CHAPTER: 1
THE STANDARD ATMOSPHERE

TROPOSPHERE, STRATOSPHERE AND TROPOPAUSE

The portion of the atmosphere below the height at which the change occurs is called the **troposphere,** and the portion above, the **stratosphere**. The interface between the two is called the **tropopause**. The lapse rate and the height of the tropopause vary with latitude. In Arctic regions, the rate of temperature change is lower, and the stratosphere does not start until around 15 500 m. The temperature in the stratosphere varies between about - 30°C at the equator to - 95°C in the Arctic. In temperate regions such as Europe the temperature in the stratosphere is around - 56.5°C.

INTERNATIONAL STANDARD ATMOSPHERE

For aircraft performance calculations, it is normal practice to use a standard set of conditions called the **International Standard Atmosphere (ISA)**. This defines precise values of lapse rate, height of the tropopause, and sea-level values of temperature, pressure and density. For temperate regions the ISA value of the lapse rate is - 6.5°C per 1000m, the tropopause is at 11 km, and the sea-level values of pressure and temperature are 101.325 k N/m^2, and 15°C respectively.

Modern long- and medium-range airliners cruise in or very close to the stratosphere, and supersonic airliners such as Concorde fly in the stratosphere well above the tropopause. When piston-engined aircraft first started to fly in the stratosphere, conditions were very uncomfortable for the crew. The low density and pressure meant that oxygen masks had to be worn, and at temperatures of - 56°C, even the heavy fur-lined clothing was barely adequate. Nowadays, the cabins of high-flying airliners are pressurised, and the air is heated, so that the passengers are unaware of the external conditions. Nevertheless, above every seat there is an emergency oxygen mask to be used in the event of a sudden failure of the pressurisation system.

Despite the low external air temperature in the stratosphere, supersonic aircraft have the problem that surface friction heats the aircraft up during flight, so means have to be provided to keep the cabin cool enough.

The upper atmosphere

The atmosphere with which we have been concerned in the flight of aeroplanes - i.e. the troposphere and the stratosphere - is sometimes called **the lower atmosphere**; the remainder is called **the upper atmosphere** (Fig. 1.1).

In the lower atmosphere the temperature had dropped from an average of + 15°C (288 K) at sea-level to - 57°C (217 K) at the base of the stratosphere, and had then remained more or less constant. The pressure and density of the air had both dropped to a mere fraction of their values at sea-level, about 1 per cent in fact. One might almost be tempted to think that not much more could happen, **but such an assumption would be very far from the truth**.

MESOSPHERE

There is a lot of atmosphere above 20 km - several hundred kilometres of it, we don't exactly know, it merges so gradually into space that there is really no exact limit to it - but a great deal happens in these hundreds of kilometres. The temperature, for instance, behaves in a very strange way; it may have been fairly easy to explain its drop in the troposphere, not quite so easy to explain why it should then remain constant in the stratosphere, but what about its next move? For from 217 K it proceeds to rise again - in what is called the **mesosphere** - to a new maximum which is nearly as high as at sea-level, perhaps 271 K; then, after a pause, **down it goes again to another minimum** at the top of the mesosphere. Estimates vary of just how cold it is at this height (only 80 kilometres, by the way, only the distance from London to Brighton), but all agree that it is lower than in the stratosphere, lower, that is to say, than anywhere on earth, perhaps 181 K (-92°C). But its strange behaviour doesn't stop at that and, once more after a pause at this level, as the name of the next region, the **thermosphere**, suggests, **it proceeds to rise again**, and this time it really excels itself **rising steadily, inexorably** to over 1200 K at 200 km, nearly 1500 K at 400 km, and still upward in the exosphere until it reaches **over 1500 K at the outer fringes of the atmosphere.**

An interesting point about these temperature changes in the upper atmosphere is their effect upon the speed of sound which, rises with the temperature, being proportional to the square root of the absolute temperature. The interest is not so much in the effects of this on shock waves, or on the flight of rockets, but rather in that one method of estimating the temperatures in the upper atmosphere is by measuring the speed of sound there.

