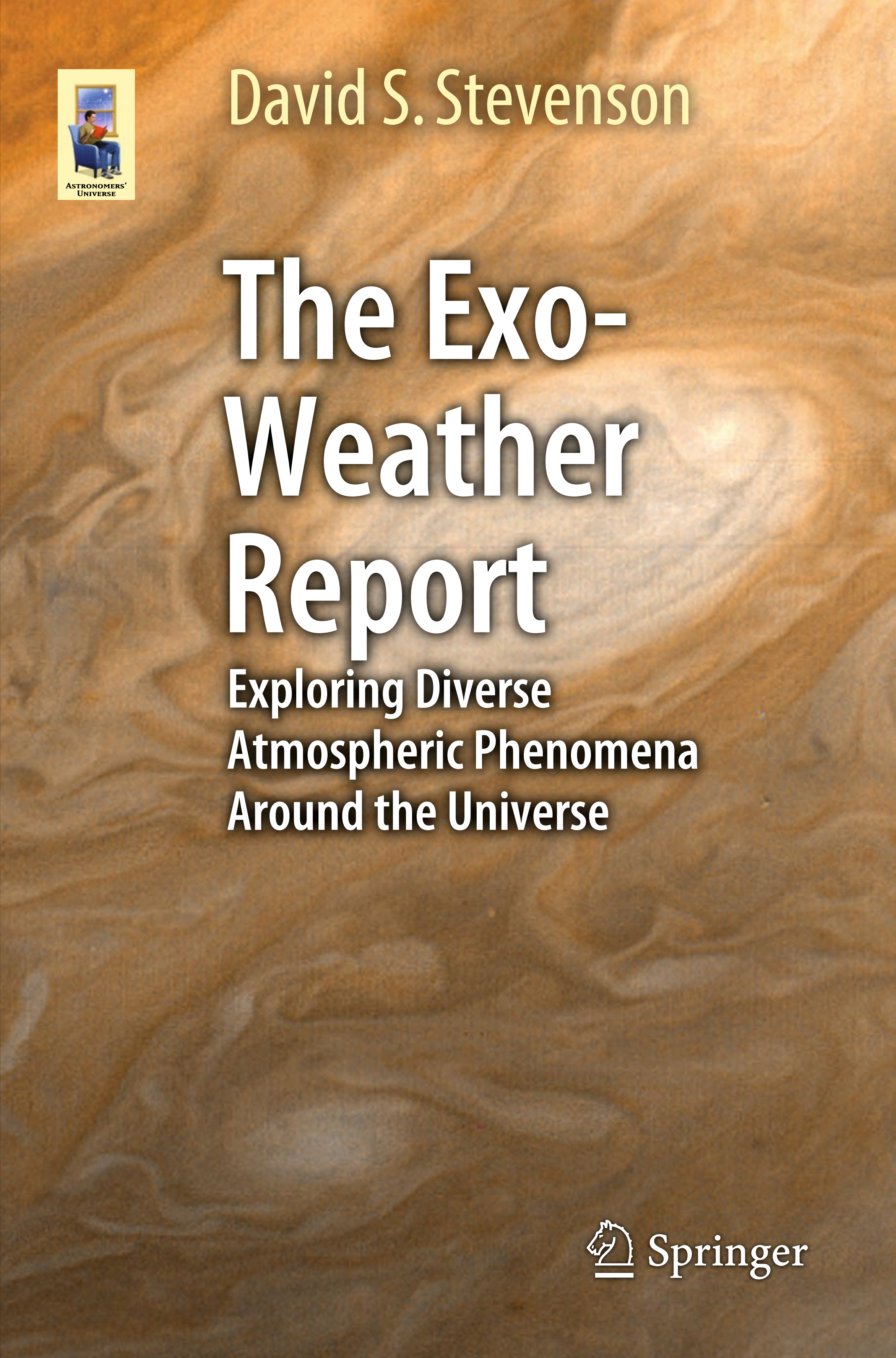

ASTRONOMERS' UNIVERSE

David S. Stevenson

The Exo-Weather Report

Exploring Diverse Atmospheric Phenomena Around the Universe

Springer

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This book is dedicated to my sisters Avril
Stevenson-Davies, Karen Suzuki, and Mairi Allardice
and their families; and to my cousin Lesley Duncan.

Preface

My father fought in both World Wars. In 1915, aged 16 he joined the British Navy, serving on HMS Orion. Training in communications, he ultimately took the surrender of the German Fleet, passing the terms of surrender to the German High Command (Fig. 1). During the Second World War, my father served in the merchant fleet and took part in the evacuation of Dunkirk. The science of meteorology took off during the First World War, because it became understood that the weather was a key variable in winning battles. There were obvious patterns, such as the "lowering of the sky" ahead of a rain, but the term front had yet to be coined, except outside the unpleasant confines of the Trenches. Changes in wind direction and cloud cover were noted as rain bands came and went as well as the turning of the seasons (Fig. 1).

However, it wasn't until the late nineteenth century before much of the underlying science was known and not until the 1920s that our understanding of frontal boundaries emerged. Later still, in the 1930s and 1940s the jet streams were discovered and the driving force behind much of the movement of our weather became apparent. My father taught me the nature of frontal systems that he had learnt while at sea, along with the names of all of the clouds. However, the idea that other planets might have weather was still in its infancy.

