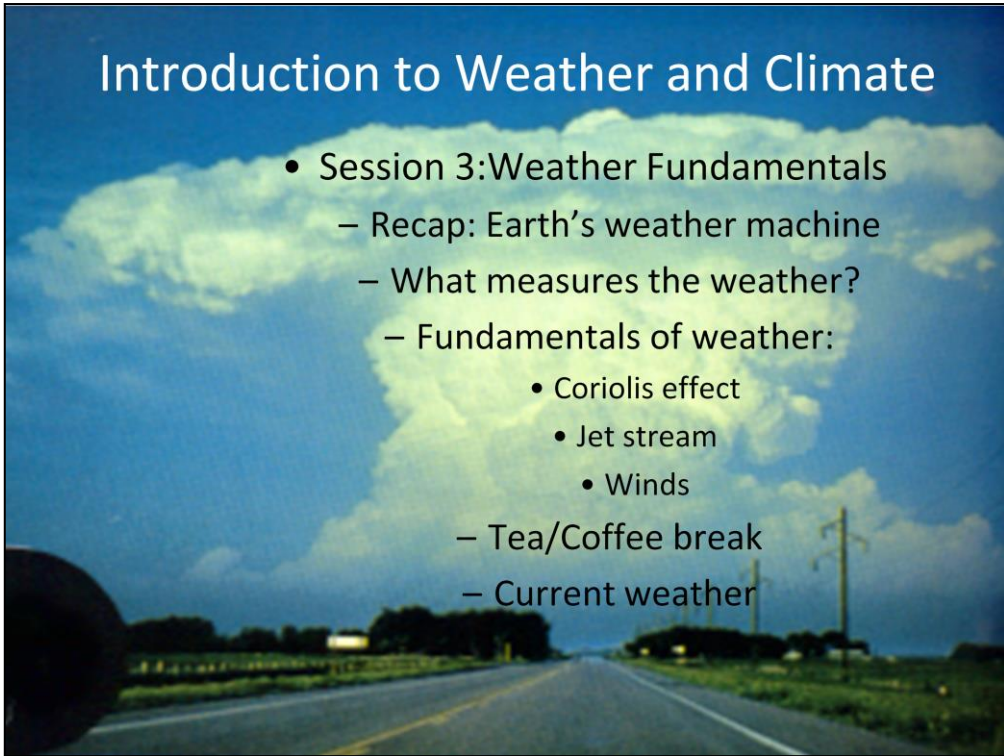


# Introduction to Weather and Climate

- Session 3: Weather Fundamentals
  - Recap: Earth's weather machine
  - What measures the weather?
  - Fundamentals of weather:
    - Coriolis effect
    - Jet stream
    - Winds
  - Tea/Coffee break
  - Current weather



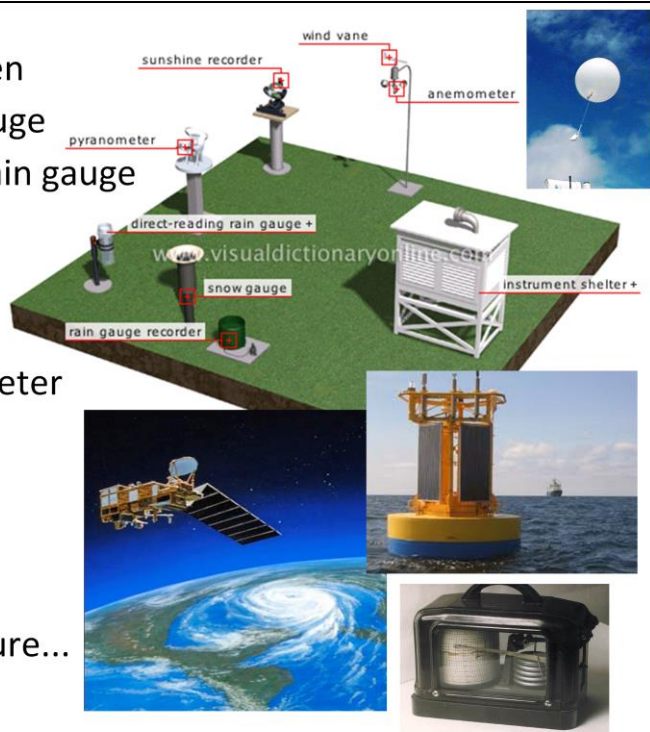
## What measures weather?



- What measures weather?
- What instruments do we use to measure the weather?

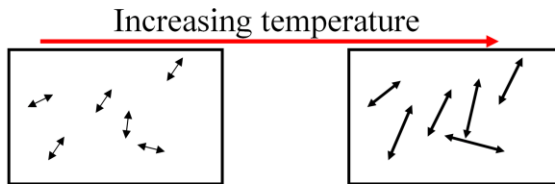
Weather encapsulates the state of the atmosphere, primarily involving the component which affects societies. This can include things which affect us directly (e.g. rainfall, temperature) or which affect the evolution of our weather (e.g. pressure, water vapour). In building up a picture of weather patterns a vast array of measurement techniques are employed. It turns out that an accurate depiction of the atmosphere is required, along with physically realistic simulations, are required to make useful weather predictions.

- Stevensons Screen
- Standard rain gauge
- Tipping Bucket rain gauge
- Anemometer
- Barometer
- Radiometer
- Whirling Hygrometer
- Infra-red sensor
- Eyes...
- Pan evaporation
- Radiosonde
- Ocean temperature...
- Satellite data...

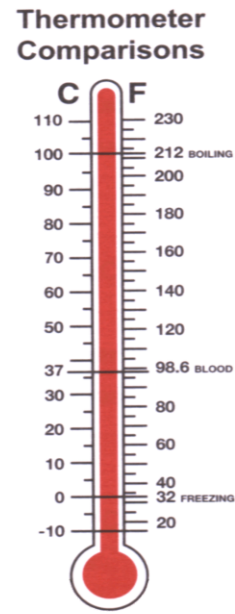


# Temperature

- Temperature measures how much the atoms and molecules are jiggling about. At “absolute zero” they are still and at higher temperatures their movement becomes more excited



- It is not only the temperature of the air that makes us feel warm/cold...

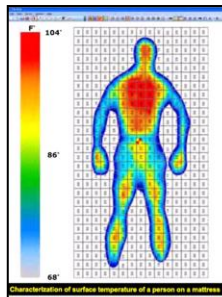


Temperature (T) – degrees Celsius (°C) arbitrary scale from 0°C at melting point of ice to 100°C at boiling point of pure water

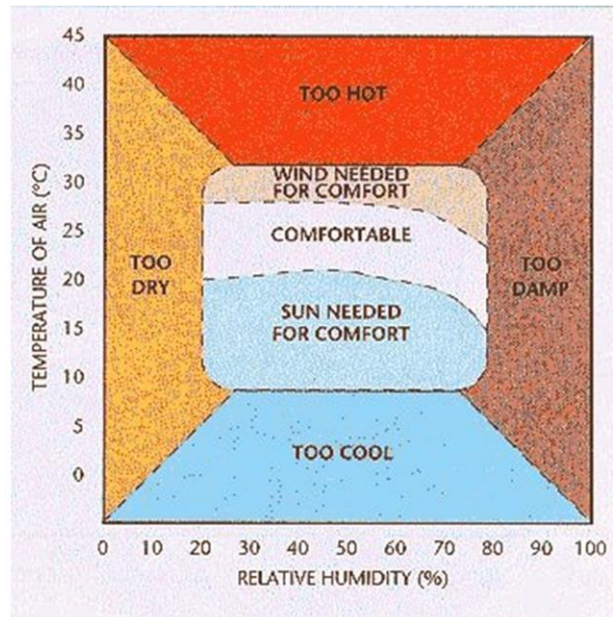
Also (Kelvin, K) = °C plus 273.15 (a change in 1 K is the same as a change in 1 °C)

0 K is absolute zero, the minimum possible temperature

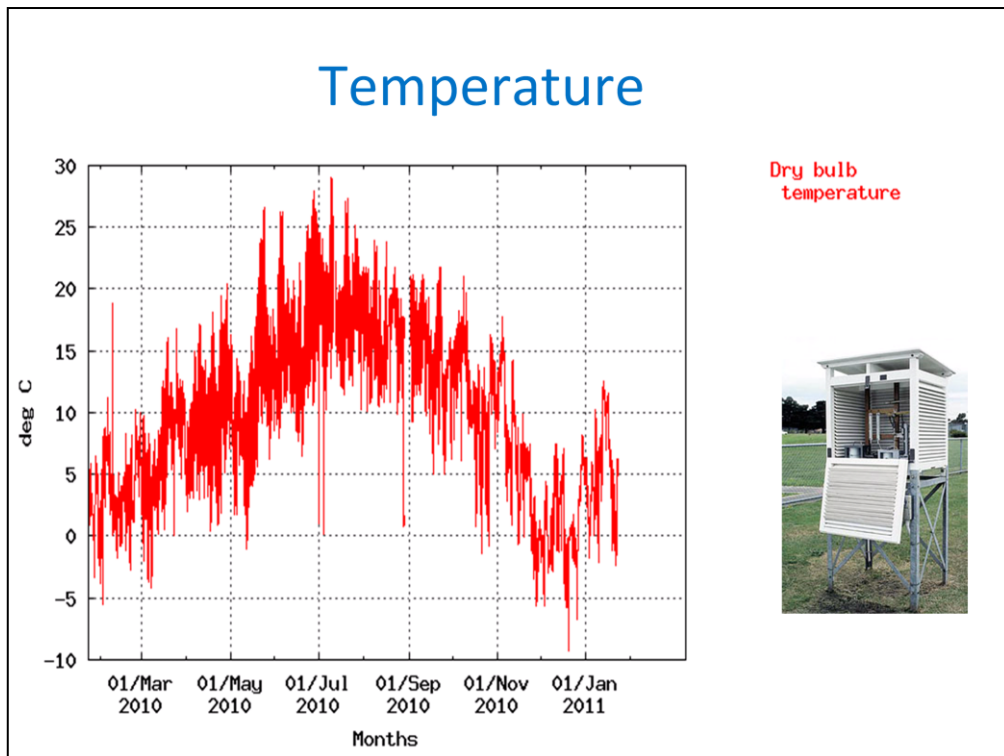
Americans and Telegraph readers tend to use °F



## Human comfort diagram



The human body has an energy balance just like the Earth (solar radiative heating, thermal radiative heating/cooling, evaporative cooling (sweat) and sensible heat loss (conduction)) although this is complicated by drinking tea. Wind makes us cool because it increases the flow of energy from the body through evaporation (sweat) and sensible heat. 15°C may feel cool on a cloudy or breezy day but warm on a sunny day (air temperature is measured in the well ventilated shade of, for example, a Stevenson's screen).

