



# Weather and its Effect on Caves: a Guide for Cavers



**British Caving Association**  
**December 2011**

Text copyright © British Caving Association 2011

This text is copyrighted under the Berne Convention.

The right of the British Caving Association to be identified as the author of this work has been asserted in accordance with Copyright, Designs and Patents Act 1988.

All rights are reserved. Apart from any fair dealing for the purposes of private study, research, criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, no part of this publication may be reproduced in any form by any means or stored in any retrieval system, or transmitted in any form, or by any means, electronic, electrical, chemical, mechanical, optical, photocopying, recording or otherwise, without the prior permission in writing of the copyright owner, save that parts of the text may be reproduced following notification of that intent to the British Caving Association and provided that the part is issued with the clear acknowledgement of the British Caving Association's copyright and is not associated with any advertisement or promotion of services or goods or other functions for the purposes of gain.

## **Preface**

Caving is a popular sport in Great Britain and is enjoyed by people of all ages, many of whom undertake the activity without incident. However, unless properly prepared a caving trip can be risky. An important part of this preparation should be consideration of the weather and its effect on the selected cave. Caves are often wild places and situated in areas that are subject to the vagaries of the British weather. This publication aims to help the caver to 'read the weather' and to understand how it may affect caves. By making this an essential part of planning any caving trip, it is hoped that people will enjoy a trip free from incidents caused by rising water levels in caves.

## **Acknowledgements**

The British Caving Association would like to thank Steve Long and Dave Baines for their input to this publication, as well as Ben Lyon for allowing us to reproduce some of his diagrams.

## **Illustrations and Photographs**

The cover photograph of Goyden Pot was kindly provided by Graham Mollard.

All other illustrations and photographs are acknowledged within the document.

The illustrations marked as "Copyright Mountain Leader Training" were created by Vertebrate Graphics.

## CONTENTS

Preface.....	3
Acknowledgements.....	3
Illustrations and Photographs .....	3
Contents.....	4
Introduction .....	7
Precipitation.....	7
Wind Speed and Direction .....	7
Temperature.....	7
Visibility.....	7
The Future .....	7
Weather Forecasts.....	7
Telephone/Fax .....	7
Television .....	7
Internet .....	8
Newspaper .....	8
Posted Bulletins.....	8
Radio .....	8
Understanding the Weather.....	9
The Atmosphere.....	9
Areas of Different Pressure.....	10
Creating Wind, Cloud and Rain. ....	10
Weather Systems.....	11
Warm Fronts.....	12
Weather Signs.....	12
Cold Fronts.....	12
Weather Signs.....	13

Occluded Fronts .....	13
Convection .....	13
Mountain Weather (Orographic Lifting) .....	16
Pressure and Temperature.....	16
Rain Shadows .....	16
Weather Maps .....	18
Winds.....	18
Analysing Weather Maps .....	20
Moving Air Masses .....	20
Localised Weather .....	20
Funnel Effect .....	20
Banner clouds .....	21
Fog, Frost and Inversions .....	21
Weather Signs.....	21
Making the Best of the Weather .....	22
Recognising the Development of Bad Weather .....	22
Problem Weather .....	25
Precipitation.....	25
Summer Storms .....	25
Heat Waves.....	25
Cave Flooding.....	25
Importance of Weather to Cavers.....	26
Annual Rainfall in British Caving Areas .....	27
Rainfall Intensity.....	27
Ground Conditions .....	27
The Catchment Area and Drainage.....	27
Run Off .....	32

Flood Pulses.....	33
Flood Hydrograph .....	35
The Cave Passages.....	36
Indicators of Flooding in Caves .....	38
Cave Formations.....	39
Weather Forecasts.....	39
Caving Emergency Card.....	40
Navigating Deep Water in Caves .....	41
Three Days in the Life of the Goyden-Manchester System.....	42
Useful References .....	46

## Introduction

The weather has a profound effect on the upland environment. An overall impression of what the weather might do for the duration of every caving trip is an essential part of the planning process. The final decisions about the trip can use this information to make the best use of prevailing conditions, after considering the following interconnected factors:

### Precipitation

As cavers it is vital to plan very carefully with regard to precipitation. This is only part of your evaluation, as you need to consider the preceding weather conditions, the characteristics of the catchments feeding the cave and the cave passageways themselves. Cold fronts and occluded fronts can have very serious consequences for caving.

### Wind Speed and Direction

The wind can have a tremendous effect on morale and safety. Strong winds can make conditions feel considerably colder than the actual air temperature (the wind-chill effect). An accurate weather forecast may allow a party to plan a caving trip where windy conditions on the walk in have minimal effect.

### Temperature

How cold is it going to be, especially in that wind? Choice of clothing and spares should be modified according to the temperature. Contingency clothing for a cold autumn day will be needed where the same walk to the cave in summer would be done in ordinary caving kit.

### Visibility

Low cloud makes navigation considerably more challenging. It may be very difficult to find the cave entrance or worse – consider emerging from a hole in the ground onto a flat plateau with no reference point visible.

### The Future

Sooner or later the weather will change. Sometimes weather systems move a little faster or slower than the weather forecasts predict, so some understanding of weather-related phenomena can enable the caver to spot warning signs of impending change and act accordingly.

## Weather Forecasts

Forecasts come in many types for different regions and users. Whilst a city businessman decides whether or not to carry an umbrella to work, a fisherman's well-being may depend on an accurate prediction of the sea state. The caver's decision may be to visit a resurgence cave knowing that a flood there would be delayed, to visit a cave with dry inactive cave passages only, or not to go down any cave at all. Cavers need to know where they can obtain forecasts and how relevant the information is to their particular situation. Forecasts are available from the following sources:

### Telephone/Fax

Various companies offer excellent weather forecast services for voice or fax. Cavers should take care to obtain forecasts produced specifically for caving areas. Normally a number is dialled followed by a specific suffix for a particular range. Telephones are becoming increasingly portable, allowing access to weather forecasts even when camping in remote places, provided of course reception is available. However, it is worth checking the cost of these calls since some are commercially run and priced at premium rates.

### Television

Television forecasts are readily available for most households but these are generally quite limited in their relevance for cavers. This is because the forecast is normally designed for the bulk of the population, who work in towns and cities. However, these forecasts can give a useful overview of weather patterns, particularly if attention is paid to the weather maps.

## Internet

The Internet holds the greatest wealth of weather information. Accurate and in-depth forecasts can be obtained for just about anywhere in the world and sometimes a live web-cam view can be used. Many sites are dedicated specifically to mountain areas. There is such a plethora of sites and change is so rapid that it is pointless to list useful sites here other than the U.K. Met. Office at [www.metoffice.co.uk](http://www.metoffice.co.uk). Useful links can easily be book-marked and updated. Some of these can be accessed in remote locations using a web-enabled WAP phone.



Figure 1 Screenshot of Weather Website ([www.metoffice.gov.uk](http://www.metoffice.gov.uk))

## Newspaper

Newspaper forecasts vary in quality. Generally the more serious newspapers also carry the most detailed forecasts and include regional variations as well as weather maps for the British Isles and Europe. Newspaper forecasts give useful information about weather systems and the movement of air masses, but give little information specific to caving regions

## Posted Bulletins

Provided by many tourist offices, outdoor shops and outdoor centres, these displayed weather bulletins are often the most specific and accurate forecasts of all. However, some local knowledge may be required to establish where they are located and also viewing times, which may well be limited to opening hours.

## Radio

Most national radio forecasts focus on the weather for major population centres, so the most useful forecasts for cavers are local stations or Radio 4's Shipping Forecast. Shipping forecasts give an indication of approaching weather patterns, and although awareness of the local shipping areas is required, these forecasts are updated every six hours. Broadcast on 198LW as well as FM, this forecast is available almost anywhere in the UK via vehicle radio or a lightweight handheld one.

From all these sources a wealth of information is available to assist in planning a trip. Effective filtering of this material can allow cavers to make informed choices, even with minimal understanding of meteorology. Sometimes an accurate forecast enables cavers to make a safe decision to not cave at all, or go to a system which does not respond to wet weather to, for example, avoid the passage of

a cold front. A basic understanding of the main weather systems allows the observant caver to spot tell-tale signs of a weather system that is moving faster or slower than forecast.

## Understanding the Weather

### The Atmosphere

A blanket of gasses some 1,000km thick surrounds the earth and protects it from the extremes of temperature that are found beyond. Known as the atmosphere, this mantle is predominantly calm and stable but the 10km in contact with the earth contains most of the inherently unstable water vapour and is consequently forever changing – bubbling in the heat of the sun like a gigantic cauldron. The lower layer of the atmosphere produces all our weather and is known as the troposphere.

### Areas of Different Temperature

Air that remains stationary for any length of time gradually forms a relatively homogenous air-mass that mirrors the relative humidity and temperature of the earth's surface with which it is in contact. There are many reasons why some air masses can be warmer than others, both locally and globally. When warm moist air of one air mass meets the cooler, drier air of another, that vapour condenses into clouds and provides the potential for precipitation.

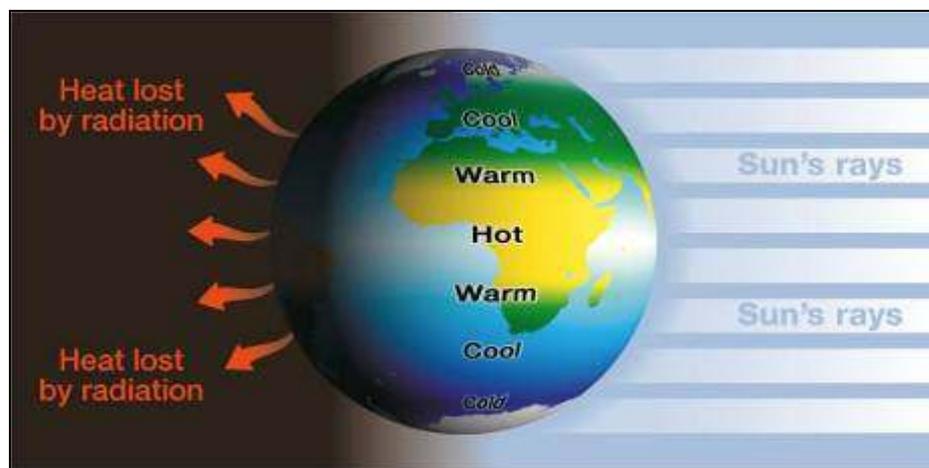


Figure 2 Hot and cold air mass distribution around the globe (Copyright Mountain Leader Training)

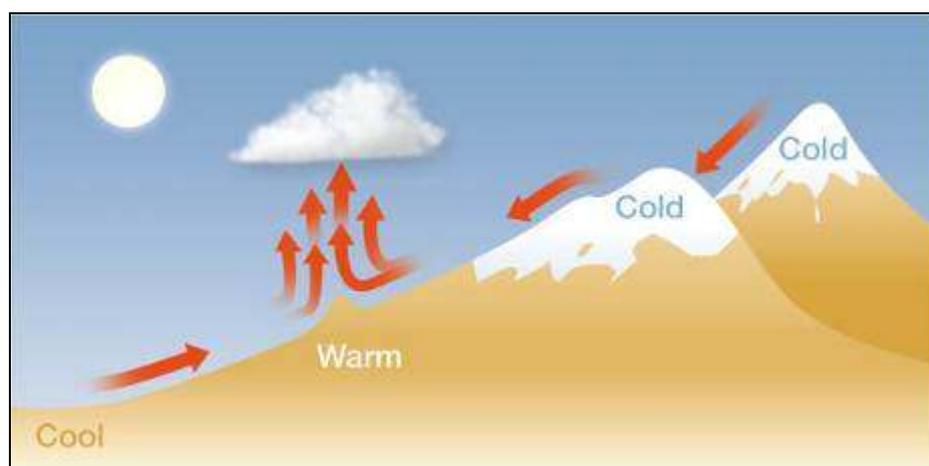
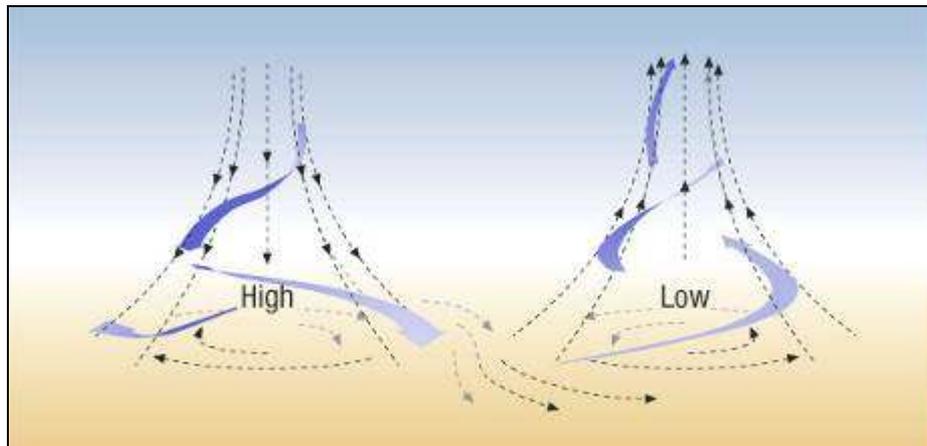


Figure 3 An example of factors leading to localised warming (Copyright Mountain Leader Training)

## Areas of Different Pressure

It is common knowledge that warm air rises. Rather like removing a weight, this reduces the pressure bearing down on the Earth below. The rising warm air is deflected sideways by the rotation of the Earth (known as the Coriolis Force Effect), so it spirals upwards in an anticlockwise direction.



