

Investigating Earth's Systems

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Welcome to GEOG 111 Earth Systems and the associated textbook. This resource is meant as a quick overview of materials you should be prepared to engage with each week. Its purpose is not to be an exhaustive textbook that gives detailed explanations of each topic, but rather to rapidly introduce you to the basics of the material we will look at each week. If you would like to access a more traditional textbook that has more detailed explanations of the topics here, I recommend the following:

Available in print through the SFU library:

[Christopherson, R. W., Byrne, M.-L., & Giles, P. T. \(2016\). *Geosystems: an introduction to physical geography* / Robert Christopherson, Mary-Louise Byrne, Philip Giles. \(Fourth Canadian edition\). Pearson.](#)

Available online in ebook format:

[Physical Geography – Lumen Learning](#) – Online textbook
[Thomas, D. S. \(2016\). *The Dictionary of Physical Geography*. Chicester: John Wiley & Sons, Incorporated.](#)

Acknowledgements:

This project was facilitated by an SFU Open Educational Research Grant to the author, and was supported through work by Matthew Watkins and Joyce Chen.

MAIN BODY

This textbook is broken down into chapters that match the topic material covered each week in class. Read each chapter before engaging with the rest of the class materials each week.

Chapter 1

Topic 1 – Welcome to Physical Geography

Learning Objectives

- *Define* physical geography as interdisciplinary, systems-based, and advanced by hypothesis testing
- *Define* the system's approach (introduce the rock cycle, hydrologic cycle etc.)

Directly defined, the term **Geography** means: *Earth Writing* or *Earth Description*; however, the concept of geography involves much more than this. As a subject, geography explores the relationship of humans with the spaces they interact with in time. Understanding these relationships allows us to consider the 'geography' of a place.



The City of Vancouver

The geography of Vancouver, for example, includes the fingerprints of human design: the transportation networks, the types of buildings and residences, the social spaces, all studied within the subdiscipline known as **Human Geography**. But it also includes how people in Vancouver are affected by the natural environment: the climate, the availability of water, the underlying geology, all topics covered in the subdiscipline known as **Physical Geography**. Recent developments in digital mapping and spatial analysis have led to the development of a third area of study known as **Geographic Information Science**.

So why have I never heard of anyone being employed as a Geographer?

The unique blend of Human and Physical Geography situates geography as a truly **interdisciplinary** subject. The interdisciplinary approach not only makes geographers experts at bridging the

physical and social sciences, it also places them perfectly to address some of the most complex challenges facing society today. Progress on climate change, for example, requires approaches that understand the natural science behind the environmental changes that are occurring (physical geography) and the social, political, and economic impacts of those changes (human geography). This also means that geographers work in many different job environments, everywhere from collecting data in field environments to analyzing spatial data in lab environments to making policy decisions in political environments to making real estate and transportation decisions in the business environment.

One of the primary advantages that Physical Geography brings as a discipline is its **systems-based** approach. The systems approach defines everything at work in the world, matter and energy, as a combination of inter-related working parts. Individual systems can work independently or interact with other systems at multiple scales.

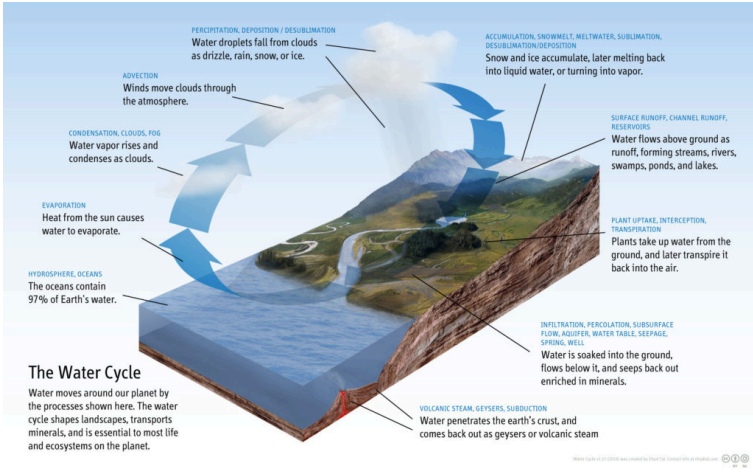
All systems are similar in several ways:

- System function is greater than the sum of the individual parts
- Systems are nested within and connected to other systems
- Systems are controlled by *positive* and *negative* feedbacks

It may be tempting to study a system by reducing it to its component parts and trying to understand these as well as possible, but if you studied the individual parts of a car without seeing them at work together, it's unlikely you would ever imagine the results when they are properly assembled and at work. Furthermore, sometimes the function of a system component is impossible to determine when analyzed from outside of the system. Imagine trying to discern the function of a windshield wiper without having the benefit of seeing it attached and in place on a working car.

We visualize system function by trying to model all of the connections, flows and roles between system components. This is

the basis for cycles like the *water cycle* which you have likely seen before:

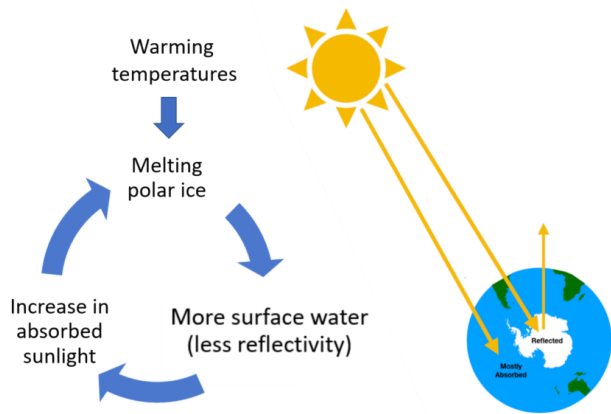


The interconnectedness of systems means that when one part of the system changes, it can have significant impacts as it feeds back into the rest of the system. Changes in a system are categorized as *positive*, *negative* or *neutral feedbacks*. A positive feedback reinforces the original function of the system, a negative feedback reduces the original function of the system, a neutral feedback causes no change.



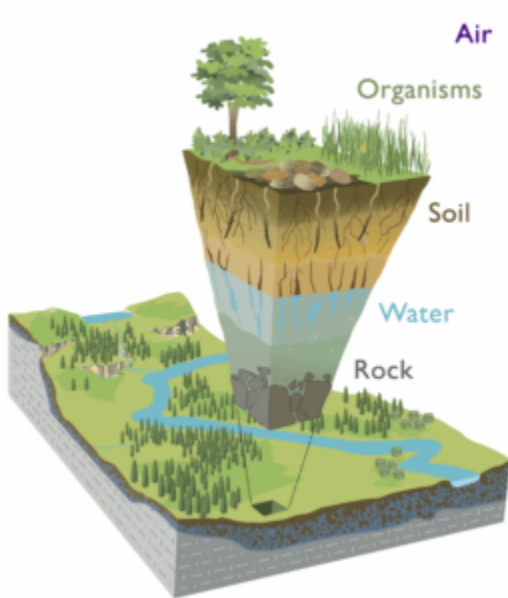
One or more interactive elements has been excluded from this version of the text. You can view them online

here: <https://pressbooks.bccampus.ca/earthsystems/?p=5#oembed-1>



One example of a positive feedback in a system is associated with changes in Arctic sea ice coverage and global glacier coverage. Ice is much more efficient at reflecting incoming energy from the Sun than either liquid water or bare ground. As global average temperatures increase, the presence of ice in the polar regions is diminishing. Less ice, means less reflection and more absorption of solar energy, feeding back and reinforcing the warming of the system.

Generally, we break down the systems present on Earth into four main spheres (keep in mind there are interactions and connections between each of these spheres):



A snapshot of the critical zone and some of the interacting units that define it.

- Biosphere Incorporates all life on Earth. Humans are part of this sphere.
- Hydrosphere The system of water across the Earth, in all three phases: solid, liquid and gas.
- Atmosphere The system of gases held against the Earth's surface by gravitational force.
- Lithosphere The solid surface of the Earth and heated layers of Earth's internal structure.

These four spheres combine most significantly in a space geoscientists have termed the **Critical Zone**, where rock, soil, water, air and living organisms interact and shape the Earth's surface. Most

environmental research is carried out within the Critical Zone. See more about the four spheres here:

<https://www.youtube.com/watch?v=VMxjzWHbyFM>

https://www.youtube.com/watch?v=UXh_7wbnS3A

Glossary:

Chapter 2

Topic 2 – Location, Location, Location

As a subject, Geography is sometimes briefly explained as: what is where, and why. The where is an important component of this question and geographers have several key ways to communicate location in 3-dimensional space. This is an introduction to location and how we represent location on maps.



How did an Egyptian well and camels help an ancient geographer discover the circumference of the Earth and lay the foundation for Earth measurement? Find out more here:

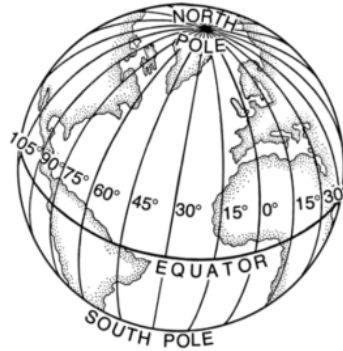
<https://www.youtube.com/watch?v=8hZl3arO7SY>

Location is generally communicated using 'coordinate systems'. These systems allow us to measure the relative location of anything in reference to an agreed datum (or point of origin). Globally, the most commonly used coordinate system is the '**geographic coordinate**' system based on **latitude** and **longitude** lines that encircle the globe. These intersecting grid lines at the surface of the

Earth are measured from a specific point of origin. The equator is one such line, and represents the zero point for lines of *Latitude*. Circling the globe, it is defined by the edge of a plane that bisects the Earth, perpendicular to its axis of rotation. All other lines of latitude run east/west, parallel to the equator, increasing in value north or south, towards the poles. Lines of *Longitude* (meridians) encircle the globe from north to south, increasing from zero at the Prime Meridian. Therefore the datum, or origin, for geographic coordinates are the Equator (0° latitude), and the Prime Meridian (0° longitude). *Note:* because all lines of longitude are perpendicular to the equator, they converge on the spherical surface of the Earth at

the exact point where the axis of rotation intersects the Earth's surface, creating the north and south **geographic poles**. There is a unique value for latitude north or south of the equator and longitude east or west of the Prime Meridian for each location on Earth.

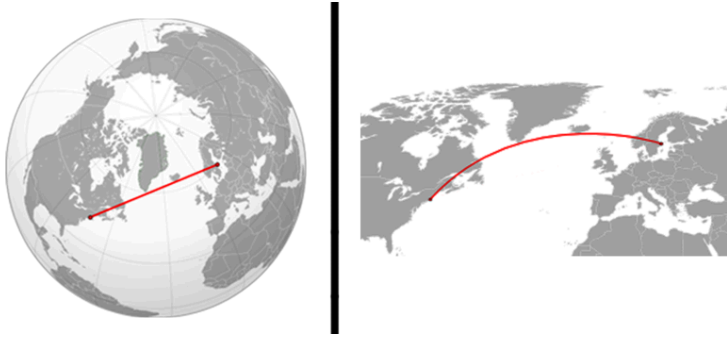
Geographic coordinates are particularly useful at the global scale because they successfully deal with the Earth as an approximate sphere and not as a flat surface. Latitude, for example, is defined as the angle given by a line drawn from the Equator to the centre of the Earth and back to the Earth's surface for your location. So these coordinates are really angle measurements, and their unit of measurement is degrees. While they do well to measure location on a spherical surface, degrees are not that intuitive for making other geospatial measurements, such as distance. As a result, other coordinate systems have been suggested.



Line of longitude and the equator distributed across the surface of the Earth.

What happens when you flatten a spherical globe onto a flat map?

In order to flatten out the Earth, a number of distortions are necessary. Flat paper maps at the global scale have significant distortion, either in shape, distance, angle or direction. The process of moving from a spherical globe to a flat paper map is called map projection. There are a multitude of ways to project a spherical globe onto a flat surface, and the choice of projection is largely based on the needs of the mapmaker, and what type of distortion they are trying to minimize.



Example of a map projection from a spherical to a flat surface. Notice how the length of the line changes from the spherical surface to the flat paper map, illustrating distortion in distance.

For maps of the entire world, the spherical shape of the Earth is significant, however when a map is focused on just a small part of the world, the curved surface is less apparent. The area of the Earth represented on a given map surface is referred to as map scale. Simply defined, $\text{map scale} = \frac{\text{distance on the map}}{\text{distance on the Earth}}$. World maps are generally low in detail, as they have to cover a large area and are referred to as **small-scale** maps. As the mapmaker focuses on smaller areas, more detail can be added, increasing the scale at which individual features are represented, we call local maps that represent the Earth's surface in high detail **large-scale** maps.

When dealing with large-scale local maps, distortion from Earth's curvature is minimized and so we can apply other coordinate systems, such as those based on cartesian grid coordinates with an x and y value, applied on a flat (non-spherical) surface. The most common grid system applied to local maps is the Universal Transverse Mercator (UTM) system. This system measures in metres from a specific origin (datum) point. For an in-depth explanation of the UTM system see [here](#) : Note: keep in mind that because the lines on a grid coordinate map do not converge at the top of the map (like on a sphere), Grid North (the top of the map) is different

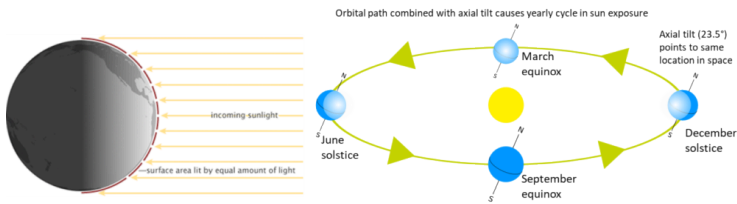
than geographic north. Furthermore, the magnetic north pole is not perfectly aligned with either of these north's. Therefore on any given map there may be up to three different definitions of *north* you should be aware of.

Chapter 3

Topic 3 – Our Private Universe

Averaged across the Earth, throughout the 24 hour day, the Sun delivers 340 watts/m² of radiation to the top of Earth's atmosphere. This constant supply of ready energy powers the critical zone of our planet in significant ways, including driving global circulation patterns in our atmosphere and oceans and providing the basis for photosynthesis and the production of biomass.

With respect to energy, the Earth is an open system. We receive energy from the Sun and we re-emit energy back to space. Energy contributed to the system by heat from the Earth's core represents a fairly small portion of this exchange, about 0.03%.



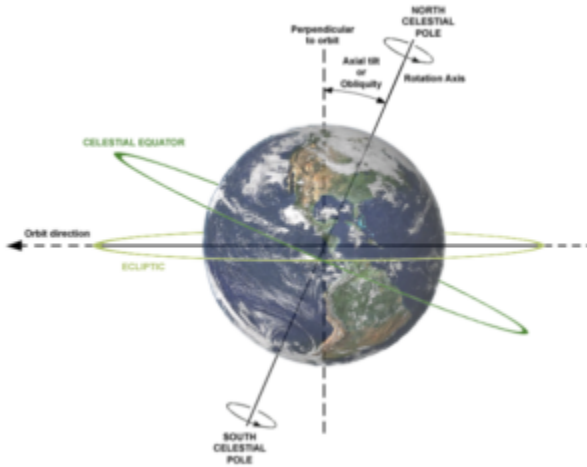
Incoming solar radiation is spread across the curved surface of the Earth, leading to differences in surface area for the same amount of radiation (the poles receive less intense radiation than the equator). The tilt of the Earth's axis, combined with its orbit around the sun lead to seasonal changes in the focus of the Sun's energy. Solstice points represent the longest and shortest daylight hours, whereas equinoxes represent equal daylight and night hours.

There are three basic controls on the delivery of this energy to the surface of the Earth:

1. The spherical surface of the Earth results in different surface area exposed to the same incoming radiation.
2. The axial tilt of the Earth results in the same parts of the Earth alternatively pointing towards or away from the Sun during

different parts of Earth's orbit around the Sun, and changes in the length of day throughout the year.

3. The rotation of the Earth on its axis results in daily changes in incoming solar radiation for a single location on the Earth's surface.