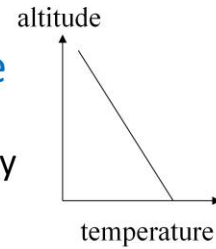


The maximum and minimum temperature are routinely measured daily at meteorological stations and are used in reconstructing past changes in local temperature. The diurnal temperature range is larger on still, clear days, when solar heating is strong at the surface and is not offset by evaporative cooling during the day, while radiative thermal cooling is efficient at night without the presence of cloud which returns some of the emitted thermal radiation back to the surface. Temperature can also be measured from satellite by choosing frequency of thermal radiation that is sensitive to surface or atmospheric temperature. Atmospheric temperature is also measured by radiosonde balloons. Temperature is also taken of the ocean surface and increasingly the ocean subsurface using automated submersible floats.





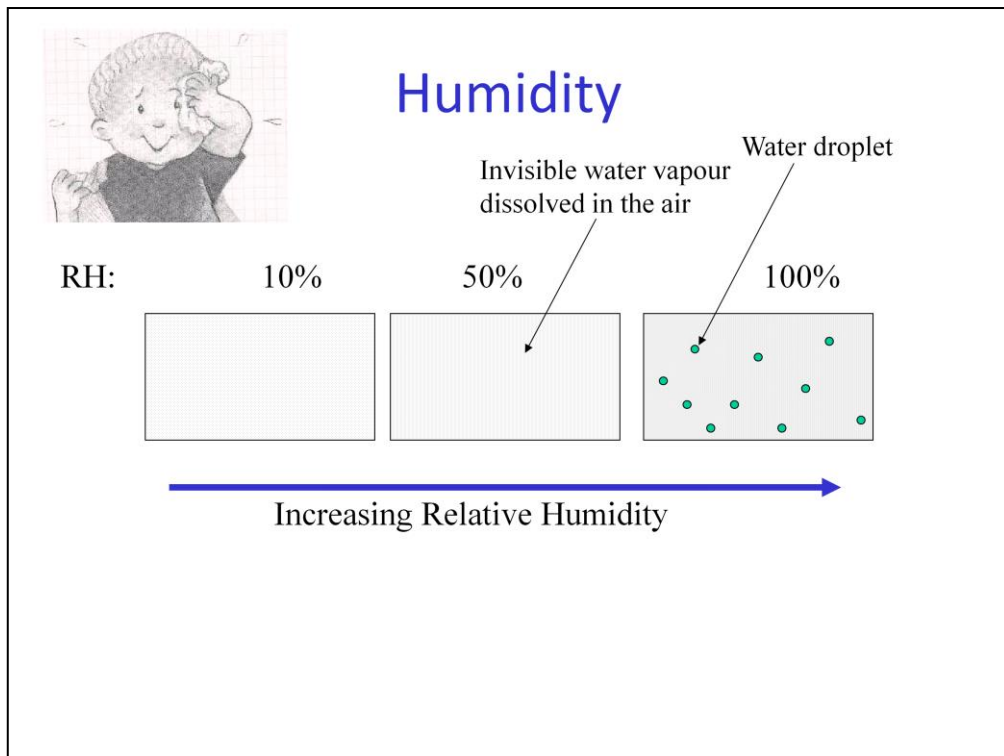
## Temperature lapse rate



- In the troposphere, temperature generally falls with altitude, the rate of which is defined as *temperature lapse rate*
- A typical lapse rate is  $\sim 0.5$  to  $1^\circ\text{C}$  per 100m
- Above the troposphere is the *stratosphere* ( $\sim 15$ -50 km) where temperatures increase with altitude
  - This is due to absorption of solar radiation by ozone
  - results in a stable layer which impedes any further rising motion from below
  - It acts as a lid for the weather below.



The temperature lapse rate is the decline in temperature as you climb in altitude. This lapse rate would be much stronger without the global water cycle. Evaporation at the surface cools the land/ocean while condensation in the atmosphere as clouds heats the atmosphere. There is therefore a transfer of “latent energy” from the surface to the atmosphere. As the lapse rate increases, the warm, buoyant lower levels become unstable and will be more likely to rise upward, leading to cloud formation, heating of the profile through latent heat and reducing the lapse rate. These radiative and latent energy flows in the atmosphere help to explain the typical temperature lapse rate of around  $6^\circ\text{C}$  per km and is termed a radiative convective balance.



Relative Humidity – a measure of the amount of invisible (or gaseous) water (vapour) dissolved in the air as a fraction (or percentage) of the maximum theoretical amount.

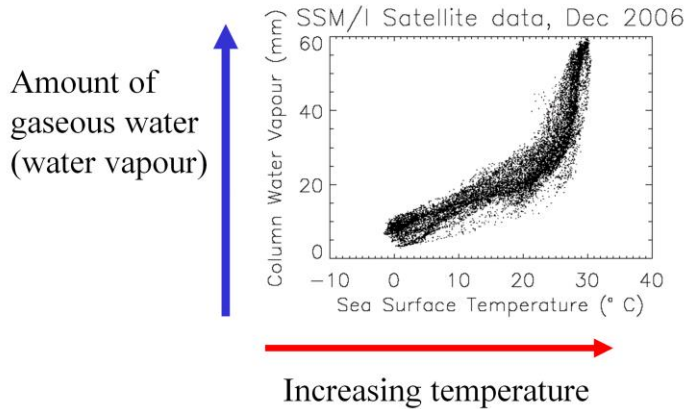
At 100% humidity, any increase in the water vapour is likely to cause condensation of liquid water drops (providing there are condensation nuclei available)

That's why it is difficult to lose heat by sweating at high humidity because it is more difficult to evaporate more water from your body (thus cooling your skin) since the air is almost saturated