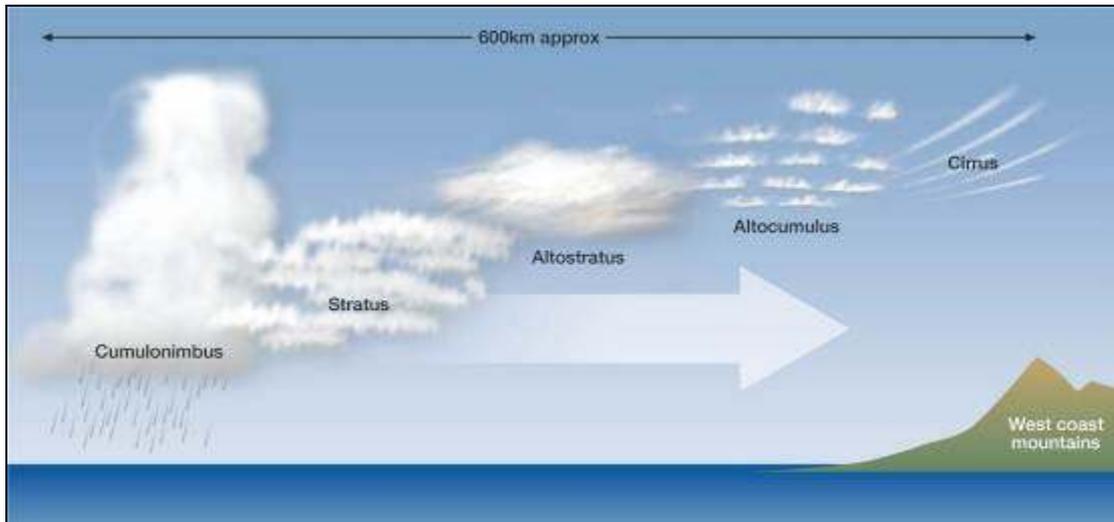
**Figure 4 Air movement in high and low pressure (Copyright Mountain Leader Training)**

On the other hand, cold air sinks and is squashed against the surface of the Earth. This results in an area of higher pressure, and the column of descending air spirals in the opposite direction (clockwise), spreading out at the base. This divergence provides the air that moves into the void left behind by rising air in neighbouring areas of low pressure.

## Creating Wind, Cloud and Rain

Imagine the act of exhaling warm breath on a cold, frosty morning. As it meets the external cold air, this warm air is cooled and condenses into a cloud. Similarly cloud and rain result when warm air comes into contact with colder air. In the Earth's atmosphere, when warm and cool masses meet, the warm air is pushed upwards and the cooler air is drawn in to fill the void: this movement is one of the factors that create wind. On moving upwards the warm air cools and clouds are formed by condensation. One or more of the following three factors usually causes the upward movement and hence condensation:

- **Frontal Weather Systems:** One air mass lifts another. These are large systems that sweep over the whole country, usually in the form of depressions.
- **Convection:** Warm, moisture-laden thermals rise and cool. This occurs on both large and local scales
- **Mountains:** Moisture-laden air is forced to rise over mountains and cools as it ascends.



**Figure 5 Weather system approaching the UK from the west (Copyright Mountain Leader Training)**

### Weather Systems

World-wide air masses range in temperature from the Poles to the Equator. The line where these different masses of air meet is known as a front. Using a military analogy is appropriate because a battle for domination ensues. Perhaps the simplest example of a front is the Polar Front. Here cooler air from the North Pole meets the warmer air from the south. This meeting or Polar Front is often found in the region of the British Isles and its specific location north or south of the country can create significant variations in weather conditions. This mixing of air masses has an enormous influence upon the weather.

Differing air masses will eventually form a homogenous mixture. In the meantime, they sit alongside each other in the same way that adding cold water to a hot bath leaves a chilly layer at the bottom – unless it is actively stirred up.

At the Polar Front the air masses begin to mix when divergence at altitude increases, resulting in less air flowing into the column than is flowing out. This reduces the total weight of the air, and the pressure it exerts at ground level therefore falls. At surface level, air flows into the base of the column of air to fill the void left behind. Now the cycle of a depression has formed, as warm air begins to flow upwards and cool air is drawn in at the base of the air column.

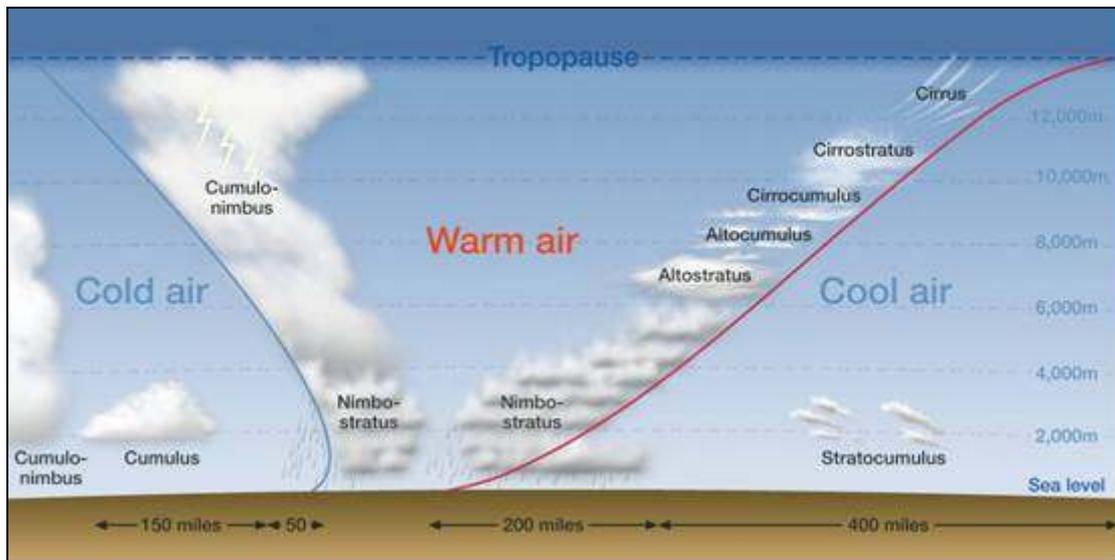


Figure 6 Cross-section through a depression (Copyright Mountain Leader Training)

In Western Europe, frontal systems (often called depressions) generally travel eastwards as a result of the prevailing wind direction being from the South West, after forming over the Atlantic. This is why the wet weather, which sweeps across the U.K. tends to affect the western side of the British Isles first.

### Warm Fronts

A warm front is a mass of relatively warm air advancing towards cooler air usually due to large air movements in the atmosphere. Warm air rises, and slides over the cooler air. The warm, moist air is lifted and progressively cooled, forming high wispy clouds at first, and then ever increasing layers of thick cloud as more moist air is forced upwards.

### Weather Signs

- A halo round the sun or moon suggests the presence of moisture in the form of ice crystals high in the atmosphere. Watch to see if this thickens.
- High wispy cirrus clouds or mare's tails develop as the leading edge of the warm air is cooled.
- Layers of cloud called stratus develop to cover the whole sky eventually.
- These layers of cloud become steadily thicker, and descend as it starts to rain or drizzle.
- The whole sky remains covered during the passage of a warm front, and it is likely to rain or drizzle persistently for some time.

Warm fronts are usually followed by a calm period preceding an even more dramatic cold front. This calm period is characterised by an easing of the wind and bright weather with good visibility. Clouds often begin to tower (cumulus clouds), but as the warm air mass is not being driven rapidly upwards at this point, the clouds do not usually cool sufficiently to cause much rainfall.

### Cold Fronts

A cold front is a mass of relatively cool air advancing towards warmer air. The denser cold air pushes under the warm air, forcing the warm air upwards. As the warm air is lifted, it cools down. Its moisture is forced to condense to produce clouds and precipitation. This happens much more quickly than with a warm front, and the effect is consequently more dramatic.

## Weather Signs

- Sudden blustery showers of heavy rain, and possibly hail
- Cumulonimbus (meaning towering rain) clouds sweep across the sky in belts.
- Clear sunny spells between the showers
- Strong gusty winds, with a possible change in direction.
- Distinct drop in temperature.
- Cold fronts bring the most dramatic weather encountered in mountains, sometimes with dangerous lightning storms.

## Occluded Fronts

In the later stages of a depression's life cycle, the whole warm sector is usually lifted from the ground and replaced by the advancing cold air which piles into the air that was ahead of the warm front. This meeting point, known as an occluded front, has characteristics caused by the relative temperatures of the two cool air masses. Usually the following air is colder and therefore undercuts the air in front. This is known as a cold occlusion, similar in behaviour to a cold front, with strong winds and rain. Sometimes (usually in winter and spring) the following air is warmer and therefore is forced to rise up and over the coldest air, resulting in a warm occlusion. This behaves much like a warm front, with rain and drizzle.

Occlusions usually mark the decline of the storm, so the wind and rain gradually decrease. However, like all weather fronts, the weather will be more pronounced in the mountains because of the increasing lift effect.

## Convection

On a clear day, a south-facing hillside and its summit will warm up in the sun. These warm the air, which then rises to produce localised warm air currents called thermals. On a day with strong thermals, it is often possible to watch gliders using the lifting force to spiral upwards.

As air rises, pressure is reduced. Put simply, there is less of the earth's atmosphere above it to squash the air. A thermal therefore carries warm, moist air upwards, expanding and cooling as it goes. As the air is cooled, the condensation rate increases until dewpoint is reached and visible droplets collect to form clouds. These droplets become steadily larger, like moisture condensing on a window pane. Soon they become so large that their weight causes them to slide down the pane – or in this case – to fall out of the sky as raindrops.

Once the cloud sheds rain, the thermal is cooled, and moisture is gone, and the whole process can start again. Thermals can be very powerful on hot summer afternoons, causing electrical imbalances leading to lightning storms.

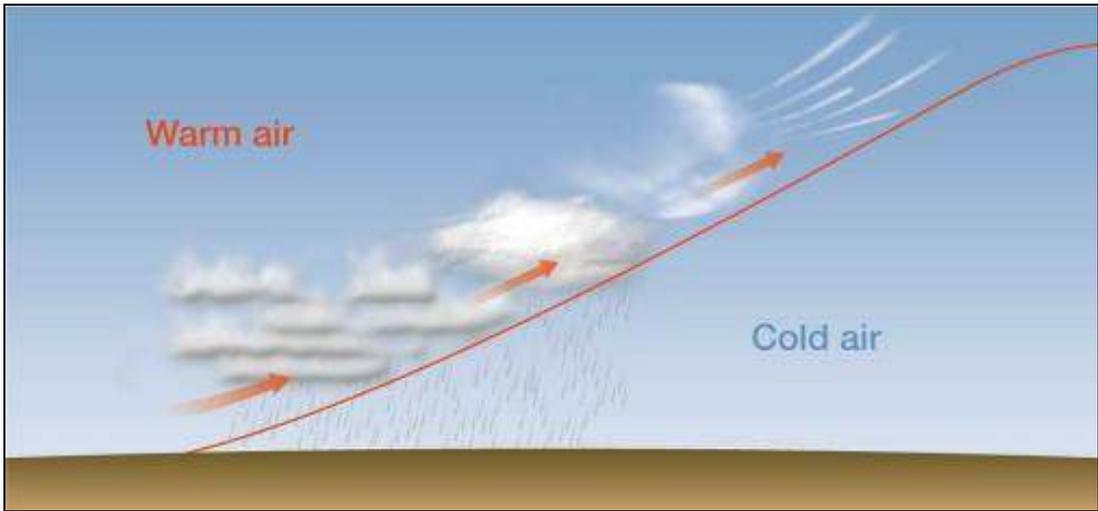


Figure 7 Warm front (Copyright Mountain Leader Training)

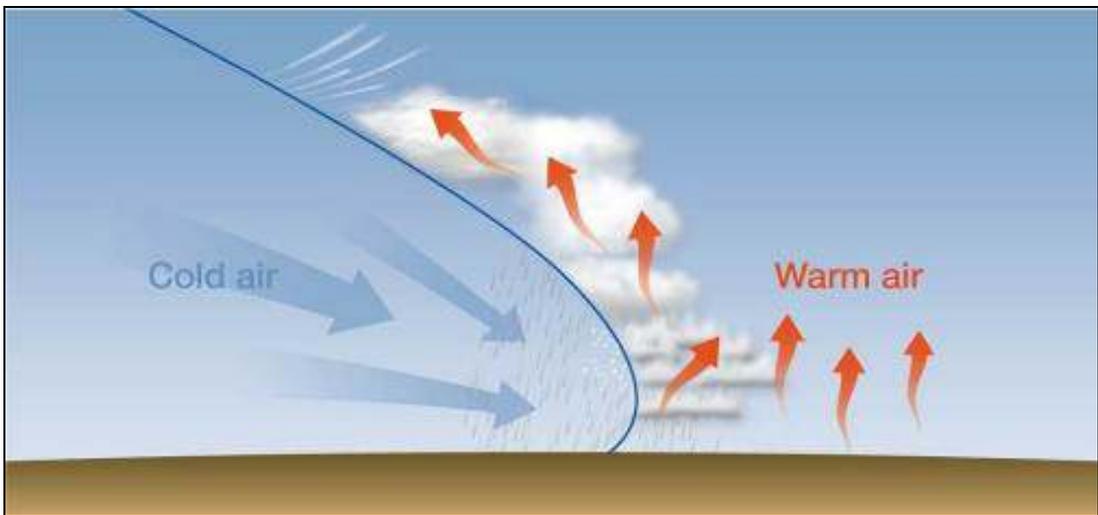


Figure 8 Cold front (Copyright Mountain Leader Training)

