THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

Department of Aeronautical and Aviation Engineering
航空及民航工程學系

Introduction to Aircraft Systems

Siyang Zhong/鍾思陽

Room: R809

Telephone: 3400 8486

Email: siyang.zhong@polyu.edu.hk

Atmospheric condition

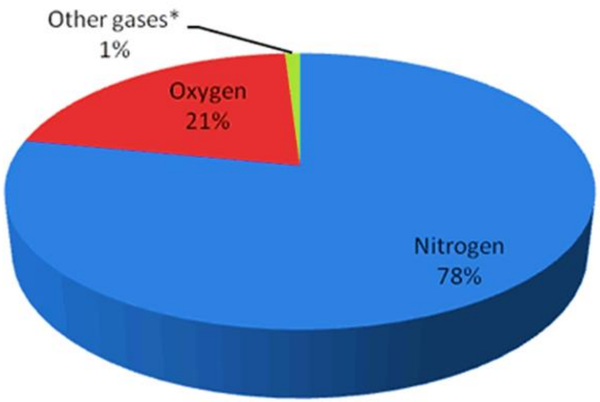
- Earth's atmosphere
- Why should atmospheric condition be considered?
- Definition of altitude
- Standard atmosphere
- Atmospheric wind and turbulence
- Summary

Earth's atmosphere

Atmosphere of Earth

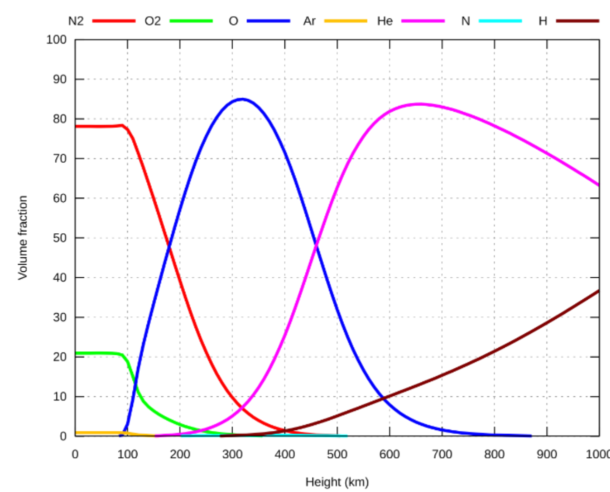
- A layer of gas mixture, known collectively as air, surrounding the Earth's surface
  - Flow particles that are retained by Earth's gravity
  - We breath and we flight in this layer
- Atmosphere also protects Earth and the lives from the outer space objects and the ultraviolet solar radiations.

Atmosphere of Earth



- Nitrogen (N_2)
- Oxygen (O_2)
- Argon (Ar)
- Carbon dioxide (CO_2)
- Neon (Ne)
- Helium (He)
- Methane (CH_4)
- Krypton (Kr)
- Hydrogen (H_2)
- Nitrous oxide (N_2O)
- Carbon monoxide (CO)
- Xenon (Xe)
- Ozone (O_3)
- Nitrogen dioxide (NO_2)
- Iodine (I_2)
- Ammonia (NH_3)

- The mass of atmosphere is about 5.15×10^{18} kg, and ¾ of them is within 11km of the surface.
- By mole fraction, dry air contains 78% nitrogen, 21% oxygen, etc.
- It can contain water vapors, depending on height.
- The volume fraction of each components varies with altitude.

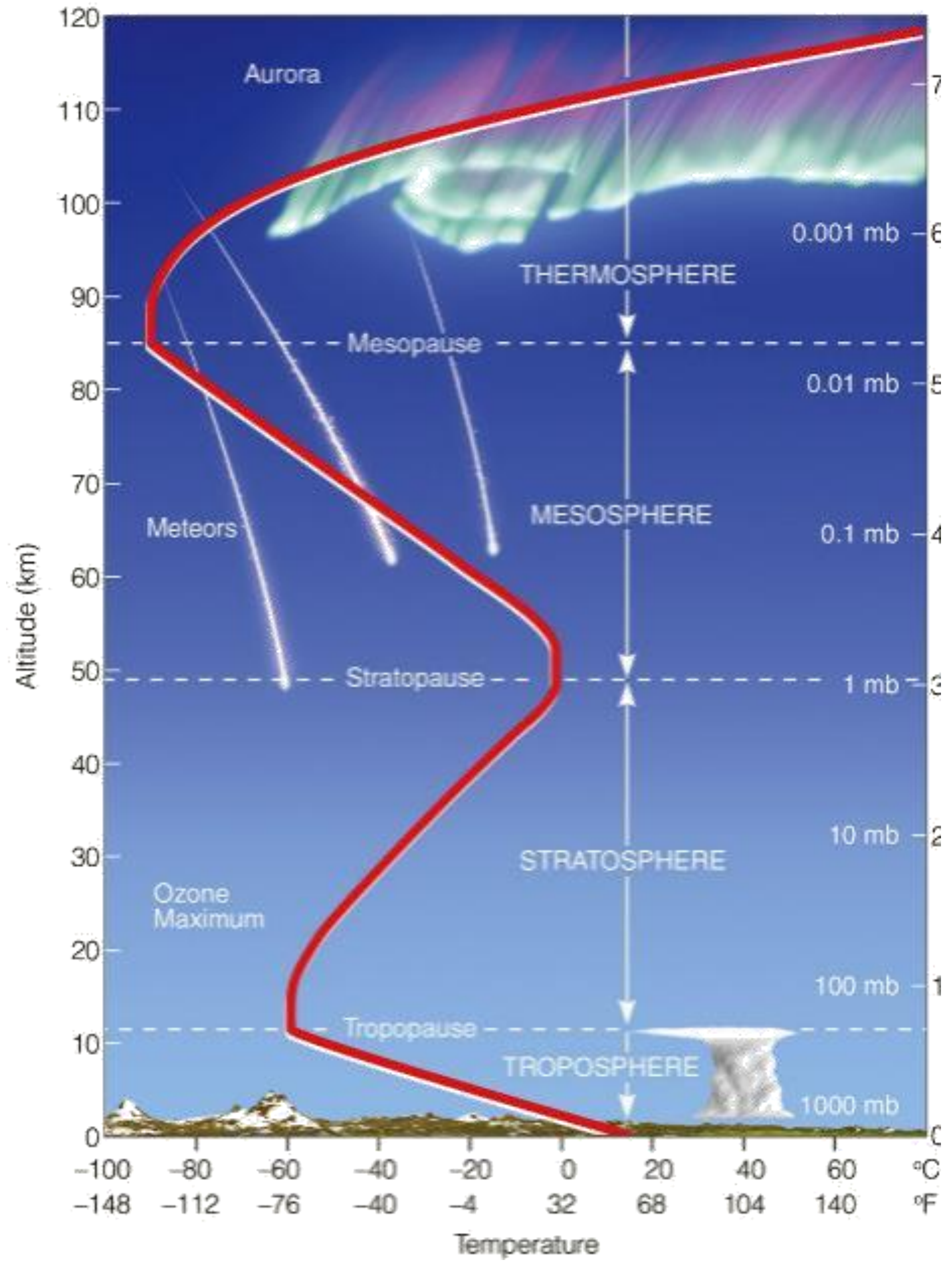


Volume fraction of main constitutes of air at different height

Karman line: around 100 km from the sea level

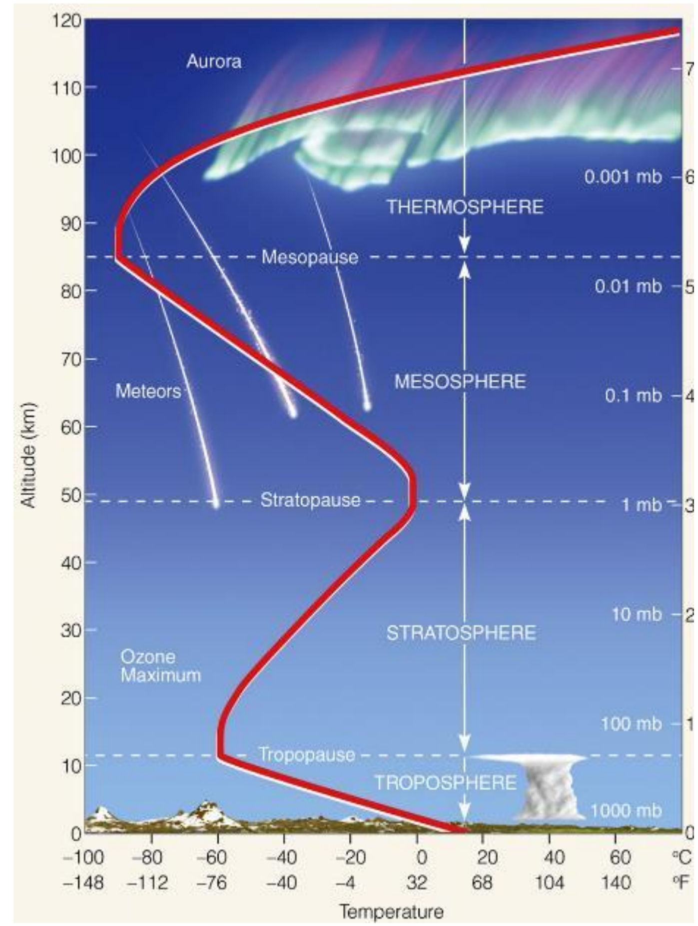
Atmosphere of Earth

- The atmosphere extends to 10,000 km above the surface, and it merges seamlessly with space.
- At different height, i.e., altitude, the air properties change dynamically. The atmosphere is divided into several layers:
  - Troposphere /對流層: 0-12 km
  - Stratosphere /平流層: 12-50 km
  - Mesosphere/中間層: 50-80 km
  - Thermosphere /熱層: 80-700 km
  - Exosphere /外逸層: 700-10,000 km