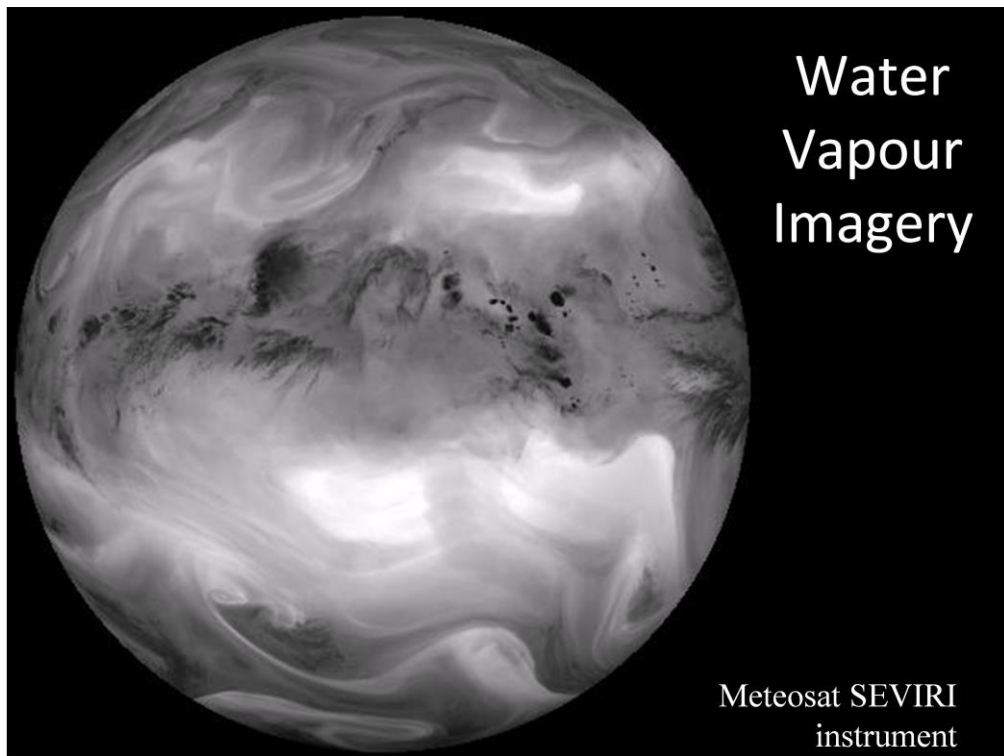
## Water vapour

- Warmer air can carry more water vapour

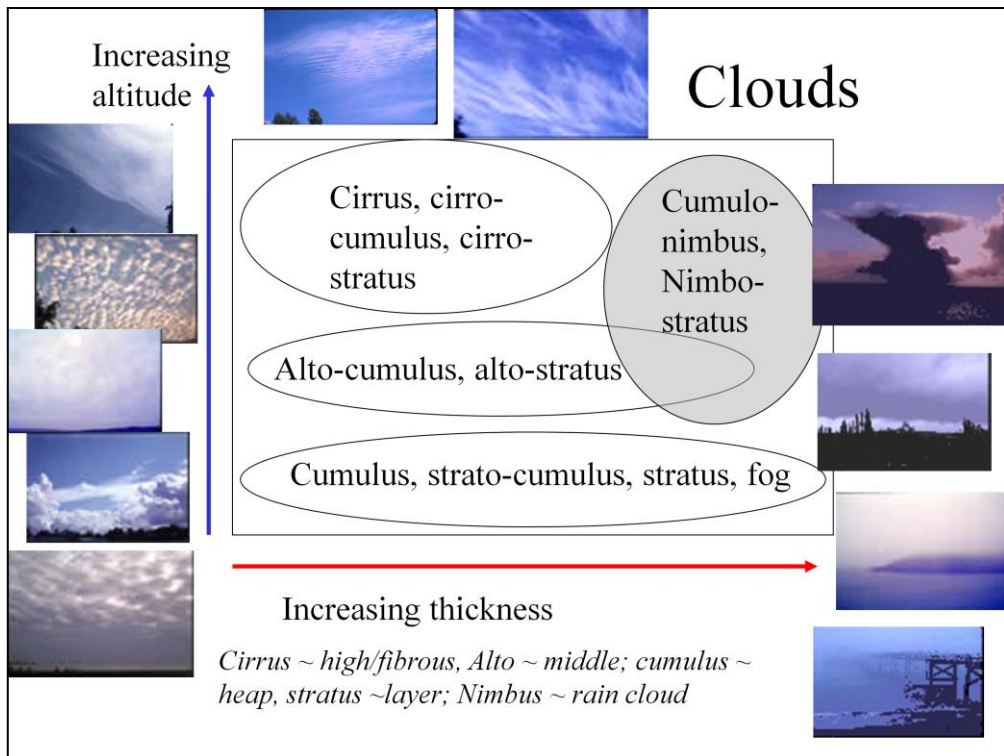


- Another measure of humidity is the *dewpoint temperature* which is the temperature that the air must be cooled to before saturation occurs (100% relative humidity)

Microwave measurements from space are sensitive to the total amount of gaseous water vapour in the atmosphere and show the strong relationship between water vapour and temperature. Note that this total column of moisture is not the same as humidity we feel. We are more sensitive to the relative humidity which is the water vapour in the air expressed as a fraction or percentage of the maximum theoretical amount.. The specific humidity tells as the total amount of water vapour in a mass of air (e.g. 1g of moisture per 1 kg of air). There is a much larger mass of invisible water vapour in the air than condensed water droplets of ice particles in clouds. However, water and ice strongly affect visible radiation which our eyes are sensitive to.



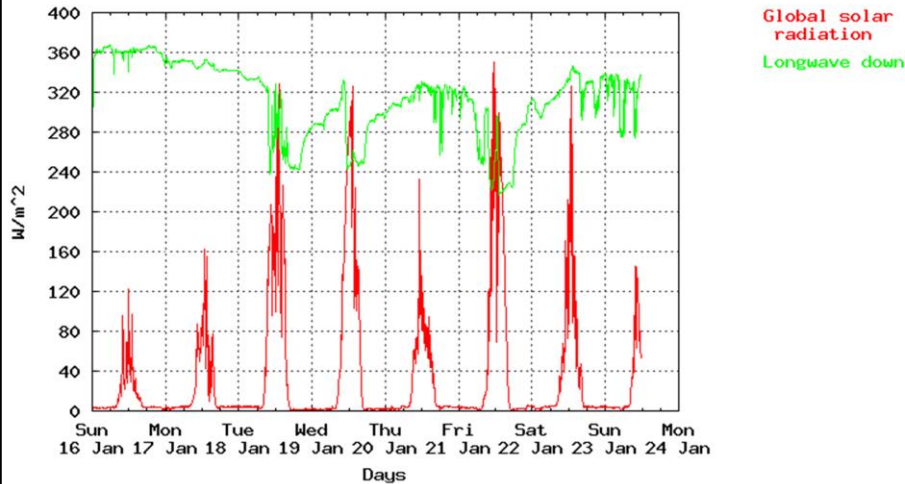
Certain frequencies of thermal radiation are readily absorbed by water vapour. In very humid regions (and cloudy regions) the thermal emission from the surface is absorbed by the atmosphere and re-emitted to space at much colder temperatures, and therefore lower emission (white regions in figure above). In very dry, cloud free regions, emission from the warmer surface layers can reach space (dark regions on image). Clouds are also measured in this way from space (cloud top height, cloud thickness, cloud extent).



“Cloud is water vapour with attitude”

Often measured as oktas (eighths of sky cover); also as %, thickness, optical depth, total water mass, etc (difficult to define “a cloud” easily!). In terms of atmospheric water, it is the tip of the iceberg; most of the water in the atmosphere is in the gaseous (invisible) state (water vapour). Since liquid water and solid water (ice) in the atmosphere profoundly impacts the cooling and heating of the atmosphere through radiative energy and latent energy (condensation, evaporation, sublimation) clouds are rather important components of the weather system. They are also a huge uncertainty in predicting weather and climate change. There are lots of different cloud types – meteorologists like this! There are a wide variety of processes that determine the formation of clouds and hence there are many distinct cloud types with differing properties (altitude, thickness, amount of water or ice, etc). See handouts and future lectures for more details.

## Radiative Energy Fluxes



Radiation – not the same sort of stuff you get from nuclear waste (although sunlight can still be harmful)

Measured by Joules of energy or Watts per square metre (a Watt is the rate of Joules per second)

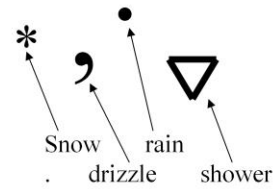
The Earth is powered by energy from the sun (solar radiation)

The Earth loses heat through thermal radiation (longer wavelength than solar)

This balance is affected by the sun, the temperature and the state of the atmosphere (e.g. clouds cool in the day but heat at night)

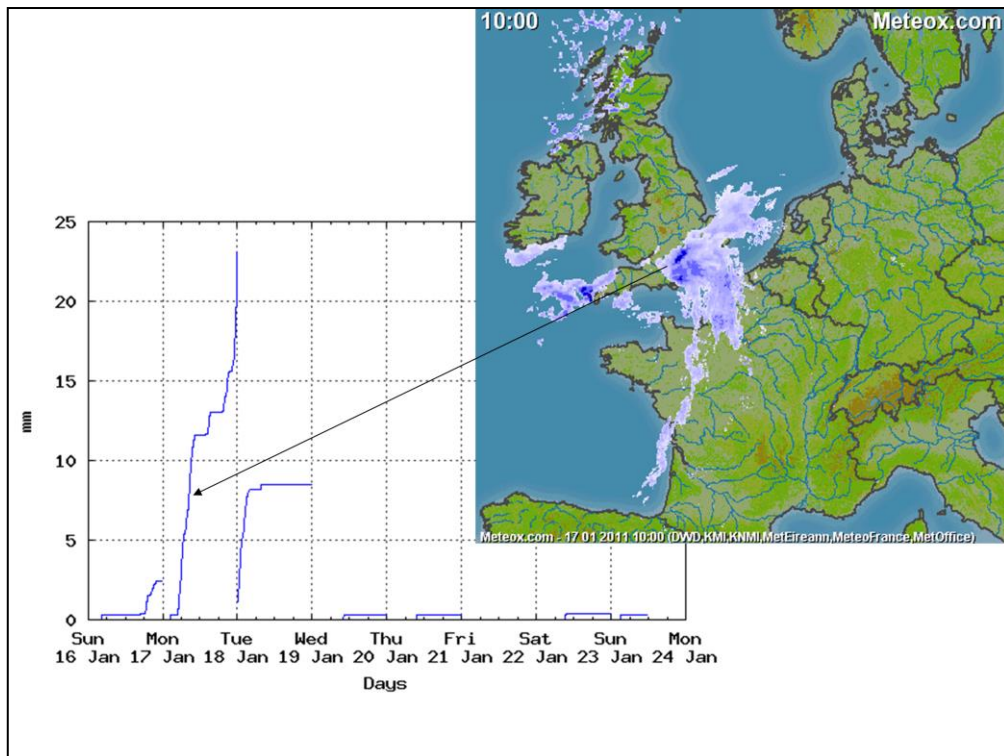


## Precipitation



- Precipitation – rain, snow, hail, etc
- The “reverse” of precipitation is evaporation
- Can be measured in mm (over a period of time) or as a rate (mm per day or mm per hour)
- Since energy is released on condensation of water droplets and energy absorbed when water evaporates, the atmospheric thermal structure is strongly influenced by precipitation in addition to radiation