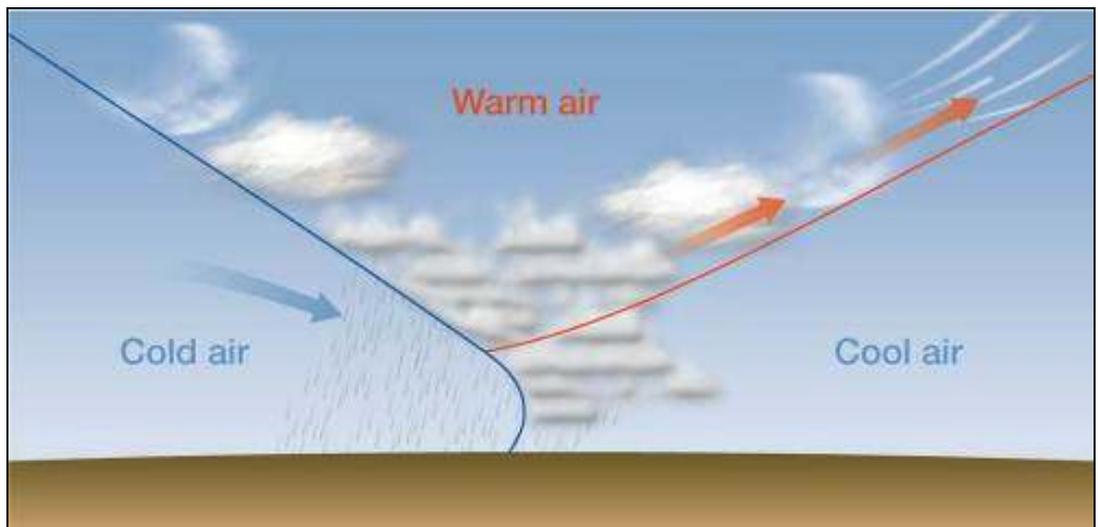


Figure 9 Occluded front (Copyright Mountain Leader Training)

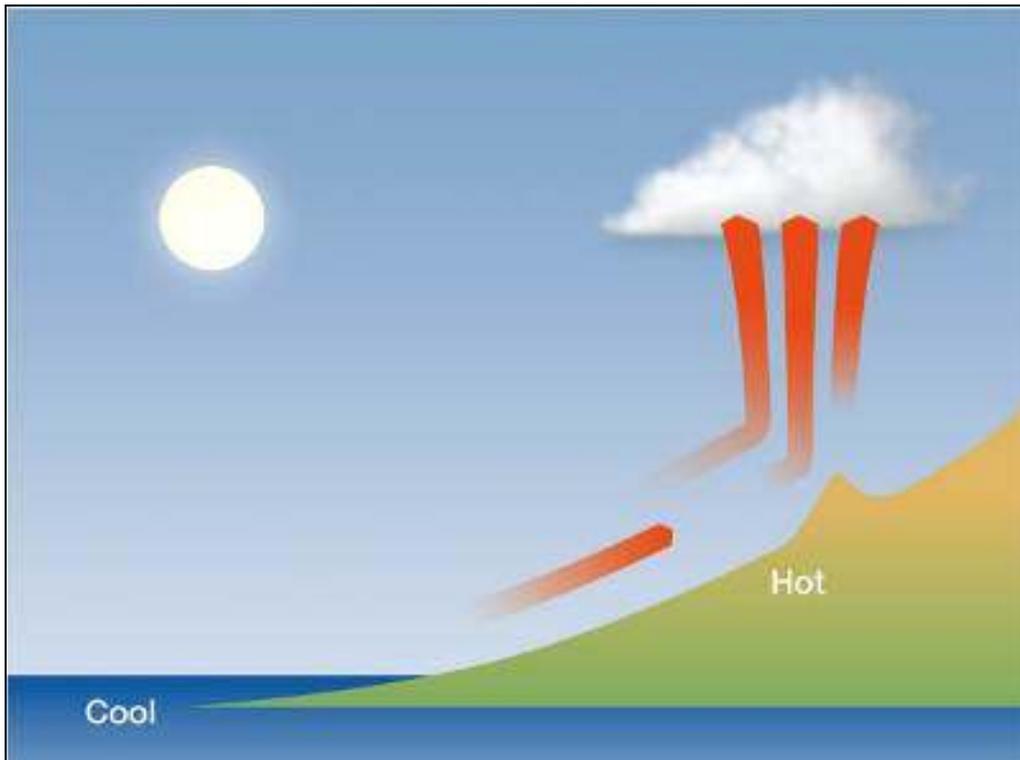


Figure 10 Pockets of air rising and cooling (Copyright Mountain Leader Training)

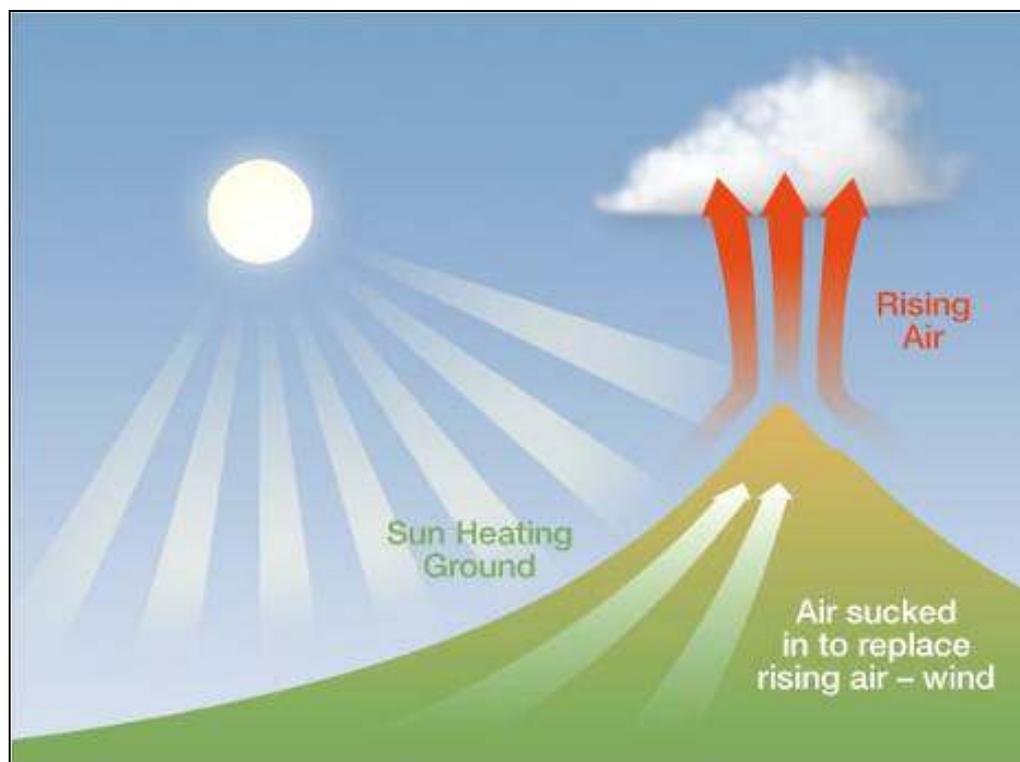
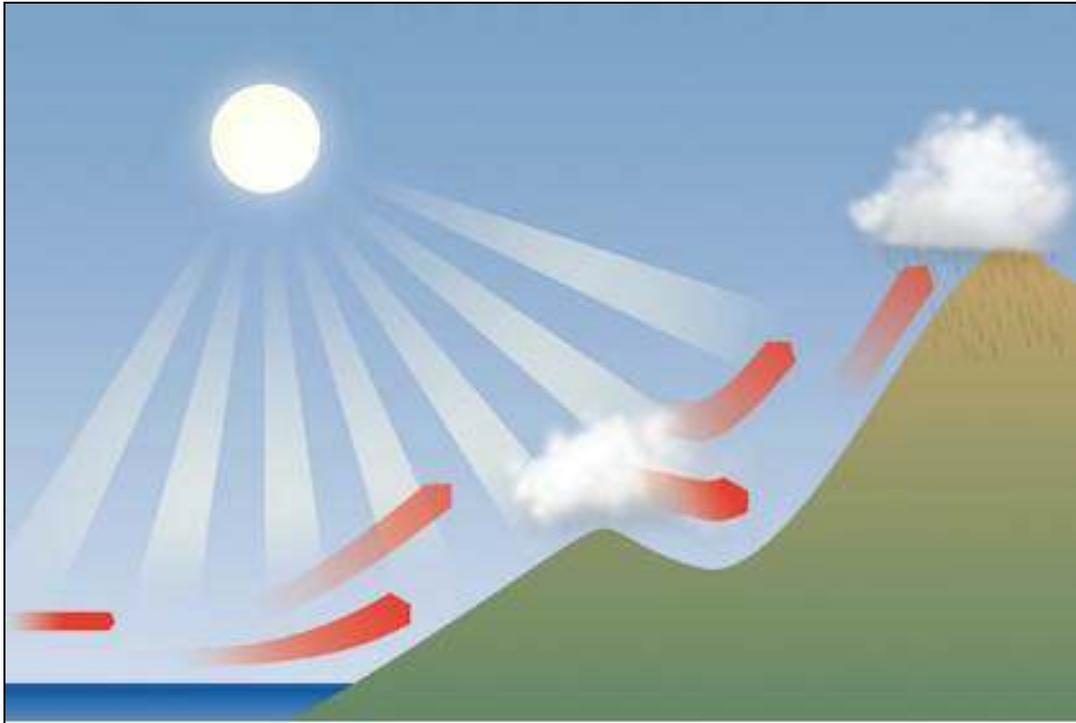


Figure 11 A thermal above a hot summit (Copyright Mountain Leader Training)

## Mountain Weather (Orographic Lifting)

Weather forecasts often mention hill fog, regularly illustrating that the weather is worse in the uplands than elsewhere. This is especially common over the higher ground close to the west coast of Britain and Ireland.

As westerly wind sweeps in from the Atlantic, the western mountains are the first things it meets. These force the warm moisture-laden air up over the tops of the hills.



**Figure 12 Warm moisture-laden air being lifted over mountains  
(Copyright Mountain Leader Training)**

### Pressure and Temperature

Ascending a fellside, the pressure decreases as the height of the air column pressing down on the Earth's surface decreases. There is also a steady reduction in temperature, known as the lapse rate.

Unsaturated air cools at the dry air lapse rate of  $1^{\circ}\text{C}$  per 100 metres. Air that is condensing into a cloud, and possibly into precipitation cools at half this rate because of the heat produced by the process of condensation. This is known as saturated air, which cools at a rate of  $1^{\circ}\text{C}$  per 200 metres (or  $0.5^{\circ}\text{C}$  per 100m). The worst-case scenario for lapse rate is  $1^{\circ}\text{C}$  per 100m, or 1 to 1, which is the easiest way to remember the rule.

### Rain Shadows

As the moist air is lifted over the caving uplands and some of the excess moisture falls as rain, it inevitably becomes drier. As this drier air sinks down the far side of the hill it warms up. The evaporation rate exceeds the rate of condensation and the skies clear.

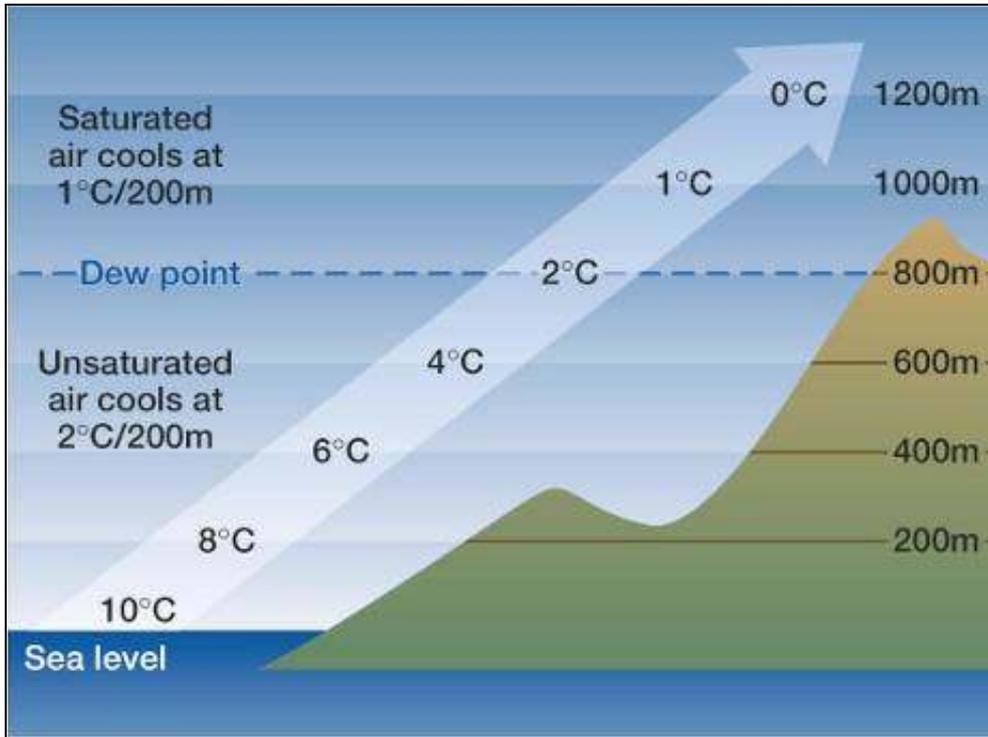


Figure 13 Rising air, dew-point and temperatures (Copyright Mountain Leader Training)

