Cave Breezes – Physics for beginners

Grant Gartrell – Part One

One of my driving interests in caves is air flows, even those that may be almost imperceptible emanations coming out of holes barely big enough to put your hand in. For some Nullarbor caves, the airflows from a cave entrance can be strong enough to be heard 100 metres away. In such a cave there is a need to be careful climbing down a rope into the cave so that when you are down and get off the rope, it doesn't blow straight back up and out of the cave, leaving you stranded. They don't get names like Hurricane Hole for nothing.

Not all caves exhibit readily detectable breezes, or airflows. When they do, some cavers find them interesting, but from the comments made, it is apparent that even most cavers do not have a clear understanding of the basic physics behind cave breezes. Quite sophisticated mathematics is needed for the analysis of some of these phenomena, particularly where caves occur in porous, sometimes coralline limestones, yet it is perhaps surprising what can be learned from a barometer, a thermometer, and an anemometer, or failing those, a simple candle flame.

Breezes encountered at a constricted part of the cave may be an indicator of further sections of cave beyond, waiting to be explored. Can it be argued that enlarging such a restriction so that we can get through and continue exploration might degrade the cave? Would such enlargement adversely affect the cave micro-climate? Must it necessarily be a trade-off between what we have and what we might find? The answer lies quite squarely in the physics.

Big Holes and Little Holes

Air is a mixture of molecules, principally nitrogen and oxygen, in the gaseous state. It usually also includes some water vapour with much smaller amounts of carbon dioxide and other compounds such as methane, each with their own partial pressures contributing to the whole. The gaseous state is an energy state in which all gas molecules have sufficient temperature related kinetic energy to rush around unconfined by the relatively weak- intermolecular forces of attraction that bind liquids and solids together. They undergo elastic collisions frequently with other similarly inclined molecules, transferring energy which is collectively perceived as gas pressure as they do so, a three-dimensional free-for-all after the fashion of those linear racks of suspended steel balls on un-cluttered office desks that once kept idle executives amused for hours on end. Airflows are a consequence of mass migrations of such air molecules from regions of higher pressure to regions of lower pressure, which is what happens when you get a flat tyre.

Air flows travel through caves in response to barometric pressure change, which itself is transmitted at the speed of sound (about 340 metres per second at normal atmospheric pressure at sea-level) except in circumstances where the air itself may be passing through the interstices of porous rocks such as some Gambier and Nullarbor limestones. The determinant in this distinction is whether the scale of the spaces in the air-path is comparable with the mean free path of the air molecules (the average distance one air molecule travels before it collides with another air molecule). At sea-level and a nominal pressure of 1 atmosphere, this distance is about one ten thousandth of a millimetre. Where there is a detectable breeze the scale of the opening is already so much greater than this threshold that any moderate enlargement of the passage cross-section, we might wish to make to be able to follow such an air-flow will have minimal impact.

A feature of caves is that because of the relatively poor heat transmission characteristics of the rock in which the cave is situated, the large variations in temperature of outside air between night and day, summer and winter, are largely averaged out to a more constant mean internal temperature within a cave. Thus, we can generalise that Tasmanian caves tend to be cold, South Australian caves tend to be more temperate, and caves in the north of Australia warmer again. This variation does not alter the previous discussion about pressure gradients. Different systems simply reach equilibrium at the appropriate temperature for that location.

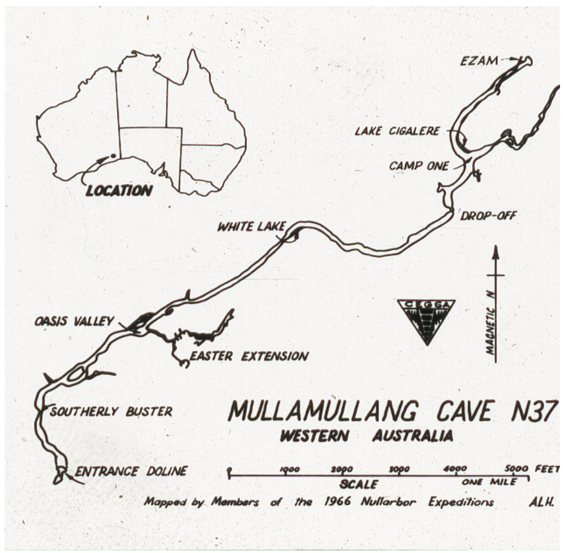


Figure 1 (right): Mullamullang Cave 1966, drawn by A.L. Hill

The classic comparison is demonstrated by large caves such as Mullamullang (Figure 1) on the Nullarbor, where airflows through the Southerly Buster, an easily accessible minor restriction in the main passage, not far from the cave entrance, have been regularly measured reaching in excess of 7.5 metres per second (about 28 km/hr – See Figure 2).

