

Insulation Explained, part 1: Staying Warm

by **Matt Fuller, Dr Matthew Morrissey and Dr Mark Taylor**  14/Dec/2012

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What's better, down or synthetic insulation? What exactly is fill power? How can you avoid hypothermia? How is warm stuff tested, and how best can you care for it?

With winter conditions firmly established on the hills, here's a timely and comprehensive look at the technicalities of staying warm. In part 1 of this detailed two-stage article outdoor-obsessed boffins Matt Fuller, Dr. Matthew Morrissey and Dr Mark Taylor discuss some of the science surrounding insulation and physiology.

In part 2 they'll present a brief history of insulated clothing and equipment, look at different materials, describe testing methods used for assessing a garment's warmth and offer some interesting ideas about how clothing might be made warmer in future.

Nb. If you're interested in the science behind outdoor clothing more generally this article should be read with the authors' piece from April 2012 - [Waterproof Breathable Fabric Explained](#).

Insulating layers are important in many climbing and hillwalking situations, separating ourselves from the often harsh environment. Through over a hundred years of mountaineering, the same principles of keeping warm have been employed: windproofness, staying dry, and trapping still air. Although insulated clothing has changed significantly since mountaineering's inception, there is still considerable room for development. Some of these possibilities will be discussed in part two. First up, the physiology...

'Even small reductions in core temperature can cause reduced coordination, poor judgement and significant discomfort. In a mountain environment this impaired performance can be dangerous, so having the correct clothing and experience is vital'

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When the going is hard it's easy to forget the basics, like keeping warm.

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Human thermoregulation

The human body is homeothermic (warm-blooded) and its core temperature must be maintained at approximately 37 °C. Humans evolved in a hot environment, and only by engineering new clothing and shelters have we managed to settle in high latitudes.

Thermal comfort is achieved when the body is in a state of heat balance, where heat loss is approximately equal to heat production. To survive cold conditions, reducing one's heat loss or enhancing one's heat production is essential. The former can be achieved through the use of clothing and the latter by increasing thermogenesis, the heat produced by the body. Our body heat is produced by four main routes:

- Our metabolism, which describes the fundamental processes that happen in the body
- The thermic effect of food, which describes the energy released on breakdown of foodstuffs
- Exercise-induced thermogenesis, which is the heat produced when exercising
- Thermoregulatory thermogenesis, which is the response to overt cold and describes processes such as shivering



It's all fun and games until the snow melts...

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Keeping warm

The human body is more naturally equipped for warm climates than cold; it is easier to lose heat through evaporation of sweat than to preserve it by shivering. In fact, the ability of shivering to raise body temperature is highly dependent on insulation: a lightly or unclothed individual may increase their heat loss by shivering as the heat production is not conserved but simply accelerates heat loss to the environment. Even small reductions in the body's normal core temperature (of approximately 37 °C) can cause reduced coordination, poor

judgement and significant discomfort. In a mountain environment this impaired performance can be dangerous, so having the correct clothing and experience is vital.

Cold injuries

Cold injuries can be described as either local or global. Frostbite is a local injury; hypothermia is a global injury. Frostbite occurs most often in the hands and feet because the body attempts to maintain core temperature, even to the detriment of the extremities. This occurs through vasoconstriction, a narrowing of small blood vessels that are often close to the skin. By reducing the blood flow to the high-surface-area digits, overall heat loss is reduced, but fingers and toes can suffer as a result.

Before the onset of frostbite a mountaineer might experience hot aches, which can be exceptionally painful. Hot aches are most serious when they affect a mountaineer's ability to carry out basic tasks such as belaying or eating. Hot aches are somewhat similar to chilblains and occur when core body temperature rises, pumping warm blood into previously vasoconstricted blood vessels. The blood flows rapidly into the constricted vessels, causing swelling which is exacerbated if the hands have been damaged by impact (eg. when ice climbing). The swelling causes pressure on nerves and the associated excruciating pain.

Hypothermia occurs when core temperature falls below 35 °C. Because of its effects on mentality and morale, even minor cases can be dangerous. As ever, fitness is important: fit individuals vasoconstrict more readily than untrained individuals, which aids core temperature regulation. Also, a high level of fitness generates a greater metabolic response to cold.