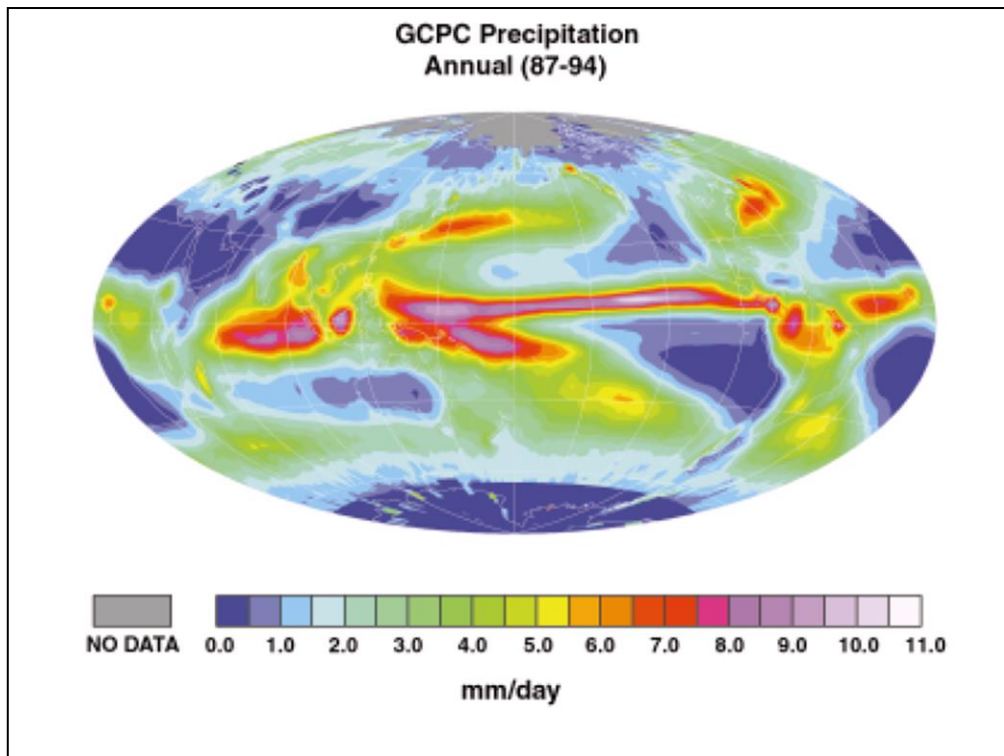
Precipitation includes rain, snow, sleet, hail, graupel, etc. It doesn't actually rain very often, believe it or not, but extreme rainfall or lack of any rainfall are clearly of importance to societies and the ecosystems and infrastructure upon which they depend. Measuring very light or very heavy precipitation is a great challenge.



Radar and tipping bucket rain gauges are used to measure rainfall rates.

It is common during intense rainfall that accumulations (in mm) are larger over a day or so than the total available moisture in the atmospheric column. This highlights that a continual supply of moisture from the surroundings is required to supply the fuel for heavy rainfall.





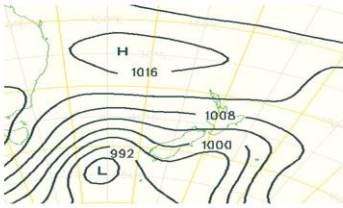
Precipitation is also estimated from satellite (infrared methods use deep, cold cloud duration as a proxy for rainfall while microwave emission and active radar returns are also used to estimate rainfall rate) as well as surface rain gauges (which are limited in areal coverage). The figure above shows the wet tropical belt of the Inter-Tropical Convergence Zone (ITCZ) as well as regions of mid latitude weather systems (or storm tracks) that we experience (e.g. top right red patch) and the dry land and oceanic deserts of the sub-tropics (blue).



## Wind



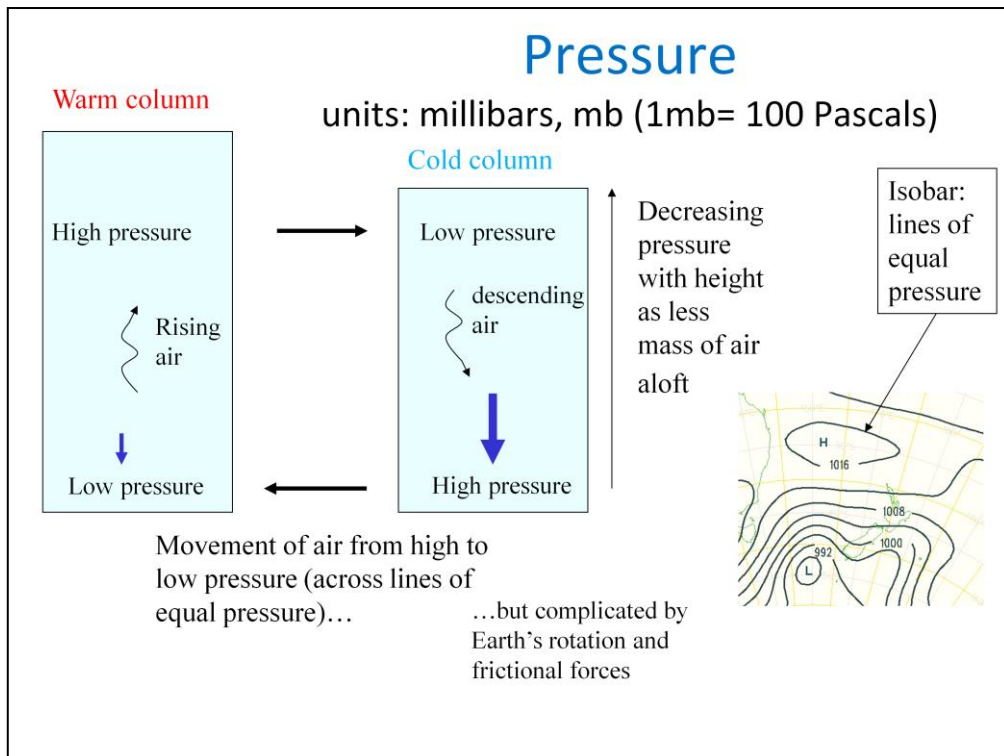
- Wind – speed and direction important
- Can cause damage, blow pollutants about and (worse still) blow in cold air with lots of rain...
- Measured in metres per second (m/s); Beaufort scale (0-12)
- Vertical wind speeds (up/down) also extremely important despite their tiny values compared to horizontal wind speed
- Wind is simply movement of air;
  - this movement is caused by a combination of forces pulling in different direction.
  - For example, there is a pressure gradient force acting to push air under higher surface pressure to lower pressure regions



# Pressure



- Pressure (millibar or 100s of Pascals)
- A measure of how much atmosphere is weighing down on your head (the more atmosphere, the greater pressure)
- Important for winds (rather than giving you a headache): air will tend to slide down from High pressure to Lower pressure... although the earth's rotation complicates this...
- Rising air is associated with surface low pressure; descending air is associated with surface high pressure
- An *isobar* measures equal lines of pressure (just as an *isotherm* measures lines of equal temperature)
- Global annual average pressure at sea level is 1013 mb

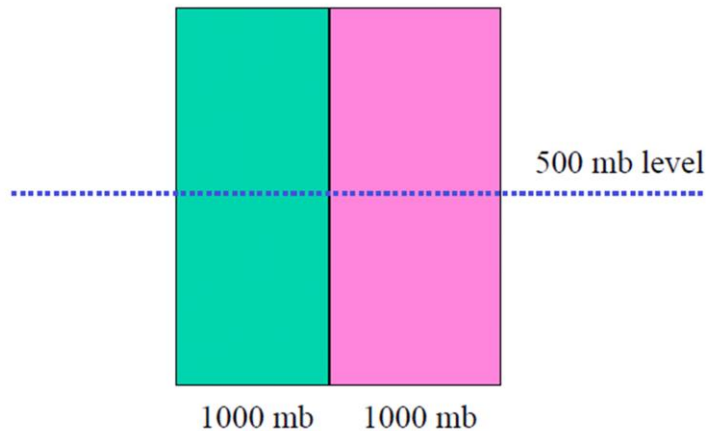


Atmospheric pressure relates to the mass of air above your head.

Surface pressure is around 1000mb which is 100000 Pascals. Above each square metre, the pressure relates to the mass aloft times the acceleration due to gravity (around  $10 \text{ m/s}^2$ ). This means that the mass is nearly 10000 kg! Air may seem thin but...there is a lot of it.

Warmer air has a lower density than colder air and so occupies a larger volume. This can mean that pressure can vary with altitude depending upon the thermal structure of the profile. However, transfer of mass from one column to another is required to change the surface pressure, which is generally plotted on synoptic charts and which strongly determines wind patterns near the surface (more later).

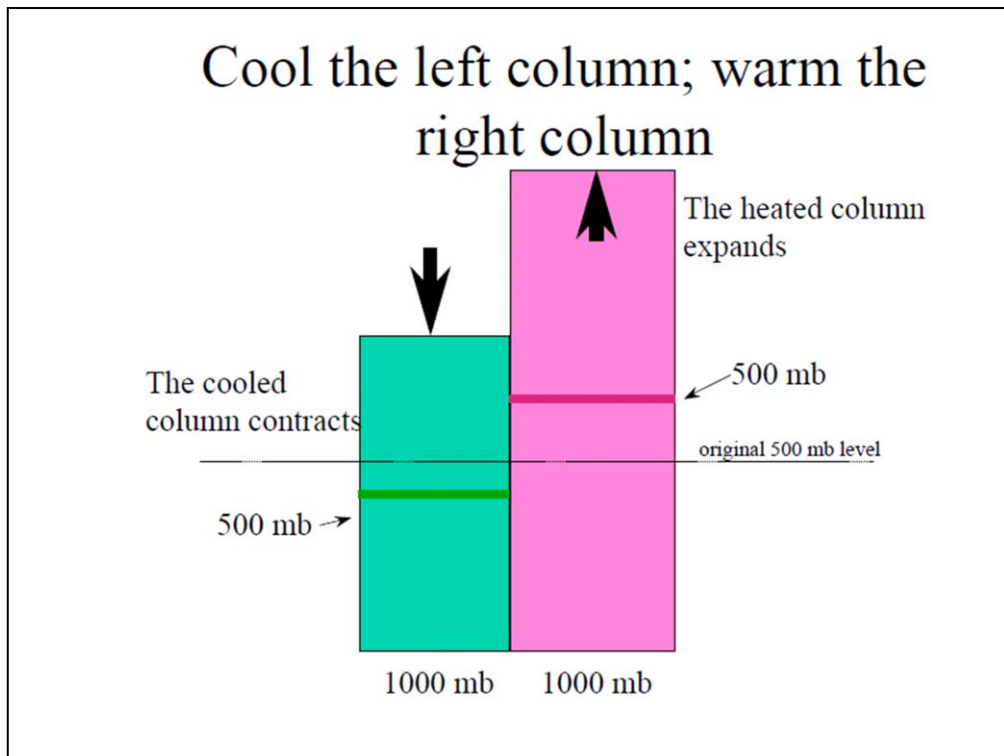
Two columns - same temperature  
same distribution of mass



