Geoff's Climate Cookbook

Geoff's homepage -> Creating planets -> Climates

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With grateful thanks to krinnen, aka Gonzalo, who drew the pictures.

Contents

Introduction

This page is part of my essay about creating an Earthlike planet; it is intended to guide the creator of such a planet, after he or she has drawn a Map, through the process of working out the climates which characterise a particular area. As far as learning about the physical causes of climates goes, there's no substitute for a good textbook; however, textbooks tend to work backwards from observed phenomena to inducing the causes, whereas the typical conworlder needs to know the causes before he or she can deduce the observed phenomena - which is what this page is for.

Please note that predicting climates is notoriously complicated and full of approximations, which is why there are no equations on this page and very little quantification. Ideally, I would be able to offer a program which would convert a Map of a planet and its physical data - such as axial inclination and distance from the sun - into a diagram showing the climate at every point of interest on the planet's surface; when I've written this program I will be able to retire for good on the money. In the meantime, the best I can do is talk in generalities without going into too much specific detail.

If you find this page useful, please let me know! As ever, I welcome corrections and suggestions for improvements.

Basic principles

Virtually everything important about climates can be deduced from the following physical principles, which are referred to in [square brackets]:

1. All heating comes from the sun.
2. Water heats and cools much more slowly than land; water thus acts as a stabilising effect on temperature.
3. Hot air rises, cold air sinks; this is because air expands as it heats up and thus becomes less dense.
4. Cold air gives rise to areas of high pressure, and hot air gives rise to areas of low pressure.
5. Wind flows from areas of high pressure to areas of low pressure.
6. Due to the Coriolis effect - the effect of the rotation of the earth on the flow of air - winds are deflected to the right in the northern hemisphere, and to the left in the southern.
7. Rising air is conducive to the fall of precipitation, sinking air is not.
8. Warm air carries more moisture than cold air.

Ingredients

You will need the following items before you can proceed any further.

1. The **axial inclination** of your planet, which is 23.5 degrees for the Earth. The lines of latitude at this distance from the equator are known as the **tropics**, and those at the same distance from the poles are called the **polar circles**.
2. Two identical copies of your Map, which should show the locations of as much **land** as you know about, the locations of the **mountains**, the lines of **latitude** in increments of no greater than fifteen degrees, and the tropics and polar circles. Label one copy "January" and the other "July".
3. A transparent drawing medium which can be marked and erased without damaging the Map. In the physical world, this means several sheets of tracing paper or something made of clear plastic; on a computer, the equivalent is a drawing program which can handle layers, such as the GIMP.
4. Something erasable with which to draw on the transparent medium; for tracing paper, coloured pencils (*not* pens) are suitable. You will need several colours.
5. Something with which to erase the above, because you *will* make mistakes, and lots of them.

The following assumptions have been made:

- Your planet rotates from west to east, like the Earth.
- Your planet has a similar diameter and rotation period to the Earth. These quantities are respectively 12750 km and 24 hours.

For ease of reference, "January" and "July" refer respectively to the periods shortly after the sun reaches its furthest south and north respectively, and "April" and "October" to those just after it passes directly above the equator northwards and southwards respectively. The "just after" is necessary because the atmosphere acts as a drag on the heating and cooling processes; thus the hottest time of the year in the northern hemisphere is typically around mid-to-late July, some weeks after the summer solstice on 21 June.

This image lets you know when you should think about drawing something.

Pressure-cooking

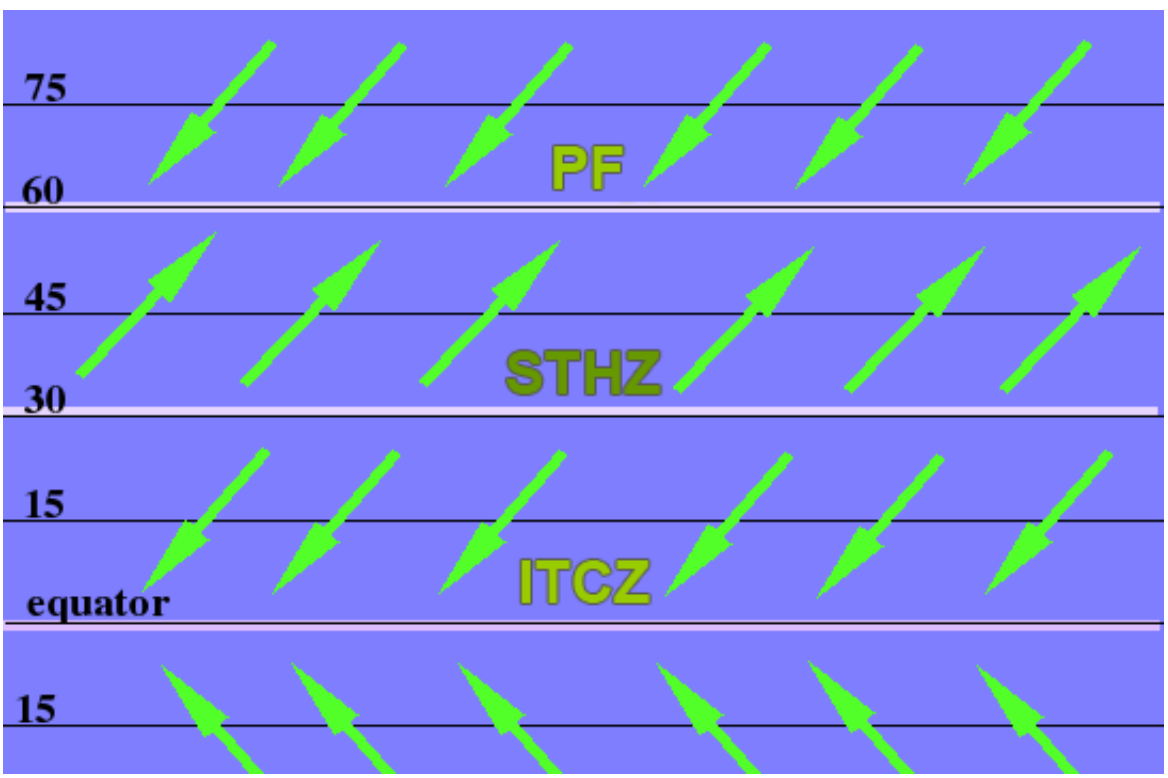
The first stage consists of locating the large-scale areas of high and low pressure.

