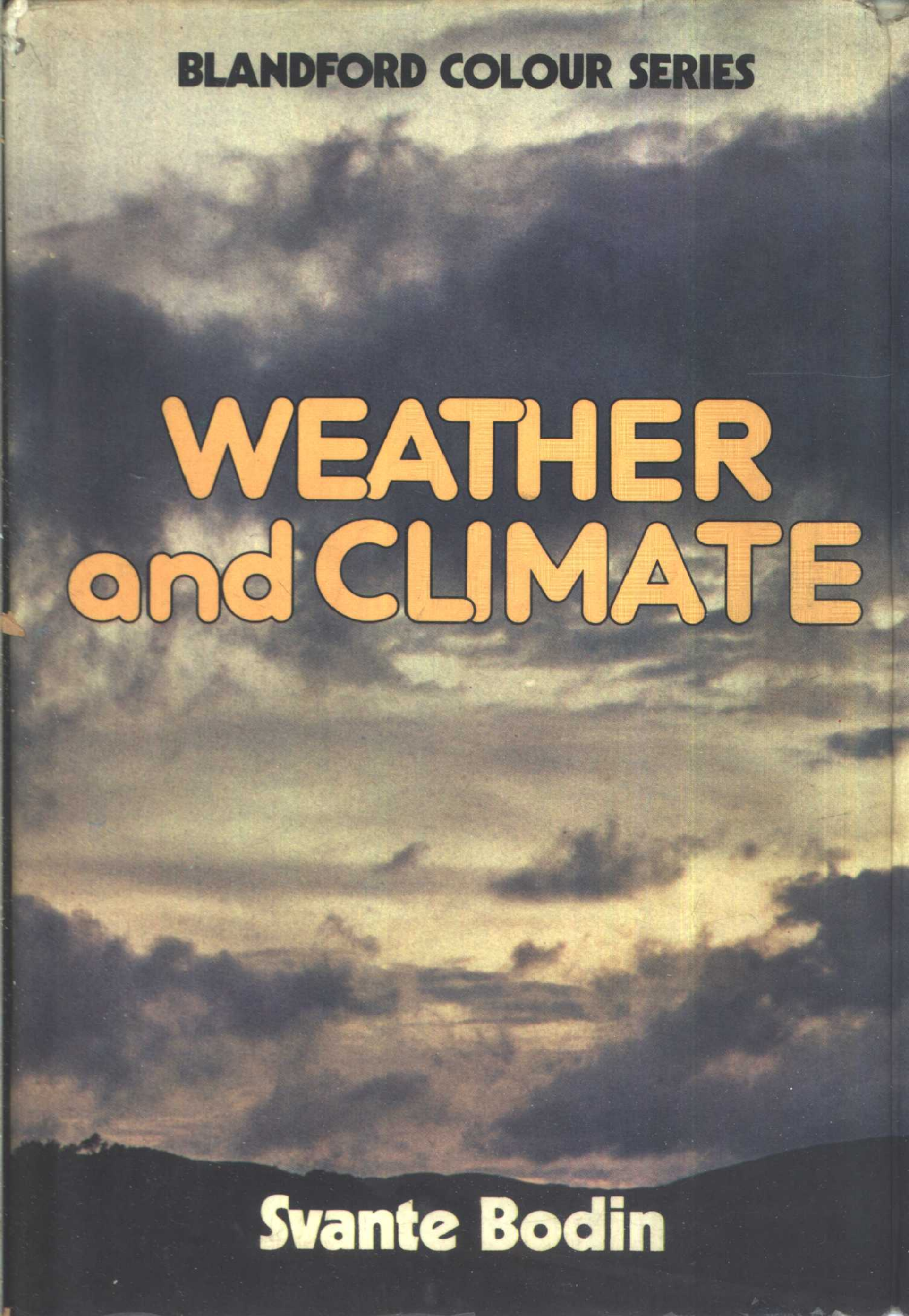

BLANDFORD COLOUR SERIES

WEATHER and CLIMATE

Svante Bodin

WEATHER AND CLIMATE

in colour

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1 INTRODUCTION

'Some are weatherwise, some are otherwise.'