Earth's axial tilt

To look at how the orbital patterns and tilt change the Sun exposure for several locations on the Earth's surface throughout the year, check out the simulation here: https://sepuplhs.org/middle/iaes/students/simulations/sepup_seasons5.html

The angle at which the Sun's radiation encounters the top of the atmosphere and the Earth's surface is known as the **angle of incidence** and is significant for two reasons:

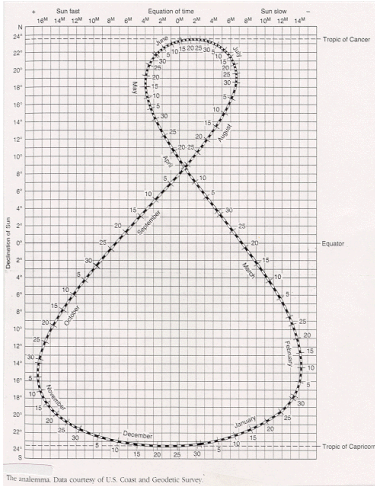
1. A steeper angle of incidence focuses solar radiation over a smaller surface area
 2. A steeper angle of incidence reduces the amount of atmosphere through which the radiation has to travel before encountering the Earth's surface
- For every latitude, the angle of

incidence changes throughout the year with the seasons.

For any given day of the year, the **latitude of the subsolar point** is the latitude where the Sun is directly overhead (angle of incidence = 90°). At the equator at midday (noon), the Sun is directly overhead (angle of incidence of 90°) twice a year, during the equinoxes. On the June solstice, the Sun is directly overhead at the Tropic of Cancer (latitude 23.5° N). On the December solstice, the Sun is directly overhead the Tropic of Capricorn (latitude 23.5° S). On these days, at any other location on the Earth's surface, the angle of incidence will be <90°. You can calculate the local **angle of the noon Sun** (ANS), for any latitude on the Earth's surface on any day of the year using the Analemma and the following equation:

$$ANS = 90^\circ - (\text{Latitude} \pm \text{Latitude of the Subsolar Point})$$

- ANS is the angle of incidence of the noon sun (expressed in degrees)
- Latitude refers to the location on the Earth for which you want to know the ANS
- Latitude of the subsolar point (LSP) read from the Analemma. We are interested in the total difference in latitude between our location and the LSP (\pm depends on its position with respect to the equator)



The analemma

The energy system is not just about delivery, its also about how that energy interacts with the Earth once it gets here. This is governed by physical processes like reflectance, transmission, and absorption within the atmosphere and at the Earth's surface. Reflectance off of any surface is determine by its **albedo**, the proportion of radiation absorbed vs. reflected (0 = perfect absorption, 1 = perfect reflectance). A higher albedo surface will reflect

more incoming sunlight. Snow, for example has a very high albedo (~0.9), whereas water is moderately reflective (~0.6) and a coniferous forest canopy has low reflectivity (~0.14). The distribution of these surfaces is a feedback on temperature distribution around the globe. For example, high albedo of snow and ice surfaces keeps an already cold Antarctic region, even colder because of high levels of surface reflectance. As Earth receives solar energy, that energy is redistributed around the globe through atmospheric and oceanic circulation. Specifically warm air and water from the Tropics are cycled towards the polar regions where they contribute to warmer temperatures. As these currents cool they cycle back to the Tropics where they are again warmed. Heat is transferred from these ocean currents to the atmosphere and back again, creating opportunities for significant global circulation of energy.

Chapter 4

Topic 4 – Earth from Top-Down

Although the **Critical Zone** focuses on the atmosphere just above the Earth's surface down to the initial few metres of the Earth's crust, the systems at work supporting the Critical Zone extend much further out into space and down beneath our feet. The atmosphere and internal structure of the Earth are similar in that both are composed of several distinct layers of material. As far as Earth Systems, we usually define these layers based on their *composition* and *function*. The atmosphere is comprised of a few main gases:

- Nitrogen (N₂ → ~78%)
- Oxygen (O₂ → ~21%)
- Argon (Ar → ~0.93%)
- Carbon Dioxide (CO₂ → ~0.04%)
- other trace gases (including methane (CH₄), water vapour (H₂O), ozone (O₃) and more).

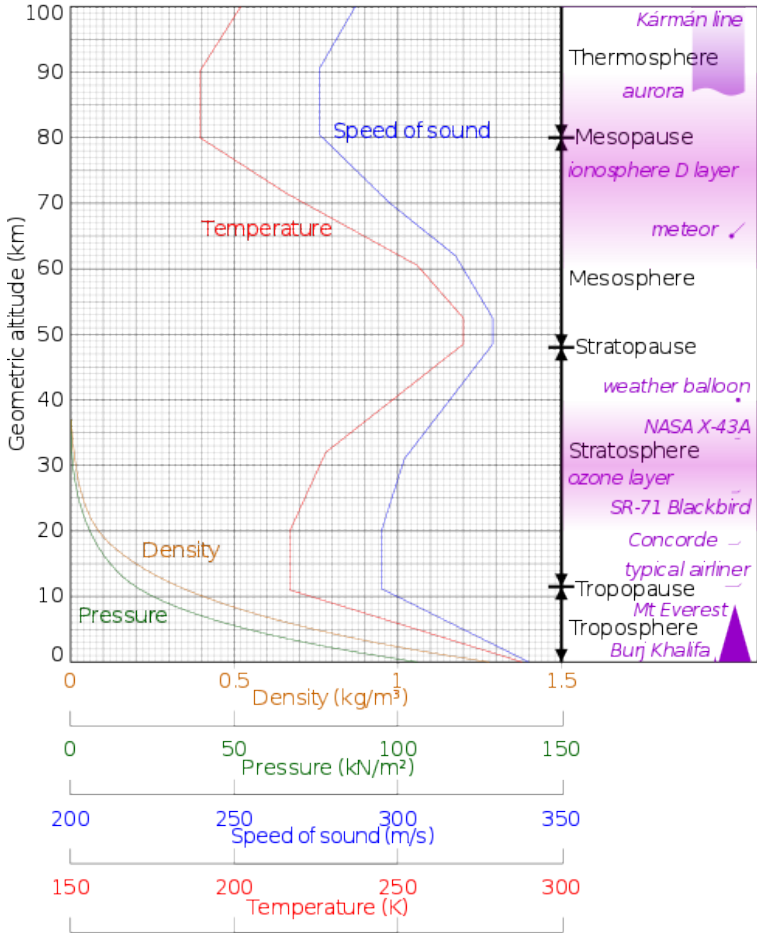
Nitrogen and Oxygen are mixed in a nearly constant ratio throughout the lower atmosphere (also known as the Homosphere, ~0-80 km), and are known as 'permanent' gases whereas the other gases vary in their amounts in the lower atmosphere across the Earth, and are known as 'variable' gases. Above the Homosphere, in the Heterosphere (>80 km), gases separate out based on density. There are three key relationships to remember with respect to atmospheric composition and gases:

As one moves up through the atmosphere:

1. Air **density** decreases
2. Atmospheric **pressure** decreases
3. Atmospheric **heat** decreases

The rate at which change occurs through the atmosphere for density, pressure, temperature and heat are referred to as **lapse**

rates. For example, the average lapse rate for temperature in the lowest part of the atmosphere is 6.4°C/km.



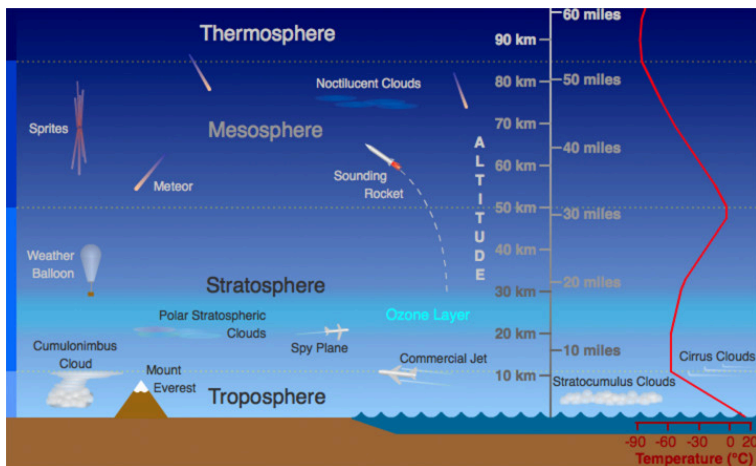
Density, pressure, temperature and speed of sound fluctuations as altitude increases in the atmosphere

Within the Homosphere, There are three distinct sub-layers of the atmosphere that vary based on **temperature** and function:

- 0-17 km – Troposphere – average temperature decreases from 15°C at the base to -57°C at the top. Where most clouds form and atmosphere/hydrosphere/lithosphere interaction takes place.
- 17-48 km – Stratosphere- average temperature increases from -57°C at the base to 0°C at the top. High concentrations of ozone in this layer absorb significant ultraviolet radiation from the Sun.
- 48-80 km – Mesosphere – average temperature decreases from 0°C at the base to -90°C at the top. Coldest part of the atmosphere in measured temperature.

In the Heterosphere, a final sub-layer of the atmosphere exists:

- >80 km – Thermosphere – average temperature increase from -90 at the base to 1200°C at the top. The thermosphere has a high temperature due to direct interaction with intense solar radiation at its upper surface, but the air particles are extremely low density here, so the felt **heat** is very low.*



Layers of the atmosphere

*Recall, temperature is a measure of average kinetic energy, whereas heat is a measure of thermal energy transfer from one system to another. Where particle density is low, the transfer of heat energy is inefficient.

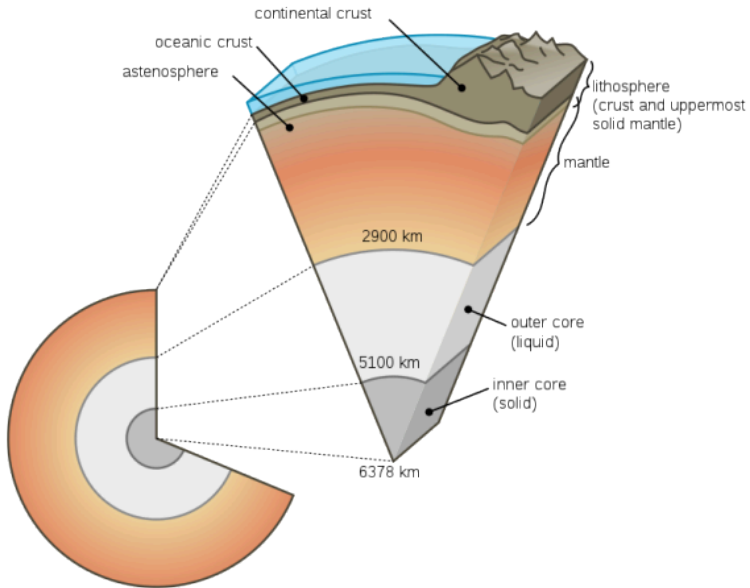
The Earth's interior:

Below the atmosphere lies Earth's **lithosphere**, or rocky surface. Our current understanding of Earth's internal structure is based on several relatively recent discoveries and the behaviour of **seismic waves** as they travel through the Earth to map out layers of **density** in the Earth's interior. The Earth's interior can be defined as having four distinct zones:

- Surface to 70 km depth – Lithospheric crust – **Rigid**, rocky outer surface of the Earth. Coolest zone of Earth's interior. Where **tectonic plates** exist and interact.
- 70 km to 2900 km depth – Mantle – Rigid to **plastic** material, which provides the driving mechanisms for **plate tectonics**.
- 2900 km to 5150 km depth – Outer core – **Molten** mineral material, mostly iron. Very high temperatures keep the material liquid.
- 5150 km to 6370 km depth – Inner core – Solid mineral material, mostly iron. Though temperatures are higher than the melting point of iron, it remains a solid because of the exceedingly high pressure imposed by the surrounding layers.

The mantle is the most complex of these zones. Where it contacts the lithospheric crust at the **Mohorovicic discontinuity** (also known as the 'moho'), it is rocky and rigid, but immediately below this zone it transitions into a plastic layer called the **Asthenosphere**, the hottest part of the mantle. Although not fully liquid, the plastic Asthenosphere allows for mobility, through convection currents driven by heat from radioactive decay of elements within the Earth's core. This mobility allows for the movement of overriding tectonic plates. Below the Asthenosphere, there is a transition to the upper mantle and then below that into the lower mantle, two layers

distinguished by **mineral** composition and slight differences in mobility (the lower mantle is under higher pressures and deforms slowly over long time periods).



Schematic of the Earth denoting oceanic and continental crust and the subsurface layers.

There are two main types of crust that make up the lithosphere.

Oceanic crust:

- Geography: underlies most of the world's ocean water.
- Mineral composition: mainly silica, magnesium and iron, combined in a rock called Basalt.
- Average density: 3.0 g/cm³.

Continental crust:

- Geography: comprises most of the world's land area.

- Mineral composition: primarily silica and aluminum.
- Average density: 2.7 g/cm³.

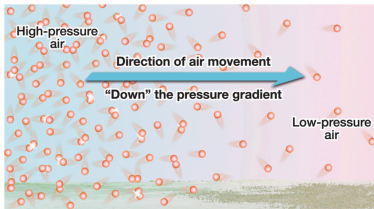
As a result of their different density, when oceanic and continental crust meet at boundaries in the Earth's lithosphere, oceanic crust normally sinks below the continental crust.

Chapter 5

Topic 5 – Hot Air Rises (Atmospheric Temperature and Circulation)

One of the most important relationships under normal conditions in the atmosphere is that **pressure** decreases upwards through the atmosphere. This relationship drives a significant amount of global circulation and weather patterns. But why does hot air specifically rise and cool in the atmosphere? It has to do with the Earth's relationship to the Sun and the **density** of warm air, and that air always moves from areas of high to low pressure, following the **pressure gradient**.

Recall from our overview of the atmosphere, that in the **Troposphere** (the atmospheric layer closest to the Earth's surface), **temperature** is highest at the surface and decreases upwards. This is because incoming solar radiation heats the surface of the Earth and that heat energy is re-radiated to the lowest parts of the atmosphere most efficiently. It warms the air just above the surface of the Earth. As this air warms, the particles become more energetic and push outwards, expanding the **air mass** and resulting in fewer particles of air in the same volume of space (a decrease in air density). As an air mass decreases in density with respect to surrounding air, it starts to rise.



(a) Side view

The pressure gradient

An air mass will continue to rise until it equals in density to the air surrounding it. Usually this happens because as an air mass rises, it is exposed to cooler air, and it starts to lose some of its heat energy. But there is another physical process at work here, referred to as **adiabatic** temperature changes.

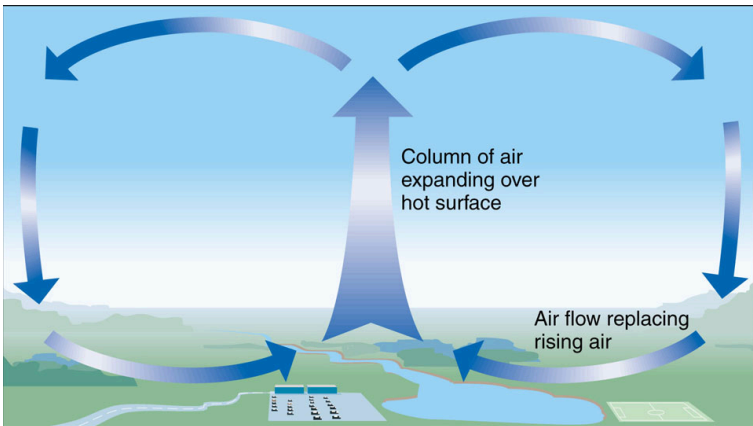
See how Wyoming mountains illustrate adiabatic heating and cooling here: https://www.youtube.com/watch?v=XH_M4jItiKw.

Adiabatic changes in temperature occur without any external change in heat energy exchange, but instead are driven by internal changes in how kinetic energy is distributed through an air mass. Remember that temperature is a measure of the average kinetic energy in a system. If you take a warm air mass of small volume at the Earth's surface and move it upwards in the atmosphere, it expands to greater volume as it rises, a natural outcome of reaching areas of lower atmospheric pressure. As it expands, the same particles, with the same kinetic energy now occupy a larger volume. The average kinetic energy of the system has decreased...and so has the temperature, without any change in external heat transfer. In this way, air masses naturally decrease in temperature as they rise. An example of adiabatic change here: <http://agron-www.agron.iastate.edu/courses/Agron541/classes/541/lesson06b/6b.6.html>

As you might imagine, air masses that are colder than surrounding air are more dense and tend to sink. This vertical movement of air (upwards and downwards) due to density differences is called **convection**. Convection drives the movement of air throughout our atmosphere and it is linked to the horizontal movement of air, called **advection**. Together, convection and advection create large atmospheric movements called convection currents.