The default

The most important is the low-pressure belt called the **inter-tropical convergence zone**, or ITCZ, about which the temperature and pressure characteristics are theoretically symmetrical; this zone is caused by the rising of hot tropical air [3][4]. In April and October, the ITCZ lies more or less along the equator. In the northern summer, it moves northwards, reaching its farthest north in July; its most southerly position is attained in January. The range of movement on Earth is about 5 degrees of latitude over the oceans, and up to 40 degrees over land.

About one-third of the way from the ITCZ to the poles is the high-pressure belt known as the **subtropical high-pressure zone**, or STHZ, which is caused by air from the ITCZ cooling and sinking back to the ground [3][4]. Between the STHZ and the poles is the **polar front** or PF, a band of low pressure where cold air from the poles meets warm air from the STHZ. The interaction between these air masses at the polar front is responsible for the rain-bearing low-pressure areas familiar from weather forecasts.

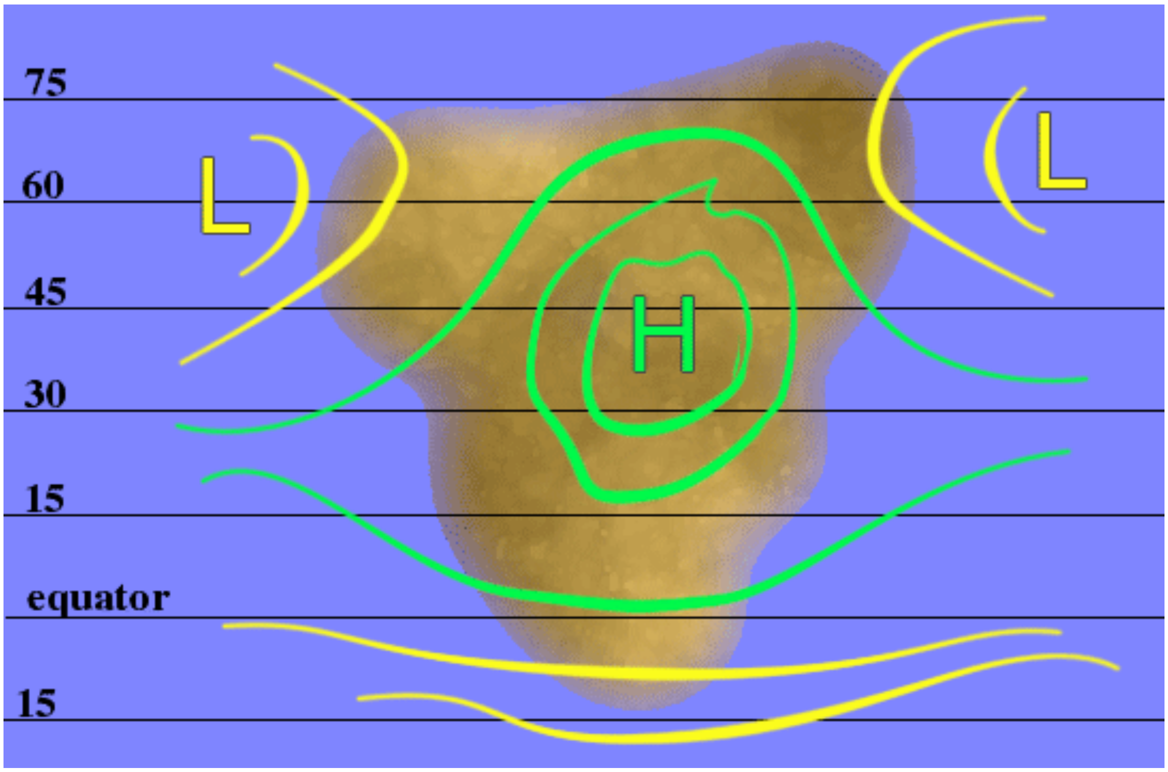
If the surface of the planet was uniformly water, the distribution of these pressure belts and the prevailing winds would be as shown below, allowing for seasonal movements, which would be slight.