Why do we have movement of air at the surface? A thought experiment:

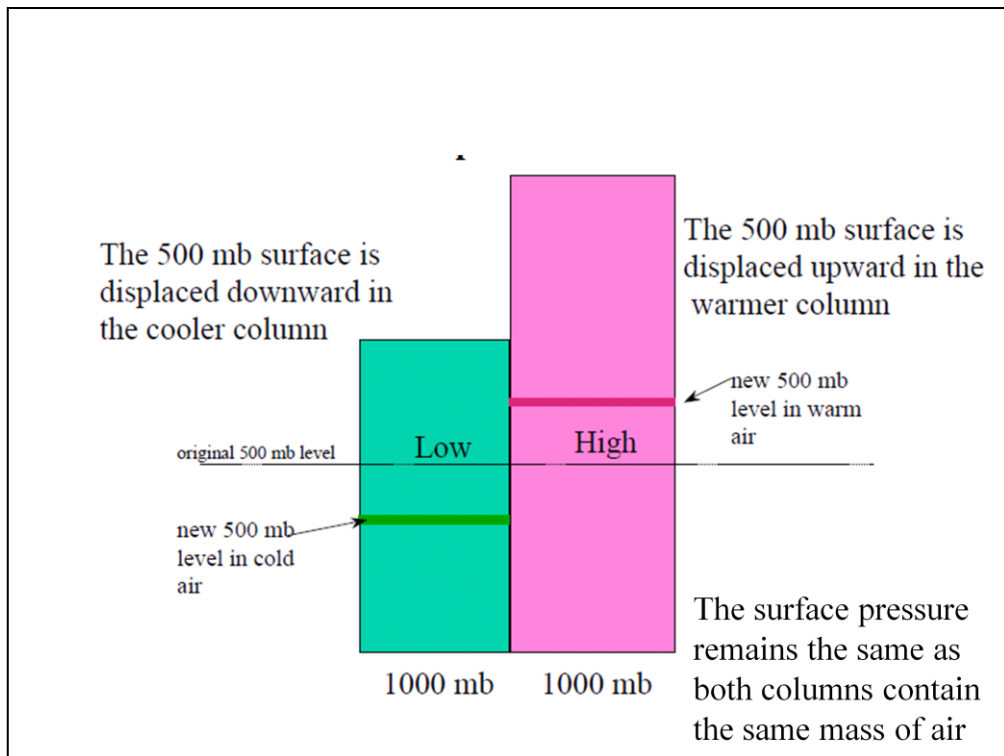
We have two identical columns of air of surface pressure 1000mb. The horizontal line shows the line above which resides half of the atmosphere (thus the pressure here is about half the surface pressure).

If we heat the column on the right, the air expands and becomes less dense. Cooling the column on the left will cause the air to contract and become more dense.

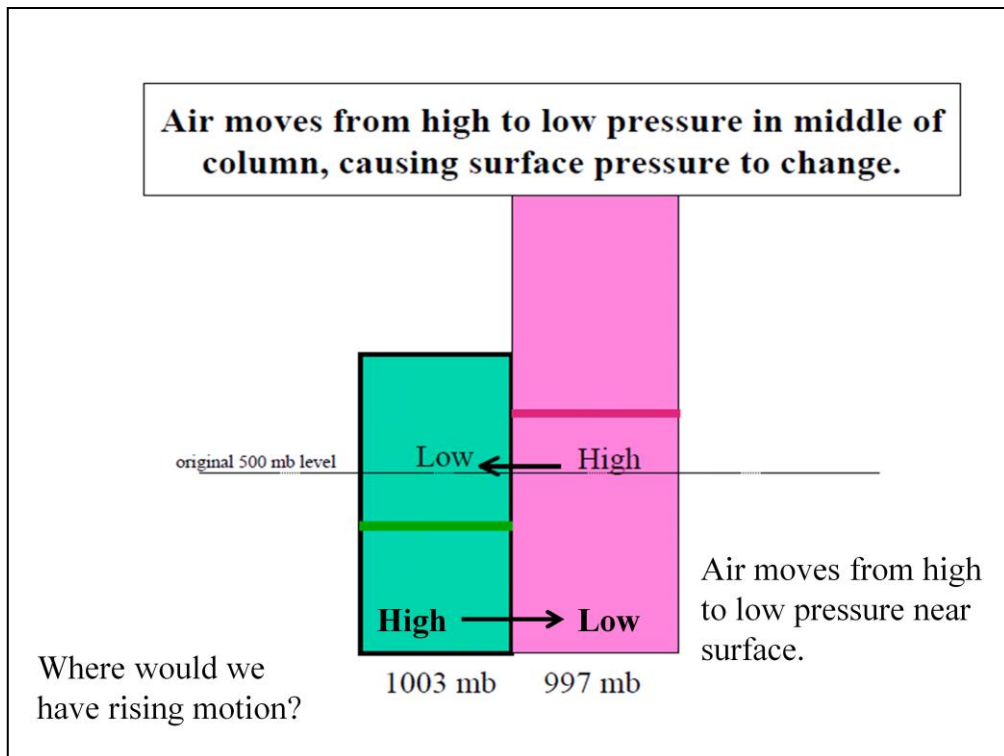


The heated column expands and the cooled column contracts. At the surface, the pressure remains constant because the mass of air aloft has not changed. However, at the horizontal line, the contracted column has relatively less atmosphere aloft while the expanded column has relatively more atmosphere aloft now.





At the horizontal line, the expanded column has more atmosphere aloft and so the pressure is higher than before. The reverse is true for the contracted column which results in lower pressure. Since air flows from high pressure to low pressure, air aloft will flow from the relatively higher pressure from the heated column to the cooled column.

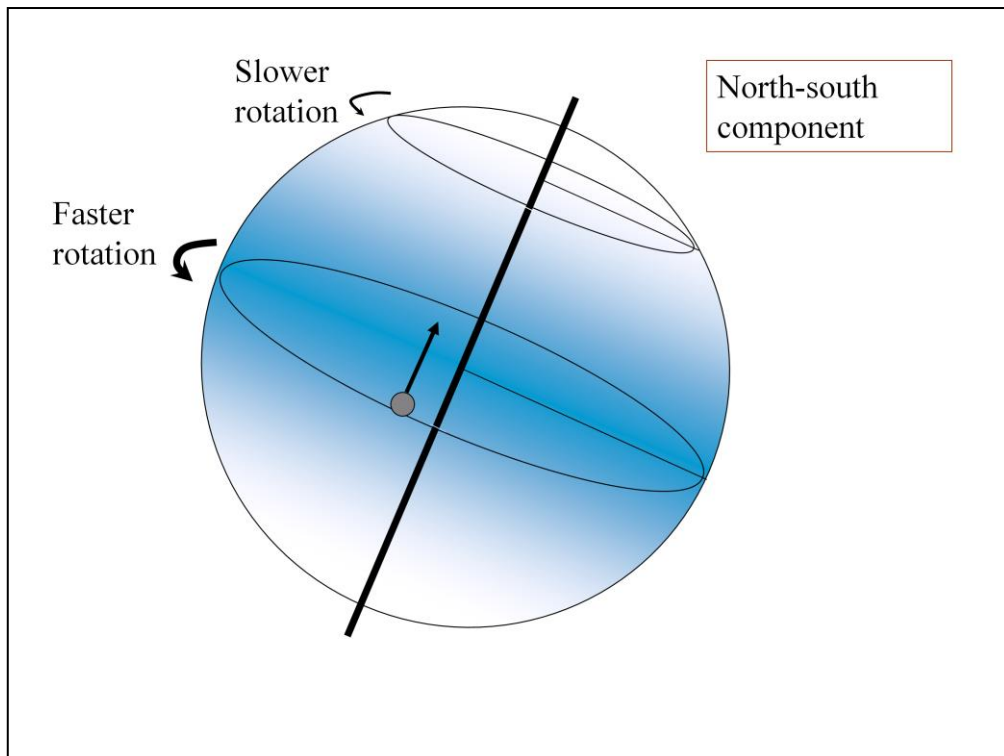


The flow of air aloft from the warm, expanded column to the cooled column results in a loss of mass from the warm column and therefore a reduction of surface pressure. The flow of air into the contracted, cooled column increases the mass of air here, increasing surface pressure. Thus, at the surface air flows from the cooled column (higher surface pressure) to the warmed column (lower surface pressure). This sets up a circulation of air. Where will the air rise?

