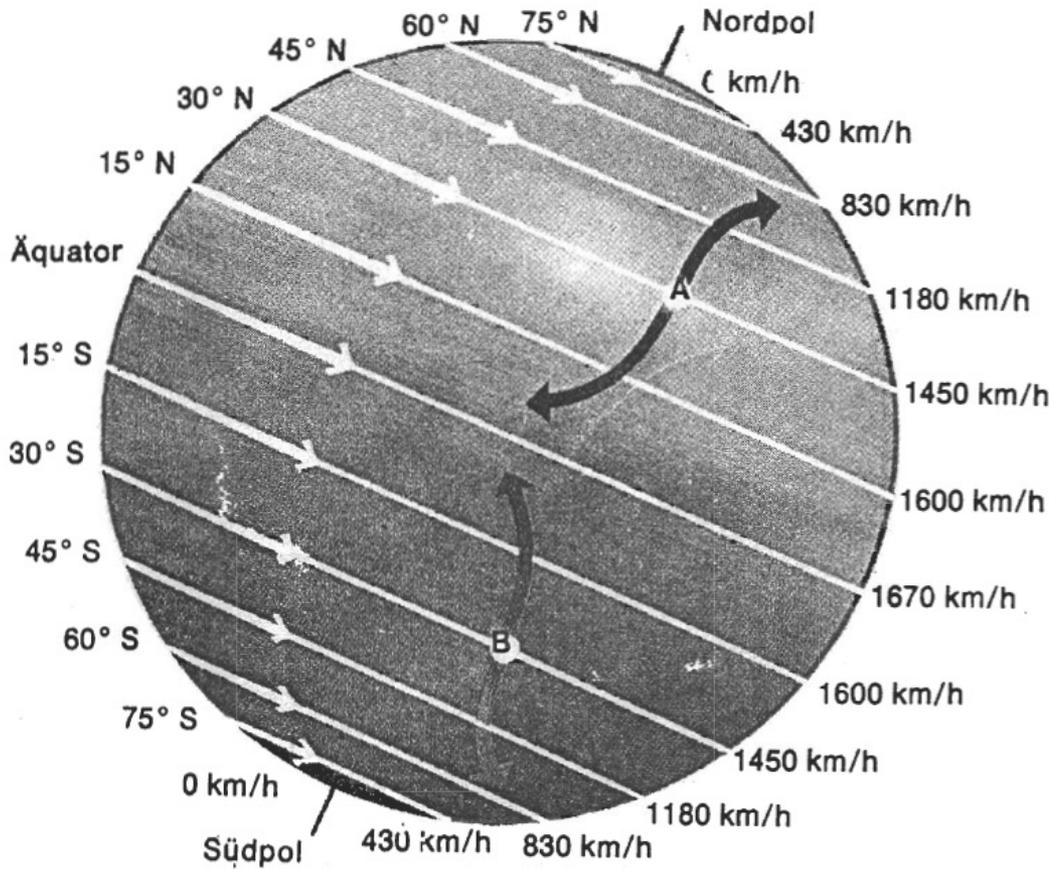
Vereinfachte Globalströmung



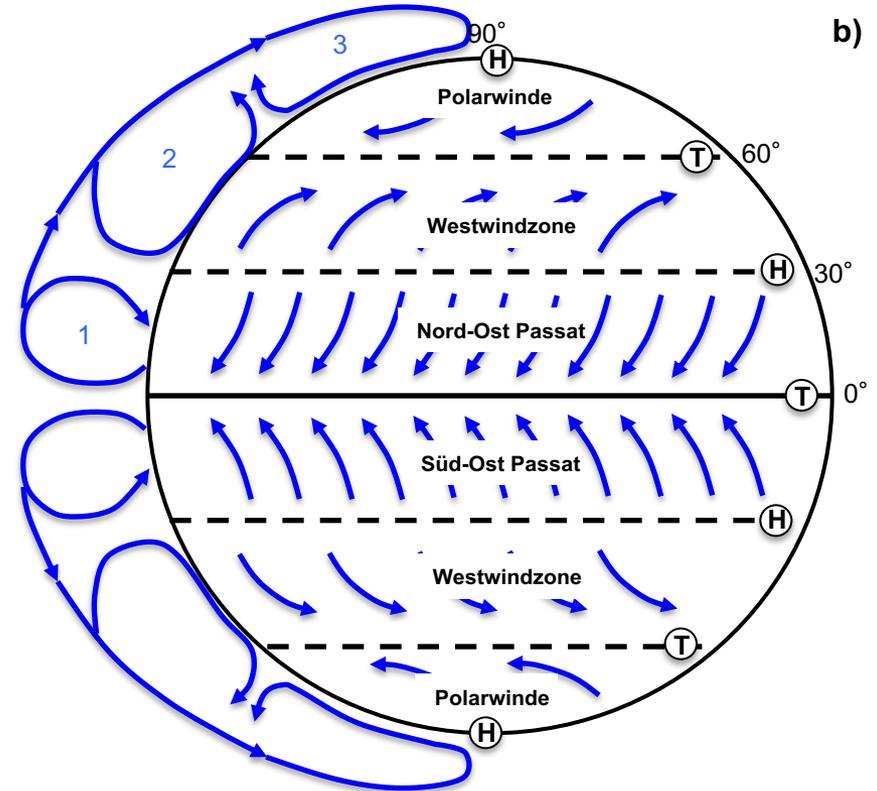
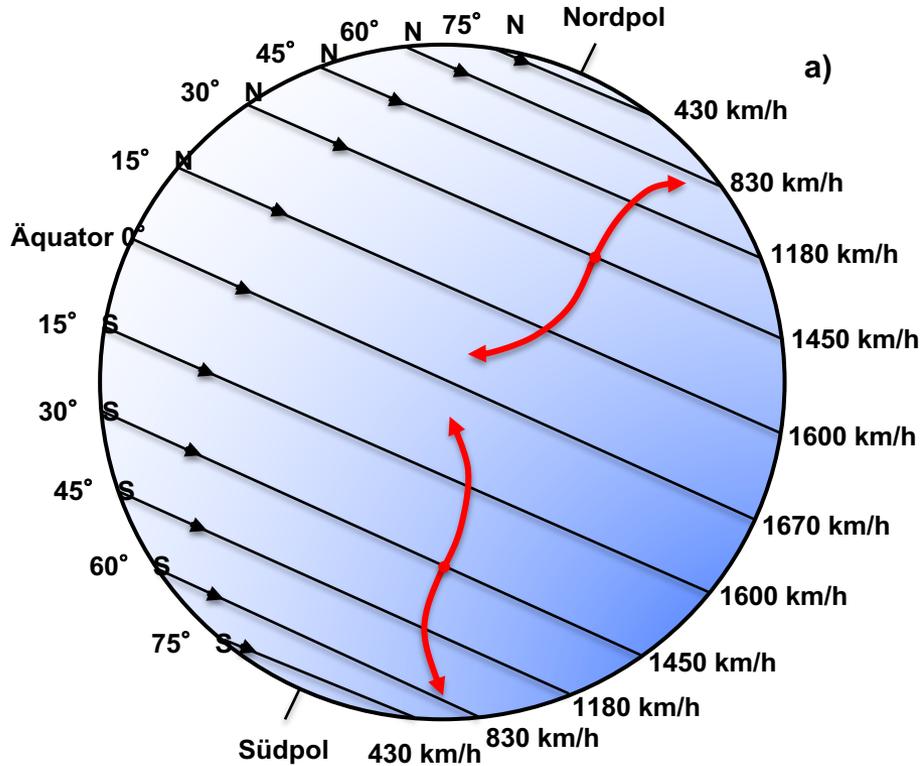
Globale Windzonen



