Memo 4: Meteorology

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Contents

1. Generally

- The more localised an area, the harder it is to forecast.

2. Atmosphere

- The atmosphere is an ovoid shape, and extends further near the equator than at the poles. The atmosphere has four vertical regions. Aviation mostly happens in the troposphere, sometimes as high as the stratosphere. The boundary layer between the stratosphere and the troposphere is known as the tropopause. Near the poles, the tropopause is at a lower altitude than near the equator.

Thermosphere
Mesosphere
Stratosphere (above the weather)

Tropopause (boundary layer, FL200 at the poles, FL600 at the equator)

Troposphere

- As you gain altitude, air pressure decreases, but the composition of gases remains constant.
- As you gain altitude within the troposphere, the air temperature decreases, approximately $2°\mathrm{C}$ per 1000ft. Within the tropopause, air temperature is fairly constant at approximately $-56.5°\mathrm{C}$.

2.1. ISA

- The properties of the atmosphere can vary significantly, so using the International Standard Atmosphere gives a way to compare atmospheric differences.

  The ISA atmosphere is completely dry and pressure, temperature and density all decrease as altitude is gained. Temperature decreases at $2°\mathrm{C}$ per 1000ft until you reach the tropopause, fixed at 36000ft AMSL. At that point, the temperature maintains $-57°\mathrm{C}$.

  The pressure also decreases at a rate of 1 hPa per 30ft, until 20 000ft.

- To summarise:

Altitude	**Pressure**	**Temperature**
0ft amsl (sea level)	1013.2hPa	$15°\mathrm{C}$
increasing…	−1hPa per 30ft	$-2°\mathrm{C}$ per 1000ft

2.2. Water Vapour

- Less dense than air, ergo humid air weighs less than dry air, ergo moist air is associated with low pressure systems.
- Content varies in the atmosphere, traces in the desert, up to 4% over oceans.
- Has a significant impact on weather.

3. Motion of the Atmosphere

3.1. Atmospheric Heating

- Before diving into this section, having a basic understanding of thermodynamics will be beneficial.
- As the sun *radiates* on the planet, a diabatic process is going on causing the atmosphere to *absorb* heat and increase in temperature. This heat is not *conducted* through the atmosphere, instead the parcel of warm air will expand adiabatically. As a result, the parcel of air becomes less dense than the colder air surrounding it, causing it to rise in the atmosphere in *convection*. As this occurs, *advection* will cause cooler, perhaps also air with more moisture, to move to replace the air parcel.
- This atmospheric heating is negligible.

> **Reminder Diabatic and adiabatic processes:** A diabatic process is one in which heat energy is transferred either into or out of the system of interest. The inverse is an adiabatic process.

3.2. Surface Heating

- The surface of the planet will also heat as the sun radiates. The amount which the surface will heat is dependent on a number of factors:
  - the surface's specific heat capacity: it's ability to hold thermal energy.
  - reflectivity of a surface: the amount the surface absorbs energy over reflecting it away.
  - emissivity of a surface: the amount the surface will radiate the thermal energy back into the atmosphere.
  - convection in the atmosphere above the surface: if air above the surface is undergoing convection, a higher thermal gradient is maintained, allowing for greater convection of heat from the surface. This is also increased further by winds and evaporation above the surface.
  - conductivity of a surface: the surface may end up warming layers beneath it with the thermal energy.
- **Surface emissivity:** Land typically has a lower emissivity than water.
- Energy from the planet's surface is re-radiated into the atmosphere, but at a longer wavelength. As a result, it is more readily absorbed by the atmosphere, especially by water vapour and carbon dioxide.

3.3. General Circulation

- The increased heating effect at the tropics as a result of the tilt of the planet causes the air to heat and rise. At the top of the troposphere, the air cannot rise further, so moves outwards away from the equator, creating an area of low pressure known as the **equatorial trough**.
- The same effect happens inversely at the poles, creating areas of high pressure.