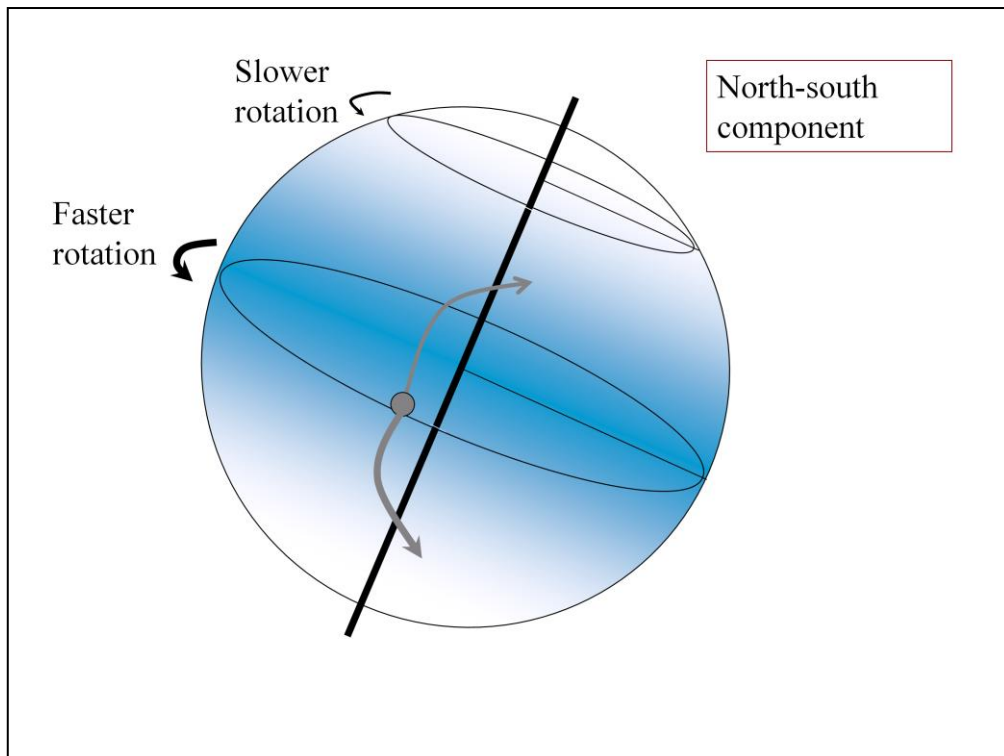
This simple, theoretical model explains simply how uneven heating of the planet can introduce the large-scale circulation of air that is instrumental for our weather and climate.

## The coriolis “force” (or effect)

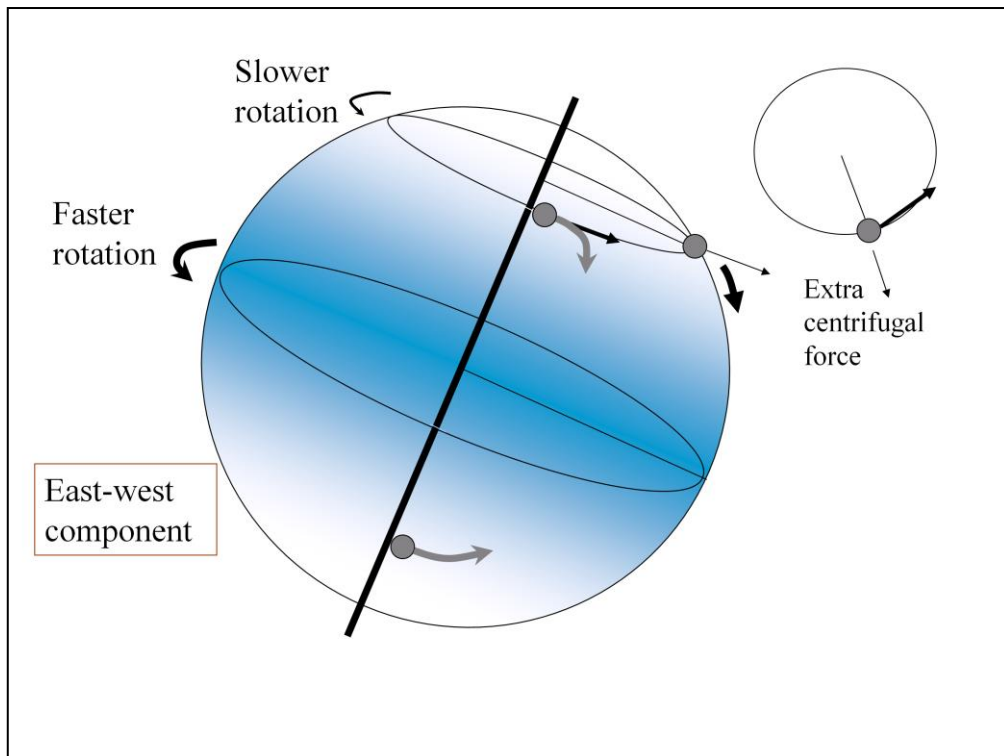
- Why does the atmosphere go round the bend?
- The coriolis “force” acts to deflect wind to the right in the northern hemisphere and to the left in the southern hemisphere
- It is caused by the rotation of the Earth acting upon atmospheric and oceanic motions



The Earth spins from west to east. The circumference around the axis of rotation (solid line) is largest at the equator and becomes smaller the closer you get to the poles. So at the equator the distance travelled in one 24 hour spin is much further than the distance travelled near to the pole (so the surface and air above it are travelling fastest at the equator).



If the atmospheric (or oceanic) circulations cause movement from the equator to the poles, this air (or water) retains this fast movement from west to east. Since this is faster than the rotation experienced at higher latitudes (closer to the poles) it will be moving faster than the surface is rotating and will appear to bend towards the west. Similarly, air moving from the poles to the equator will retain the slower rotation rate at higher latitudes and will appear to bend to the west (it is moving slower than the rotation rate near the equator).

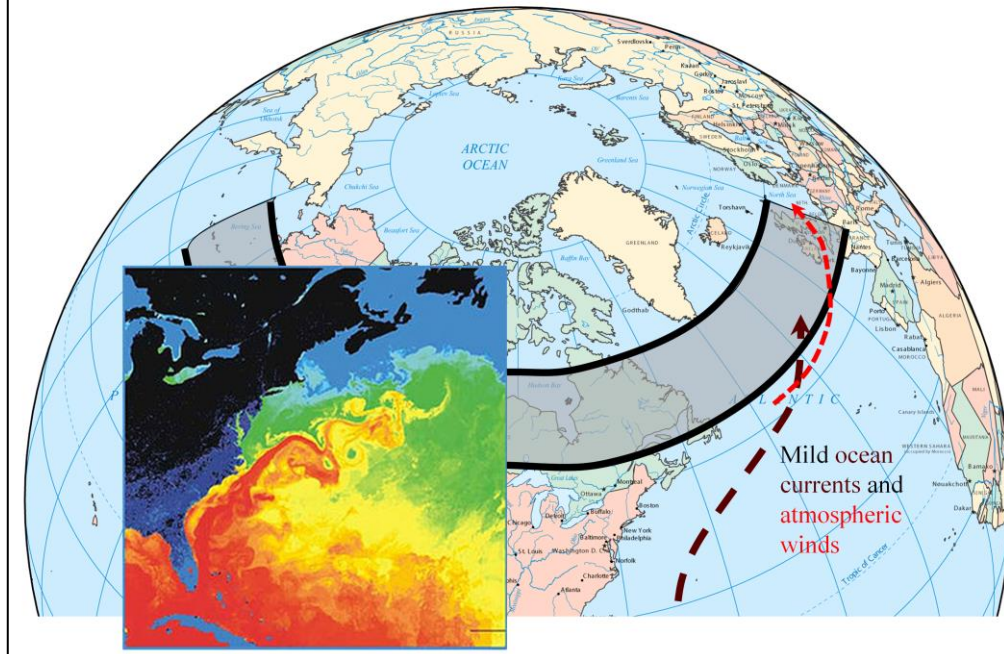


If air is moving from west to east it will also experience a coriolis “force” although this is more complex to explain. If you imagine being on a roundabout, you experience an outward pull (centrifugal force). If air is moving from west to east it will be moving faster than the rotating Earth below it and will experience an additional centrifugal outward pull. This pulls the air towards the equator (so bending to the right in the northern hemisphere and to the left in the southern hemisphere).

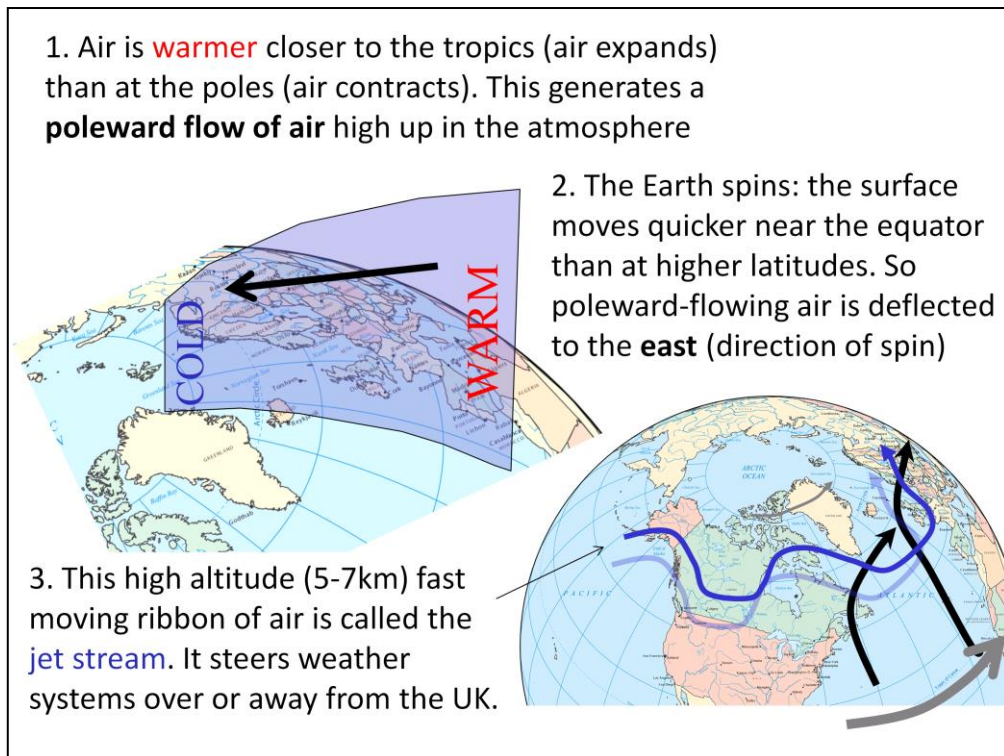
The coriolis force makes air (or water masses) bend to the right in the northern hemisphere and to the left in the southern hemisphere. It is what gives depressions (weather systems) and Hurricanes (tropical cyclones) their spin.