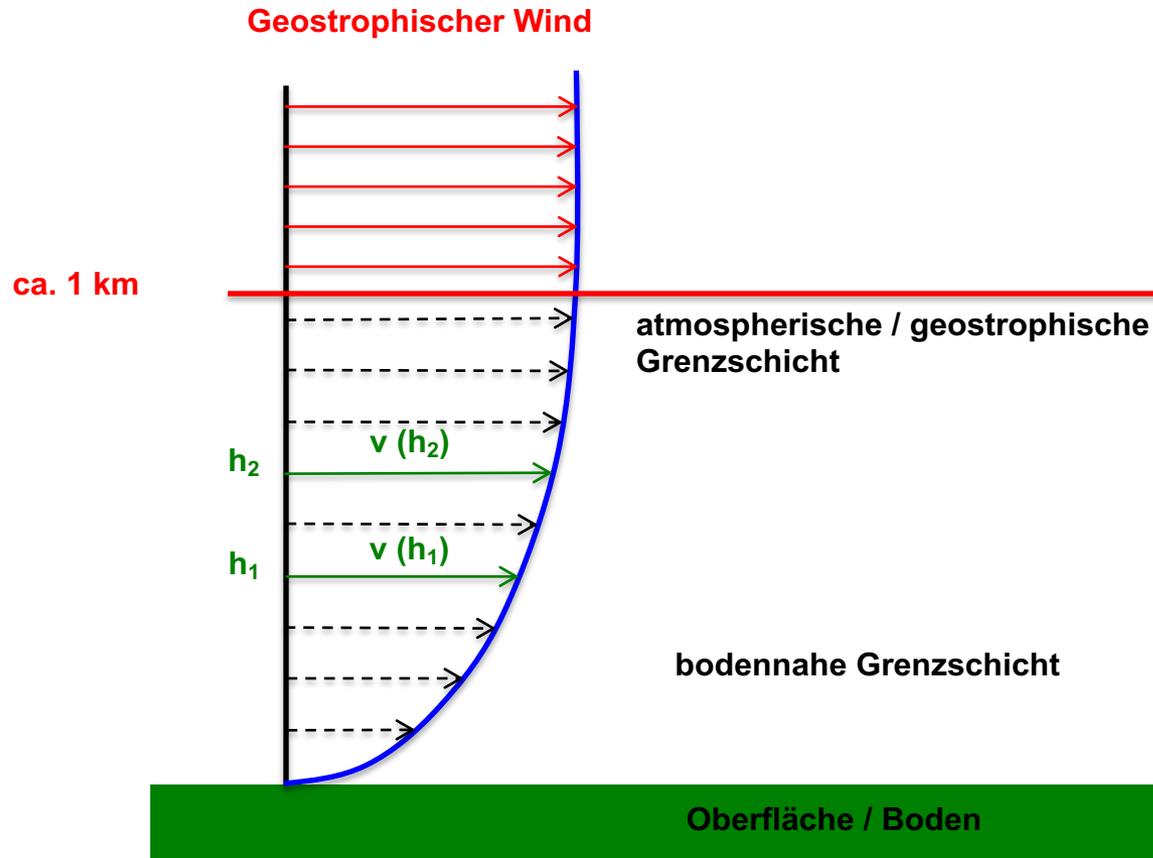
Corioliskraft



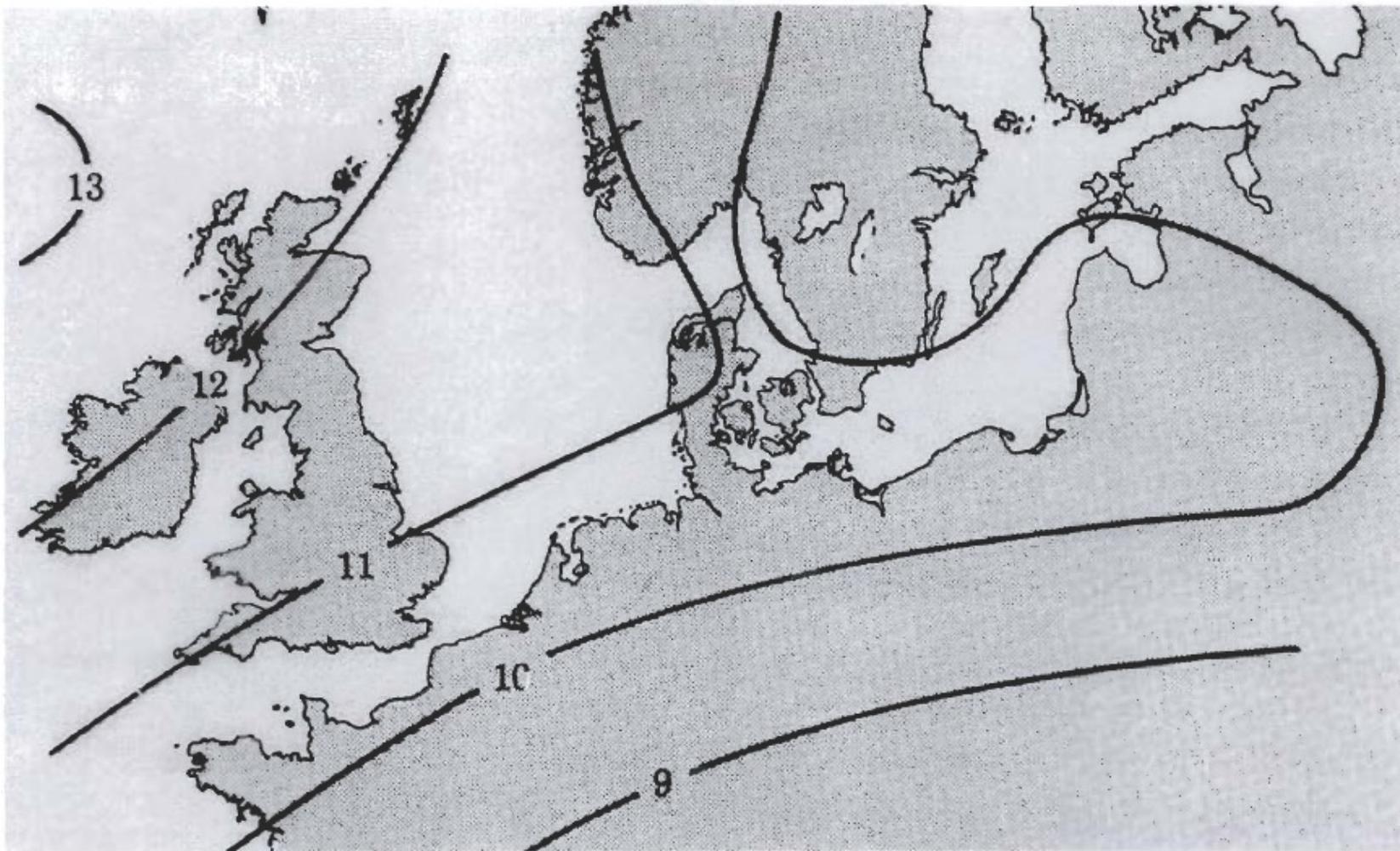
Globale Winde und Corioliskraft



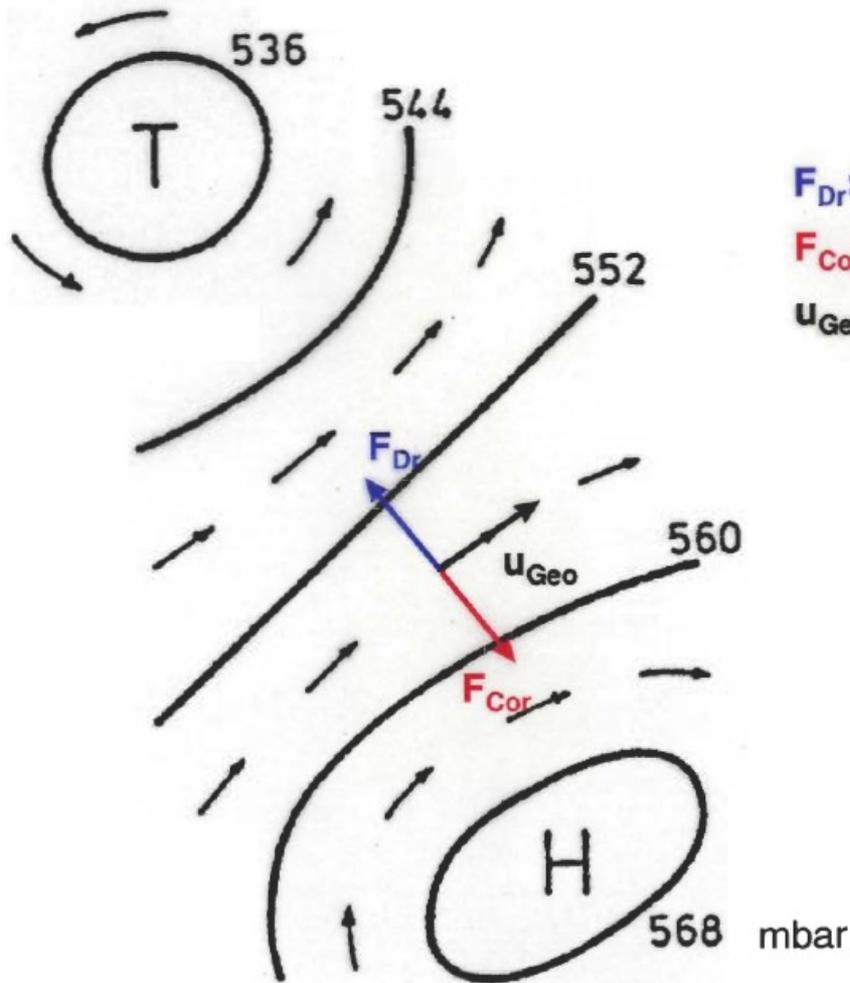
Geostrophischer Wind



Geostrophische Winde Nordeuropa



Hoch-Tiefdruck geostrophisch

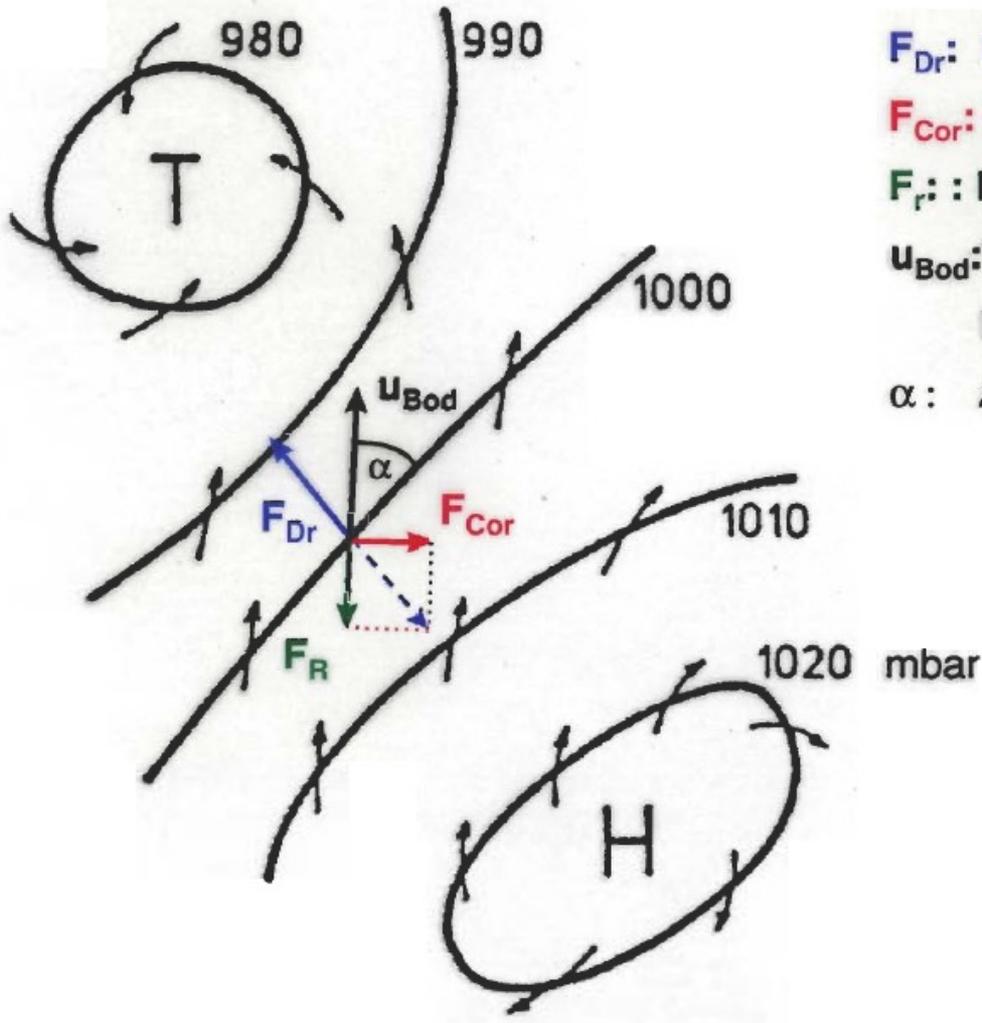


F_{Dr} : Druckgradientenkraft

F_{Cor} : Corioliskraft

u_{Geo} : Vektor des
geostrophischen Windes

Hoch-Tiefdruck bodennah



F_{Dr} : Druckgradientenkraft

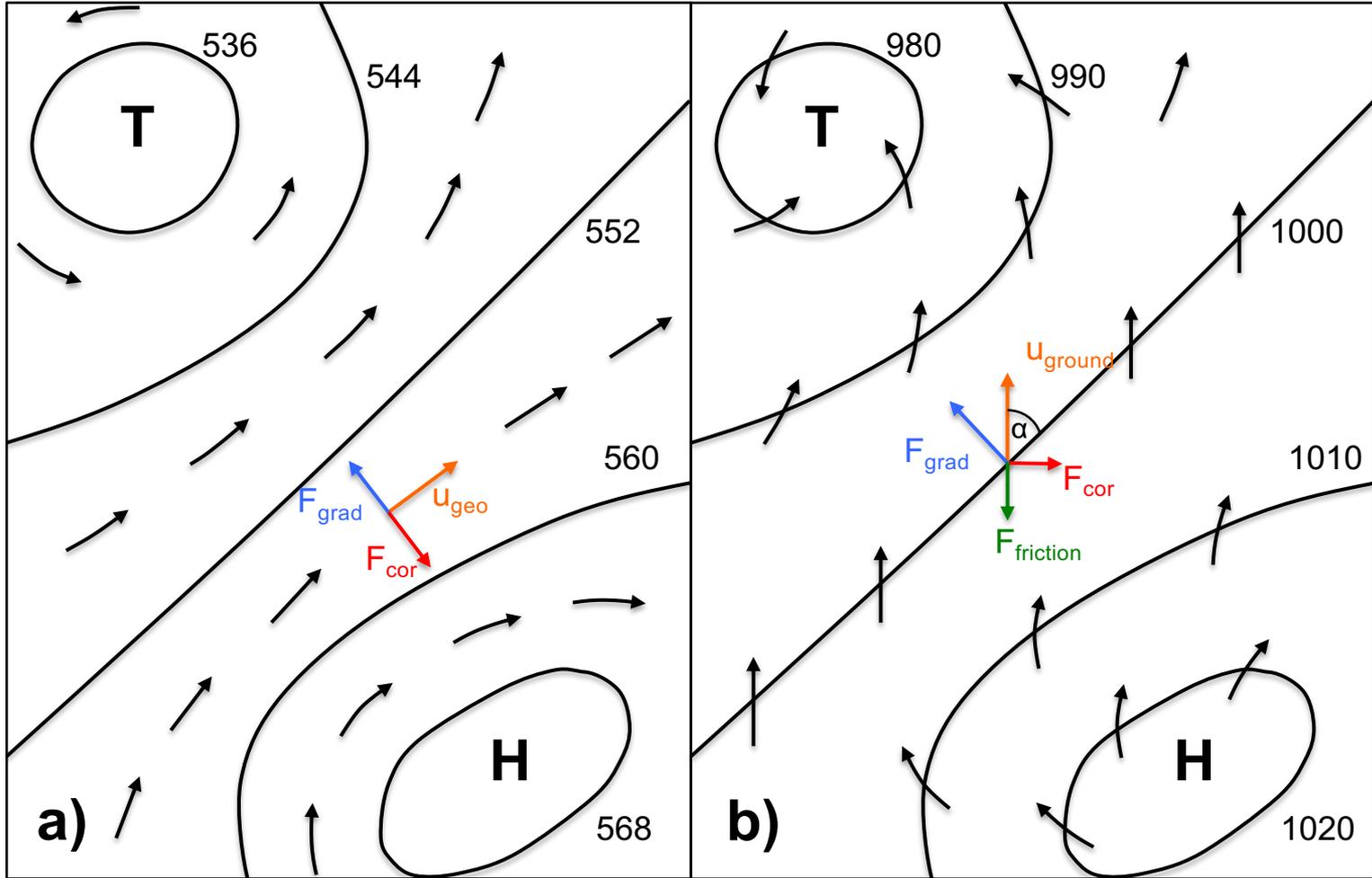
F_{Cor} : Corioliskraft

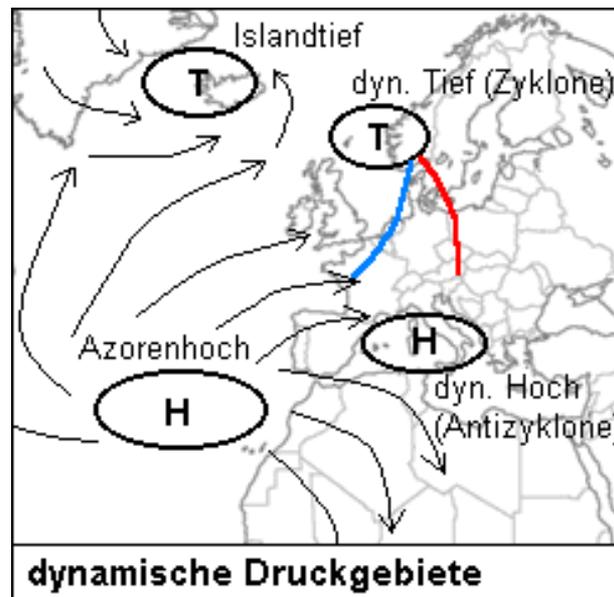
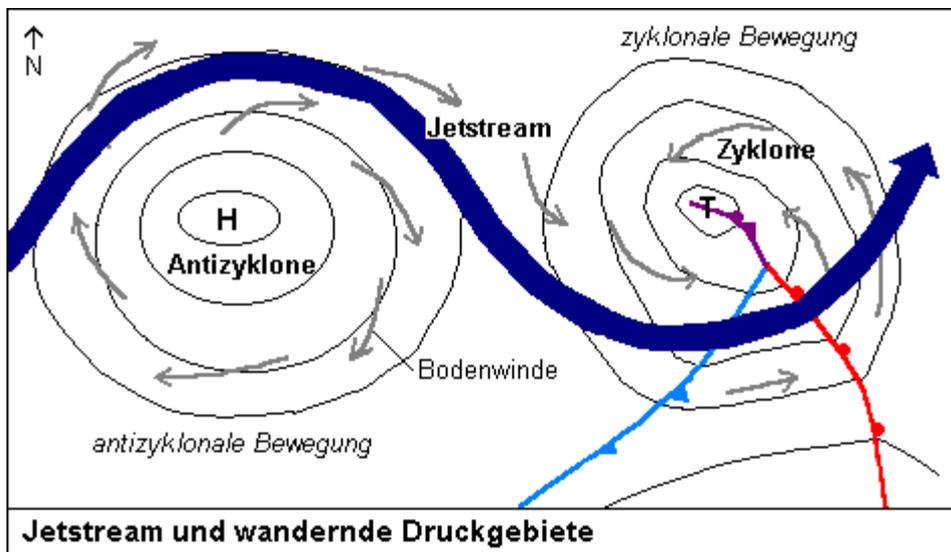
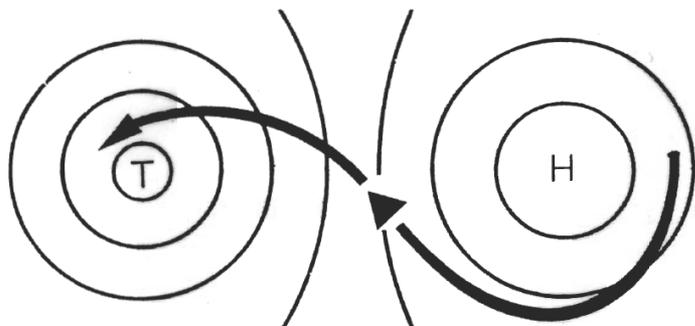
F_R : Reibungskraft

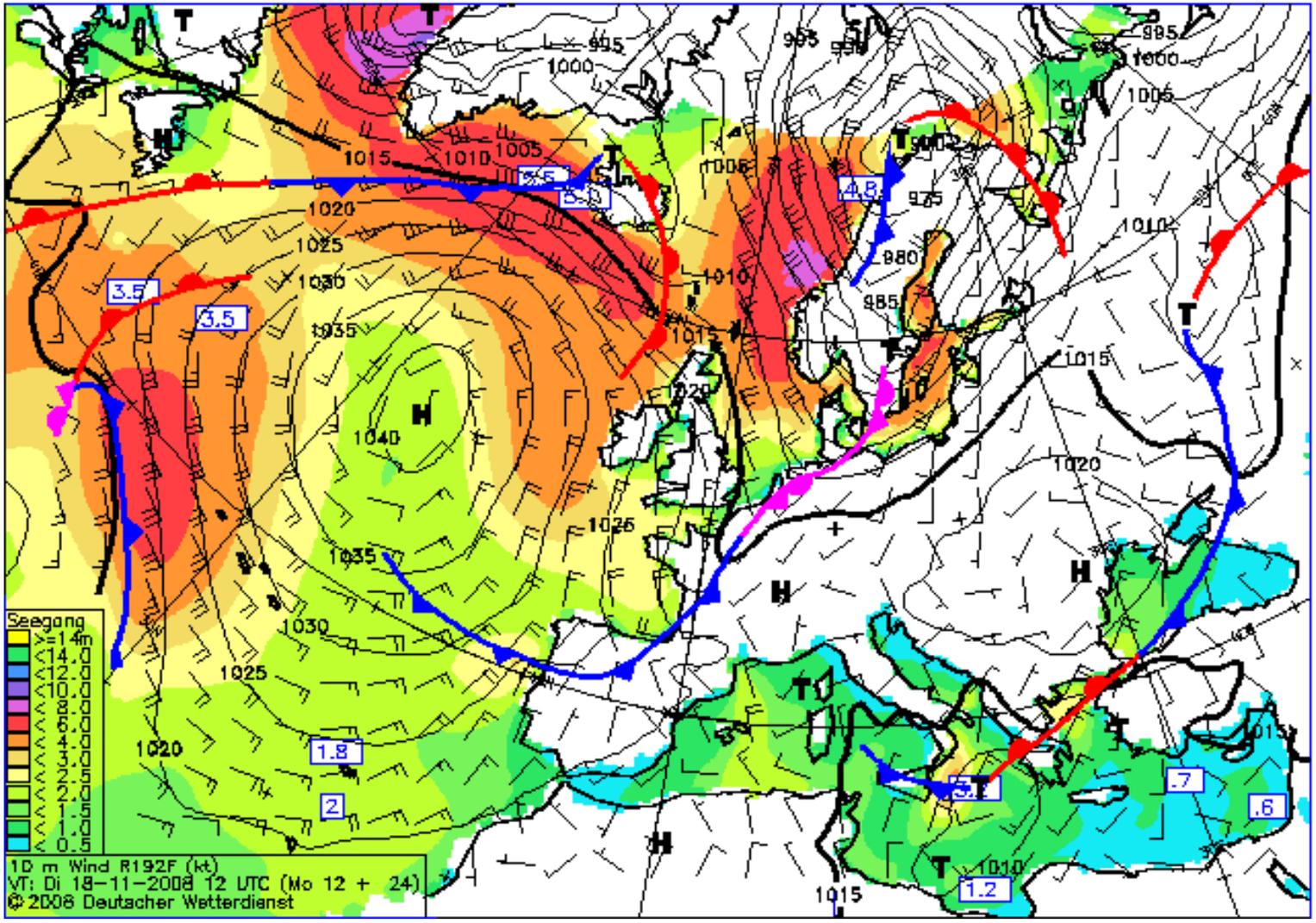
u_{Bod} : Vektor des
bodennahen Windes

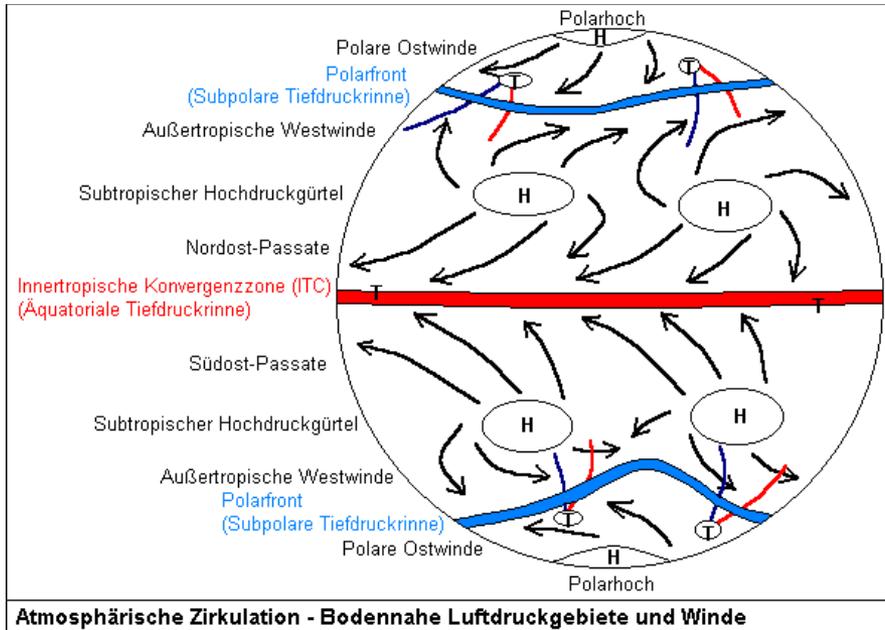
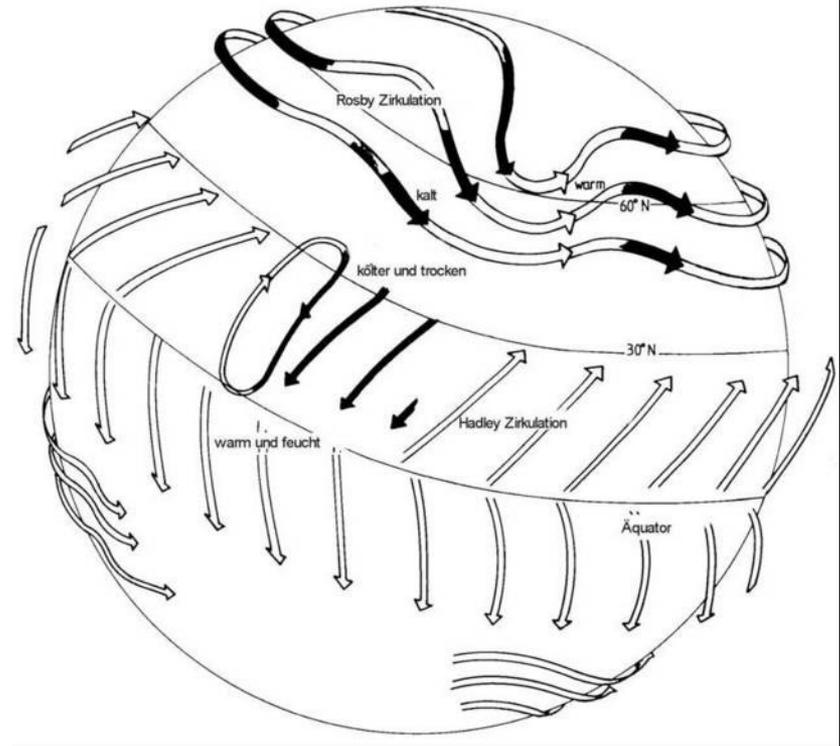
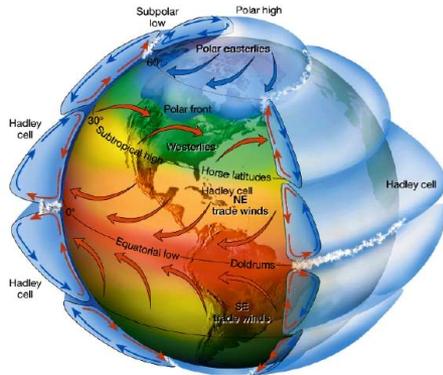
α : Ablenkungswinkel