Until the Soviet Venera probes landed on Venus, it was thought rather likely Venus was a rather pleasant tropical world. That Venus could experience a runaway greenhouse effect, driven by carbon dioxide, was simply not understood. John Tyndall may have done the first experiments with various gases as early as 1850, but the implications of such discoveries were not realized until much later. Indeed, the idea that altering the concentration of greenhouse gases can have an impact on terrestrial climate is still rather contentious in some circles.

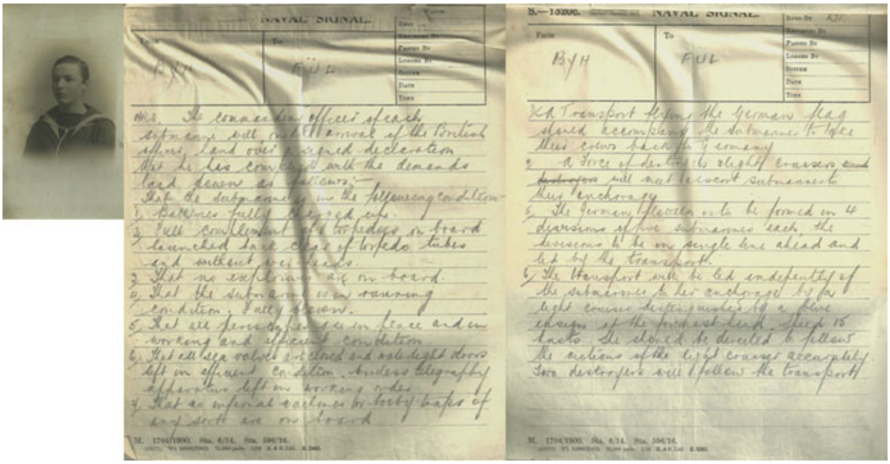

Fig. 1 The original transcript of the terms of surrender of the German fleet in 1918, taken by my father David Stevenson. My father rather mischievously kept a copy of the transcript he recorded to be passed onto the fleet admiral. In amongst the tragedy of the First World War, and in large part because of it, the science of meteorology really took off. Respective Navies and fledgling air forces needed to know how the weather would impact their activities

We are at a point that we have gathered a lot of data on the atmospheres of the planets in our solar system and are beginning to gather information on planets hundreds or thousands of light years away. Through a greater understanding of our planet, we can see how the climate of other planets is affected by the composition of their atmosphere; the influence of their parent star and the proximity of such worlds to their stars. Take Kepler 452b, for example. This world is a fairly good match for the Earth a billion years into our future. As its Sun-like star slowly advances its years, Kepler 452b is being stranded on the hot side of its star's habitable zone. Our observations of this world will paint a more accurate picture of how our world will eventually find its habitability coming to an end.

Meteorology is a broad physical science, but this breadth is its strength. It encompasses simple, generic observational skills, through to complex mathematical modeling of fluids. Models are best tested by comparison with observation and it often turns out that simple observations can provide some very useful truths. In Chap. 1 I describe a workable model for predicting winter weather in the UK several months in advance. This is testable, which is the hallmark of good science. However, it can be underpinned by solid mathematics, something I could with brushing up on.

I've arranged the chapters in increasingly hierarchical but overlapping structures that provide clear links between phenomena on all the worlds described. Lightning is introduced in Chap. 4, but links to all of the subsequent chapters (bar Mars) on the worlds of our solar system. The greenhouse effect emerges in Chap. 3 then links to the others, while terrestrial monsoons are described in Chap. 2 before linking through to the climate of Mars and extrasolar worlds. Hopefully, this approach provides clear links and shows the interconnectedness of the underlying science.

Meteorology and climate science are truly fascinating aspects of planetary science where we humble earthlings get to experience firsthand how the physics of other worlds plays out.

Nottingham, UK David S. Stevenson

Contents

1. What We Know About the Weather on Earth

Why Do We Have Weather?

Weather is such a ubiquitous part of our lives that most of us take it completely for granted. Yet it controls nearly every aspect of our life, from our route to and from work to the food we eat and more. The weather is the talking point for the random meeting, or the casual chat on the Metro. The weather is something that we all have an opinion on; most notably the accuracy, or perceived lack-thereof, of TV weather forecasts, or the dress sense of their presenters. Yet, most have little understanding of why weather happens at all.

Weather, for all its daily and geographical complexity, can be broken down to one simple statement: it is the transfer of energy from one area to another. Weather is a manifestation of our parent star's inability to heat the Earth's surface evenly. A round, three dimensional planet is notoriously difficult to deliver energy to in any kind of even-handed manner. Areas under more direct sunlight, such as at the equator, warm most strongly as heating is more intense when the Sun is overhead. This is simply because the energy is delivered to a smaller surface area than if it were illuminated at an angle.

Worse still, the presence of an atmosphere ensures that energy from our star is diluted or diverted on its multimillion kilometer passage from star to planet. Much of the energy is reflected by clouds or particles in the air, or absorbed by elements and compounds that swirl within it (Fig. 1.1).

