

# Contents

---

ARC Protocols for Cool Buildings .....	2
Success criteria for building modelling & performance. ....	2
Thermal Comfort .....	2
Climate and weather .....	3
Two steps for making cool buildings .....	4
Step 1 Meeting everyday comfort needs .....	4
Step 2: Comfort at the extremes .....	8
Resources .....	11
Outstanding research questions.....	13
Appendix 1: measuring thermal comfort .....	15
Dry Bulb Temperature - $T_{db}$ .....	15
Wet Bulb Temperature - $T_{wb}$ .....	15
Dew Point Temperature - $T_{dp}$ .....	15
Heat Index.....	16
Dangerous heat.....	17
Further discussions on factoring in Humidity to air temperature .....	20
Thermal comfort models.....	22
Appendix 2: heat waves and climate change in the global south: definitions, monitoring, and organizations .....	27
WMO Official Definition .....	27
UK Met Office Definition .....	27
Temperature Thresholds .....	27
Monitoring and Recording.....	27
Why It Matters for the Global South.....	27
Central Coordinating Body.....	27
Summary .....	27
Actionable Starting Points .....	28
Appendix 3: technical R&D brief for air-conditioning and ventilation for hot and humid climates.....	29
1. Objective .....	29
2. Core Design Challenge.....	29
3. R&D Focus Areas .....	29
4. Context and Practical Constraints .....	30
5. Outputs Required .....	30
6. Success Criteria .....	30
ARC technical meeting: cooling individual rooms in a Tanzanian context.....	31
Misc. ARC expert comments.....	36
Appendix 3 Definitions .....	37

## ARC Protocols for Cool Buildings

### Success criteria for building modelling & performance.

The ARC Cool Buildings performance success criteria described below is concerned with **delivering thermal comfort in hot, and hot and humid climates and specifically on preventing overheating of buildings**. As such its focus is not as broad as more comprehensive comfort criteria. However, we do also focus on indoor air quality – and the ventilation strategies and measures required to deliver that. We also aim to minimise:

- operational and embodied energy consumption
- peak power usage
- capital and running costs
- lifetime carbon emissions

Also, we recognise the need for the ruggedisation of strategies and as-built solutions.

### Thermal Comfort

Thermal comfort is influenced by many factors that relate to the user

- clothing level
- activity level
- acclimatisation
- time spent outdoors
- expectation of the experience
- **thermal history** with air conditioning
- etc

and the surrounding environment

- temperature
- solar radiation
- air speed
- humidity
- etc

It is extremely difficult to apply both a practical and economically viable *universal building standard* across different socio-economic contexts, cultures and regions with different regional and micro-climates, where different combinations of thermal comfort factors interact with climate change, social, economic and cultural factors in complex ways.

Whether a particular building design or feature will deliver adequate thermal comfort in a specific localised context can also be hard to reliably assess at concept or detailed design stage. This is often made more challenging where evidence of (effective) performance of existing traditional buildings and features is hard to come by, or inconclusive. In addition, because of fossil fuel pollution and environmental degradation of ecosystems leading to regional and localised changes in climatic conditions, historic or modern buildings that are adequately comfortable now may not be comfortable - or even safe - in the coming years.

## Climate and Weather

Changes in global and regional climates and in the frequency and intensity of extreme weather are occurring now and will increasingly impact the performance of long-lived structures such as buildings (and their occupants!) over time, through gradual increase of average temperatures and increasing frequency and intensity of hot weather events such as heatwaves.

Building performance is typically reported relative to the 'current climate' - which is changing globally, with changes varying regionally and locally. The current climate is defined according to measured conditions over an agreed period of time – typically 30 years. Different time periods or benchmarks are used for different purposes and may or may not be universally used across governments and organisations. Benchmarks are periodically updated – the UK's Met Office has recently updated UK regional benchmarks for heatwaves as a result of the changing climate (note that different regions have different benchmarks to reflect regional variations in climate).

ARC therefore adopts the principle that Building performance is most usefully assessed relative to the 'current climate' in any particular climate *zone*, climate *region* or even relative to the climate in a very specific *locality*. Because of faster than predicted climate change, performance now urgently needs to be assessed relative to both *current* and *predicted future* extreme weather events, particularly extremes of heat and humidity – heatwaves.