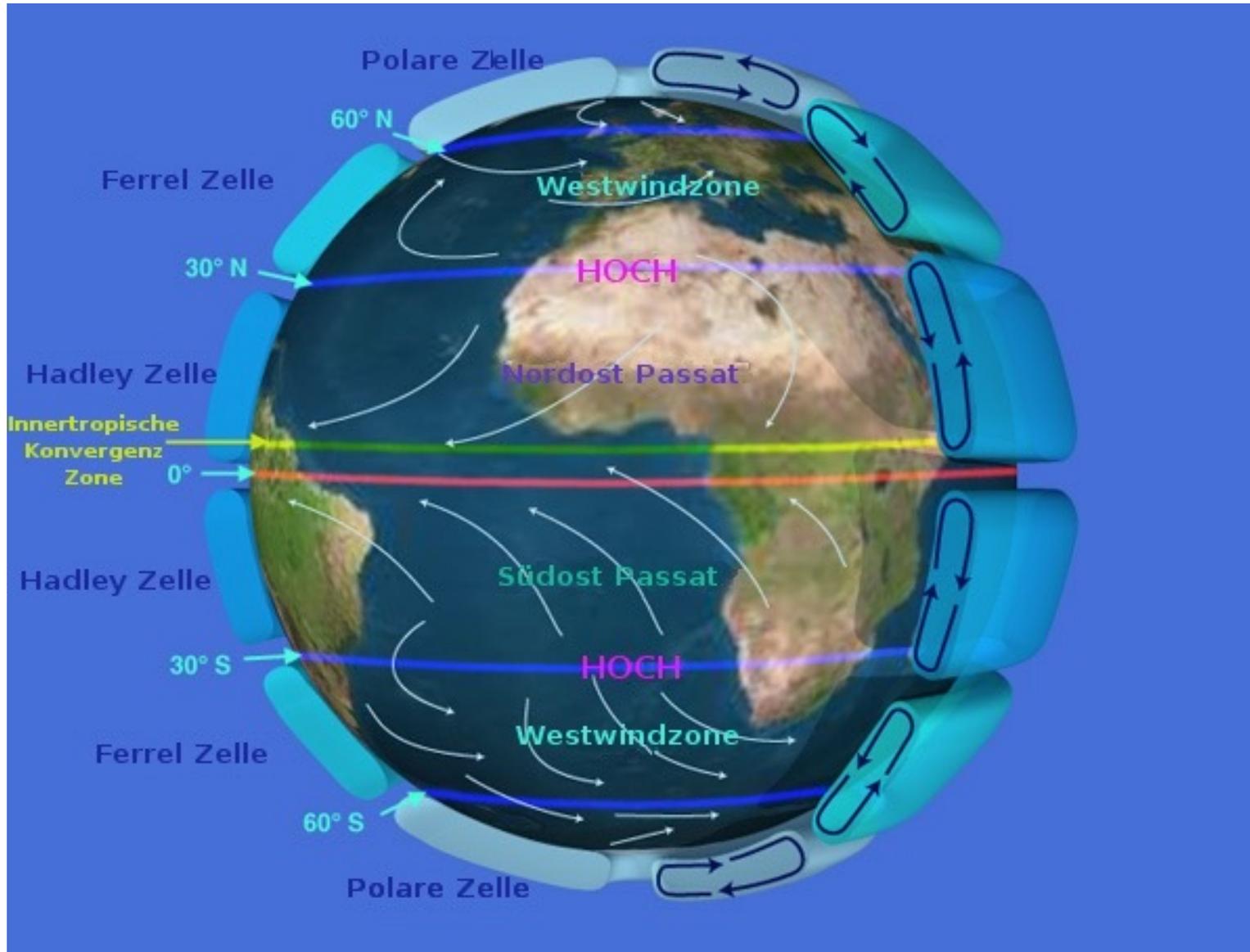
Hoch- Tiefdruck Vergleich



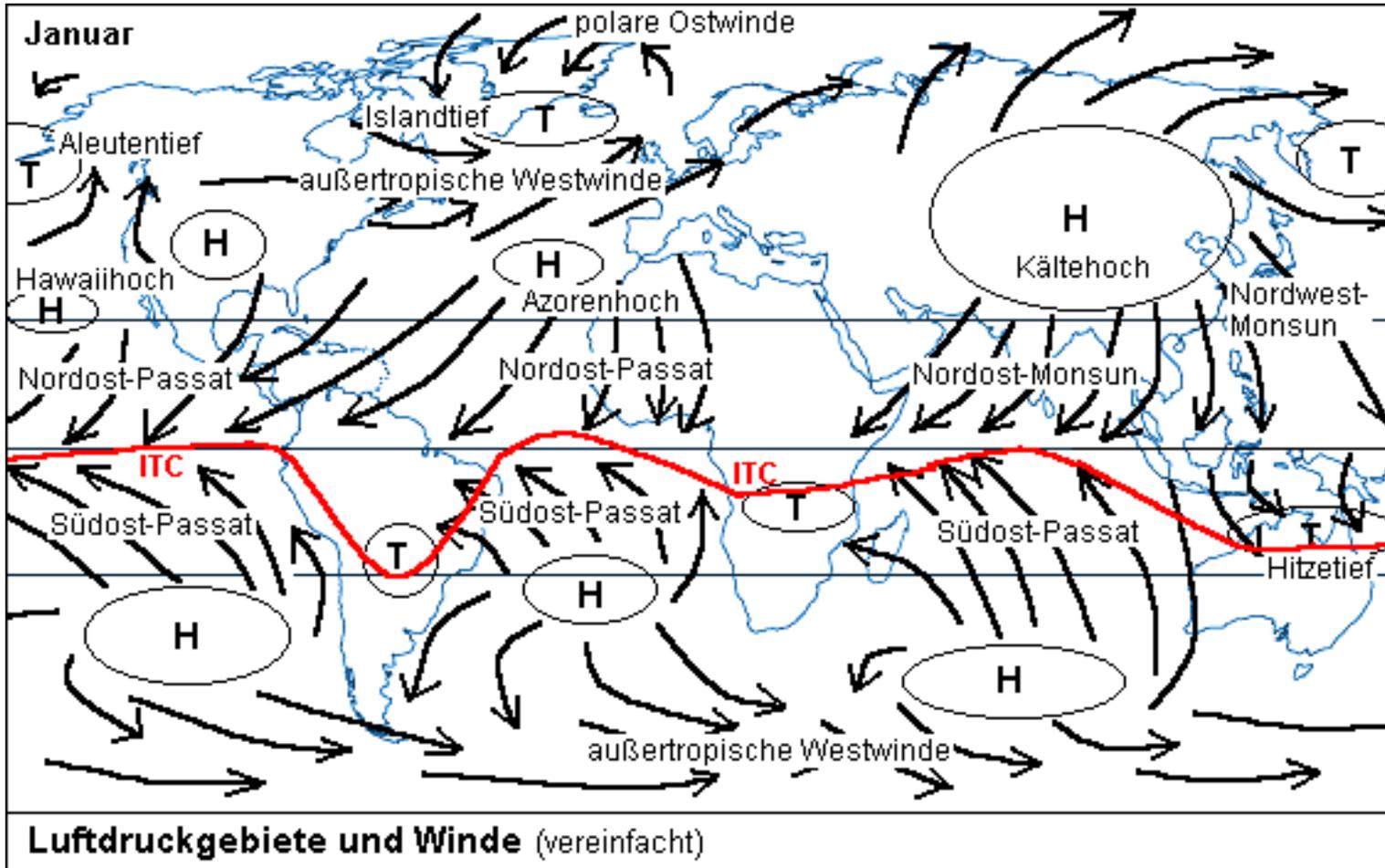




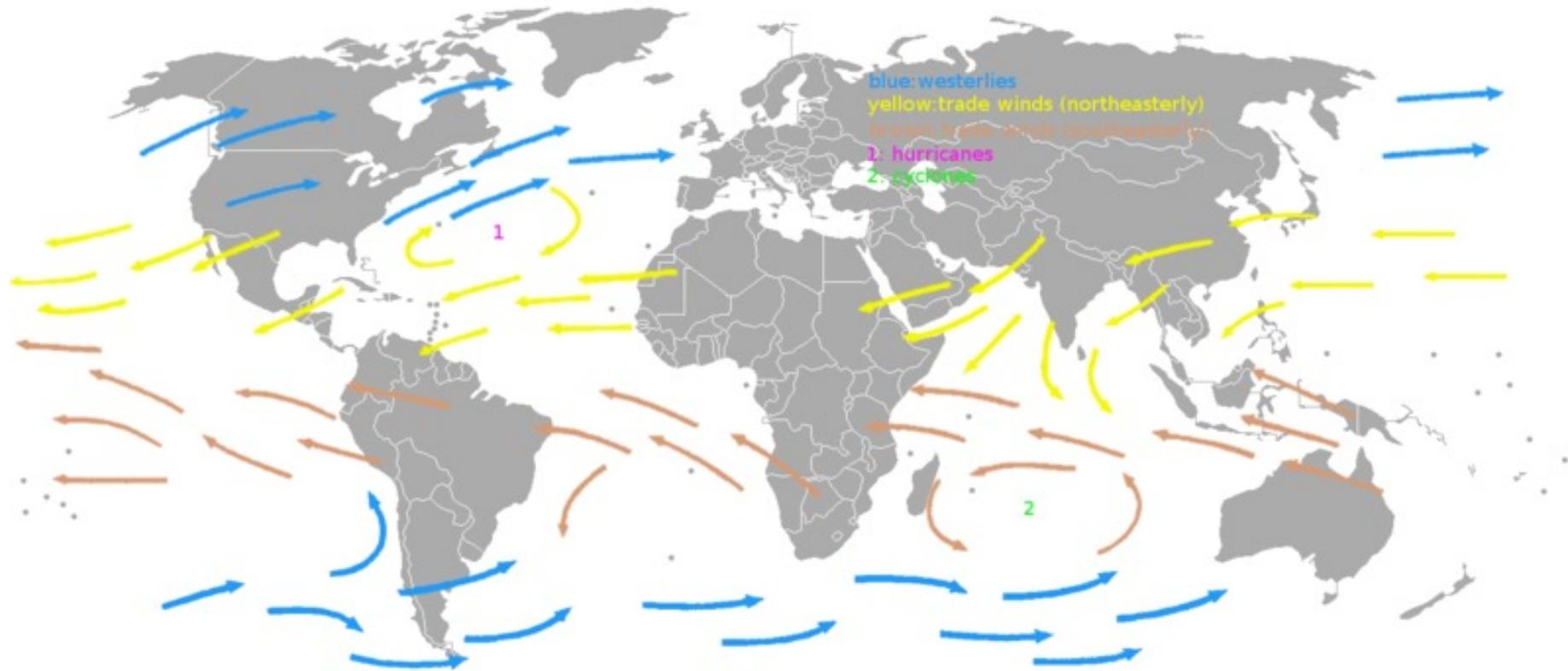


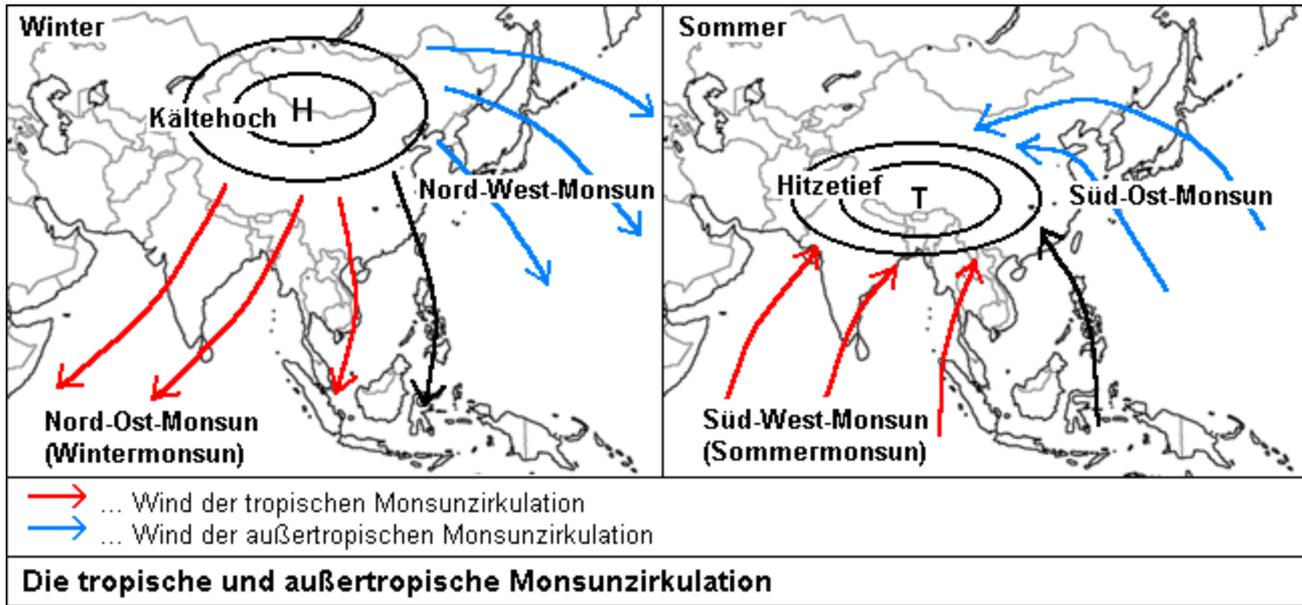
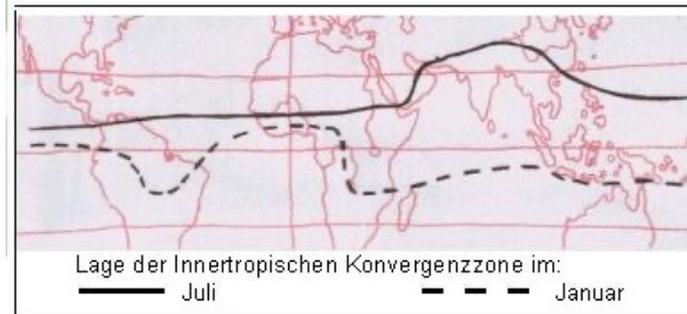


„Globale“ Winde



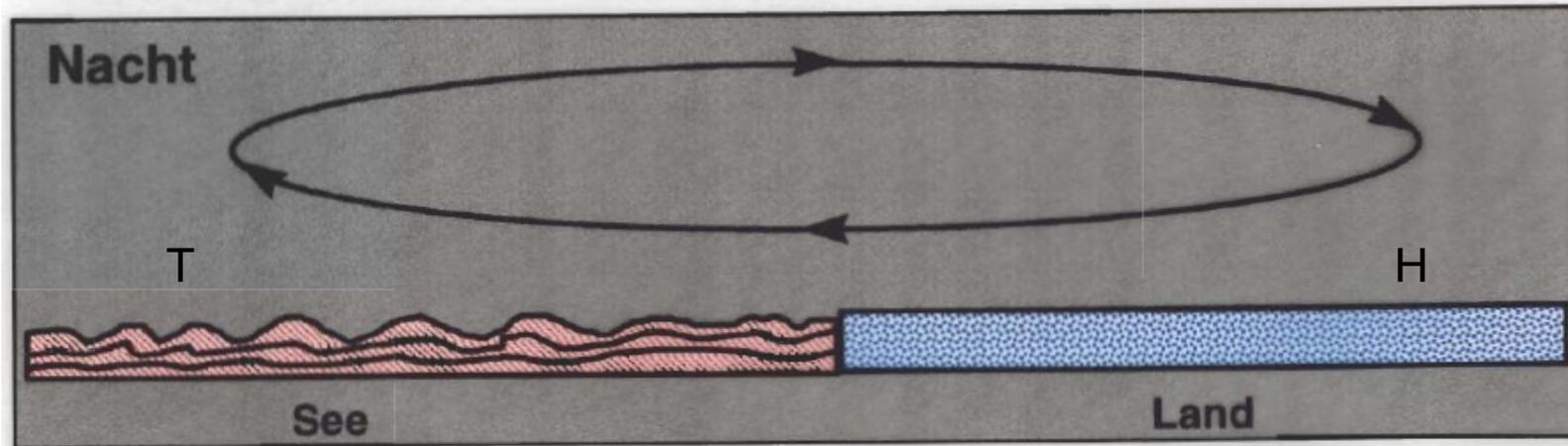
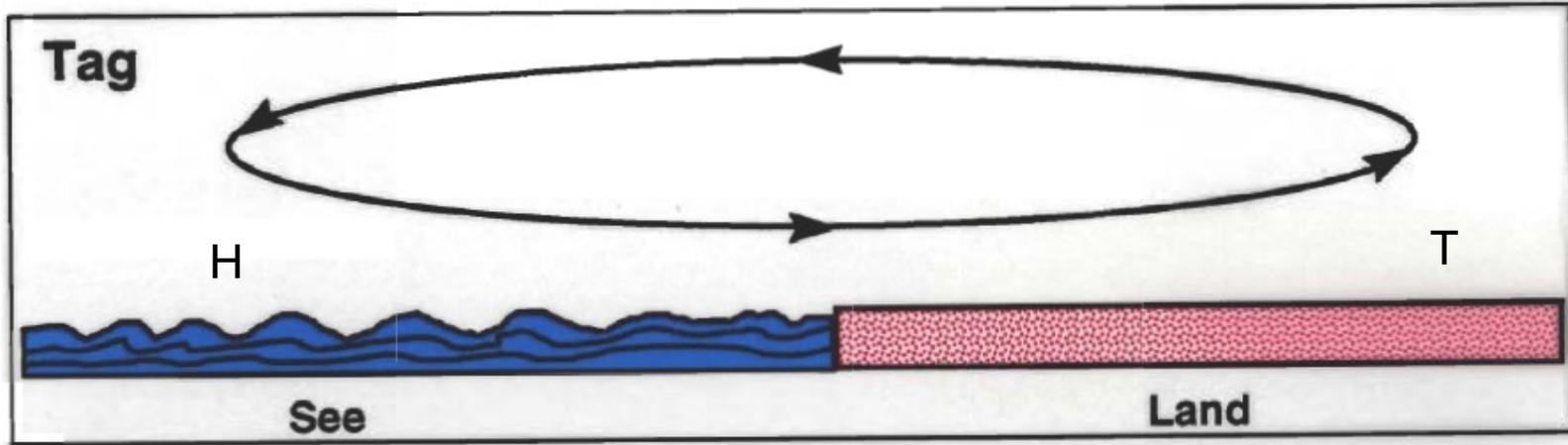
„Globale“ Winde





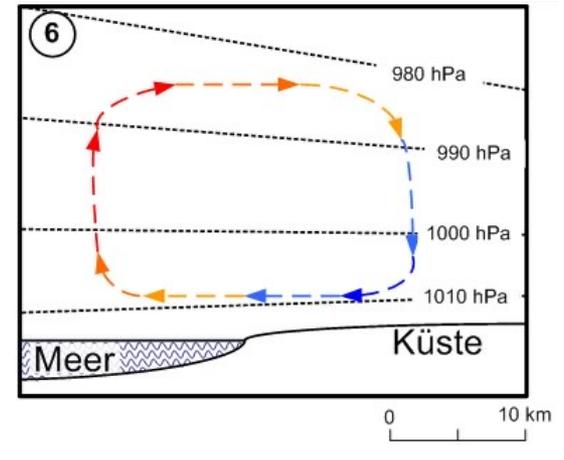
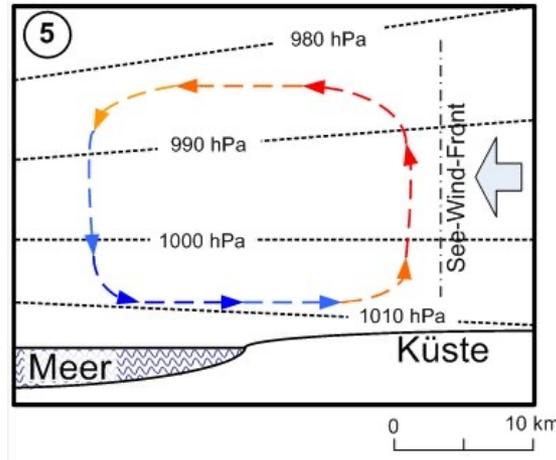
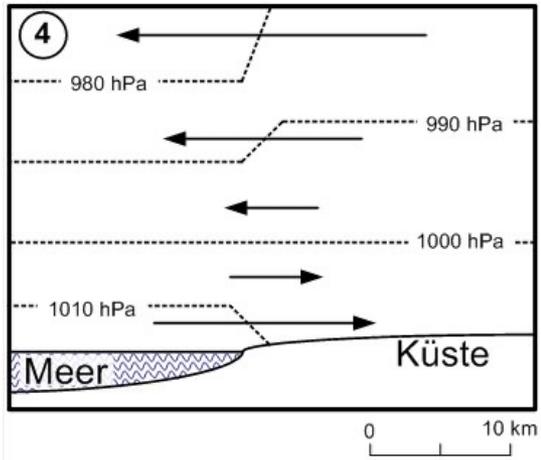
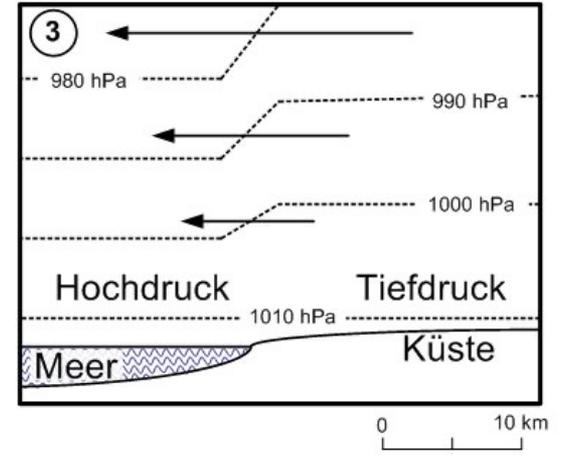
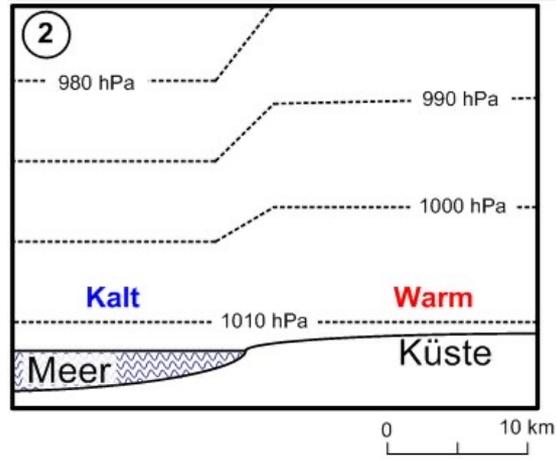
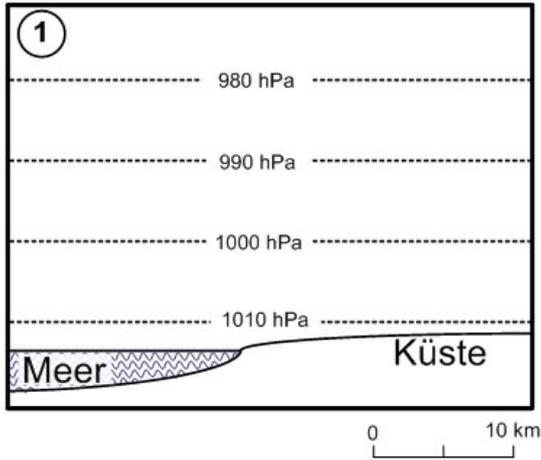
Lokale Windsysteme

Land- Seewind



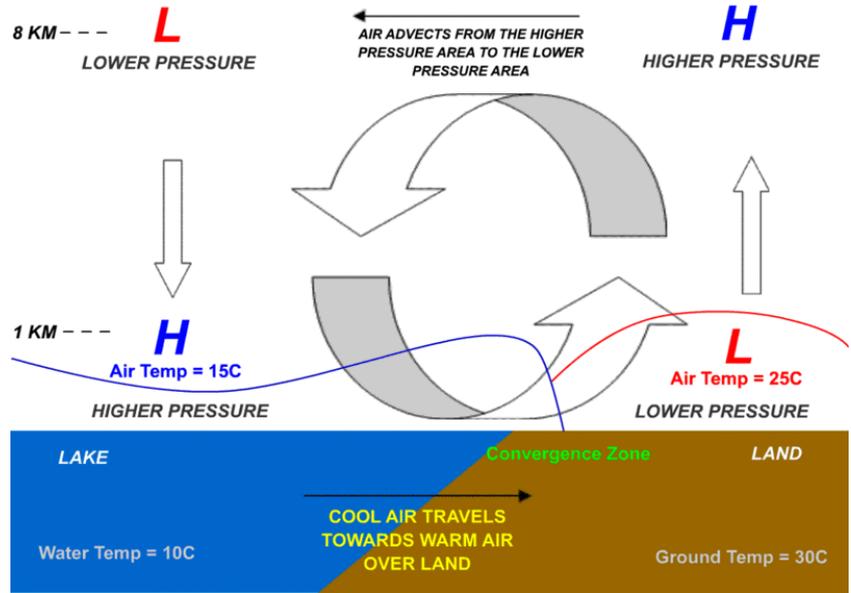
Lokale Windsysteme

Seewind Entwicklung (Landwind Nachts)