If the Earth were more like our Moon, with little or no atmosphere, then the daytime temperatures would soar to nearly 175 °C, while at night we would languish at –125 °C: a range of 300 °C. The atmosphere cushions the rise and fall of temperature,

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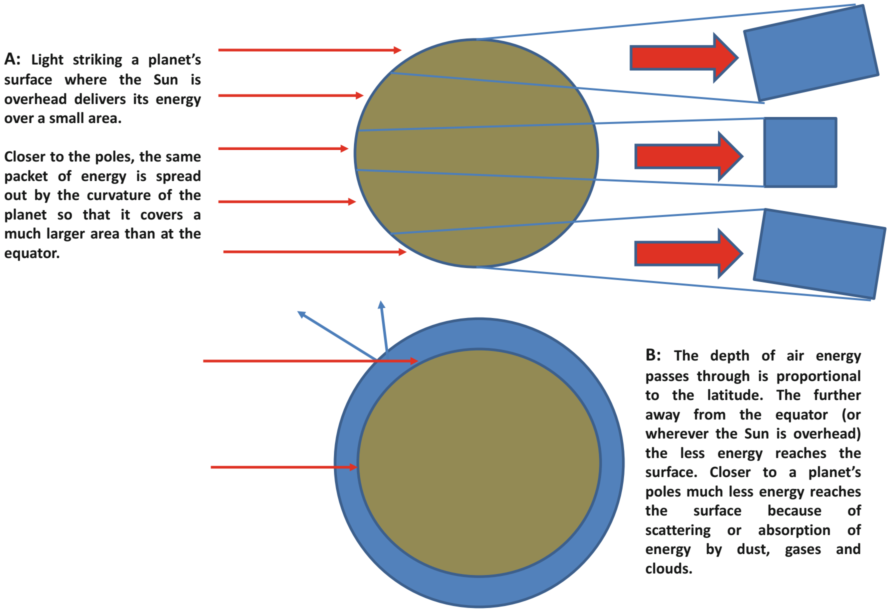

Fig. 1.1 The effect of the curvature of a planet and any atmosphere on the amount of heating different parts of its surface will experience. Were the Earth a pancake facing directly into the sunlight all of it would be heated to the same extent and weather, although it would exist, would be profoundly dull. (**a**) Light striking a planet's surface where the Sun is overhead delivers its energy over a small area. Closer to the poles, the same packet of energy is spread out by the curvature of the planet so that it covers a much larger area than at the equator. (**b**) The depth of air energy passes through is proportional to the latitude. The further away from the equator (or wherever the Sun is overhead) the less energy reaches the surface. Closer to a planet's poles much less energy reaches the surface because of scattering or absorption of energy by dust, gases and clouds

in part by absorbing and retaining some of the Sun's energy, but also by effectively transporting it from place to place. This transfer of energy we call wind.

On any object with significant gravity energy can be transported vertically from the bottom to the top of the atmosphere by convection. Advection is the transport of energy from place to place in a (roughly) horizontal direction. This can happen in response to convection pulling and pushing air around or, more directly, in response to temperature differences and the spin of our planet. On the Earth, convection dominates the transport of energy at the hottest and (in our case) most equatorial regions, but is prevalent elsewhere where conditions are suitable, particularly in the summer months when heating is strongest. By contrast, advection dominates energy transport between the tropics and the poles.

The Highs and Lows of Meteorology

Where air rises, it exerts less pressure on the underlying layers or the surface: this creates an area of lower pressure that draws in air from the surroundings. Where the air is moist, clouds can form and precipitation falls. Essentially: what goes up must come down. Otherwise, when air is sufficiently cold and dense, it descends under its own weight. As it falls it compresses the air underneath, generating an area of higher pressure—an anticyclone—and warms somewhat as it compresses under its own weight. In addition, pressure will rise and fall if it is forced to do so. Pressure falls where air is forced to rise over hills and mountains, and conversely in the extreme environs of tornadoes and hurricanes, as the air circulates rapidly around the central low pressure core, inflowing air cannot keep pace with the air that is being sucked out of the storm's top. Some air then is forced to descend inside the center of the storm: the eye of the hurricane in particular is a region of descending, warming air that breathes a brief window of calm in the otherwise violent storm.

In addition to this simple relationship overall, warm air exerts a higher pressure than colder air. Thus, if you move vertically in a column of warm air pressure falls more slowly with height than if you are moving upwards through a column of cold air. This has some interesting effects. Over Siberia (and North America) during the winter, the air becomes extremely cold. This generates an intense area of high pressure over Siberia. Yet, if you rise above 3000 m the high pressure area has been replaced by a finger-shaped area of low pressure—a trough. Conversely, Scandinavia is commonly the location of what is known as blocking anticyclones. These are areas of high pressure, with a warm core, which extend through the full height of the troposphere. Although the air may be very cold at the surface, you don't have to travel far upwards to encounter air that is much warmer than you would expect for that latitude and altitude in the winter. Blocking anticyclones are also common over the North Pacific in the winter, particularly in La Niña years, and over the same region in the summer of El Niño years (Chap. 2). It is the presence of the core of warm and relatively high pressure air that makes these atmospheric features so stubbornly difficult to move. Indeed, the current climatic tribulations taking Alaska and California by force, are largely down to the persistence of a blocking anticyclone over the northern Pacific; this is one block that has lasted, with only minor interruptions, for several years.

Likewise, low pressure areas tend to become colder with height. The major low pressure areas of the mid and high latitudes develop cold cores as they deepen. However, in the summer, and over the Tropics, many low pressure areas, including hurricanes, are warm-cored throughout. Within these thermal lows pressure is low at the surface but soon morphs into an area of high pressure at greater heights, due to warmer air exerting a higher pressure than cold air.