While these strange and erratic changes of temperature have been taking place the density and the pressure of the air have fallen to values that are so low that they are almost meaningless if expressed in the ordinary units of mechanics; at a mere 100 km, for instance, **the density is less than one-millionth of that at ground level.**

IONOSPHERE AND EXOSPHERE

It is believed that at these heights there may be **great winds**, of hundreds, perhaps even a thousand kilometres per hour. The air above about the 70 km level is 'electrified' or ionised, that is to say it contains sufficient free electrons to affect

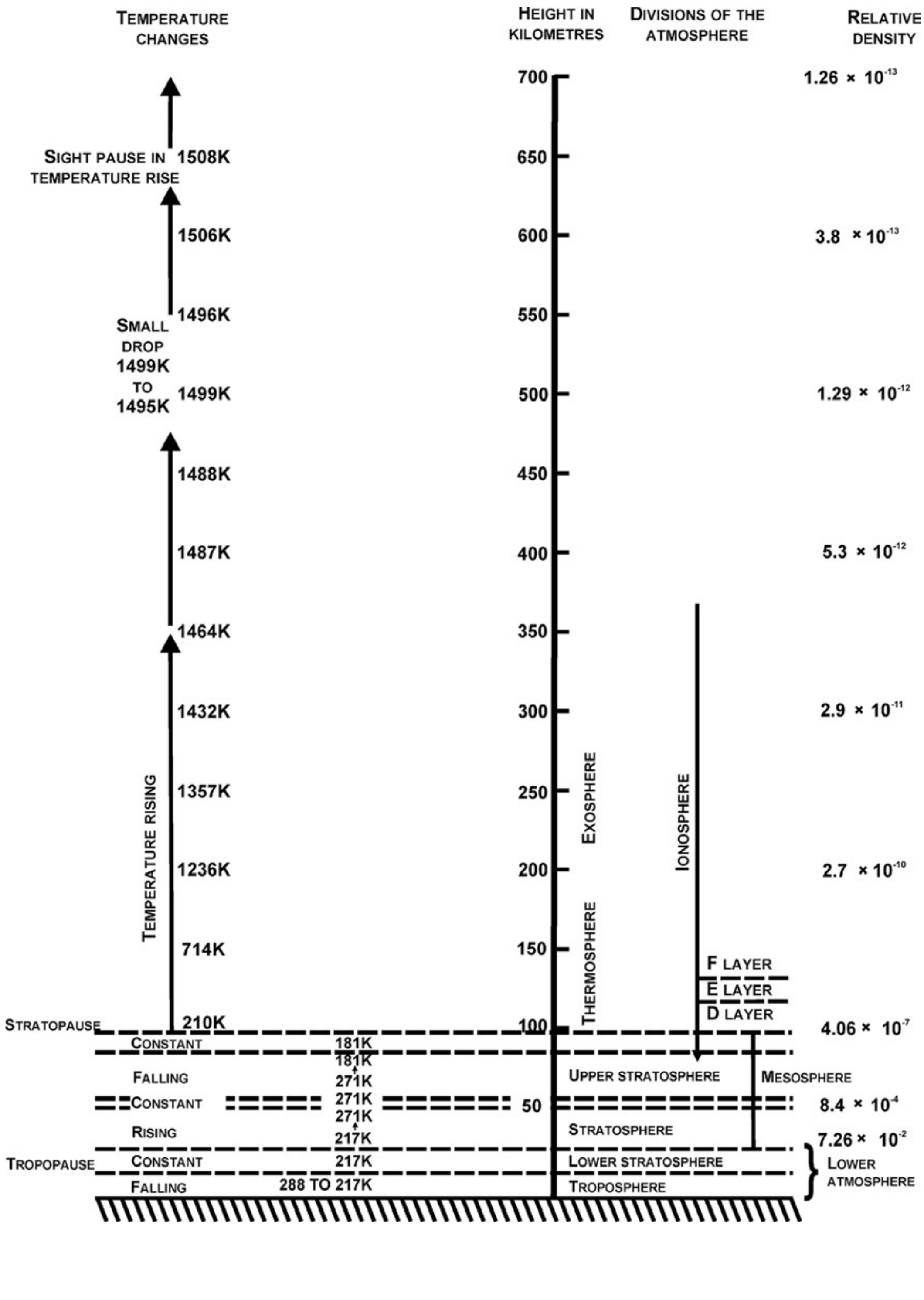
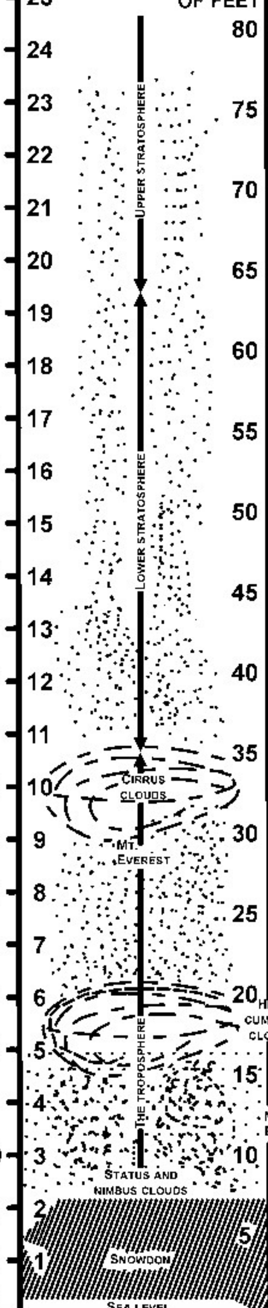