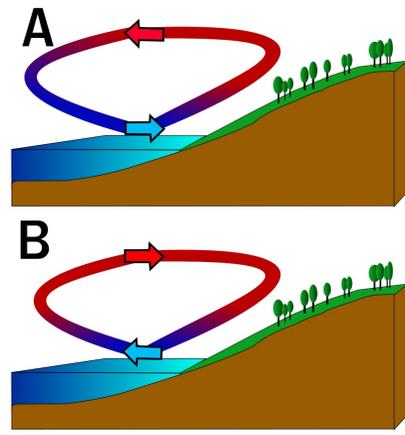


Lokale Windsysteme

Seewind



Lake Breeze



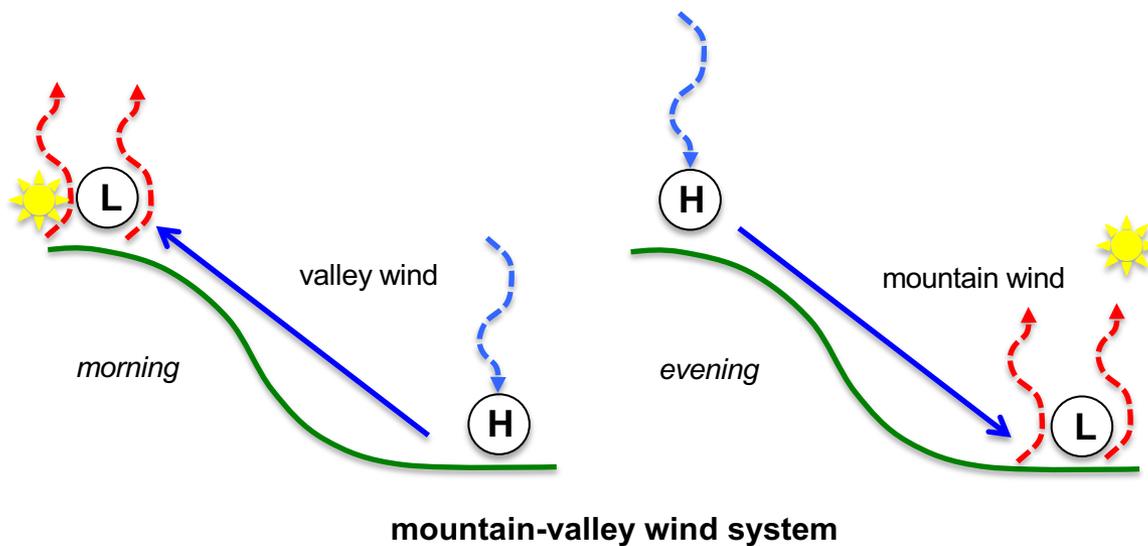
Daytime

Nighttime

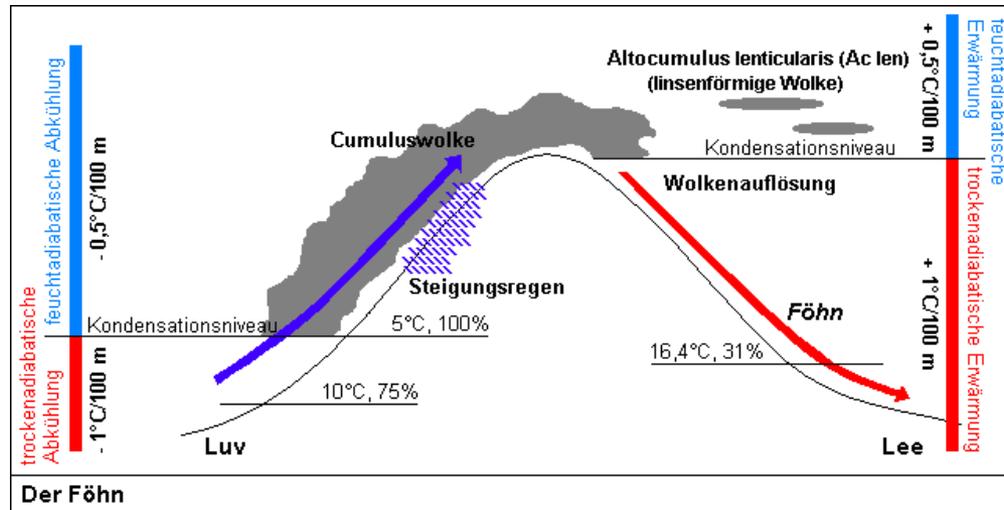
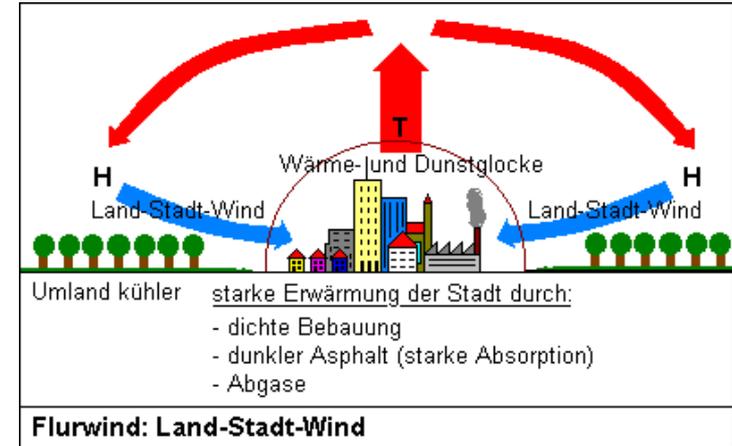
- Lake Breeze
- Sea Breeze / Land Breeze
- Shore Side Wind
- Onshore Wind
- Diurnal Coastal Wind

Lokale Windsysteme

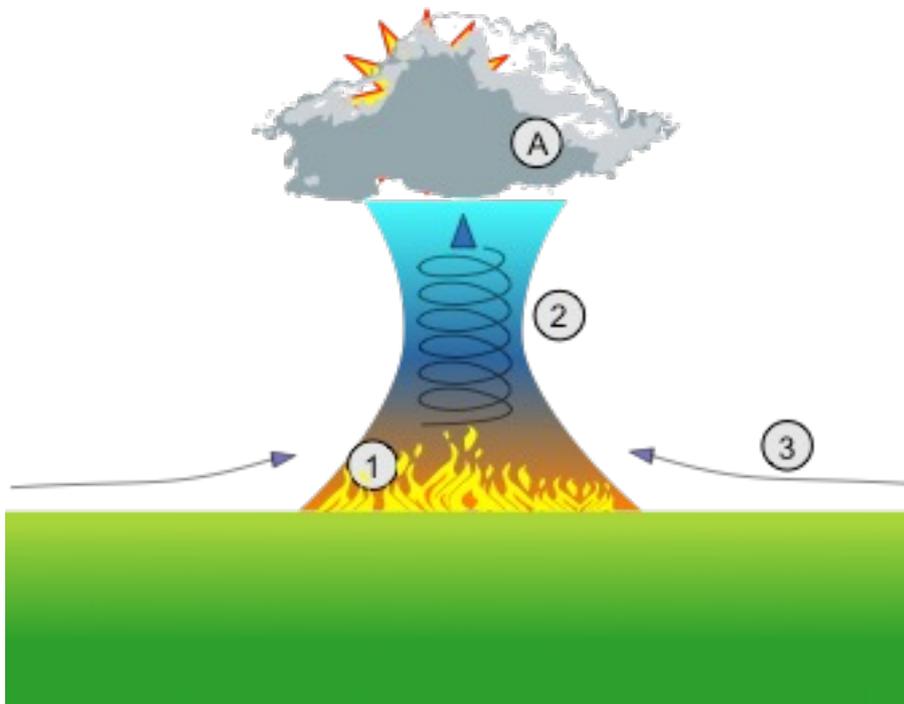
Seewind / Berg- Talwind



- *Land-See Wind*
- *Berg-Tal Wind*
- Flurwind Land-Stadt
- *Fallwinde*
- Föhn

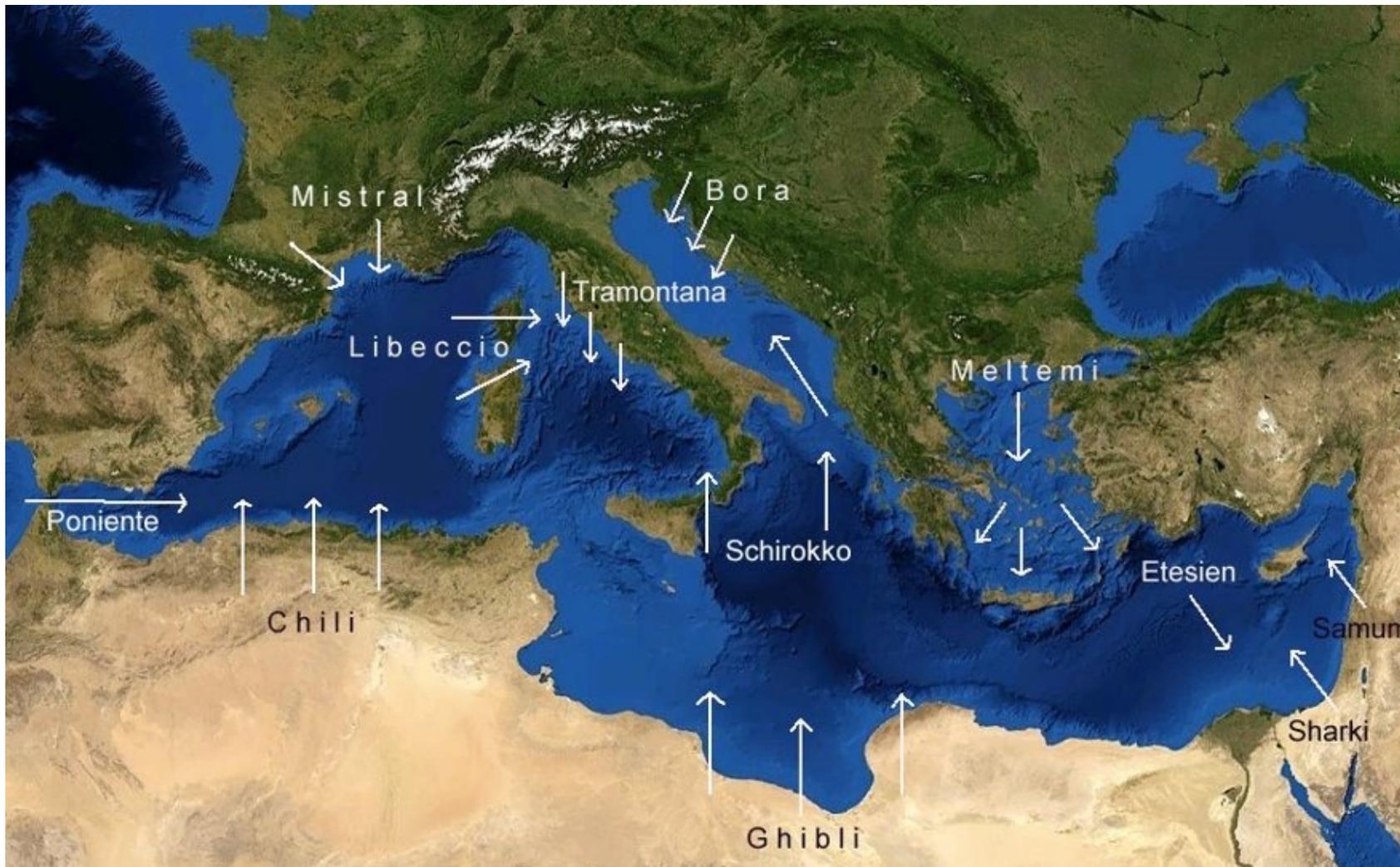


„Lokale Winde“ Feuersturm



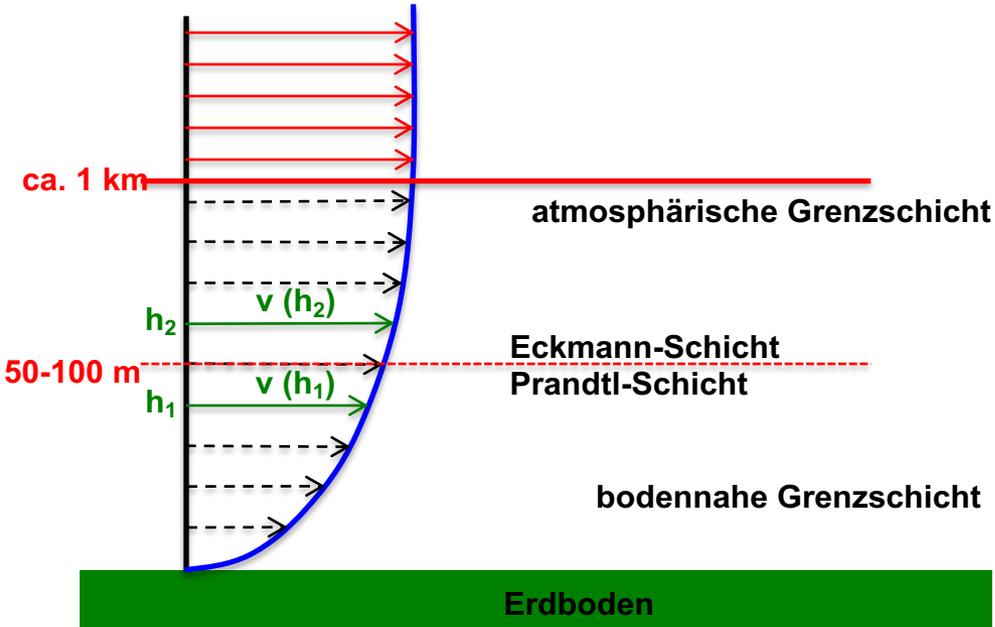
Von Thermal_column.svg: Dakederivative work: RicHard-59 - Thermal_column.svg, CC BY 2.5, <https://commons.wikimedia.org/w/index.php?curid=15364096>

Lokale Windsysteme Mittelmeer



Höhenprofil / Grenzschichtformel

geostrophischer Wind



$$v(h) = c \cdot \left[\ln\left(\frac{h}{z_0}\right) - \Psi\left(\frac{h}{L}\right) \right]$$

allgemeine Form
mit Störungsterm

$$v(h) = c \cdot \ln\left(\frac{h}{z_0}\right)$$

Vernachlässigung des
Störungsterms

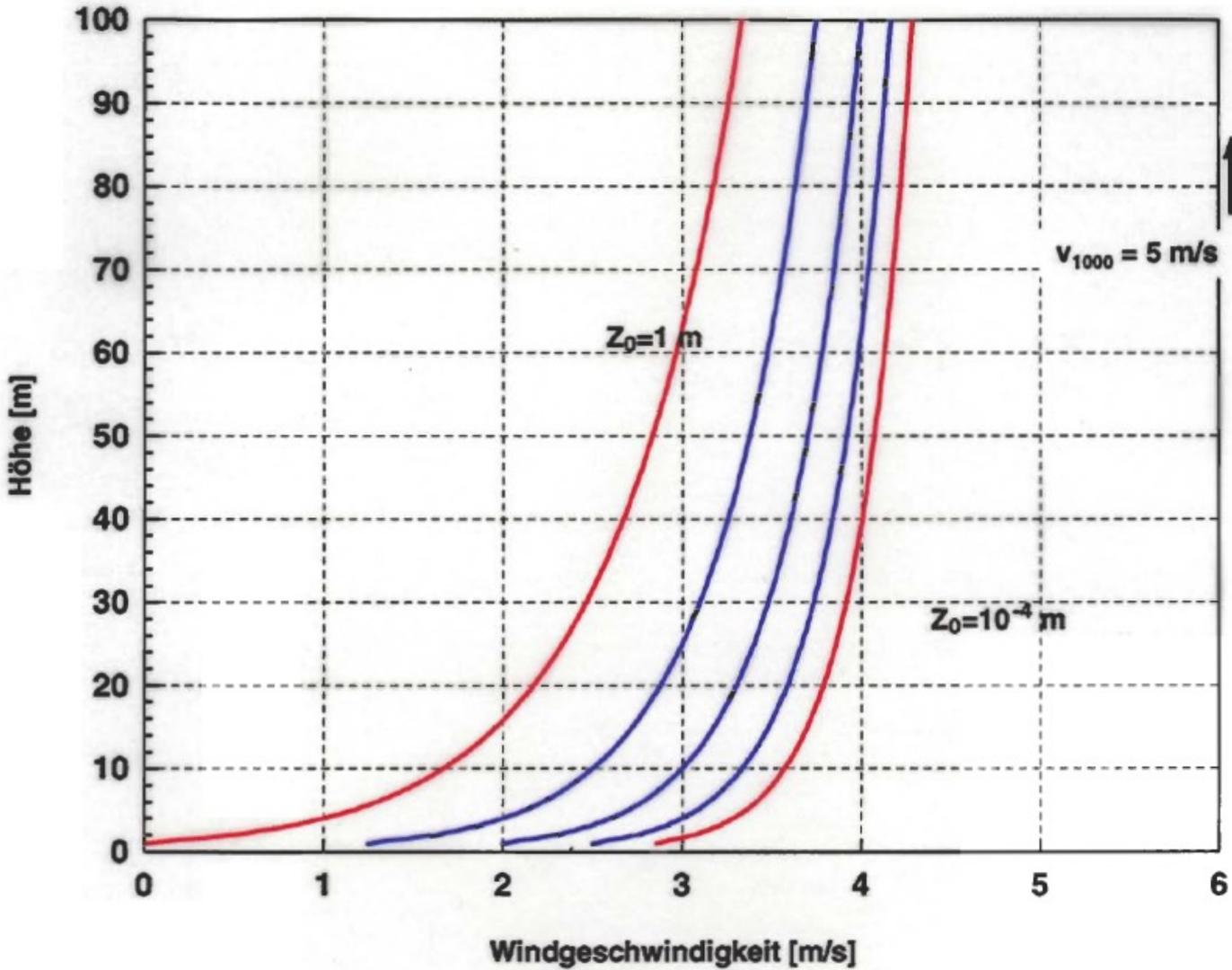
$$\frac{v(h_2)}{v(h_1)} = \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)}$$

Eliminierung der nur
empirisch zu bestimmenden
Konstanten c

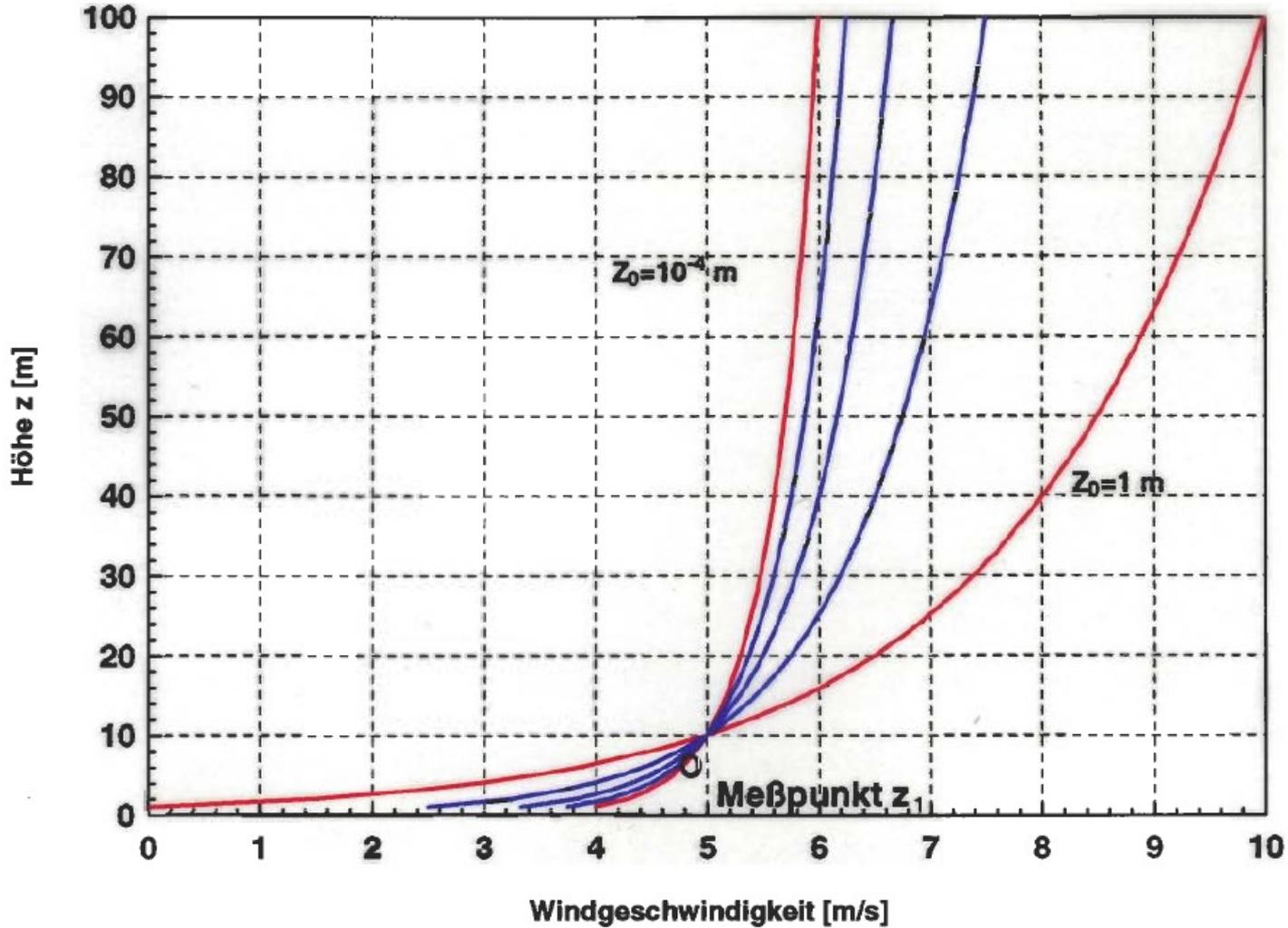
z_0 ist die Rauigkeitslänge
Ein Maß für die
Bodenbeschaffenheit

Höhenprofil

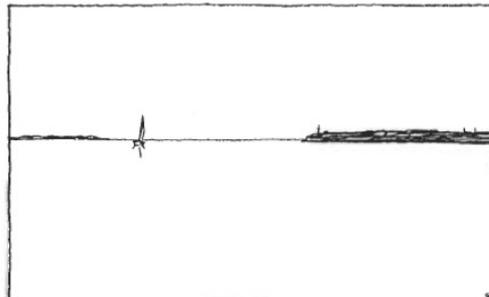
Abhängigkeit von Rauigkeitslänge



Höhenprofil Geschwindigkeitsprofile



| z_0 [m] | Typen von Geländeoberflächen | Rauhigkeits-Klasse |
|-------------------|---|--------------------|
| 1.00 | Stadt Wald | 3 |
| 0.50 | Vorstädte | |
| 0.30 | Bebautes Gelände | |
| 0.20 | Viele Bäume und/oder Büsche | 2 |
| 0.10 | Landwirtschaftliches Gelände mit geschlossenem Erscheinungsbild | |
| 0.05 | Landwirtschaftliches Gelände mit offenem Erscheinungsbild | 1 |
| 0.03 | Landwirtschaftliches Gelände mit sehr wenigen Gebäuden, Bäumen usw. | |
| | Flughäfen mit Gebäuden und Bäumen | |
| 0.01 | Flughäfen, Start- u. Landebahn Weidegras | 0 |
| $5 \cdot 10^{-3}$ | Blanke Erde (glatt) | |
| 10^{-3} | Schneeoberflächen (glatt) | |
| $3 \cdot 10^{-4}$ | Sandoberflächen (glatt) | 0 |
| 10^{-4} | Wasserflächen (Seen, Fjorde und das Meer) | |