## Two steps for making cool buildings

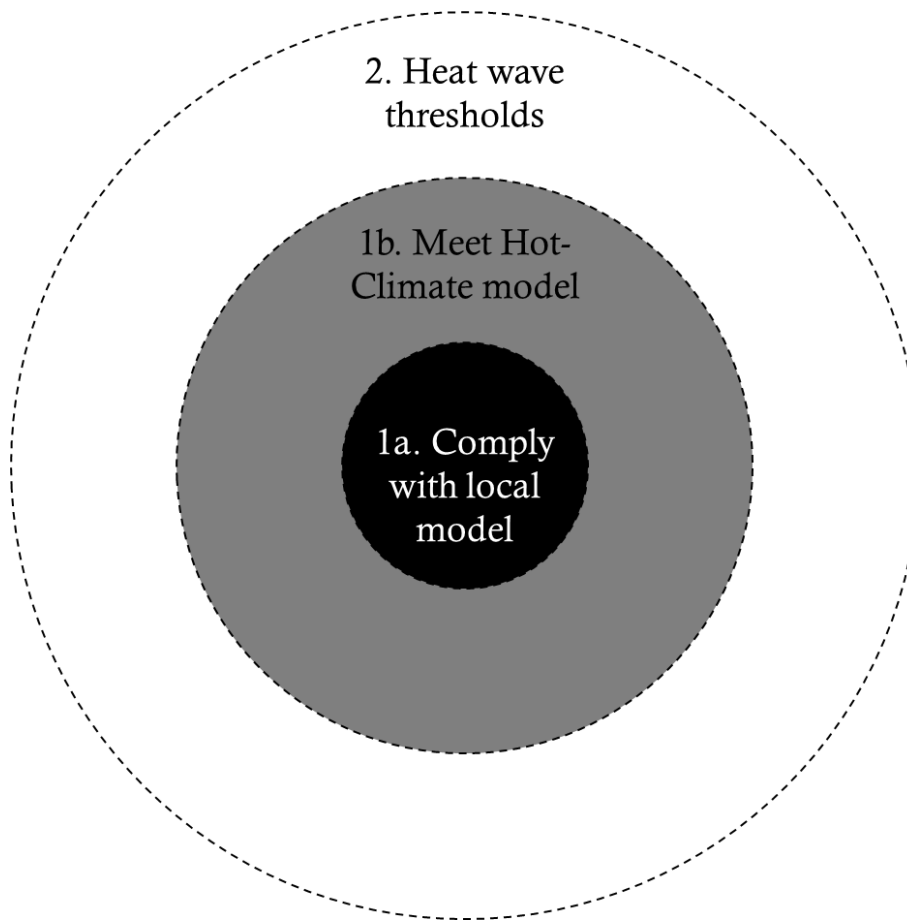


Figure 01: The two-step approach

### Step 1: Meeting everyday comfort needs

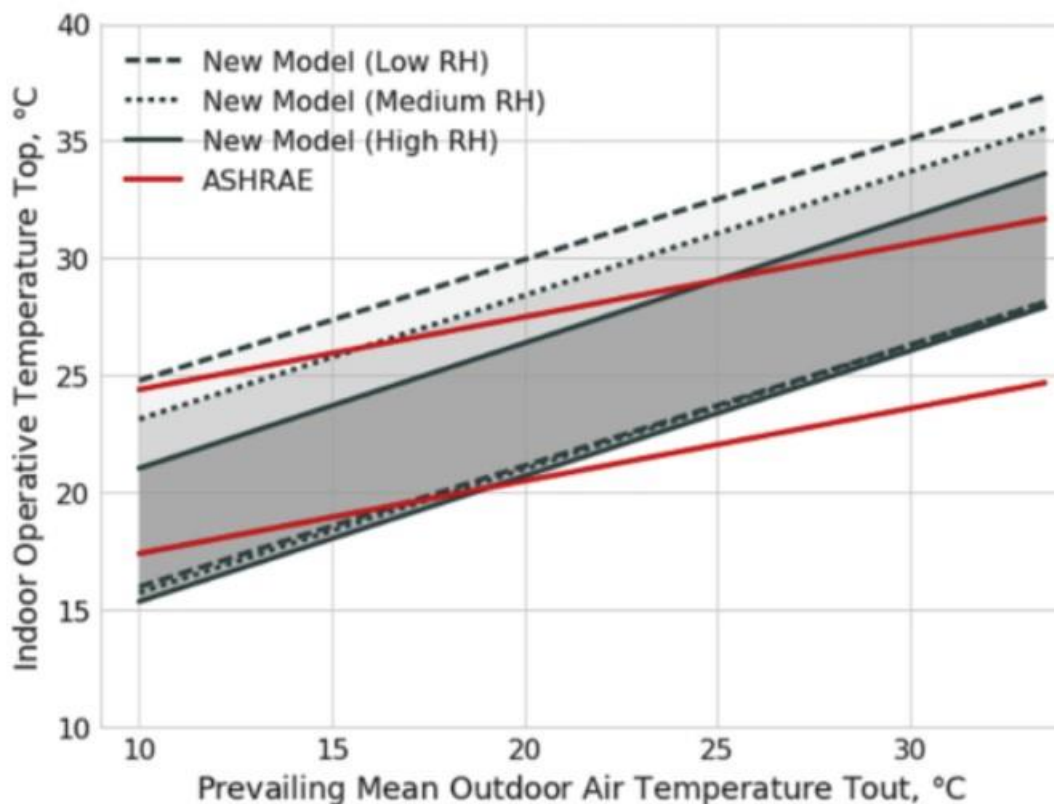
ARC's Cool Buildings Programme takes a two-step approach, with the longer-term thinking required for Step 2 informing decisions made for Step 1.