Wind Direction: Waterwheels and a Suspect Tale from the Front

Air flow on any rotating planet is driven by two opposing forces: pressure and spin. Pressure is the simplest to understand. Air of lower pressure effectively draws air into it from regions with higher pressure. Strictly speaking a force is exerted by the high pressure air, which directs gases towards the regions with lower pressure. This is the pressure force. Intimately linked to this idea is temperature: air of a higher temperature has a higher pressure. There are three fundamental gas laws describing this relationship of pressure, temperature, volume and amount of gas. Boyle's Law dictates that the volume of gas increases as the pressure decreases: gas under higher pressure has a smaller volume, if you keep the temperature and mass of gas the same. Charles' Law requires that the volume of gas increases as the temperature increases. And Avogadro's Law tells us that equal volumes of all gases, at the same temperature and pressure, have the same number of molecules: for a given mass of an ideal gas, the volume and amount (moles) of the gas are directly proportional if the temperature and pressure are constant. Together, these laws guide much of modern science and are integral to our understanding of how atmospheres work.

Charles's law, incidentally, is often misattributed as Gay-Lussac's Law, as it was published in 1802 by the French chemist, Joseph Louis Gay-Lussac. However, the publication followed a century after from the work of Guillaume Amontons and Jacque Charles, whose work Gay-Lussac extended. Amonton's work languished for a century before Gay-Lussac revamped it, along with many unpublished results from Charles. Gay-Lussac's triumph lay in the use of individual gases, such as oxygen and nitrogen, unavailable in Amontons's day and his ability to interpret, unite and extend the work of Charles and Amontons, producing two of the three core gas laws biologists, chemists and physicists use today.

If we look simply at pressure and temperature, particles of the various gases that make up the air will exert a higher pressure at a higher temperature because they move faster (they have greater kinetic energy). Collisions between the particles and any surface will, therefore, carry more energy and thus exert a greater force than those in a colder and denser gas. Imagine a baseball hitting a wall at 10 km per hour versus 80 km per hour. This idea has important ramifications for the structure of the atmosphere as we shall see later in this chapter.

Spin is a more complex concept. The Earth rotates on its axis once per day. That means that a piece of soil at the equator has to move at nearly 1700 km per hour to make a full rotation in this interval. Conversely, standing at the Earth's rotation poles, you don't rotate at all (except slowly around your middle, of course). That means that any stray packet of air trundling north or south towards the poles will find itself, increasingly, moving faster than the ground underneath; and this means that, relative to the surface, it will steadily bend towards the east as it travels away from the equator. Similarly, but in the opposite direction, air moving from either pole towards the equator will curve towards the west

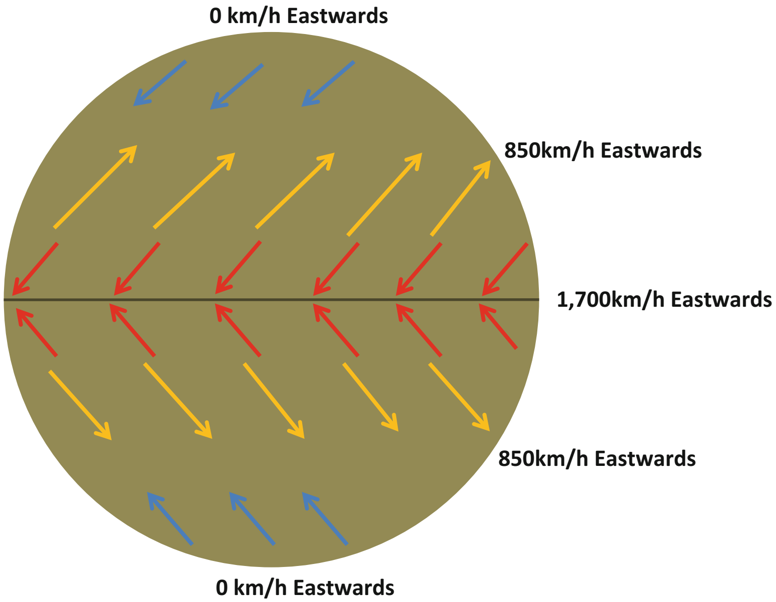

Fig. 1.2 The effect of a spinning Earth on the movement of air to and from the equator. Air moving away pole-wards is deflected eastwards while air moving towards the equator moves to the west. Numbers indicate the rate of rotation of the surface around the polar axis

because the ground underneath it is moving more swiftly towards the east than it is (Fig. 1.2). A similar thing happens when a person steps off a moving bus or train—their speed, doesn't match that of the ground underneath.

Known as the Coriolis Effect, this made its presence known during the latter part of World War I. In 1918, German troops positioned a large gun 120 km to the northeast of Paris. The gun was used to shell Paris from behind the German lines with the aim of terrorizing the population rather than inflicting significant damage. Because the distance was so far, the Earth's rotation had an impact on the shell's trajectory; they reached higher than any other projectiles up to that time, and their path was therefore subject to forces that had theretofore unaccounted for. Initially most of the shells fell to the west of the French capital, because when they began their journey they were moving eastwards at a slower speed than Paris, which lay to the southwest and thus had further to travel in its rotation around the Earth's axis (Fig. 1.3).