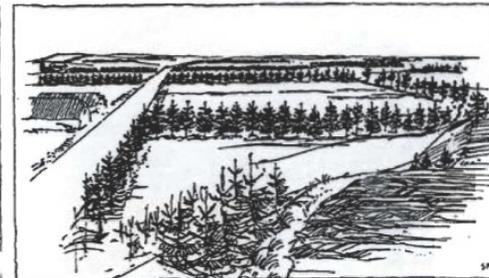
Rauhigkeitsklasse 0 ($z_0=0,00(2)$ m)



Rauhigkeitsklasse 2 ($z_0=0,10$ m)



Rauhigkeitsklasse 1 ($z_0=0,03$ m)

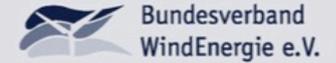


Rauhigkeitsklasse 3 ($z_0=0,40$ m)

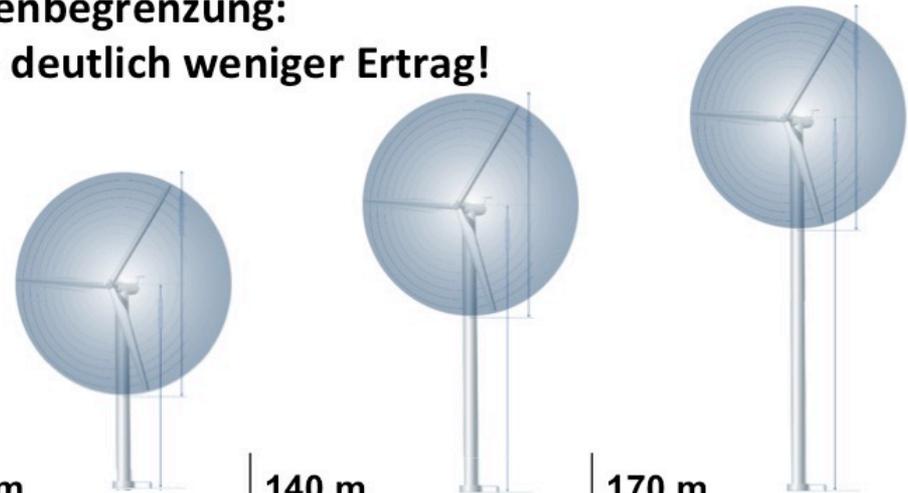
Höhenprofil Höhengradient



Höhenabhängigkeit der Ertrags



Auswirkung einer Höhenbegrenzung: Gleiche Nennleistung - deutlich weniger Ertrag!



| Gesamthöhe | 100 m | 140 m | 170 m |
|------------------|----------------|----------------|----------------|
| Nennleistung | 2000 kW | 2000 kW | 2000 kW |
| Rotordurchmesser | 80 m | 80 m | 90 m |
| Nabenhöhe | 60 m | 100 m | 125 m |
| Ertrag | 4,4 Mio. kWh/a | 5,2 Mio. kWh/a | 6,5 Mio. kWh/a |
| Volllaststunden | 2.200 h/a | 2.600 h/a | 3.250 h/a |

Windmessung

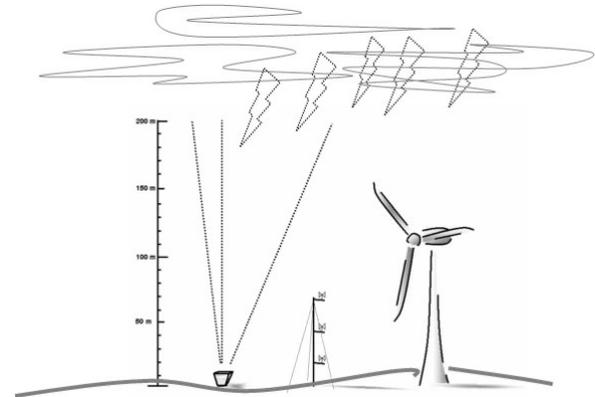
Anemometer & SODAR



Schalenkreuz-
Anemometer



Ultraschall-
Anemometer



SODAR
Sonic Detecting
And Ranging
40 – 600 m
20 m Schichtung

LiDAR
Light Detection
And Ranging

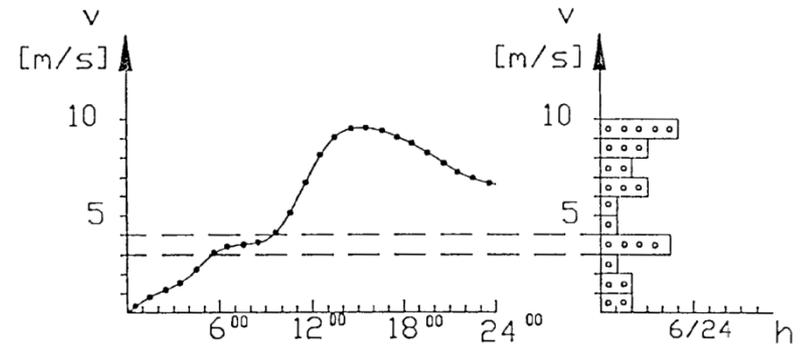
LaDAR
Laser Detection
And Ranging

40 - 200m
 v 0 – 70 m/s
 Δv 0,1 m/s



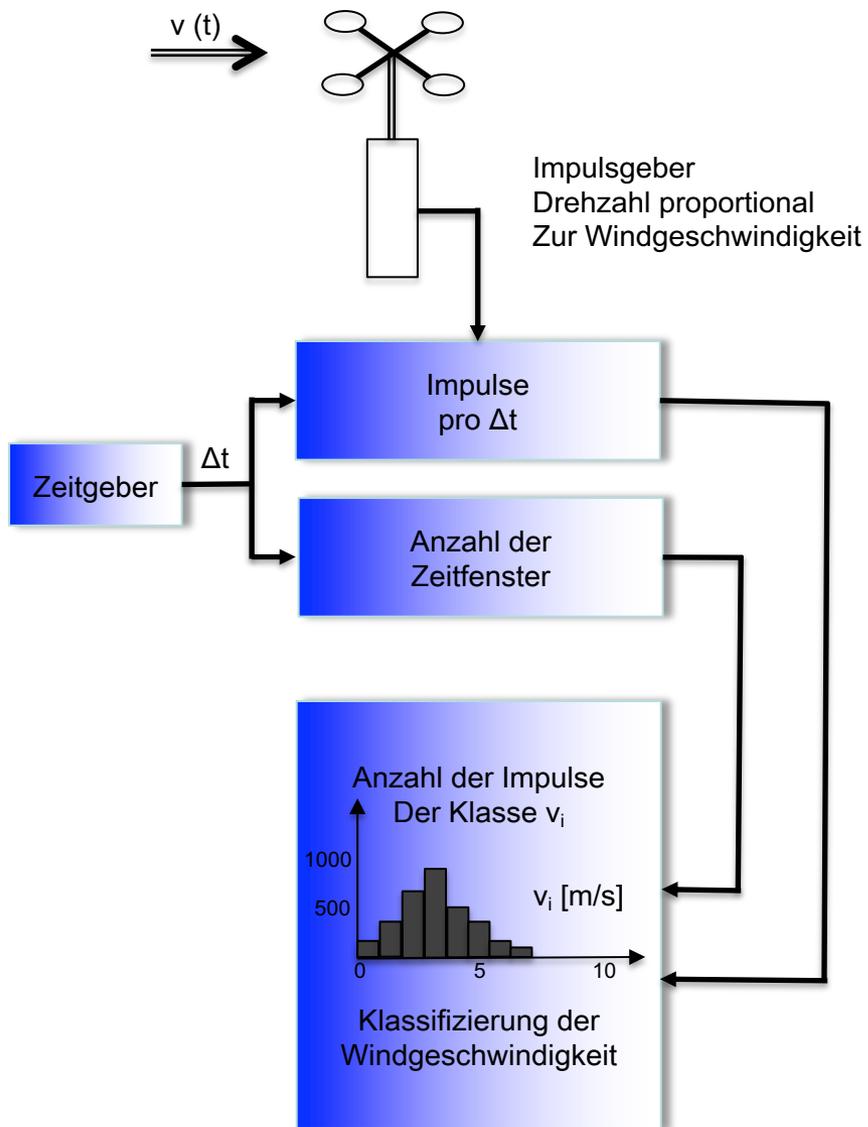
Häufigkeitsverteilung

Grundprinzip / Histogramm

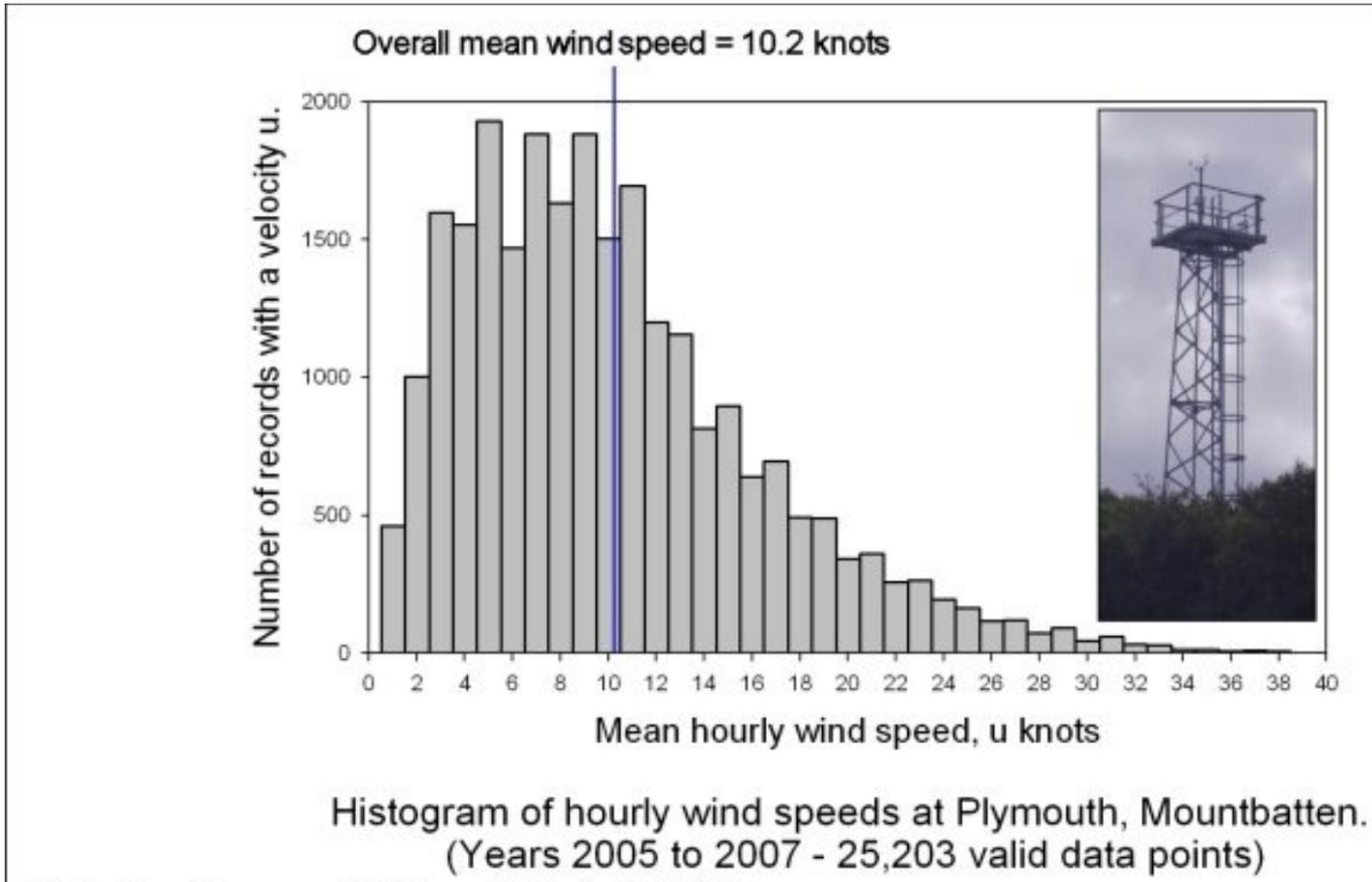


Häufigkeitsverteilung

Grundprinzip / Histogramm



Windhistogramm

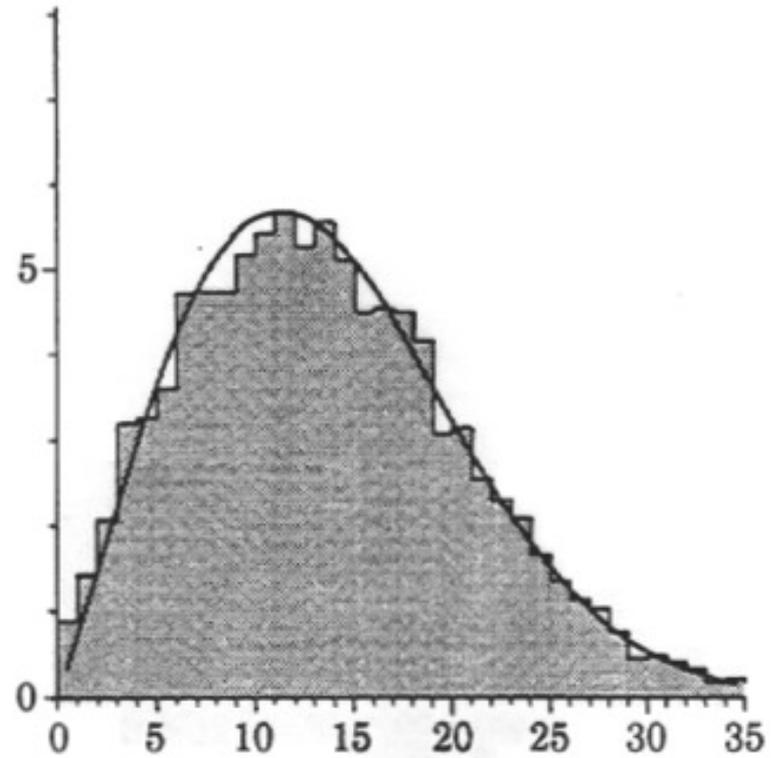
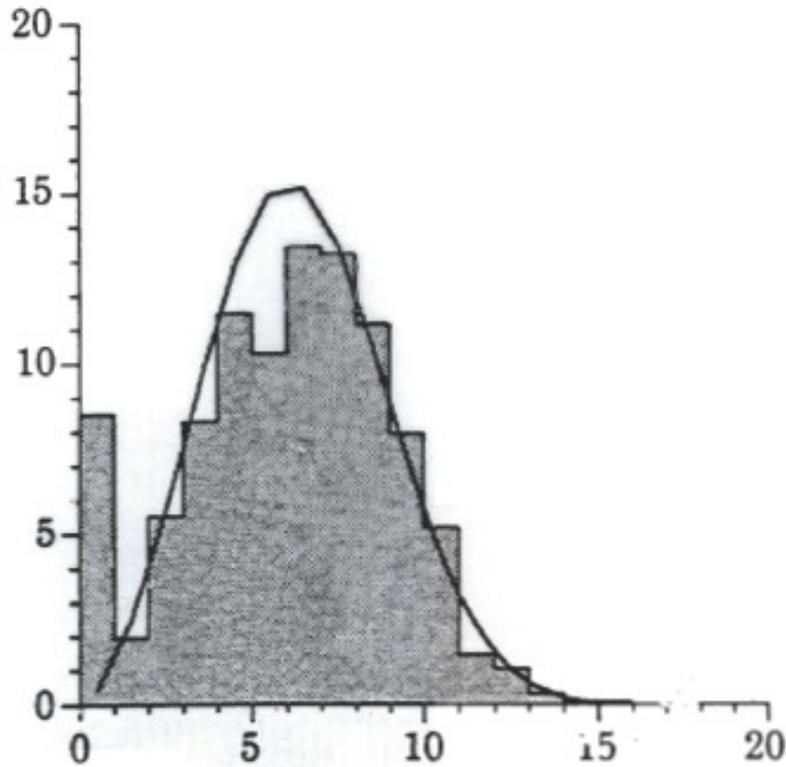


Häufigkeitsverteilung

Beispiele I

Fuerteventura, Kanarische Inseln, Spanien
 $A = 7.2 \text{ m s}^{-1}$, $k = 2.78$

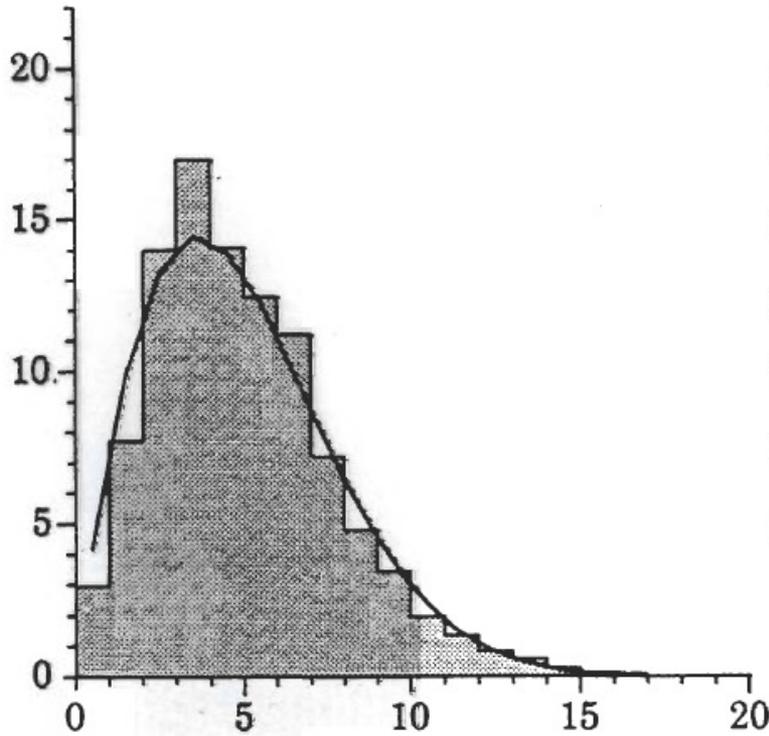
Snaefell, Großbritannien
 $A = 15.4 \text{ m s}^{-1}$, $k = 2.08$



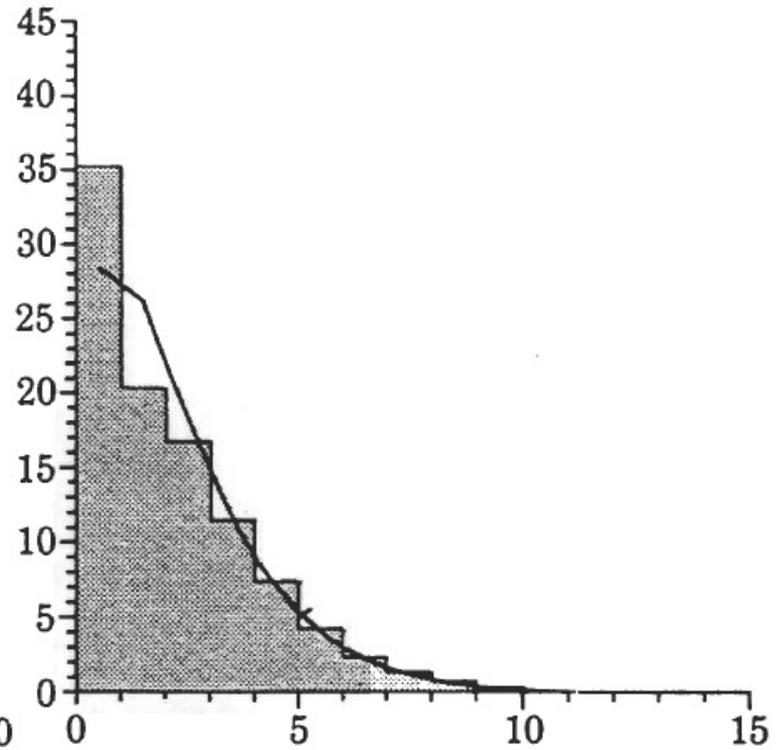
Häufigkeitsverteilung

Beispiele II

Schiphol, Niederlande
 $A = 5.6 \text{ m s}^{-1}$, $k = 1.83$



Mont de Marsan, Frankreich
 $A = 2.4 \text{ m s}^{-1}$, $k = 1.24$



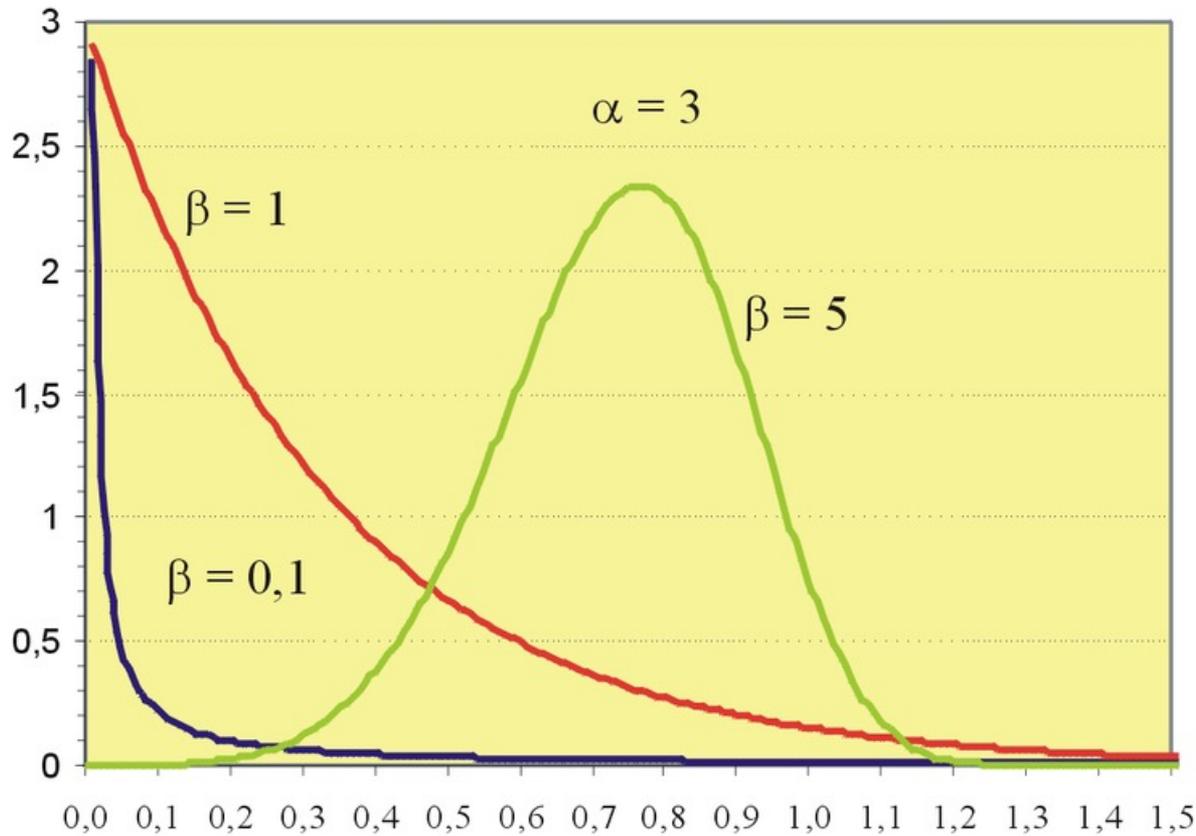
$$f(v) = \frac{K}{A} \cdot \left(\frac{v}{A}\right)^{K-1} \cdot e^{-\left(\frac{v}{A}\right)^K} \left[\frac{\text{Prozent}}{m/s} \right]$$