**Step 1 requires demonstrating that, under normal circumstances, the building is comfortable 90% of the time.** The comfort model that is used will depend on the location. With hundreds of local surveys conducted, based on the adaptive comfort method worldwide, **many countries have identified what is found to be comfortable for their local populations**, with some countries e.g. India incorporating it into an official standard. **Where these local survey results are available, projects owners can show that their building meets localised comfort expectations.** It's important that the local study used matches the project's specific context as much as possible. For example, a comfort study carried out of residents in naturally ventilated houses would not be appropriate to be applied to assessing the performance of a centrally airconditioned office tower in the city centre. This is due to the differing expectations, acclimatisation (to unconditioned vs. conditioned spaces) and occupants' differing levels of control and opportunities to adapt their environment. However, the study might be used to assess designs for

naturally ventilated office space where occupants have desk-fans and relaxed dress codes. The ARC website provides a database of these studies, with toolkits to show compliance.

For countries where a local model is not available, ARC has developed simple 'success criteria' to guide designers and builders. These are based on standard comfort models but informed by a 'designer-friendly **relative humidity-inclusive** **adaptive comfort model** that 'significantly extends the range of acceptable indoor conditions for designing low-energy naturally conditioned buildings all over the world'<sup>1</sup>.

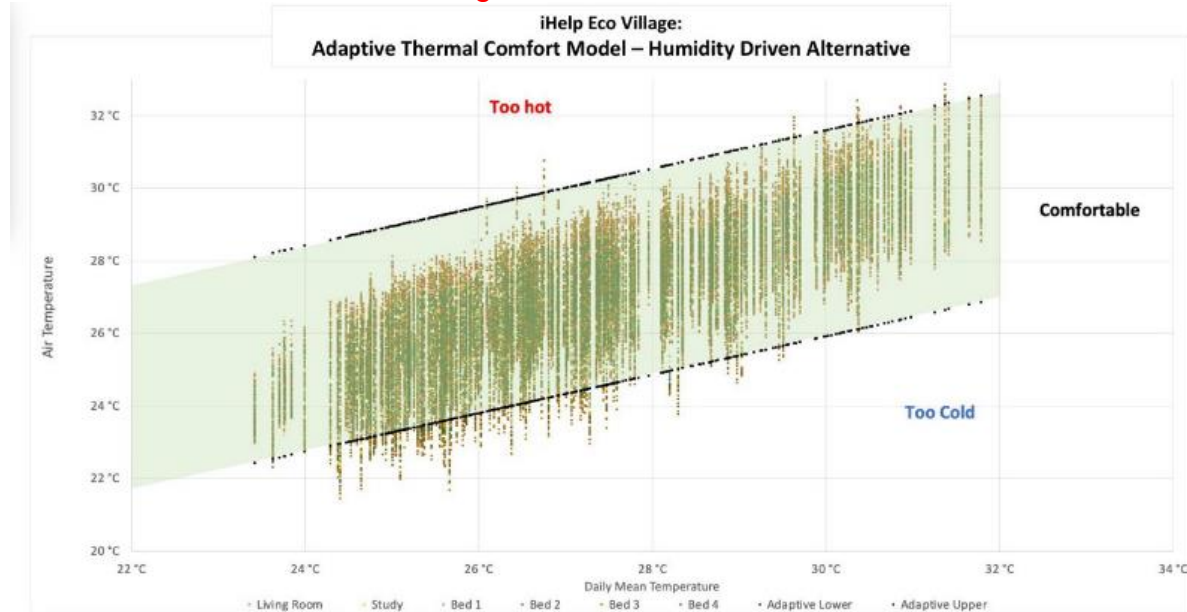
The humidity-inclusive comfort model, researched by Marika et al, is based on 63 studies in 13 countries with hot climate regions. The principal benefit of the model is that it acknowledges that *more humid climates require more stringent comfort standards*, because the human body's ability to sweat is diminished in more humid climates. The acceptable range for comfort in the comfort model allows for projects in different locations to adopt a bespoke target based on local humidity levels. This safely widens the applicability, range and accuracy of the ARC Cool Buildings approach: in their published research, the researchers show that the widely adopted ASHRAE method *overestimates* overheating by 30%.



<sup>1</sup> [Humidity-Adapted adaptive comfort model \(Marika Vellei, Manuel Herrera, Daniel Fosas, Sukumar Natarajan\)](#)

Credit: Marika et al: The influence of relative humidity on adaptive thermal comfort.<sup>2</sup>

Example: demonstrating measured performance for a 10-person communal domestic accommodation building in Tanzania.



Credit: HEIs, AS, AW.

Note: in this illustration of a completed and monitored project the graph's vertical axis shows dry bulb air temperature only - not the combined effects of radiant and air temperature (operative temperature) which technically is the correct metric for demonstrating building performance using this model. Where operative temperature can be calculated (from monitoring of room radiant temperatures using black bulb thermometers) then the graph can be improved for accuracy by using operative temperature.

People adapt to their local environment in the short term, by adjusting their behaviour and clothing to the outdoor environment they've experienced recently. Some adaptive comfort models reflect this by taking *the average mean temperatures in the past month* as an indicator of predicted comfort temperatures, like the ASHRAE model. However, studies<sup>3</sup> have shown that after only 7 days human adaption to changes in outdoor temperatures is significantly reduced (see Figure # below). Instead, the running mean is a more accurate indicator. The running mean temperature is *an average of the temperatures in the last week; however, the model puts more emphasis on more recent days than earlier days*. **This is because you are more likely to be impacted by the temperatures from yesterday than 6 days**

<sup>2</sup> Building and Environment, Volume 124, 2017, Pages 171-185, ISSN 0360-1323, <https://doi.org/10.1016/j.buildenv.2017.08.005>.