Fig.1.1. The upper atmosphere

The figures given are based on the US Standard Atmosphere, 1962, which was prepared under the sponsorship of NASA, the USAF and the US Weather Bureau

Speed of sound m/s	Density kg/m³	Press. Kn/m²	Temp. °K	Height above sea-level Km
299	0.040	2.5	222	25
298	0.047	3.0	221	24
298	0.055	3.5	220	23
297	0.065	4.0	219	22
296	0.076	4.7	218	21
295	0.089	5.5	217	20
295	0.104	5.5	217	19
295	0.122	7.6	217	18
295	0.142	8.8	217	17
295	0.166	10.4	217	16
295	0.195	12.1	217	15
295	0.228	14.2	217	14
295	0.267	16.6	217	13
295	0.312	19.4	217	12
295	0.365	22.7	217	11
299	0.414	26.6	223	10
304	0.467	30.8	230	9
308	0.526	35.7	236	8
313	0.590	41.1	243	7
317	0.660	47.2	249	6
321	0.738	54.0	256	5
325	0.819	61.7	262	4
329	0.909	70.1	269	3
333	1.007	79.5	275	2
337	1.112	89.9	282	1
340	1.225	101.3	288	



Thousands of feet	Temp. °C	Press. Mb	Relative density P/P₀	Relative pressure P/P₀
80	-52	28	0.036	0.028
75	-54	35	0.046	0.035
70	-55	45	0.059	0.044
65	-56	57	0.075	0.056
60	-56	72	0.095	0.071
55	-56	92	0.121	0.091
50	-56	117	0.153	0.115
45	-56	148	0.194	0.145
40	-56	188	0.247	0.188
35	-54	239	0.311	0.236
30	-44	301	0.375	0.298
25	-34	377	0.449	0.372
20	-25	466	0.533	0.460
15	-15	572	0.629	0.565
10	-5	697	0.739	0.688
5	-5	843	0.862	0.832
	15	1013	1.000	1.000

Fig.1.2. The international standard atmosphere

Based on the US Standard Atmosphere, 1962, which was prepared under the sponsorship of NASA, the USAF and the US Weather Bureau the propagation of radio waves. For this reason the portion of the atmosphere above this level is sometimes called the **ionosphere**, which really overlaps both the mesosphere and the thermosphere. Then there are the mysterious **cosmic rays** which come from outer space, and from which on the earth's surface we are protected by the atmosphere, but beyond this we know very little about them except that they may be the most dangerous hazard of all since they affect living tissues. Then there are the much more readily understandable **meteors**, 'shooting stars' as we usually call them, but actually particles of stone or iron which have travelled through outer space and may enter the earth's atmosphere at speeds of 100 kilometres per second, and which have masses of anything from a tiny fraction of a gram up to hundreds of kilograms. The larger ones are very rare, but some of these have actually survived the passage through the atmosphere without burning up, and have 'landed' on the earth causing craters of considerable size - these are called **meteorites**.

To prospective space travellers all this may sound rather alarming, but there are some redeeming features. The winds, for instance, wouldn't even 'stir the hair on one's head' for the simple reason that the air has practically no density, no substance. For the same reason the extreme temperatures are not 'felt' by a satellite or space-ship (what is felt is the temperature rise of the body itself, caused by the skin friction at the terrific speeds; it is this which burns up the meteors, it is this which has eventually caused the disintegration of many manlaunched satellites on re-entering the atmosphere - but all this has little or nothing to do with the actual temperature of the atmosphere). Then, as regards the very low densities and pressures, no-one is going to venture outside the vehicle, or walk in space, or even put his head out of the window to see whether the wind stirs the hair on his head, unless he is wearing a space-suit, and we have long ago learned to pressurise vehicles because this is required even for the modest heights in the lower atmosphere. Moreover, the strong outer casing of the vehicle which is required for pressurising will in itself give protection at least from the small and common meteors, and to some extent even from the cosmic rays, the greatest unknown. So altogether the prospect is not as bad as it might at first seem to be.