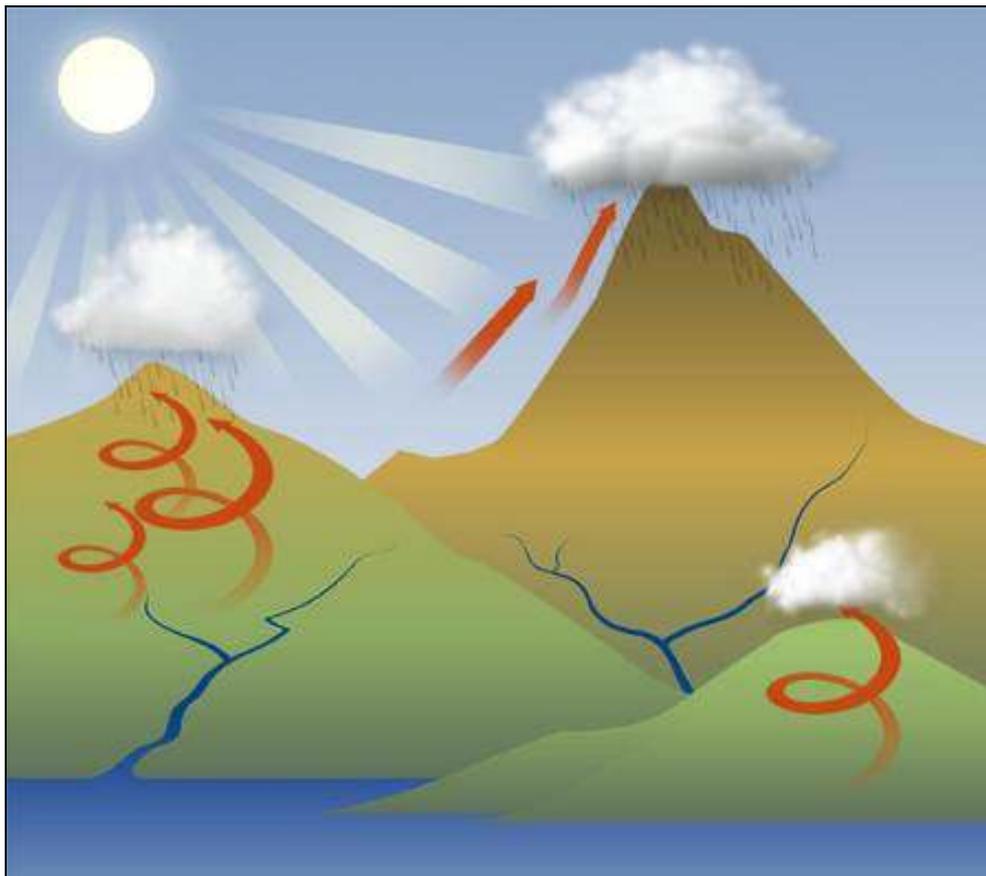
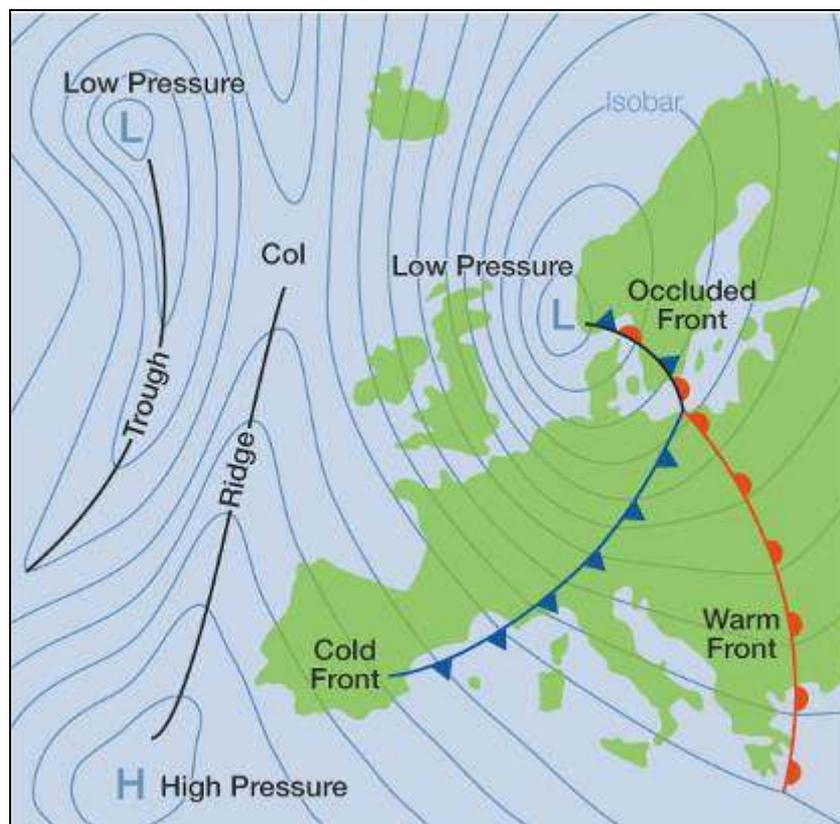


Figure 14 Cloudy foothills and a rainy summit (Copyright Mountain Leader Training)

As moist air reaches the coast the lowlands and beaches may be clear of cloud. Westerly mountains however, force this moist air upward to form mist, hill fog, cloud and rain. Snowdonia, the Brecon Beacons or the western side of the Yorkshire Dales would be typically damp on such a day. However, further east, Derbyshire, which is in the rain shadow of Snowdonia, and Mendip, which is protected by Dartmoor and Exmoor, would be likely to receive less precipitation. Much of the moisture has already fallen and the clouds may start to break up. Rainfall graphs confirm that these areas do indeed have lower annual rainfall figures.

## Weather Maps

Weather maps, or **synoptic charts**, plot the differences in pressure and use symbols to represent the reported or anticipated weather at a given time. Lines, called isobars, are similar to contour lines on a map – except that they join points on the earth's surface of equal air pressure. Isobars are grouped more closely where the pressure is falling rapidly, known as a steep pressure gradient. The contour-lines metaphor can be extended to winds.



**Figure 15 A synoptic chart showing features (copyright Mountain Leader Training)**

A steep pressure gradient results in strong winds. Just as balls roll faster down a steeper slope, air movement is faster when there is a marked difference in pressure. As a rule of thumb, lots of information on the chart suggests plenty of weather activity. Areas of little information suggest calmer weather.

### Winds

Air will always flow from areas of high pressure to fill areas of low pressure.

It follows that the cooler air, which is heavy and spiralling downwards, will flow outwards as it spreads over the surface of the earth. Likewise, the areas of warmer air spiral upwards and suck in air to fill the space left behind.

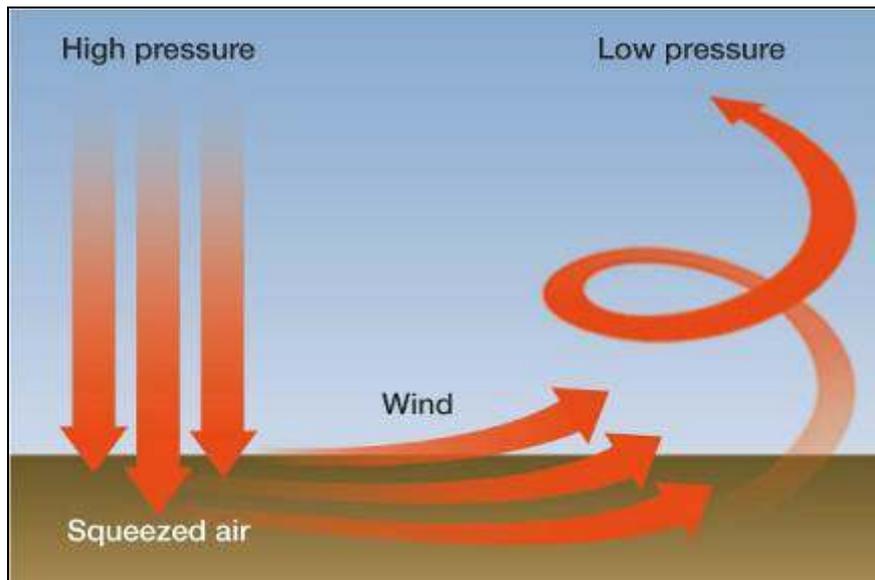


Figure 16 Air squeezed from high to low pressure (Copyright Mountain Leader Training)

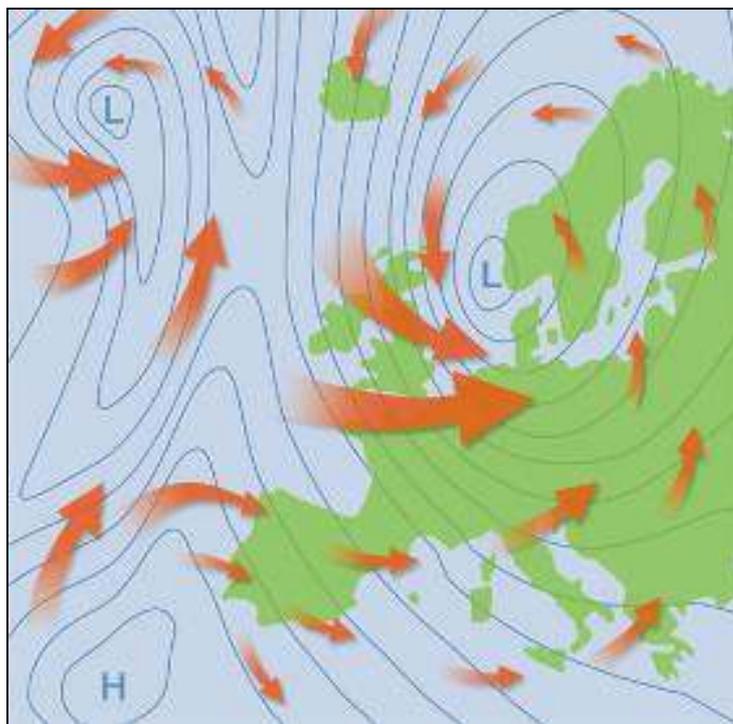


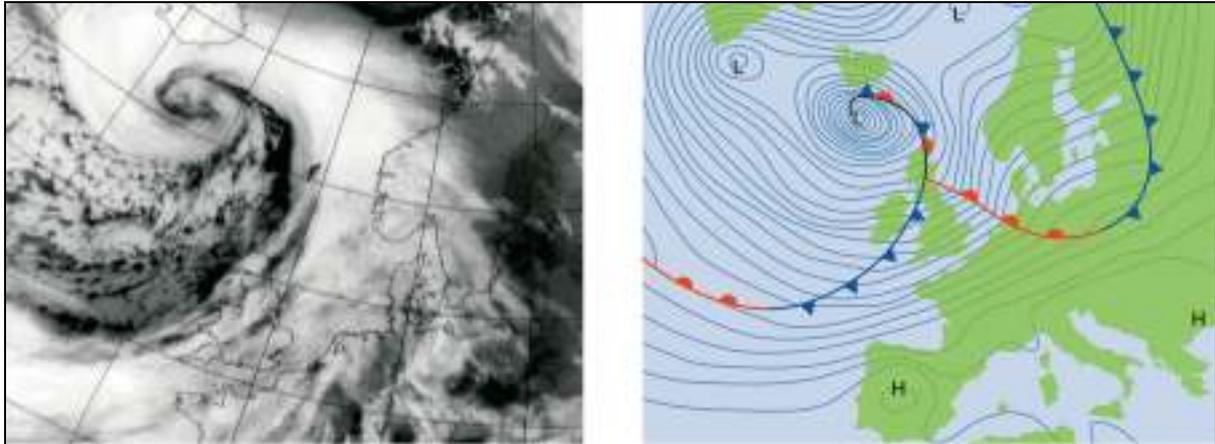
Figure 17 Wind direction associated with pressure systems (Copyright Mountain Leader Training)

The following rules help to interpret the wind speed and direction from a synoptic chart:

- Low-pressure air masses rotate anticlockwise and the winds blow slightly inwards from the isobars;
- High pressure air masses rotate clockwise, and the winds blow slightly outwards from the isobars;
- The closer the isobars, the stronger the wind.

## Analysing Weather Maps

A simple analysis of a synoptic chart allows covers to understand the mechanisms behind the weather forecast and builds an awareness of any changes that develop. Weather forecasting is not an exact science, and sometimes weather systems change speed or direction due to unforeseen factors.



**Figure 18 A satellite photo of a 'model' depression (left) with the same information plotted on a synoptic chart (right) (Copyright Mountain Leader Training)**

With practice, the key components on a synoptic chart can be quickly spotted. Low and high pressure zones can easily be identified and the spacing of isobars gives an indication of wind speeds.

For frontal systems the key information is:

- The type of front. That is, warm air rising over cold air, or cold air diving under warm.
- The direction of movement. The best charts include the past direction travelled.
- As a rough rule, the more a front deflects from the line of an isobar, the more dramatic the resulting weather will be.
- Any occlusions, where two fronts have combined. This is a sign of frontal systems starting to stabilise and decline, although in the short term it may bring prolonged rain and cloud.