(<https://www.sciencedirect.com/science/article/pii/S0360132317303505>)

<sup>3</sup> Yang, D., Xiong, J., & Liu, W. (2017). Adjustments of the adaptive thermal comfort model based on the running mean outdoor temperature for Chinese people: a case study in Changsha China. *Building and Environment*, 114, 357-365.

**ago.** This is in line with the European standard method set out in Standard EN 15251.

Where localised survey information is available which uses both methods, the running mean figures should be used in preference. The ARC Cool Buildings toolkits provided will build in this preference. The tools will only require the user to input the hourly outdoor temperatures, and the internal temperatures that were recorded. To demonstrate building performance using the comfort model it is therefore necessary to have access to measurements of both the internal and outdoor humidities and temperatures inside and outside of your building. Ideally, internal and external temperature measurements should be recorded on an hourly basis via data loggers placed in permanently shaded spots. The external data logger outside the building, should also be both well shaded and also protected from rain.

Where this measured data is not available data from other sources, as local as possible could be used – for example publicly available airport weather<sup>4</sup> data or from other publicly managed weather stations. An airport is likely of course have a different temperature profile than the building and surroundings, because airports are typically located in open landscapes and may or may not be impacted by the urban heat island effect<sup>5</sup>.

<sup>4</sup> In the UK for example this data is freely available:

<https://www.metoffice.gov.uk/services/transport/aviation/regulated/airfield-climate-data>

<sup>5</sup> ChatGPT: is the weather data collected at airports skewed towards higher temperatures because of the urban heat island effect affecting airports or is it skewed in the other direction because it represents an open landscape away from urban environments? “Airport weather stations sit in a rather particular niche between those two influences. A few key points:

- **Siting standards:** International standards (WMO, ICAO) require that meteorological instruments at airports are installed in open, grassy, level areas, away from large buildings, tarmac, and runways where possible. The idea is to capture free-air conditions that best represent the wider atmosphere, rather than the microclimate of paved or built-up surfaces.
- **Airport microclimate:** Despite the standards, many airports are dominated by large expanses of tarmac, concrete, and low vegetation. These absorb and re-radiate heat, particularly in strong sun, which can push temperatures higher than they would be in a natural rural setting. Jet exhaust and ground operations can add localised heat, though siting guidelines try to minimise this influence.
- **Relation to urban heat island (UHI):** Airports are often located on the periphery of cities, in more open landscapes. This means they typically avoid the *strongest* UHI effects found in dense city cores. In many cases, they're cooler than city-centre stations at night, since they lack dense building fabric that stores and releases heat.
- **Bias direction:**
  - **Daytime:** Airports can record *slightly higher* maxima than nearby rural fields, due to tarmac and paved expanses.
  - **Night-time:** They often record *lower* minima than urban sites, because of their relatively open, exposed locations that allow more radiative cooling.
- **Overall:** Compared with rural grassland sites, airports tend to be a little warmer in the day, a little cooler at night. Compared with inner-city sites, airports are usually cooler, especially overnight. The "bias" depends on the comparator: they're not cleanly representative of untouched rural landscapes or of dense urban fabric.

In practice, climate services use airports because they provide long, continuous, well-maintained records and global coverage, even if they don't perfectly represent either extreme of land use.”