By far the larger volume of air accessed by this cave system lies within the porosity of the rock itself. Barely measurable airflows through the rock surface along the entire length of the cave collectively add up to a large volume of air that is clearly identifiable through significant phase lags to the cave breathing.

Incidentally, measurements show a stable variation of several degrees for the equilibrium temperature along the known approximately four-kilometre lateral extent of Mullamullang Cave, presumably imposed by an underlying geothermal influence.

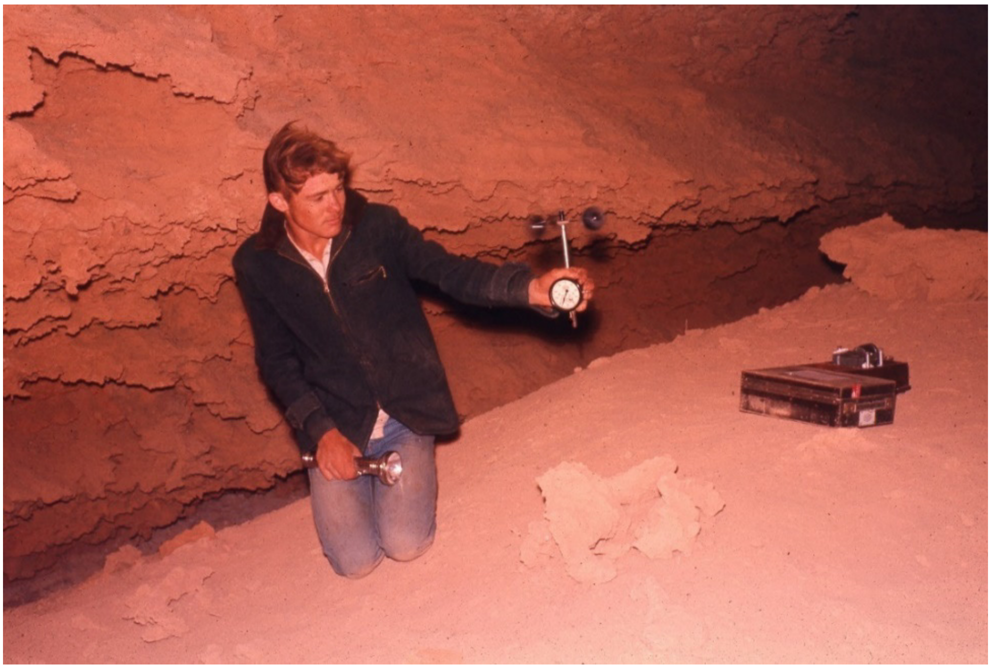


Figure 2: Measuring Southerly Buster airflow

Phase Lags

No, a phase lag is not an old gaol-bird indulging in a mind-altering substance. To explain what is meant by a phase lag a little more clearly, it should be noted that atmospheric pressure at the cave entrance varies both in response to diurnal tidal motions in the atmosphere and to the passage of longer-term weather systems as well. These phenomena drive quasi-periodic cyclic fluctuations of the pressure in the cave itself which may be simply read on a recording barograph or by taking periodic readings of a barometer. The externally imposed pressure variations themselves are the “forcing function” or the driving force for the system. The cave airflows are a measurable response to this forcing function and will also be quasi periodic. In the theoretical case of a cave with completely impermeable walls, only the volume of the cave passage itself can contribute to the airflows, which will thus respond instantaneously to the forcing function and therefore without any measurable lag between the maximum gradients of the pressure variation and the maximum speed of the airflow. In the case that the cave itself provides a conduit which permits a much larger volume of porous rock to “breathe”, the result will be that the periodicities of the pressure change themselves take significant time to propagate away from the cave wall and into the rock itself. The airflows within the rock in turn will be driven by those changes as they are experienced and will also take time to propagate back out of the rock into the cave itself. The delays are measurable as time shifts, or phase lags, between the forcing function and the resultant flows, and depend on the system geometry.