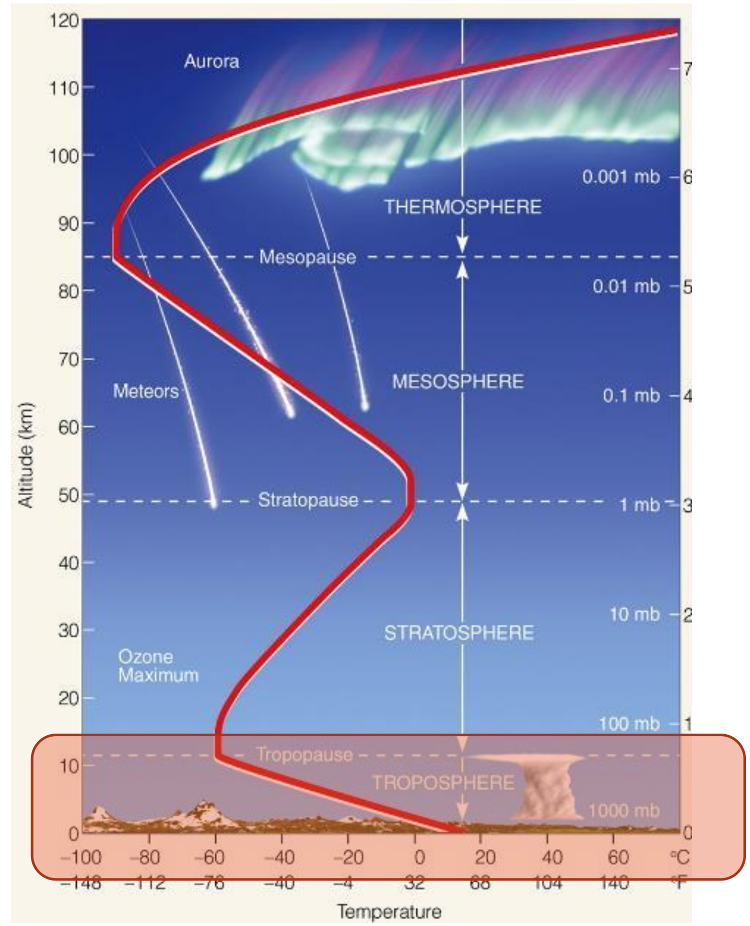
Atmosphere of Earth

- The invisible boundaries between the various layers maybe characterized by abrupt changes in properties, temperature and/or other behavior. The interfaces between the layers are called:
  - Tropopause
  - Stratopause
  - Mesopause
  - Thermopause



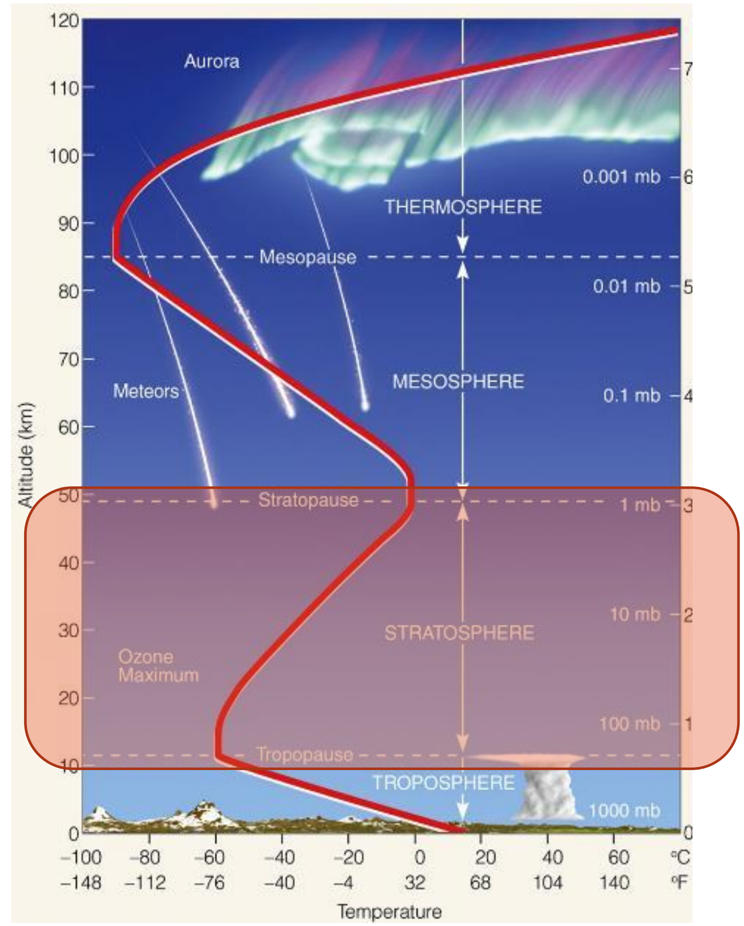
Atmosphere of Earth

- Troposphere/對流層 (0-12 km)
  - Lowest layer human activities take place
  - The temperature usually decreases with altitude due to the decreased heat transfer from the surface
  - It contains about 80% mass of Earth's atmosphere
  - The vertical mixing of the air and water vapor take place in this layer.
  - Most conventional aviation activities take place in this layer.
    - The only accessible layer by propeller-driven aircraft.



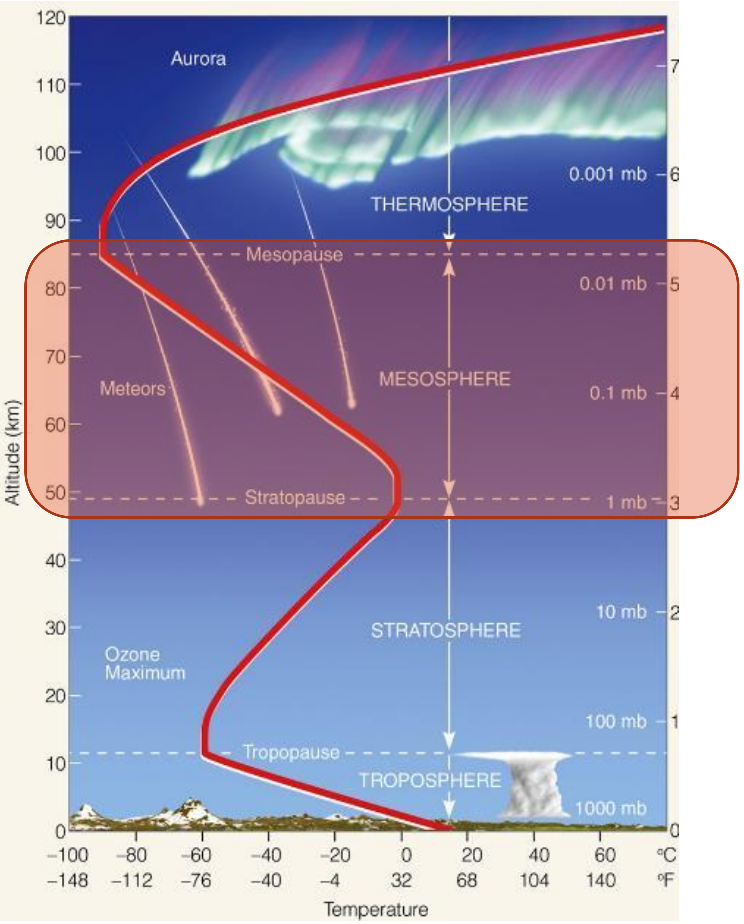
Atmosphere of Earth

- Stratosphere/平流層 (12-50 km)
  - It contains the ozone layer/臭氧層 that contains relatively high concentrations of gas.
  - The temperature rise with the altitude due to the ultraviolet radiation
  - At the top of the layer, the pressure is about 1/1000 of that at the sea level.
  - It is the highest layer that can be accessed by **jet-powered aircraft**.



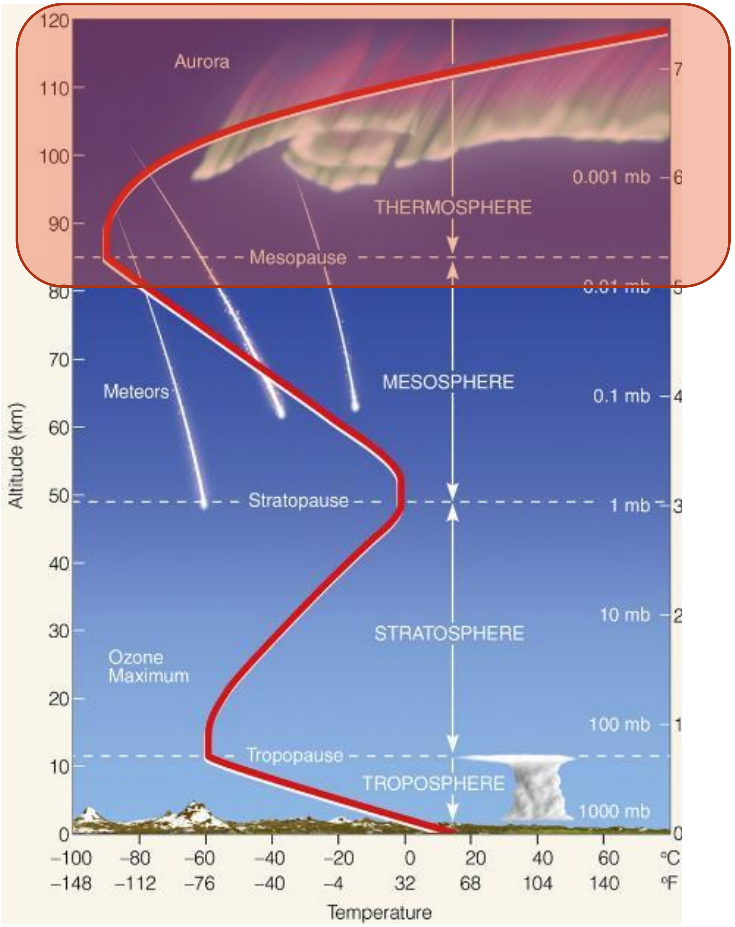
Atmosphere of Earth

- Mesosphere/中間層(50-80 km)
  - The temperature drop with the altitude.
  - It is the coldest place on Earth with the averaged temperature as −85℃
  - The condensed water forms the noctilucent clouds
  - It is mainly accessed by **rocket** powered aircraft