Fig. 1.3 The 1918 "Paris gun". Shells were fired at Paris from 120 km to the north-east of the capital. Shells curved to the west of the city as a result of the Coriolis Effect (*red arrow*). The gunners soon corrected for this and repeatedly shelled Paris. French map courtesy of Wikipedia Commons

Unfortunately, after some tweaking of the trajectory, Paris was positioned firmly in the gun's sights and was shelled up to 20 times a day, killing 250 people. The "Paris Gun" was notable for one other meteorological first. The gun fired the first man-made object 42.3 km into the stratosphere; a feat not beaten until Germany launched the infamous V2 rockets in 1944. The sheer height of the trajectory combined with the distance brought Gustav Coriolis's effect into play.

Otherwise, the Coriolis Effect is mostly experienced by air or liquids that are moving northwards or southwards on any rotating body. Its discoverer, Gaspard–Gustave de Coriolis, first described the Coriolis Effect while thinking about machinery. Coriolis was interested in *work*, or more fully *work done,* a definition of energy: the ability of a force to move a mass over a distance. He investigated "work" in relation to objects that were rotating, in particular water wheels, which were very much in demand to drive the hardware of the early industrial revolution. Coriolis had no interest in the dynamics of the Earth's atmosphere, or indeed any planetary atmosphere, although the title of his 1832 paper was inadvertently suggestive of this: "On the equations of relative motion of a system of bodies." In this work Coriolis detailed various forces which afflict rotating bodies, including planets, but it would take nearly 70 years before Coriolis' name became clearly associated with the meteorological effect he inadvertently described.

The Coriolis Effect is proportional to the speed that the body spins and its overall diameter. Thus a small planet has a weak effect, as does a planet that rotates slowly. Therefore, both Mars (small) and Venus (slow) have weak Coriolis Effects, while mighty Jupiter, with its 17 h rotation has an effect much stronger (about three times) than that found on the Earth.

This effect works at the surface and throughout the bulk of the atmosphere. On the Earth hot air rises above the Equator (or more precisely where the Sun is overhead) and sinks at the poles. You might then expect a simple pattern of air flow from pole to equator. Easterly winds would dominate the planet[1] because these would be returning cold air from the poles towards the equator; indeed, this pattern is evident on Venus (Chap. 5). However, this is not seen in the Earth's atmosphere, because the Coriolis Effect prevents air from flowing in such a simple pattern. The issue is the air rising above the equator. This air rises over 10 km through the lowest layers of the atmosphere, until it hits a wall, called the tropopause, the nature of which we shall return to later. At the tropopause the air is diverted to the north and south and the Coriolis Effect begins to work its magic.

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[1] An interesting consequence of this would be that the Earth's spin would decelerate. Winds would be blowing in the opposite direction to its spin and thus exert a frictional force on its surface.

High above the band of rising air, air flows north and south. The Coriolis force diverts this towards the east, in a westerly flow. Initially, the winds move northeastwards or southeastwards towards the pole, but by the time the air has reached roughly 30° N or 30° S the air has been turned right angles to its original direction and flows strongly to the east. There is no further north or south movement. Were this all that happened then the tropics would be completely isolated from the poles and the only means by which heat could be transported further north or south would be via ocean currents. However, the planet has a trick to play with this air. The air steadily cools as it initially rises near to the equator. By the time it has traveled 30° north or south it is dense enough to sink towards the ground once more. So down it falls towards the ground in a steady stream, pouring over the Tropics of Cancer and Capricorn. The planet's steadiest belt of weather, the dry Horse Latitudes, are created from this pattern, called Hadley cells. Past the 30th parallel most of the air returns to the equator, while the rest streams northwards or southwards towards the poles, entraining air from outside the Hadley cells.

Once more the Coriolis Effect comes into play as air moving towards the North Pole is again bent towards the east, producing the mid-latitude westerly winds. The southern hemisphere mirrors this with the winds arcing round to form the roaring forties and even more descriptively screaming fifties. The Coriolis Effect keeps the air turning towards the east so once again it fails to reach either pole and the atmosphere comes to the rescue. Cold air streaming away from either pole, towards the west, collides with the westerly belt and directs much of it upwards towards the tropopause.

Finally, after a fairly exhausting trip a portion streams northwards (in the Northern Hemisphere) and southwards (in the Southern Hemisphere) to reach the Polar Regions. The circuit completes when this now profoundly chilly air sinks under its own weight towards the surface. From here the only way is away from the pole to complete the loop, reuniting the air of our planet in three great circulations between pole and equator. This is illustrated in Fig. 1.4. It must be emphasized that this pattern is broadly symmetrical around the equator, meaning that the same overall pattern of air flow is seen in the Southern Hemisphere.