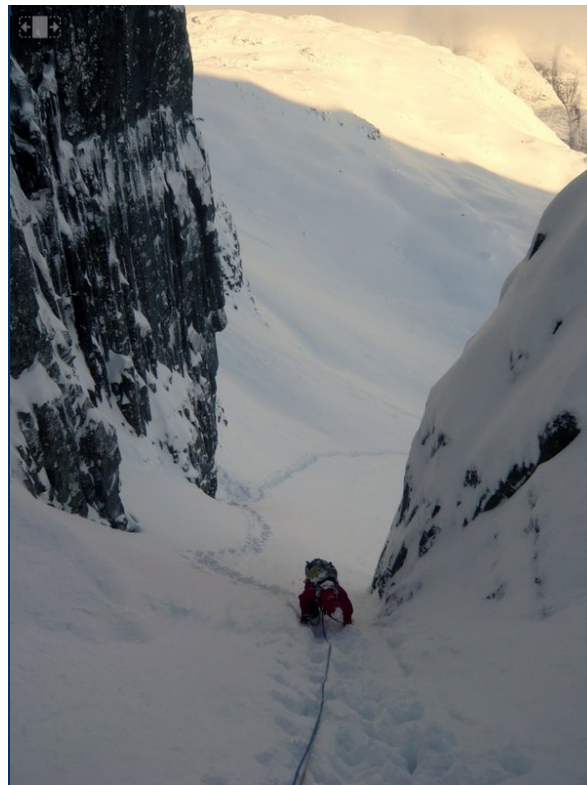
Adaptation to cold can also be local or global. In the local case, vasoconstriction in the extremities of cold-adapted individuals is less than in non cold-adapted individuals. This leads to higher skin temperatures and better manual performance; higher skin temperature of the hands of Yukon and Arctic Inuit (routinely exposed to intermittent cold) have been recorded. Whole-body (global) adaptations are more complex and disputed, but several types of cold adaptation have been observed, studied and reported. These develop based on the time-frame and intensity of the cold exposure, and may include development of a higher basal metabolic rate to account for greater heat loss, or conversely development of a lower skin temperature to decrease the skin-environment temperature gradient.

'It is important to remember that the human body is the heat source in a clothing system. The role of insulating clothing is therefore to conserve the body's heat'

How insulation works

It is important to remember that the human body is the heat source in a clothing system. The role of insulating clothing is therefore to conserve the body's heat. The body loses heat by four routes:

- Conduction. Heat transfer by conduction in a material or between two objects involves the transfer of energy without any large-scale motion of the



Powder-bashing is exhausting; this can lead to overheating and then rapid cooling.

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material(s). Therefore when there is no movement of air, conduction is one of the more important heat transfer mechanisms through clothing layers. Note that clothing layers are comprised of a mixture of air (approximately 95% by volume in a down jacket) and fibres (approximately 5% by volume in a down jacket), so the heat transfer by conduction through fibres is minimal, and therefore the thermal conductivity of the fibres is practically irrelevant. It is the low conductivity of still air that makes effective insulation. The role of the fibres is to keep the air still so no convection (see next point) occurs, which would greatly increase heat transfer. Conduction is particularly relevant if leaning against a cold surface such as ice, or when gripping metal objects such as ice axes. It could also be significant in footwear.

- **Convection.** Heat transfer by convection occurs by the mass motion of a fluid, such as air or water, carrying energy with it. The mass motion of the fluid can be 'natural', caused by density-driven effects, or 'forced' by external means such as a fan. Convection can be a major source of heat loss in windy conditions, though it can be minimised by using windproof clothing, such that the internal air layers of the clothing remain static.
- **Radiation.** Radiation does not require molecular contact for heat to be transferred; it can occur through a vacuum, such as from the sun to the earth. Most conventional fabrics block radiative heat transfer quite effectively and radiative losses can be minimised by increasing the density of insulation, decreasing the fibre diameter or by decreasing the relative emitting ability of the fibre surfaces (eg. by coating them in metal). Whilst metallic surfaces are quite effective in increasing insulation when air gaps exist or with very low density materials, their relevance to conventional-density textiles is minimal. This is especially true of clothing ensembles, where stitched garment construction and rucksacks compress clothing and air layers.
- **Evaporation.** Heat loss by evaporation occurs when a liquid changes into a gas, such as when sweat evaporates. When resting, approximately 15 % of the body's heat loss is by sweating, though this increases significantly when in hot weather or when working hard.



The body loses heat by four routes...