- $F(v)$ Auftrittswahrscheinlichkeit der Windgeschwindigkeit je Windgeschwindigkeitsintervall
- v Geschwindigkeit im betrachteten Intervall
- A Skalierungsfaktor (scale parameter)
- K Formparameter (shape parameter)
- A & K z.B. „Europäischer Windatlas“

$$f(v) = \frac{\pi}{2} \cdot \left(\frac{v}{v_m^2} \right) \cdot e^{-\left(\frac{\pi}{4}\right) \cdot \left(\frac{v}{v_m}\right)^2} \left[\frac{\text{Prozent}}{m / s} \right]$$

- v_m mittlere Windgeschwindigkeit
- v Geschwindigkeit im betrachteten Intervall
- A entsprechend mittleren Verteilungen
- K Formparameter $K=2$

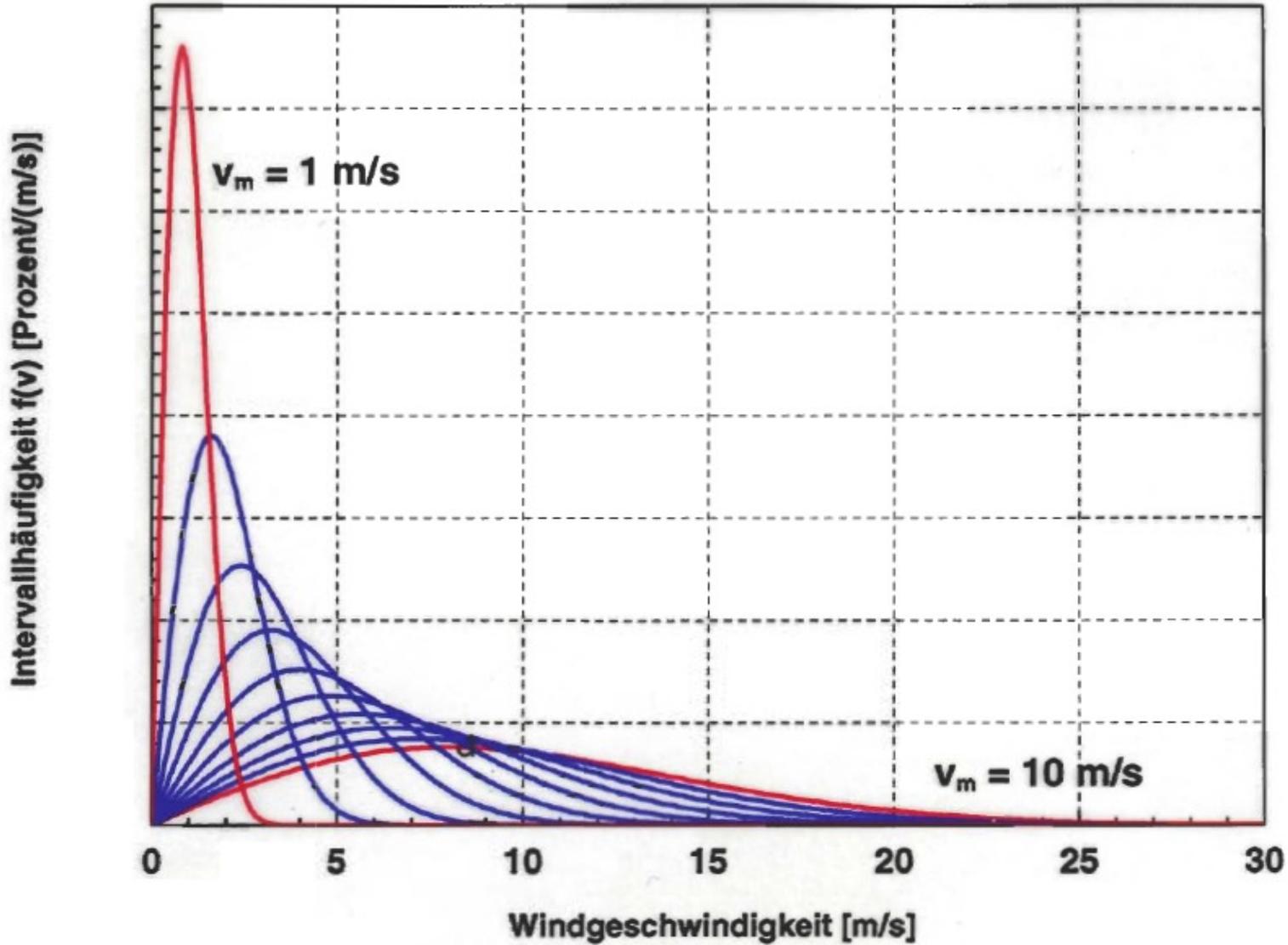
Weibullverteilung verallgemeinert



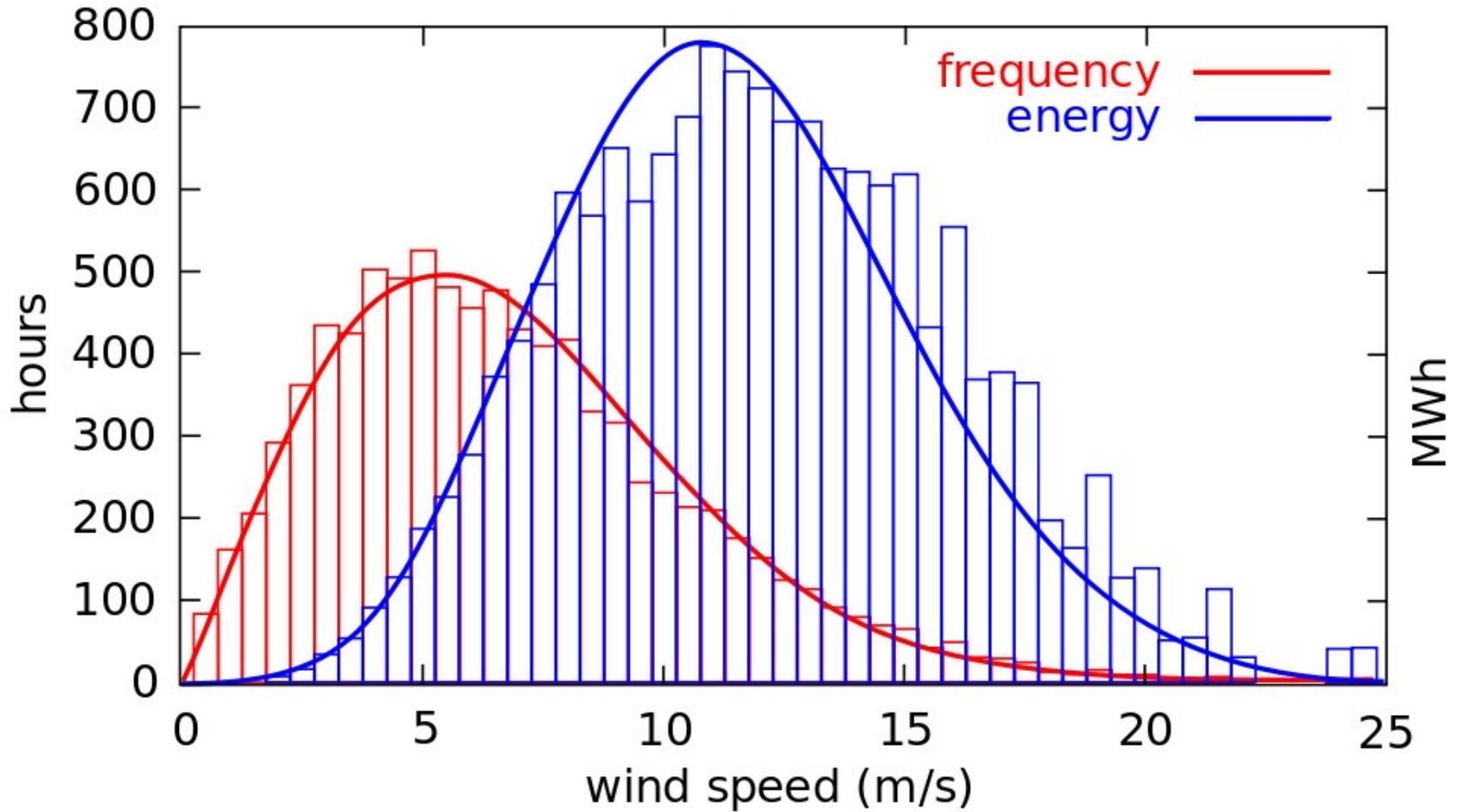
$$f(x) = \alpha \beta x^{\beta-1} e^{-\alpha x^\beta}$$

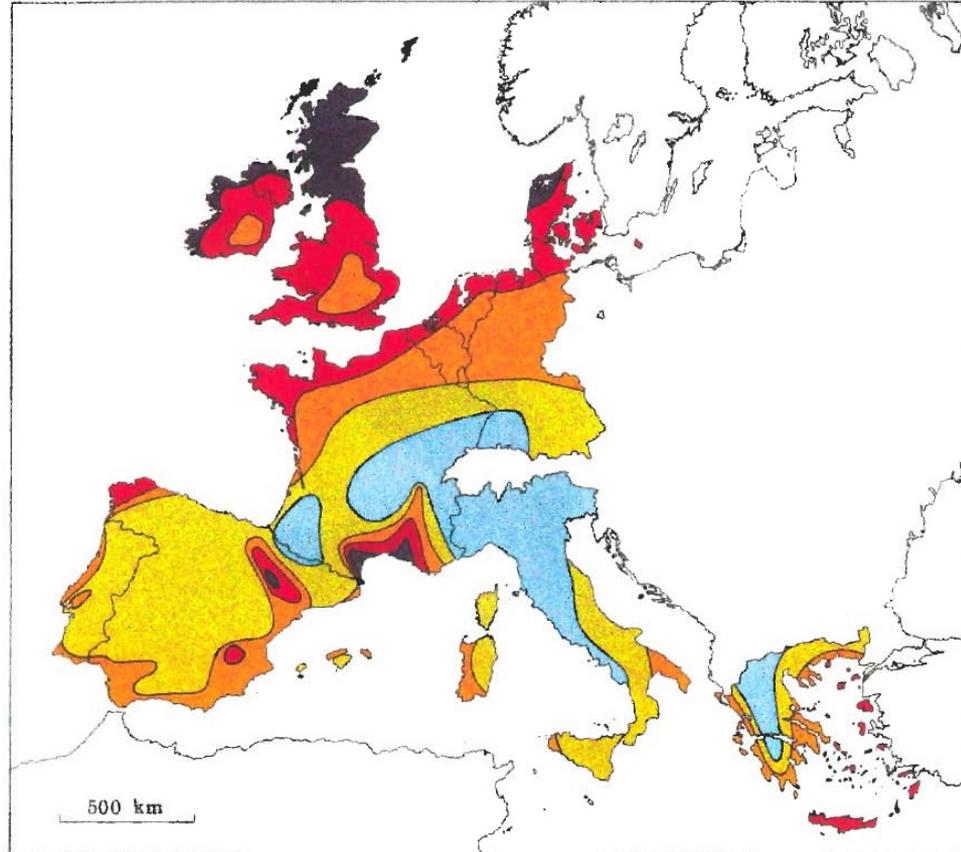
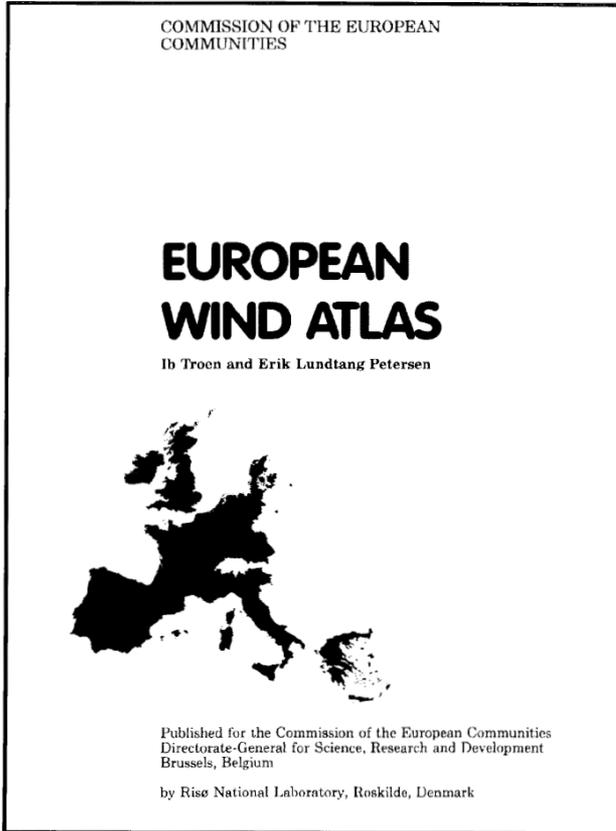
$$\text{Wei}\left(\frac{1}{2\sigma^2}, 2\right) = \text{Rayleigh}(\sigma^2)$$

Rayleigh-Verteilung



Geschwindigkeits- und Energieverteilung





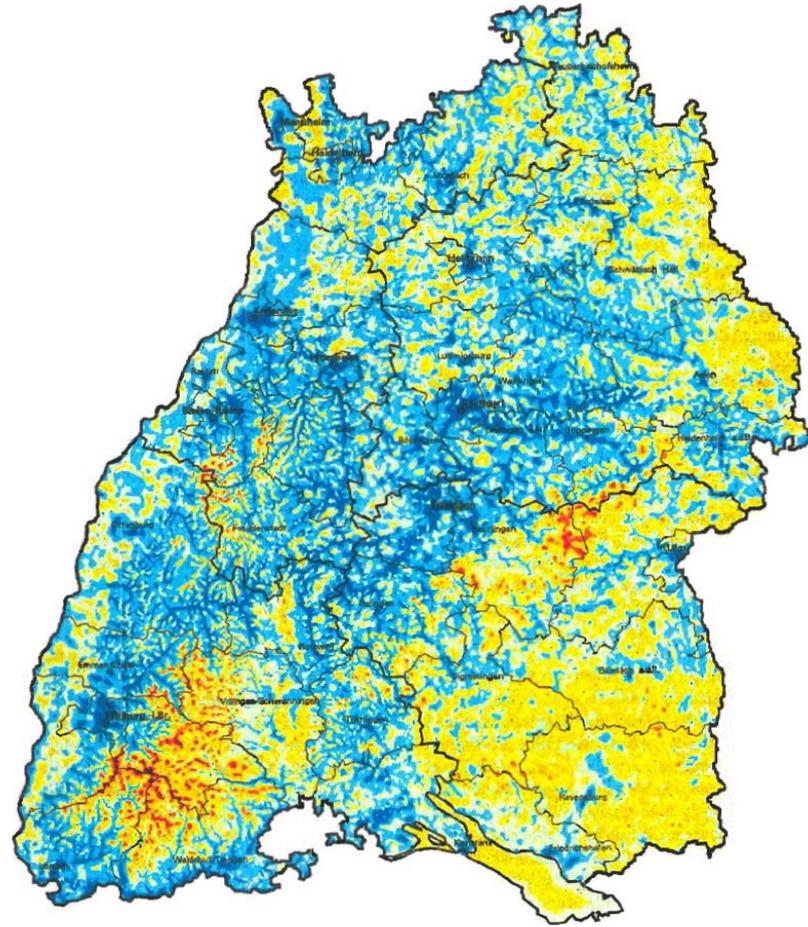
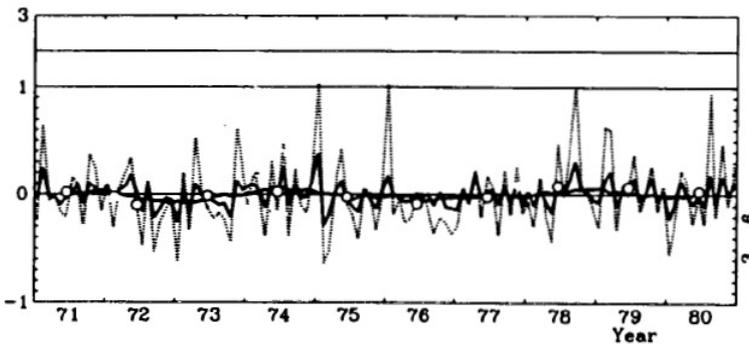
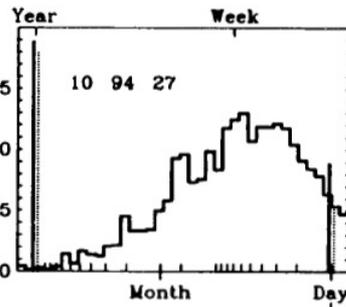
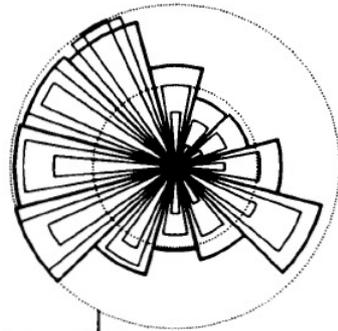
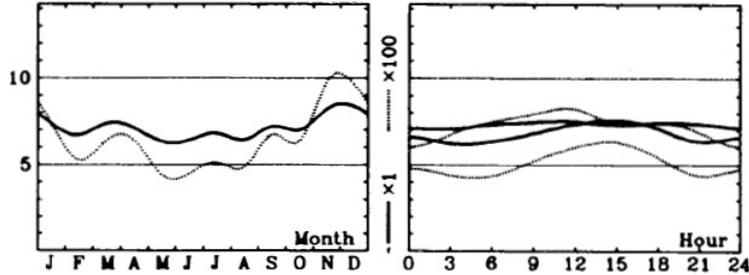
Wind resources¹ at 50 metres above ground level for five different topographic conditions

| | 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 |

List/Sylt, Germany (FRG)