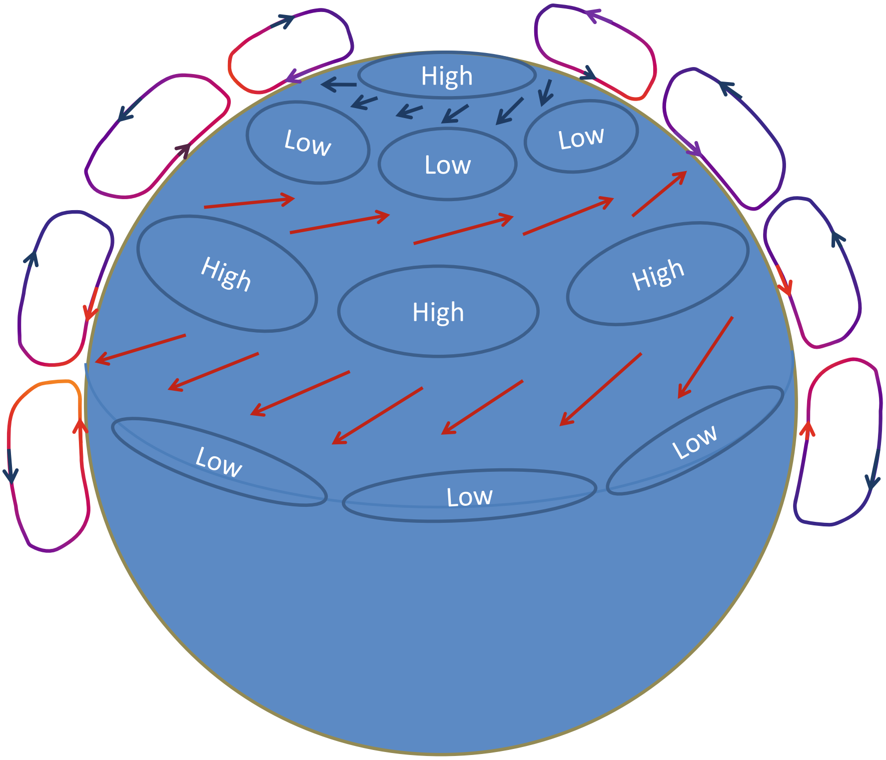

Fig. 1.4 The general pattern of wind flow and pressure on the Earth in the Northern Hemisphere. Geographical features such as oceans and mountains strongly affect this generic pattern; as does the tilt of the Earth throughout the seasons

The Vertical Structure of the Earth's Atmosphere

As well as horizontal transitions across the globe at different latitudes, the atmosphere can be broken into different layers as it increases in altitude. In each layer temperature and pressure vary in predictable ways.

Extending through the first few kilometers of the atmosphere is the region of densest and most turbulent air, known as the troposphere. This is thickest (17 km) over the Tropics where the air is warmest and exerts the greatest pressure. The depth of the troposphere decreases in a series of steps as you go further towards each pole. Each step is marked by a current of fast moving air known as a jet stream (returned to later in this chapter). Thus, where as above the equator the top of the troposphere is 17 km high, it is only 10 km or so above the ground over Spain, the bulk of the US and southern Australia. Even closer to the poles and it drops even closer towards the surface, ultimately lying 7–8 km above the ground at the Poles.

Throughout the troposphere temperatures fall as altitude rises—indeed this is a defining feature of this layer. This can make the air unstable and prone to convect. However, there is such variability in this region that simply describing it as a simple layer would do it a great disservice. The troposphere is broken horizontally into different regions that move under the influence of pressure and the Coriolis Effect, leading to a very dynamic and complex zone. Fortunately, as you go higher the complexities subside and things become somewhat simpler to understand.

Above the troposphere lies the stratosphere. As the name implies, air in this layer is stratified, displaying relatively little vertical movement. The dividing line between the troposphere and the stratosphere is a boundary called the tropopause. Here temperatures stop falling with increasing altitude and begin to rise. This change causes the air to stop convecting as from this point upwards the air is warmer the higher you go. The reason the temperatures rise is down to one gas: ozone. Ultraviolet light is absorbed by oxygen, which is found in the form of a molecule (O_2). In this diatomic (two atom) form, the bonds can be broken and then reassembled into ozone (O_3). Ozone is superbly efficient at absorbing ultraviolet light, particularly that in the range of longer wavelengths closest to the visible part of the spectrum. It is these wavelengths that are most harmful to life, thus ozone helps ensure complex life can populate the solid surface of the Earth. Without it, life would be confined to the ocean depths where UV is unable to penetrate deeply (Fig. 1.5).

As you progress upwards through the atmosphere, the density of gases steadily diminishes. The stratosphere begins where the atmospheric pressure is approximately one fifth that found at the surface (200–300 mb) and ends with a pressure less than one tenth this value. Although very dense compared to the vacuum of space, the air is so rarified that any living organism (for example a stray microbe) would be rapidly freeze-dried.