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*'A thicker material will trap a thicker layer of air,
thereby making it warmer to wear'*

Heat transfer mechanisms are summarised below (adapted from 'The comfort and function of clothing', L. Fourn, N. R. S. Hollies, 1969):

Route	Environmental factors	Clothing factors	Body factors
Conduction	Temperature	Thermal resistance of clothes and air layers	Surface temperature
Convection	Air temperature and wind	Windproofness of fabrics and garment design (eg. cuffs)	Surface temperature and proportion exposed
Radiation	Temperature and emissivity of surfaces; sunlight	Emissivity, surface temperature	Surface temperature and proportion exposed
Evaporation	Vapour pressure	Breathability, area of wet clothing	Surface temperature and area of wet skin

The key to the insulating performance of down, Primaloft and any other fibrous material is their ability to trap air and block heat transfer by radiation. Thickness is therefore crucial to a material's insulation: a thicker material will trap a thicker layer of air, thereby making it warmer to wear. The table below shows thermal conductivities for various materials. Note the difference in conductivity between a typical fabric, which is mostly air by volume, and the conductivity of wool or cotton fibre: fabrics are warm because they trap still air. If the air is not still then the insulation is ineffective because of the onset of natural convection. This happens when an air gap reaches approximately 13 mm in thickness.

Material	Thermal conductivity (W m ⁻¹ K ⁻¹)	Notes
Still air	0.025	If air can move then convection occurs, making air insulation ineffective
Typical fabrics	0.04	
Cotton	0.45	
Wool	0.36	
Water	0.60	
Metals	15-400	This is why gripping bare ice axes can be unpleasant

An interesting note is that when the thickness of cylindrical insulation (i.e. a sleeping bag or jacket) increases, its outer surface area also increases, and this additional surface area is available for heat exchange with the cold environment. Therefore, above a certain thickness of cylindrical insulation further increases in thermal resistance are very hard to achieve; this can have pragmatic implications, for example the huge insulation required for restful sleep at -40 °C is extremely difficult to attain.

'Water is 24 times more conductive than air... The key is to stop water accumulating in insulation, and to force it as far away from the body as possible'

Wet layers

Your body's main cooling mechanism is sweating. Without it, you'd die on the flog up to Stob Corrie nan Lochan or while marching across a sunny glacier. But sweat that remains in your clothes will make them less warm, which is not ideal if you're about to belay or bivouac. Thus, adjusting your clothing to prevent overheating is every bit as important as preventing chilling. Wicking baselayers, that transport moisture away from the skin without evaporation, will prevent overly-rapid cooling, but equally reduce the effectiveness of sweating when it is required. If the air temperature is below freezing then it is extremely difficult to force moisture out from all your clothes and condensation is inevitable. The key is to stop water accumulating in insulation in the first place, and to force it as far away from the body as possible.

Water is 24 times more conductive than air (see table above), and consequently wet clothing provides less insulation than dry clothing. Wet clothes struggle to trap air and as they dry the evaporation chills the wearer and the other garments. Whether it is wet from sweat or the outside environment is irrelevant. Furthermore, as discussed below, down insulation may collapse when wet and become thinner.

A synthetic belay jacket is a worthy investment. Because of the loft-retaining properties of wet synthetic insulation, their ability to provide the warm human body with the opportunity to dry the layers underneath the insulation is better than with wet down insulation. Because this additional insulation allows for normal or higher than normal skin temperatures, water can evaporate and either leave the clothing system or condense further away from the body where its cooling effect is less pronounced. With no insulation or less effective insulation (such as wet down) the drying of the inner layers would be slower.

In very cold conditions, the dew point (temperature at which condensation occurs) may be present inside a clothing system or, of arguably greater relevance, a sleeping bag. Over a long period this will lead to a build-up of moisture inside the sleeping bag and will reduce its performance. In extreme conditions, this moisture may freeze. A hundred years ago, polar explorers struggled with this as their furs became heavy and inflexible as ice formed inside them. Modern insulation is more resistant to wetting and freezing but excessive moisture build-up is still highly undesirable. Highly breathable shell fabrics are very important in trying to stop moisture accumulating, though vapour barriers that completely stop evaporation of sweat from the user may also be used to avoid insulation being saturated by water.

Wind chill

The wind chill index represents the air temperature perceived by uncovered skin, rather than the absolute air temperature. The reason the perceived temperature is lower than the actual temperature is because wind strips away the insulating layer of air (the boundary layer) that surrounds the body in still conditions. A windchill chart summarises the effects of wind and the one below, taken from Wikipedia, has different colours referring to the chance of frostbite occurring.