- As a result of the combination of these, three cells are found:
  - polar cell
  - mid-latitude cell (Ferrel cell)
  - tropical cell (Hadley cell)

3.4. Pressure Gradients

- Air flows from high to low pressure.
- Winds can be visualised by the isobars on a weather chart. The closer the isobars, the stronger the pressure gradient, the stronger the wind.
- In reality, the Earth's rotation causes the Coriolis force, which means that the winds tend to blow to the right in the Northern hemisphere.
- When the air flow is sufficiently deflected, the coriolis force will balace with the pressure gradient wind and the air will flow parallel to the isobars. This is known as **geostrophic wind**.
- The Coriolis force is also the cause of winds circulating around areas of high and low pressure in different directions. In the Northern hemisphere, high pressure causes an anticyclone (clockwise rotation of air).
- In a cyclone, warm air is brought inwards, rises and cools.
- In an anticyclone, cold air falls and warms up, then spreads outwards.
- Buys Ballots Law: "If you face the wind, you're **left** high and dry" (in the Northern hemisphere)

3.5. Air Masses

- An air mass is a large body of air with similar values of temperature and humidity over an extensive area.
- An air mass gains its properties by travelling over a certain region for days or weeks.

4. Wind

- Wind is the horizontal flow of air across the planet. Wind is described as a velocity, with both it's direction (relative to true north) and strength (in knots), written as direction/strength, for example 350/15.
- Forecasted winds have direction given in true heading. Wind information provided during the course of a flight (through an ATIS, or ATC) is given by magnetic heading.
- A wind changing direction in a clockwise direction is known as a **veering** wind. A wind changing direction in an anti-clockwise direction is known as a **backing** wind.
- If a wind is not accelerating, but is steady, it is known as **balanced flow**. Wind tends to start off by air parcels in high pressure regions moving towards lower pressure regions. This **pressure gradient force** can be visualised on weather maps, and close together isobars (lines of constant pressure) indicate a significant pressure gradient.

- Moving winds are also affected by the Coriolis force. This is an apparent force that comes about as a result of the rotation of the Earth.
- When the pressure drops by more than 1hPa per hour for more than 12 hours, expect very strong winds.

4.1. Balanced (Geostrophic) Wind

Wind that is balanced, that is travelling parallel to the isobars and not across any pressure gradient, is known as geostrophic wind. It always travels in the direction such that if you stand with your back to the wind, the low pressure is on your left side (Buys Ballot's Law).

As a result of these effects, in the Northern hemisphere, if an aeroplane experiences a wind from the port side that causes right drift, the aeroplane is heading toward an area of low pressure, and vice versa.

In addition, as a result of these affects, the following is true:

Area of	Hemisphere	Wind journey
Low pressure	Northern	Anti-clockwise around the region
High pressure	Northern	Clockwise around the region
Low pressure	Southern	Clockwise around the region
High pressure	Southern	Anti-clockwise around the region

4.2. Surface Wind

- Winds near the surface are slowed as a result of friction with the ground, known as the friction layer.
- Obstacles can cause additonal variation to surface wind, and this should be considered by pilots.
- At 2000ft, the wind is considered free of surface influence, although this might be up to 5000ft on blustery days.
- Land has more surface friction (50% of speed at 2000ft) than sea (80% of speed at 2000ft)
- The effect of the Coriolis force is reduced near the surface (due to the slower speed)
  - This affects wind direction
  - Over land, the wind is back 30°-40°
  - Over sea, the wind is back 10

4.3. Local Air Movements

4.3.1. Breezes

- Not found above 1000ft, limited to around 10kt
- Usually affected by the Coriolis force

4.3.1.1. Sea Breeze by Day

- As a result of quicker heating of the land, air parcels over land warm quicker and rise. Advection draws cooler air from over the sea onto the land, resulting in a sea breeze.
- As this air often carries more moisture, effects like mist and fog are possible.

