

Human Performance & Limitations · Module A — The Ocean of Air

The Atmosphere

Chapter 2 — The atmosphere and its constituent gases, the five Gas Laws, and the International Standard Atmosphere. The foundation on which every physiological effect of flight is built.

BOOK

Human Performance & Limitations

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EXAM

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CHAPTER

2 of 26 · Module A

In this chapter

1. [The Atmosphere & its Constituent Gases](#)
2. [The Gas Laws \(Boyle · Henry · Charles · Graham · Dalton\)](#)
3. [Variation of Pressure & Temperature with Altitude \(ISA\)](#)

GHOST AVIATOR



Plate 2.1 — The ocean of air: from the dense, weather-filled troposphere to the thin stratosphere the pilot must respect.

WHY THIS CHAPTER MATTERS TO A PILOT

Aviation Physiology deals with the **physical and mental effects of flight on aircrew personnel and passengers**. In aviation, the demands upon the compensatory mechanisms of the body are *numerous and of considerable magnitude*. The environmental changes of greatest physiological significance involved in flight are:

- Marked changes in **barometric pressure**
- Considerable variation in **temperature**
- **Movement at high speed in three dimensions**

This part of the syllabus familiarises you with the physiological problems of flight and assists in human compensation for the numerous environmental changes encountered in flight. **Remember: every human is physiologically different and can react differently in any given situation.**

§ 1 The Atmosphere

Human beings live their lives in the **lower reaches of the atmosphere** where temperatures, pressures and oxygen supply are able to support life. The moment we climb, every one of those three variables shifts against us. To fly safely, you must first understand the layer you're flying in and what it is made of.

1.1 The Layers — Troposphere & Stratosphere

TROPOSPHERE – AVERAGE TOP

13 km • 8.1 mi • 43,000 ft

STRATOSPHERE – REACHES ABOVE

100,000 ft

WHERE ALMOST ALL WEATHER LIVES

Troposphere

WHERE AIR IS DENSEST

Lowest Layer (Surface)

The Troposphere height **varies**. On average it stretches from the Earth's surface to about

13 km (8.1 mi; 43,000 ft)

. The Stratosphere reaches up to over

100,000 ft

. The troposphere contains **almost all the weather**, the air is densest in this lowest layer, and in fact the troposphere contains **three-quarters of the mass of the entire atmosphere**.