Atmosphere of Earth

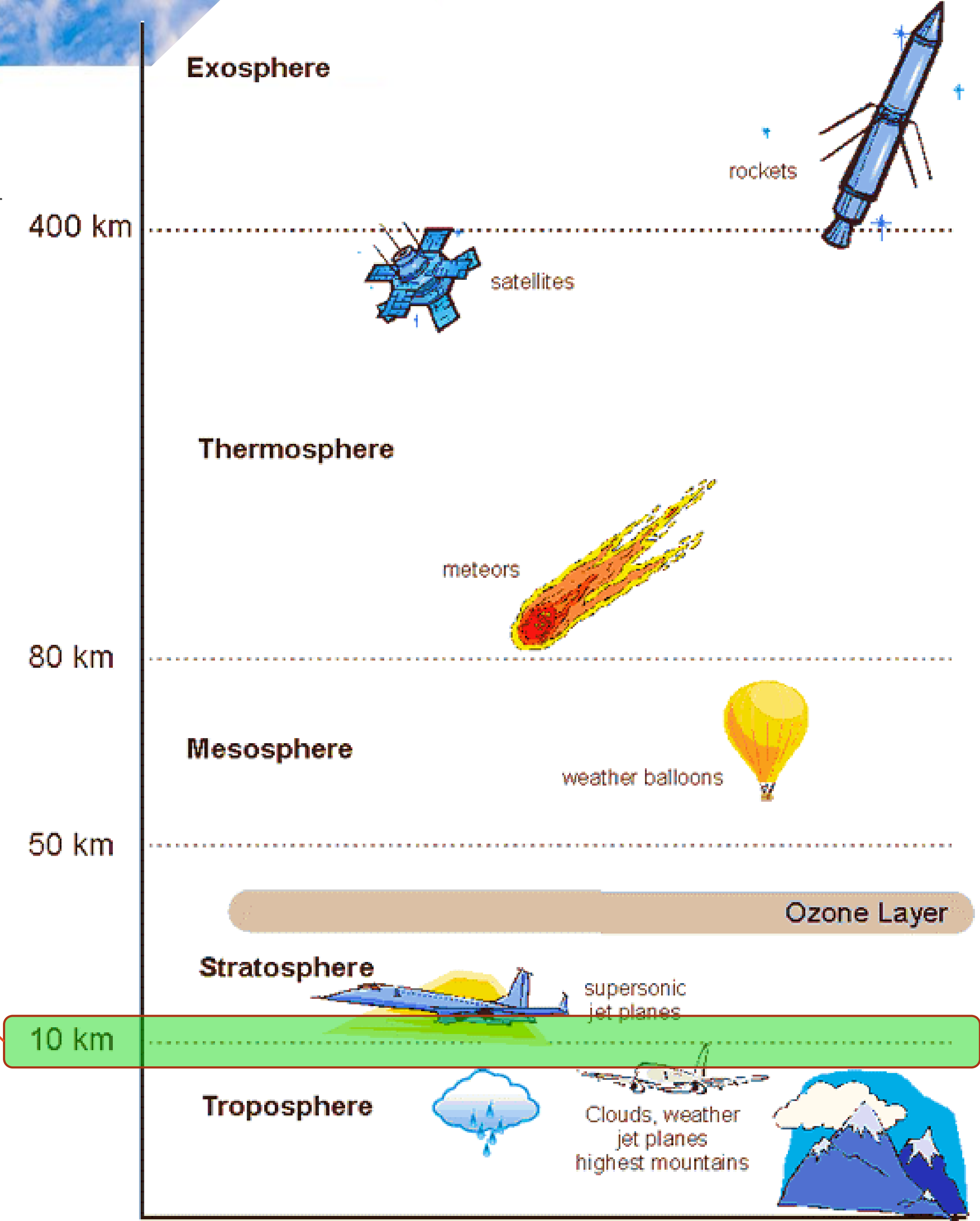
- Thermosphere /熱層 (80-700 km)
  - The lower part of the thermosphere contains the ionosphere
  - The temperature gradually increases with height and can reach 1500°C
  - The layer is completely cloudless and free of water vapor.
  - Many satellites orbits are located in this layer.



Atmosphere of Earth

Typical operational height of commercial aircraft:

- Atmospheric property
- Number of aircraft…



Limits of air-breathing-engine aircraft

- Each airframe-engine combination is designed to operate only within a certain range of altitudes and Mach numbers (velocities).
- Air-breathing engine aircrafts can only operate within the stratosphere and the troposphere.
  - Air-breathing engine, i.e., ducted jet engine.
- At higher altitudes, the air in the atmosphere is too thin for air-breathing combustion engines to be feasible. At such altitudes, rocket-type engines are necessary to generate the propulsion needed for flight.

- Airplanes designed for subsonic flight operate within the lower stratosphere and the troposphere.
- A good understanding of the atmospheric properties in this region is needed.

Why air is important for flight?

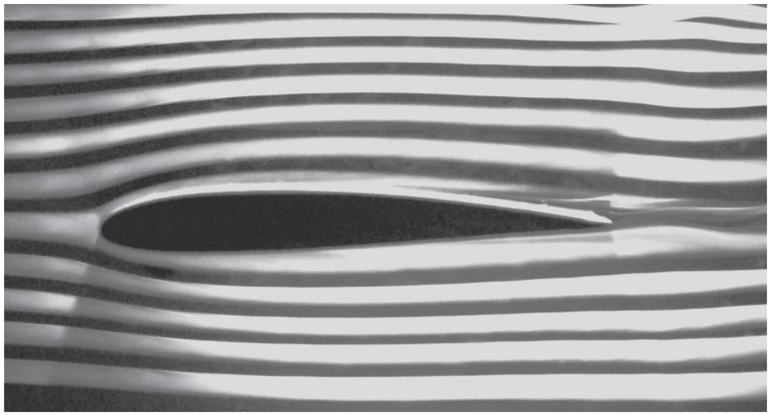
Properties of air gas

- The aerodynamic properties of the air gas is characterized by many factors, including:
  - Pressure p: is the normal force per unit area exerted on a surface due to the time rate of change of momentum of the gas molecules impacting on that surface.
    - Unit: Pa, or $\mathrm{N/m^2}$, atm, etc.
  - Density ρ: is the mass of the substance per unit volume.
    - Unit: $\mathrm{kg/m^3}$
  - Temperature T: a measure of the average kinetic energy of the participle of the gas.
    - Unit: Kelvin (K) or ℃

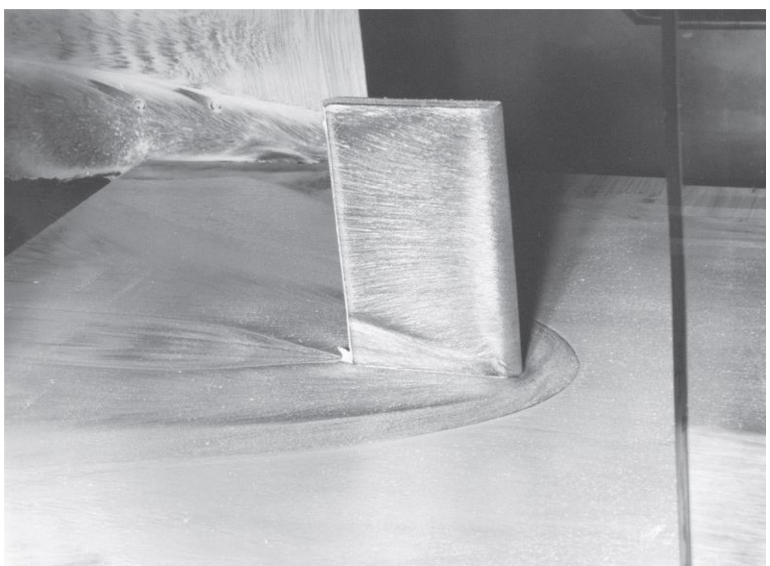
$$T(\mathrm{K}) = T(^\circ\mathrm{C}) + 273.15$$

  - Viscosity μ: a measure of the friction between neighbouring participles in fluid that are at different velocities.
    - Unit: $\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$

Flow variables



Visualization of flow around an airfoil



Visualization of surface streamline on a fin

- The *velocity* at any fixed point B in a flowing gas is the velocity of an infinitesimally small fluid element as it sweeps through B.
- The flow properties, including the pressure, density, temperature and velocity can vary with space:

$$\begin{cases} p = p(\boldsymbol{x}, t) \\ \rho = \rho(\boldsymbol{x}, t) \\ T = T(\boldsymbol{x}, t) \\ \boldsymbol{V} = \boldsymbol{V}(\boldsymbol{x}, t) \end{cases}$$

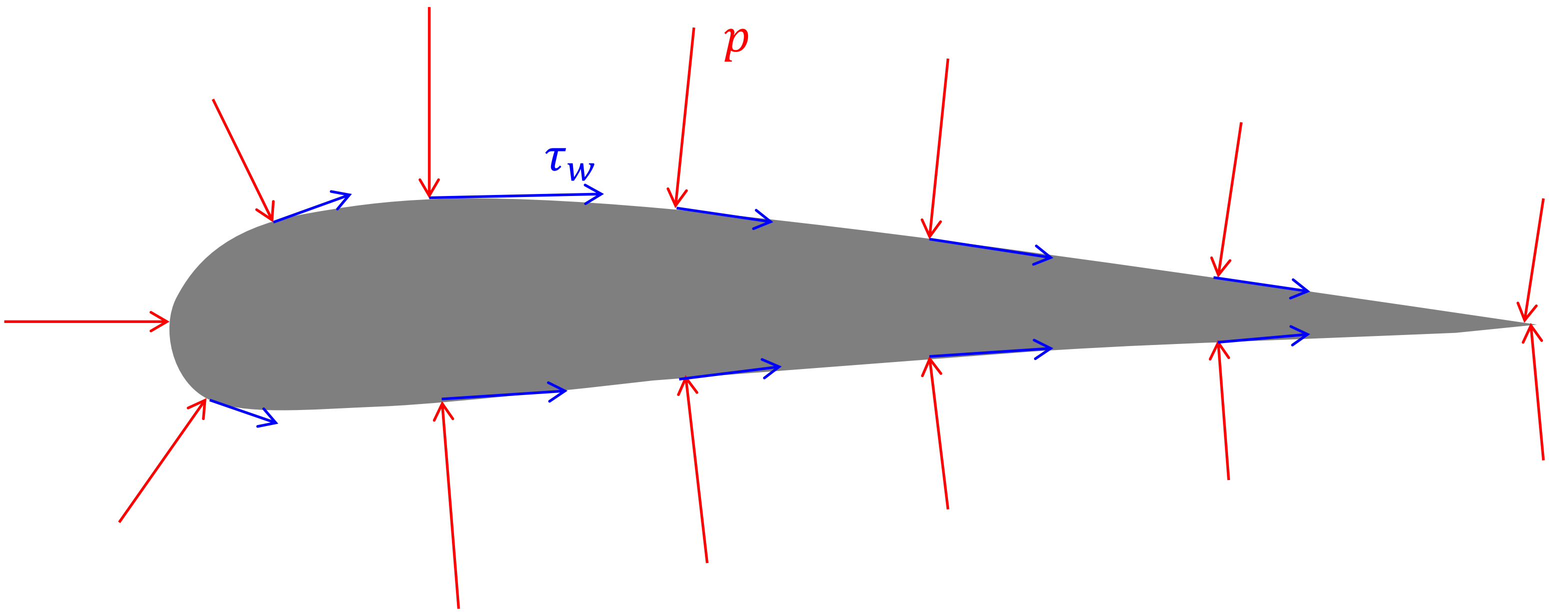
Source of aerodynamic forces

- The aircraft must provide sufficient lift to overcome the weight by itself and by the extra payload
- The force is provided during the interaction of the air medium

- The wing motion can cause vortex structures, corresponding to downward forces acting to the air.
- Based on Newton’s third law, the air provide upward force acting to the airplane.