Phase Lag Maths

Half a century ago (now Professor) Tom Wigley, joint editor and contributor to both the Cave Exploration Group of South Australia (CEGSA) Occasional Paper No.4, Mullamullang Cave Expeditions 1966, and the joint Sydney University Speleological Society (SUSS) and CEGSA publication, *Caves of the Nullarbor*, included in both those publications observations from the meteorological work in Mullamullang and other Nullarbor caves. At this time he also published in the *Journal of Geophysical Research,72*: 3199-3205 a more mathematical analysis of this work entitled: “Non-steady Flow through a Porous Medium and Cave Breathing” in which experimentally observed phase lags were matched with those from idealised models of caves for which theoretical lags were generated with the use of appropriate mathematical functions. That the outcome of this comparison was so good was a clear demonstration that the modelling was eminently satisfactory for the purpose, which in turn indicated that Tom’s understanding and analysis of the mechanism generating the phase lags was accurate.

The Flat Tyre?

We now have enough information to revisit our counter intuitive perception of what happens when we enlarge an entrance, or an internal constriction in a cave. First, let us go back to our more familiar example of getting a flat tyre. When an inflated tyre gets a puncture it will go flat more slowly if the hole is very small, or more quickly if the hole is bigger. But then that is the end of the matter. We are all reasonably familiar with this concept, and probably have it in the back of our mind when considering air passing through a cave entrance.

Perhaps that is how we get the idea that if we make the entrance bigger, the air will rush out of (or into) the cave faster. But that concept is entirely wrong. The air doesn't rush out and stop. The cave doesn't go flat. As has already been made crystal clear by the physics and by observation, the cave wasn't initially inflated to a high pressure like a tyre. Its internal pressure remains to all intents exactly the same as the outside atmospheric pressure. It is that outside pressure which is continually changing, in response to the inevitable progression of weather systems and atmospheric tides.

That the cave keeps on breathing is because the internal pressure of the cave must continually adjust to keep pace with the changes in outside pressure. Because any hole from which we can detect a significant airflow is already so much larger in cross-section than the mean free path of air molecules, then all we would do by, for argument, doubling the cross-section of the hole, would be to make it possible for the same volume of air that previously passed through the hole in a unit time to still pass through the hole in that same amount of time, but at half the speed.

Other Effects

There are other effects that might have a bearing on the movement of air in or out of a cave entrance in some circumstances. Wind blowing across the cave entrance could possibly set up a Helmholtz resonator effect, a periodic low frequency oscillation of the air column within the cave somewhat akin to exciting vibrations in an organ pipe. Helmholtz resonance is more common with regularly shaped cavities such as empty bottles, and quite unlikely in the vast majority of irregularly shaped caves, which is probably why organ pipes are not shaped like caves.

A cave with multiple entrances at different altitudes could tend to have cool and therefore more dense cave air breathing out of a lower entrance and being replaced with air entering through a higher entrance during the warm part of the day, with the circulation reversing once the outside temperature falls below the internal cave temperature, late in the day or at night.

While such scenarios add complexity, the same basic principles still apply, and again where it might be appropriate for other reasons to consider enlarging a constriction in a cave, it may well be the case that as far as airflow is concerned the constriction is only a pseudo-constriction and its removal inconsequential in terms of cave atmospherics.

Water Vapour

Water can enter a cave in several ways. It might be in the form of an active stream, or perhaps as groundwater percolating. It could enter the cave as the humidity component of a flow of atmospheric air. Irrespective of by how many of these individual pathways it enters the cave, and the processes to which it may be contributing in the cave environment, all the forms of water available will contribute to the total partial pressure of the water component of the resultant cave atmosphere in accordance with pre-determined limitations. At any particular time, the activity of drip water might depend on rainfall events several months or even years prior, whereas some cave streams might flood almost instantaneously. Similar, sometimes seasonal, variability may apply to cave breathing. Fortunately, it is not necessary to consider in detail every combination of these variables in order to arrive at basic guidelines in regard to the effects of moderate enlargement of entrances.

In terms of the influence of changes or modifications to constrictions in air flow on the water vapour content we have already established that changes to pressure gradients consequential to reducing the impact of restrictions are generally minimal. Any reduction to the degree of such restrictions would tend to minimally reduce the ability, if any, of the restriction to alter the water content of the air passing through.