GHOST AVIATOR

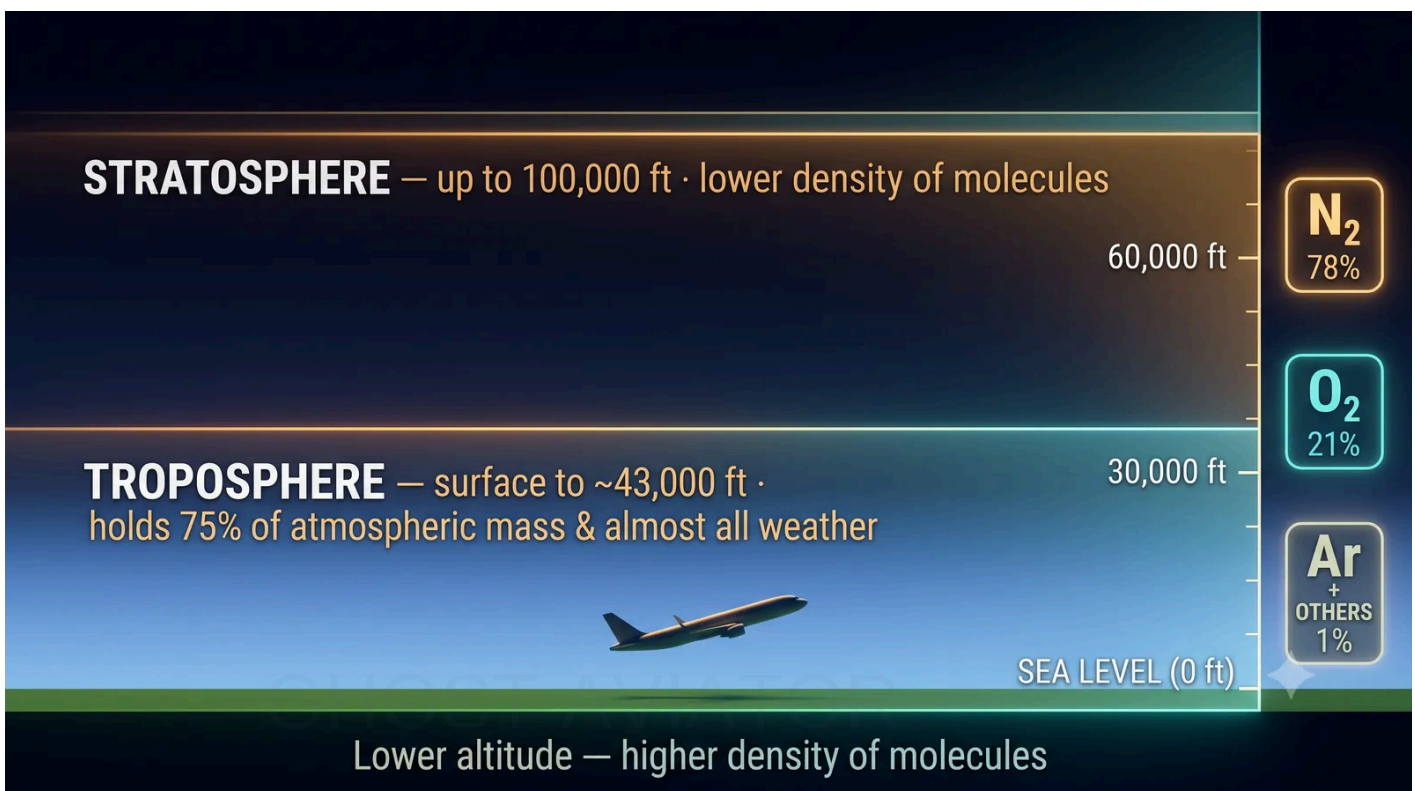


Figure 2.2 — Vertical structure of the atmosphere: the troposphere holds $\frac{3}{4}$ of all atmospheric mass and nearly all weather.

1.2 Constituent Gases of the Atmosphere

The earth's atmosphere near the surface is composed primarily of **Nitrogen** and **Oxygen**. Together, the two comprise **about 99%** of the gas in the atmosphere. The remaining 1% is made up of Argon plus traces of other gases.

Composition of the lower atmosphere — exact percentages

Gas	Percentage	Gas	Percentage
Nitrogen (N ₂)	78.084 %	Oxygen (O ₂)	20.95 %
Argon (Ar)	0.934 %	Carbon Dioxide (CO ₂)	0.036 %
Neon (Ne)	0.0018 %	Helium (He)	0.0005 %
Methane (CH ₄)	0.00017 %	Hydrogen (H ₂)	0.00005 %
Nitrous Oxide (N ₂ O)	0.00003 %	Ozone (O ₃)	0.000004 %

In addition, **water vapour** is variable but typically makes up about **1 – 4 %** of the atmosphere.

CRITICAL PRINCIPLE TO REMEMBER

The relative proportions of these gases remain **CONSTANT** in the **Troposphere** and **Stratosphere**. What changes with altitude is not the *percentage* of oxygen — it is the *total pressure*, and therefore the **partial pressure** of each gas. Oxygen continues to make up 21 % of the air by volume **at every altitude**; only the partial pressure of oxygen, pO_2 , falls.

MNEMONIC

"Never Ought An Cool Naval Helmsman Make His Nasty Owl" — Nitrogen, Oxygen, Argon, Carbon dioxide, Neon, Helium, Methane, Hydrogen, Nitrous oxide, Ozone — in descending order of abundance. (Optional aid — feel free to invent your own.)

§ 2

The Gas Laws

The body responds to barometric pressure changes in temperature, pressure, and volume. These changes are **rapid and continuous** in the aviation environment. It is therefore essential to know the implication of these changes on our body and take preventive measures to counter them. The gas laws explain to us the **science behind what goes on within our body** when exposed to changes in pressure and temperature.