Sources of the aerodynamic forces

- The forces acting on the vehicle by the gas can be classified to:
  - The pressure p distribution on the surface: normal to the surface
  - The friction τ_w distribution on the surface: tangent to the surface



Air properties & aircraft performance

- The variables are related:
  - The state equation for a gas

    $$p = \rho R_s T$$

    R_s is called the gas constant.

    For normal air, $R_s = 287\mathrm{J} \cdot \mathrm{kg}^{-1} \cdot \mathrm{K}^{-1}$
  - For generic cases, the flow variables are governed by the Navier-Stokes equations, a set of partial differential equations.
  - A simplified relationship for the inviscid, incompressible and irrotational flow:

    $$p + \frac{1}{2}\rho|\boldsymbol{V}|^2 = \text{const.}$$

- Lift and drag are often evaluated as

$$\begin{cases} F_L = \frac{1}{2} C_L A \, \rho V^2 \\ F_D = \frac{1}{2} C_D A \rho V^2 \end{cases}$$

- A is the reference area
- $\frac{\rho V^2}{2}$ is called the dynamic pressure
- C_L and C_D are called the lift and drag coefficients.

Air properties & aircraft performance

- Aerospace vehicles can be classified to:
  - Atmospheric vehicles such as airplane and helicopters, which operate within the sensible atmosphere
  - Space vehicles such as satellites, which operate outside the sensible atmosphere. However, the launch and re-entry are also within the atmosphere
- Earth's atmosphere is dynamically changing. The pressure and temperature can depend on:
  - **Altitude**
  - Location
  - Time of day, season
  - Solar sunspot activity, etc.

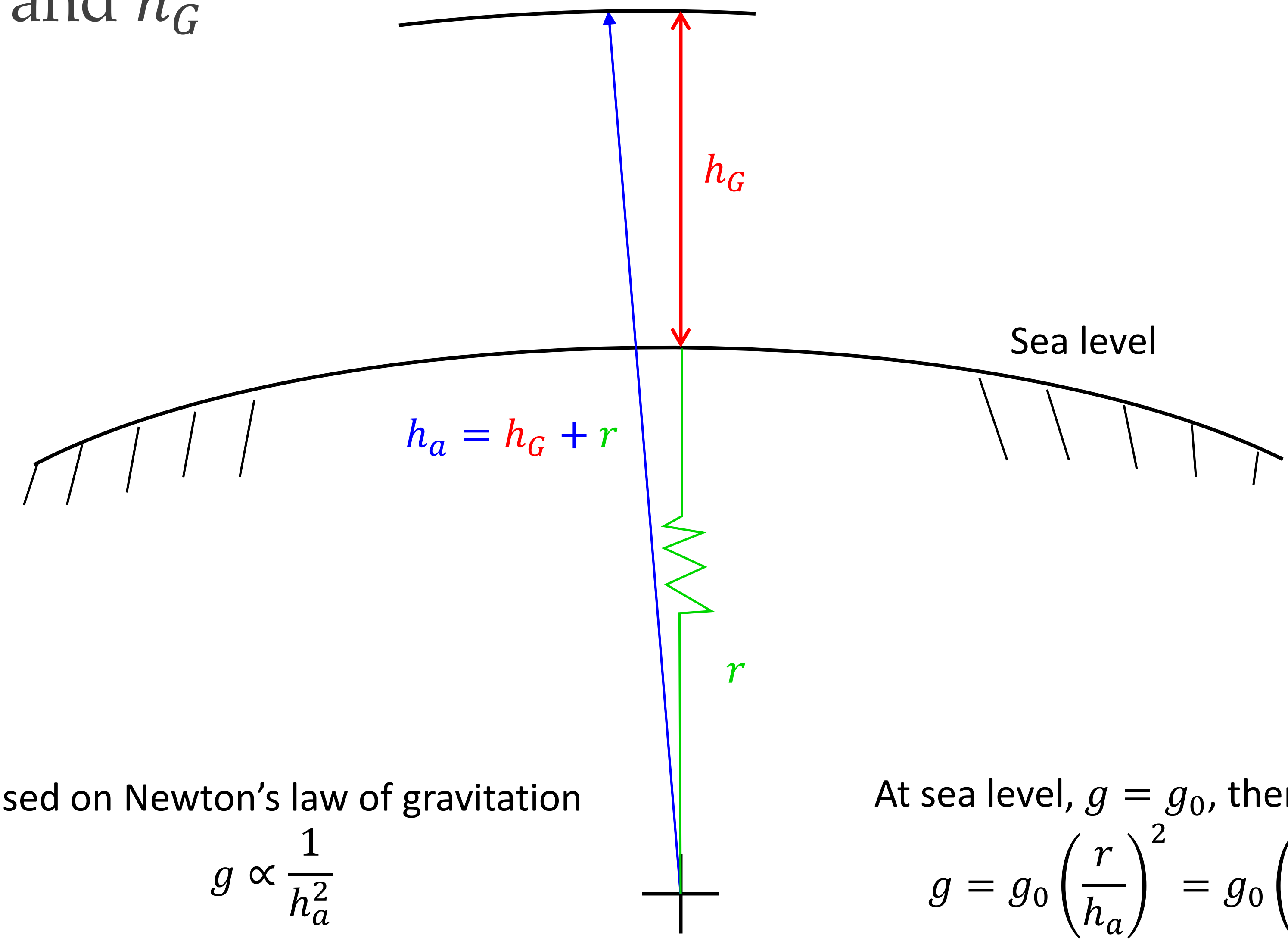
A standard atmosphere is defined to relate flight tests, wind tunnel results, airplane design, etc.

Definition of altitude

Altitude

- Altitude means the distance above the ground. However, the ground itself may vary from location to location!
- For quantitative use, 6 types of altitudes are defined. Two of them that are often used are:
  - Geometric altitude h_G: the geometric height above sea level
  - Absolute altitude h_a: the distance to the centre of earth.
    - It is important for space flight because gravity g varies with h_a

h_a and h_G



Based on Newton's law of gravitation

$$g \propto \frac{1}{h_a^2}$$

At sea level, $g = g_0$, then we have

$$g = g_0 \left(\frac{r}{h_a}\right)^2 = g_0 \left(\frac{r}{r + h_G}\right)^2$$

We will use g_0 for some calculation!

Geopotential altitude h

- The height refereeing to Earth's mean sea level with the constant gravity through a hypothetical space.
  - It is different from h_G because the actual g can vary with space!
  - The geopotential altitude h is used in many standard atmosphere tables.
- How to understand it?

Geopotential altitude h

- We consider the force balance of static air in a cubic control volume
  - Gravity force (downward)

    $$\mathrm{d}G = \rho g \mathrm{d}V = \rho g(\mathrm{d}x \cdot \mathrm{d}y \cdot \mathrm{d}h_G)$$

  - Pressure force on top (downward)

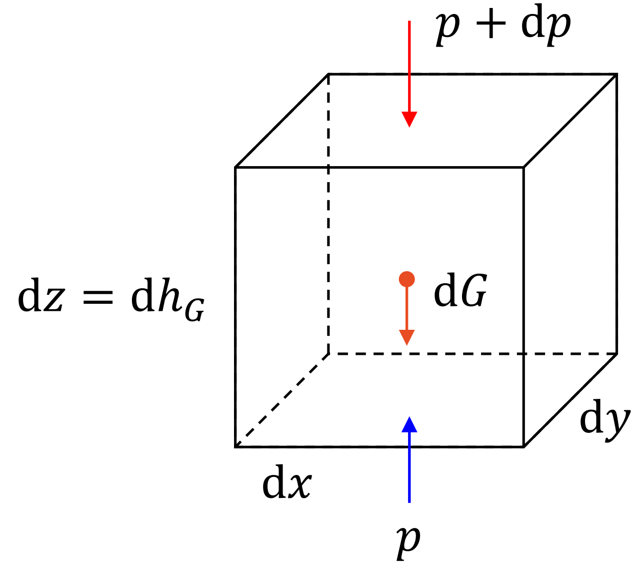
    $$\mathrm{d}F_t = (p + \mathrm{d}p) \cdot (\mathrm{d}x \cdot \mathrm{d}y)$$

  - Pressure force on bottom (upward)

    $$\mathrm{d}F_b = p \cdot (\mathrm{d}x \cdot \mathrm{d}y)$$

  - Force balance:

    $$\mathrm{d}G + \mathrm{d}F_t = \mathrm{d}F_b \quad \Rightarrow \quad \mathrm{d}p = -\rho g \mathrm{d}h_G$$



$$\boxed{p = -\int \rho g \mathrm{d}h_G}$$

g: vary with height!