The particular physical property of water for which we need to give special consideration is that the water vapour carrying capacity of air reduces as the temperature of the air itself reduces. As outside air cools overnight, it is not uncommon in some regions for dew to start settling particularly on bushes and grass once the temperature falls below a certain value. That particular temperature is known as the dew point, and is the temperature at which the air becomes saturated and can hold no more moisture. When the air cools further below this point, some water vapour must condense out, depositing a layer of dew on cold surfaces. Often leaves which are themselves cooled by evaporative transpiration are colder than the ground itself, which tends to retain some residual warmth from earlier in the day. Water vapour thus cooling into dew will release a significant amount of energy, known as latent heat of vaporisation, when doing so. This mechanism is quite important in the vegetable garden, providing a temporary buffer against frost.

In a cave it is usually on a very much smaller scale and may not be perceptible at all. It is also a negative feedback mechanism, which reducing the impact of a constriction in the cave would minimally diminish. Generally if the water vapour in the cave air does not become saturated when it passes through such a constriction, it will remain not saturated if the degree of restriction is reduced, in which case there should be no perceptible effect whatsoever. Evaporation of any drip water entering the cave must raise the atmospheric humidity within the cave, as would the presence of a flowing stream.

In such circumstances the limit to increasing humidity will remain the same. Once saturation pressure is reached for a certain temperature, then no further increase in moisture holding capacity of the atmosphere is possible.

There is at least one chamber in the huge Mulu Clearwater Cave system which provides a connection between a large section of the upper cave and a major lower-level river passage both containing saturated air but at different temperatures. The quite rapid mixing of both sources of air in the linking chamber fills it with a continually replenished pool of supersaturated air from which some water vapour has to condense out, manifesting itself as a dense fog which turns an otherwise straightforward rock-pile chamber into a considerable challenge.

For alpine caves we should also consider the effects of yet another change of state for water turning from liquid to ice and releasing further latent heat. The same principles apply, but as the effects tend to be minimally diminished rather than exacerbated, if at all, by enlarging restrictions, that should be adequate consideration for the current discussion.

Since it would appear that the main worry people have about enlarging cave restrictions is that it might be responsible for caves drying out, it is very reassuring to establish that the physics does not back this up. Where there is evidence of caves drying out in recent times, we should not overlook the potential impact of other factors such as climate change or possible lowering of the local water-table consequential to the nearby establishment of extensive plantations of the notoriously thirsty Tasmanian Blue Gum.

The Old Homestead Cave, dry ever since I have known it, and located under the undoubtedly arid Nullarbor, could reasonably be described as an intermittently dry cave. As well as break-down chambers it contains extensive fields of maze-like tunnels and tubes of phreatic origin several metres in diameter, indicating that wetter periods in the past have played a major role in its development. This is a gentle reminder that we should not assume static weather conditions over the life of any cave. The evidence is clear that the reality has often been a succession of drier and wetter periods, ice ages and interglacials.

Some Examples of Nullarbor Cave Air Flows

While it takes only about 13 seconds for any pressure changes to be propagated from one end of Mullamullang to the other, it can take hours for those same changes to be propagated significant distances sideways into the surrounding rock. The same principles apply to cave breathing at Kelly Hill and Naracoorte, as well as caves occurring in any other limestones with significant porosity.

Because the scale of the constriction in Mullamullang at the Southerly Buster is many orders of magnitude greater than the mean free path of air molecules in the vicinity, the restriction to air flow is insignificant, and the pressure gradient through the Southerly Buster at any particular time is barely discernible from the pressure gradient over the entire length of the cave. At a reasonably normal rate of pressure change caused by the passage of weather systems and atmospheric tides, say about half an hectopascal per hour, the rate at which such changes would be transmitted would result in a total variation of the pressure from one end of the cave to the other of the order of 1 part in a million, considerably less than the resolution of many pressure recording devices, and insignificant in terms of environmental processes.

The air must flow faster through that restriction than it would in the larger adjoining chambers of the same cave. The physical characteristics of that airflow will undergo only such minimal change that there is no discernible difference other than airspeed between environmental factors within the constriction itself and the larger chambers on either side of it.