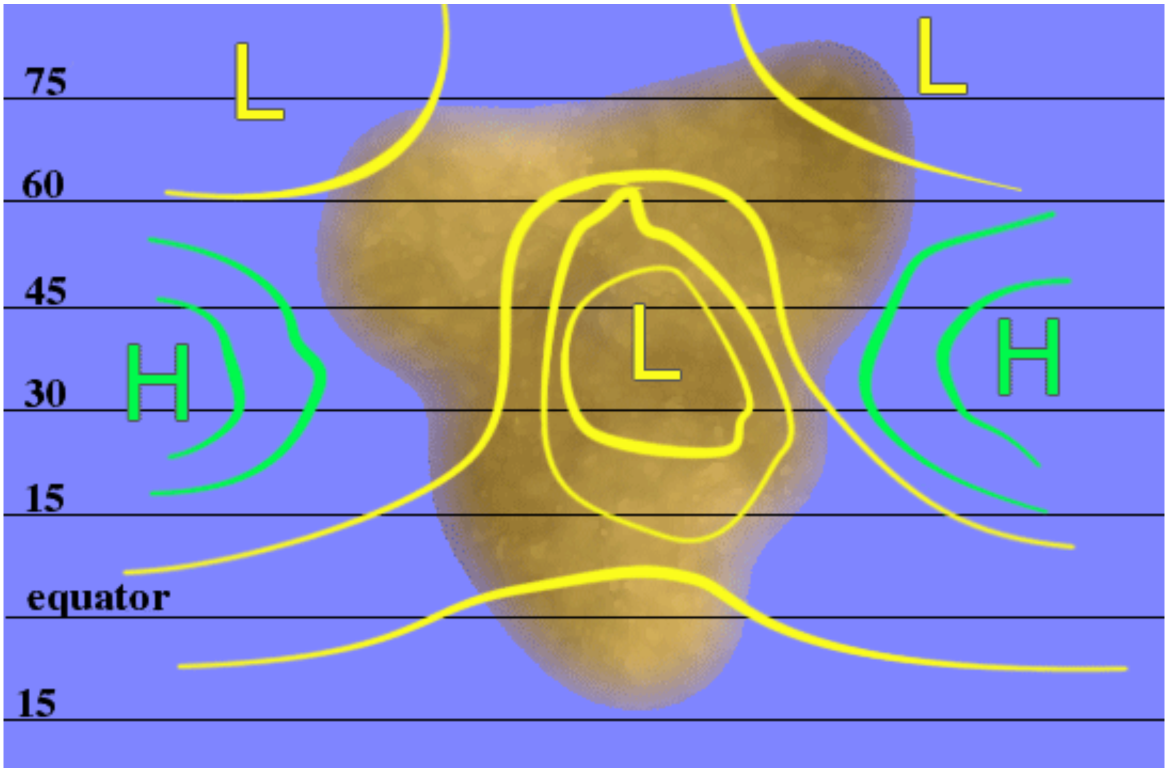
Adding land

The presence of land has two effects on the pressure distribution, both results of principles [2][3][4]: the pressure belts front bend northwards over land in July and southwards in January, and they are broken up by seasonal pressure-areas over the land. In general, the larger the area of land, the more noticeable the effect.

In winter, the cooling of the land creates a high-pressure area over the interior, which merges with the high pressure area around the STHZ and leaves low-pressure systems over the oceans:



while in summer the land warms to create a low-pressure area, which joins up with the ITCZ and the PF, leaving high-pressure areas over the oceans:



In general, these pressure areas are located east of the longitudinal (east-west) middle of the continent, and are more intense when the surrounding land mass is larger. This is particularly noticeable with Asia; if the Eurasian landmass was reversed laterally, the pressure areas would be considerably less intense. Correspondingly, the pressure gradient is greater on east coasts than on west coasts; the precise difference depends on the shape of the continent.

Figures 7p-4 and 7p-5 on this page show how this works out for the Earth; the animation, one of many from here, is also here. Note particularly the considerable northward movement of the ITCZ in July over Africa and Asia, the continuous low-pressure zone over the Antarctic Ocean where there is no land to disrupt the southern PF, and the change in the air pressure over the interior of eastern Asia.

You need to draw similar diagrams showing the pressure for January and July. Start by drawing with the ITCZ, STHZ, and PF, then locate the continental pressure-areas, and finally join them up as in the diagrams. Different colours for each stage are a good idea.

Ventilate...