4.3.1.2. Land Breeze by Night

- As a result of the land cooling quicker, air parcels over the sea will eventually be warmer and rise. Advection will then draw coole air from the land to the sea, resulting in a land breeze.

4.3.2. Diurnal Variation in Surface Wind

- During the day, surface heating leads to increased air mixing. As a result, daytime surface winds are usually stronger and veered.
- During the night, air mixing is lesser. The surface winds will drop and back in comparison with day winds. Wind shear maybe greater at night, though turbulence may be greater during the day.

4.3.3. Katabatic Winds

- Sometimes called a mountain wind
- When regularly experienced, often given a local name
- Air parcels cool down at night, and become more dense. If these air parcels are on a mountain side, the increased density will cause the air parcel to move down the mountain slope, causing a katabatic wind.

4.3.4. Anabatic Winds

- Conversley, if an air parcel warms during the day and becomes less dense on a mountain slope, it will tend to drift up the mountain slope, leading to anabatic wind. As this flow opposes gravity, it is often much slower than katabatic winds.

4.4. Turbulence

- Turbulence is unsteady, sudden changes in the air. As a result of the interaction of the air with the surface, there can be changes in wind speed and direction near the surface. This mixing of air can lead to turbulence.
- Turbulence can occur at any altitude.
- Turbulence reduces at night.
- Cloud bottoms like lumpy egg boxes indicate turbulence.

4.5. Windshear

- Windshear is a variation of wind speed and/or direction from place-to-place. Windshear is most often present during takeoff and landing due to the difference in wind speed and direction at the surface.
- Windshear can also be expected near sea or land breezes (as at increased altitudes the direction is reversed), in the vicinity of mountain waves, temperature inversions (the wind can suddenly get a lot stronger above the inversion) and thunderstorms (Cb clouds are associated with strong downdraughts).

4.6. Microbursts

- Localised ($< 4 \text{ km}$) downdraughts

4.7. Flight in Turbulence and Windshear

- Do not exceed $V_{\{\text{no}\}}$
- Do not force the aircraft to fly a set altitude, get a block clearance if needed
- Allow the A/C to ride the turbulence
- Never uses abrupt full-scale control deflections
- Add 5kts to approach speed (if runway length allows)
- Consider a steeper approach

5. Density, Pressure & Temperature

- Density is important, as it is the main factor affecting A/C performance. Lower density gives lower performance.

5.1. Gas Laws

- Boyles Law, $P \propto V$
- Charles Law, $V \propto T$

5.2. Altimeter

- The altimeter is a pressure measuring instrument.
- Altimeters are calibrated against the ISA, $+15°\text{C}$, a lapse rate of $-2°\text{C}$ per 1000ft, density of $1.225\frac{\text{kg}}{m^3}$.
- When flying from High to Low pressure, the altimiter will show you higher than you are (over reading)
- When flying from High to Low temperature, the altimiter will show you higher than you are (over reading)

5.3. Transition Level

- When taking off, the switch from QNH to SPS is at the **transition altitiude**, usually 3000ft (or 6000ft around London and Manchester.)
- When approaching, the switch from SPS to QNH is at the **transition level**, which is the first available FL that gives a transition layer of 1000ft. This will vary depending on the QNH.

5.4. Temperature Inversion

- Inversions can be caused by subsidence from anti-cyclones (high pressure systems)
- Also can be caused by frontal inversion and radiation inversion

6. Humidity and Stability

- The ability of a parcel of air to contain water vapour depends on pressure and temperature.
- Hotter air can hold more water.
- Typically in a parcel of air, the absolute amount of water remains the same
- The temperature at which 100% RH is reached is the dew point
- Because water vapour is less dense than air, a parcel of humid air will rise and cool.