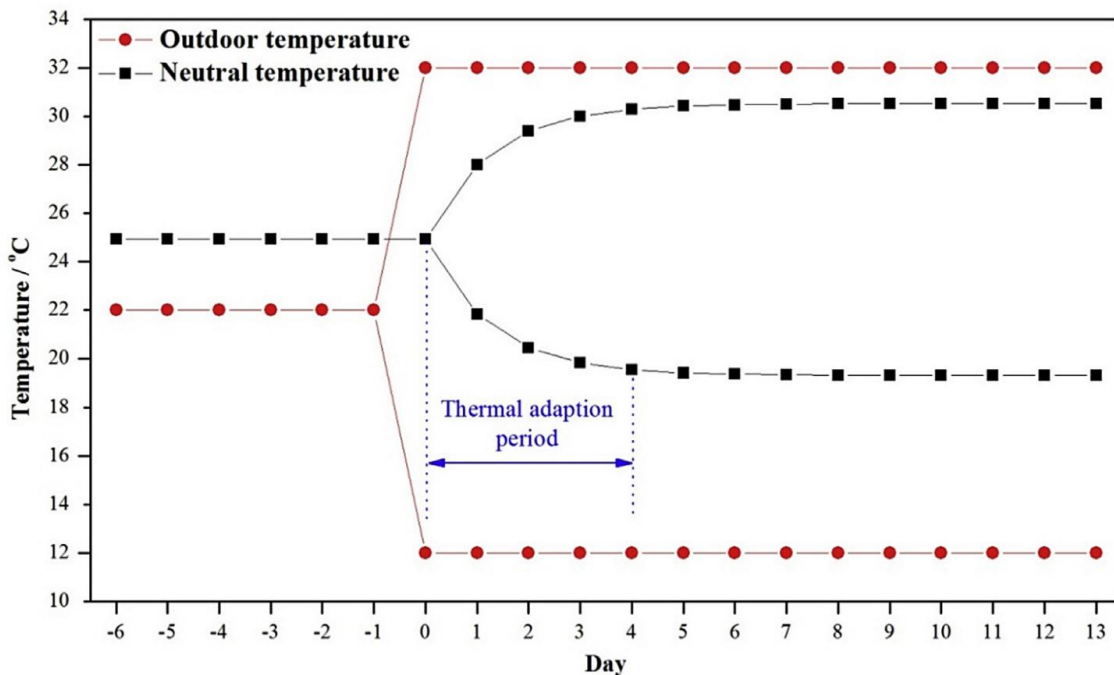


Figure 2Figure#: ###

## Step 2: Comfort at the extremes

**Step 2 in the ARC approach is intended to ensure more comfortable conditions during heatwaves.**

**Heatwaves** are defined as periods of extreme heat, typically expressed using dry bulb air temperature for ease and simplicity of communication to the general public.

However, organisations increasingly factor in humidity (and often radiant temperature and wind effects as well) **to help warn on heatwave conditions where these combined effects may cause risks to human health**: for high-risk occupations e.g. working outside, military personnel, construction workers, workers operating dangerous machinery or for higher risk demographics such as babies or older people, or people in poor health. This expresses temperatures for hot weather as a **'feels like'** value, or **'heat index'**.

**Heatwaves often come with power cuts as power grids struggle to handle the demand of people turning on their air conditioning.** In line with the need to manage this increasing risk, ARC's approach is to design for **operational resilience**, to safely manage interruptions to energy supplies, typically electricity supply, whilst continuing to provide thermal safety and wellbeing during power outages. This requires simple and robust 'passive' designs for buildings. The same principle of simplicity and robustness applies to the building services equipment, for example the use of standardised or locally made and repairable equipment and components, and adequate access to local and affordable skills and services, along



with business and authorities building and maintaining suitable and reliable supply chains.

Heatwaves pose serious risks to people's health and wellbeing and limit their daily lives at work and at home - as in order to manage heatwaves and even survive, managing and reducing heat stress becomes the sole focus. **Therefore, it is important to ensure that people have access to at least one space at home, at work and in community settings for practical use and refuge during heatwaves. Let's call this the 'Heat Shelter'.**

We recommend two thresholds:

## Temperatures in Heat Shelters

The Heat Shelter is a cooler, sheltered space which building occupants are able to use for extended periods during heatwaves, and which stays below certain temperature limits even when electrical mains power cuts out. The Heat Shelter may be a single space or may be a zone including several rooms in a building.

- **Designers and builders must ensure the Heat Shelter remains below 32°C through passive (non-mechanical) design measures**
  - **Orientation** – to minimise the amount of time direct sun heats the walls, roofs and floors and external surroundings. Typically, this involves aligning the longest /largest external faces of the building to face north and south (in hot climates the sun is higher in the sky to the north and/or south during the day) and aligning the narrow/smallest faces of the building to face east and west (the sun is lower in the sky to the east and west, and more sunlight falls on east and west facing walls and windows. Good solar orientation of a building is an extremely effective way to reduce the amount of heat from the sun from getting into a building.
  - **Shading** to walls and windows include
    - extending the roof edges to extensively shade walls and windows and even shade external ground areas around the building is highly effective at keeping buildings cool.
    - Adding lean-to or canopy roofs against walls
    - Tops and side of windows can be shaded using various features fixed to the walls
    - ventilated window shutters (on the *outside* of the window)
    - ventilated shading louvres within the window opening
    - externally positioned perforated security screens (Mashrabiya)
  - **Reflective surfaces** – brilliant white (the most reflective) or paler colours help reflect the sun's heat away from the building's roof and walls. This is particularly important where there is no ceiling in the room, and occupants are exposed to the radiant heat coming off metal roof sheets. It also works well to reduce heat being radiated onto (and

through) any e.g. plasterboard or concrete ceilings below. Keeping ceilings cooler is important.