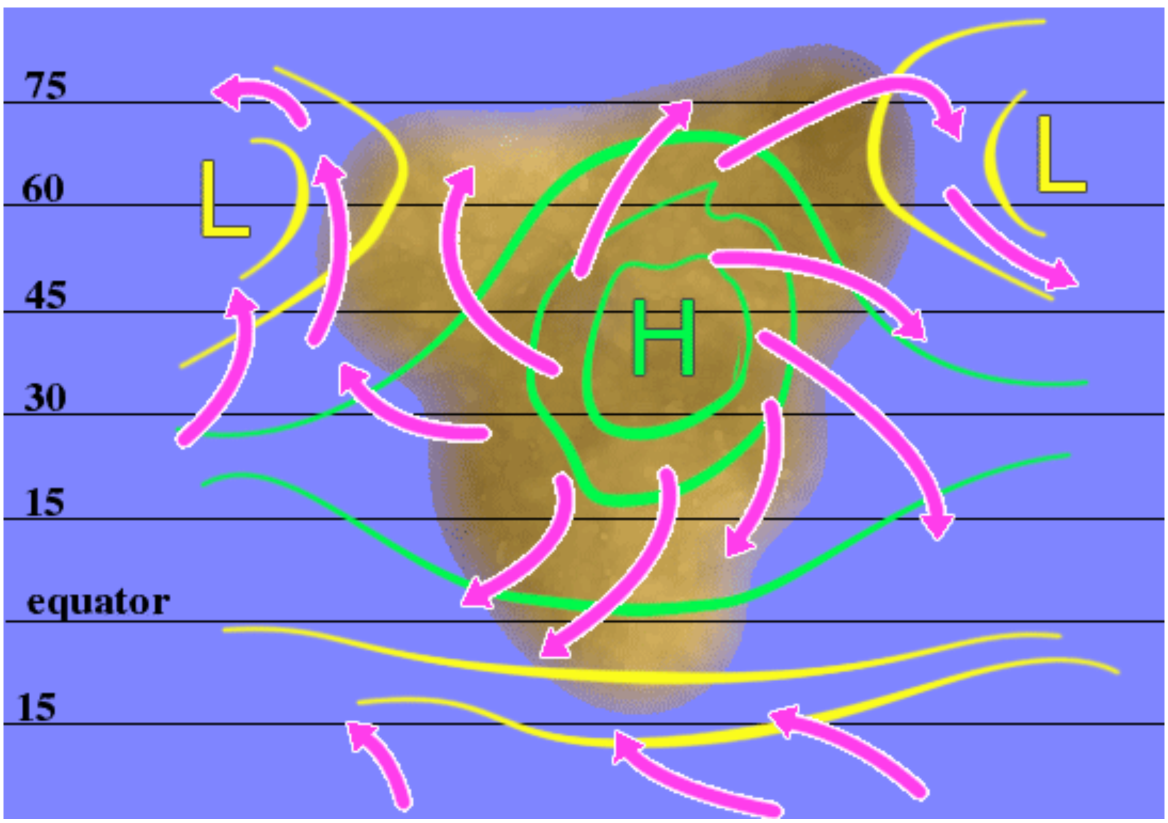
Wind, in meteorological terms, is a flow of air from an area of high pressure to an area of low pressure [5]; the strength (speed) of the wind increases with the difference in pressure. Winds have two important effects on climate: they transport **moisture**, and - for our purposes - they are the principle cause of the **ocean currents**. Winds pick up moisture as they blow over the oceans and deposit it as rain or snow over land. Obviously, a wind can only carry a finite amount of moisture, so it wil become dry after blowing across a large area of land.