THE FIVE GAS LAWS OF FLIGHT

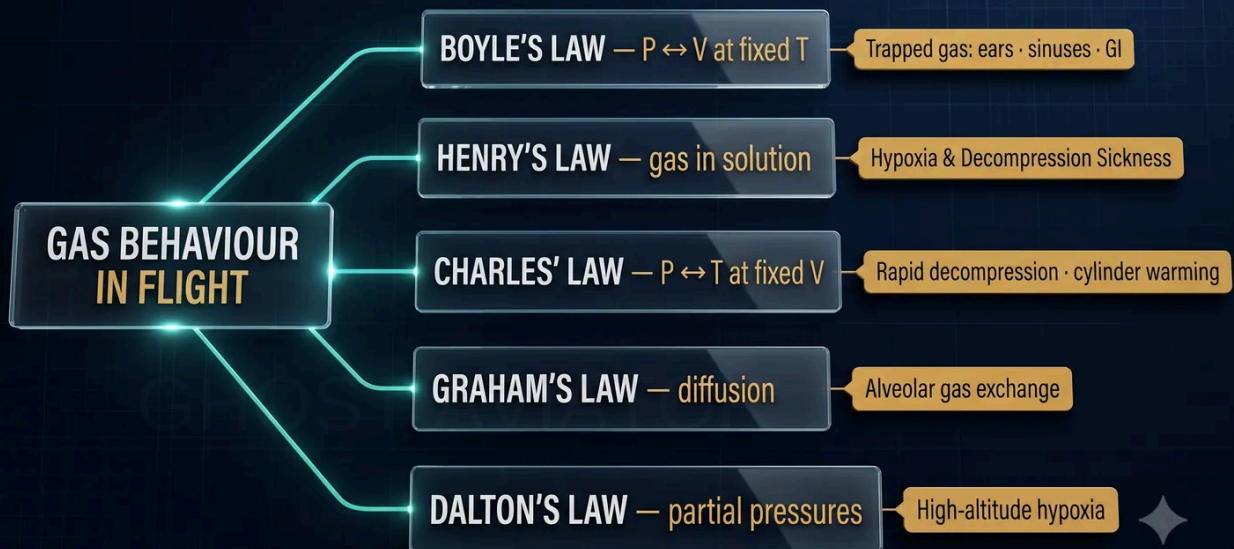


Figure 2.3 — The five gas laws of flight and what each one explains in the cockpit.

2.1 Boyle's Law

DEFINITION

At a **constant temperature**, a given volume of gas is **inversely proportional to the pressure** surrounding the gas. The volume of gas **expands as the pressure surrounding the gas is reduced**.

- **As altitude increases** → **gas expands**.
- **As altitude decreases** → **gas compresses**.
- The amount of volume expansion is **limited by the pliability** of the structure or membrane which encloses the gas.

EXAMPLES IN AVIATION & MEDICINE

PASG / Air Splints · Respiratory Rate & Depth changes · Flow rates of **IV sets** · **ETT** or **Tracheal cuff** pressures · **Trapped gas effects** within the body (middle ear, sinuses, GI tract — every pilot has felt these).

BOYLE'S LAW — as pressure halves, volume doubles

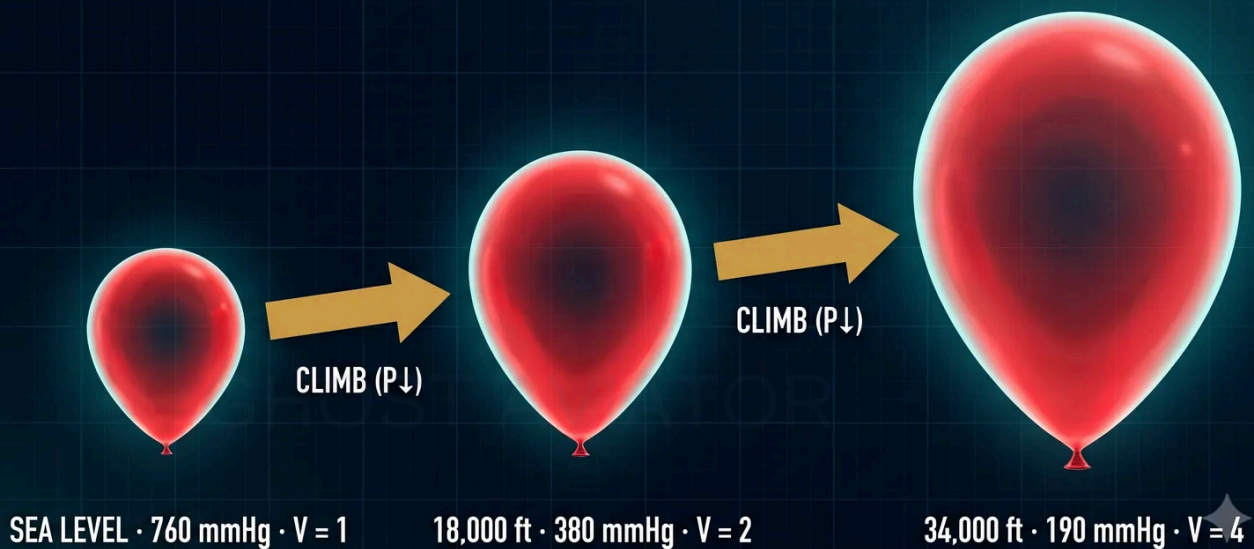


Figure 2.4 — Boyle's Law: as pressure halves, a fixed mass of gas doubles in volume. Trapped gas in sinuses, ears, gut and fillings expands as you climb.