- **Heat shedding roofs** – heat builds up quickly in enclosed roof spaces, - if the hot air cannot escape from the roof space it transfers its heat to the ceiling materials, making the ceilings hotter. Heat is then radiated from the ceilings onto the occupants below. Provide ventilation to the roof space at the eaves, allowing cooler air in, and have dedicated areas that let the hot air out of the roof towards the top of the roof, also designed to keep the rain out.
- **Use the window openings to provide air movement for cooling breezes.** Make sure window openings are large enough to allow a high level of air movement. Ventilated shutters, louvres or venetian blinds can be used to increase or decrease how much air passes through a window – i.e. air movement can be controlled by the occupants. The important thing is to avoid sizing the openings to be too small in the first place, and to make sure they are placed on opposing walls of the space, or at least on adjacent walls – rooms with a single window should be avoided. This also requires windows to be placed carefully, to provide *cross-ventilation* - ideally openings of equal size on opposing sides of spaces to allow the free flow of air across the space. If the space is to be sub-divided with an internal wall, consider making the partition 'perforated' to avoid blocking air movement from the window thereby improving cooling cross ventilation. Lowering the window cills of windows provides better cooling by allowing air to pass across more of the body area of occupants, standing, sitting or lying inside on windows also works well. Creating openings in ceilings 'to let hot air rise out of the room' is not generally considered to be very effective in domestic buildings and may allow more heat into the space than it lets out – treat this potential passive measure as 'experimental' at this time.
- **Draughtproof glazed windows for when air conditioning is turned on** - inward-opening casement windows or glazed bifold patio-doors will be needed for the operation of the Heat Shelter in two modes – natural ventilation mode and air conditioning mode. In natural ventilation mode, the casements are open, to allow for full opening of the window area for effective cross ventilation. Fitting an insect mesh screen across the window opening is necessary for areas with mosquitoes. This typically reduces airspeed (**the critical factor for cooling the body is the speed of the air movement**) through the window by about 50%. The glass areas of sliding type glazed windows typically occupy 50% of the opening area of the window and the insect mesh areas of these windows slow air movement by 50% - so the reduced distribution of cooling breeze across occupants' bodies when using sliding type glazed windows needs to be considered carefully by designers and builder.
- **powered fan(s)**
- **lighting**

- **power socket(s)**

The temperature limit is based on the fact that with an air temperature above 32°C, air movement alone cannot cool the skin.

- **If an adequate mains power supply is available, this space should also be fitted with mechanical cooling.**

The reason for installing air conditioning in the Heat Shelter is that in places where power cuts are anticipated or even scheduled, occupants can pre-cool a room with the air conditioner and rely on the good design of the space to preserve that coolth for as long as possible during the power cut.

For a room (or rooms) in a hot dry climate with adequately cool nights, this means that well shaded, high thermal mass, cooled at night by natural ventilation via large openings is important.

**In a hot humid climate, the room (or rooms) should be provided with the following features:**

- **Additional wall, floor and/or ceiling insulation - to preserve the coolth.**
- 

### Temperatures of transient spaces during heatwaves

These are spaces that people need to use for more than an hour each day like kitchens, bathrooms and corridors. These spaces should not exceed the human limits for temperature. This limit is exceeding an air temperature of 40°C is in a hot dry climate<sup>6</sup>. For hot humid climates a wet bulb temperature of 32-34°C is the limit of human capacity<sup>7</sup>. *See Appendix for more information on the heat index.*

### Resources

#### **ASHRAE global database of thermal comfort field measurements**

<https://datadryad.org/dataset/doi:10.6078/D1F671>

Research reference: **Development of the ASHRAE Global Thermal Comfort Database II:**

<https://www.sciencedirect.com/science/article/pii/S0360132318303652#fig>

<sup>6</sup> <https://pmc.ncbi.nlm.nih.gov/articles/PMC8374383/>

<sup>7</sup> <https://www.nature.com/articles/s43017-024-00635-w>

# ARC

Architecture for resilient communities

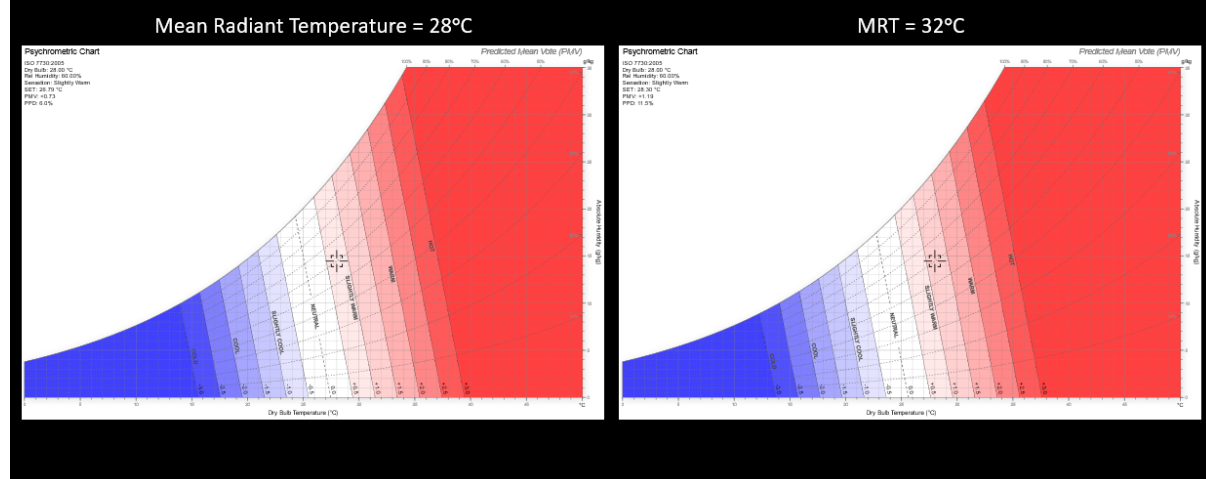
## Outstanding research questions

Air summer radiant asymmetry: the effect of hot surfaces on perception of 'warm stuffy conditions'. Nick Grant (NG) provides example conditions: RH c.50%, air 23°C, CO<sub>2</sub> c. 500ppm ("windows opened because of 'stuffiness' whilst MVHR working fine"). "Definitely felt stuffy but air temperature not high." NG: "Also experienced in schools, a cafe in a care home (not PH but all tables had been moved away from warm glass and cold drafts from the aircon.) As it says in attached (abstract) it must be sensitivity to asymmetry as the MRT was not very high at all as far as I could tell. More sensitive than winter case, I think. In the UK it is the glass, but warm ceilings will be significant in other situations. More research needed."