Actual:
$\mathrm{d}p = -\rho g \mathrm{d}h_G$

Geopotential altitude h

- In practice, the gravity g varies with space.
- As a historical convention in aeronautics, people make assumptions of using a constant g_0 in the integration. The corresponding differential equation is

$$\mathrm{d}p = -\rho g_0 \mathrm{d}h$$

- Here h corresponds to the variation in the geopotential altitude h
- To ensure the pressure by both approaches, we have

$$\rho g_0 \mathrm{d}h = \rho g \mathrm{d}h_G$$

Equation to determine the geopotential altitude h

$$\mathrm{d}h = \left(\frac{g}{g_0}\right) \mathrm{d}h_G$$

Geopotential altitude h

- We denote the radius of earth as r, the gravitational at sea level as g_0, then the local gravitational acceleration g is

$$g = g_0\left(\frac{r}{r+h_G}\right)^2$$

- Therefore,

$$\mathrm{d}h = \left(\frac{g}{g_0}\right)\mathrm{d}h_G = \left(\frac{r}{r+h_G}\right)^2 \mathrm{d}h_G$$

$$\boxed{\Rightarrow h = \int_0^{h_G}\left(\frac{r}{r+h_G}\right)^2 \mathrm{d}h_G = \frac{r}{r+h_G}h_G}$$

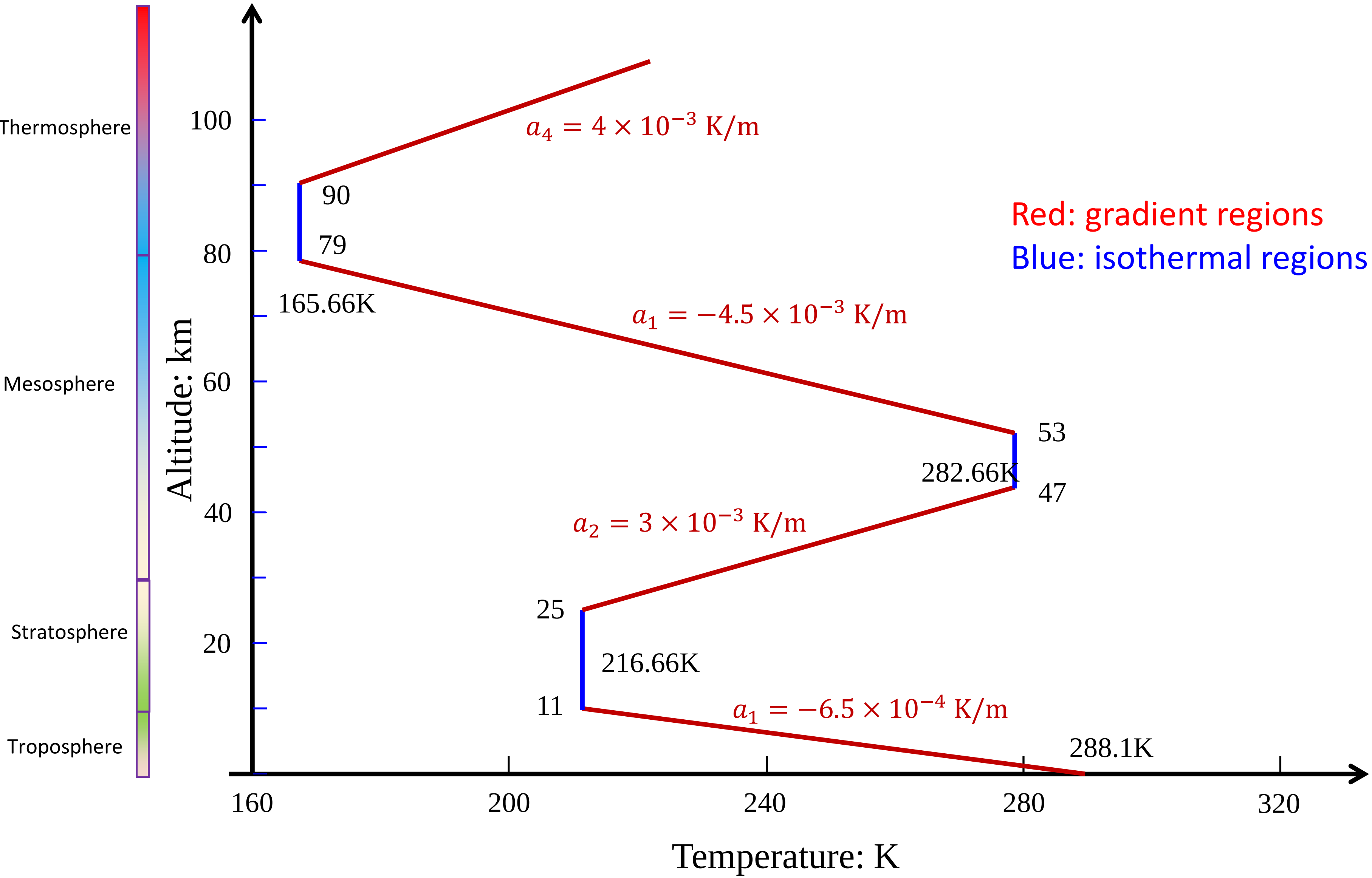
Taking $r \approx 6.35 \times 10^6\mathrm{m}$, the difference between h_G and h is within 1% below 65 km!

Standard atmosphere

Seek the variation of pressure, density, and temperature as functions of the geopotential altitude h

Temperature variation with h

The keystone of the standard atmosphere is a defined variation of T with altitude, based on experimental evidence



State equation for ideal gas

$p = \rho R_s T$

density

Gas constant

Pressure variation with h

- From the fluid static equation

$$\mathrm{d}p = -\rho g_0 \mathrm{d}h$$

- From the state equation

$$\frac{\mathrm{d}p}{p} = -\frac{\rho g_0 \mathrm{d}h}{\rho R_s T} = -\frac{g_0}{R_s}\frac{\mathrm{d}h(T)}{T}$$

- To solve the equation, we perform integral on both sides

$$\int \frac{\mathrm{d}p}{p} = -\frac{g_0}{R_s}\int \frac{\mathrm{d}h}{T}$$

The result is dependent on the temperature profile of $T(h)$

$$\int \frac{\mathrm{d}p}{p} = -\frac{g_0}{R_s}\int \frac{\mathrm{d}h}{T}$$

Pressure variation with h: isothermal layer

- We consider the solution in the isothermal layer.
  - $T = T_1$ is a constant
  - The integration is

$$\int_{p_1}^{p} \frac{\mathrm{d}p}{p} = -\frac{g_0}{R_s T_1}\int_{h_1}^{h} \mathrm{d}h$$

$$\Rightarrow \ln\left(\frac{p}{p_1}\right) = -\frac{g_0}{R_s T_1}(h - h_1)$$

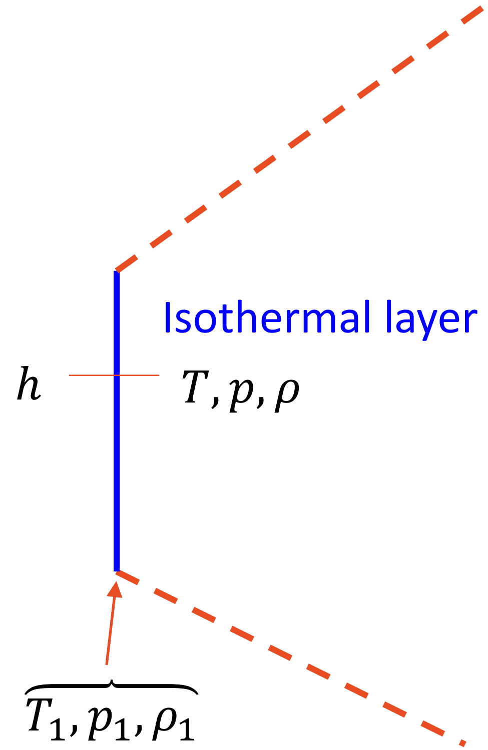
  - The solution is:

$$p = p_1 \exp\left(-\frac{g_0}{R_s T_1}(h - h_1)\right)$$

  - Density profile is determined as

$$\frac{p}{p_1} = \frac{\rho T}{\rho_1 T_1}$$

$$\Rightarrow \rho = \rho_1 \exp\left(-\frac{g_0}{R_s T_1}(h - h_1)\right)$$



$$\int \frac{\mathrm{d}p}{p} = -\frac{g_0}{R_s}\int \frac{\mathrm{d}h}{T}$$

Pressure variation with h: gradient layer

- We define the temperature gradient (lapse rate) as

$$a = \frac{\mathrm{d}T}{\mathrm{d}h} = \frac{T - T_1}{h - h_1}$$

- It is easy to see that $\mathrm{d}h = \mathrm{d}T/a$. The equation is

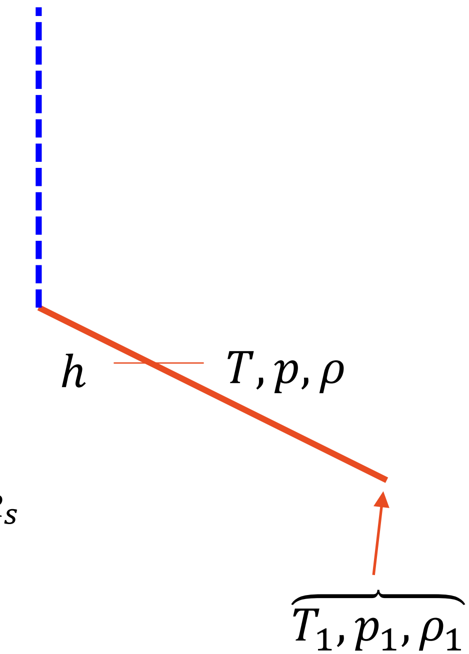
$$\int_{p_1}^{p} \frac{\mathrm{d}p}{p} = -\frac{g_0}{aR_s}\int_{T_1}^{T} \frac{\mathrm{d}T}{T}$$

- The integration yields

$$\frac{p}{p_1} = \left(\frac{T}{T_1}\right)^{-g_0/aR_s} = \left(1 + \frac{a(h - h_1)}{T_1}\right)^{-g_0/aR_s}$$

- The density profile is given as

$$\frac{\rho}{\rho_1} = \frac{p}{p_1}\cdot\frac{T_1}{T} = \left(\frac{T}{T_1}\right)^{-\frac{g_0}{aR_s}-1}$$



Standard atmosphere

- The standard atmosphere is thus determined by combining the piecewise functions.
- Particularly, at the sea level, i.e., $h = 0$, the reference atmosphere variables are given as
  - $p_s = 1.01325 \times 10^5 \mathrm{Pa}$
  - $\rho_s = 1.225\ \mathrm{kg/m^3}$
  - $T_s = 288.16\ \mathrm{K}$
- It is emphasized that the standard atmosphere is a reference atmosphere. It does not predict the actual atmospheric properties that actually vary with space and time!