### Moving Air Masses

A synoptic chart that shows the direction of movement of weather systems gives a simple indication of where air masses have travelled. Air that has travelled over an ocean will naturally be relatively moist, while air from a continent will be drier. In the northern hemisphere, air masses that are being pushed northwards from further south will be relatively warm, while cool air from the north will be gradually warming as it travels southwards.

### Localised Weather

Most weather features drawn on charts are countrywide. Uplands may exaggerate their characteristics, but the entire country will be affected by the associated weather. The shape of the ground can influence the weather, and form mists and fogs. The fells and uplands where caves are often found can create their own weather by lifting and cooling air masses, and also due to the following localised effects:

#### Funnel Effect

The hills can funnel winds, resulting in dramatic localised variations. As the air is squeezed between the hills, it is forced to accelerate through the narrower gap. Summits and saddles are therefore often much windier than surrounding country. However, powerful eddies can form on the leeward side, resulting in strong winds flowing in a different direction to the main weather pattern. Be aware that in Europe and further afield, cave entrances are often located on the flanks of big mountains.

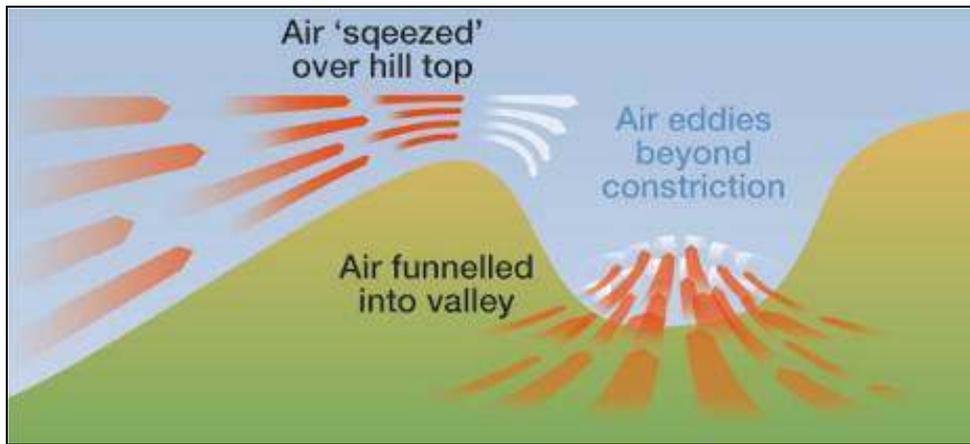


Figure 19 Funnel effect and eddies (Copyright Mountain Leader Training)

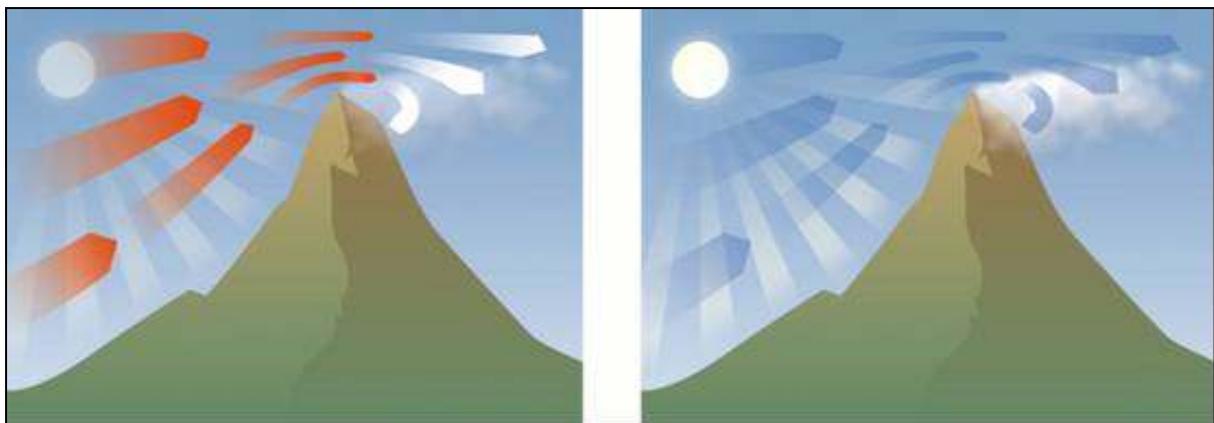


Figure 20 The formation of banner clouds (Copyright Mountain Leader Training)

### Banner clouds

High winds squeeze over the summit, squashing the air over the top. On the lee side of the ridge, the air expands, cools down and condenses into a banner cloud. This effect giving warm sunshine on one side of the ridge, and cool clammy mist on the other, is often associated with high pressure.

### Fog, Frost and Inversions

As cool air sinks, it can pour into hollows and become trapped by its own density, with a layer of warm air above. This effect is called temperature inversion.

Valley fog in the mornings and hazy hill fog on higher ground is associated with high pressure, which allows temperatures to fall dramatically during the clear night due to convection.

### Weather Signs

- Layers of mist in the bottom of valleys the morning after a clear or frosty night. Notice how this fog quickly disappears in the sunshine, and lasts longer in the shade.
- Sheets of hazy hill fog pouring over ridges as the cooler air spills over into the next valley. It will probably be beautifully sunny elsewhere.

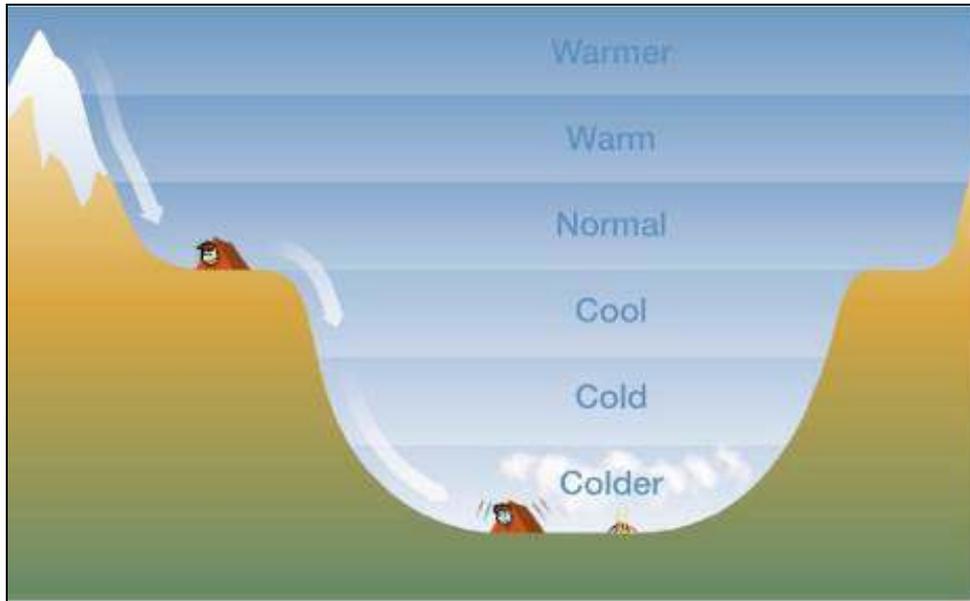


Figure 21 A temperature inversion (Copyright Mountain Leader Training)

## Making the Best of the Weather

Safe, enjoyable caving usually involves an element of good timing. An accurate weather outlook can allow a caving trip to go ahead, be modified, or if necessary be scrapped. On the day itself a weather forecast allows cavers to choose an appropriate trip.

### Recognising the Development of Bad Weather

Weather systems bring identifiable clouds as a front approaches. Observation of these developing clouds can therefore help cavers anticipate weather changes or compare the clouds with the weather forecast and predict changes in its timing.

At a very basic level, a progression from high wispy clouds (cirrus types) through to lower and lower layers of clouds (stratus types) is a clear indication of an approaching warm front. The higher stratus layers, known as cirrostratus, often form a halo around the sun or moon, so a halo around the moon is often a good early warning of rainfall arriving in the morning. The time taken to progress from cirrus to altostratus is generally similar to the time remaining before the rain arrives.

When a low-pressure system is approaching, the high-altitude winds move in a different direction to the air movements below. The practical application of this is known as the crossed winds rule: cirrus clouds oriented in a different direction to low clouds or even the smoke from a chimney stack are reliable indications of changing weather.

Recognising the passing of a warm front can allow the prediction of a cold front that is likely to arrive after perhaps a day of more settled weather.

'Cotton wool' shaped clouds, (known as cumulus), show cells of rising air, but if they do not continue to expand vertically the air mass is reasonably stable. However, in unstable conditions the clouds will tower upwards to form cumulonimbus clouds, which may be sheared off by high-level jet stream winds. These are often referred to as 'anvil clouds' and are a good indicator of cold fronts. These can bring thunder and lightning storms, often associated with hailstones, which are formed by the cooling of raindrops forced upwards within the cloud by the powerful spiralling updraughts.

In showery conditions, the blackening of cloud can often be seen developing on the horizon, allowing plenty of time for waterproofs to be donned.

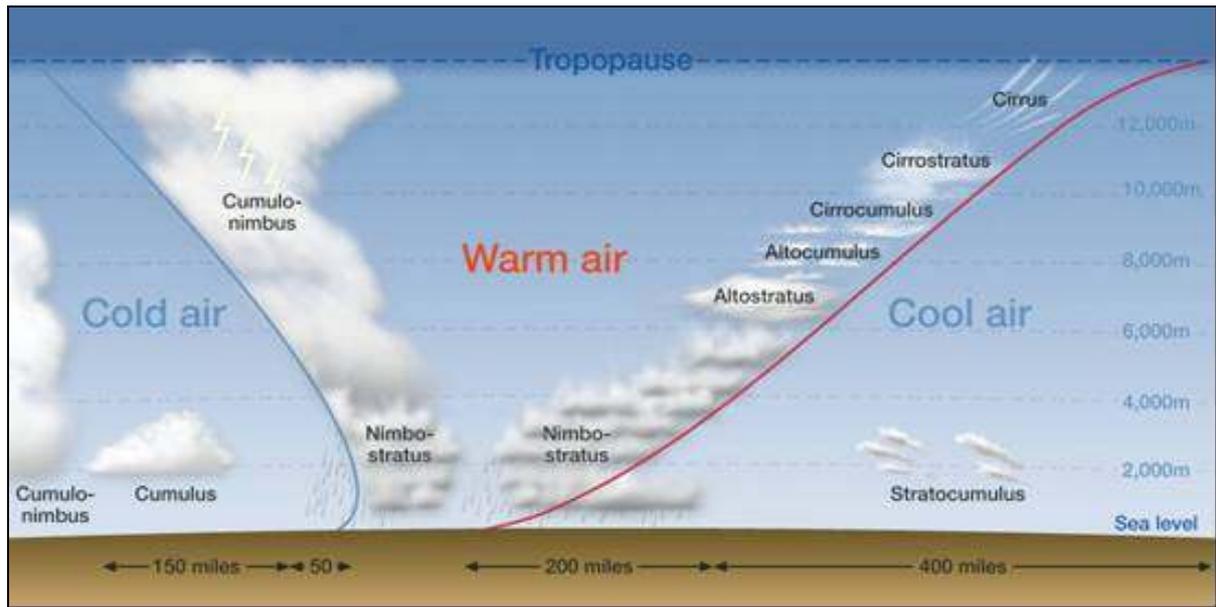


Figure 22 Cross-section through depression showing cloud types (Copyright Mountain Leader Training)

## Types of clouds

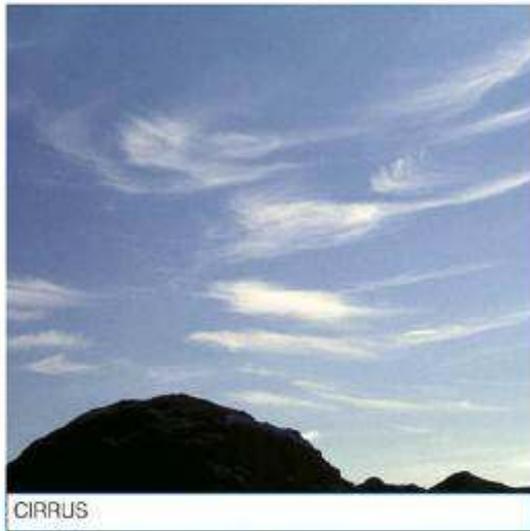


Figure 23 Types of clouds (Copyright Mountain Leader Training)

## Problem Weather

### Precipitation

As cavers, it is vital to plan very carefully with regard to precipitation. However, this is only part of the evaluation. Also important are the preceding weather conditions, the characteristics of the catchments feeding the cave and the cave passageways themselves. Cold and occluded fronts can have very serious consequences for caving.

### Summer Storms

In summer, a prolonged period of high pressure can result in humid conditions that are dissipated by afternoon thunderstorms. If towering clouds begin to develop, this should be seen as a warning. In these conditions it is best not to go caving. The storm can begin very quickly and disastrous flash flooding can occur within 20 minutes of the onset of rain, which will be extremely heavy. Do not be tempted to go underground if thunder storms had been forecast on previous days and not materialised. The risk is too great.

### Heat Waves

The British are notorious for underestimating the debilitating effect of heat exhaustion and dehydration. Weather planning allows the group to seek out caves that do not have a steep or long approach. Walking to the cave in light clothing with caving gear in a rucksack is a common-sense approach to caving in hot weather.