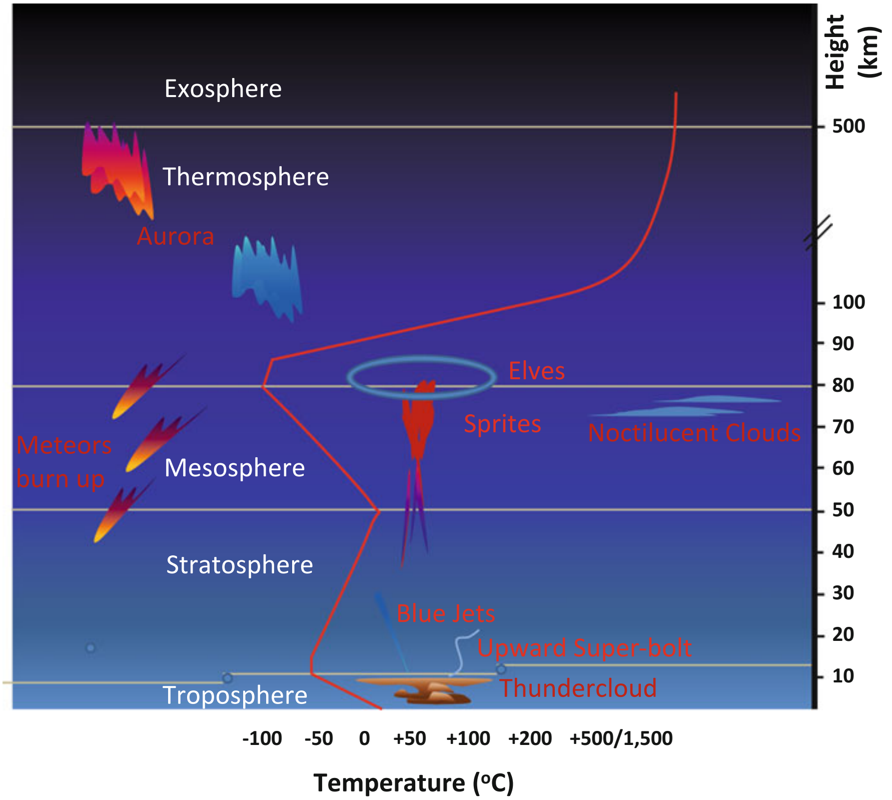

Fig. 1.5 The overall structure of the Earths Atmosphere. The different layers are separated by *white lines*. The thickness of the troposphere varies with latitude and is thickest nearest the equator. Jet streams (*small, blue circles*) mark the position of the jumps. The *red line* indicates how temperature changes with height. The temperature of the thermosphere varies from 500 °C to over 1000 °C when the Sun is most active. Various phenomena are indicated. Sprites, Elves and Blue Jets that are associated with thunderstorms are described in Chap. 4

Above the ozone layer, the mesosphere begins and the temperature falls once more from around zero Celsius to around −100 °C. The air is very dry but does hold a small amount of water vapor—just enough to form rare noctilucent clouds out of water ice crystal. These form at an altitude of around 70–80 km, predominantly in the early spring at the poles where the air is coldest. Their frequency is increasing, which suggests that more moisture is escaping through the stably stratified layer below from the moist troposphere at the atmosphere's base. This may be a sign that rising global temperatures (Chap. 2) are driving more water vapor into the higher atmosphere.

As you ascend through the mesosphere the abundance of molecules falls as ultraviolet light and increasing amounts of x-rays and gamma rays break them apart. Atomic oxygen, nitrogen, and the molecule hydroxyl, which is unstable at the Earth's surface, dominate the composition of the gases in the mesosphere. Hydroxyl is produced when water vapor is split by UV releasing hydrogen to space. The left-over oxygen and hydrogen remain bound together, but are ultimately split up at higher altitudes. The atmospheric pressure is less than 1000th that at the surface making the mesosphere a fairly good analog for the atmosphere that rests on the surface of Mars.

The mesosphere is also home to some enigmatic electrical phenomena known as sprites, elves and tendrils. These microsecond long features appear above some, but not all thunderstorms and appear to form electrical connections between the turbulent troposphere and the thermosphere above (see Chap. 4).

Additionally, the mesosphere is also the region where most meteorites are vaporized. This leads to a regional enhancement in the abundance of silicates and metals, particularly iron and nickel. All told, the mesosphere is one of the atmosphere's most inscrutable regions. It is too high for balloons and jet craft to probe, yet too low for satellites to sample. Measurements are always taken remotely from the surface or from space and are as yet relatively piecemeal in nature. Some of these recent observations are described in Chap. 10.

Above 80 km in height, the temperature begins to rise once more. Gases are increasingly ionized forming bands of rarified gases at different heights. These ionized regions are important for ground-based radio communication as they efficiently reflect electromagnetic waves to allow humans to communicate with one another around the curved surface of the planet. These gases also give this layer its name, the ionosphere. Technically, the ionosphere encompasses both the mesosphere and the ionized layer above which we now call the thermosphere. Whereas the amount of ionization is limited in the mesosphere, all of the gases are ionized to varying extents in the thermosphere. Temperatures rise to over 500 °C in this region. Not that you would feel it hot were you able to experience it: the concentration of gases is so low that you would still freeze solid if out of the glare of the Sun. The maximum temperature can exceed 1000 °C when the Sun is active and the Earth is subjected to the highest intensity of ultraviolet and x-radiation.

Towards the top of the thermosphere you might bump into passing orbiting craft, including the International Space Station which orbits at 400 km altitude. As you went higher you would enter the magnetosphere. In its regions above the equator the Earth's magnetic field guides the vapors and the solar wind into warped donuts of plasma. Here the density of gas is trillions upon trillions of times lower than the density found at the Earth's surface. It is effectively an extension of the near vacuum of space, where hydrogen and helium pause on their way out into the Solar Wind. The hydrogen comes mostly from the break-up of water vapor that results from ultraviolet light splitting the molecule up, while the helium comes from the Earth's crust and interior. Helium is synthesized by the radioactive decay of heavy elements, such as uranium, or was originally trapped there when the Earth formed. In addition, small amounts of oxygen and nitrogen are drawn outwards into space. This is partly as a result of their entrapment within the flow of escaping hydrogen and helium, something called hydrodynamic escape. Alternatively, oxygen and nitrogen escape directly from the effect of ultraviolet light bombarding these gases and energizing them sufficiently to escape in their own right.