Benjamin Franklin

The American journal *Weatherwise* has taken this quotation as its motto and there is still a lot of truth in what Benjamin Franklin said. The person who understands weather *is* wise.

In earlier times, weather was not merely a topic of casual conversation, but a matter of life and death. Indeed, in many places in the world today it determines the vital factor in the feeding of your family for another year with a successful crop, or facing the consequences of a drought or flood.

The atmosphere can release enormous power in the form of tropical revolving storms which frequently threaten the coastal regions around, for example, the Gulf of Mexico or the densely populated coastal regions of Asia. Strong winds destroy houses, torrential rains and storm-surges cause flooding and put whole regions under water. Each year hundreds of people die in typhoons, as the tropical cyclone is called in Japan, or in hurricanes, as they are called around the Gulf of Mexico. In middle latitudes, polar depressions often disrupt the day-to-day life of society. In northern countries, such storms produce heavy snowfalls during the winter, paralysing communications, blocking highways and isolating parts of the country for several days. These Atlantic low-pressure areas are usually accompanied by strong winds, sometimes reaching up to hurricane force. Ships along the coasts of Europe have to remain in harbour. Crews of fishing boats usually recognize the signs of an approaching storm, but they also receive warnings from the weather services.

During the summer, intense thunderstorms often occur. The up- and down-draughts in a thundercloud create enormous differences in electric charge between different parts of the cloud, and between the cloud and the ground. These charge differences are then released as bolts of lightning. Very often, thunderstorms occur after a long period of dry weather and they can start extensive forest and prairie fires. In the American Midwest the much feared tornado occurs which is an intense whirlwind which can pull up trees, lift cars and cattle high up in the air and smash houses to dust. The damage so caused amounts to several hundred million dollars each year and many people lose their lives. The worst outbreak of tornadoes ever recorded occurred on April 3 and 4, 1974, when more than eighty tornadoes were observed. The little town of Xenia in Ohio was practically wiped off the map.

The weather can be very dramatic, but most of us will probably never see a tornado. For most people the weather is something which only seems to be important when planning our leisure activities, such as a fishing trip or an outing to the seaside at the weekend. Although the rain is unwelcome during our few weeks of vacation, in some parts of the world the opposite may be true; in India, for example, where millions of people are dependent on the summer monsoon rains for growth of their crops. If the summer monsoon is late, a catastrophe lies just around the corner. In many parts of the world, water is the most precious substance of all and the weather is the major supplier of water.

It is easy to see how knowledge of the weather, its consequences and perhaps most important of all the ability to forecast the weather may be of great value. Even when it is not a matter of life or death, forecasts and an understanding of weather patterns can save large sums of money. Governments all over the world have realized this and in most countries there are national weather services providing warnings, forecasts and climatological information. People who are engaged in weather-sensitive jobs or activities have learned to work with the weather. Pilots seek information about weather on their route before take off. Farmers listen intently to the long-range forecast during harvest time or during the spring to find out the best time to sow. In many places, knowing just when the first night's frost will occur can be hard to predict and this is where the meteorologist can help the farmer and grower. Warnings of approaching storms can help everybody. For instance, snow clearing vehicles can be alerted, and people may be able to close their shutters and lock up the house prior to the onset of a hurricane.

There are also other ways in which we can use our knowledge of the weather. We know quite well that there are variations in the amount of rainfall from time to time in any one place, but if we measure the annual rainfall this total is fairly constant from year to year. The same is true for the average annual temperature for a certain place. These average conditions, which are the results of weather patterns influencing a specific location, are studied in *climatology*. Other questions a climatologist may try to answer are: How often does it rain more than 30 mm during a twenty-four-hour period? How often does it rain a given amount in one hour? This information makes it possible for us to calculate the correct dimensions for water pipes, sewage and drainage systems, etc.

The mean temperature and annual rainfall are also helpful in deciding how well suited a particular place is for farming and which crops could best be grown. The climatological information tells us what we can expect, and it can also help the holiday-maker in his or her choice of destination by giving data on sunshine probabilities and typical temperatures.