## Cave Flooding

The subject of cave flooding requires an understanding of 3 areas: U.K. limestone caves, weather and hydrology.

In 1979 an analysis of incidents from the Clapham-based Cave Rescue Organisation records showed that "falls", as might be expected, accounted for the highest percentage (24%) of the total call-outs. What may be a surprise is that flood-related incidents were almost equal to this at 23% (Forder 1979). By 1993 the situation had reversed with floods now marginally higher than falls as the main cause of call-outs. By 2008, of the 15 cave-based incidents handled by Cave Rescue Organisation that year, 46% were due to flooding and only 13% were caused by falls or slips.

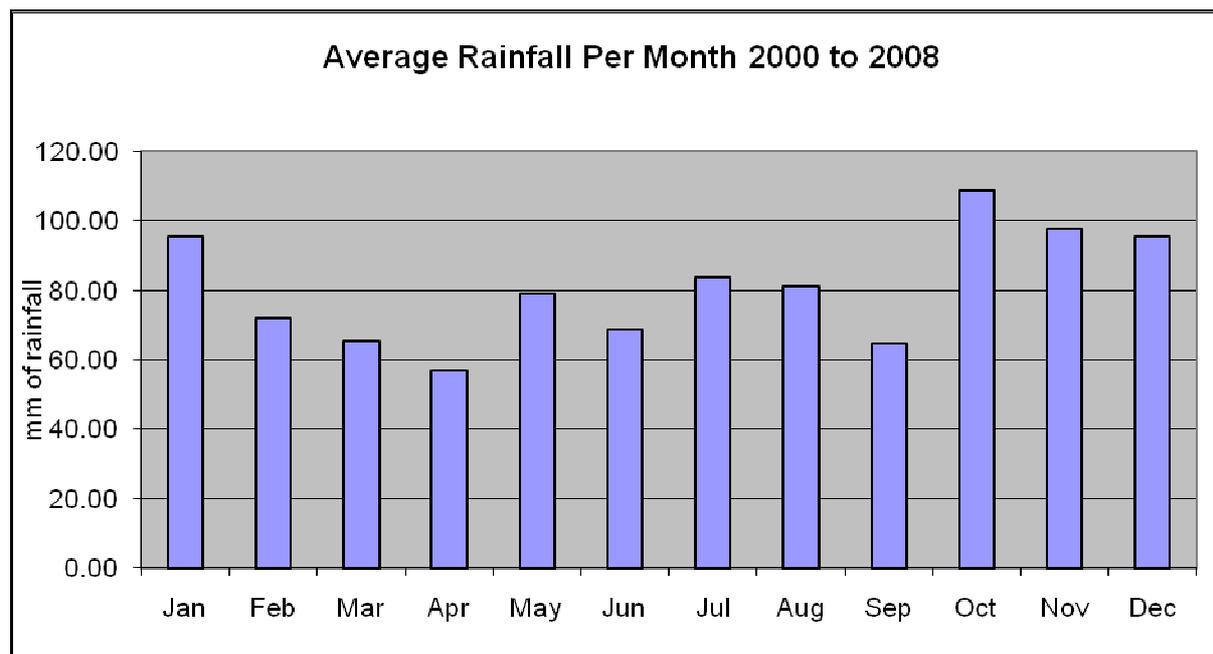
There are four major factors that can affect how a cave will flood:

1. The rate, type and amount of precipitation;
2. The conditions prior to the current precipitation;
3. The characteristics of the area draining into the cave;
4. The characteristics of the cave itself.

When several of these factors occur together, then rapid and disastrous flooding is likely underground. For example:

- Snow (stored precipitation) lying on high ground, possibly with the ground beneath frozen hard, followed by a warm and cold front, (heavy rain coupled with temperature rise and snow melt).
- In summer with high pressure and baked ground which will not absorb water, a thunderstorm onto a high catchment area with little soil cover, will result in sudden & intense run-off.
- Under low pressure with the ground saturated by a succession of frontal systems and stream levels high, a warm front tops up the levels, then a cold front delivers a deluge.

The chart below shows the average rainfall for England and Wales per month for the period 2000 to 2008, based on figures available from the Met Office.



**Figure 24 Chart showing average rainfall in England and Wales, per month since 2000**

Severe flooding events can occur at any time. The BBC Weather website highlights some events from the past including:

- Rainfall for September to November 2000 was the highest since records began in 1766.
- In 2000 catchments became waterlogged so that rivers responded rapidly to even modest rainfall. The River Ouse in Yorkshire reached its highest level since 1625.

Indeed few people will have forgotten the flash floods in August 2004 that devastated the village of Boscastle in Devon, or more specifically, December 2007 when flooding resulted in a fatal incident in Long Churn Caves, Yorkshire.

## Importance of Weather to Cavers

Precipitation is the most important factor in deciding if and when a cave is liable to flood. Duration, intensity and direction of rainfall affect the rate of run off from a catchment area, i.e. how much water actually flows into the cave per unit of time.

- Duration: the longer it rains, the more saturated the ground becomes.
- Intensity: the intensity of rainfall can force a rapid increase in the stream flow, particularly on open upland areas where run off is very rapid.
- Direction: the slope facing into the driving rain will “collect” the rain more effectively, leaving the lee slope less affected.

Precipitation stored as snow will give rise to stream flow when it melts. If this is accompanied by rainfall, the combined effect is the same as rainfall of greater intensity.

## Annual Rainfall in the Major British Caving Areas

Mendip	1380 mm	300 m+ uplands
South Wales	1750 – 2250 mm	600 m+ hills *
Derbyshire	1250 mm	400 m limestone uplands
Yorkshire Dales	1750 – 2750 mm	600 m+ hills *

\*Note that the Yorkshire Dales & South Wales are the first areas of high ground reached by westerly depressions. Derbyshire is in the rain shadow of the Welsh hills and the Mendips is in the rain shadow of Exmoor and Dartmoor.

## Rainfall Intensity

Continuous drizzle	Around 1 mm per hour
Light rain	2 mm per hour
Continuous rain (warm front)	4 mm per hour
Heavy driving rain (cold front)	6 – 8 mm per hour
Thunderstorm rain	25– 100+ mm per hour

Predicting rainfall is best done by obtaining at least two weather forecasts, as late as possible before the trip, and relating the information to knowledge of weather in upland areas. Very local forecasts can now be gained from the Internet, e.g. Met Office, BBC, RAF Met Station.

## Ground Conditions

Current situations and those of the preceding day(s) are best assessed by observation and local knowledge. If you do not have the benefit of both of these, the questions to ask are:

- How much rain fell yesterday / this week? How heavy was it? What was its duration etc?
- How are stream levels generally in the area? In the Yorkshire Dales, for example, there are often particular places to observe the levels, e.g. God's Bridge in Chapel le Dale, the road-side stream at Ribblehead, Easegill Beck viewed from the road approaching Bull Pot Farm, the river at and above Keld Head in Kingsdale etc. Examples in the Mendips include the streams that run into Swildon's and the Longwood Swallet.
- Can many little streams be seen flowing down the hillsides in just about every little gully and dry valley?
- How dry or sodden is the ground in the locality?
- What is an acceptable / safe level for the stream which flows into or out of the cave?
- How does the cave respond to rainfall?

If you do not have the benefit of local knowledge, there are key places to find this in each caving area. Caving equipment shops can be a good starting point, or cafes where cavers are usually catered for and caving club huts, e.g. South Wales Caving Club hut at Penwyllt, or the Red Rose Cave & Pothole Club at Bull Pot Farm.

## The Catchment Area and Drainage

In looking at the catchment area for a cave, it is necessary to consider whether the cave is a swallet (a cave where the water goes underground), or a resurgence (where the water emerges), since they both respond differently to rainfall. All swallets lie at the bottom of a drainage basin – the catchment - and resurgences are either the outfall of one or a number of swallets, e.g. Dan yr Ogof, or collect water discretely by percolation, originating from a catchment area with no surface streams, e.g. Lathkill Head Cave.

<b>SWALLET</b>	<b>EFFECT</b>	<b>EXAMPLES</b>
<b>Often on high ground with smallish, local catchment</b>	Flooding quite rapid, possibly 30 minutes from onset of rain.	<i>Meregill Hole Black Shiver Sunset Hole Ogof Fawr</i>
<b>Situated lower but with large catchment</b>	Flooding may be less rapid & more gradual but reaches huge proportions & lasts longer.	<i>Easegill System into Lancaster Hole Porth yr Ogof</i>
<b>With stream flowing into entrance</b>	Stream may enlarge to quickly make entrance impassable or quite difficult.	<i>Mosssdale Caverns P8 / Jackpot Swildon's Hole Longwood Swallet</i>
<b>Descends steeply via pitches</b>	Pitches and steep cataracts become impassable	<i>Diccan Pot Marble Steps Pot Slaughter Stream Cave (Wet Sink)</i>
<b>Large boggy area with surface vegetation, usually of moorland type e.g. sphagnum moss, grass and soil type peat</b>	Capable of releasing copiously when saturated. Called a "bog burst".	<i>Waun Fignen Felin Sink (Dan yr Ogof) OFD Streamway</i>
<b>Situated at foot of steep fellside in own small valley basin</b>	Steep slope & semi-circular basin + high ground combine to focus flooding with streams rising simultaneously at entrance.	<i>Long Churn Caves, Pwll Byfre (sink for O.F.D.) Llethrid Swallet Ireby Fell Caverns</i>
<b>Situated on river bank of normally dry river bed</b>	Entrance inundated by rising water in river or pulse running down river, possibly very quickly and rising several feet above entrance.	<i>Ibbeth Peril Cave, Little Neath River Cave Pool Sink Redhouse Swallet New Goyden Pot</i>
<b>Normally dry river bed flows directly to entrance</b>	Flooding from large catchment area with corresponding catastrophic results	<i>Goyden Pot Cwm Pwll y Rhyd</i>

RESURGENCE	EFFECT	EXAMPLES
Usually in or near valley having large catchment from one or several swallets	Flooding steadily to a peak over 24-36 hours from the onset of rain. Reaches large proportions and remains high reducing slowly.	<i>Speedwell Cavern</i> <i>Ingleborough Cave</i>
May be no obvious feeder swallet but high percolation catchment area	Produces unpredictable response to rainfall possibly 2-3 days later.	<i>Sleets Gill Cave</i> <i>Llygad Lluchwr</i>
May have permanent stream flowing from entrance or spring close by	Flooding enlarges stream to become too powerful or deep for safety.	<i>Llygad Lluchwr River Chambers</i> <i>Kingsdale Master Cave</i> <i>Craig a Ffynnon</i> <i>OFD 1</i> <i>White Lady Cave</i>
Often quite horizontal in nature, possibly wide & low – developed on bedding plane	Low passage can flood totally cutting off escape.	<i>Lathkill Head Cave</i> <i>Porth yr Ogof</i>
Surface vegetation / soil type on catchment – possibly large high moorland area similar to swallet example	Gathers large amount of water, which is released into cave system via percolation & small sinks.	<i>Dan yr Ogof</i> <i>Sleets Gill Cave</i> <i>Hospital Cave</i>
Surface sinks & feeders in different valley or other side of mountain	Very localised rainfall (e.g. thunderstorm), which may not be evident at the entrance, can produce surprise floods.	<i>Skirwith Cave</i> <i>White Scar Cave</i>



Figure 25 The stream flowing into the entrance of P8 in the Peak District in normal conditions (photograph by Nigel Ball)



Figure 26 The stream flowing into the entrance of P8 in the Peak District in wet conditions (photograph by Rob Eavis).