6.1. Lapse Rates

- We have already seen the environmental lapse rate, ELR, approx $2°\mathrm{C}$ per 1000ft, although this can be measured properly.
- We also have the Dry Adiabatic Lapse Rate (DALR), which is the temperature lapse rate of a parcel of dry air. Because the composition of gases in a dry parcel of air is always the same, this is fixed at $-3°\mathrm{C}$ per 1000ft.
- Logically, we have the corresponding Saturated Adiabatic Lapse Rate (SALR), for a parcel of air with 100% RH. The SALR is always $-1.5°\mathrm{C}$ per 1000ft.
- These are both adiabatic, as in a thermodynamic process that maintains heat in the thermodynamic system.

6.2. Atmospheric Stability

- If the ELR < DALR, the atmosphere is absolutely unstable.
  - A dry parcel of air cools as it rises, but faster than the surrounding atmosphere. As a result of this difference, it accelerates vertically.
- If the ELR > SALR, the atmosphere is absolutely stable.

  - A saturated parcel of air would would quickly cool faster than the surrounding atmosphere and sink again, hence resisting vertical motion.

- If the DALR < ELR < SALR, the atmosphere is conditionally unstable.
  - A parcel of air cools at a rate similar to the ELR. However if an external influence causes it to rise, when it reaches 100% RH (the dew point), the lapse rate changes to the SALR and the parcel beings to vertically accelerate.

- The reverse is also true. As a parcel descends, it warms at the ALR (depending on humidity). This is why the lee side of hills are warmer than the windward side. This is adiabatic warming.

6.2.1. Recognising Stability Conditions

- Instability usually occurs by atmospheric heating from below, resulting in air moving upwards. Cumulus or convective clouds are likely present.

- Stability usually occurs by atmospheric cooling from below. Stratus clouds are likely present.

6.3. See also

The Met Office have a very interesting document discussing these topics and how to diagram them on a tephigram. It is beyond the scope of the PPL exam, but is good knowledge: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/library-and-archive/library/publications/factsheets/factsheet_13-upper-air-measurements_2023.pdf

7. Clouds and Precipitation

7.1. Cloud Naming

- There are four main groups of clouds:
  - cirriform (fibrous)
  - cumuliform (heaped): caused by vertical instability
  - stratiform (layered): associated with stability, caused by a large scale ascent of air
  - nimbus (rain-bearing)