Weather affects practically all aspects of our lives, whether we like it or not. The air we breathe must be clean and not too polluted. In our homes we want a steady temperature and a comfortable air humidity. If the humidity level gets too low, throats become sore or we start coughing. If the humidity is too high the room feels close and muggy.

Weather takes place on many different scales. The gust we feel when turning the street corner is only a couple of metres wide while the Atlantic storms, the polar front cyclones, involve distances of some 3000 km. We cannot see the largest weather systems directly. These are the jet-stream waves, the so-called Rossby waves, which have dimensions of 5000–10,000 km and circle the whole globe.

In the same way that we have different space scales, we also have different time scales. A gust only lasts for a few seconds. A thunderstorm may be active for a couple of hours, after which it starts to die. The low-pressure system with its fronts and snowstorms usually passes after a day or two. On the other hand, the long waves in the free atmosphere move only slowly and can affect the weather in a particular spot for weeks. How much does the climate change over the centuries? Why did the last ice age happen 10,000 years ago? These are time intervals which are difficult to comprehend, but they are time spans which the meteorologist must think about. Climatic changes have recently become the focus of attention in connection with the last three years of drought in the Sahel area in Africa. The field is very much open to speculation. Some people say that another ice age is coming, while others believe that mean annual temperatures will increase.

In this book we shall try to explain weather on all of these scales – both in time and in space. We shall also study climate and see how far scientists have come in understanding the reasons for climatic changes. This also opens up the fearsome possibilities of tampering with the weather and meteorological warfare. We have already used the word *meteorology*. Meteorology is the science which deals with the atmosphere and the weather. The meteorologist tries to discover the physical laws which govern the processes in the atmosphere and he also tries to apply this knowledge to predict the weather. To do so some of the most sophisticated products of modern technology such as giant computers, satellites and weather radar are employed. All are needed in order to analyse the complicated weather patterns of our world.

The atmosphere can concentrate its energy into huge outbursts. A polar front storm contains more energy than thousands of hydrogen bombs. Where does the atmosphere derive all this energy from? What source sustains the winds over the earth year in and year out? We now know that the sun is the ultimate energy source as it radiates huge quantities of energy towards Earth. But the sun rays are unevenly distributed over the surface of the planet, from north to south. The polar region only receives a small fraction of the energy that the tropics receive. An important function of the atmosphere is to transport this excess heat from the tropics to the northern parts, thus preventing a massive freeze-up. The storms of the middle latitudes play an important role in this process.

Yet the major part of the heat is not transported as heat that we feel with our skin or can measure with a thermometer – discernible heat – but in the form of heat which was used to evaporate water to vapour over the tropical oceans. When water vapour condenses again to water, this heat is added to the air as discernible heat. At the same time, the vapour in the air supplies us with the necessary rain, creates rivers and lakes, is stored in the ground and finally returns to the sea in an endless cycle. Water is almost as essential to weather as the air itself. In fact, a lot of what we call weather is merely water in one form or the other. This means that we must understand the weather in its entirety, and in order to do that we must also be able to understand the exchange between the oceans and the atmosphere. We must go even further than that. We shall see how human activity has already had a marked influence on the atmosphere and that threats to the atmosphere are increasing every year. We are gradually becoming aware that we are part of a huge ecological system which naturally comprises the atmosphere and the seas. If we tamper with one part in this complicated system, it can lead to adverse and unexpected effects in other parts.

We can consider the whole system as a heat engine, comprising the atmosphere and the oceans, and driven by the sun. This heat engine can show amazing diversity; it can give us beautiful summer days, or lightning flashes in the sky; in northern countries during the winter it can enshroud everything in a white cover of snow. It can be cruel and hard, but can also gently caress us with its warm spring breezes or let us lie on the grass on warm summer days creating imaginative figures out of the clouds. The heat engine works unceasingly to transport heat from the equator towards the poles, making life possible over a major part of the globe.