Locally, this pattern may occur as the Sun's rays strike a part of the Earth's surface in the morning, warming it and causing rising air over a small area. Globally, this pattern is in almost constant operation, as solar energy is focused over the equatorial regions between the tropics, resulting in consistent, rising air over the equator. As this air rises, it creates a low pressure space beneath it where new air rushes in to replace it. This air is supplied by sinking (colder) air masses over areas north and south of the equator at about 30° latitude. So a cycle of air, rising over the equator, diverging to flow north and south, and then descending to the Earth

to flow back to the equator, is formed. This cycle of air is called the **Hadley Cell**, and it exists in a nearly constant state year round. See how global circulation works here: https://www.youtube.com/watch?v=xqM83_og1Fc&t=60s



Air flow replacement

On average, around the globe, atmospheric pressure at sea level is about 101.3 kiloPascals (kPa). But this is an average, and is generally not the actual pressure at any given time for any given location on the Earth's surface. Atmospheric pressure is defined in part, by the density of the air column above that point. A low density air column will rise, yielding low pressure below it. A high density air column will sink, resulting in higher pressure below it. Therefore, warmer air usually corresponds with low pressure air masses and colder air usually corresponds with high pressure air masses. These high and low pressure air masses are the starting point to understanding the development and interaction of weather systems.

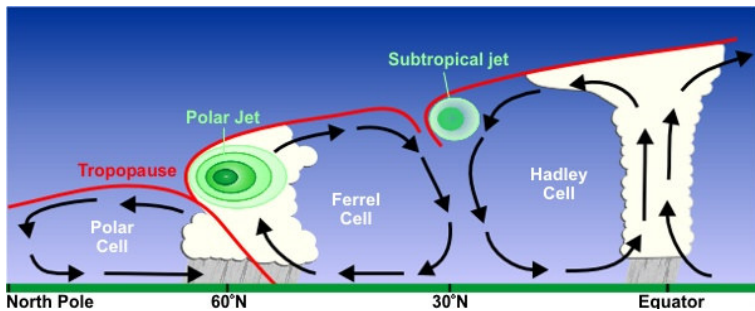
Chapter 6

Topic 6 - Global Circulation

“When we try to pick out anything by itself, we find it hitched to everything else in the Universe.” – John Muir

Recall from earlier class discussions that the Earth is heavily dependent on the Sun's energy. This is not just for providing humans with the energy needs we have come to be dependent on, or even just for plant productivity and photosynthesis, but it extends all the way to driving the weather patterns we experience on a daily basis. In the atmosphere, low pressure air masses are defined by rising air, warmed by the Sun's energy, and high pressure air masses are defined by descending air. This air moves vertically and horizontally following the pressure gradient (flowing from high to low pressure areas). The **Hadley Cell** is one example of this movement, but there are others including the **Polar Cell** which exists over the north and south polar regions, circulating mild air from the midlatitudes towards the extreme environments at the poles. These **convection** cells work to circulate air from the equator where it is warmed most efficiently, towards the coldest parts of the globe, resulting in a planet with less extreme temperature patterns. See how the Coriolis Effect works here:

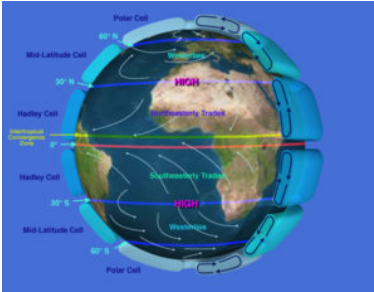
<https://www.youtube.com/watch?v=PDEcAxfSYaI&>



Latitude wind circulation

But the path of air towards the poles is not as straightforward as it might seem. The **pressure gradient** is the primary driving force for air circulation, but there is a secondary force, the **Coriolis effect**, that acts on air circulation at the global scale. The Coriolis effect impacts any **fluid** that travels over a rotating body. With respect to Earth, this includes atmospheric gases and liquid surface water that exist atop the rotating Earth. The Earth's rotation appears to deflect the movement of fluids as they travel. In the **northern hemisphere**, fluids appear to deflect to the right from their place of origin, and in the **southern hemisphere** they appear to deflect to the left. This means that an air mass traveling north from the equator will not travel in a straight line towards the north pole, but instead will appear to deflect to the right, relative to the Earth's surface.

If we apply this new force to the horizontal components of the Hadley Cell model of circulation, we find that as air rises above the equator and flows to the north (in the northern hemisphere) it is deflected to the right (or from west to east). When it descends over midlatitudes and some of it flows south back towards the equator, it is again deflected to the right (this time from east to west). This generates a series of airflow patterns that are nearly as constant as the Hadley Cell itself over the tropical regions of the Earth. In the **tropics**, air flowing from east to west at the surface is referred to as the **Trade Winds**, and these are 'easterly' winds (flowing from the east). Aloft, high up in the atmosphere, air flowing from west to east is known as the **anti-Trade Winds**, and these are 'westerly' winds (flowing from the west).

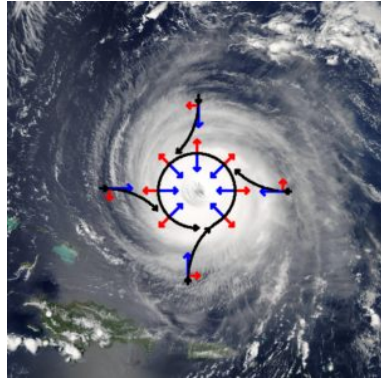


NASA depiction of earth global atmospheric circulation

Through satellite imagery, we're now used to seeing images of massive storms like hurricanes that travel across our planet. Storms are carried through the atmosphere by winds like the Trade Winds. But you may have also noticed that these storms rotate around a central point. This rotation is produced by the compound

effect of the Pressure Gradient force and the Coriolis force. If you visualize a low pressure centre, air should flow in towards the middle, along the pressure gradient. As that air encounters the Coriolis effect, it curves to the right (in the northern hemisphere). As these two forces balance, the air rotates endlessly around the Low pressure centre in a counter-clockwise direction. This is called cyclonic flow or a **Cyclone**. For high pressure centres the air flows from the high pressure zone outwards, following the pressure gradient. Again, it curves to the right, rotating this time in a clockwise direction. This is called an **anti-cyclone**. The winds generated by this endless rotation around the pressure centre are referred to as **geostrophic winds**. Closer to the Earth's surface, **friction** generated as air moves overtop of the Earth's crust begins to impact air movement. Surface winds are also impacted by surface friction, and are a balance between the **frictional force**, the pressure gradient force and the Coriolis force. Surface friction acts more to reduce the pressure gradient force than the Coriolis force and therefore winds eventually cycle in towards the centre of a low pressure system or out of a high pressure system.

Solar energy drives rising and sinking air around the globe, which in turn drives high and low pressure systems. As different parts of the globe are exposed to different amounts of sunlight throughout the year, global scale circulation shifts north and south with the seasons. This creates dynamic weather patterns for areas outside of the equatorial zone



The eye of Hurricane Isabel

throughout the year. The latitude of highest temperatures (where sunlight is most direct) for any given time of year is referred to as the **Thermal Equator**. The thermal equator shifts north and south seasonally roughly in step with the latitude of the subsolar point. This causes the **ITCZ** to move north and south seasonally, and specific areas of the globe experience seasonally changing weather patterns as a result. For example, the **Monsoon** climate is driven by this annual north/south shift, as is the shift in Vancouver's weather from generally stable, clear weather in the summer to alternating stormy/wet and cold/dry patterns in the winter.

Chapter 7

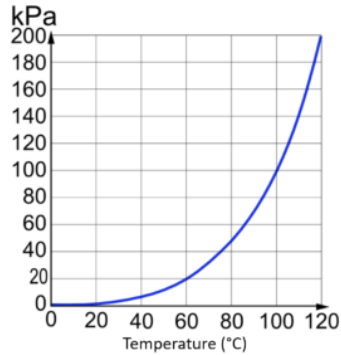
Topic 7 – Humidity

Water in its gaseous state, commonly called **water vapour**, is present in variable amounts from place to place in the atmosphere. The amount of water vapour in an air mass is called its '**humidity**'. Some air masses hold significant amounts of water vapour, whereas others are very dry. The amount of water vapour an air mass holds has significant implications for water delivery to Earth's continents, without which the ecological systems that exist on the continents would fail. Here is a water vapour interactive exercise and further explanation: https://earthobservatory.nasa.gov/global-maps/MYDAL2_M_SKY_WV

There are three basic ways in which we define humidity:

- Absolute humidity – mass of water per volume of air (usually in g/m³)
- Specific humidity – mass of water per mass of air (usually in g/kg)
- Relative humidity – ratio of water vapour compared to potential capacity of air mass to hold water vapour (usually expressed as %)

Each method has its own uses, but we will focus on **relative humidity** as it is most useful in considering weather patterns. In order to fully understand humidity, there is another concept useful to consider: **vapour pressure**. Earlier in these readings we discussed air pressure. Air pressure is the result of air molecules pushing outwards on a surface as they move in a system. Similarly, vapour pressure is the result of water



Saturation vapour pressure as it varies with temperature. Notice that at higher temperatures, the vapour pressure at which saturation occurs is higher.

vapour molecules pushing outwards on a surface. At sea level, the pressure an air mass exerts is a combination of the air molecules and water vapour molecules pushing outwards in the system. If you imagine a cubic metre of air, the more water vapour molecules you squeeze into that cubic metre, the higher the vapour pressure. In the critical zone, water is squeezed into air masses through the process of evaporation. An increase in vapour pressure corresponds to an increase in humidity. But air masses have a limit on the amount of vapour pressure they can sustain before water vapour is forced back out into liquid form through condensation. This limit is called the saturation vapour pressure . When an air mass reaches saturation vapour pressure, no more water vapour can be forced into it through evaporation without a corresponding amount being released through condensation. Relative humidity measures how close an air mass is to saturation vapour pressure. Further reading on saturation pressure here: <https://www.chemguide.co.uk/physical/phaseeqia/vapourpress.html>

$$\text{Relative Humidity} = \frac{\text{Actual Water Vapour in Air}}{\text{Water Vapour Capacity}} \times 100\%$$

Critical to understanding saturation vapour pressure is that it is dependent on temperature. The higher the temperature, the higher the saturation vapour pressure. In other words, the warmer the air mass, the more water molecules it can hold.

Imagine a cubic metre of air that is at 100% relative humidity (that is, it is at its **saturation vapour pressure**). According to the above statement on the relationship of temperature and saturation vapour pressure, you could create condensation from that air mass in two ways:

1. Evaporate more water into the air mass, causing some to be forced out as condensation because it is already at capacity.
2. Without adding more water vapour to the system, simply reduce the temperature of the air mass, decreasing the saturation vapour pressure, and forcing some of the water vapour to condense.

You can see from the above example, that relative humidity and temperature have an inverse relationship. Without the addition or subtraction of water vapour to a system, if you increase the temperature, the capacity to hold moisture increases, and the relative humidity goes down. If you decrease the temperature, the capacity to hold moisture decreases and the relative humidity goes up.

When you apply this principle to the atmosphere you find that a change in temperature is enough to force condensation to occur, resulting in **precipitation**. The temperature at which an air mass will reach saturation (or 100% relative humidity) is called the **dew point** temperature.

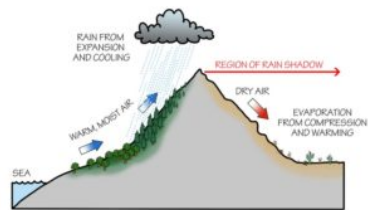
You can probably think of several ways in which an air mass could be forced to reach its dew point temperature. Over the course of a 24 hour day, an air mass will go through big temperature swings as it is warmed by the sun, and cools at night. These temperature differences may be enough for it to reach its dew point. Alternatively air masses may be forced to rise through the

atmosphere as they encounter low pressure, or are forced above topographic obstacles, like mountain ranges. In the troposphere, this change in elevation usually comes with a decrease in temperature, pushing air masses towards their dew point. The elevation at which the dew point is reached is referred to as the **lifting condensation level**. The rate at which temperature change occurs in the atmosphere with elevation change is called the **lapse rate**. There are three significant atmospheric lapse rates to be aware of:

1. **Environmental lapse rate (ELR)**: the actual, measured change in temperature as one moves upward through the atmosphere at specific location. Usually about $6.5^{\circ}\text{C}/1000\text{ m}$, but variable.
2. **Dry adiabatic lapse rate (DAR)**: the average rate at which an unsaturated ($<100\%$ humidity) air mass will cool as it rises through the troposphere. $10^{\circ}\text{C}/1000\text{ m}$
3. **Moist adiabatic lapse rate (MAR)**: the average rate at which a saturated (100% humidity) air mass will cool as it rises through the troposphere. $6^{\circ}\text{C}/1000\text{ m}$

If an air mass encounters environmental conditions that are cooler than it is, it will rise because it is less dense. If the air mass is unsaturated, it will rise at the dry adiabatic lapse rate, until it reaches the lifting condensation level, at which point it will rise at the moist adiabatic lapse rate.

This concept leads into a significant geographic pattern in mountainous environments. Where air masses are forced to rise up and over mountain ranges, they often reach their lifting condensation level, and



Orographic Lift

water vapour is forced out of the air mass. As they reach and pass over the mountain range, they descend the other side, but because they have condensed much of their water vapour, they are no longer saturated and descend at the dry adiabatic lapse rate, creating the opportunity for little precipitation on the far side of the mountain range. This process is called the **rain-shadow effect** and can be used to explain drier climates located behind topographic barriers like mountain ranges.

Chapter 8

Topic 8 – Clouds and Weather Systems

When water in the atmosphere reaches 100% relative humidity, it condenses, forming liquid water or ice. This liquid water reflects and scatters sunlight in many different directions and wavelengths, and when enough water droplets combine, they create the appearance of white clouds. Different types of clouds form from different environmental mechanisms, all of these mechanisms are related to air masses being pushed towards high relative humidity due to temperature changes.

Some cloud-forming processes :

1. Orographic lift: air is pushed up and over topography (a mountain range, for example), and cools as it rises.
2. Convective lift: The Sun heats the Earth's surface in a specific location, causing the air to warm in that space. The warmer air is less dense, causing it to rise and expand.
3. Frontal lift: Two air masses interact, one is forced to rise above the other because it is warmer and less dense. The boundary where the two air masses meet is called a **front**.
4. Convergent lift: Rising air in a zone of low pressure creates space below it. Air rushes in to fill this space, converges on other air and has nowhere to go but up.

In all of these cases air is forced to rise. As it does so it cools, increasing the relative humidity, with the potential for cloud formation.

Sometimes the temperature of an air mass might change because it moves over a surface that is a different temperature. For example, when an air mass moves from travelling over relatively warm water, to relatively cool ground, it may cool and condense without rising. Clouds formed next to the ground surface are called **Fog**.

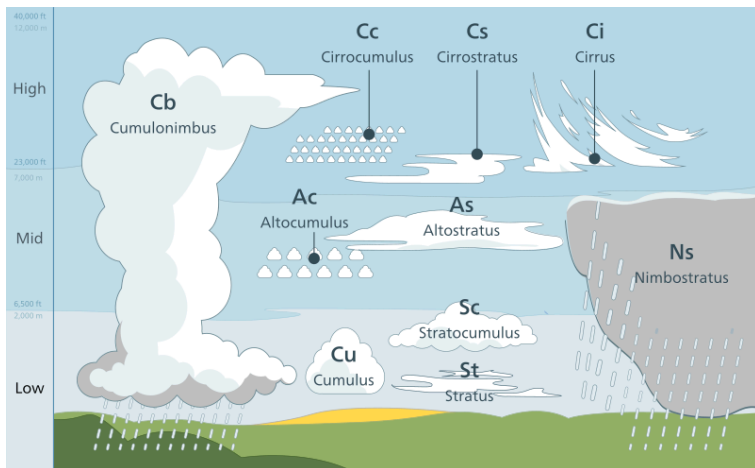
Cloud types are separated based on their appearance, both in shape and height in the atmosphere.