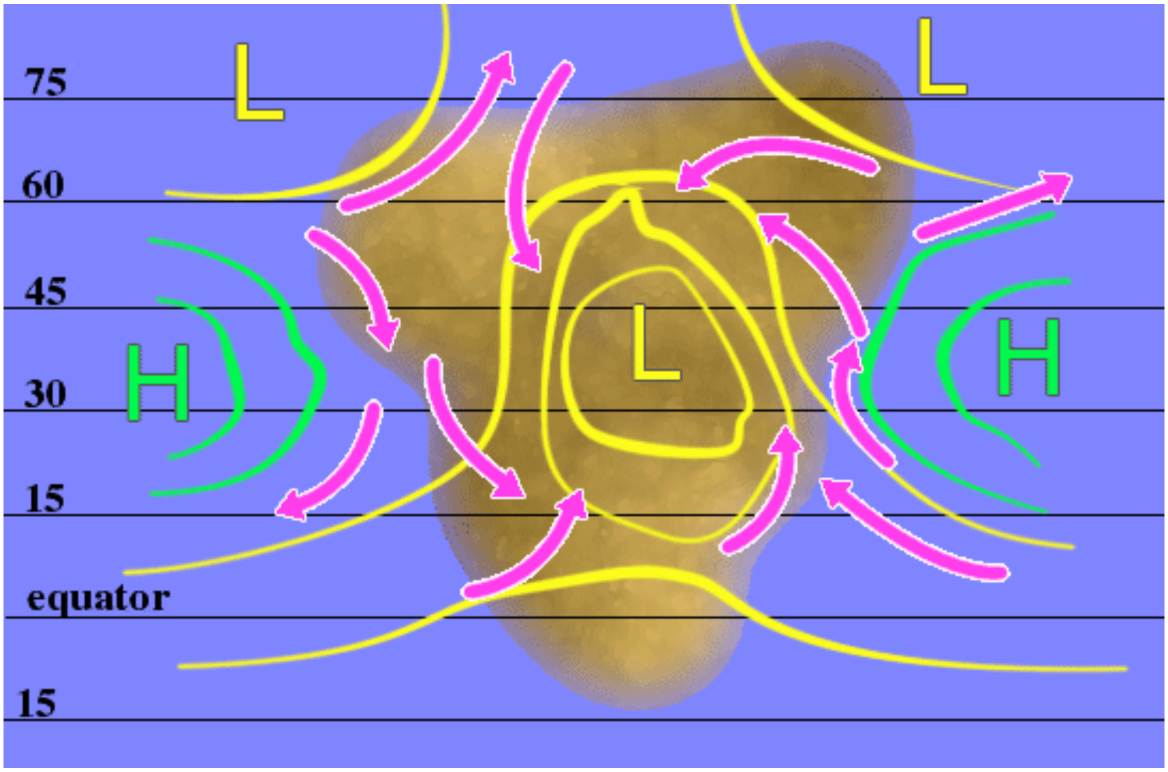
Winds

The winds we are interested in here are those which blow at the surface. Because of the Coriolis effect [6], the winds do not blow directly from high pressure to low pressure, but are deflected to blow, in the northern hemisphere, clockwise around high-pressure areas and anticlockwise around low-pressure areas. In the southern hemisphere the deflection is in the opposite direction. This deflection gives rise to the **trade winds** over the oceans; in the northern hemisphere they are south-westerlies in mid-latitudes and north-easterlies otherwise, and in the southern hemisphere north-westerlies and south-easterlies respectively.

The monsoon

On the east and south-east coasts of sufficently large land masses, pressure gradient will be sufficiently extreme that the resulting winds will override the prevailing trade winds; they will blow offshore into the ocean in winter, while the summer low-pressure area will pull in moisture-laden air from the ocean. This important seasonal reversal of the winds is, of course, the **monsoon**; it is prototypically observable in south-east Asia. The two pictures below show the general directions of the prevailing winds in winter (above) and summer (below). Note particularly the monsoon effect on the east coast.





A good question is: How large is "sufficiently large"? North America has no monsoon as such, so somewhere between the size of it and of Asia is probably as good an answer as any.

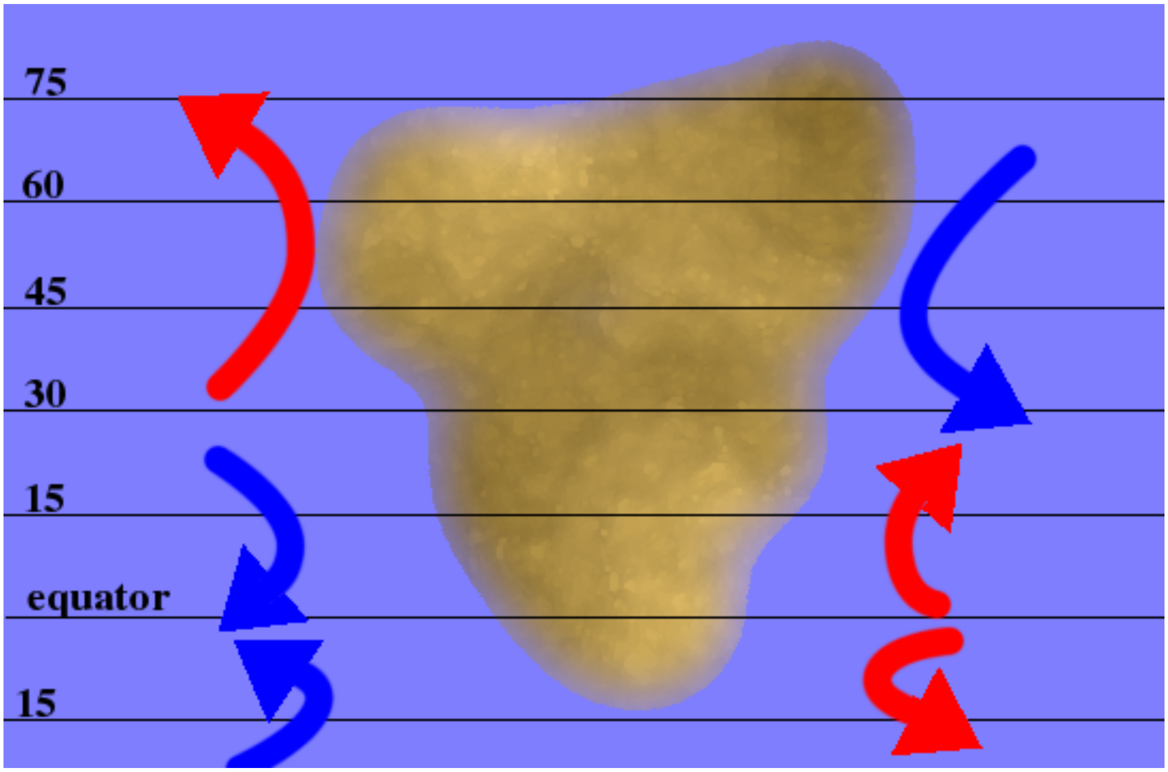
In winter, the continental high-pressure areas are responsible for **cold waves**, which are flows of very cold air eastwards to the offshore oceanic low. These cold winds pick up moisture as they pass over the sea, which will be deposited as snow on any mountains they encounter; western Japan is a terrestrial example.