Figure 3: The Dune

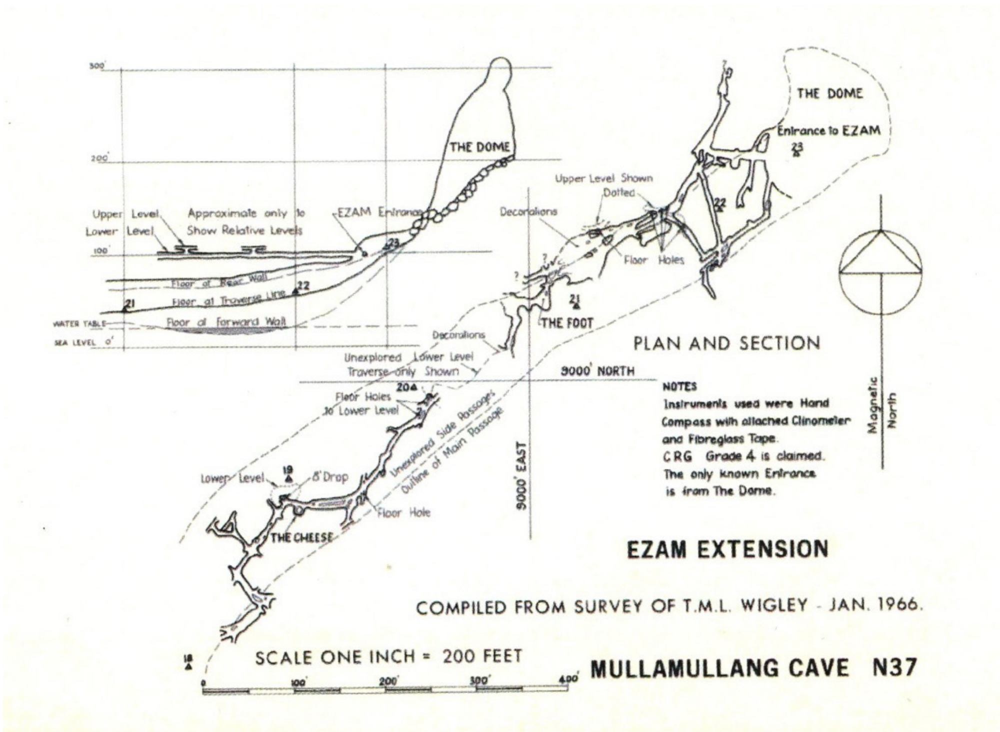
Located about 80 metres towards the entrance of Mullamullang from the Southerly Buster, and occupying most of the passage, is a beautiful sand dune (Figure 3). The two features would appear to be inter-related. If the silt floor of the Southerly Buster were to build up, further reducing the cross-sectional area of the Buster, then the air speed through the Buster would have to increase to compensate. The increase in air speed would enable more sand grains to be picked up and entrained by the air flow, depositing them in the larger cross-section and therefore lower air speed Dune Chamber, and restoring some measure of equilibrium.

A fringe benefit is that lines of footprints in the sand from those passing through the chamber alongside, and even higher up the dune, are imperceptibly but thoroughly obliterated over time.

Breezes coming from most Nullarbor blowholes, while often noteworthy, are rarely indicative of imminent breakthroughs to new cave. Blowholes, in response to pressure variations of only 1 part in 2000 have been measured as pumping out enough air to achieve a total vacuum of the accessible volume in 3 minutes, and then continuing to breathe out at the same rate for a further 12 hours or more. The answer to this conundrum seems to be that the blowholes frequently access a large network of small anastomosing tubes which in turn give access to large volumes of porous limestone. A program of measurement of phase lags associated with a representative range of blowholes might reveal whether such anastomosing tube networks tend to be radially symmetric around individual blowholes, or whether they tend to a directional anisotropy possibly indicating a broader property of the rock itself not necessarily directly related to those individual blowholes.

On the other hand, it is worth considering with a cave such as Mullamullang that should we locate a breeze emanating from a constriction that we haven't previously noticed, for example, a crawl-way, whether through the rock-pile or even off the Ezam (Figure 4), that might enable us to find a way past "The Dome", which is considered to be the current northernmost end of the main run of the cave, then that breeze would certainly be worth following, simply because of the expected structural nature or shape of the cave, even if most of the air in the breeze came from the porous wall of passage beyond the constriction.

Figure 4: Mullamullang Ezam extension 1966, drawn by A.L. Hill



Grant Gartrell – a brief bio in his own words!

Grant Gartrell is an Honorary Life Member both of ACKMA and of the Cave Exploration Group of SA.

He gained a PhD in Physics from the University of Adelaide in 1971. He worked for almost 40 years as a Defence Scientist, and these days still messes around in mud being a commercial blueberry grower.

Mud features in a major way in his life because he also still enjoys messing around in mud attempting to find new caves.

He has now attained the age of 80 years, and therefore thinks that perhaps he should be expected to devote more effort into deciding what he wants to be when he grows up, but fears that he may have left it a little too late.

Editor's Note:
I know exactly how Grant feels – but my philosophy is you are never too old to decide what you want to be when you grow up!