Shape:

- Cirrus = thin/wispy
- Cumulus = heaped/puffy
- Stratus = layered

Height:

- High – Mostly cirrus clouds
- Middle – Alto clouds
- Low – Mostly stratus clouds



The formation of a raindrop begins with a surface on which that droplet can form. Condensation is much easier when there is a surface for water to condense on. In the atmosphere, these surfaces are provided by particulate matter like dust or ash. Microscopic water droplets begin forming on these surfaces called **condensation nuclei** and grow through collisions with other water droplets. Water droplets or ice crystals in clouds are generally so small and low density that they are less dense than the air below them. This keeps them within the cloud until they form particles large enough to fall.

Once a droplet has coalesced into a large enough mass, it becomes more dense than the air below and falls from the cloud.

One of the most important factors in weather forecasting is determining how an air mass will behave when it reaches a geographic location like a city. Some of this is based on what lifting mechanisms might be at work, or the environmental lapse rate at the location of the forecast. But more important than all of this, are the pre-existing conditions of the air mass itself. These conditions are often defined based on where the air mass is travelling from. Air masses that have their source over water (maritime air masses) are generally higher in water content than those travelling over land (continental air masses). Air masses travelling from high latitude areas are generally cooler (polar air masses) than those travelling from equatorial locations (tropical air masses).

As described earlier, when two air masses interact they form a boundary between them based on temperature differences called a front. Two main types of front exist, based on the type of advancing air mass. A cold front exists where cold, dense air is advancing and pushing warmer air out of the way. A warm front exists where cold air has moved out of a region and is replaced by advancing warmer air. Warm air is significantly different density to cold air, and this is reflected in the different shape of these fronts as they move across the landscape. The cloud types produced by rapidly rising air (cumulonimbus in the case of cold fronts) and gradually rising air (stratus in the case of warm fronts) are also different.

In the Pacific Northwest region of North America, during the winter we experience alternating patterns of cold and warm fronts, brought to us by the westerly midlatitude surface winds. The constant change in weather conditions is noticeable as winter storms associated with low pressure systems and warm fronts move through but may be followed by incoming cold fronts and high pressure, stable conditions. These frontal systems are commonly impacted by larger scale weather patterns like El Nina or La Nina, the position of the Jet Stream, and the presence of warm or cold water off the Pacific coast.

Chapter 9

Topic 9 – Rogue Atmosphere: Severe Weather

“Climate is what you expect...weather is what you get.”

Short term measurements of temperature, precipitation, humidity, pressure, cloud cover, windspeed and direction are all measures of weather. The difference between weather and climate is simply a matter of time. Weather conditions are measured over minutes to hours to days to weeks, whereas climate conditions are averaged over decades (usually at least 30 years). Climate averages the weather conditions for a specific location over a long period of time building a picture of the general range of conditions expected for a given place. On any given day, the actual conditions are variable, but should be found within this range. The most common climate variables recorded for a given location are temperature and precipitation. The spatial distribution of these two variables have been used in global climate classifications and analyzing relationships between climate and the biosphere.

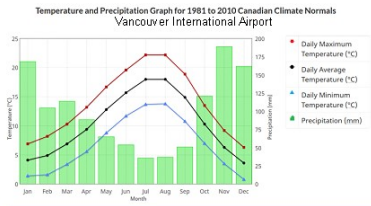
We frequently hear about how scientists are observing changing climate patterns. This means the long term average conditions of temperature and precipitation for specific locations are changing. The reason scientists are confident that changes are occurring is because we have a long record of **climate normals**. Climate normals refer to the range of normal temperature readings for a given location over a long period of time (usually at least



Stevenson screen and anemometer are used to measure weather conditions.

30 years, but often longer). Using such a long time-frame allows extreme measurements to be balanced out in the record, and gives a good sense of the overall variability for a specific location. Comparing current conditions against climate normals allows scientists to determine if current conditions are within the expected range of what is normal, or outside of that range.

Figure: Long-term climate normal for Vancouver International Airport. This is a typical graphic for representing climate called a climograph, where the two y-axes represent temperature (line graph) and precipitation (bar graph), and the x-axis covers a time range (usually a year). How do the expected climate values compare to the current weather conditions for this month?



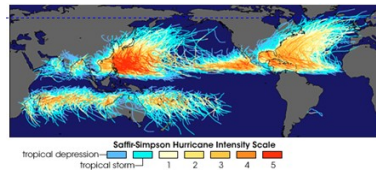
For this reason, there is a significant difference between ‘extreme’ weather and ‘severe’ weather at a specific location. Severe weather refers to weather that creates hazardous

conditions for the humans inhabiting the environment in which it occurs. Extreme weather refers to very rarely occurring weather events for a specific region. For some places, severe weather may also be very rare and extreme, but for other places, severe weather may be normal. For example, the state of Florida commonly experiences powerful storms known as hurricanes. These storms can release hundreds of millimetres of rainfall in a matter of hours and produce windspeeds in excess of 200 km/hr. Although this weather is ‘severe’ in its impact on the Florida region, it is not necessarily ‘extreme’ because it is part of the normal climate pattern. If, however, there was a shift in conditions and average precipitation and windspeed started to change, we might say we were experiencing ‘extreme’ weather patterns, because the observed conditions were at the far edge of what is considered normal under the expected climate.

Hurricanes are incredibly powerful low pressure systems that

develop from rapidly rising unstable air. Their intense power comes from energy released as water changes state from gas to liquid (condensation). This phase change releases significant amount of energy to the surrounding environment and is made possible when water evaporates from a warm ocean surface and is rapidly transported upwards through the atmosphere to much cooler temperatures where it condenses to form clouds and precipitation. Hurricane formation is therefore restricted to areas where warm surface water ($\geq 26^{\circ}\text{C}$) is plentiful, between the Tropics of Cancer and Capricorn. The strong rotational element of these storms is provided by the Coriolis effect. Low pressure systems rotate counter-clockwise in the northern hemisphere. Near the equator where water temperature is high enough, but the Coriolis effect is too weak hurricanes will not form. Therefore hurricanes generally form in a band between 8° and 20° latitude.

Given the effects of climate change (general increases in air and ocean temperatures) one might think it would be possible to predict a change in hurricane formation and activity based on the conditions under which hurricanes form.



Tropical storm pathways for all recorded storm pathways since 1850 (NASA 2004).

The reality is that the systems which underpin hurricane formation are much more complex. It has also been challenging to construct a reliable record of hurricane activity that spans longer than 30 years, given that satellite observations of hurricane activity only began in the late 1970's. As a result it has been difficult to confirm a trend in changing hurricane conditions, and the topic has sparked considerable scientific debate. Here is the statement on hurricane activity from the most recent Intergovernmental Panel on Climate Change (IPCC) report (AR5): *note – they refer to hurricanes as “tropical cyclones”

“Projections for the 21st century indicate that it is likely that the global frequency of tropical cyclones will either decrease or remain

essentially unchanged, concurrent with a likely increase in both global mean tropical cyclone maximum wind speed and rain rates.”

Often when thinking of issues related to severe weather we focus on the human impacts, while not paying attention to the larger system . Large storms like hurricanes crossing ocean basins have been found to be significant in transporting dust and sediment between continents. For example, dust from the African Sahara, rich in phosphorous appears to play a critical role in biological productivity in the South American Amazon river basin. Weakening future storms have the potential to reduce this mechanism of nutrient transport, impacting the biosphere.

Chapter 10

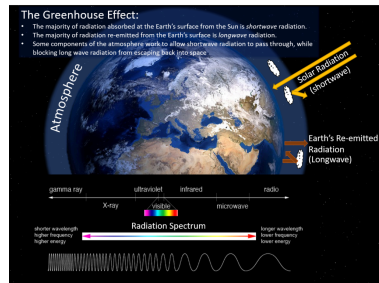
Topic 10 – Rogue Atmosphere: Climate Change

According to Wien's Law, objects radiate energy in relation to their temperature. This means that the electromagnetic radiation emitted by the Sun is much shorter wavelength than the same energy once it has been absorbed by the Earth and re-emitted. This difference in wavelength is critical in producing the conditions necessary for heating the Earth using atmospheric absorption. The gases in our atmosphere allow significant amounts of shortwave energy through, while blocking the emission of long-wave energy, trapping heat energy in the Troposphere. Some of these effective heat-trapping gases, like Carbon Dioxide (CO₂), Methane (CH₄), and water vapour (H₂O) have been changing in balance over at least the last century. A primary source for these emissions is from human industrial process.

Recent trends in climate are fairly straightforward for scientists to track. Reliable temperature records from weather stations around the world are available for the last century, and since the launch of weather satellites, space-based, global temperature measurements have been possible. As a result, a strong record of global temperature and precipitation trends, as well as changes to atmospheric composition exists for the last century. The IPCC (Intergovernmental Panel on Climate Change) reports the following (AR5):

Temperature:

– Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850



- The period from 1983 to 2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere, where such assessment is possible (medium confidence)
- The globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85 [0.65 to 1.06] °C over the period 1880 to 2012

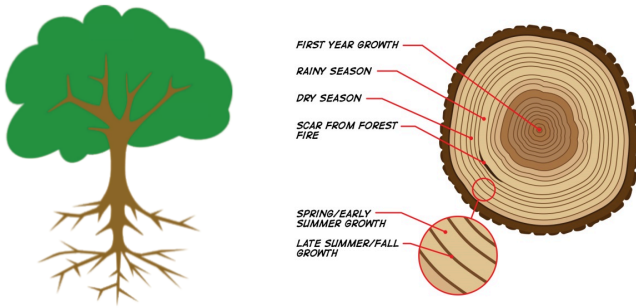
Precipitation:

- Averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901 (medium confidence before and high confidence after 1951)

These measured changes in climate conditions are supported by predicted changes in Earth's environmental systems. For example:

- Over the period 1901 to 2010, global mean sea level rose by 0.19 [0.17 to 0.21] m
- Arctic sea-ice extent has decreased in every season and in every successive decade since 1979, with the most rapid decrease in decadal mean extent in summer (high confidence)
- Since the beginning of the industrial era, oceanic uptake of CO₂ has resulted in acidification of the ocean; the pH of ocean surface water has decreased by 0.1 (high confidence), corresponding to a 26% increase in acidity

The linkages between shifting climate normals and human activity are clear. Human contributions to atmospheric gases like CO₂, CH₄, and others have increased since pre-industrial times and are at their highest emissions rate in history. About 40% of our emissions of these gases since 1750 have remained in the atmosphere. Current atmospheric concentrations of these gases appear to be at their highest concentrations in the last 800 000 years.



Measuring climate and atmospheric conditions into the deep past for comparison with current conditions requires methods beyond direct measurement of temperature and precipitation. The measurements used for this purpose are called “proxy records”. These data sources do not directly measure temperature or precipitation, but indirectly reflect atmospheric conditions. For example, tree rings grow at a rate proportional to environmental conditions. Where precipitation is a dominant control on growth, tree ring size can be used to approximate precipitation for a region. Tree-rings provide a proxy record going back several thousand years in some areas of the globe. Extending the record even further requires other proxy records like ice cores and deep-sea sediment cores that have similar relationships to temperature and precipitation conditions.

Trees respond to their environment and illustrate past environmental conditions through their growth rings.

Chapter II

Topic 11 – The New Global Tectonics

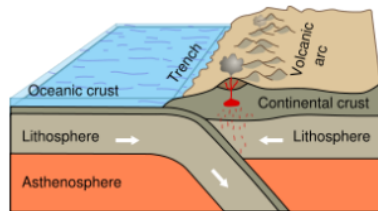
“The plates in dynamic mosaic through history both fresh and archaic like bold engineers for some two billion years have kept Earth from becoming prosaic.” – Jack Oliver

Before the 1960s, theories on how mountain ranges like Asia's Himalayas and North America's Rocky Mountains had been built to such staggering heights were largely based on ideas about how the Earth's crust must have **folded** and contorted during contraction as it cooled after its original formation. In the early 1960s evidence for movement at a continental scale in Earth's outermost crust began to fall into place. Now measurements by high precision laser and global positioning systems (GPS) confirm that the **lithospheric crust** of the Earth is comprised of a series of interlocking plates that move, deform and dynamically interact through the process of **tectonics**.

Earlier in these readings we defined the solid Earth as being composed of distinct layers, the outermost layer a relatively thin, brittle material representing the lithospheric crust. Immediately below this layer heat and pressure support a more plastic, deformable layer of rock, near its melting point called the **Asthenosphere**. Recall that there are two general types of tectonic plates (based on mineral composition) that make up the upper surface of the lithospheric crust:

- oceanic crust (Density $\sim 3.0 \text{ g/cm}^3$)
- continental crust (Density $\sim 2.7 \text{ g/cm}^3$)

See the overview of plate tectonics here:



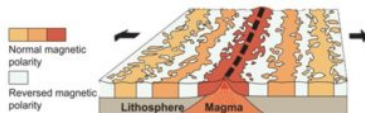
An oceanic-continental convergent plate boundary

<https://www.youtube.com/watch?v=zbtAXW-2nz0>
<https://www.youtube.com/watch?v=kwfNGatxUJI&>

In the early 1900s some scientists hypothesized that the continents had moved significantly in the geologic past. This was based on a few lines of evidence:

- Similarity in geology and apparent age of mountain ranges now on separate continents
- Apparent fit of continental margins like a jigsaw puzzle
- Similar fossil remains found on now widely separated continental locations
- Record of significantly different climate in the geologic past for some continental locations, indicating they had moved from different latitudes

Although this evidence demanded some consideration at the time, it was not conclusive on its own. One of the defining moments in driving plate tectonics forward as a viable theory was the systematic mapping of major ocean-floor ridges (for example, the mid-Atlantic ocean ridge). These ocean ridges represented locations where the oceanic crust was separating and diverging in opposite directions as the underlying tectonic plate was exposed to extensional stress, allowing **magma** (liquid rock) to come to the surface and form new crust. **Magnetic surveys** and **age dating** of the rocks around spreading ocean ridges confirmed that the rocks on either side of the ridges had matching magnetic fields and were similar age and therefore had likely formed in the same location, later drifting apart. It was also found that the accumulation of ocean-floor sediment increased with increased distance from ocean ridges, indicating the further away from the ridge you travelled, the older the crust became.



Polarity within the rock originating from a mid-ocean ridge

If new crust is being created in one location, it indicates that it must be recycled at another. Where two tectonic plates actively meet (converge), the higher density crust sinks

(**subducts**) beneath the less-dense crust, eventually sinking into the mantle where it can be recycled as new rock. As the crust sinks into the mantle it acts to heat and melt the continental crust above, generating surface volcanic activity. Where tectonic plates of similar density converge, they compress and deform, thrusting the crust vertically into mountain ranges (**obduction**), where the material is exposed to extreme weather conditions and rapidly weathered into sediment.

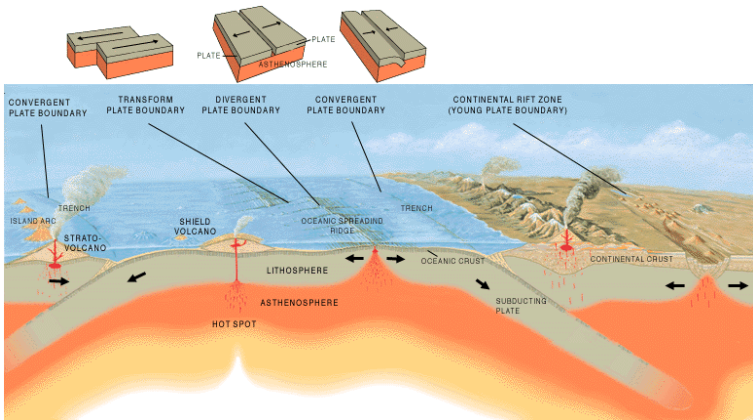






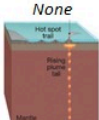
Plate boundaries and the regional landforms they create.