		Air Temperature (Celsius)																
		0	-1	-2	-3	-4	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50	-55	-60
Wind Speed (km/hr)	6	-2	-3	-4	-5	-7	-8	-14	-19	-25	-31	-37	-42	-48	-54	-60	-65	-71
	8	-3	-4	-5	-6	-7	-9	-14	-20	-26	-32	-38	-44	-50	-56	-61	-67	-73
	10	-3	-5	-6	-7	-8	-9	-15	-21	-27	-33	-39	-45	-51	-57	-63	-69	-75
	15	-4	-6	-7	-8	-9	-11	-17	-23	-29	-35	-41	-48	-54	-60	-66	-72	-78
	20	-5	-7	-8	-9	-10	-12	-18	-24	-30	-37	-43	-49	-56	-62	-68	-75	-81
	25	-6	-7	-8	-10	-11	-12	-19	-25	-32	-38	-44	-51	-57	-64	-70	-77	-83
	30	-6	-8	-9	-10	-12	-13	-20	-26	-33	-39	-46	-52	-59	-65	-72	-78	-85
	35	-7	-8	-10	-11	-12	-14	-20	-27	-33	-40	-47	-53	-60	-66	-73	-80	-86
	40	-7	-9	-10	-11	-13	-14	-21	-27	-34	-41	-48	-54	-61	-68	-74	-81	-88
	45	-8	-9	-10	-12	-13	-15	-21	-28	-35	-42	-48	-55	-62	-69	-75	-82	-89
	50	-8	-10	-11	-12	-14	-15	-22	-29	-35	-42	-49	-56	-63	-69	-76	-83	-90
	55	-8	-10	-11	-13	-14	-15	-22	-29	-36	-43	-50	-57	-63	-70	-77	-84	-91
	60	-9	-10	-12	-13	-14	-16	-23	-30	-36	-43	-50	-57	-64	-71	-78	-85	-92
	65	-9	-10	-12	-13	-15	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93
	70	-9	-11	-12	-14	-15	-16	-23	-30	-37	-44	-51	-58	-65	-72	-80	-87	-94
	75	-10	-11	-12	-14	-15	-17	-24	-31	-38	-45	-52	-59	-66	-73	-80	-87	-94
	80	-10	-11	-13	-14	-15	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95
	85	-10	-11	-13	-14	-16	-17	-24	-31	-39	-46	-53	-60	-67	-74	-81	-89	-96
	90	-10	-12	-13	-15	-16	-17	-25	-32	-39	-46	-53	-61	-68	-75	-82	-89	-96
	95	-10	-12	-13	-15	-16	-18	-25	-32	-39	-47	-54	-61	-68	-75	-83	-90	-97
	100	-11	-12	-14	-15	-16	-18	-25	-32	-40	-47	-54	-61	-69	-76	-83	-90	-98
	105	-11	-12	-14	-15	-17	-18	-25	-33	-40	-47	-55	-62	-69	-76	-84	-91	-98
	110	-11	-12	-14	-15	-17	-18	-26	-33	-40	-48	-55	-62	-70	-77	-84	-91	-99
		0 to -10 Low			-10 to -25 Moderate			-25 to -45 Cold			-45 to -59 Extreme			-60 Plus very Extreme				

Wind chill can be negated by windproof layers and by covering up skin. However, wind has a further influence on insulation: if strong enough, it can compress insulated clothing, reducing the thickness of the insulation and making it less effective. Therefore, stiff and heavy outer fabrics, and insulation that resists compression, may be more appropriate when strong winds are expected than thin and supple fabrics such as Pertex.

Altitude

Altitude affects the body in many ways, which are only briefly covered here. Altitude reduces the heat-producing effect of food, and makes food harder to eat; it increases vasodilation, and reduces power output. The only beneficial effect of altitude is that the air trapped in your clothes is less conductive than at sea level, being less dense. On very high peaks this may make up to a 30% difference in insulation versus the insulation at sea level.