Standard atmosphere

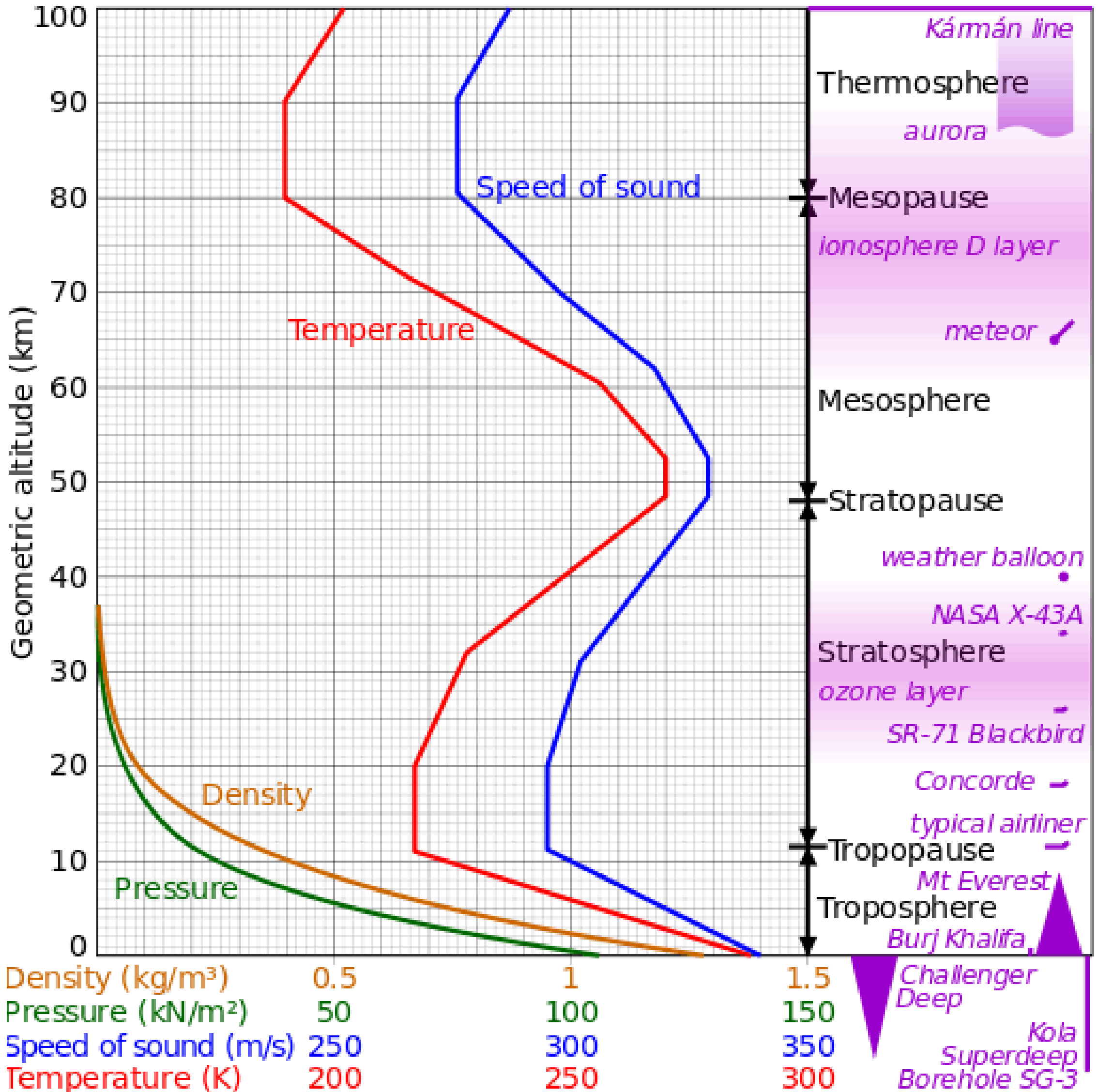
- By selecting different temperature distribution, the standard atmosphere profiles will be changed accordingly.
  - The profile we just introduced corresponds to the standard of the International Civil Aviation Organization (ICAO)
  - We will also the introduce the International Standard Atmosphere (see next page)
  - U.S. Government also developed the US Standard Atmosphere
- All standards are the same up to an altitude of 32 km from sea-level.
- The Standard Atmosphere reflects the mean values of pressure, temperature, density and other properties as a function of altitude.

International standard atmosphere (ISA)

- ISA is published by the International Standardization Organization (ISO): ISO 2533:1975
  - It contains more pieces in temperature variation

	layer	Base h (km)	Base h_G (km)	Lapse rate (K/km)	Base T (K)	Base p (Pa)	Base ρ (kg/m^3)
0	Troposphere	0	0	-6.5	288.15	101,325	1.225
1	Tropopause	11	11.019	0.0	216.65	22632	0.364
2	Stratosphere	20	20.063	+1.0	216.65	5474.9	0.088
3	Stratosphere	32	32.162	+2.8	228.65	868.02	0.013
4	Stratopause	47	47.350	0.0	270.65	110.91	0.0014
5	Mesosphere	51	51.412	-2.8	270.65	66.94	0.0009
6	Mesosphere	71	71.802	-2.0	214.65	3.96	0.0001
7	Mesopause	86	84.852	-	186.95	0	0

International standard atmosphere (ISA)



Pressure, temperature and density altitudes

Motivation & pressure altitude

- In practical aviation activities, the actual geometric altitude varies, which is often immaterial for discussion. But other properties of gas, e.g., pressure, density, and temperature can be measured.
- The measured result, e.g., the pressure, can correspond to a geopotential height in the standard atmosphere model.
  - By definition, one can specify the pressure altitude.
- Pressure altitude: For a given atmospheric pressure measurement, it means the altitude that has the same pressure as predicted by the International Standard Atmosphere (ISA) model.

$$p = 10132.5 \times \left(1 - \frac{h[m]}{44307.694\ [\mathrm{m}]}\right)^{5.25530} \quad [\mathrm{Pa}]$$

Pressure, density and temperature altitudes

- Similarly, one can define density and temperature altitudes based on the standard atmosphere models.
- For convenience, one can look at the ISA table to find out the values

Example:
If an airplane is flying at an altitude where the actual pressure and temperature are 4.72×10^4 Pa and 255.7 K, respectively, what are the pressure, temperature, and density altitudes?

Solution:

The density of the can be computed from the equation of state

$$\rho = \frac{p}{R_s T} = \frac{4.72 \times 10^4}{287 \times 255.7} = 0.643 \text{ kg/m}^3$$

Looking at the table, we can find:

- Pressure altitude: 6km
- Temperature altitude: 5km
- Density altitude: 6.24 km

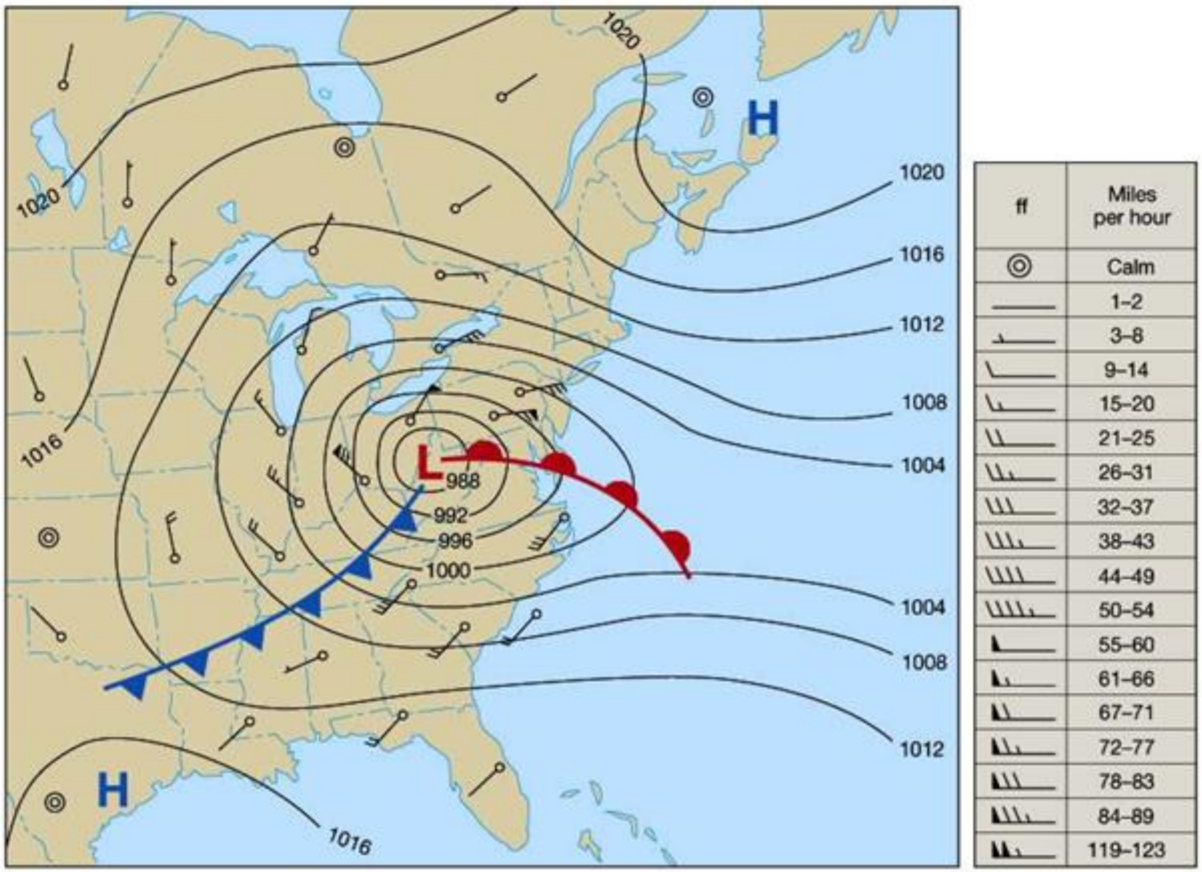
Altitude				
h_G, m	h, m	Temperature T, K	Pressure p, N/m²	Density ρ, kg/m
5,000	4,996	255.69	5.4048 + 4	7.3643 − 1
5,100	5,096	255.04	5.3331	7.2851
5,200	5,196	254.39	5.2621	7.2065
5,400	5,395	253.09	5.1226	7.0513
5,500	5,495	252.44	5.0539	6.9747
5,600	5,595	251.79	4.9860	6.8987
5,700	5,695	251.14	4.9188	6.8234
5,800	5,795	250.49	4.8524	6.7486
5,900	5,895	249.85	4.7867	6.6746
6,000	5,994	249.20	4.7217 + 4	6.6011 − 1
6,100	6,094	248.55	4.6575	6.5283
6,200	6,194	247.90	4.5939	6.4561
6,300	6,294	247.25	4.5311	6.3845
6,400	6,394	246.60	4.4690	6.3135
6,500	6,493	245.95	4.4075	6.2431
6,600	6,593	245.30	4.3468	6.1733
6,700	6,693	244.66	4.2867	6.1041
6,800	6,793	244.01	4.2273	6.0356
6,900	6,893	243.36	4.1686	5.9676

Atmospheric wind

Atmospheric wind

- Wind is the movement of air relative to the Earth's surface.
- It is caused and affected by forces acting on the air:
  - Pressure gradient force (PGF): a change of pressure over distance:
    - The Sun heats different part of the Earth differently, resulting in temperature difference and thus pressure difference
  - Centrifugal force: due to the inertia of wind along curved path
  - Coriolis force: related to the rotation of earth
    - To the right in the Northern Hemisphere
    - To the left in the Southern Hemisphere
  - Turbulent drag: the surface objects can resist the airflow.
    - The bottom layer of the troposphere around 0.3 to 3km is called the atmospheric boundary layer (ABL).