While we understand the relationship between tectonic plates somewhat well, the driving mechanism for plate movement is less well understood. For a long time scientists have hypothesized that large-scale **convection currents** move heat from Earth's core, through the mantle towards the lithospheric crust. Upon encountering the crust, it is likely that these currents have the ability to invoke some drag on the underside of the crust; however, it appears this is not enough force to generate the apparent movement of the plates. Instead a second mechanism called '**slab pull**' linked with the movement of the plates themselves may be more significant. As new material is erupted at a divergent boundary, it cools and becomes more dense, sinking into the

mantle. This sinking acts to exert a small pull on the divergent boundary. Furthermore, as a tectonic plate subducts into the mantle, the sinking of this plate likely exerts a large pulling force on the rest of the still buoyant plate, dragging it towards the subduction zone.

When two neighbouring plates move at different rates of speed, a **shear zone** forms between them to accommodate the different lateral movement. This is called a **transform boundary** and may generate moderately large earthquakes, such as those along the San Andreas fault system in California.

Where volcanic activity occurs far from any apparent plate boundaries, it appears that an upwelling of material in the mantle at that point location may be responsible. These '**hotspot**' locations in the mantle are responsible for volcanic activity in relatively remote locations, like the Hawaiian Islands.

Boundary Type	Force applied	Plate types involved	Geomorphology	Seismicity	Volcanism
Divergent	<i>Extension</i> 	oceanic/oceanic or continental/continental	Low ridge with central trench	Low energy, shallow depth	Low explosivity, fluid lava
Convergent (subduction)	<i>Compression</i> 	oceanic/continental	Trench with offset, uplifted mountains	Moderate to high energy, shallow to very deep	Moderate to high explosivity, thick lava
Convergent (obduction)	<i>Compression</i> 	Continental/continental	Uplifted mountains	Moderate to high energy, moderate to very deep	Not common
Transform	<i>Shear</i> 	Oceanic/continental, oceanic/oceanic, continental/continental	Offset surface	Low to moderate energy, shallow	Not generally present
Hotspot	<i>None</i> 	Within plates	Ridges or peaks associated with volcanic activity	Low energy, shallow depth	Low to high explosivity, fluid lava
Passive	<i>None (plates are passively locked together)</i>	Oceanic/continental, oceanic/oceanic, continental/continental	Elevation change between crust types	Not common	Not common

Chapter 12

Topic 12 – Seismicity and Western North America

One does not have to look very far across the varied, rugged terrain of British Columbia to notice that it differs significantly from the rest of Canada. The topographic differences are matched by differences in precipitation, temperature range, hazards, population distribution, economic production, geology, and other parts of the provincial geography. These differences have their roots in BC's geologic past and how Western North America was formed.

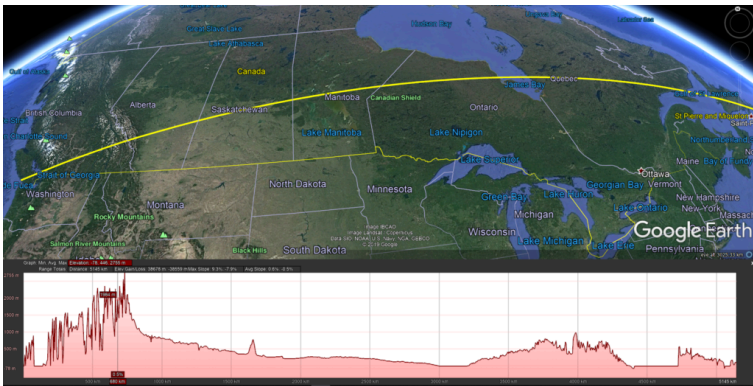


Figure 1: Topographic profile across Canada, highlighting topographic variation in BC.

About 290 million years ago according to the Geologic Timescale, the Rocky Mountains did not exist and the west coast of what is now North America was located near the current border of Alberta. The coastline approximated a low angle shoreline, similar to what exists now on the east coast of the United States. Over the next several hundred million years, as the subduction zone off the West Coast of North America operated, new materials in the form of islands were brought the edge of the continent. As the oceanic plate

subducted beneath the continental plate, these islands merged with the western edge of North America, compressing it and starting the process of mountain building.

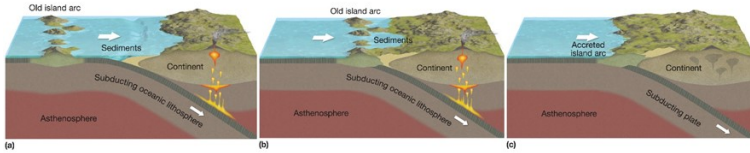


Figure 2: Process of Terrane Accretion, where exotic islands are brought to a new location through the process of plate tectonics.

This process of exotic material being brought from far away and slamming into our coastline has been termed ‘terrane accretion’, and it does a good job of explaining two challenging observations of BC’s geology:

- 1) the significant variation in geology type from west to east across BC (especially when compared with the relatively straightforward geology across the rest of Canada)
- 2) the north/south orientation of mountain ranges and zones of similar bedrock geology in BC

Additionally, the idea of **terrane accretion** aligns within the broader model of plate tectonics.

See this image for an example: <https://commons.wikimedia.org/wiki/File:AccreWedge.jpg>.

There are several pieces of additional evidence that subduction is occurring off the west coast of North America, potentially driving terrane accretion. Global Positioning System measurements confirm that the western parts of the North American continent (e.g., Vancouver Island) are drifting horizontally to the east and also increasing in vertical height, whereas interior locations in the Okanagan Valley are stable in position. This indicates compression of the western edge of the continent.

Other evidence present is in the structural patterns of rocks present across British Columbia. When rocks are compressed they

respond by either folding or faulting. Folding occurs under intense heat and pressure when the rock is soft enough to bend. Faulting occurs when the rock is brittle and breaks under the applied compressional stress. The Rocky Mountains display impressive instances of both structural **folding** and **faulting**.



Figure 4. Intense folding and faulting, Mount Kidd, Rocky Mountains, AB.

Three types of folds structures may form under compression:

1. **Monoclines**
2. **Synclines**
3. **Anticlines**

See this quick overview of the types of fold structures here:
<https://www.youtube.com/watch?v=XDlpz9cp4Ko>

The folding and faulting process significantly affects topography where these structures connect with the land surface, and so they are an important part of a region's geography.

Further evidence for active subduction off the coast of western North America is the history of infrequent, large magnitude earthquakes that are the result of slippage along the boundary between the subducting oceanic plate and overriding continental

plate. Occurring, on average, every 300-600 years, these earthquakes are recorded in the oral history of indigenous peoples up and down the coastline, and by the record of tsunami events triggered by these earthquakes and observed in Japanese harbours, hours after they travelled across the Pacific Ocean. The last of these events happened in the year 1700, releasing a ~Mw 9 earthquake.

Earthquake energy is released when stress built up in rock mass overcomes the strength of the rock, rupturing it and forming a fault. Energy released from earthquakes travels in seismic waves, in all three dimensions away from the initial rupture zone as '**body waves**'. There are two main types of earthquake waves that travel through the Earth:

- **P-Waves** - a pushing/pulling motion, travel rapidly through both solids and liquids.
- **S-Waves** - a shearing motion, travel more slowly and generally only through solids.

Further reading on earthquake generation and their waves here:

<http://www.geo.mtu.edu/UPSeis/waves.html>;
<https://www.bgs.ac.uk/discoveringGeology/hazards/earthquakes/seismicWaves.html>

Once these waves reach the surface they translate into slow moving '**surface waves**'. There are several types of surface waves, and these are responsible for the majority of the rolling motion felt at the surface during an earthquake.

The process of subduction and uplift of land surfaces through folding and faulting play important roles in the rock cycle and the production of topographic variation on the Earth's surface. The uplift process has lifted former seafloor rocks to the heights of the Rocky Mountains, where some of the richest fossil beds of former sea life have been found. As they are uplifted, these mountains are worn down through exposure to active weather and the rock is slowly broken down into sediment. Sediment is carried back to the topographic lows such as ocean basins, where it can form new sedimentary rock or be carried into the subduction zone and recycled along with the sinking oceanic crust.

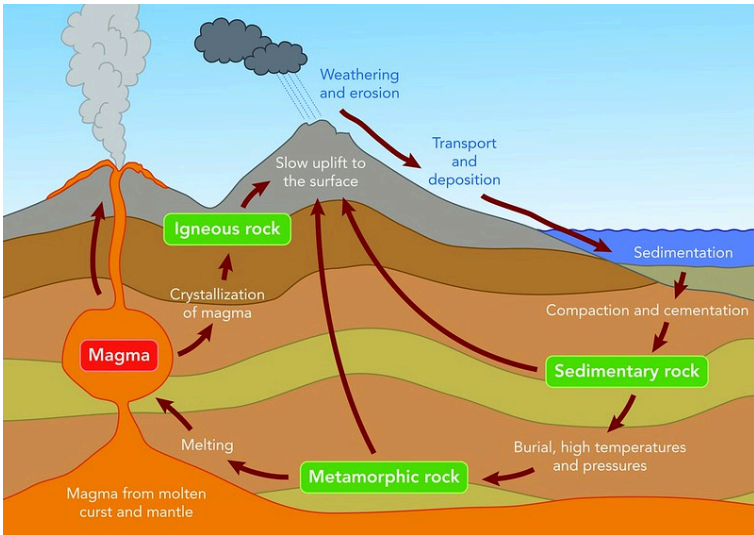


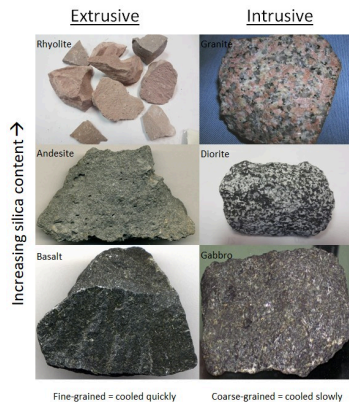
Figure 5. The rock cycle. Note the pathway from uplift to sediment and back to melting

Chapter 13

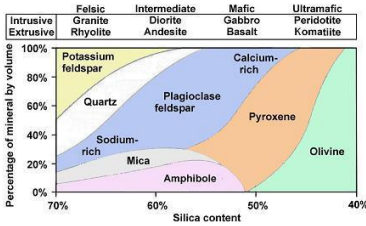
Topic 12 – Recycling Rocks

“This planet is essentially a body of crystallized and uncrystallized igneous material. The final philosophy of earth history will therefore be founded on igneous-rock geology.” – Reginald Aldworth Daly, 1914.

Volcanic eruptions are one of the most destructive of all natural hazards. Yet within this destructive potential, we see a significant connection between Earth’s lithosphere and atmosphere. Chemicals are released, ash and dust are dispersed to high levels, sometimes reaching the stratosphere. Perhaps most importantly, new rocks are solidified from liquid rock as its delivered to the surface. Underground, liquid rock is called **magma** and at the surface it is referred to as **lava**. Rocks formed directly from cooled liquid rock are called



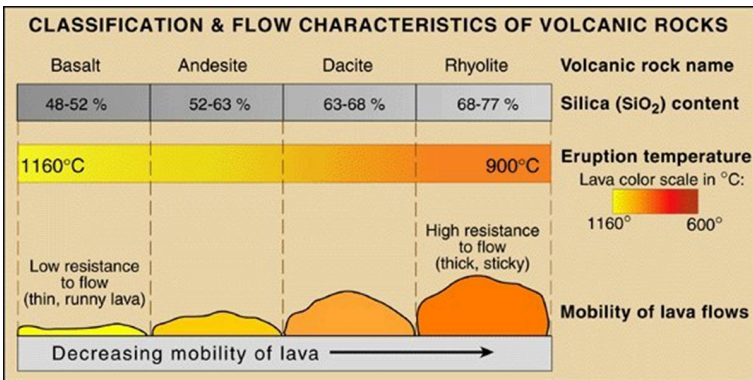
Igneous rocks, and represent a significant portion of the rock cycle. Where these rocks form from rapidly cooling at or near the surface, they are called **extrusive** igneous rocks. Where they cool deep underground they are referred to as **intrusive** igneous rocks. The slower cooling possible in the underground environment generally allows the mineral crystals within intrusive rocks to grow larger than an extrusive rock with the same mineral content.



How the mineral make up in igneous rocks reflects magma composition

Volcanic activity occurs when liquid rock makes its way to the Earth's surface. Much like air masses in the atmosphere, liquid rock moves through Earth's crust based on density differences with surrounding material. Warmer liquid rock is less dense than the

surrounding, cooler crust and as a result tends to rise towards the surface, melting through overlying rocks as it goes. The melting rock mixes with the existing magma and affects the chemistry of the mix, resulting in a unique chemical signature for each centre of volcanic activity. While rising through the lithospheric crust, intense pressure keeps volatile gases dissolved within the magma. When the magma reaches the surface, this pressure is removed and the gases are rapidly released in an explosive eruption. The violence of this explosion is associated with the chemistry of the magma and how easily it flows (**viscosity**). Generally, magma with higher **silica** content is higher viscosity (high resistance to flow). Magma with lower silica content is lower viscosity (low resistance to flow).



According to the diagram above, basalt has a low silica content and low viscosity. Basaltic lava is often found in association with volcanic eruptions with low explosivity (effusive eruptions), like those in Hawaii and Iceland. Rhyolite has a high silica content and high viscosity. Rhyolitic rock is often found in incredibly high explosive eruptions like the volcanic centre that underlies Yellowstone volcanic field. In between, andesitic and dacitic volcanoes (like Mount St. Helens in Washington) have explosive behaviour but on a smaller scale.

Magmatic chemistry affects the type of eruption at a volcanic centre and, as a result, the type of landforms generated:

Type	Magmatic chemistry	Shape	Visualization
Shield	<ul style="list-style-type: none"> Basaltic Highly fluid Effusive <p>Commonly found over mantle hotspots or near divergent plate boundaries</p>	Low, broad	
Composite cone	<ul style="list-style-type: none"> Andesitic to rhyolitic High viscosity Explosive <p>Commonly found at subduction zone boundaries</p>	High, conical	

There are many other volcanic landforms that you can explore, and a good summary exists here:

<https://opentextbc.ca/geology/chapter/4-3-types-of-volcanoes/>

Volcanic activity plays a critical role in the rock cycle, moving magma to the surface where it can solidify and form new rock. It functions in many other critical zone cycles, including mineral cycles like the Phosphorus Cycle, and the Sulphur Cycle, supplying significant nutrients necessary for soil development and plant growth.

Chapter 14

Topic 13 – Weathering

Tectonics and volcanic activity have the potential to uplift or form rock at the surface of the lithospheric crust. Processes like these, that occur largely within the crust to *build* landscapes, are referred to as **endogenous forces**. At the surface of the Earth, a set of other processes is at work, balancing the uplift and formation of new rock to create equilibrium in the landscape. These external processes are called **exogenous forces**. Together these two sets of forces produce the landscapes and landforms that define the Earth's surface, and they are studied in the science of **geomorphology**.

The rock cycle depends not only on the formation of new rock, but also the breakdown of existing rock. The part of the rock cycle focused on disintegrating rock and transporting it away from its source is called **denudation**. The first stage in denudation occurs when rock is exposed at or near the surface of the lithospheric crust, it begins to break down through several types of processes collectively termed **weathering**.



The breakdown of limestone in Rhodes, Greece.

Taking advantage of pre-existing weakness in rock structure, weathering may affect the physical and chemical characteristics of the rock, with the overall effect of reducing rock strength, leading to its breakdown. This breakdown is significant not only for the rock cycle, but also for many other biogeochemical

cycles as it presents an opportunity for the transfer of minerals normally found in rocks to the hydrologic cycle and from there into many other systems. For example, as precipitation falls over a rock

surface it can dissolve the minerals within the rock and the runoff may carry them away to a new environment where to be used by the systems there. Furthermore, the continued development of healthy soils is heavily dependent on the provision of rock fragments and minerals generated through weathering processes. For further explanation on the types of weathering, see: <https://www.geolsoc.org.uk/ks3/gsl/education/resources/rockcycle/page3461.html>

There are two main categories of weathering:

- Physical (also called 'mechanical') weathering
 - Rock breakdown occurs without chemical alteration to rock material
- Chemical weathering
 - Rock structure is decomposed through chemical reactions

Primary types of physical weathering include:

- Frost wedging
- Salt weathering
- Exfoliation
- Root expansion

All of these weathering processes are based on the expansion or contraction of materials over time, usually due to climatic influence.