Related information: unpublished abstract by NG (PHI's Wolfgang Hasper also looking into it and "it is complex".)

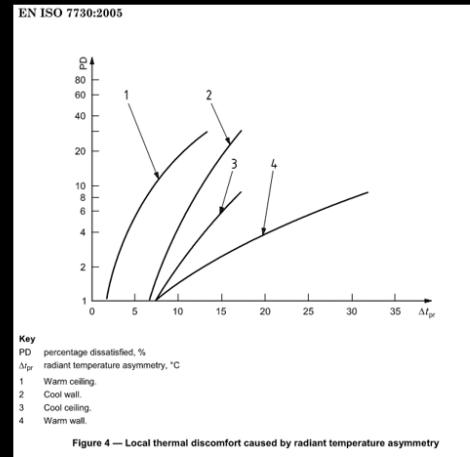
HEIs: "Yes, I agree, especially the idea of warm ceilings for houses with metal sheet roofing. There is also metal doors and windows too that feel like standing next to an iron (when unshaded). But as we mentioned in meeting, the issue with radiant heat is the availability of technology to capture it. How likely is it that people would have access to a thermal camera? At best, we could add guidance on how to avoid it or PHPP becomes more adept to hot climates (as Nick said) and we adopt that."

## Influence of Radiant Temp



## Radiant discomfort - asymmetry

- Discomfort arises not just from high radiant, but asymmetrical temperatures
- So, a hot ceiling gives a double whammy of discomfort



So my supervisor (who specialises in thermal comfort outdoors) said that for indoor spaces, the air temperature isn't typically that different to the radiant temperature. So we can use air temperatures on site as a 'good enough' measure.

However, design wise, you can easily get operative temperatures in the software simulations. So we could say that teams should aim to design for operative temperature comfort levels.

Also a few anecdotes :

1. For the Tanzania simulations, I could calibrate the rooms easily but couldn't calibrate the roofs because the roofs had too much radiant heat that the data loggers weren't capturing. So a space that is that exposed to solar radiation would have a big difference between operative and air temp. A well shaded one would have a smaller difference.

2. In a recent UK project, when I set the cooling set point to 26°C air temp, some rooms failed the adaptive overheating test where temperatures have to be below 26, because they use the operative temp as a criteria. (it was a small fail but just shows that it does have an impact)

## Appendix 1: measuring thermal comfort

### Dry Bulb Temperature - $T_{db}$

The Dry Bulb temperature, usually referred to as "*air temperature*", is the air property that is most commonly used. When people refer to the temperature of the air they are normally referring to the dry bulb temperature.

The Dry Bulb Temperature refers basically to the ambient air temperature. It is called "Dry Bulb" because the air [temperature](#) is indicated by a thermometer not affected by the moisture of the air. Dry-bulb temperature -  $T_{db}$ , can be measured using a normal thermometer freely exposed to the air but shielded from radiation and moisture. The [temperature](#) is usually given in degrees Celsius (°C) or degrees Fahrenheit (°F). The SI unit is Kelvin (K). Zero Kelvin equals to -273 °C.

The dry-bulb temperature is an indicator of heat content and is shown along the bottom axis of the [psychrometric chart](#) or along the left side of the [Mollier diagram](#). Constant dry bulb temperatures appear as vertical lines in the psychrometric chart or horizontal lines in the Mollier diagram.

### Wet Bulb Temperature - $T_{wb}$

The **Wet Bulb** temperature is the adiabatic saturation temperature.

Wet Bulb temperature can be measured by using a thermometer with the bulb wrapped in wet muslin. The adiabatic evaporation of water from the thermometer bulb and the cooling effect is indicated by a "wet bulb temperature" lower than the "dry bulb temperature" in the air.

The rate of evaporation from the wet bandage on the bulb, and the temperature difference between the dry bulb and wet bulb, depends on the humidity of the air.

The evaporation from the wet muslin is reduced when air contains more water vapor. The Wet Bulb temperature is always between the Dry Bulb temperature and the Dew Point. For the wet bulb, there is a dynamic equilibrium between heat gained because the wet bulb is cooler than the surrounding air and heat lost because of evaporation.

The wet bulb temperature is the temperature of an object that can be achieved through [evaporative cooling](#), assuming good air flow and that the ambient air temperature remains the same.

By combining the dry bulb and wet bulb temperature in a [psychrometric chart](#) or [Mollier diagram](#) the state of the humid air can be determined. Lines of constant wet bulb temperatures run diagonally from the upper left to the lower right in the [Psychrometric chart](#).

### Dew Point Temperature - $T_{dp}$

The **Dew Point** is the temperature where water vapor starts to condense out of the air (the temperature at which air becomes completely saturated). Above this temperature the moisture stays in the air.