1971-80

12.0 m agl, mean 7.1 m/s, st dev 3.5 m/s, cube 641. m³/s³

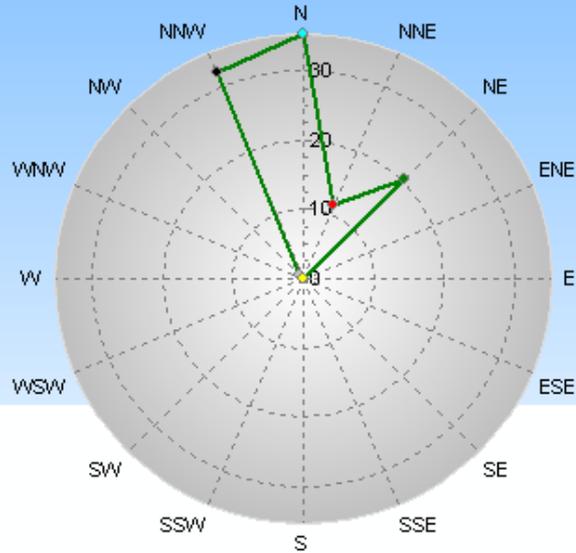


Windverteilung

Wetterstation Emden / Windpower.org

Verteilung Windrichtung Montag / Dienstag, 23.11.2010

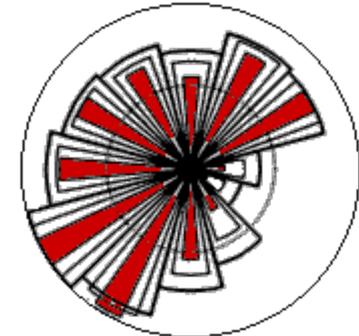
Emden / Ostfriesland



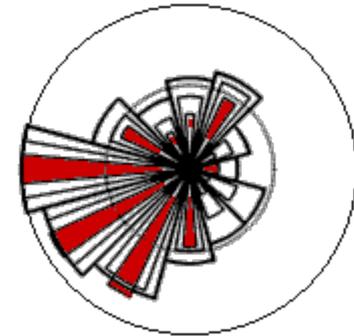
| Direction | % |
|-----------|-------|
| N | 35,36 |
| N-NW | 32,14 |
| NW | 0,71 |
| W-NW | 0,00 |
| W | 0,00 |
| W-SW | 0,00 |
| SW | 0,00 |
| S-SW | 0,00 |
| S | 0,00 |
| S-SO | 0,00 |
| SO | 0,00 |
| O-SO | 0,00 |
| O | 0,00 |
| O-NO | 0,00 |
| NO | 20,36 |
| N-NO | 11,43 |

280 / 0 Werte -> 0.0% Windstille - Ø 15,0km/h - Max. 33,9km/h - 336.4 km

© WsWin32 - Wetterstation Emden



© 1998 www.WINDPOWER.org



© 1998 www.WINDPOWER.org

Simulationsmodelle

Skalenbereiche

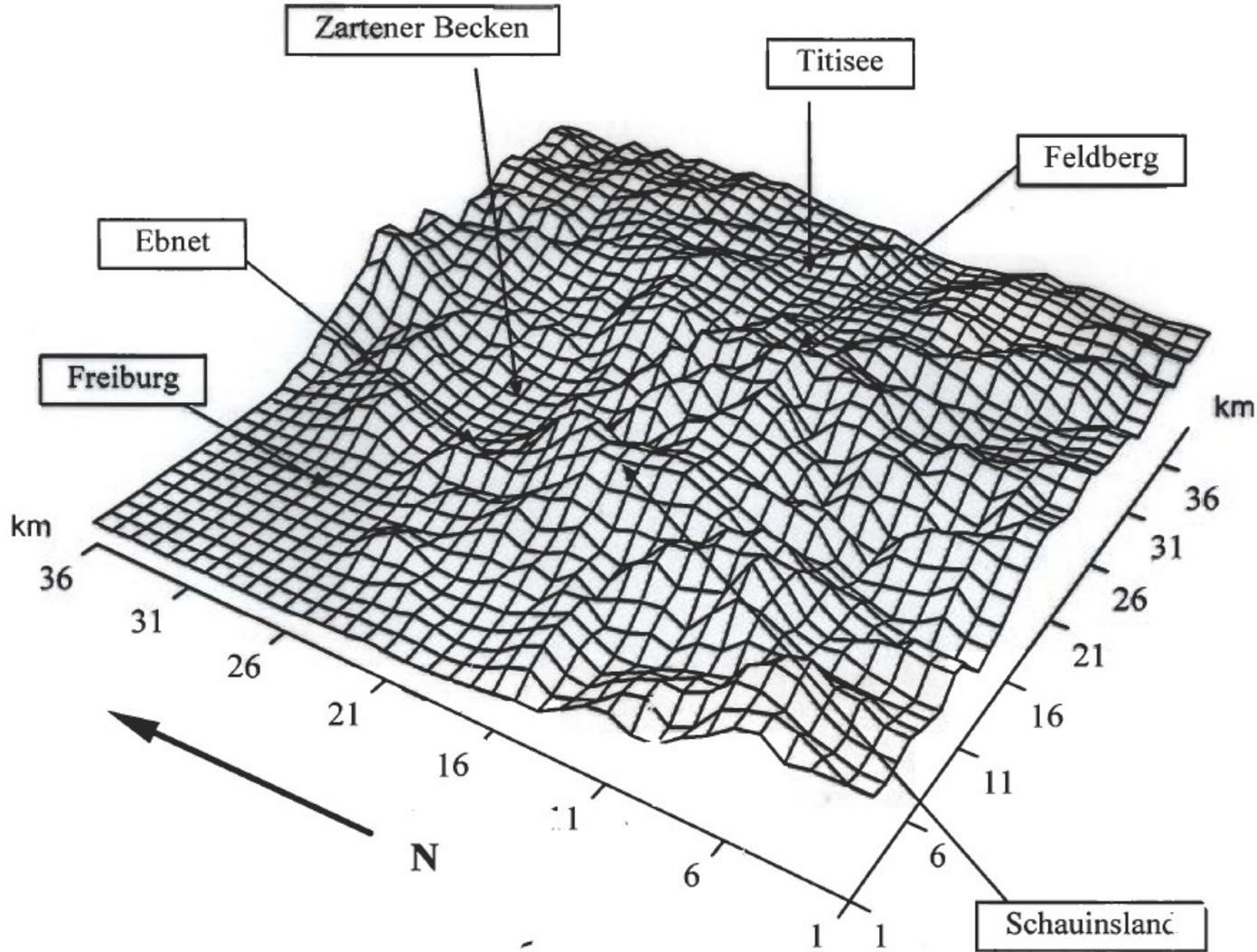
| Skalenbereiche | Längendimension | Zeitdimension | Typische Phänomene |
|----------------|-----------------|--------------------|--------------------|
| Makroskala | α | > 10.000 km | Planet. Wellen |
| | β | 2.000 - 10.000 km | Antizyklonen |
| Mesoskala | α | > 1 Tag | Hurricane |
| | β | 1 h - 1 Tag | Land- Seewind |
| | γ | einige Min. - Std. | Berg- Talwind |
| Mikroskala | α | bis zu 1 Stunde | Hangwinde |
| | β | im Minutenbereich | Tornado |
| | γ | bis zu 1 Minute | Staubwirbel |

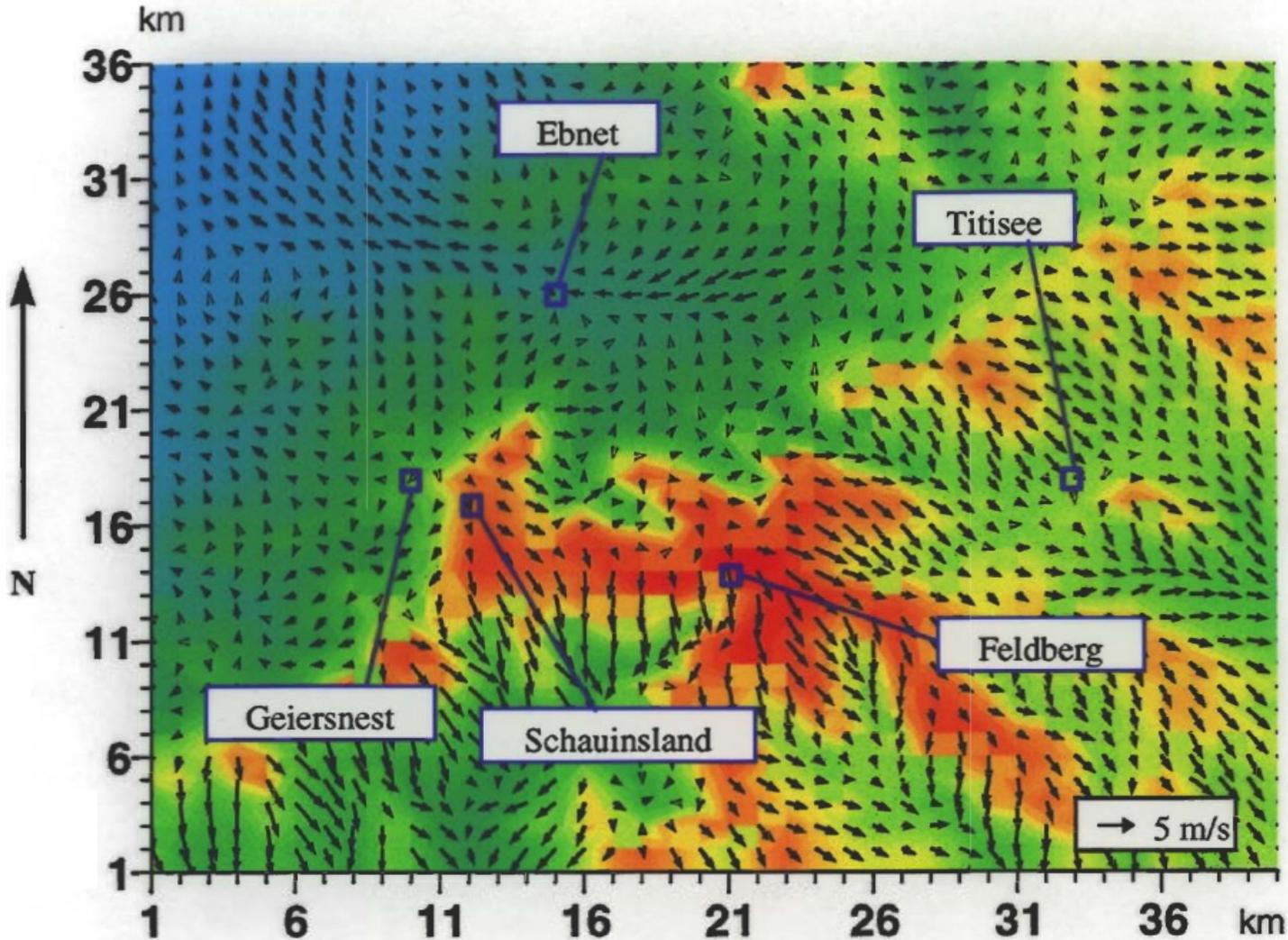
Physikalische Gesetzmäßigkeiten des 3- dimensionalen Rechenmodells MEMO (Mesoskaliges Modell)

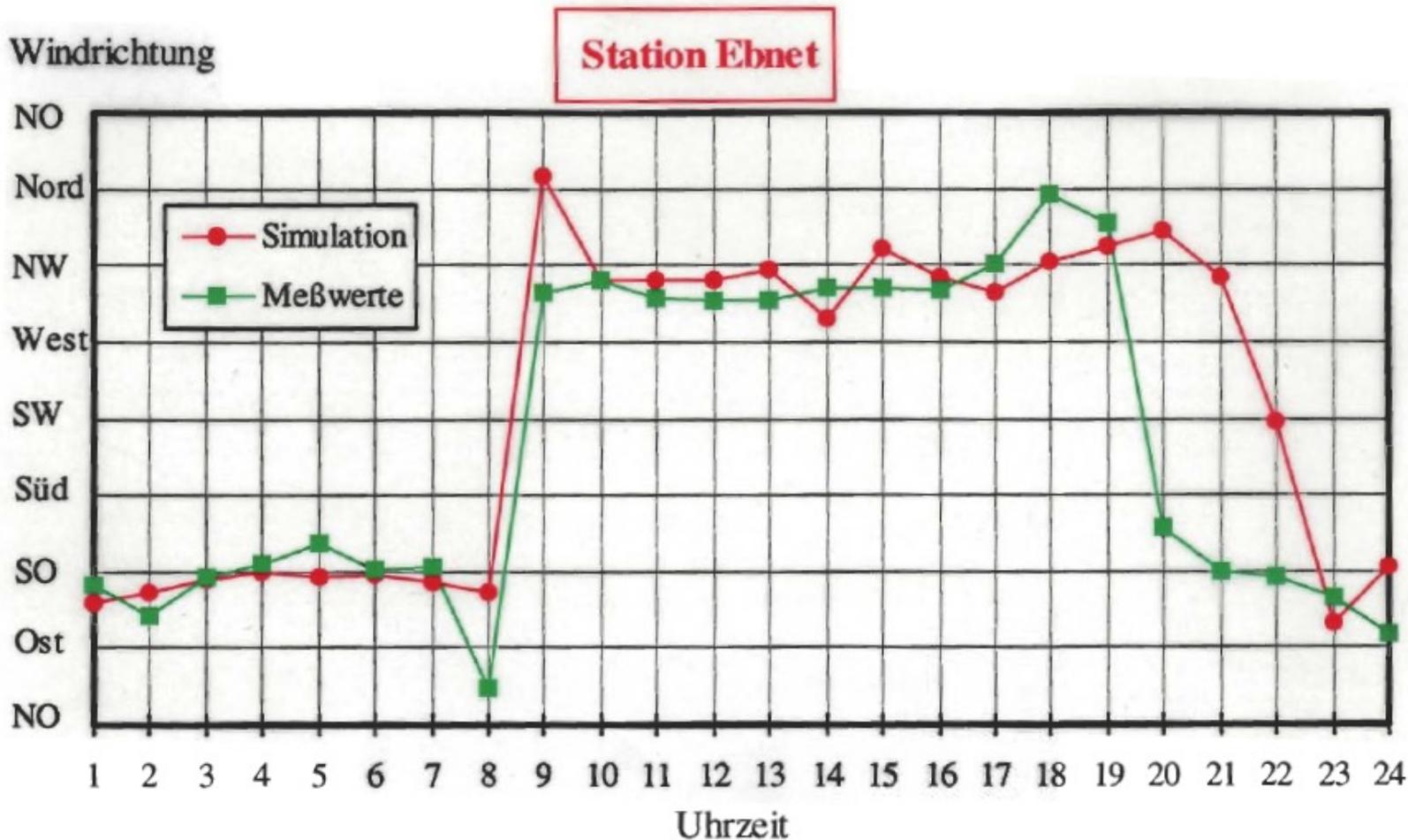
- Impulserhaltung
- Massenerhaltung
- Erhaltungssätze für skalare Größen
 - Temperatur (1. HS Thermodynamik)
 - Luftfeuchte
 - Turbulenzenergie
 - ...

Simulationsmodelle

Geländemodell

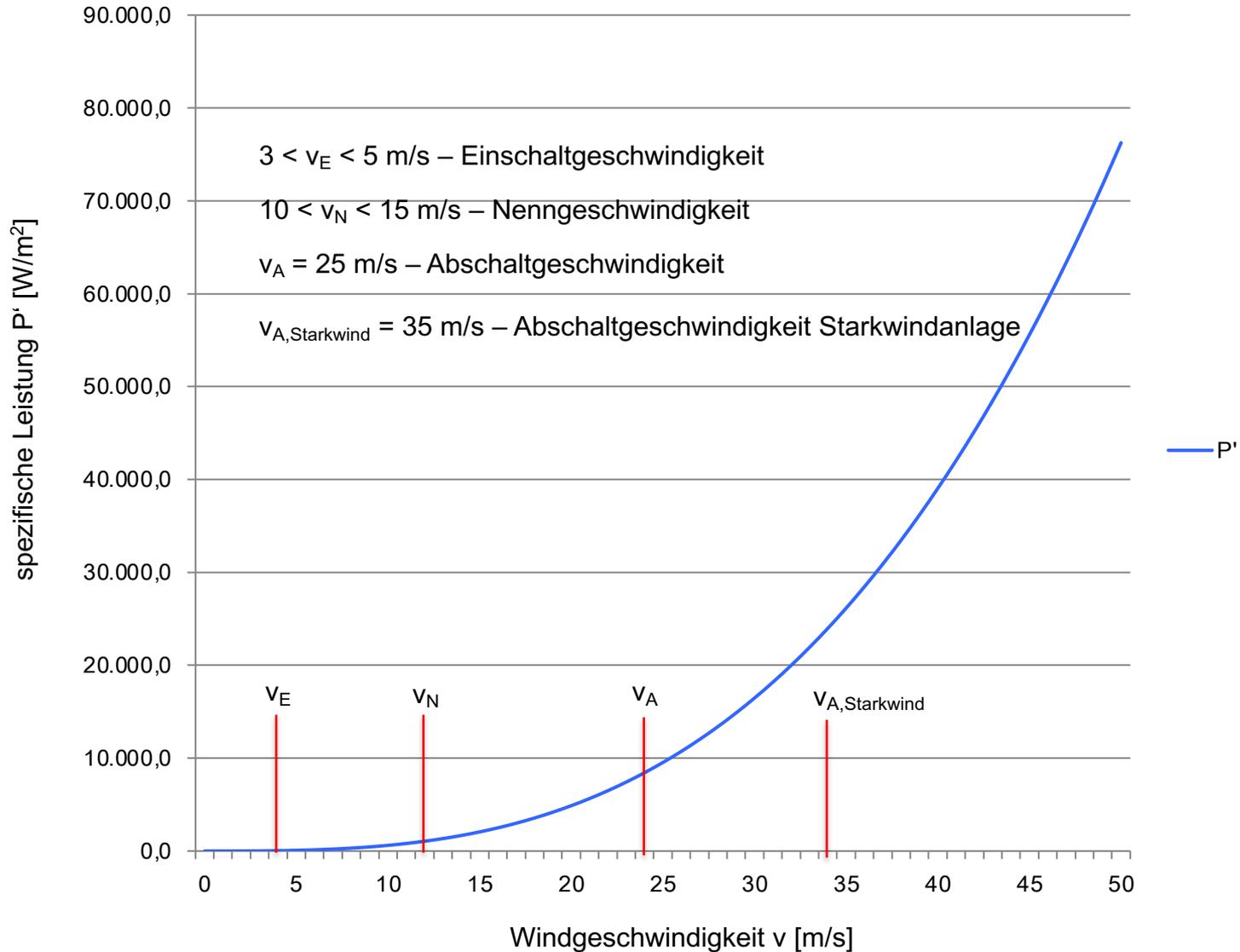






Spezifische Leistung des Windes

P'



Beaufort Skala

| Stärke in Bft. | Bezeichnung Windstärke | km/h | kn | m/s | mph |
|-------------------|---------------------------|-----------|---------|-------------|-------------|
| 0 | Windstille | 0 - <1 | 0 - <1 | 0 - 0,2 | 0 - 1,1 |
| 1 | leiser Zug | 1 - 5 | 1 - 3 | 0,3 - 1,5 | 1,2 - 4,5 |
| 2 | leichte Brise | 6 - 11 | 4 - 6 | 1,6 - 3,3 | 4,6 - 8,0 |
| 3 | schwacher Wind | 12 - 19 | 7 - 10 | 3,4 - 5,4 | 8,1 - 12,6 |
| 4 | mäßiger Wind | 20 - 28 | 11 - 15 | 5,5 - 7,9 | 12,7 - 18,3 |
| 5 | frischer Wind | 29 - 38 | 16 - 21 | 8,0 - 10,7 | 18,4 - 25,2 |
| 6 | starker Wind | 39 - 49 | 22 - 27 | 10,8 - 13,8 | 25,3 - 32,1 |
| 7 | stelfer Wind | 50 - 61 | 28 - 33 | 13,9 - 17,1 | 32,2 - 39,0 |
| 8 | stürmischer Wind | 62 - 74 | 34 - 40 | 17,2 - 20,7 | 39,1 - 47,1 |
| 9 | Sturm | 75 - 88 | 41 - 47 | 20,8 - 24,4 | 47,2 - 55,1 |
| 10 | schwerer Sturm | 89 - 102 | 48 - 55 | 24,5 - 28,4 | 55,2 - 64,3 |
| 11 | orkanartiger Sturm | 103 - 117 | 56 - 63 | 28,5 - 32,6 | 64,4 - 73,5 |
| 12 | Orkan | ab 118 | ab 64 | ab 32,7 | ab 73,6 |

© Meteomedia

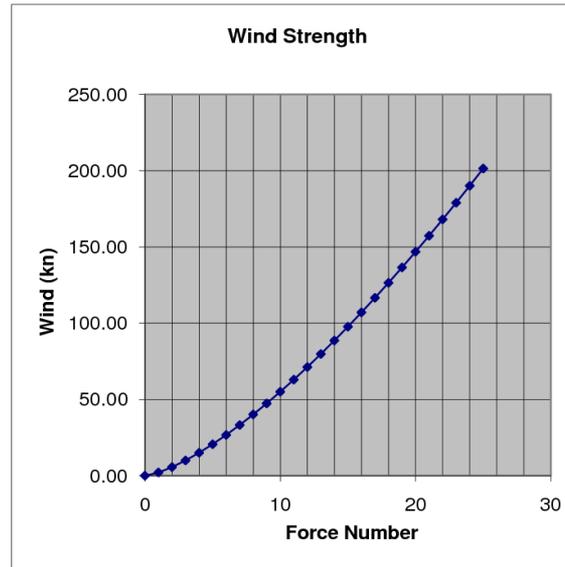
Beaufort Skala Extended

EXTENDED BEAUFORT SCALE

N = Force Number W = Wind Strength

| Force No. | Wind kn | $W = 2.11N^{1.416}$ | Waves ft | |
|-----------|-----------|---------------------|-----------|-----------------|
| 0 | 0 - 1 | 0.00 | 0 | Calm |
| 1 | 1 - 3 | 2.11 | 1/4 | Light air |
| 2 | 3 - 6 | 5.63 | 1/2 | Light breeze |
| 3 | 6 - 10 | 10.00 | 2 | Gentle breeze |
| 4 | 10 - 16 | 15.02 | 4 | Moderate breeze |
| 5 | 16 - 21 | 20.61 | 6 | Fresh breeze |
| 6 | 21 - 27 | 26.68 | 10 | Strong breeze |
| 7 | 27 - 33 | 33.18 | 14 | Near gale |
| 8 | 33 - 40 | 40.09 | 18 | Gale |
| 9 | 40 - 47 | 47.37 | 23 | Strong gale |
| 10 | 47 - 55 | 54.99 | 29 | Storm |
| 11 | 55 - 63 | 62.94 | 37 | Violent storm |
| 12 | 63 - 71 | 71.19 | 45 | Hurricane |
| 13 | These are | 79.73 | These are | |
| 14 | "Given" | 88.55 | "Given" | |
| 15 | data | 97.64 | data | |
| 16 | | 106.98 | | |
| 17 | | 116.57 | | |
| 18 | | 126.40 | | |
| 19 | | 136.46 | | |
| 20 | | 146.74 | | |
| 21 | | 157.23 | | |
| 22 | | 167.94 | | |
| 23 | | 178.85 | | |
| 24 | | 189.96 | | |
| 25 | | 201.26 | | |