PROPERTIES OF ATMOSPHERE AND ITS VARIATION WITH ALTITUDE

a. Temperature

Another change which takes place as we travel upwards through the lower layers of the atmosphere is the gradual drop in temperature, a fact which unhappily disposes of one of the oldest legends about flying - that of Daedalus and his son Icarus, whose wings were attached by wax which melted because he flew too near the sun. In most parts of the world, the atmospheric temperature falls off at a steady rate called the lapse rate of about - 6.5°C for every 1000 metres increase in height up to about 11000 metres. Above 11000 metres, the temperature remains nearly constant until the outer regions of the atmosphere are reached.

b. Pressure

The weight of air above any surface produces a pressure at that surface - i.e. a force of so many newtons per square metre of surface. **The average pressure at sea-level due to the weight of the atmosphere is about 101 kN/m^2**, a pressure which causes the mercury in a barometer to rise about 760 mm. This pressure is sometimes referred to as 'one atmosphere', and high pressures are then spoken of in terms of 'atmospheres'. The higher we ascend in the atmosphere, the less will be the weight of air above us, and so the less will be the pressure

Decrease of pressure and density with altitude

The rate at which the pressure decreases is much greater near the earth's surface than at altitude. This is easily seen by reference to Fig. 1.2; between sea-level and 10000 ft (3480 m) the pressure has been reduced from 1013 mb to 697 mb, a drop of 316 mb; whereas for the corresponding increase of 10000 ft between 20000 ft (6096 m) and 30000 ft (9144 m), the decrease of pressure is from 466 mb to 301 mb, a drop of only 165 mb; and between 70000 ft (21336 m) and 80000 ft (24384 m) the drop is only 17 mb.

This is because air is compressible; the air near the earth's surface is compressed by the air above it, and as we go higher the pressure becomes less, the air becomes less dense, so that if we could see a cross-section of the atmosphere it would not appear homogeneous - i.e. of uniform density - but it would become thinner from the earth's surface upwards, the final change from atmosphere to space being so gradual as to be indistinguishable. In this respect air differs from liquids such as water; in liquids there is a definite dividing line or surface at the top; and beneath the surface of a liquid the pressure increases in direct proportion to the depth because the liquid, being practically incompressible, remains of the same density at all depths.

c. Density

Another property of air which is apt to give us misleading ideas when we first begin to study flight is its low density. The air feels thin, it is difficult for us to obtain any grip upon it, and if it has any mass at all we usually consider it as negligible for all practical purposes. Ask anyone who has not studied the question what is the mass of air in any ordinary room - you will probably receive answers varying from 'almost nothing' up to 'about 5 kilograms'. Yet the real answer will be nearer 150 kilograms, and in a large hall may be over a metric tonne! Again, most of us who have tried to dive have experienced the sensation of coming down 'flat' onto the surface of the water; since then we have treated water with respect, realising that it has substance, that it can exert forces which have to be reckoned with. We have probably had no such experience with air, yet if we ever try we shall find that the opening of a parachute after a long drop will cause just such a jerk as when we encountered the surface of the water. It is, of course, true that the density of air - i.e. **the mass per unit volume** - is low compared with water (the mass of a cubic metre of air at ground level is roughly

1.226 kg - whereas the mass of a cubic metre of water is a metric tonne, 1000 kg, nearly 800 times as much);**yet it is this very property of air - its density - which makes all flight possible,** or perhaps we should say **airborne** flight possible, because this does not apply to rockets. The balloon, the kite, the parachute, and the aeroplane - all of them are supported in the air by forces which are entirely dependent on its density; the less the density, the more difficult does flight become; and for all of them flight becomes impossible in a vacuum. So let us realise the fact that, however thin the air may seem to be, it possesses the property of density.

d. Viscosity

An important property of air in so far as it affects flight is its **viscosity**. This is a measure of the resistance of one layer of air to movement over the neighbouring layer; it is rather similar to the property of friction between solids. It is owing to viscosity that eddies are formed when the air is disturbed by a body passing through it, and these eddies are responsible for many of the phenomena of flight. Viscosity is possessed to a large degree by fluids such as treacle and certain oils, and although the property is much less noticeable in air, it is none the less of considerable importance.

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