Primary types of chemical weathering include:

- Dissolution
 - Minerals in rock material are dissolved in running water and carried away.
 - Example: $CaCO_3 + H_2CO_3 \rightarrow CA^{2+} + 2(HCO_3)^-$
- Hydrolysis
 - Hydrogen ions in water replace other elements in the

minerals, weakening it.

- Example:
$$4KAlSi_3O_8 + 4H^+ + 2H_2O \rightarrow 4K^+ + Al_4Si_4O_{10}(OH)_8 + 8SiO_2$$
- Oxidation
 - Oxygen ions in water replace other elements in the minerals, weakening it.
 - Example:
$$3Fe^{2+}SiO_3 + \frac{1}{2}O_2 \rightarrow Fe_3O_4 + 3SiO_2$$



Ayers Rock in Australia is an example of oxidation of iron-bearing minerals

In the case of chemical weathering, the new minerals formed by replacing the original materials with oxygen and hydrogen ions are generally weaker than the original minerals, leading to more rapid breakdown.

Not all rock weathers at the same rate, even in the local environment. A few key variables influence the rate at which a rock surface will weather.

1. Material hardness – Some mineral types are harder than others

may more easily resist weathering.

2. Climate – The precipitation amounts and temperature range a rock is exposed to will influence its weathering rate.
3. Water – The presence of water significantly increases the rate of weathering for all rock surfaces
4. Surface area – A rock that has a greater number of joints or surface area exposed to weathering will weather faster.
5. Slope aspect – The direction a slope is facing controls the amount of sunlight and daily temperature variation for the surface and can affect weathering.
6. Vegetation – Vegetation cover can protect a rock surface, but root growth can also increase its weathering rate.
7. Porosity/Permeability – The ability of water to efficiently move through a material or be stored in a material affects its weathering rate.

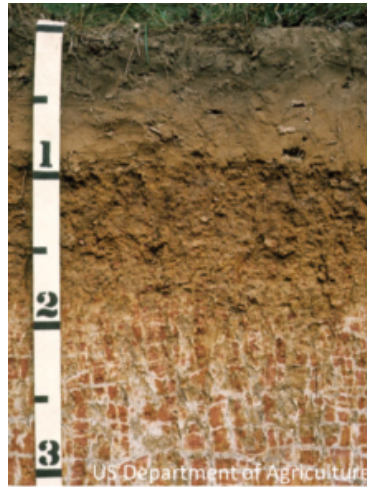
Weathering is consistently happening on surfaces all around us. Keep an eye out for weathering on the human-made infrastructure around you, and in the natural landscapes you see. It is a significant part of biogeochemical cycling and therefore represents a foundational component of healthy critical zone function. Another resource for a deeper look into chemical weathering is found here: <https://teach.albion.edu/jjn10/chemical-weathering/>

Chapter 15

Topic 15 – Dirt, Soil and Biospheric Interactions

In the lithosphere the thin layer of surface materials above bedrock but below the atmosphere are the accumulated products of weathering and erosion. On its own, solid rock that is broken down

into smaller rock particles through weathering is called **sediment**. When chemical or biological processes act on this sediment, modifying it in place, it develops into a **soil**. This can happen from the top down, for example, through the decay of leaf material that falls on the surface. It can also happen from the bottom up, as water moves minerals through the sediment, and supports chemical reactions and physical



weathering. The original sediment is referred to as 'parent material' for the developing soil. A well-developed soil has undergone significant transformation from its original parent material and can support a variety of living organisms from bacteria and insects to plant life and burrowing animals. In fact the type of soil which develops in a region acts as a major control on the living systems both above and below the ground and for that reason soil plays a dominant role in the the *critical zone*.

Soils represent a unique part of the physical environment where the abiotic (non-living) and biotic (living) components of Earth Systems interact significantly. Biological material like dead plants and animal matter are broken down by bacteria and insects in the upper layer of the soil and minerals are contributed by soil parent

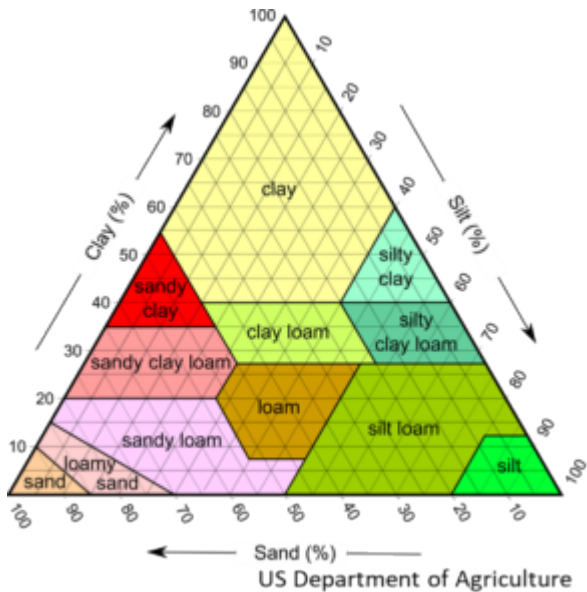
material. Water and oxygen are moved through and stored within pore spaces between soil particles. This creates an opportunity for plants to access the nutrients they need to live and grow, supporting broader life at the surface of the Earth.

Here are a few key things to understand about why soils are so significant to Earth System function:

- Soils regulate water flow and nutrient delivery in the upper lithosphere
- Soils act as filters, buffers, and catalysts for chemical reactions
- Soils are significant storehouses for conserving and cycling nutrients like nitrogen, phosphorous, potassium and carbon
- Soils support the engineered structures we build on top of them, like houses, bridges and roads

Considering how important soils are to the critical zone and ecosystem function, it is important to remember that:

- How we manage the soil affects its quality
- A soil that develops in place is unique to that space, based on its physical, chemical, and biological properties
- Soil forms based on specific soil-forming factors including:
 - o Parent material
 - o Climate
 - o Living organisms
 - o Topography
 - o Time
- Most soils form very slowly and have limits (which need to be understood for appropriate management)



- Soil erosion and degradation can happen very quickly if not managed properly
- The study of soils is a science of its own, known as ‘pedology’

The average soil is constructed of sediment particles like clay, silt and sand (~45%), organic material (~5%) and pore space between soil particles that may be filled with water or air (~50%). The dominant particle size plays a significant role in soil properties like drainage and root capacity.

A soil texture diagram visually demonstrates the different range of soil textures based on which of the three sediment sizes are most dominant in the mixture.

Soil scientists further characterize soils based on the layers they have developed over time. These layers are referred to as ‘soil horizons’ and contain specific indicators of soil maturity. The most common soil horizons and their defining characteristics are labelled here:

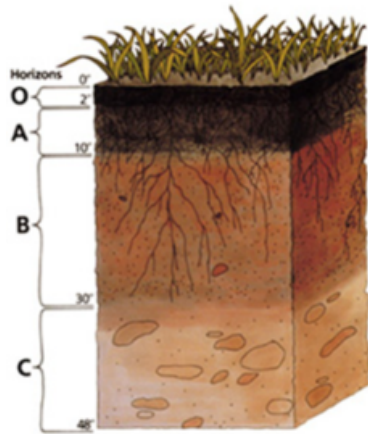
O horizon – decomposing organic material

A horizon – mixed mineral material and decomposed organics

B horizon – mineral material altered by soil forming processes

C horizon – base layer of weathering parent material

Soil horizons are recognized by their colour and other physical attributes, like how well they drain water, their clay content, the amount of organic material they contain, and many others.



US Department of Agriculture

In many ways, soils are the connecting point for the

Critical Zone between the biotic and abiotic parts of Earth Systems. The many microorganisms in soil play a significant role in breaking down both mineral and organic materials, and they also produce and consume atmospheric gases. The vegetation that soil supports also interacts with the atmosphere and hydrosphere and plays a critical role as a food source in the biosphere, supporting larger life forms (including humans!). Yet, even soil can be linked back to the basic relationship we have with the Sun. Climate and soils are linked together because the type of vegetation that can grow in a specific climate affects the chemical balance of a soil. For example, the soils in a coniferous forest in northern Canada are very acidic, given the natural acidity of coniferous needles. Soils closer to the equator generally experience greater rates of evaporation from their surface and can have a buildup of salt, leading to more alkaline (basic) soil chemistry. Of course, there are also many other local factors that can affect the chemistry of a soil as well.

Remember, understanding Earth Systems is all about better understanding the linkages between the systems and how they interact to create something bigger than the sum of the parts. Soils play a significant role in this understanding and geoscientists that

work on understanding soils better are a key part of our future shared success.

The short video below illustrates just one of the connections between broader Earth Systems and soils, focusing in on soils as a carbon storage system. Watch to see what happens if we misuse the soils we have:

https://youtu.be/8_69vy7ZBxE?

Chapter 16

Topic 16 – Gravity Never Sleeps – Mass Wasting

On March 22, 2014 at 10:37 am a hillside just outside of Oso, Washington collapsed, sending a wall of mud and debris across the Stillaguamish River towards a small settlement of people and Washington State highway 2. The material buried the community in about 7.6 million cubic metres of debris, claiming the lives of 43 people and injuring 10 others, and causing over \$50 million in damages. It is the deadliest recorded landslide in US history. After the event, there was significant discussion about whether the event could have been predicted or avoided, and the various roles that natural causes and human influence increased the impact of the disaster.



When Earth materials like rock or sediment exist on a sloped surface, gravity continuously pulls downward on those materials. When the force of gravity overcomes the resisting forces, holding the material against the slope, it moves downslope. Sometimes this movement occurs rapidly, over a number of seconds. Sometimes it occurs over the course of years or decades, at a rate imperceptible to the human eye. Collectively, all processes that involve the downslope movement of Earth materials are referred to as ‘**mass wasting**’.

As a process, mass wasting is part of a larger geomorphic cycle

called '**dynamic landscape equilibrium**'. The landscape equilibrium concept suggests that endogenous and exogenous forces interact to create a balance across the Earth's surface. For example, tectonic forces are acting to uplift the Himalayan Mountains in Asia at a rate of 2-4 mm/year but are balanced by erosion of up to 1.5 mm/year, leading to dynamic equilibrium in the actual amount of uplift. The balance is 'dynamic' meaning it changes over time. Most of the time this change is slow, but sometimes a geomorphic threshold is reached where change is large over short time periods, destabilizing the original equilibrium, and replacing it with a new one. Using mass wasting as an example, you can imagine how a slope may undergo weathering and slow erosion over a number of years, until it is finally too weak to hold the material on its slopes. In the example of the Oso mass wasting event above, a new dynamic equilibrium on the landscape was established after the landslide occurred. The Stillaguamish River naturally rerouted, and the slope re-stabilized at a new slope angle.

Mass wasting can be influenced by a number of natural variables. Anything that reduces the stability of a slope is considered a variable that drives the slope towards failure. Anything that increases the stability of a slope is considered a variable that resists slope failure. When the **driving forces** increase above the **resisting forces**, mass wasting is likely to occur.

Some examples of driving and resisting forces:

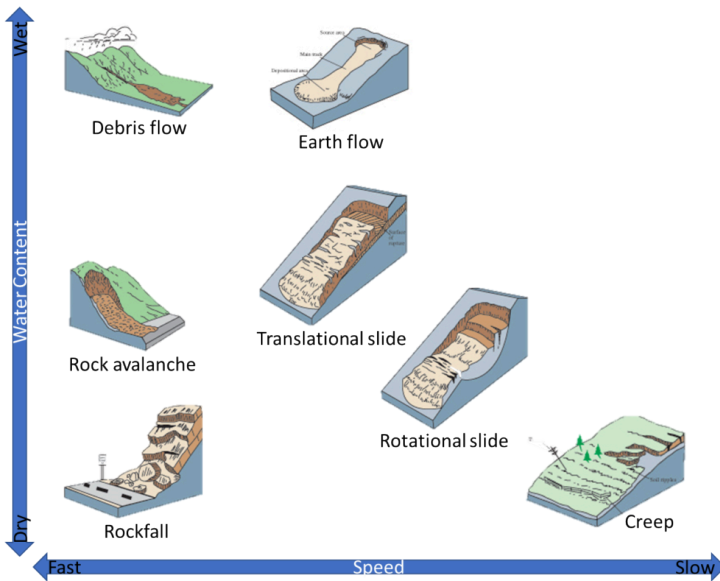
Potential driving forces	Potential resisting forces
Increase in water content	Decrease in water content
Weak geologic structure	Strong geologic structure
Increase in slope angle	Decrease in slope angle
Reduction of support at base of slope	Increased support at base of slope
Removal of vegetation (fire, human activity)	Addition of vegetation cover
Weathering (freeze-thaw, chemical weathering)	
Destabilizing event (earthquake, erosion)	

In the case of the Oso landslide a few driving forces were identified. Intense rainfall occurred in the three weeks before the landslide event, increasing water content in the material. The Stillaguamish River was actively eroding the base of the slope, increasing the slope angle. Deforestation in the years before the event, likely allowed more water to infiltrate the slope materials. It was likely a combination of these factors that ultimately led to the mass wasting event.

Mass wasting processes are classified based on how the material involved is moving. There are three main types of movement that can occur:

- Fall – Material free-falls through the air
- Slide – Material moves as one coherent mass, along a discrete failure surface
- Flow – Material breaks apart and particles move independently
 - *Avalanche* is a subtype of flow where movement is not confined to a channel and may not be fully saturated with water

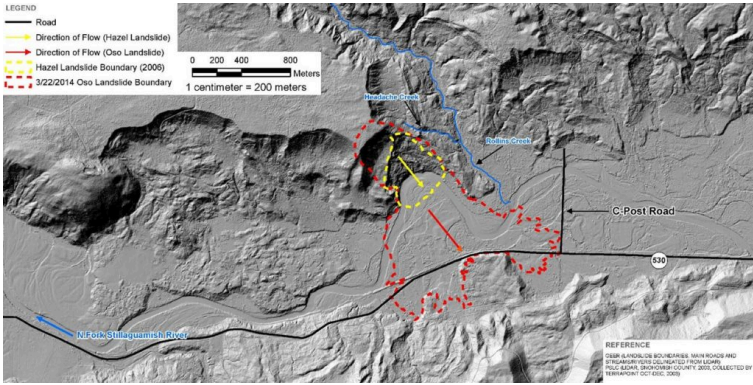
These movements are further classified based on the speed at which they move and their water content.



In this context looking at the shape of the Oso landslide from the image above, you can probably tell that it has characteristics of several of these mass wasting types. This is because most mass wasting events are not simple, one-category events, but are 'complex' and include several different types of movement. The Oso event initially included elements of translational and rotational sliding as well as debris flow behaviour. Many mass wasting are complex, changing from one style of movement to another as variables like slope or water content vary along their path.

Below is a high resolution image of topography around the Oso landslide. It's possible to easily see not only the scar of the Oso landslide on the image, but also previous mass wasting events beside the most recent event. These events happened long before historic records began for the area. The promise of imagery like this

is that future events may be predicted based on the observation of past events.



Chapter 17

Topic 17 – Drainage Basin Hydrology

Hydrology is the *science of water*. Water moves through Earth systems by following stages in the hydrologic cycle. Most of the water (~96%) in the hydrologic cycle is stored in the Earth's oceans. About 86% of global evaporation occurs over the oceans, but because of global winds and precipitation mechanisms (like orographic rainfall), only about 77% of precipitation occurs over the oceans, the rest falls on land. Precipitation falling over the land surface is received in a 'drainage basin' a unit of land defined by topography and the collection of water as it flows downslope. A drainage basin (also known as a 'watershed') is defined by drainage divides, topographically high points of land that divide water flow from one location to another. The water in a drainage basin all drains into a common outlet, like a river, lake, or ocean.