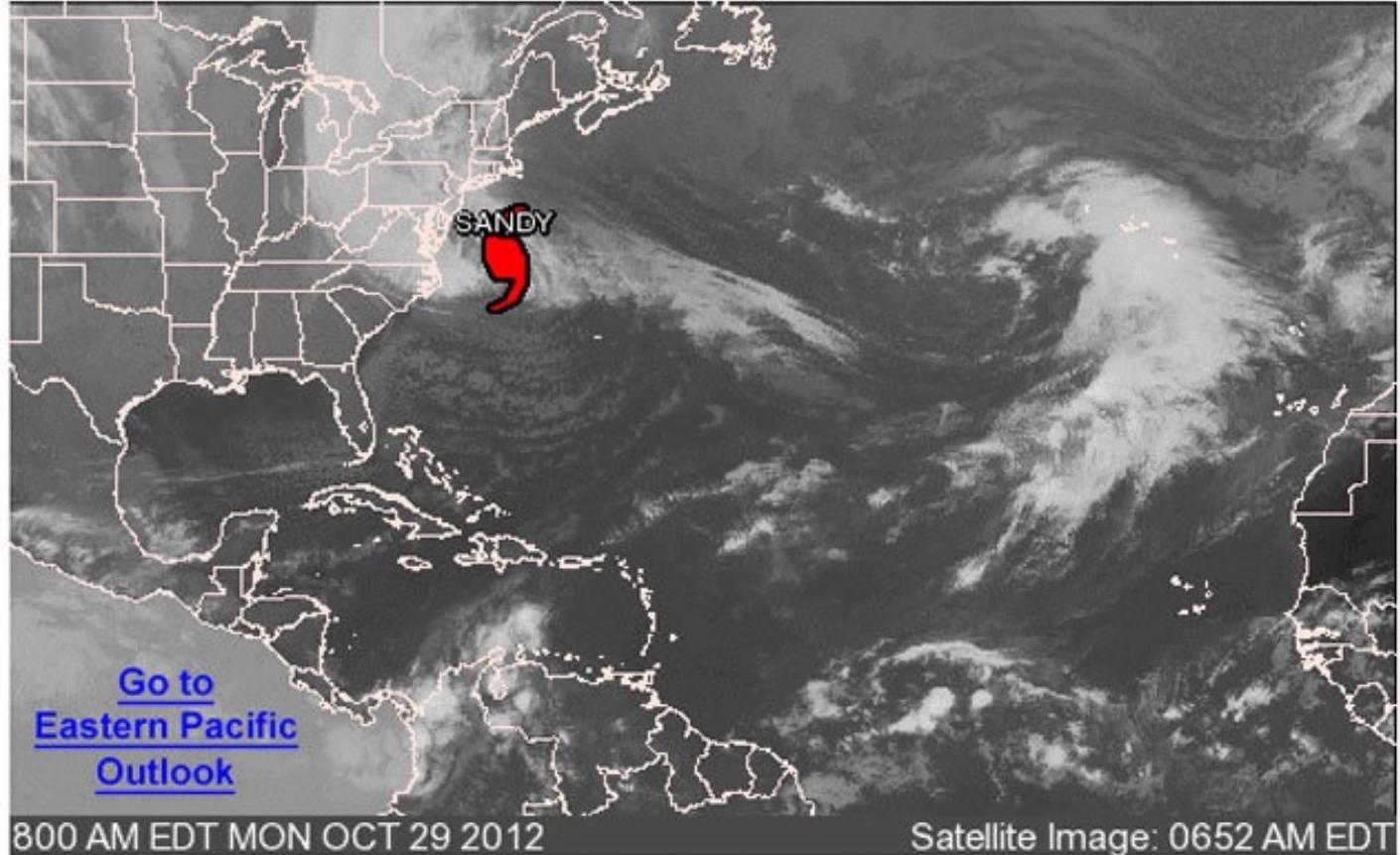
These are
calculated
upper end
of range
data



See sheet 2 for waves

Hurricane Sandy 2012

Ø 1.800 km



[Go to
Eastern Pacific
Outlook](#)

Outlined areas denote current position of systems discussed in the Tropical Weather Outlook. Color indicates probability of tropical cyclone formation within 48 hours.

 Low <30%

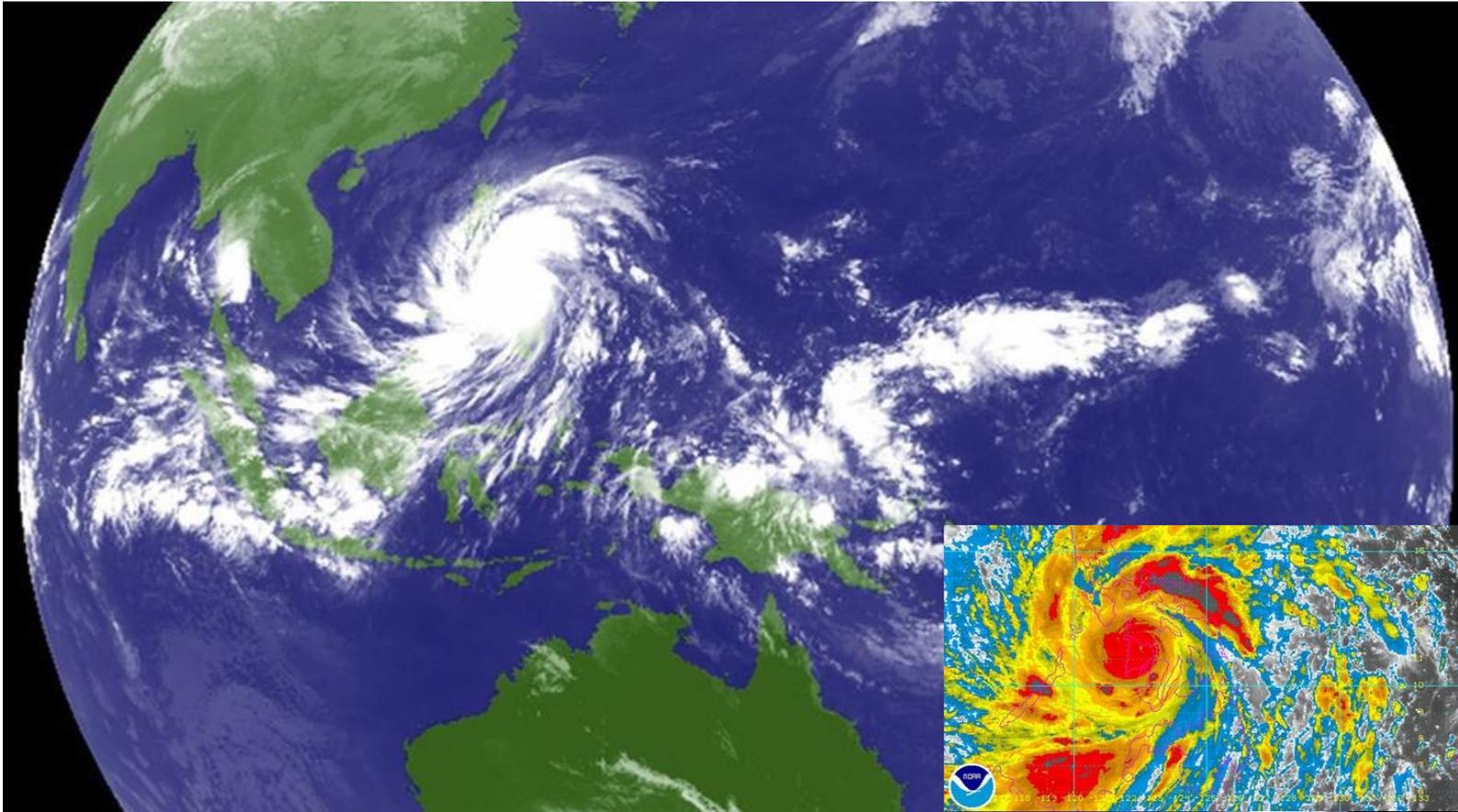
 Medium 30-50%

 High >50%

GIS data: [.shp](#)

Taifun Haiyan 2013

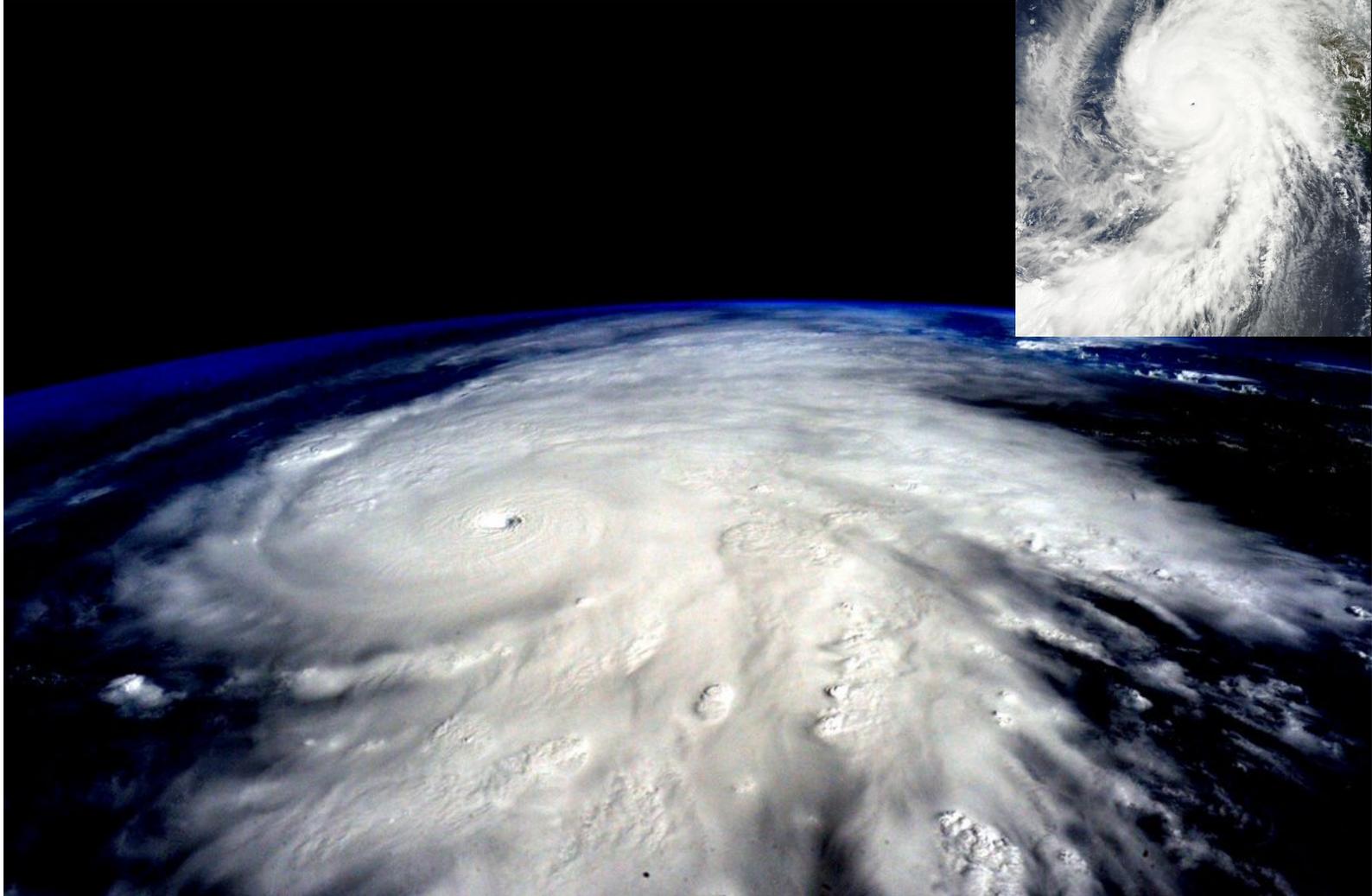
379 km/h = 105 m/s = 204 kn = 25 bf
300-500 l/m²



Hurricane Patricia 2015

400 km/h = 111 m/s = 216 kn = 25 bf

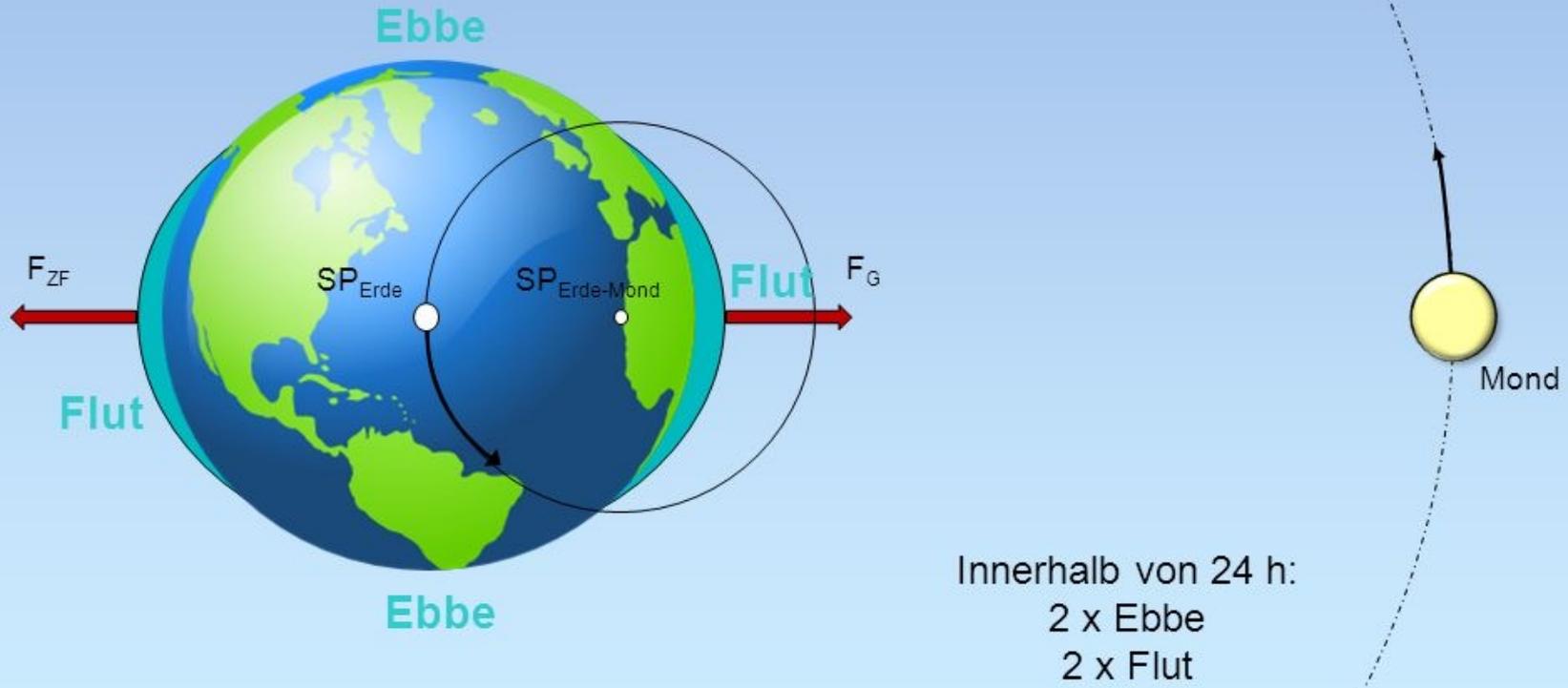
879 hPa Category 5



Gezeitenkräfte

System Erde-Mond (Sonne)

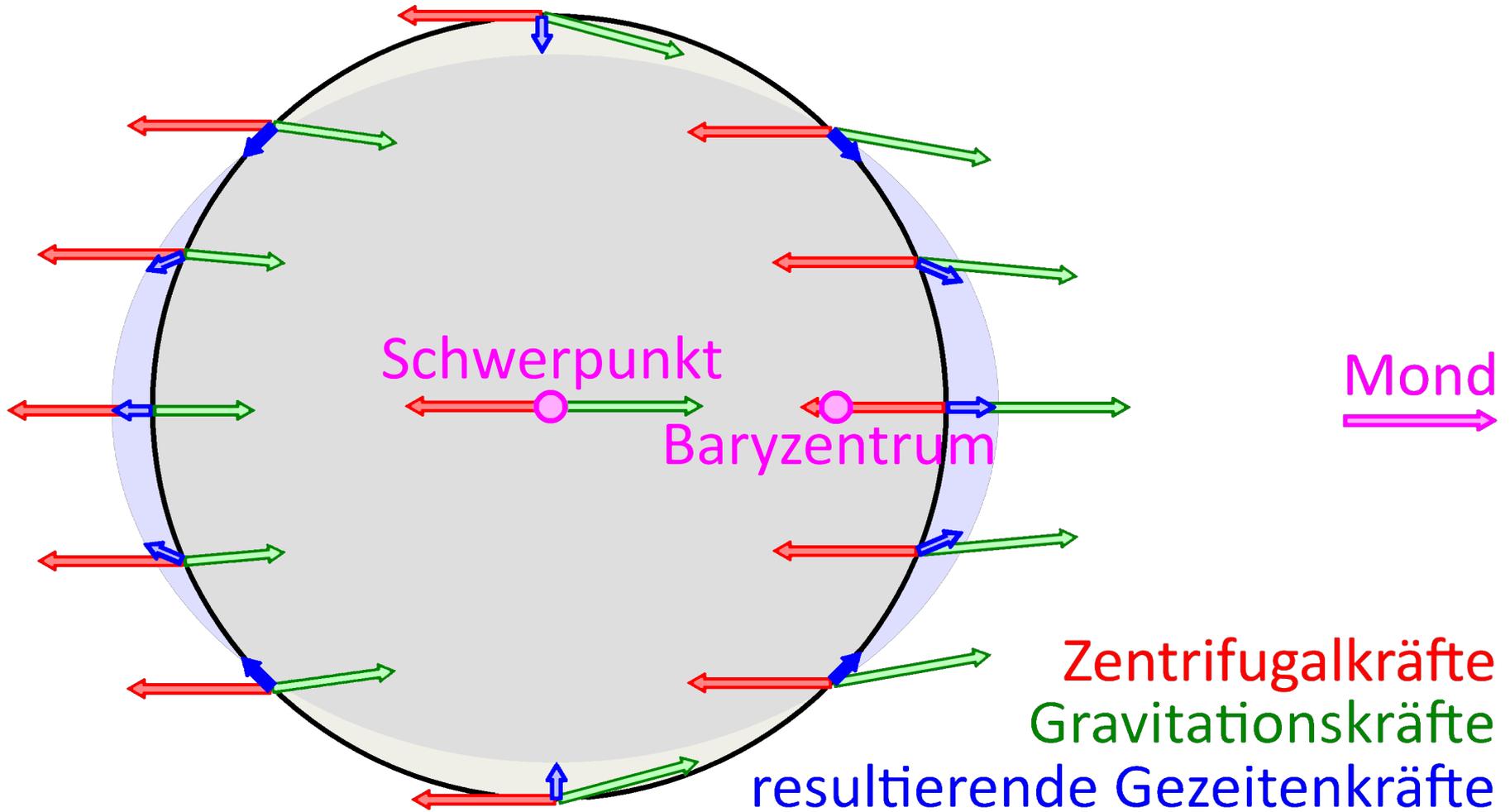
Gezeiten



Kraftwirkungen

11

Gezeitenkräfte



Gravitationskräfte

Auswirkungen offener Ozean

| Himmelskörper | Rel. Beschl. | Auslenkung |
|------------------------------|-------------------|-------------------|
| Mond | 1 | 30 cm |
| Sonne | 0,45 | 14 cm |
| Venus in unterer Konjunktion | $5 \cdot 10^{-5}$ | 17 μm |
| Jupiter | $6 \cdot 10^{-6}$ | 2 μm |
| Mars in Opposition | $2 \cdot 10^{-6}$ | 0,5 μm |
| Mars in Konjunktion | $1 \cdot 10^{-8}$ | 3 nm |

- Verformung von Himmelskörpern
 - Ellipsoide
- Abbremsung der Eigenrotation
 - Mond (gebundene Rotation)
- Erhitzung des Himmelskörpers
 - „Durchwalken“
 - Erhitzung des Erdkerns
 - Jupitermond Io Vulkanismus
- Maritime Gezeiten
 - Ebbe und Flut (Küsten)
- Atmosphäre
 - Atmosphäre hat zu geringe Masse für größeren Beitrag