2 THE ATMOSPHERE

The air which we breathe is a part of the huge envelope of gases which surrounds the earth and which we call the atmosphere. Air is transparent, tasteless and odourless (if we haven't polluted it); despite this, however, its existence is obvious. The oxygen it contains is the basis for human life and, since air is in constant motion, we can feel the wind against our bodies. The air is also responsible for our verbal contacts as it carries sound waves and makes it possible for us to speak to each other. Without air there would be no sounds.

A most important ingredient of what we call weather is water vapour. Water vapour is also colourless, tasteless and odourless, and under normal conditions we cannot see it. However, when vapour condenses it forms fog or clouds, which are tiny water droplets or ice crystals suspended in the air. The clouds can give us rain and snow, hail and thunderstorms.

The composition of the atmosphere

Oxygen (chemical symbol O, but normally occurring as the molecule O_2) and carbon dioxide (CO_2) participate in the complex cycle called *photosynthesis*. Plants receive heat from the sun to use as energy, and take in carbon dioxide and water vapour from the air to produce the carbohydrates in the crop and the oxygen which is released into the atmosphere. The carbohydrates in plants are some of the most important components of our food. In fact, the whole oxygen content of the atmosphere was once formed as a 'waste product' of photosynthesis in the vast forests covering the earth several billions of years ago. When these forests became covered over and decayed under pressure, large deposits of oil and coal were created. In these deposits a substantial part of the carbon dioxide of the primitive atmosphere is bound up, as well as vast amounts of energy from the sun. We are using this energy now at an ever-increasing rate.

There is a tremendous amount of matter in constant motion around the earth. The mass of the atmosphere is about 5,243,000 billion tonnes. We have already mentioned some of the constituents of the atmosphere. The following table gives the most important gases and their amounts as a percentage of the total mass.

Principal gases in the atmosphere

Name of gas	*Chemical symbol*	*Percentage of mass*
Nitrogen	N_2	75
Oxygen	O_2	23
Argon	A	1·28
Carbon dioxide	CO_2	0·05 (variable)
Water vapour	H_2O	0·01–3 (variable)

A surprising fact shown in the table is the large amount of argon; 1·28% corresponds to around 66,000 billion tonnes in the atmosphere. Argon, however, is an inert gas which does not react chemically with other gases or compounds; it does not form molecules like oxygen and nitrogen, and because of these properties it does not have any important effects on the atmosphere. Besides the above mentioned gases there are a number of compounds in the atmosphere which can have important local effects although their percentage contribution is small. Taken over the whole globe, they represent a fair amount. Among these constituents we have two other inert gases, neon and helium, which exist together in an amount of over 70 billion tonnes. Another important compound is sulphur dioxide (SO_2), which may be the greatest air pollutant. The amount of sulphur dioxide in the atmosphere is about 10 million tonnes. Another very important gas is ozone (O_3), which is a variety, or allotrope, of oxygen. The amount of ozone is about 4 billion tonnes and the bulk of the ozone exists at heights of 15–50 km in the atmosphere. Electric discharges such as lightning, can also produce ozone in small amounts. After a storm ozone may sometimes be recognized by its characteristic sharp 'fresh' smell.

Water vapour and water

Besides oxygen, water vapour is the most important constituent of the atmosphere, yet, as shown in the table, the amount varies quite a lot. In the colder areas, as for example northern Siberia, the content of water vapour can be as low as 0·01%, but over the tropical oceans it rises to 3% at sea level. Water vapour is important because it can appear in all three physical states: ice (solid), water (liquid) and vapour (gas). We know the usual visual appearance of ice and water, but even these forms can take on strange appearances at times. Frozen water can appear as snow or hail. Snow can exist in a multitude of different crystalline forms. Water almost invariably exists as water drops in the atmosphere but their size can vary from a diameter of 0·001 mm in fog droplets to about 1 mm in rain drops. If the drops become bigger than 2 mm, they break up into smaller droplets. Water droplets found in clouds are usually of an intermediate size. Clouds can also appear in many different forms, depending on their altitude, method of formation and illumination by the sun. At an altitude of 6–10 km, the temperature is very low (usually below —40°C). At such a low temperature water drops cannot exist and are frozen into ice crystals. These give the clouds a special diffuse or fibrous appearance (cirrus clouds).