2.2 Henry's Law

DEFINITION

The amount of **gas in solution** is proportional to the **partial pressure of that gas over the solution**. As the pressure of the gas above a solution *increases*, the amount of that gas dissolved in the solution *increases*; the reverse is also true — as the pressure of the gas above a solution *decreases*, the amount of gas dissolved *decreases* and forms a "**bubble**" of gas within the solution.

In normal physiologic function, this law can be seen in the **transfer of gas between the alveoli and the blood**. This is **significant physiologically** for the occurrence of evolved gas disorders, e.g. **decompression sickness**. It explains the hypoxia experienced with increasing altitude — as the pressure of gases is reduced with ascent, the amount of gases dissolved in solution decreases, and this leads to hypoxia and may lead to **nitrogen bubble formation**.

EVERYDAY EXAMPLE

Bottle of soda. With the cap on, the gas within the solution is at equilibrium. With the cap removed, the gas pressure decreases and bubbles are released into the solution. Your blood does exactly the same thing on a sudden cabin depressurisation.

CLINICAL LINK — DCS (DECOMPRESSION SICKNESS)

A pilot who has been SCUBA diving cannot climb shortly after surfacing because Henry's Law is still working against them — dissolved nitrogen in their blood will come out of solution as bubbles when ambient pressure falls. (*Strict wait-times before flying after diving are covered in a later section.*)

2.3 Charles' Law

DEFINITION

The **pressure of a gas is directly proportional to its temperature** with the **volume remaining constant**. Temperature increases make gas molecules move faster, greater force is exerted, and volume expands.

The law explains:

- The **temperature changes associated with rapid decompression**.
- The **pressure changes that induce temperature changes with an oxygen cylinder** (a freshly-charged O₂ bottle feels warm; a discharging one feels cold).

CLASSIC ILLUSTRATION

Shaving cream can be placed into a fire — heat raises the internal pressure of the can until the structure fails. Same physics governs the rapid heating of an oxygen cylinder during fast filling.

2.4 Graham's Law — Law of Gaseous Diffusion

DEFINITION

Gases **diffuse or migrate from a region of higher concentration (or pressure) to a region of lower concentration (or pressure)** until equilibrium is reached. The physiological significance is in the explanation of **gas exchange**.

SOP — HOW YOUR LUNGS USE THIS LAW

Oxygen moves from the alveoli into the blood, and from the blood into the tissues due to this phenomenon. The whole architecture of the respiratory system relies on Graham's Law for survival.

2.5 Dalton's Law — Law of Partial Pressures

DEFINITION

Partial pressures describe the **distribution of certain gases in a mixture** and follows Dalton's law which states that the **total pressure of a mixture of gases is equal to the sum of the partial pressures of the gases which compose the mixture**. As altitude increases — gases exert **less pressure**. This explains the **hypoxia that occurs with flight to higher altitudes**.

WORKED EXAMPLE — OXYGEN AT DIFFERENT ALTITUDES (DALTON'S LAW IN ACTION)

At Sea Level: $O_2 = 21\%$ & $pO_2 = 21\% \times 760 \text{ mm} = \approx 160 \text{ mmHg}$

At 8,000 ft: $O_2 = 21\%$ & $pO_2 = 21\% \times 565 \text{ mm} = \approx 119 \text{ mmHg}$

The barometric pressure at **36,000 ft** is **one-fourth** of that at sea level. Hence the quantity of oxygen available is **proportionately low**. *Whatever the air pressure, oxygen continues to make up 21 % of the air by volume.* In other words, the **proportion of oxygen in the air always stays the same whatever the altitude. The partial pressure of Oxygen decreases with altitude as does the total pressure of air.**

EXAM-CRITICAL TAKEAWAY

The percentage of O_2 in air does **NOT** change with altitude — it is always **21 %**. What kills the pilot is the falling **partial pressure** of that oxygen, because diffusion across the alveolar membrane depends on *pressure gradient*, not percentage.