Ocean currents

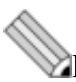
The formation and movement of the ocean currents is a complicated subject, much of which is not of interest here; for our purposes we are only concerned with currents on the surface of the oceans, which are caused wholly or mainly by the winds. The Coriolis effect comes into play again here, deflecting the currents from the path of the wind; the deflection is greatest (up to 45 degrees) at high latitudes and least (about 5 degrees) at the equator.

Ocean currents come in two flavours, depending on the direction in which they flow: poleward currents, which carry water from hotter areas to colder areas, are classified as **warm**, while equatorward currents are similarly classified as **cold**. Note that these are relative terms, thus a particular warm current flowing to a cold region may actually be colder than a cold current which flows to a warm region.

The oceanic high-pressure areas of the STHZ give rise in low latitudes to warm currents along the east coasts of continents and cold currents along the west coasts. The reverse distinction obtains in mid-latitudes, because the wind blows around the oceanic low-pressure areas in the opposite direction. The currents affecting the sample continent shown above would thus be as follows, with warm currents shown in red and cold currents in blue:



The Gulf Stream, which keeps western Europe much warmer in winter than the north-eastern USA and south-eastern Canada, is a classic warm current.

Now is a good time to add the prevailing winds and ocean currents to your Maps for both January and July. The currents are easy; don't forget that the winds will blow more or less in S-shaped double spirals.

... add water...

The annual distribution of the fall of precipitation in the form of **rain** and **snow** is one of the factors which characterise a particular climate. Rain and snow result from four processes:

- **Moist winds** blowing onto land, as previously mentioned.
- **Orographic lifting** of moisture-carrying winds as they blow over mountains and are forced to rise; the air cools as it rises, depositing its moisture on the windward side of the mountains [8].
- **Convection** due to the heating of the air. Again, the air cools as it rises and loses its moisture [8]. (Although the ITCZ passes over the Sahara Desert, it does not cause rainfall because of the dryness of the air; there is very little moisture for the rising air to pick up.)
- **Frontal lifting** along the polar front. Here the warm air from the STHZ is lifted up by the colder air from the poles, causing the low-pressure areas which weather forecasts warn about; further details are beyond the scope of this page.

An important detail about orographic lifting should be observed: after the wind crosses the mountains it sinks, expands, and warms back up again. These winds on the leeward sides of mountains (the **rain-shadows**) are thus characteristically warm and dry, and are known as *chinook* or *Föhn*, or colloquially as "snow-eaters" after their ability to melt snow in otherwise cold climates.

Finally, cold currents cool and stabilise the air, inhibiting the formation of precipitation, while warm currents heat and destabilise it, encouraging precipitation [2][7]. The relative amounts of precipitation due to various factors are shown in the following table.

Factor	High precipitation	Low precipitation
Pressure	ITCZ, on or near the equator	STHZ
Mountains	Windward sides	Leeward sides, in rain-shadow
Prevailing winds	Onshore	Offshore or parallel
Coastal currents	Warm	Cold, especially in low latitudes
Location	West coasts subject to the PF, and some way inland	Interiors

You should now be able to work out, for both January and July, the relative amounts of precipitation on your Map.

... and place in the oven.

The annual variation in temperature is the other characteristic feature of a climate. As a first approximation, the temperature is highest at the equator and decreases steadily towards the poles [1], subject to the following modifications.

Effect of the oceans

Variations in temperature are lowest along the coasts and highest in areas remote from maritime influence [2]. The variation increases with the distance from the oceans, and less so with distance from the west coast; the eastern regions of continental interiors thus experience the greatest variations in temperature. Incidentally, another consequence of [2] is that the hottest and coldest times of the year occur two to three weeks earlier in these regions than at the coasts.

Effect of moisture

Heat is more readily transmitted through clear skies than cloudy skies; consequently, the less cloud an area receives, the greater will be its temperature variation during a single day. The higher the temperature, and the clearer the skies, the more moisture will be lost during the day through **evaporation**, which is the opposite of precipitation. The greatest amounts of evaporation are found in land areas influenced by the STHZ, where the high-pressure belt is not conducive to precipitation and thus cloud-formation [7]. These areas are thus the hottest of all during the day, and cold at night.

You should now be able to work out, for both January and July, the relative levels of temperature on your Map.