The most important feature of water is its ability to store heat when it turns into vapour. Let us consider a simple example. To heat a quart of water in a pot from room temperature to its boiling point at 100°C we need 340,000 Joules of heat (1 Joule = 1 watt second, Ws), or as much energy as it takes to keep a 100-watt light bulb burning for one hour. On the other hand, to evaporate this water to vapour without changing its temperature, we need 2,500,000 Joules or *seven times as much energy*! The amount of vapour existing in the atmosphere must have evaporated from somewhere; usually this takes place out over the seas, especially in the tropics. Huge amounts of energy are stored in the water vapour in the air. We call this energy the *latent heat of the air.* This heat can later be given back to the air when the vapour condenses to form clouds, so heating the air. This heating effect has a substantial impact on the formation of many weather phenomena, such as thunderstorms and tropical cyclones (hurricanes) as well as the common mid-latitude storms. In the same way that heat is required to evaporate water into vapour, it is also needed to melt solid ice into liquid water. That heat is about one tenth of the heat needed for evaporation; both are known in physics as 'latent' heats.

There is still another thing we should know about the water in the atmosphere. The amount of water which can exist as vapour depends upon the temperature of the air. Because water vapour is a gas, we can measure this amount by means of its pressure. Another way to state the maximum amount of vapour possible at a given temperature is by the mass of water vapour per cubic metre of air (usually grams per cubic metre or g/m^3). The maximum amount of water vapour the air can hold at a given temperature is called the *saturation value*. The actual amount held can, of course, be less than the saturation value, but rarely greater. (However, vapour can be transformed into liquid water by condensation. The saturation value only tells how much *vapour* is possible. Clouds contain both liquid water and water vapour.) The higher the temperature, the more vapour that the air can contain and the higher the saturation value. The following table gives a rough idea of how the saturation values vary. We see that grams per cubic metre (g/m^3) is an absolute measure of the content of vapour in the air. Another commonly used unit for measuring water content in the form of water vapour is the *Relative Humidity* (R.H.). The relative humidity tells us how much water vapour is present, expressed as the percentage of the maximum amount possible at the given tem-

Temperature °C (°F)	*Saturation value* (g/m^3)	
+40 (104)	40·0	(at normal atmospheric pressure, 1000 mb)
+30 (86)	30·4	
+20 (68)	18·7	
+10 (50)	9·8	
0 (32)	4·9	
−10 (14)	2·9	
−20 (−4)	1·0	

perature. At the temperature +20°C we see from the table that we can have a maximum of 18·7 g/m^3. If we actually had that amount at that temperature, we would have 100% R.H. If, on the other hand, we only had 10 g/m^3, then our R.H. would be $\left(\frac{10}{18\cdot7}\right) \times 100 = 54\%$. We also sec that 100% R.H. at +20°C is 18·7 g/m^3, but 100% at 0°C is only 4·9 g/m^3! Now, if we have 1 m^3 of air with a 100% R.H. at 20°C, and cool this volume of air to 10°C, then a certain amount of water vapour has to condense to liquid water. We see from our table that the maximum amount of vapour at 10°C is 9·8 g/m^3. That means that the difference between this amount and what we had at 20°C (8·9 g/m^3) must condense, so that the amount of vapour at 10°C does not exceed its saturation value. The atmosphere has many ways of accomplishing this cooling, and the study of weather processes is largely a study of how temperature does actually change within it. Evaporation and condensation of water are two of the most basic and important weather processes.

Pressure, temperature and density

As we have seen, the atmosphere consists of a mixture of gases, of which oxygen and nitrogen are the most abundant. This mixture in essence remains unchanged up to an altitude of about 100 km. Below this height, the density of the air is great enough for the collisions that constantly occur between the gas molecules to keep the air well mixed. Above 100 km, the air gradually becomes less dense until its density is so low that the number of collisions that occur between the molecules can no longer keep the air well mixed. The composition changes, so that the heavier gases are found in a layer at the bottom and the lightest gases at the top. This means that, vertically, the atmosphere's composition gradually changes from oxygen, to nitrogen, and finally to hydrogen, which is the lightest of all elements. However, even this part of the atmosphere, where the air is extremely thin, is of particular interest because it absorbs the dangerous X-rays and gamma radiation from the sun. These rays would otherwise penetrate down through the atmosphere to the surface of the earth. However, this is a subject which is rather beyond the scope of this book.