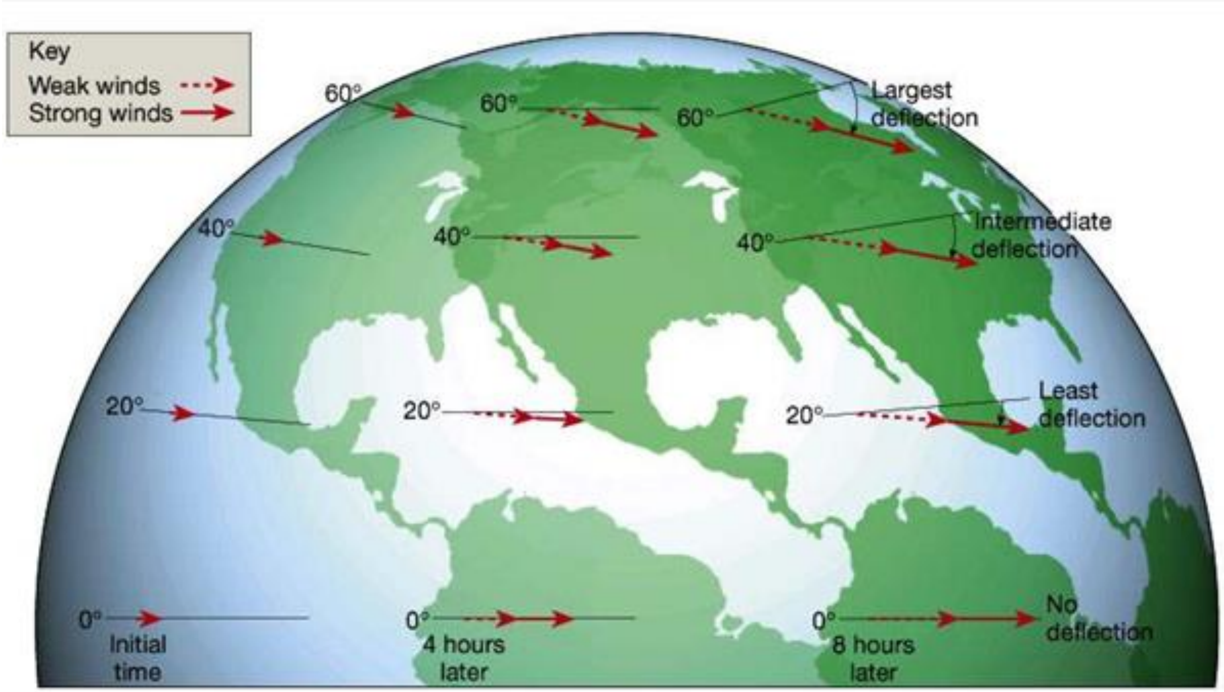
Pressure gradient force (PGF) effect



The Atmosphere, 8th edition, Lutgens and Tarbuck, 8th edition, 2001

- One can draw the iso-pressure maps
- “H” denotes the high pressure
- “L” denotes the low pressure

Coriolis force effect

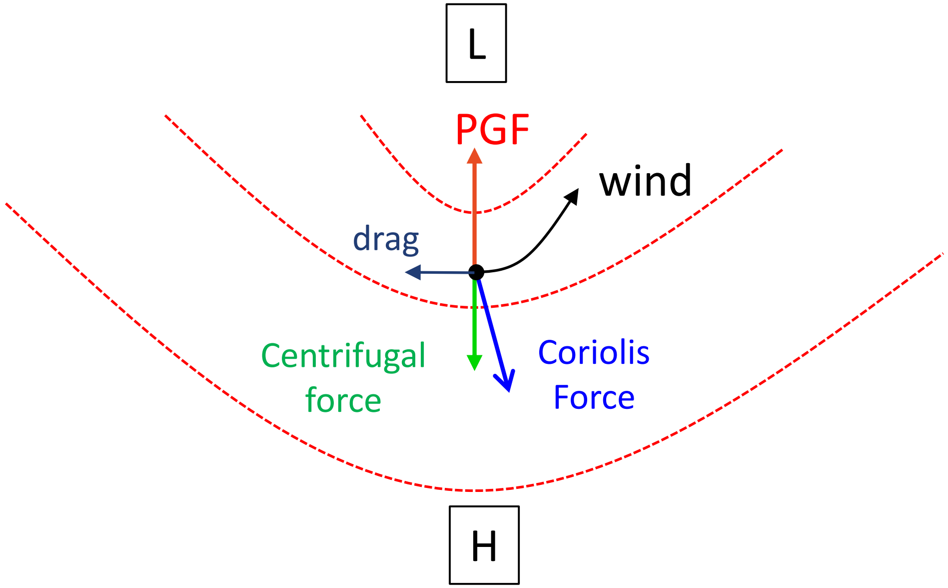


The effect of the Coriolis Force (for various latitudes).
Figure 6.12 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001.

- Moving objects, including winds, are deflected due to the Earth motion
- The faster the wind is, the greater the deflection is.

Atmospheric wind and weather

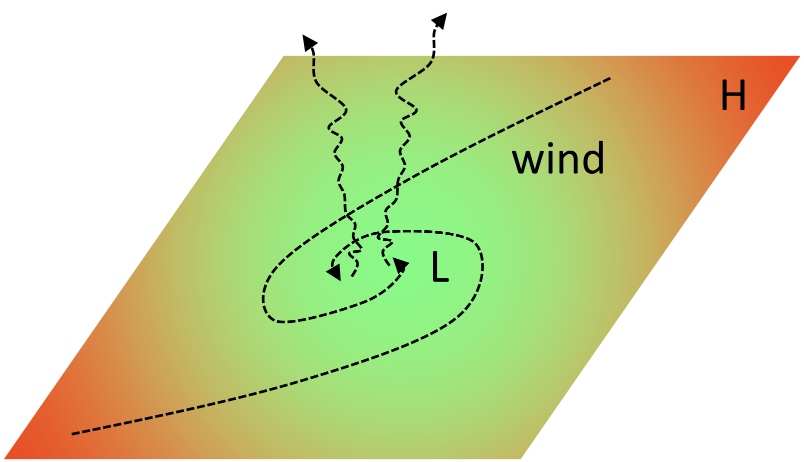
- Usually, there is a balance of the forces acting on the wind
- Near the ground, the wind is affected by the turbulent drag.
  - In the opposite direction to the wind
  - The air will be slow down, reducing the Coriolis force
  - The force imbalance will be adjusted by the atmosphere by turning the wind toward the low pressure region

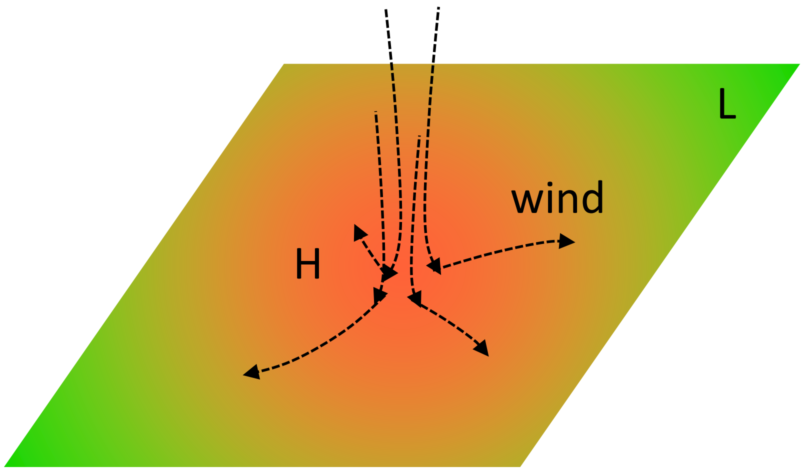


During the adjustment, the air must go somewhere!

Atmospheric wind and weather

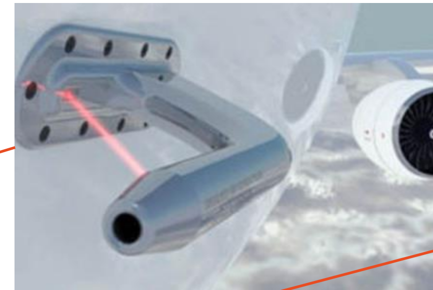
- For wind towards low-pressure region
  - Directional convergence
  - Lifting of air
  - Bad weather
- For wind leaving high-pressure region
  - Directional divergence
  - Sinking of air
  - Good weather





Wind measurements

- Speed:
  - Pitot tube (aircraft)
  - Heat dissipation
  - Speed of sound: expensive
  - Cups
- Direction:
  - Wind vanes
  - Wind socks



Digital wind anemometer

Atmospheric turbulence

Atmospheric turbulence

- Turbulence is one of the most unpredictable of all the weather phenomena that are of significance to pilots.
- Turbulence is an irregular motion of the air resulting from eddies and vertical currents.
- It may be as insignificant as a few annoying bumps or severe enough to momentarily throw an airplane out of control or to cause structural damage.
- Turbulence is associated with wind fronts, wind shear, thunderstorms, etc.