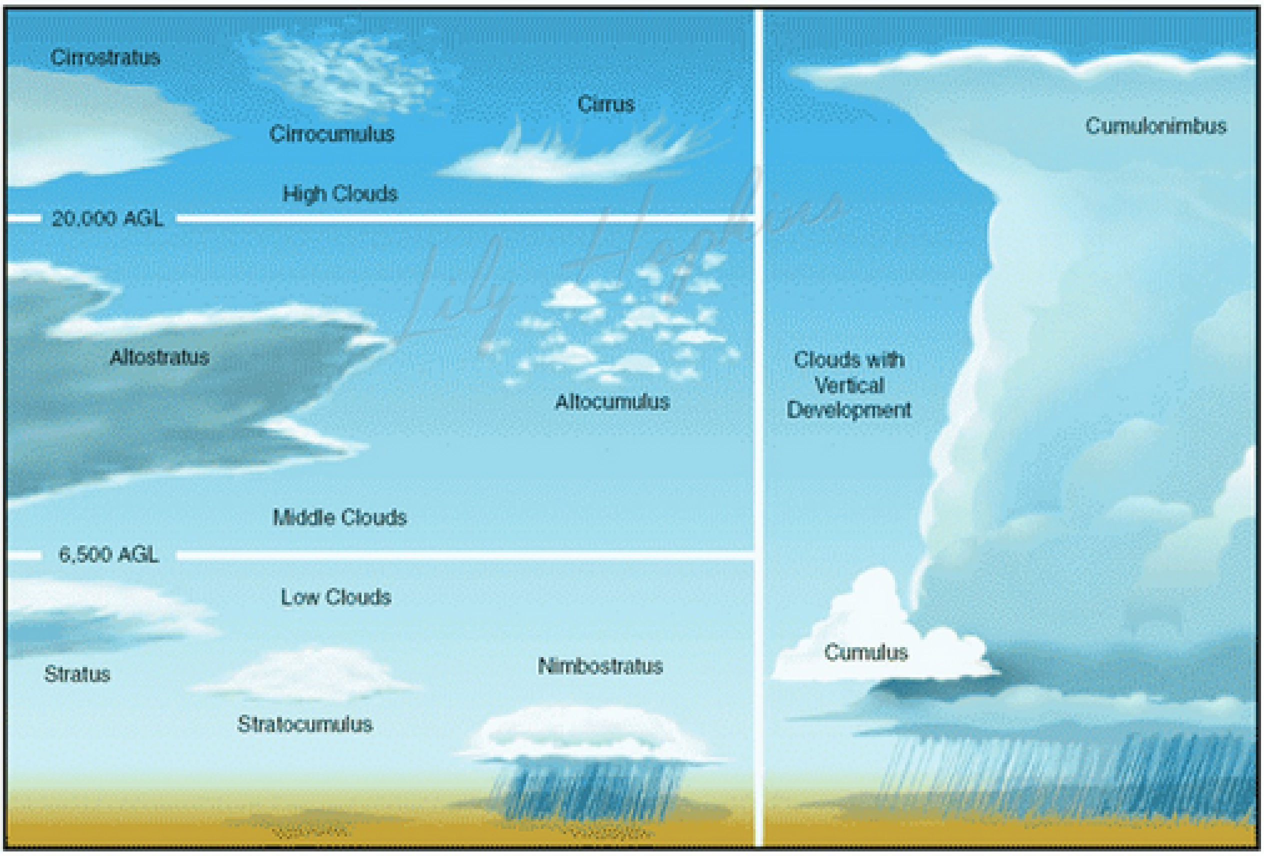

Figure 1: Different cloud types

7.2. Cloud Formation

- Clouds form from the dewpoint upwards
- You can estimate the cloud base in ft by $(\text{temp} - \text{dewpoint}) \times 400$
- Convection: Warm air rises, air cools, condenses and clouds are formed
- Orographic lifting: air is forced to rise by an obstruction (hill, etc.), cools, condenses.
  - In an unstable atmosphere: produces heaped clouds
  - In a stable atmosphere: produces layer clouds
- Convergence: two air masses meet causing forceful lifting and cooling
- Advection: warm air moves over a cool surface, condenses and produces low level cloud
- Mixing: turbulent air causes air parcels to mix, some of which may condense
- Coastal breezes: sea and land breezes can cause localised cloud

7.3. Cloud Reporting

- Coverage is measured in oktas, and converted for aviation:
- FEW: 1-2 oktas
- SCT: 3-4 oktas
- BKN: 5-7 oktas

- OVC: 8 oktas

8. Precipitation

- Rain/snow typically requires a cloud thickness of 4000ft or more (drizzle requires less)
- Layer clouds typically produce light drizzle, light rain or light snow
- Heaped clouds typically bring heavier precipitation.
- Precipitation that doesn't reach the ground is called "virga".

9. Visibility

- Haze
  - normally assicated with high pressure systems
  - particularly bad below an inversion layer
  - makes the horizon feel closer than it is
  - areas below cloud are dark!
  - flying above haze negates some of it's effects
- Mist/Fog
  - clouds on the ground
  - fog vis $< 1000m$
  - mist vis $1000m < \text{vis} < 5000m$
- Advection fog
  - Fog caused by advection
  - Prevalent on south western coasts during the summer
  - Generally predictable
- Radiation fog
  - Unpredictable
  - Forms over land during the night due to surface cooling
  - Requires a light wind to mix the shallow layers
  - More likely to occur just after dawn
  - More likely to occur in high pressure systems
  - More likely to occur during the autumn (greater diurnal temperature variation)
- Frontal fog
  - Caused by warm or occluded fronts
  - Occurs just ahead of the front
  - Rain ahead of the front falls and saturates the air beneath it causing fog
- Hill fog
  - Just regular cloud covering a hill
- Flight in rain
  - Visibility reduced
  - Refraction effects, especially at night
- Flight in drizzle