You can virtually interact with the world's drainage basins here to get a sense of their geography:



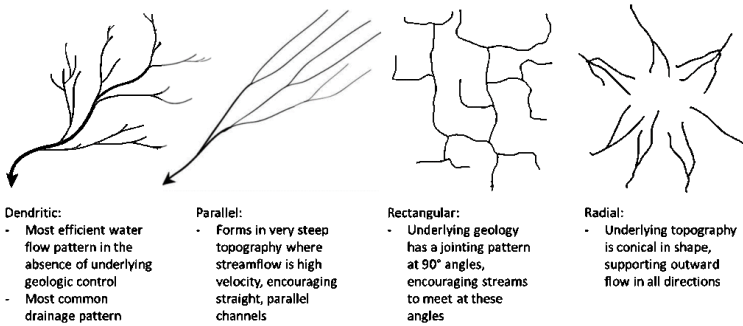
<http://riverbasins.wateractionhub.org/>

The systems approach of understanding the Earth often looks at environments from the perspective of the drainage basin. Drainage basins are effective units of ecological management because the availability of water is a significant limiting factor for many other parts of the critical zone including soil and vegetation. Hydrologists

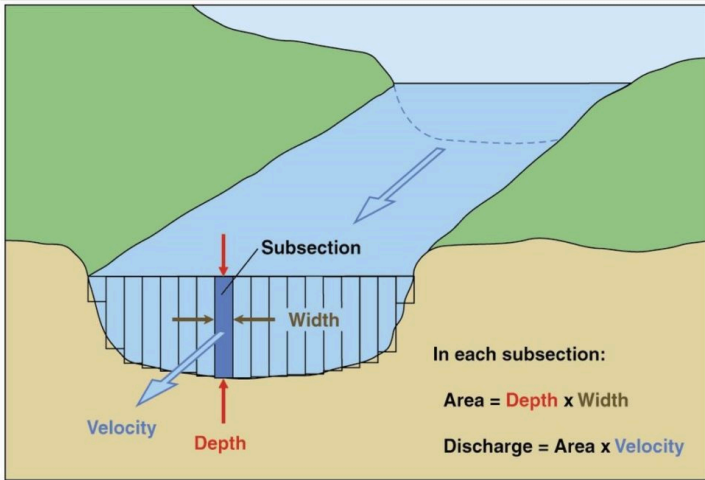
focus their work on understanding the quality, quantity, and patterns of movement for water through a landscape.

As water falls as precipitation on a landscape, it has multiple pathways it can take. If it falls as snow it may be stored in place for a time, or freeze into glacial ice over longer time periods. If it falls as rain, it may flow over the surface, collect in rivers or lakes, or infiltrate into the surface where it can enter the groundwater system. Each part of this system has differences in residence time (how long the water stays in that part of the system).

As water initially flows over the land surface unconstrained by a channel, it is referred to as overland flow. Eventually, increased depth of water flow makes this type of movement unstable and the water separates into channels, referred to as streamflow. The organization of different drainage patterns on the landscape is related to underlying geology and the efficiency of water flow. A few of the more common drainage patterns and their controlling factors are listed below:



Streamflow is quantified by ‘discharge’ which measures the volume of water passing a point in the stream over a period of time, usually cubic metres/second. Discharge is measured by multiplying the area of the stream by the velocity of the water passing through that area.



Discharge in an individual stream can be highly variable over different timescales, from year to year, season to season, and day to night. Changes in discharge may be related to different parts of the hydrologic cycle, such as storm events within the drainage basin, snow or glacier melt, inflow from groundwater, or other factors. Often discharge is represented using a discharge hydrograph that shows discharge on the y-axis of a graph, with time on the x-axis:

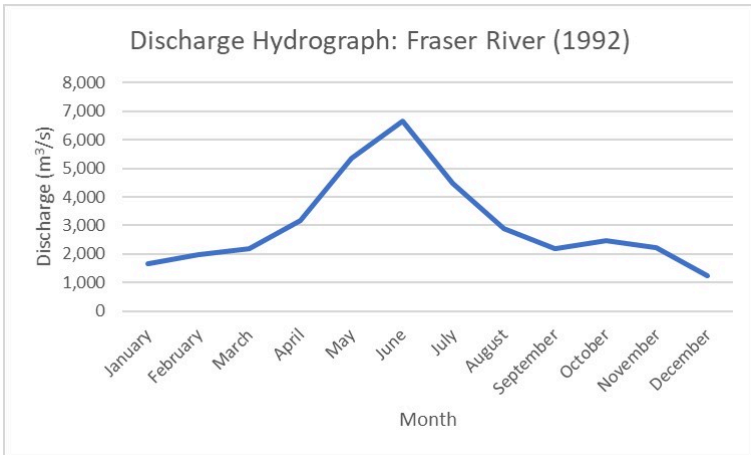


Figure: Fraser River discharge for the year of 1992. Note the increase in discharge for late spring/early summer months, corresponding to increased snowmelt in the drainage basin for the Fraser River.

Understanding discharge is significant because:

1. Changes in discharge lead to significant changes in erosion and deposition patterns in the hydrologic system.
2. Higher discharge allows a stream to transport a larger load of sediment.
3. Discharge patterns can be used to monitor for potential flooding and periods of low water availability.
4. Monitoring long term discharge allows better management of stream resources when humans remove water from a system for irrigation or other purposes.
5. Understanding the range of potential discharge in a stream is important when engineering critical structures like bridges.

Changing climate has the potential to disrupt current patterns of hydrology around the globe. Environmental research has demonstrated that climate has a significant impact on things as

simple as the angle at which tributaries flow into a river (e.g., drainage pattern)

See this article for more info: <https://eos.org/research-spotlights/stream-network-geometry-correlates-with-climate>

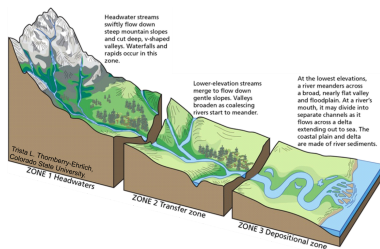
More complex relationships occur where hydrologic resources are shared across political borders in areas where water resources may be scarce. Future changes in climate and hydrologic discharge could increase stress on available water resources.

Chapter 18

Topic 18 – Fluvial Geomorphology



Rivers are a critical part of the water cycle, and one of the most visible components of the hydrosphere. They support diverse ecological habitats. The shape and patterns present in a river system are based on the dynamics of water flow through the system (for example: discharge) and the environment the water is flowing through (river bed material, topographic slope of the river bed). These factors combine to produce the *geomorphology* of the river system (fluvial geomorphology). Generally the fluvial system can be split into three separate zones, based on topographic differences:



1. Headwaters
2. Transfer zone

3. Depositional zone

These zones are related to conditions external to the fluvial system itself, specifically topographic slope.

There are three critical components to the fluvial geomorphology system:

1. Erosion (most active in the headwater zone)
2. Transportation (dominant in the transfer zone)
3. Deposition (most active in the depositional zone)

The idea of *erosion* in the fluvial system is based on removing material from the surrounding environment and making it a part of the *stream load* (what the stream is carrying). Once material is removed and caught up in the stream load, it is being *transported*. At some point downflow, the fluvial system stops transporting the material, and *deposits* it at the stream bed. It stays in this position until the erosion process begins again. Material eroded, transported, and deposited in the fluvial system is referred to as *alluvium*.

There are several styles of erosion that commonly occur in the fluvial system:

Environment	Erosion Type	Erosive Power	Process
Overland flow	Splash erosion	Low	Individual raindrops impact the surface, dislodging particles at the surface.
Overland flow	Sheet erosion	Low	Shallow sheets of water running over the surface abrade the surface material.
Stream flow	Hydraulic action	Moderate to high	The motion of water directly over the stream bed rubs material away directly from the stream bed.
Stream flow	Bank undercutting	Moderate to high	Water flowing at the base of river banks removes materials, destabilizing the above slopes, leading to collapse.
Stream flow	Abrasion	Moderate to high	Stream load (like sand and silt particles carried by the stream itself) rub against the stream bed, scraping the material away.
Stream flow	Corrosion	Moderate to high	Material in the stream bed that is soluble (can be dissolved) in water is dissolved into the water itself and carried away.

Once eroded, material becomes part of the stream load, and is transported. Transport can happen in several modes, dependent on the size of the sediment and the velocity of the stream (a higher velocity stream can transport larger sediment). The two principles governing these limits on transport are referred to as *competence* and *capacity*.

Competence: the largest material size a stream can transport in a given stream segment. This value is largely based on velocity of the stream.

Capacity: the overall volume of material a stream can transport in a given stream segment. This value is based on both the velocity and volume of water in the stream.

Three types of stream transport:

1. Dissolved load: Materials that are soluble in water and have been dissolved into the stream water itself. Usually this material is not deposited until the water in which it dissolves is evaporated.
2. Suspended load: Materials light enough to be carried high in the water column itself. Usually this is limited to the lightest clay and silt-sized particles. This material is deposited when water velocity slows to the point where competence is no longer sufficient to carry the load.
3. Bed load: Materials too heavy to be carried high in the water column, but that have been dislodged at the stream bed. These are bounced, dragged and rolled at the stream bed by traction from the overlying stream flow.

Differences in stream velocity lead to deposition of stream load at various points in the fluvial system. This is based on where the *thalweg*, or zone of fastest flow, is in the stream. In a perfectly



straight stream channel, the thalweg would be at the centre of flow. In a sinuous or curved channel, the thalweg bounces back and forth across the channel, leaving zones of lower velocity on alternating sides of the channel. This alternating pattern creates a situation

where bends in the river alternately promote the *aggradation* (accumulation) of sediment, and *degradation* (erosion) of sediment. The result is an alternating pattern of point bars, the result of sediment aggradation, on the inside bend, where stream velocity is lowest, and cut banks, the result of degradation, on the outside bend where stream velocity is highest. Over time, these complementary

patterns shift the entire course of the stream from one location to another.

This leads to streams with different planforms (what a stream looks like from above). As shown on the figure at the beginning of this chapter, in the steep, upper reaches of a stream, more energy is devoted to downcutting, creating deeply incised valleys, and relatively straight channels. In the lower reaches of the stream, lower gradient results in more energy applied to eroding the edges of the stream, resulting in a more meandering, broader channel.

Ultimately some stream load makes it all the way to base level, the lowest elevation of the river flow. Here it is deposited in a fan or delta, that builds outwards.



Figure: Delta forming at the outlet of the Red River as it reaches Cook Inlet in Alaska (NPS: Public Domain)

Figure: Delta forming at the outlet of the Red River as it reaches Cook Inlet in Alaska (NPS: Public Domain)

In this way a stream can lengthen itself, by building its fan or delta outwards at the terminus. It can also stretch itself backwards through erosion at its headwaters where water initially transitions from overland flow to channelized flow.

Rivers represent some of the most dynamic drivers of landscape change around the world. They have the ability to do significant geomorphic work and transform landscapes over very long to very short periods of time.

This is where you can add appendices or other back matter.

Glossary

body waves

A seismic wave that travels through the interior of the earth and is not related to a boundary surface. (bgs)

a seismic wave that travels through rock (e.g., a P-wave or an S-wave (opentext physgeo)

condensation nuclei

Microscopic particle of dust, smoke or salt that allows for condensation of water vapor to water droplets in the atmosphere (PhysGeo)

Hygroscopic aerosol particles that can serve as nuclei of atmospheric cloud droplets, that is, particles on which water condenses (activates) at supersaturations typical of atmospheric cloud formation (AMS)

Fog

Fog exists if the atmospheric visibility near the Earth's surface is reduced to 1 kilometer or less. Fog can be composed of water droplets, ice crystals or smoke particles (PhysGeo)

Water droplets suspended in the atmosphere in the vicinity the earth's surface that affect visibility (AMS)

ground-level condensation caused if the dew point is reached in this part of the atmosphere by advection, evaporation, radiation or at a warm front or over ice (ItsEdu)

folding

A bend or flexure in a rock unit or series of rock units that has been caused by crustal movements (geology.com)

when one or stacks of originally flat and planar surfaces such as sedimentary

beds become bent or curved as a result of plastic (i.e. permanent) and ductile deformation (files.ethz.ch/structuralgeology)

magma

molten rock below the surface, either held within the crust or in the mantle. (itsEducation)

Molten rock originating from the Earth's interior (PhysGeo.net)

P-Waves

a seismic body wave that is characterized by deformation of the rock in the same direction that the wave is propagating (compressional vibration) ([opentext physg](http://opentext.physg))

The first and faster of the body waves which moves by a series of compressions and dilatations, similar to a sound wave. They can travel through both solid and liquid. (bgs)

The fastest set of earthquake vibrations - also known as P-waves. They move through the Earth in compression and expansion motions (much like sound waves move through air). Called primary because they are the first recorded at a seismograph. Primary waves are able to travel through both solids and liquids. (geology.com)

rain-shadow effect

Reduction of precipitation commonly found on the leeward side of a mountain (PhysGeo)

the area on the leeward side of a mountain range which experiences drier conditions than the windward side. This is due to the air being drier as it has experienced condensation and precipitation on the windward side, plus the fact that the air will be sinking and therefore warming meaning relative humidity is falling and condensation cannot occur (ItsEdu)

A region of sharply reduced precipitation on the lee side of an

orographic barrier, as compared with regions upwind of the barrier (AMS)

S-Waves

a seismic body wave that is characterized by deformation of the rock transverse to the direction that the wave is propagating (opentext physg)

The second arrival on a seismogram, the S wave, is slower than the P-wave. It is a shear wave and cannot travel through liquids. (bgs)

saturation vapour pressure

The vapor pressure of a system, at a given temperature, for which the vapor of a substance is in equilibrium with a plane surface of that substance's pure liquid or solid phase (AMS)

The vapor pressure at which the gaseous phase of a substance can coexist with the liquid or solid phase in equilibrium at a given temperature (Wiki)

shear zone

may be more precisely defined as approximately tabular regions of concentrated deformation and flow across which adjacent relatively undeformed rock units are offset (Shear zones – an introduction and overview)

also sometimes called ductile faults, are intensely strained zones that separate less severely deformed units (UA Online course lecture)

surface waves

Seismic waves with motion restricted to near the ground surface (Love and Rayleigh) (bgs)

A type of seismic wave that travels along Earth's surface. These are the waves that cause the most damage during an earthquake. (geology.com)

Synclines

a convex-downward fold is a synform. Synclines have younger strata at the core (ethz)

a downward fold where the beds are known not to be overturned (physgeology open text)

A downward fold of sedimentary rock put under pressure by Earth movements (bgs)

terrane accretion

a block of crust that has geological features that are distinctive from neighbouring regions, and is assumed to have been moved from elsewhere by tectonic processes (opentext physg)

is technically a tectonostratigraphic terrane, a piece of the earth's crust or lithosphere that has been accreted to the edge of one tectonic plate from another tectonic plate. (commons.wvc.edu)

Accreted terranes are the blocks of continental fragments and oceanic islands that have collided with a continent and are now permanently attached (national park service)

viscosity

the resistance of a fluid to flow (geology.com)

how resistant a substance is to a change in form (itseducation)

is the quantity that describes a fluid's resistance to flow (physics handbook)

adiabatic

A process in which heat does not enter or leave a system. adiabatic processes are often used to model internal energy changes in rising and descending parcels of air in the atmosphere (PhysGeo.net)

change in temperature due to expansion or contraction of a

parcel of air which thus change the pressure and therefore the temperature (ItsEducation)

advection

The process of transport of an atmospheric property solely by the mass motion (velocity field) of the atmosphere (AMS)
horizontal transfer of heat by a horizontally moving air mass (ItsEdu)

age dating

All absolute isotopic ages are based on radioactive decay, a process whereby a specific atom or isotope is converted into another specific atom or isotope at a constant and known rate. (Britannica)

Radiometric dating calculates an age in years for geologic materials by measuring the presence of a short-life radioactive element, e.g., carbon-14, or a long-life radioactive element plus its decay product, e.g., potassium-14/argon-40. The term applies to all methods of age determination based on nuclear decay of naturally occurring radioactive isotopes (nps.gov)

air mass

large body of air with shared temperature and humidity characteristics associated with its area of origin e.g. maritime or continental; tropical or polar (ItsEducation)

A body of air whose temperature and humidity characteristics remain relatively constant over a horizontal distance of hundreds to thousands of kilometers (PhysGeo.net)

albedo

is a measure of how much light that hits a surface is reflected without being absorbed (NC Climate Office)

angle of incidence

the angle at which the Sun's rays strike the Earth's surface (PhysGeography.net)

In reference to solar energy systems: the angle a ray of sun makes with a line perpendicular to a surface (OpenEI)

anti-cyclone

Areas of sinking air which result in high pressure (UK Environmental)

a region of high atmospheric pressure relative to the surrounding air (Weatheronline)