The fact is that 90% of the *mass* of the atmosphere is contained in the lowest 15 km – and the layer in which all our weather is formed is about 6–8 km thick and comprises 66% of all the air. One can easily see that in relation to the dimensions of the earth, the atmosphere is a very thin envelope around our planet. The radius of the earth is 6370 km, while the atmosphere (from all practical respects) is about 15 km thick. Put another way, it is about $\frac{1}{400}$ of the radius of the earth. The atmosphere is like the skin around an apple. The horizontal dimensions of the atmosphere are much larger than the vertical ones.

Pressure

We can measure the air pressure at ground level with a *barometer*. Pressure is simply force per unit area per square centimetre; the unit in common use not so long ago was called an *atmosphere* (1 kg/cm^2). Nowadays meteorologists measure pressure in *millibars* (abbreviated as mb), 1 mb being $\frac{1}{1000}$ of a *bar*. One atmosphere corresponds to the pressure 1013 mb. Another common unit is *inches of mercury* or *millimetres of mercury*. This unit stems from the time when most barometers were mercury filled and one measured the height of a mercury column in an evacuated glass tube. Air pressure at the surface of the earth was normally capable of pressing the mercury in the tube up about 760 mm (30 in.) which corresponds to the mean sea-level pressure, 1013 mb. (In the metric SI units, or the *Système International*, the pressure unit is the *Pascal* which is the same as 1 Newton/m^2; 1 mb is 100 Pascal or 1 hektopascal.)

Temperature

Temperature is an important meteorological variable. Unfortunately, we also have different units for temperature. In some English-speaking countries, degrees Fahrenheit are still used while in most other countries degrees Celsius are used – often called degrees Centigrade. In this book we will use the term Celsius, and explain how to convert Fahrenheit degrees to Celsius, and vice versa. The construction of a temperature scale is based on finding two *fixed points*, where we define the temperature to be either 100 or 0 (zero). The Celsius scale, named after the Swedish physicist Anders Celsius, has the temperature at which water boils at normal sea surface pressure as +100 degrees. The freezing point of water is chosen to be 0. The Fahrenheit scale is based on the normal temperature of the human body as being 100 and the zero point is the temperature achieved by a mixture of ice and salt.

$$100°\text{F} = +37{\cdot}8°\text{C and } 0°\text{F} = -17{\cdot}8°\text{C}.$$

To convert between Fahrenheit and Celsius

$$\text{Temperature in } °\text{C} = \frac{5}{9}(\text{Temp. } °\text{F} - 32).$$

There is also another temperature scale which is used mainly by scientists. That scale is called the *absolute temperature* scale and the units used are degrees *Kelvin*, after the English physicist Lord Kelvin. The zero point in this scale is the *absolute zero*, i.e. the temperature at which all motion ceases, all atoms and molecules come to a rest. This temperature on the Celsius scale is −273°C or 0 degrees Kelvin which is written as 0 K (no degree sign being used). The freezing temperature of water, the zero point of the Celsius scale, is then 273 K. We simply get the Kelvin temperature by *adding* 273 to the Celsius degrees. For example, +20°C is 293 K.

Density

All objects have a weight which depends on the gravitational pull of the earth. Everything also has a mass, which is independent of gravity and is an expression of the amount of matter in the object. In metric or SI units, this quantity is usually expressed in kilograms (kg). (Imperial units express mass in stones, pounds or ounces.) The more mass an object has, the heavier that object is. In order to compare different objects we need to know how much a standard volume of weight is found in different elements. In other words, how much mass there is in a cubic unit. In the SI system, we take one cubic metre and find out how much mass we have measured in kilograms. That will give us the *density* in kilograms per cubic metre (kg/m^3). On this scale of units water has the