  - Usually $< 3\ \mathrm{km}$ vis
  - Droplets may also stick to windshield

- Flight in snow
  - Often zero vis
  - Very disorientating

- Flight in hail
  - Don't!
  - Very noisy
  - Likely damage to airframe

- Flight in sunlight
  - better to fly away from the sun

- Flight in moonlight
  - better to fly towards the moon, lights up with diffuse light

9.1. Reporting

- In metres
- CAVOK
  - No cloud below 5000ft
  - Vis >9999m
  - No CBs or TCUs
  - NOSIG

10. Low Pressure Systems

- Anti-clockwise wind
- Air generally rising (unstable)
- Air being less dense

10.1. Fronts

- Warm front: warm air catching cool
  - The slope of the front is about 1:150, spreading over 500nm
  - stratiform clouds form ahead of the front (Ci, Cs, As, Ns, St)
  - fog just ahead of the front
  - Sc and veering wind just behind
- Cold front: cold air catching warm
  - cirriform clouds form just behind the front (Cb, Ac)
  - sometimes Ci and Cs ahead of the front
- Occluded front: cold air catches cool air, with warm air above
  - The beginning of the end of a depression
  - Complex weather
  - Cu squalls and embedded CBs

- Stationary fronts: warm and cold air next to each other
- Cold fronts move faster than warm fronts
- “Sectors” follow their respective fronts
- Ahead of a warm front is a cool sector

10.1.1. Formation

- When stationary, air masses sit beside each other
- Typically, a depression is responsible for front formation, this produces a kink in the stationary front. The depression continues to deepen, airflow begins due to the Coriolis force and a defined front begins.

10.1.2. Trough

- Concentrated low pressure
- Increased mixing can lead to more severe weather
- 50nm wide

10.1.3. Squall Lines

- A line of showers with no breaks between them
- No way around!

11. High Pressure Systems

- Anticyclones, clockwise wind
- As the air subsides, it warms, usually at the DALR
- Since air is warmed:
  - dewpoint rises
  - less chance of clouds
  - stable atmosphere
  - light winds

11.0.1. Ridge

- An elongated area of high pressure, bringing fine weather

11.0.2. Col

- A region of stagnant air between two high pressure and two low pressure systems
- Winds light and variable
- In summer, may lead to TS
- In winder, low cloud and poor vis may result

12. Icing

- Generally found in cloud at $< 0°C$
- The freezing level is on forecast charts
- Worst icing is between $0°C$ and $-12°C$
- Super cooled droplets in clouds can contact a sub-zero airframe and freeze
- Classified as either:
  - Trace
  - Light
  - Moderate
  - Severe
- Clouds that hold larger water droplets have more severe icing conditions at lower temperatures

12.1. Icing Types

- Rime Ice
  - Formed by water droplets impacting airframe
  - Brittle
  - Traps air so is semi opaque

- Clear ice
  - Forms as water droplets flow backwards along airframe
  - Often behind Rime ice
  - difficult to remove
  - More dense

- Hoar frost
  - Formed by sublimation
  - The type of frost seen on cold mornings
  - Can dramatically affect aerodynamics
  - Can also form when a cold aircraft flies into warmer air, regardless of clouds
    - Maybe by descending

- Freezing rain
  - Rain falling from a cloud descends into colder air
  - Very difficult to remove
  - Often associated with warm fronts

- Carburettor icing
  - The dewpoint reduces in the venturi tube of the carb
  - Can lead to condensation
  - Fuel evapouration cools air further, leading to enough of a drop to cause icing
  - Can restrict flow or freeze the throttle valve
  - Mostly driven by humidity, more likely on humid days
  - Using carb heat may initially cause rough running (whilst the ice melts), but will eventually return to normal