## The jet stream, the coriolis force & UK weather

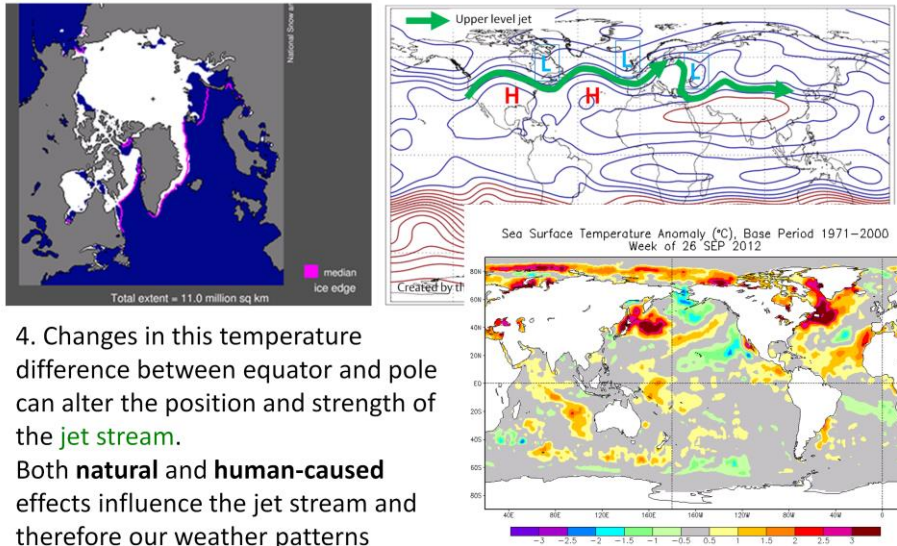


Why are UK winters much milder than at similar latitudes over Canada and Russia? One reason is that land warms and cools more quickly than the ocean (just as a pan of water warms more slowly than a pan that has boiled dry) so continental land masses have much larger seasonal changes in temperature. The UK is at the edge of a continental land mass (Eurasia) and is influenced by the Atlantic ocean (which tempers the seasons). The UK is influenced by warm ocean currents (Gulf Stream) and prevailing Westerly winds from the ocean. But why does our weather usually come from the Atlantic ocean? The Coriolis force helps to explain this.

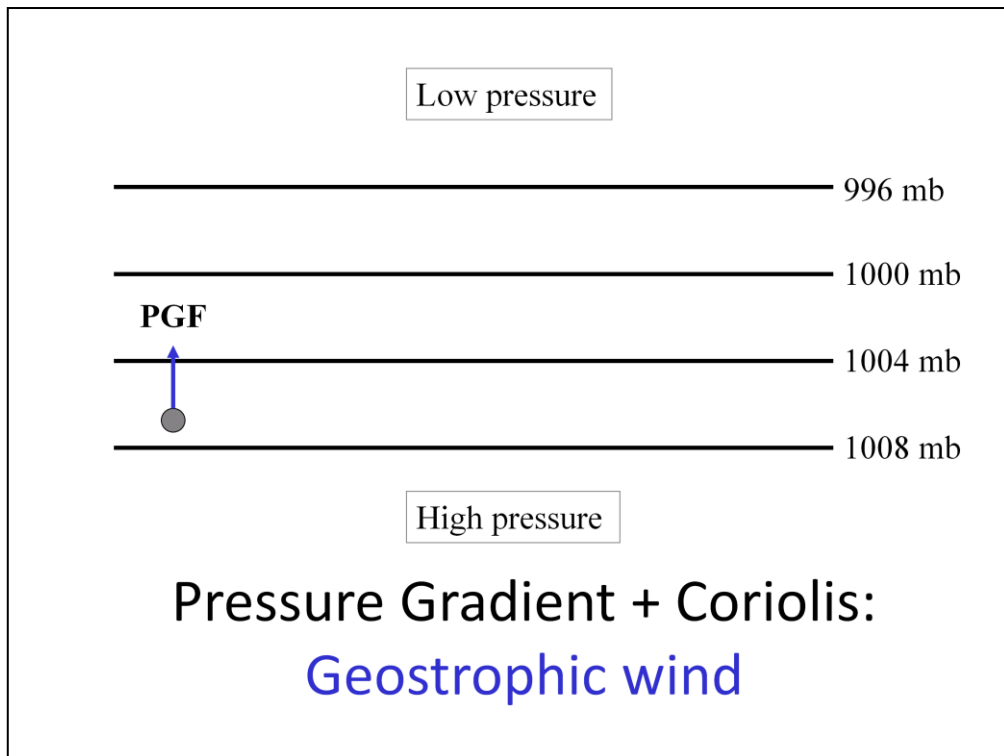


There strong gradient in atmospheric temperature from the warm tropics to the cold poles. This sets up a gradient in atmospheric pressure causing movement of air at higher levels in the atmosphere to blow from the tropics towards the poles. Since the Earth is spinning (from West to East), the surface near the equator is moving faster than at higher latitudes (a larger circumference so a longer distance to travel in one 24 hour rotation). As air moves from the equator to the poles, this “spin” is retained and so the air moves faster (from East to West) than the rotating surface (so air deflects towards the East, so to the right in the Northern hemisphere and to the left in the Southern hemisphere). This sets up eastward movements of air above middle latitudes (around 8km above our heads) which are termed jets and characterized by strong winds (jet airlines use or avoid these jets depending upon whether they are travelling east or west).

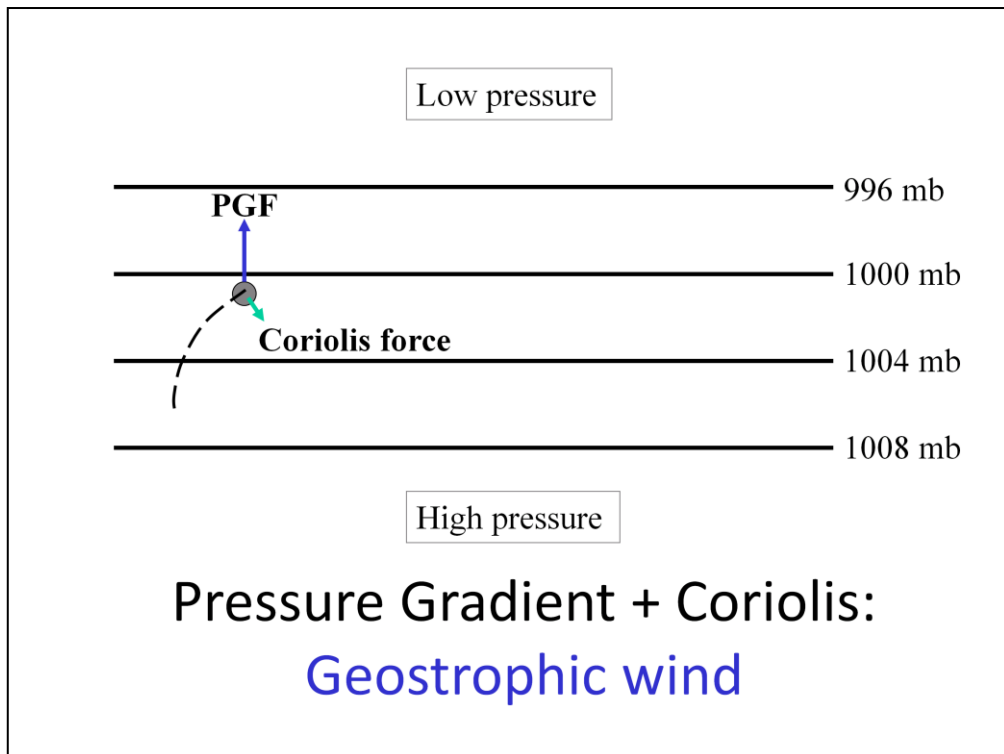
## Arctic Ice, ocean temperature and the jet stream