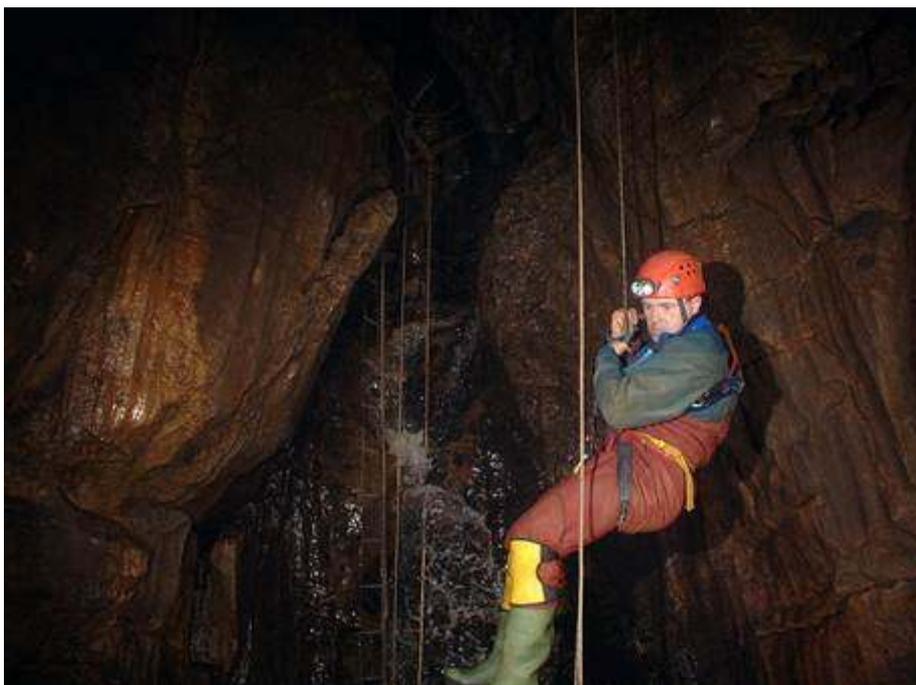
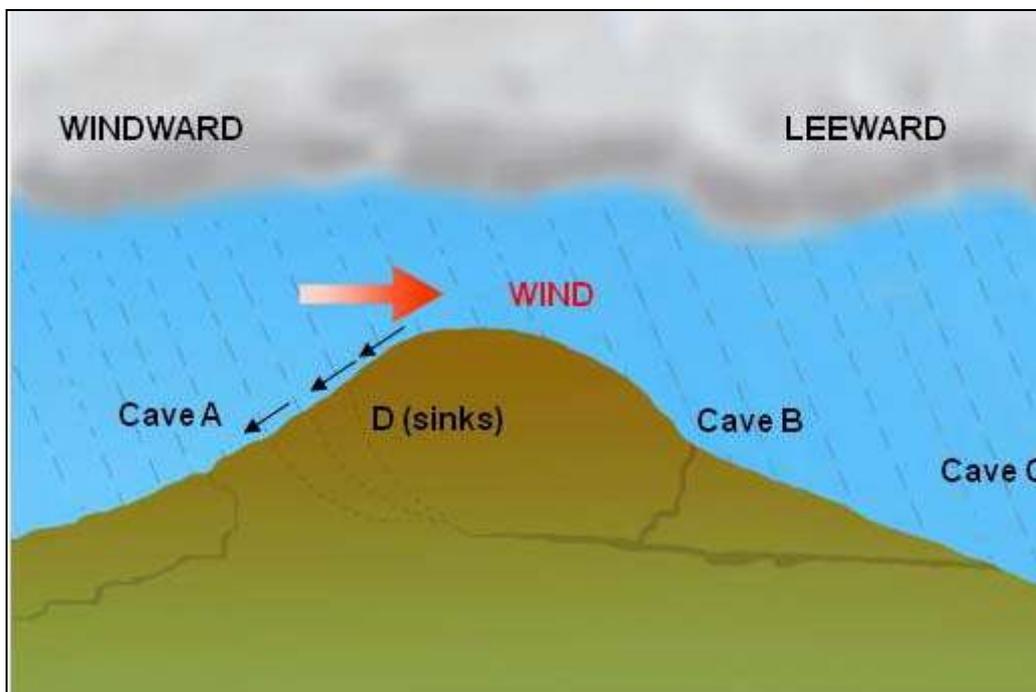


Figure 27 A pleasant trip on the first pitch in P8 during dry conditions (Photograph by Duncan Jones)



**Figure 28** In wet conditions the same pitch in P8 can become a far more serious prospect. (Photograph by Rob Eavis)

Cavers should be aware of possible emergency escape routes or 'safer' areas to sit out a flood if available. Rain blowing onto a slope creates greater run off on the windward side. This can be the other side of the mountain, but it can still run into the cave. This can be seen with cave C in the example below.



**Figure 29** Cave locations (Tony Boyle)

Cave A will respond quickly & possibly alarmingly to the rainfall. A pulse may be triggered as the sinks at D feeding cave C reach capacity & overflow down to cave A.

Cave B will probably be affected less than A. The effect may not be particularly serious, but the pitches in this more vertical system may become impassable. A wait at the junction with C might be involved, as the low passages here may sump.

Cave C will be affected later than A, as it will take time for the water to feed through from the sinks D to the known end of the cave. If this is a sump, its outlet could be a dangerous place to be, given that sumps are known to respond quite suddenly. A caver would then be a long way from the entrance. The horizontal section from the junction with B to the entrance may sump completely, cutting off escape.

### Run Off

Not all rain that falls is converted immediately into stream run off. The art is being able to judge the effect that the predicted rainfall will have. A number of factors have to be taken into account.

Those tending to increase run off are:

- Prolonged rainfall
- Intense rainfall
- Windward slope
- Altitude of the catchment

The following also need to be taken into consideration:

- Slope of the catchment - the steeper the slope, the faster rain runs off it.

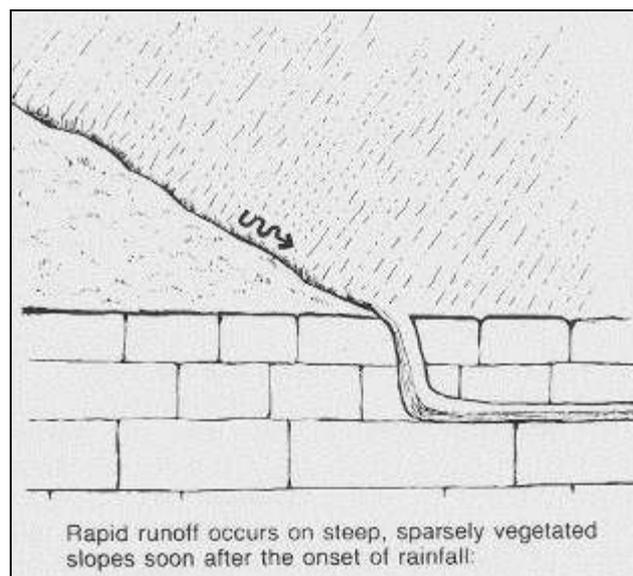
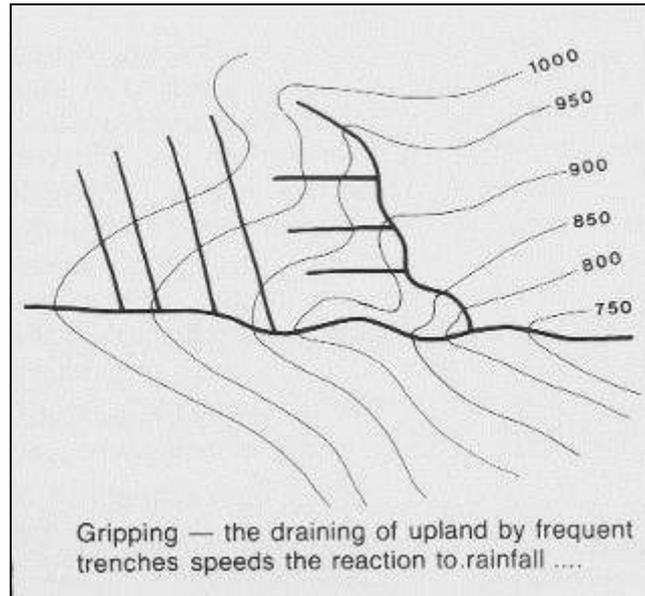


Figure 30 Diagram showing rapid run-off (Ben Lyon)

- Gripping - artificial drainage channels. The sooner surface water reaches gullies and streamlets, the faster it runs off, such as above Calf Holes, Yorkshire.



**Figure 31 Diagram showing gripping (Ben Lyon)**

- Smooth channel streams - water flows slowly down irregular rocky stream beds. It flows rapidly down smooth peat or similar gutters.
- Bare limestone surfaces - on any surface with no soil or vegetation, the rain just runs straight off.
- The state of the soil surface - baked dry ground (summer), frozen hard ground (winter)

Those tending to decrease run off are:

- Dry ground (not baked) - the earth will soak up water like a sponge instead of running through or flowing over the surface. This tends to increase during the summer, due to greater evaporation and plant uptake, but if the ground becomes baked hard in prolonged dry weather this will increase run off.
- Plant interception - vegetation cover prevents rain from reaching the ground until a certain amount has fallen. This increases during the summer or all year round under conifers. For instance, broad-leaved woodland can decrease run off by up to 60%. Conifer plantations may have gripping, which may in turn increase run off.

### Flood Pulses

Water flows most slowly down a stony stream bed. At normal rates of flow in upland streams – say more than 24 hours after rain, the flow will only be a mere fraction of the bank full discharge perhaps 1/1000<sup>th</sup> to 1/10<sup>th</sup> full. An increase in flow will be effectively lubricated by the existing flow, and so flows faster. In limestone stream beds where in normal conditions all the flow has sunk through into caves below, the stream bed may be dry. However an increase in water flow due to increasing run off will appear in the dry section as a sudden pulse, with no warning. Due to the friction of the river bed on the initial flow of water, coupled with the faster flow of water behind the initial “head”, the flood pulse will be both sudden and rise to greater flow volume. The stream then settles down to a steady, high volume state of run off afterwards. This settling down will take 5 to 10 times as long as the initial build up of the pulse. Inside a cave of course, there are no banks to spill over, and so “bank full” discharge will possibly equate to water touching the roof.

A classic example of a cave and catchment area which quite commonly produces flood pulses is the Long Churns / Alum Pot system. Upper Long Churn Cave is fed by 13 individual streams that flow down into a bowl-shaped catchment. If they all start to rise at once, the effect at the entrance to Upper

Long Churn will be something like a 13-fold increase in flow volume almost at once. Since this occurs on the first high ground reached by the incoming south-westerly winds, this helps to explain why there are so many rescues and near misses in this system.



**Figure 32 (above left) The stream flowing into Alum Pot in normal conditions (photograph 'Dave Gallivan - Yorkshire Dales Guides') and (above right) in flood conditions (photograph by Andy Plimmer).**



**Figure 33 (above left) Long Churn Cave in dry conditions (photograph 'Pam Hickin - Yorkshire Dales Guides') and (above right) in flood conditions (photograph 'Dave Gallivan - Yorkshire Dales Guides')**

In general, swallet cave systems are liable to flood thirty minutes to four hours after the onset of heavy rain. Flooding will occur more rapidly the smaller the catchment area. This is less than the time of an average caving trip! Some caves are more flood prone than others of course, but as an indication, serious flooding is likely in many holes if more than 25mm of rain falls in 12 hours. In the Northern Pennines this happens about 20 times a year. (NOTE - this is occurring more frequently now, probably as one of the effects of climate change). Remember also that this is true of any cave, which contains a streamway, not just the ones for which the caving guidebooks give a flood warning.

During a thunderstorm, there is often insufficient time for the water to be absorbed into the dry ground, and dry ground will act as if saturated. After prolonged frost the ground will be frozen and subsequent rain will run off without hindrance as if on bare rock.

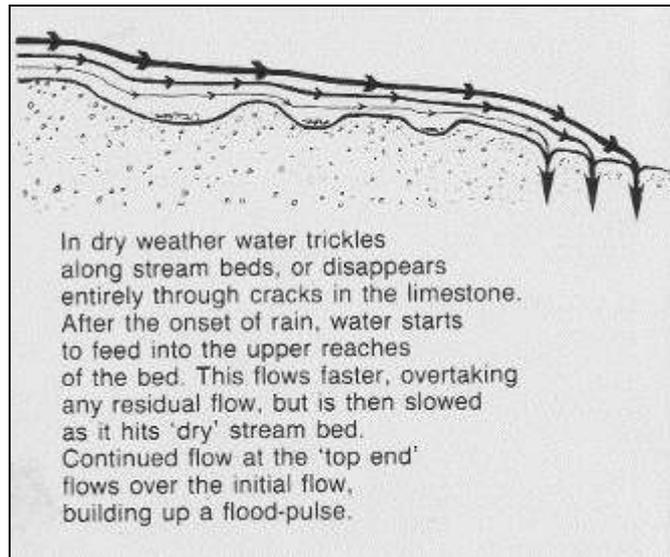


Figure 34 Diagram showing the effect of rain after a period of dry weather. (Ben Lyon)

### Flood Hydrograph

What happens in a serious flood can best be illustrated by the graph below which shows how a total lack of flow (or trickle) can change very quickly with no warning for a party underground to a peak which tails off more slowly.

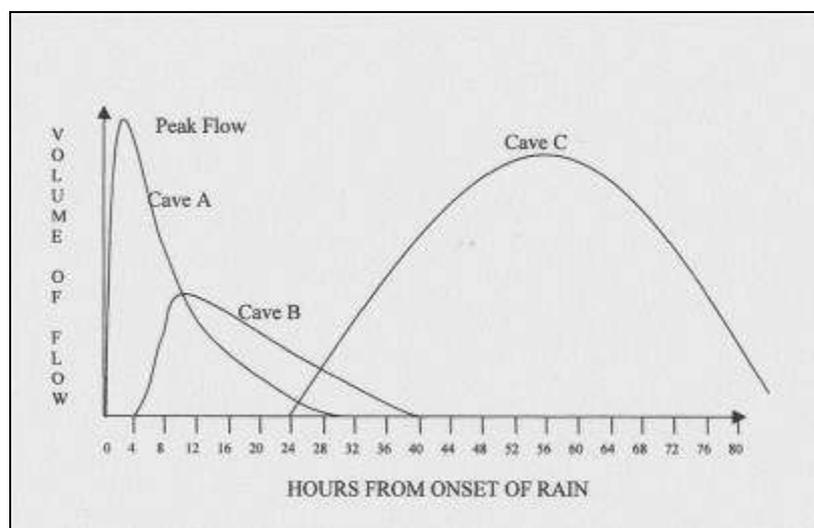


Figure 35 Flood hydrograph (After diagram by Dave Baines)

## The Cave Passages

Characteristics of cave passages liable to cause flooding:

PASSAGE TYPE	EFFECT	EXAMPLES
<b>Low siphon-shaped passage (undulations)</b>	Sumps off	<i>Bagshawe Cavern Otter Hole</i>
<b>Passage getting smaller</b>	Incapable of coping with extra water so backs up	<i>Sell Gill Holes Yordas Cave Peak Cavern</i>
<b>Boulder choke</b>	a) Rise in water level floods route through choke. b) Causes constriction to water making it back up.	<i>Hush Sump choke, O.F.D. I, Holbeck Junction, Easegill Caverns, Bridge Cave  Boulder Piles, Speedwell Cavern</i>
<b>Overflow passage</b>	Increased stream level flows down normally dry passage	<i>Lower Long Churn Cave, Merlin's streamway, Carlswark Cavern, OFD I, Porth yr Ogof</i>
<b>Low bedding plane passage</b>	Floods to roof	<i>Mosssdale Caverns, Lathkill Head Cave .Porth yr Ogof</i>
<b>In close proximity to sumps at bottom of cave</b>	Backing up of sump	<i>Near to the Confluence (Cwm Dwr), Goyden Pot</i>
<b>Downstream end of sump</b>	Sudden unpredictable outflow	<i>Sleets Gill Cave, Magnetometer Pot, OFD1</i>
<b>Overflow entrances</b>	Surface stream overwhelms entrance to capacity (sumped).	<i>Pool Sink &amp; other Easegill sinks, Little Neath River Cave, Town Drain, Ibbeth Peril, Porth yr Ogof, Will's hole, Cross Joint</i>
<b>Major streamway</b>	a) Cumulative effect of tributary streamways giving rise to huge-scale flooding. b) Becoming deep with impassable current & turbulence	<i>Lost John's Cave, O.F.D.1 &amp; 2, Peak Cavern  Kingsdale Master Cave, Lancaster Hole, Little Neath River Cave.</i>
<b>Canals and ducks</b>	Becoming sumped	<i>Dowbergill Passage, Dow Cave, The Lakes DYO, Shakespeare's Cave</i>
<b>Floor surfaces - normally dry passage or cobbles</b>	Causes friction or retarding effect creating flood pulse or pebble movement (saltation) making walking impossible	<i>Calf Holes, Poacher's Cave</i>
<b>Pitches</b>	Become impassable, cobbles washed down pitch	<i>Diccan Pot, Meregill Hole</i>

The effect of flooding in caves can be dramatic as the following photographs clearly show:



Figure 36 (above left) Lumbago Walk in Peak Cavern in dry conditions (photograph by Nigel Ball) and (above right) in flood conditions (Photograph by Rob Eavis)

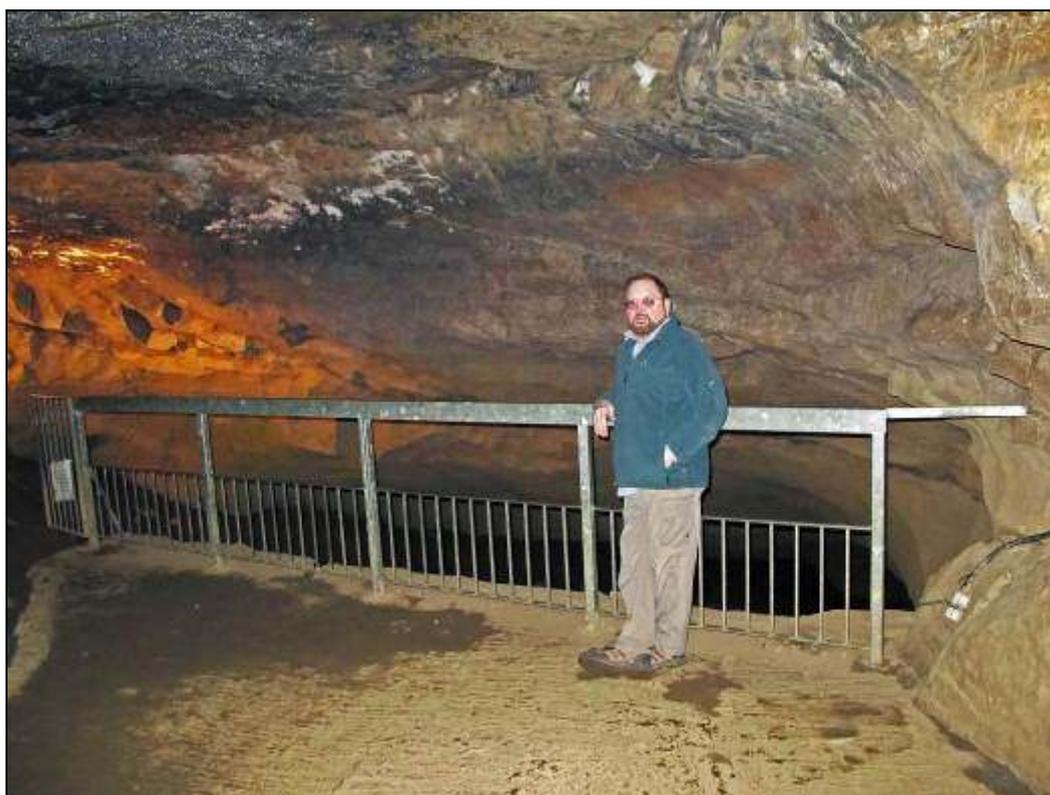


Figure 37 The Devil's Staircase in Peak Cavern in dry conditions (photograph by Nigel Ball)



**Figure 38 The Devil's Staircase, Peak Cavern, in flood conditions (photograph by Rob Eavis)**

## Indicators of Flooding in Caves

There are numerous signs of flooding, which when used in conjunction with the type of cave passage (above) can be very useful aids in evaluating how safe the cave will be. Some of these are different for swallets and resurgences.

### Swallet Indicators

- Grass, twigs, (even larger debris, e.g. trees in Porth yr Ogof & Goyden Pot)
- Rubbish trapped by rocks, (e.g. fence wire, dead sheep in Calf Holes)
- Passage floor – sand, pebbles, ripples in sand, absence of sand etc. - clean washed
- Passage walls – scarring on pitches, cascades – signs of violent torrent
- Boulders thrown or piled up in corners or on ledges in line of the current e.g. across the plunge pool of Dr. Banister's Handbasin in Upper Long Churn Cave.
- Static pools left in low spots (e.g. the Lake & the Dungeon in Bagshawe Cavern)
- Mud deposits on walls – where the stream backs up upstream of sumps and constrictions (e.g. bottom of Lost John's system).

### Resurgence Indicators

- Mud deposits – big banks of it sloping down sides of passage (e.g. Poacher's Cave / O.H.F.), with lines down created as water level falls. Mud on ceiling – often in little blobs, (e.g. Bagshawe Cavern).
- Sand / mud ripple patterns on floor, (canoeists will observe the same kind of features in river beds). If it looks like a dry stream bed, it is without doubt a streamway from time to time e.g. the passage at either side of Mucky Ducks in Peak Cavern.
- Static pools left in low spots.
- Grass is most unlikely, especially if the cave is fed by percolation, or a long way from sinks with a lot of sump passage in between.

## Cave Formations

Mud, grass or debris sticking to formations can often be a good indicator particularly in swallets. Stalactites do not easily grow in places where the passage is regularly swept by strong flood waters, but where this is not for much of the time, they will readily establish themselves. It is also possible to find clean formations on a wall or roof with recent mud deposits. Examples of both of these situations can be seen in Bagshawe Cavern.

## Weather Forecasts

Twenty, or even ten, years ago many people were totally unaware of how to find and use a weather forecast to assess the way this would affect their caving area. Fortunately this has changed, perhaps thanks to the television weather presenters giving the public more information with some degree of visual presentation.

Weather forecasts are often accused of being inaccurate, but experience shows that this is normally just by a matter of degree, e.g. they get the rain right but perhaps not the duration, intensity or timing.

Overall for the best forecast it is recommended that as close to the time of the caving trip as possible, two independent forecasts be consulted, or that the local forecast be read in the setting of the overall weather pattern prevailing. It is therefore valuable to understand weather and to be able to read and interpret a synoptic chart.

Remember that cold fronts tend to give bad weather and heavy precipitation for around 6-8 hours, whereas warm fronts tend to give less severe weather and precipitation levels, but the situation lasts a lot longer, usually 12-18 hours.

Before going caving you need to know:

- what the weather was doing over the previous few days;
- what the current forecast is, from more than one source;
- whether there are any known observation points from which to measure water conditions;
- if it is possible to access local knowledge about the cave system due to be visited.

## Additional Guidance

### 1) Caving Emergency Card

In order to bring the message about flooding to cavers, the emergency card shown below has been produced. The card is laminated and has been distributed free of charge with BCA membership, LCMLA registrations and at various caving equipment shops.

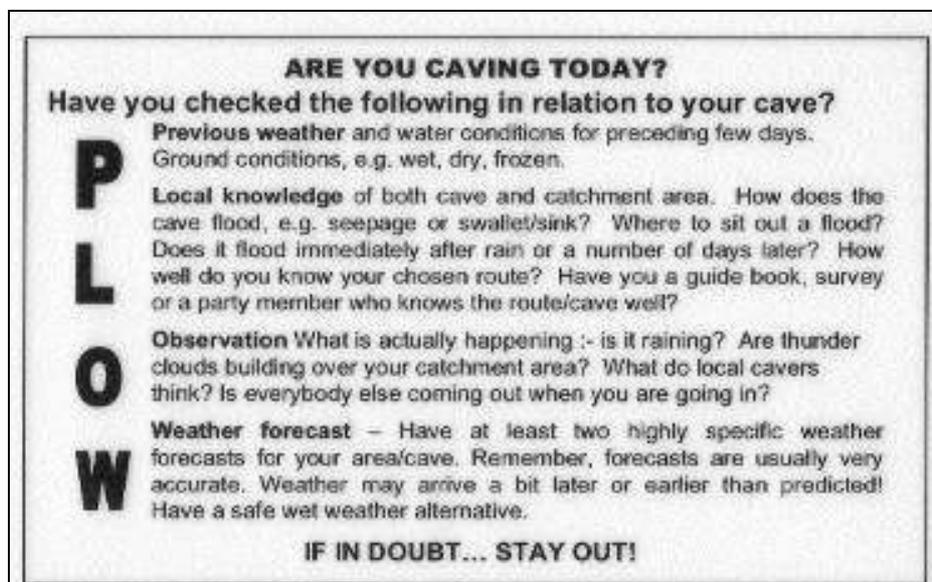


Figure 39 Emergency card side one (British Caving Association)



Figure 40 Emergency card side two (British Caving Association)

## 2) Navigating Deep Water

BCA's Training Committee has published the following guidance on navigating deep water in caves:

### **Navigating Deep Water in Caves**

Are you swimming through a resurgence pool today or swimming in any other deep water in a cave? If so...

- ? Are you wearing a buoyancy aid and wetsuit?**
- ? Have you checked the resurgence or deep water area for potential hazards, i.e. high water, fast flowing water, entrapping debris such as trees?**
- ? Does your party have an experienced caver leading it?**
- ? If you are an instructed group, is your leader a qualified BCA Local Cave Leader or a BCA Cave Instructor?**
- ? Are you intending to fix a rope through the resurgence or deep-water area or carry a floating throw line?**
- ? Are all your party members confident, strong swimmers in good health?**

If the answer to any of the above questions is negative you should consider staying away from deep water areas - come back another time when conditions are better and you are more prepared.

A journey through deep water cave sections is a serious undertaking and **people have lost their lives** in recent times attempting to go through such areas. These areas may be particularly dangerous if deep, narrow or with smooth severely undercut sidewalls.

### **Swimmers have drowned in areas such as this.**

The journey can be a fun and rewarding experience but it is not a trip to be attempted without adequate planning and preparation.

Recognised best practice suggests that:

- **all party members wear wetsuits and buoyancy aids**
- water levels are low and the route is obstruction free
- a competent, highly experienced caver is in charge
- a fixed rope or floating throwline should be considered
- all party members are strong, confident swimmers in good health
- no pressure should be put on any party member to undertake this journey

**If you have doubts, come back another day – the cave won't go away!**

## Three Days in the Life of the Goyden-Manchester System

### Dry Conditions



Figure 41 Scar Reservoir Dam on a dry day - there is no water entering Goyden Pot and conditions are still dry between Manchester sinks and Goyden Pot. (Photograph by Graham Mollard)

### Wet Conditions



Figure 42 Scar Reservoir Dam in wet conditions (Photograph by Graham Mollard)



Figure 43 River at the entrance to Manchester Hole (Photograph by Graham Mollard)



Figure 44 The entrance to Goyden. Goyden is impassable but not totally full. Manchester Hole is still passable. (Photograph by Graham Mollard)

## Flood Conditions



Figure 45 Scar Reservoir in very wet conditions (photograph by Erica Caswell)



Figure 46 The river alongside the entrance to Manchester Hole (Photograph by Graham Mollard)



**Figure 47** The entrance to Goyden Pot in flood. Goyden is full and ponding down the normally dry stream bed to Church Pot. Water is also flowing into the entrance to Manchester Hole.

## References

- Dean, R. & Long, H. 1992 "The Sleets Gill Rescue – the inside story" in: *Descent* 106, pp. 20-1
- Eyre, J. & Frankland, J. 1988 *Race Against Time* Dent: Lyon Books
- Forder, J. 1979 "An Analysis of Cave Rescue Statistics" in: *Caves & Caving* 6 pp.11-19
- Halliwell, R. 2001 "Debris Hanging from the Walls ..." in: *Caves & Caving* 91, pp. 42-7
- Ramsden, P. 1982 "Yorkshire Dales Flash Floods: the lessons learned" in: *Descent* 52, p. 12
- Ramsden, P 1984 "Cave Flooding and Underground Survival" in: *BCRA Transactions* 11(3), pp. 160-6

## Further Reading

See the new book *Flood Hazard* to be published imminently by Dave Baines.