13. Thunderstorms

- Requires:
  - an unstable atmosphere
  - a supply of moist air
    - humidity
    - high temperature
  - a triggering lift
    - convection from ground heat
    - frontal lift (can cause embedded TSs as well, esp with warm and occluded fronts!)
    - orographic lifting
    - convergence
      - two air masses meeting, for example where land and sea meet
- Thunderstorms can be split into cells, each at a stage of the life cycle:
  - towering cumulus (taller than it is wide, upwards air movements at > 4000ft/min)
  - mature (upwards air on one side and VC, rain on the other, lasts about an hour)
  - dissipating (general rain all over)
- Supercells occur when the winds aloft within the cell move the precip away from the updraughts
  - produces a long living cell
- Associated turbulence with downdraughts
- Mammatus clouds
  - Look like an egg box
  - Do not fly beneath them
- Can affect the aircraft:
  - airframe damage
  - ADF unrealiability
  - other nav equipment damage
  - temporary pilot blindness
  - temporary pilot deafness
- Thunderstorms tend to travel in the direction of 500hPa (FL180) winds, not at lower level prevailing winds

14. Mountain Flying

- Cumulus Granit (CG) clouds
- CFIT risk!
- Winds may not be in prevailing direction
- Air flow over a mountain sets up a standing wave (“mountain waves”)
  - occurs when wind speed > 15 kts
  - wind is within $30°$ of right angles of the mountain
- Clouds can form above mountains as a result of orographic lifting
  - Lenticular clouds form at the peaks of the standing wave

    - Very high icing risk
  - Rotor clouds (roll clouds) form downwind of the mountain range
    - Air movement rotating around the cloud
    - Turbulent air!

- The Foehn effect
  - A hillside is warmer on the lee side than the windward side
  - The warm descending air can be referred to as a Foehn wind
- Terrain funnelling can cause pressure differences and speed differences (Bernoulli effect)
- Katabatic winds caused by air cooling at the surface due to surface radiation (can be very strong)
- Anabatic winds caused by air in contact with the surface warming (very light winds)
- Be alert for turbulence
- If flying parallel, fly upwind
- Cross ridges at right angles to minimise risk

15. Climatology

- Tropical Maritime (from the SW)
  - warm & wet
  - generally stable
  - winter brings dull weather, low cloud, poor vis, possible advection fog
  - summer brings improved vis, possible radiation fog
- Tropical Continental (from the SE)
  - warm & dry
  - generally stable
  - summer heat wave, but often poor vis due to haze and dust
- Polar continental (from the E)
  - cold & dry
  - clear skies and excellent vis
  - winter can bring convective clouds and east coast showers
  - summer brings banks of sea fog
- Polar maritime (from the NW)
  - cold & wet
  - picks up moisture from the Atlantic
  - generally moist and unstable
  - brings convective clouds, showers and TS
  - good vis
- Arctic Maritime (from the N)
  - very cold & dry
  - excellent vis
  - can bring very low night temperatures

- *(This is provided for interest and reference, but is not in the exam material)* Spanish Plume (from the S)
  - very warm
  - often leads to thunderstorms
  - gusty winds
  - hail
  - sometimes tornadoes
  - *See also: https://youtu.be/-nurmSsotk4?t=1055*

16. Weather Reports and Forecasts

- GAMETs (previously AIRMETs)
  - provide a textual description of the current wx situation and an outlook
- Form F215 abbreviations:
  - altitudes relative to MSL
  - frequency abbreviations:

    ISOL (Isolated) $< 25\%$
    OCCL (Occasional) $25\% < x < 50\%$
    FREQ (Frequent) $> 50\%$ with little separation
    WDSPR (Widespread) $> 50\%$ difficult to avoid