Tips for keeping warm

- Garment design is absolutely crucial: a loose hem or collar can cause massive heat losses. Tighten garment draw cords.
- Fit is equally important. A garment that is too baggy will allow air to circulate inside it; too tight and it will trap insufficient air. Two similar jackets from different manufacturers may vary massively in their fit, even if the label says they are the same size.
- Your body aims to maintain core temperature and doesn't care about your hands and feet. If they're getting cold, try putting on another hat or jacket.
- Your body is the heat source in a clothing system. Keep it fuelled, as hypothermia and hunger go hand-in-hand.
- Sweating into your insulation makes it less effective. Cut your work by 10% and you can drastically reduce sweating.
- Non-membrane softshells or Pertex windproofs are brilliant ways to stay warm if it's windy. Their breathability means they are also excellent at warding-off overheating.
- If you are cold then work harder. You are the source of heat.
- Wet baselayers are arguably worse than no baselayer. Bring a spare dry one.
- Bare skin loses the most heat. Covering up any exposed skin, even with just a thin layer of insulation, can make a huge difference to overall warmth.
- A hat is extremely easy to take on and off and makes a massive difference to overall warmth. If you've a helmet on then make sure your hood will go over it.
- Alcohol does not help you keep warm, even if it feels like it does. It is a vasodilator so reduces core body temperature.
- Thickness is roughly equivalent to warmth. Two sleeping bags can easily be compared 'by hand' by judging their thicknesses: the thicker one is likely to be warmer.
- More layers is good, but only if they keep the air still inside them. Tight-fitting layers that squash air from underneath them do not add warmth.
- Shake your sleeping bags and down jackets out once they've been compressed. Don't store them compressed when wet and avoid long-term compression.
- Overlapping fabric is so much warmer than bunched fabric and bare skin. Tucking shirts into trousers and glove wrists into jacket sleeves virtually eliminates convective heat flow from these areas.
- Powder snow isn't a massive problem, but once it melts it can be. Sometimes easier said than done, but try to avoid getting drowned in spindrift.



Stay well fuelled to keep warm
 UKC Articles, 13 Dec 2012
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Further reading

There is a mass of information available on insulated equipment. A quick search of the UKC and UKH [forums](#) will bring up pages and pages of solid advice and of course some hearsay, and the [gear reviews](#) are helpful too. A full internet trawl will bring up a lifetime's worth of stuff. Books on the subject, however, are few-and-far between with the exception of *Invisible on Everest* by M. Parsons and M. B. Rose. Papers on the subject are often less 'academic' than you might think and can be quite readable to the non-specialist, as long as you can access them. Some links are posted below. The physics of heat transfer is in any physics textbook, and is also discussed on this [website](#).

Cold injuries:

- (Papers): 1) J. M. Stocks, N. a S. Taylor, M. J. Tipton, and J. E. Greenleaf, *Aviation, Space, and Environmental Medicine*, 2004, 75, 444–57.
 2) D. Gavhed, *Human responses to cold and wind*, PhD thesis, Karolinska Institutet, 2003.

The effects of altitude:

- (Papers): 1) K. Cena, N. Davey, and T. Erlandson, *Applied ergonomics*, 2003, 34, 543–50.
 2) T. Fukazawa, H. Kawamura, Y. Tochiara, and T. Tamura, *Textile Research Journal*, 2003, 73, 657–663.
 3) C. M. Blatteis and L. O. Lutherer, *Journal of Applied Physiology*, 1976, 41, 848–858.
 4) G. P. Burton, I. Parker-Dodd, and D. Ed, in *The Science of Climbing And Mountaineering*, eds. N. Messenger, D. Brook, and W. Patterson, Human Kinetics Publishers, Leeds, 1st Edn., 2000.
 5) H. Wang, S. Hu, G. Liu, and A. Li, *Energy and Buildings*, 2010, 42, 2044–2048.

General advice:

Andy Kirkpatrick's [website](#) offers typically excellent advice on how not to freeze to death.

The complex calculation of clothing required in different situations is given on this [website](#)

About the Authors

All three authors are current or past members of Leeds University's internationally renowned [Performance Clothing Research Group](#). Matt Fuller is an experienced hill walker, keen mountaineer, and terrible rock climber. He is studying for a PhD investigating the insulating materials used in the outdoor industry. Dr. Matthew Morrissey is interested in all kinds of protective clothing and recently finished his PhD; he is most at home falling off waterfalls in a kayak but also harbours suppressed aspirations to climb back up them in winter. Dr. Mark Taylor usually prefers to go under mountains rather than over them. He has been testing outdoor clothing for the Performance Clothing Research Group since 2000.

Thanks to Tom Hartland for his helpful suggestions.

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