Turbulence intensity

- Turbulence is usually classified as light, moderate, server and extreme, determined by the degree of stability of air

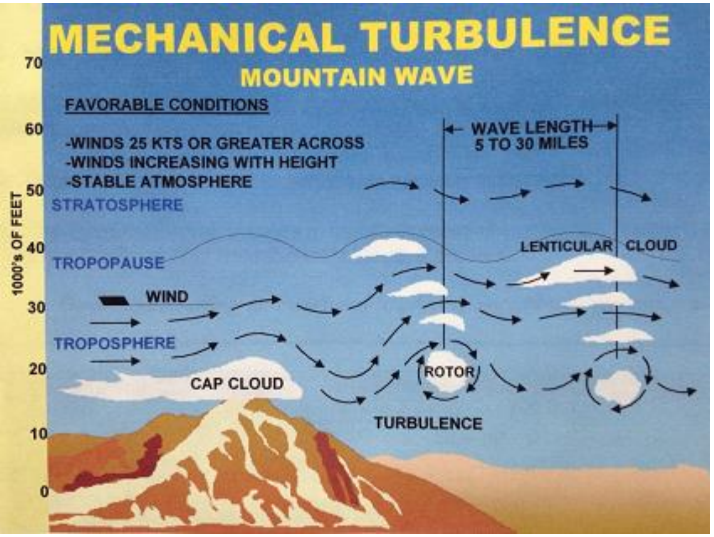
Turbulence intensity classification (for aviation)		
Intensity	Aircraft reaction	Inside aircraft
Light	• Slight erratic changes in altitude and/or attitude	• Unsecured objects may be displaced slightly. • No difficulty in waling
Moderate	• Change in altitude and/or attitude, • Aircraft remains in positive control at all times	• Unsecured objects dislodged; • Food service and walking difficult
Severe	• Large, abrupt changes in altitude and/or attitude. • Aircraft may be momentarily out of control	• Food service and walking impossible
Extreme	• Aircraft is violently tossed about and practically impossible to control. • May cause structural damage	• Strong desire to land

Causes of atmospheric turbulence

- The causes of the turbulence can be classified to
  - Mechanical turbulence: friction between the air and ground
  - Thermal turbulence: uneven heat transfer from the sun
  - Frontal turbulence: the interaction between warm and cold air
  - Wind shear: the change in the wind direction and wind speed can cause turbulent flows

Mechanical turbulence

Flow passing irregular terrain and man-made obstacles



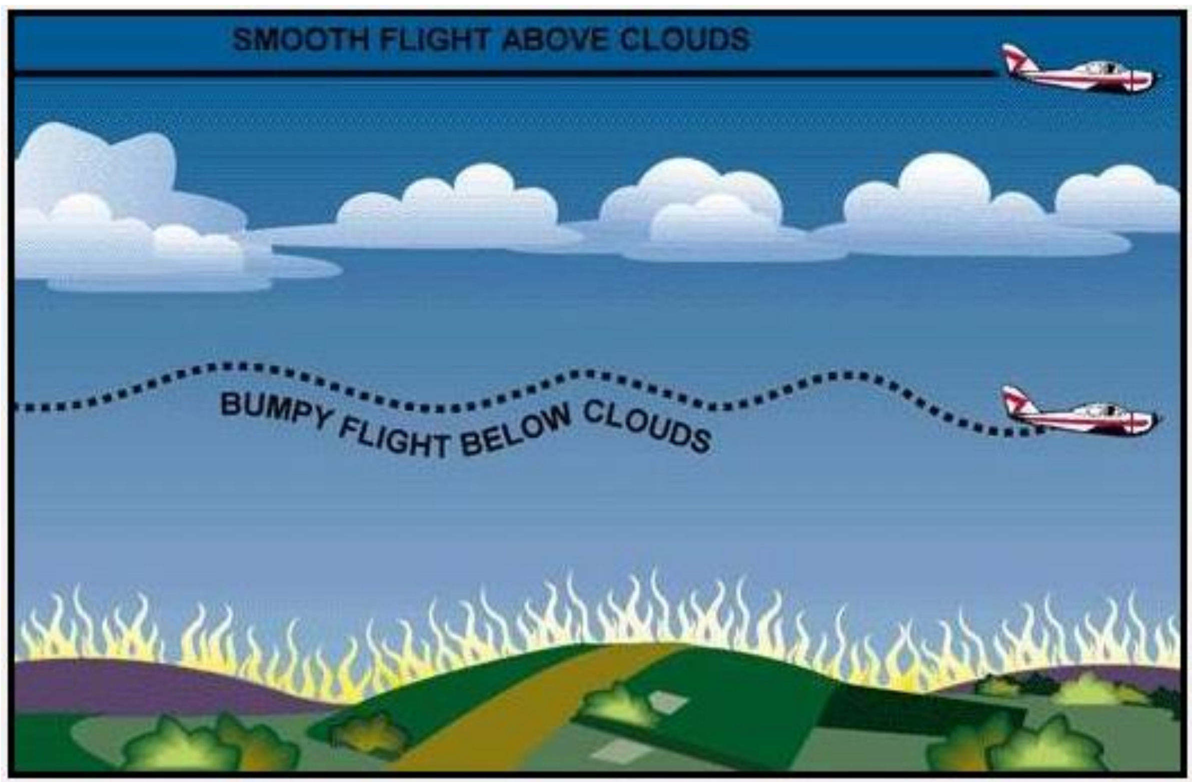
Turbulent eddies resulting from downwind of mountain ridges

- The wind is often gusty;
- If the wind is heated below, the vertical motion will make the turbulence more significant

- Warm air: raising
- Cold air: descending

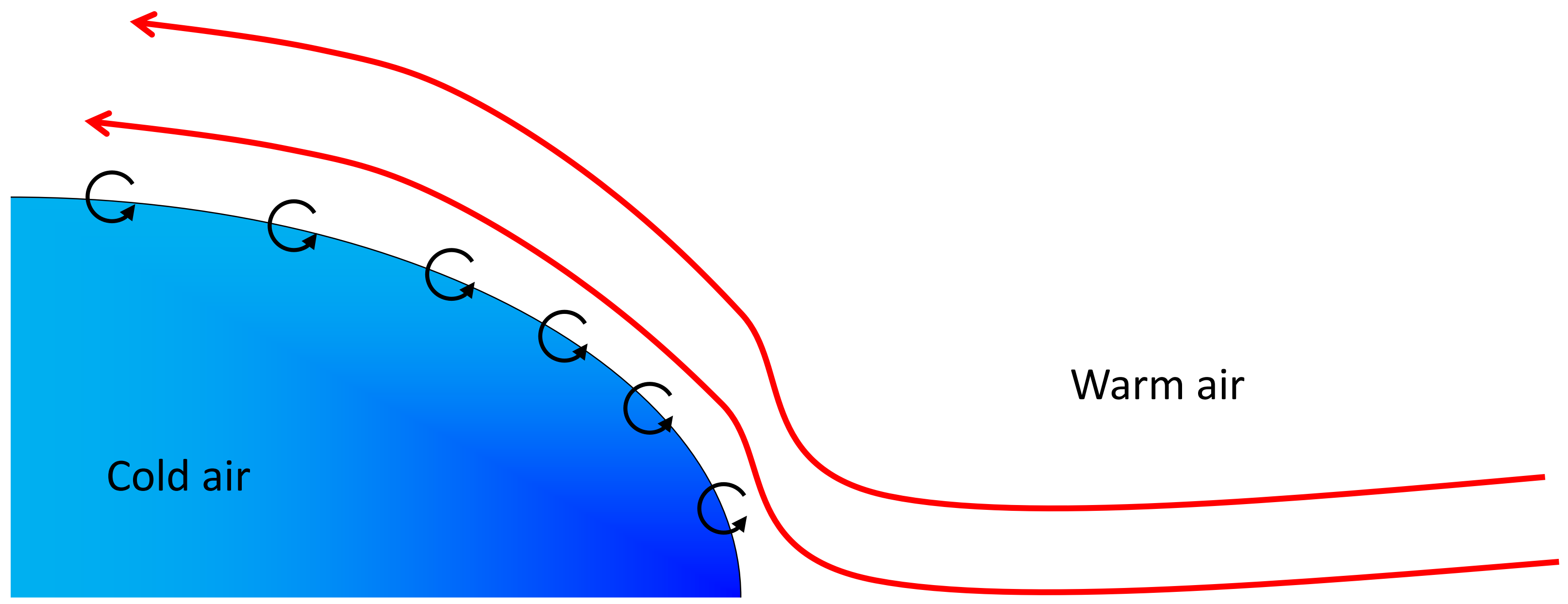
Thermal turbulence

- The heat capacity of the surface condition, e.g., sea, rock, grass, etc., are different, leading to the motion of air:
- The received energy can be affected by the shielding of clouds



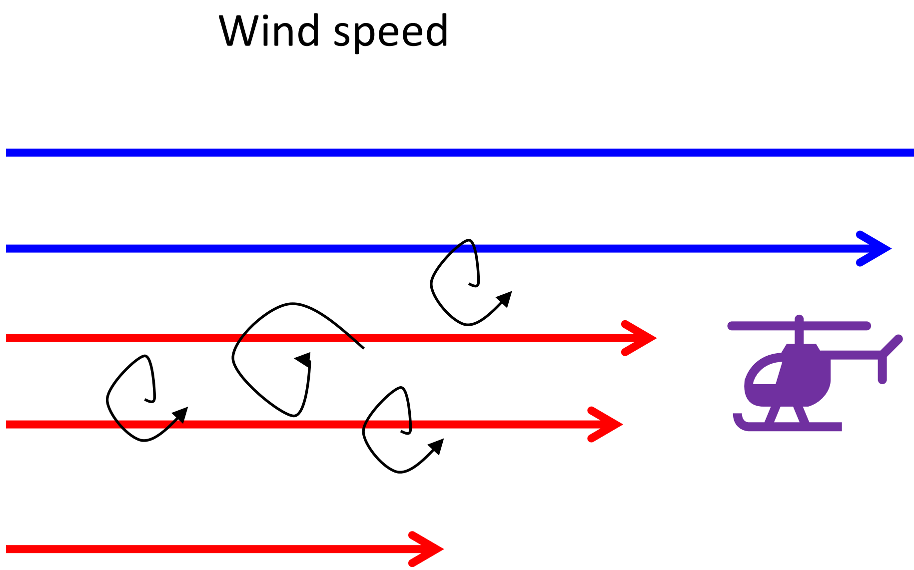
Frontal turbulence

- The lifting of warm wind can be affected by the curvature and friction of the cold air in opposite direction.



Wind shear turbulence

- Wind shear is the change in wind direction and/or wind speed over a specific horizontal or vertical distance
- When the change in wind speed or direction is pronounced, severe turbulence can be expected



The temperature inversion is an important source of wind shear turbulence

Summary

Summary

- Classification of atmosphere layer
  - Troposphere /對流層: 0-12 km
  - Stratosphere /平流層: 12-50 km
  - Mesosphere/中間層: 50-80 km
  - Thermosphere /熱層: 80-700 km
  - Exosphere /外逸層: 700-10,000 km
- Properties of air: variations with height
- Definition of altitude
  - Geometric altitude & geopotential altitude
- Standard atmosphere
  - ISA and ICAO models
- Atmosphere wind and turbulence
  - Causes of the wind and turbulence and the features
  - Impact on the aircraft operation