An atmospheric pressure system consisting of an area of high pressure and outward circular surface wind flow (PhysGeo.net)

anti-Trade Winds

the dominant west-to-east motion of the atmosphere, centered over the middle latitudes of both hemispheres (AMS)

Dominant winds of the mid-latitudes. These winds move from the subtropical highs to the subpolar lows from west to east (PhysGeo.net)

Anticlines

A convex-upward fold is an antiform. Anticlines have older strata in the core. (ethz)

an upward fold where the beds are known not to be overturned (opentext physgeo)

Upwardly arched folds of Sedimentary rocks put under pressure by movement in the Earth

Asthenosphere

Zone in the Earth's mantle that exhibits plastic properties. Located below the lithosphere (PhysGeo.net)

climate normals

Climate Normals are three-decade averages of climatological variables including temperature and precipitation (NOAA)

Climate Normals and Averages are used to summarize or describe the average climatic conditions of a particular location (Gov't of Canada)

the arithmetic average of a climate element such as temperature over a prescribed 30-year interval (Wisconsin State Climatology Office)

convection

involves the transfer of heat energy by means of vertical mass motions through a medium (PhysGeo)

transfer of heat in a gas or liquid by upward movement of the hotter, less dense portion. (ItsEducation)

convection currents

Heat generated by the breakdown of radioactive minerals in the mantle is redistributed by currents that rise at the mid ocean ridges and descend at the ocean trenches. Convection currents were long thought to be responsible for driving plate motion but this is still the subject of intense debate. (Geo Society)

occur within the molten rock in the mantle, act like a conveyor belt for the plates. Tectonic plates move in different directions. The direction of movement and type of plate margin is determined by which way the convection currents are flowing. (ALevelGeo)

Critical Zone

where rock, soil, water, air and living organisms interact and shape the Earth's surface

density

The density of air or atmospheric density, denoted ρ , is the mass per unit volume of Earth's atmosphere (Wiki)

Density is defined as the ratio between mass and volume or mass per unit volume (Study.com)

denudation

The erosion or wearing down of a landmass. (2) Removal of the vegetative cover from an area (PhysGeo)

involves the processes that cause the wearing away of the Earth's surface by moving water, by ice, by wind and by waves, leading to a reduction in elevation and in relief of landforms and of landscapes (Wiki)

is an erosive process of breaking and removing the rocks from the surface of the earth (Chegg)

dew point

the temperature at which water vapor saturates from an air mass into liquid or solid usually forming rain, snow, frost or dew (PhysGeo)

temperature at which air becomes saturated i.e. relative humidity is 100% (ItsEdu)

Dry adiabatic lapse rate

the rate of fall in air temperature by adiabatic change as unsaturated air gains altitude. Approximately 1 degree C per 100m. (ItsEdu)

process lapse rate of temperature, the rate of decrease of temperature with height of a parcel of dry air lifted by a reversible adiabatic process through an atmosphere in hydrostatic equilibrium (AMS)

endogenous forces

produced or synthesized within system (Webster)

forces having an internal cause or origin (Google)

Processes that are caused by forces from within the Earth (Kiddle)

Environmental lapse rate

The rate of decrease of temperature with elevation, $-\partial T/\partial z$, or occasionally $\partial T/\partial p$, where p is pressure (AMS)

change in temperature with altitude above a particular point at a particular time. Average is 6.5 degrees C per 1000m. (ItsEdu)

The rate of air temperature increase or decrease with altitude.

The average ELR in the troposphere is an air temperature decrease of 6.5° Celsius per 1000 meters rise in elevation (PhysGeo)

exogenous forces

(extra-terrestrial) forces are as a result of other bodies in space(Kiddle)

come from forces on or above the Earth's surface (Wiki)

external processes ultimately driven by the sun's energy (CState University)

extrusive

Igneous rocks that are erupted from a volcano and crystallize at Earth's surface (geology.com)

igneous rock that cooled at surface (opentext physgeo)

faulting

A fracture in the rock along which movement takes place. A weak area in the Earth's crust where two sides of a fracture or fracture zone move relative to each other. (bgs)

A fracture or fracture zone in rock along which movement has

occurred. When movement occurs the vibrations that are produced are known as an earthquake (geology.com)

fluid

Substance that flows and is not solid; smooth and continuous (Merriam)

folded

fold is used in geology when one or a stack of originally flat, level surfaces, such as sedimentary strata, are bent or curved as a result of pressure and high temperature (Wiki)

A wave-like geologic structure that forms when rocks deform by bending instead of breaking under compressional stress. (Geologypage)

friction

Resistance between the contact surfaces of two bodies in motion (Physgeo.net)

frictional force

Force acting on wind near the Earth's surface due to frictional roughness. Causes the deceleration of wind (PhysGeo.net)

Friction slows the wind down at the surface or in areas with winds of different speeds (wind shear). When the wind is blowing near the surface, the ground creates friction that makes the wind blow slower (NCSU climate)

front

the boundary where two air masses meet. (ItsEdu)

the interface or transition zone between two air masses of different density (AMS)

Transition zone between air masses with different weather characteristics (PhysGeo)

geographic coordinate

A geographic coordinate system is a three-dimensional reference system that locates points on the Earth's surface. The unit of measure is usually decimal degrees. A point has two coordinate values: latitude and longitude. Latitude and longitude measure angles.

geomorphology

The field that investigates the origin of landforms on the Earth and other planets (PhysGeo)
is the study of the nature and history of landforms and the processes which create them (DartmouthU)
is the study of landforms and landscapes and the processes that act to modify the Earth's surface (SFU 213)

geostrophic winds

Horizontal wind in the upper atmosphere that moves parallel to isobars (PhysGeo.net)
wind blowing parallel to isobars because of deflection of the pressure-gradient force by the Coriolis Force

Hadley Cell

A direct thermally driven and zonally symmetric circulation under the strong influence of the earth's rotation (AMS)
portion of the tricellular model of air circulation where air rises at the equator due to convection, spreads in the upper troposphere and then sinks over the tropics before returning to the equator. (ItsEdu)

heat

Heat is defined as energy in the process of being transferred from one object to another because of the temperature difference between them. In the atmosphere, heat is commonly

transferred by conduction, convection, advection, and radiation (PhysGeography.net)

hotspot

are places within the mantle where rocks melt to generate magma (oregonstate online)

A hot spot is an area on Earth that exists over a mantle plume. A mantle plume is an area under the rocky outer layer of Earth, called the crust, where magma is hotter than surrounding magma (NatGeo)

humidity

Generally, some measure of the water vapor content of air (AMS)

A general term used to describe the amount of water vapor found in the atmosphere (PhysGeo.net)

Igneous

a rock formed through the cooling of magma or lava (itseducation)

A rock that originated when a molten magma or lava cooled and solidified (bgs)

A rock formed by the crystallization or solidification of molten rock material (geology.com)

intrusive

Igneous rocks that crystallize below Earth's surface. They typically have mineral crystals that are large enough to easily see with the unaided eye (geology.com)

an igneous rock that has cooled slowly beneath the surface (opentextbc physgeo)

ITCZ

Zone of low atmospheric pressure and ascending air located at or near the equator. Rising air currents are due to global wind convergence and convection from thermal heating (PhysGeo.net)

The axis, or a portion thereof, of the broad trade-wind current of the Tropics (AMS)

lapse rates

the rates at which air temperature decreases with altitude (Itseducationglossary)

large-scale

Large scale maps show a smaller amount of area with a greater amount of detail. The geographic extent shown on a large scale map is small. A large scaled map expressed as a representative scale would have a smaller number to the right of the ratio. For example, a large scale map could have a RF scale of 1 : 1,000. Large scale maps are typically used to show neighborhoods, a localize area, small towns, etc. (GISLounge)

latitude

The angular distance, usually measured in degrees north or south of the equator. Lines of latitude are also referred to as parallels. (ESRI)

Geographic coordinate that specifies the north-south position of a point on the Earth's surface. Latitude is an angle (defined below) which ranges from 0° at the Equator to 90° (North or South) at the poles. (Wiki)

latitude of the subsolar point

At any moment there is one spot on the Earth where the sun is directly overhead. This spot, called the subsolar point, moves

around the Earth in one solar day, 24 hours, thus the subsolar point moves 15 degrees of longitude for each hour of the day. Where this subsolar point is located defines our seasons. (NY University online)

lava

molten rock flowing on the surface (itseducation)

Molten magma that extrudes onto the Earth's surface as a result of a volcanic eruption (bgs)

Molten rock that has erupted onto Earth's surface (geology.com)

lifting condensation level

The level at which a parcel of moist air lifted dry-adiabatically would become saturated (AMS)

lithosphere

Is the solid inorganic portion of the Earth (composed of rocks, minerals, and elements) (PhysGeo.net)

the crust and upper mantle. Either solid or highly viscous, this layer is not easily deformed or manipulated (itseducation)

longitude

is the distance on the earth's surface, east or west of a defined meridian, usually the meridian of Greenwich, England (0° Longitude), expressed in angular measurements from 180° West (or -180°) to 180° East. (Caliper)

The angular distance, usually expressed in degrees, minutes, and seconds, of the location of a point on the earth's surface east or west of an arbitrarily defined meridian (usually the Greenwich prime meridian). All lines of longitude are great circles that intersect the equator and pass through the North and South Poles. (ESRI)

Magnetic surveys

one of the tools used by exploration geophysicists in their search for mineral-bearing ore bodies or even oil-bearing sedimentary structures and by archaeologists to locate and map the remains of buried structures (Britannica)

are a geophysical method to image anomalies in the earth's magnetic field caused by source bodies within the sub-surface (SEGwiki)

mineral

naturally occurring inorganic solids with a definite chemical composition, and an ordered internal structure (Geology.com)

**ordered \diamond regular repeating structure

A naturally occurring inorganic solid with a crystalline structure and a specific chemical composition (PhysGeo.net)

Mohorovicic discontinuity

The lower boundary of the crust. At this boundary seismic wave velocities show an increase in speed as they enter the upper mantle (PhysGeo.net)

is the boundary between the crust and the mantle (Geology.com)

Moist adiabatic lapse rate

The rate of decline in the temperature of a rising parcel of air after it has reached saturation. This rate is less than the dry adiabatic lapse rate (9.8° Celsius per 1000 meters) because of the heat energy added to the ascending air parcel from condensation and deposition processes (PhysGeo)

The rate of decrease of temperature with height along a moist adiabat (AMS)

Molten

object that's reduced to liquid form by heating
rock that has been transformed into liquid form by being heated

Monoclines

only one tilted, step-like limb in an otherwise subhorizontal or gently dipping sequence (ethz)
a step-like fold in rock strata consisting of a zone of steeper dip within an otherwise horizontal or gently-dipping sequence (wiki)

Monsoon

A name for seasonal winds (AMS)
A regional scale wind system that predictably change direction with the passing of the seasons (PhysGeo.net)
a seasonal prevailing wind (ItsEdu)

northern hemisphere

half a sphere. In geography, the division of the earth either into north and south by the equator, or into east and west by any one line of longitude (ItsEducation)

obduction

the sideways and upwards movement of the edge of a crustal plate over the margin of an adjacent plate. (google)
The process whereby ocean crust (and even upper mantle) are scraped off the descending ocean plate at a convergent plate boundary and thrust onto the adjoining plate. Often associated with an accretionary wedge (prism). (Geological Society)

Physical Geography

studies the spatial patterns of weather and climate, soils, vegetation, animals, water in all its forms, and landforms while

also examining the interrelationships of these phenomena with human activities.

plastic

ability of certain solids to flow or to change shape permanently when subjected to stresses of intermediate magnitude between those producing temporary deformation (Britannica)

Polar Cell

A weak meridional circulation in the high-latitude troposphere characterized by ascending motion in the subpolar latitudes (50°–70°), descending motion over the pole, poleward motion aloft, and equatorward motion near the surface (AMS)

Three-dimensional atmospheric circulation cell located at roughly 60 to 90° North and South of the equator (PhysGeo)

precipitation

Is any aqueous deposit, in liquid or solid form, that develops in a saturated atmosphere (relative humidity equals 100%) and falls to the ground generally from clouds (PhysGeo)

- movement of water from the atmosphere to the earth's surface (ItsEdu)

All liquid or solid phase aqueous particles that originate in the atmosphere and fall to the earth's surface (AMS)

pressure

It is the force exerted on a surface by the air above it as gravity pulls it to Earth (NatGeo)

The definition of air pressure is the force exerted onto a surface by the weight of the air (YourDictionary)

Is defined as the force acting on a surface from another mass per unit area (PhysGeography.net)

pressure gradient

rate of change of pressure over a certain distance (usually is denoted in mb/km) (IowaState University)

The change in pressure measured across a given distance (UIUC online ed)

relative humidity

The ratio of the vapor pressure to the saturation vapor pressure with respect to water (AMS)

Rigid

stiff and inflexible; not pliant or flexible; firmly set. (Vocabulary.com)

silica

most common mineral component of rock (itseducation)

a hard, unreactive, colorless compound which occurs as the mineral quartz and as a principal constituent of sandstone and other rocks (google definitions)

is the name given to a group of minerals composed of silicon and oxygen, the two most abundant elements in the earth's crust (EUROSIL)

slab pull

As oceanic lithosphere cools, it becomes denser and thicker. At a convergent plate boundary the oceanic lithosphere sinks beneath the adjacent plate forming an ocean trench and subduction zone. As a result of its own weight, the descending plate is pulled by gravity through the mantle asthenosphere, which is hotter and less rigid. This force is known as slab pull. It is believed to be the major force driving plate motions. (Geo Society)

older, colder plates sink at subduction zones, because as they

cool, they become more dense than the underlying mantle. The cooler sinking plate pulls the rest of the warmer plate along behind it. (bgs.uk)

small-scale

Small scale maps show a larger geographic area with few details on them. The RF scale of a small scale map would have a much larger number to the right of the colon such as 1 : 1,000,000. Small scale maps are used to show the extent of an entire country, region, or continent. (GISLounge)

southern hemisphere

half a sphere. In geography, the division of the earth either into north and south by the equator, or into east and west by any one line of longitude (ItsEducation)

subducts

Subduction occurs when an oceanic plate runs into a continental plate and slides beneath it. (usgs.gov)
the sideways and downward movement of the edge of a plate of the earth's crust into the mantle beneath another plate. (google)

tectonic plates

Theory suggesting that the Earth's surface is composed of a number of oceanic and continental plates. Driven by convection currents in the mantle, these plates have the ability to slowly move across the Earth's plastic asthenosphere. (PhysGeo.net)

temperature

is a measure of the intensity or degree of hotness in a body. Technically, it is determined by getting the average speed of a body's molecules (PhysGeography.net)
Temperature is the degree of hotness or coldness of the

atmosphere on some chosen scale. It is commonly measured in Celsius or Fahrenheit (Wikibooks)

Thermal Equator

The line that circumscribes the earth and connects all points of highest mean annual temperature for their longitudes (AMS)
Continuous area on the globe that has the highest surface temperatures because of the presence of the Intertropical Convergence Zone (PhysGeo.net)

Trade Winds

Surface winds that generally dominate air flow in the tropics. These winds blow from about 30° North and South latitude to the equator (PhysGeo.net)

The wind system, occupying most of the Tropics, that blows from the subtropical highs toward the equatorial trough; a major component of the general circulation of the atmosphere (AMS)

transform boundary

one in which two plates slide past one another and crust is neither created nor destroyed, but is conserved (Geo Society)
are places where plates slide sideways past each other. At transform boundaries lithosphere is neither created nor destroyed (Cornell Online)

tropics

Latitude of 23.5° North. Northern limit of the Sun's declination
Latitude of 23.5° South. Southern limit of the Sun's declination (PhysGeo.net)

vapour pressure

Pressure exerted by water vapor molecules in a given quantity

of atmosphere (PhysGeo.net)

The pressure exerted by the molecules of a given vapour (AMS)

water vapour

the gaseous phase of water (Wiki)

water in its gaseous state-instead of liquid or solid (ice)
(weatherstreet)

weathering

Physical, chemical or biological breakdown of rocks and minerals into smaller sized particles.

breakdown of rock in situ by physical and chemical processes due to the presence of water, plants and animals (Itseducation)
is the breakdown of rocks at the Earth's surface, by the action of rainwater, extremes of temperature, and biological activity (Geological Society)