Quick-Reference — The Five Gas Laws of Aviation Physiology

Law	One-line Statement	What it Explains in Flight
Boyle's	$P \times V = \text{constant}$ (at fixed T) — pressure $\uparrow \rightarrow$ volume $\downarrow$	Trapped-gas pain in ears, sinuses, teeth, GI tract; tracheal-cuff & IV behaviour
Henry's	Gas dissolved $\propto$ partial pressure over the solution	Decompression sickness, hypoxia mechanism, alveolar gas transfer
Charles'	$P \propto T$ (at fixed V) — warming raises pressure	Rapid-decompression temperature drop; O_2 cylinder heating
Graham's	Gases diffuse from high $\rightarrow$ low concentration	O_2 from alveoli $\rightarrow$ blood $\rightarrow$ tissues; CO_2 in opposite direction
Dalton's	Total $P = \Sigma$ partial pressures	Why high-altitude hypoxia happens despite air being "21% oxygen"

§ 3 Variation of Pressure & Temperature with Altitude

3.1 The International Standard Atmosphere (ISA)

WHAT ISA ACTUALLY IS

The International Standard Atmosphere is used to show **standardised values for temperature, pressure, density and lapse rate**. Pressure decreases with altitude *throughout* the atmosphere. Temperature decreases with altitude *in the Troposphere*.

ISA Sea-Level Values (memorise these cold)

SEA-LEVEL PRESSURE

1013.25 hPa

EQUIVALENT (MB)

1013.25 mb

EQUIVALENT (PSI)

14.7 lb/in²

EQUIVALENT (HG)

29.92 in Hg

EQUIVALENT (MMHG)

760 mm Hg

ISA LAPSE RATE

1.98 °C / 1000 ft

STRICT ISA LIMITS — EXAMINATION VALUES

Temperature reduces at 1.98 °C per 1000 ft up to 36,090 ft. Thereafter it remains constant at -56.5 °C.

(The 1.98 °C figure is the precise ISA lapse rate; many texts round to 2 °C / 1000 ft for mental maths — never round in your exam paper.)

THE ISA TEMPERATURE PROFILE

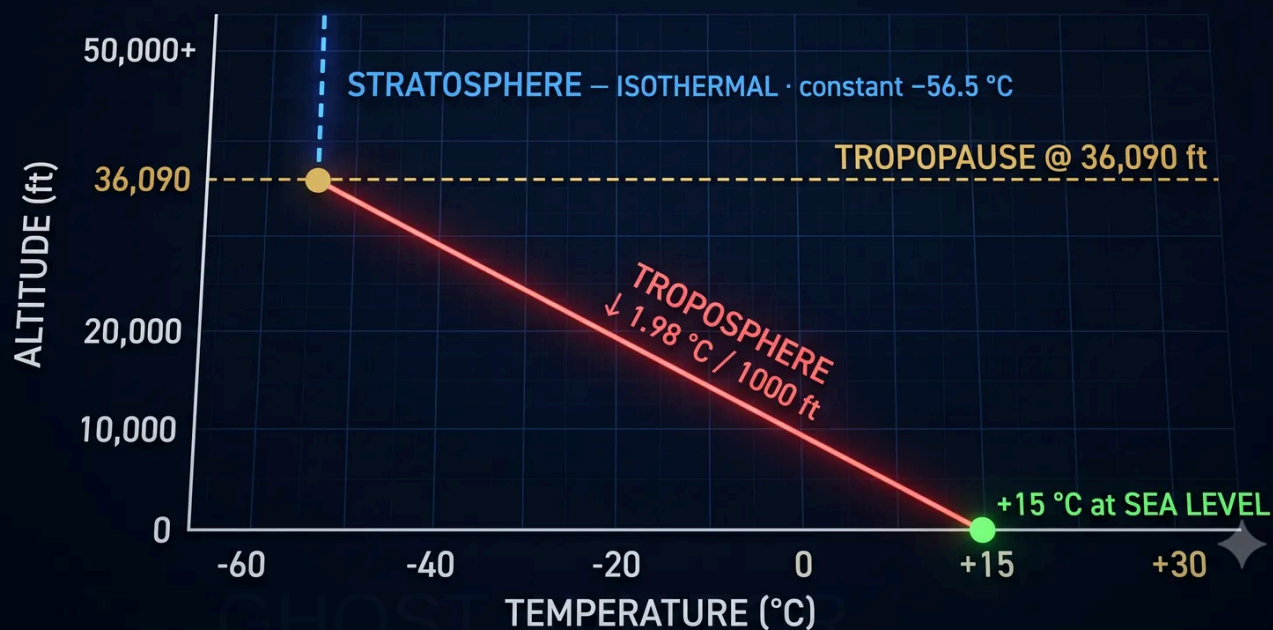


Figure 2.5 — The ISA temperature profile: 1.98 °C / 1000 ft up to 36,090 ft, then constant at -56.5 °C through the isothermal stratosphere.

✦ END OF CHAPTER 2 ✦

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