This region where gases escape from the thermosphere to the magnetosphere or the vacuum of space is known as the exosphere. The exosphere is less of a region of atmosphere as much as it is a transition from atmosphere to space. The density of gases isn't so much measurable in millibars rather in terms of individual particles per cubic centimeter. The only thing that would exert noticeable pressure upon you would be the impact of a passing meteor or a man-made satellite.

As far as weather and climate are concerned most of the action occurs in the troposphere, with its upper surface, the tropopause, keeping a lid on most meteorological activity. However, within the stratosphere and mesosphere, meteorological phenomena do occur that are at least visible from, if not having a direct effect upon, the surface below. With our sortie of the atmosphere complete we return to the troposphere to engage in some atmospheric hand-to-hand combat. However, in Chap. 4 we will look again at some of the more exotic atmospheric phenomena that stir the layers above.

The Language of War-Fronts

During the First World War, and in it immediate aftermath, meteorologists were trying to understand patterns within the flow of air and the link to the weather in general. A group of scientists working within the Bergen School of Meteorology harnessed the language of the Great War to describe the observed patterns of temperature and wind flow. The term "front" became established as a generic term that described the boundary between two *competing* air masses. In the Bergen scenario, known as the "Norwegian Cyclone Model", a low pressure first develops as a disturbance along the so-called polar-front: this is the boundary between tropical air that is moving pole-wards from the equator and polar air that is moving towards the equator. A wave develops along the polar front as warm air nudges into it. Along this boundary, the overriding warm air condenses as clouds and precipitation intensifies. As it does so pressure falls along this portion of the boundary (Fig. 1.6).

To the rear of this surface feature, cold air begins to undercut the warm air, again driving the warm air upwards as a second band of precipitation develops. This region will become the cold front. Between the two fronts is a region of warm air that has intruded into the colder polar air: this is the warm sector. The idea of fronts is most closely tied to Jacob Bjerknes at the Bergen School. Bjerknes often referred to the warm front as the steering line, while the cold front became known as the squall line (Fig. 1.7). Although these terms are still often in use in the US they are generally not used in Europe. Here, the terms cold and warm fronts have stuck and most actively describe the changes in conditions associated with the passage of each frontal boundary.

In the Bergen model, the low pressure moves along the frontal zone as an intensifying wave. As it does so, the warm front advances effectively at the same rate as the low pressure as a whole, while the cold front progressively undercuts the warm air to the rear.

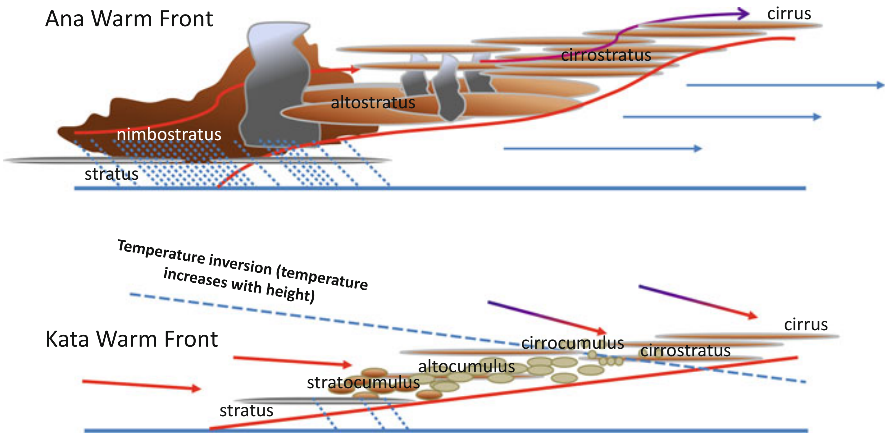

Fig. 1.6 Idealized warm fronts. In the *top diagram*, the warm air advances quickly and is unstable, meaning that it is able to rise by convection, as well as rise because it is being forced over the wedge of colder air. This "Ana warm front" brings extensive precipitation, a strong rise in temperature and a significant change in wind direction. On occasion thunderstorm cells may be embedded (*grey*). Above the "kata front" air is descending from higher up in the atmosphere. This may be associated with frontal boundaries in the upper air. Descending air causes it to warm and evaporate much of the cloud layer. Clouds are typically more broken and precipitation lighter (more *dispersed blue dots*). *Red*, *blue* and *graded arrows* indicate overall direction of air flow. The vertical scale is exaggerated relative to the horizontal scale. The frontal surfaces are typically only a few degrees to the horizontal

After anything from one to several days, the cold front advances so far that it undercuts the warm front, forming an occluded front (Fig. 1.8). The low pressure center, which is often referred to as an extra-tropical cyclone, then typically becomes isolated within the cold air to the rear of the cold front. Denied access to the energy contained in the warm air, the low pressure progressively fills in and decays.

The Bergen Model was based exclusively on surface observations of clouds, pressure, temperature and wind direction. There was little access to data from greater elevations; therefore, the link to processes happening further up in the atmosphere was not understood. Nonetheless, the model has worked extremely well and accurately describes the processes occurring in frontal low pressure areas. For most scenarios involving the formation and development of low pressure areas, the Bergen model works more than adequately.