Checklist

On both of your Maps you should now have indications of the following:

- The main pressure-belts (ITCZ, STHZ, and PF);
- The oceanic and continental areas of high and low pressure;
- The prevailing winds;
- The main ocean currents;
- Temperature and precipitation, on land at least.

The final stage consists of identifying the closest matching climate from the table below; it uses a classification sytem similar to the widely-used system developed by Wladimir Köppen.

		Temperature		**Precipitation**		**Location, for checking**
Name	**Köppen**	**Summer**	**Winter**	**Summer**	**Winter**	**latitude in degrees**
Tropical rainforest	Af	Hot	Hot	Wet	Wet	0-10
Tropical monsoon	Am	Hot	Warm	Very wet	Short and dry	5-15; east and south-east coasts only
Savannah	Aw	Hot	Warm	Wet	Long and dry	5-15
Hot desert	BWh	Very hot	Warm	Dry	Dry	10-30, especially on west coasts with cold currents
Hot steppe	BSh	Hot	Warm	Low to dry	Low to dry	10-35; typically next to deserts
Cold desert	BWk	Hot	Cold	Dry	Dry	Interiors, rain shadow
Cold steppe	BSk	Warm	Cold	Low to dry	Low to dry	Interiors, rain shadow
Maritime east coast	Cfa	Hot	Warm to mild	Wet	Moderate	20-40; east coasts only
Maritime west coast	Cfb, Cfc	Warm to mild	Cool to cold	Wet	Wet	40-60; west coasts only
Mediterranean	Csa, Csb	Hot	Mild	Dry	Moderate	30-45, west coasts only
Temperate monsoon	Cwa, Cwb	Hot	Mild to cold	Wet	Dry	20-40; east coasts only
Laurentian	Dfa, Dfb	Warm to mild	Cold	Moderate	Low	40-60; not on west coasts
	Dfc	Mild to				

Subarctic	Dfc, Dfd	Mild to cold	Very cold	Moderate	Very low	60-80; not on west coasts
Manchurian	Dwa, Dwb	Warm to mild	Cold	Moderate	Dry	40-50; east coasts only
Subarctic east	Dwc, Dwd	Mild to cold	Very cold	Moderate	Dry	45-70; east coasts only
Tundra	ET	Cold	Very cold	Low	Dry	60-80
Icecap	EF	Very cold	Very cold	Low	Dry	75+

The climates given in *italics* are those which, generally speaking, are subject to the same influences throughout the year. The other climates may be regarded as transitions between these; for example, the mediterranean climate is a combination of hot desert in the summer and maritime west coast in the winter.

Note the following:

- **Steppe** and **desert** climates experience large diurnal variations in temperature, which means cold nights.
- In the **subarctic** and **tundra** climates, winters are long, dark, and cold, and the other seasons are short.
- Some sources mention Köppen climate types As and Ds, which are like Aw and Dw but with the dry season in summer rather than winter. I don't know what causes these particular climates; they are very rare anyway and can probably be safely ignored.

The progression of climates

Moving from the equator to the poles, the climates appear in the well-defined sequences described below. It is instructive to compare these found on the Earth.

The climates appear on the **west coast** in the following order:

- **Tropical rainforest**.
- **Savannah**.
- **Hot steppe**, with dry winters. The boundary between this and the savannah is the line where evaporation equals precipitation.
- **Hot desert**, due to the influence of the cold current, which is also responsible for coastal fog on the west coasts of desert climates.
- **Hot steppe** again, this time with dry summers.
- **Mediterranean**. The boundary between this and the steppe is, again, the line where evaporation equals precipitation. Coastal fog is often experienced in summer.
- **Maritime west coast**, cooling steadily poleward. These climates are warmed by the ocean currents.
- **Tundra**.
- **Icecap**.

Continental interiors, and areas in the **rain-shadows** of north-south mountain ranges, will experience dry versions of the climates to the west. The equivalent order of climates would be:

- **Tropical rainforest** or **savannah**.
- **Hot steppe**, with dry winters.
- **Hot desert**.
- **Hot steppe**.
- **Cold desert** in areas far from the west coast.
- **Cold steppe**.
- **Laurentian** in its colder incarnations. Round about here, the colder temperatures reduce evaporation to the point that it no longer exceeds precipitation.
- **Subarctic**.
- **Tundra**.
- **Icecap**.

On the **east coast**, there are two cases to consider, depending on whether the land mass is large enough to generate monsoons. East coasts *not* subject to the monsoon will feature the following climates:

- **Tropical rainforest**, or **savannah** if the land is high enough, as in east Africa.
- **Maritime east coast**. The difference between this and the preceding is largely one of winter temperatures.
- **Laurentian**, becoming steadily colder polewards.
- **Subarctic**.
- **Tundra**.
- **Icecap**.

East coasts of continents where there is a monsoon will feature the following climates:

- **Tropical rainforest**, which may be absent.
- **Tropical monsoon**, prototypically.
- **Temperate monsoon**. This is the same as tropical monsoon, but with colder winters; equivalently, it is equivalent to maritime east coast with dry winters.
- **Manchurian**. Effectively a laurentian climate with dry winters.
- **Subarctic east**. Similarly, this is the subarctic climate with dry winters.
- **Tundra**.
- **Icecap**.