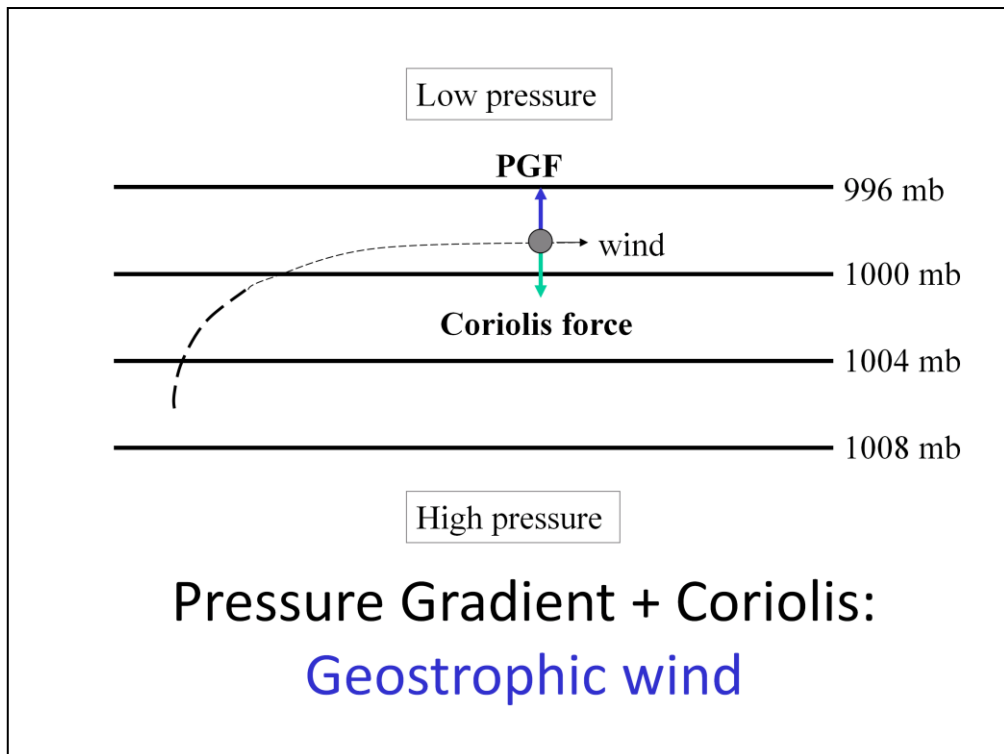
The jet stream which affects the UK does not simply blow from west to east. There are usually waves and meanders. These steer weather systems over or away from the UK and also determine whether cold polar air encroaches the UK or warmer tropical air masses. Since the jet stream depends upon this gradient in temperature from the tropics to the poles, changes to this gradient can alter how the jet stream influences our weather. A weaker gradient (warmer Arctic or cooler sub tropical Atlantic for example) is thought to slacken the jet stream, causing disruption to our usual westward travelling weather systems. Changes in the jet stream can alter weather in the UK. If weather systems are continually steered away from the mainland we can experience a lack of rainfall and even drought (e.g. 2010-2011). If weather systems are steered over and stall across the UK we can have prolonged rainfall and flooding. In winter, a disruption to our usual westerly wind flow can cause frozen temperatures and snowfall. Recent research suggests that both Natural cycles in ocean temperature and heating of the Arctic, in part relating to warming due to greenhouse gas emissions, can affect our jet stream and lead to unusual weather patterns and extremes both in summer and winter.



Air initially flows from high pressure to low pressure, across the isobars, due to the pressure gradient force.



As the air moves, the coriolis force will begin to act, giving the air a nudge to wards the right in the northern hemisphere and to the left in the southern hemisphere.



Eventually, the parcel of air reaches a speed at which the pressure gradient force is exactly balanced by the coriolis force. This speed is termed the geostrophic wind and is a theoretical estimate of how strong the wind will be, given the pattern of isobars (isobars close together mean stronger wind).

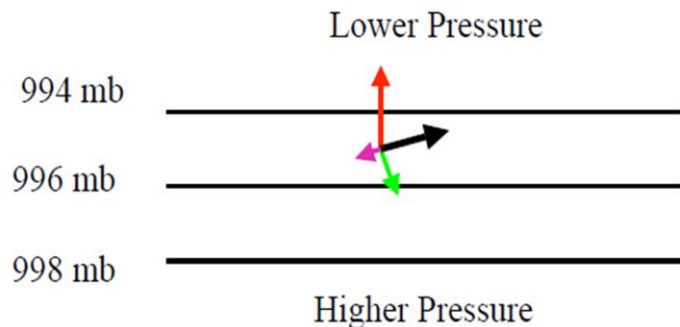
At 50°N geostrophic wind  $\sim 3000/x$ ;  $x$  is the distance between 4 mb interval isobars

E.g. if 300 km between 4 mb interval isobars, geostrophic (expected) wind  $\sim 3000/300 = 10$  m/s

In practice, the curvature of the isobars and friction near the surface affect this



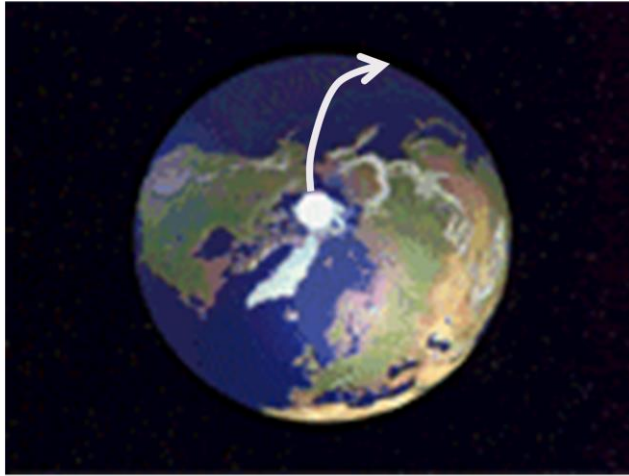
## Geostrophic wind plus friction



The wind no longer blows parallel to the isobars, but is deflected toward lower pressure; this happens close to the ground where terrain and vegetation provide friction

Friction complicates things: a three-way tug of war! The result of this is that wind tends to blow along isobars but slightly towards the lower pressure. Additionally, if the isobars are curved you get another force (centrifugal, what you experience on a roundabout).

Recall: coriolis force deflects wind to right in northern hemisphere and to the left in the southern hemisphere



The coriolis force...

Air flows from high pressure to low pressure

Away from the equator, the air flow is deflected by the rotation of the Earth

To the right in the northern hemisphere

To the left in the southern hemisphere

The curvature of the isobars and friction near the surface complicate this

Wind will be weaker and flow across the isobars near to the surface

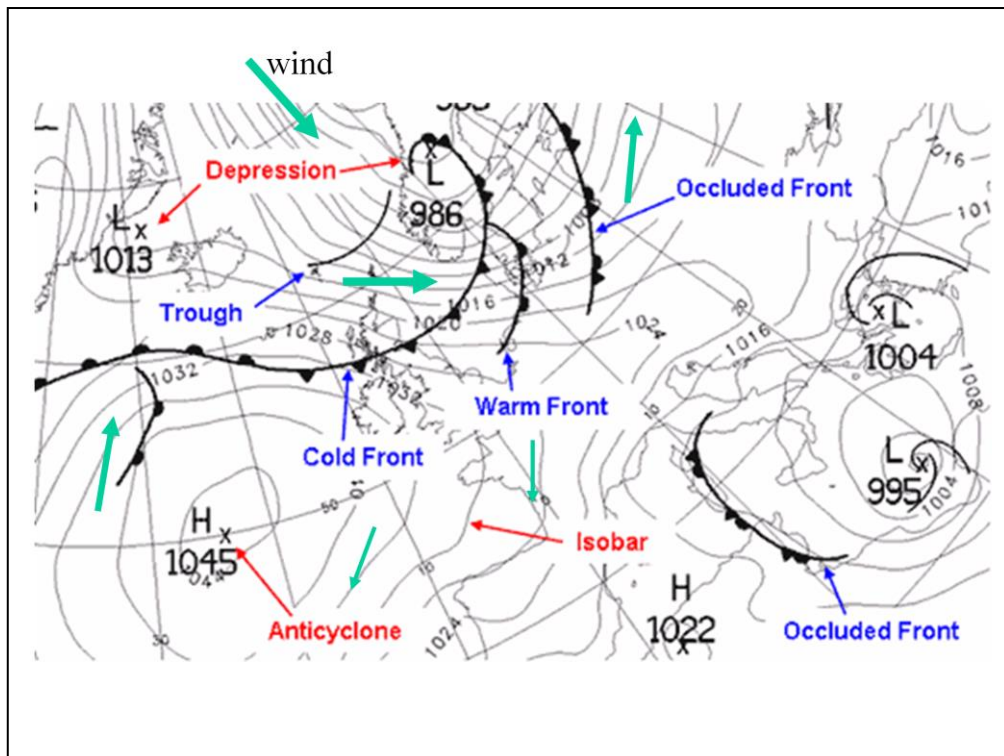
For a given pressure gradient, air flows faster round high pressure; in reality wind is stronger around low pressure as isobars usually tighter

Wind flows clockwise round high pressure and anticlockwise around low pressure in the northern hemisphere

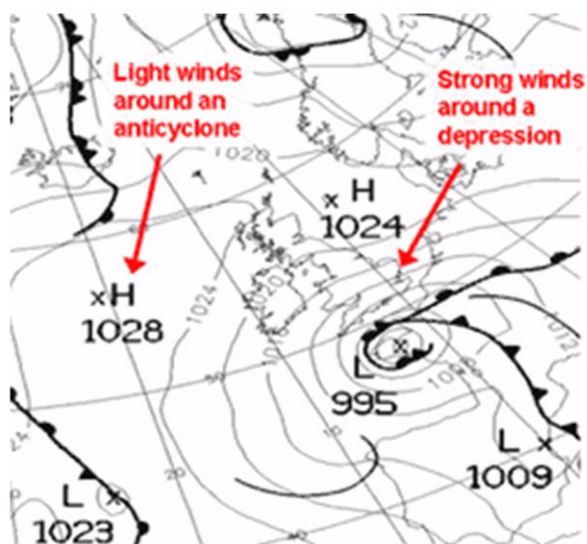
Reverse is true for southern hemisphere

## Synoptic Chart

- Invented in Scandinavia
- A convenient way of displaying the important information on the current weather situation
- Isobars – lines of equal pressure, important for the wind speed and direction and the movement of air masses
- Fronts – battleground between cold and warm air and likely source of clouds and rain



The effect of the coriolis force causes air to flow anti-clockwise around a low pressure and clockwise around a high pressure in the northern hemisphere. The reverse is true in the southern hemisphere.



## Some key points

- Warm air expands, becoming buoyant
- Warmer air holds more gaseous water vapour
- Air flows from high pressure to low pressure
- Surface pressure relates to the mass of air aloft; pressure diminishes rapidly with altitude

## Conclusions and outlook

- Aspects of the weather are important for society
  - Direct: Temperature, Rainfall, Wind, ...
  - Indirect: Pressure, humidity, ...
  - Extremes are important
- Measuring the weather
  - Ground based instruments (e.g. Met field site)
  - Radiosondes
  - Satellite instruments increasingly important
- Observations are vital for:
  - Determining current changes in the weather
  - Building physical models
  - Initialising weather forecast models