Vegetables

One of the reasons for being interested in climate is to discover the types of vegetation which grow in a particular region. This section describes, in general terms, the vegetation types asociated with the climate types. More detail, with information about the fauna, can be found with a Google for "biomes"; for example Introduction to biomes, Habitats and biomes, Blue Planet Biomes, World Biomes, and - the most detailed - Köppen biomes.

The vegetation of the **icecap** climate is the simplest to describe: there is none at all, because the temperature is below freezing for most or all of the year. **Tundra** climates similarly discourage growth for most of the year, but some vegetation grows in the short summer, typically small mosses, lichens, and alpine plants. Equatorward, where the climate borders subarctic, stunted trees may grow.

The characteristic vegetation of the **subarctic**, **subarctic east**, and **manchurian** climates is extensive coniferous forest known as **taïga**, typically made up of spruce, fir, scots pine, and larch; larch is commonest in the coldest and driest climates, and the deciduous birch, aspen, and alder are also found in the lower altitudes. Despite the low amounts of precipitation, even lower evaporation means that enough moisture is retained to allow the growth of vegetation. Conifers have needle-like leaves to preserve water and strong branches to endure the snow which lies on them for much of the winter.

A mixture of coniferous forests and broadleaved forests characterises the **maritime** and **laurientian** climates; the dominant type of forest depends on the proportion of the year in which the temperature is less than 5.5 degrees centigrade (this is 42 degrees Fahrenheit, interestingly). The progression is from evergreen broadleaved through deciduous broadleaved to coniferous as the winters become colder; thus if the temperature is always above 5.5 degrees (i.e. the proportion is zero), the forest wil be mainly or entirely evergreen broadleafed. The dominant type of tree will be coniferous if the proportion is greater than 50%, and deciduous broadleafed if it is between 0% and 50%.

Mediterranean vegetation needs to guard against losing water in the dry summers, and tends towards scrub made of small plants with hard leaves, similar to the chaparral familar from many Western movies. The trees are either coniferous or evergreens with small waxy leaves and thick bark; evergreen oak, pine, cedar, and above all olive are typical mediterranean trees.

Too little moisture is retained in the **steppes** to allow trees to grow; the principal vegetation is thus extensive grassland, including many cereals. Grassland is also characteristic of the **savannah**, in which the vegetation dies back in the dry winter but grows vigorously in the summer, reaching heights of up to six feet. Trees in the savannah tend to be isolated and adapted to retain water for the long dry season, such as the baobab. The vegetation of the **deserts** is scanty, patchy, and specially adapted to the conditions; plants tend to be fleshy and leafless, such as the cactus.

The characteristic vegetation of the **tropical rainforest** climate is, of course, tropical rainforest: lush, abundant forests with massive trees and an enormous variety of other plants which grow all year round in the ever-present moisture, The large amounts of precipitation leach nutrients from the soil, and as a result the trees have shallow roots and large buttresses at the bases of their trunks. **Monsoon** vegetation is intermediate between rainforest and savannah: the forests are less dense, many varieties of tree become deciduous to cope with the dry winters, roots are longer, and the plant types are less diverse.

What if?

The principles described up to now should work well enough for an Earthlike planet. This section is intended as a catch-all for questions not otherwise answered.

... my planet rotates in the opposite direction?

Easy - just interchange "east" and "west".

... my planet rotates very fast?

The three bands of prevailing winds in each hemisphere are due to the speed of the planet's rotation. Above a certain speed of rotation, for which I am unable to provide figures, the three will become five (they cannot become four), and in between the STHZ and PF there will appear another belt each of of low pressure and high pressure. These will still move north and south with the sun, and the principles can be applied as before.

Bear in mind that above a certain speed of rotation the planet will disintegrate; I have no idea what limit this fixes on the maximum number of bands of prevailing winds. A faster rotation will also lead to shorter days and nights, which will doubtless have other consequences.

... my planet has a small axial inclination?

The north-south movement of the pressure belts will be correspondingly less, and smaller areas will be subject to the climates which undergo seasonal changes; annual temperature ranges will also be less. The tropical rainforest, maritime, hot desert, and icecap climates will be favoured.

... my planet has a large axial inclination?

The reverse of the preceding; season effects will be increased, and the areas subject to the tropical rainforest, maritime, hot desert, and icecap climates will be less. A large enough inclination - about 40 degrees - will eliminate these climates altogether.

Paper references

- *Meteorology and Climatology*, fourth edition (revised), E.S. Gates; Harrap (London) 1972. I rescued this from a wheelie-bin on Raeburn Place one evening.
- *Earth Science*, fourth edition; Tarbuck & Lutgens, Merrill (Columbus, OH) 1985.
- *The Climate Revealed*, by the unenviably-named William J. Burroughs, Mitchell Beazely 1999.
- *The Edinburgh World Atlas*, John Bartholomew & Son Ltd, 1970. Has useful diagrams of the relevant climatic information.