- if the dew-point temperature is close to the dry air temperature - the relative humidity is high
- if the dew point is well below the dry air temperature - the relative humidity is low

If moisture condenses on a cold bottle taken from the refrigerator the dew-point temperature of the air is above the temperature in the refrigerator.

The Dew Point temperature is always lower than the Dry Bulb temperature and will be identical with 100% relative humidity (the air is at the saturation line). As air



temperature changes the Dew Point tends to remain constant unless water is added or removed from the air.

The Dew Point temperature can be measured by filling a metal can with water and some ice cubes. Stir by a thermometer and watch the outside of the can. When the vapor in the air starts to condensate on the outside of the can, the temperature on the thermometer is pretty close to the dew point of the actual air.

The Dew Point is given by the saturation line in the [psychrometric chart](#).

Source: [https://www.engineeringtoolbox.com/dry-wet-bulb-dew-point-air-d\\_682.html](https://www.engineeringtoolbox.com/dry-wet-bulb-dew-point-air-d_682.html)

[https://en.wikipedia.org/wiki/Wet-bulb\\_globe\\_temperature](https://en.wikipedia.org/wiki/Wet-bulb_globe_temperature)

Wet-bulb globe temperature

From Wikipedia, the free encyclopedia

"WBGT" redirects here. For the TV station, see [WBGT-CD](#).  
Not to be confused with [Wet-bulb temperature](#).

The **wet-bulb globe temperature (WBGT)** is a [measure of environmental heat](#) as it affects humans. Unlike a simple temperature measurement, WBGT accounts for all four major environmental heat factors: air temperature, humidity, [radiant heat](#) (from sunlight or sources such as furnaces), and air movement (wind or ventilation).<sup>[1]</sup> It is used by industrial hygienists, [athletes](#), sporting events and the [military](#) to determine appropriate exposure levels to high temperatures.

A WBGT meter combines three sensors, a dry-bulb thermometer, a natural (static) wet-bulb thermometer, and a black globe thermometer.<sup>[2]</sup>

For outdoor environments, the meter uses all sensor data inputs, calculating WBGT as:

$$\text{WBGT} = 0.7T_w + 0.2T_g + 0.1T_d$$

where

- $T_w$  = [Natural wet-bulb temperature](#) (combined with dry-bulb temperature indicates humidity)
- $T_g$  = [Globe thermometer temperature](#) (measured with a globe thermometer, also known as a [black globe thermometer](#))
- $T_d$  = [Dry-bulb temperature](#) (actual air temperature)
- Temperatures may be in either [Celsius](#) or [Fahrenheit](#)

Indoors the following formula is used:

$$\text{WBGT} = 0.7T_w + 0.3T_g$$

If a meter is not available, the WBGT can be calculated from current or historic weather data.<sup>[2]</sup> A clothing adjustment may be added to the WBGT to determine the "effective WBGT", WBGT<sub>eff</sub>.

Electronic WBGT meter

Analog WBGT meter consisting of three thermometers and a slide rule to compute WBGT

Source: [https://en.wikipedia.org/wiki/Wet-bulb\\_globe\\_temperature](https://en.wikipedia.org/wiki/Wet-bulb_globe_temperature)

## Heat Index

And Heat Index (a news channel utilised format that may confuse wrt our model)

[https://en.wikipedia.org/wiki/Heat\\_index](https://en.wikipedia.org/wiki/Heat_index)

"The **heat index (HI)** is an index that combines [air temperature](#) and [relative humidity](#), in [shaded areas](#), to posit a human-perceived equivalent temperature, as how hot it would feel if the [humidity](#) were some other value in the [shade](#). For example, when the temperature is 32 °C (90 °F) with 70% relative humidity, the heat index is 41 °C (106 °F) (see table below). The heat index is meant to describe experienced temperatures in the shade, but it does not take into account heating from direct sunlight, physical activity or cooling from wind.

The human body normally cools itself by [evaporation](#) of [sweat](#). High relative humidity reduces evaporation and cooling, increasing discomfort and potential [heat stress](#). Different individuals

perceive heat differently due to body shape, metabolism, level of hydration, [pregnancy](#), or other physical conditions. Measurement of perceived temperature has been based on reports of how hot subjects feel under controlled conditions of temperature and humidity. Besides the heat index, other measures of [apparent temperature](#) include the Canadian [humidex](#), the [wet-bulb globe temperature](#), "relative outdoor temperature", and the proprietary "[RealFeel](#)".

### Dangerous heat

#### Table of values [\[ edit \]](#)

The table below is from the U.S. [National Oceanic and Atmospheric Administration](#). The columns begin at 80 °F (27 °C), but there is also a heat index effect at 79 °F (26 °C) and similar temperatures when there is high humidity.

App

Text

**NOAA national weather service: heat index**

Temperature Relative humidity	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	86 °F (30 °C)	88 °F (31 °C)	90 °F (32 °C)	92 °F (33 °C)	94 °F (34 °C)	96 °F (36 °C)	98 °F (37 °C)	100 °F (38 °C)	102 °F (39 °C)	104 °F (40 °C)	106 °F (41 °C)	108 °F (42 °C)	110 °F (43 °C)
40%	80 °F (27 °C)	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	94 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	105 °F (41 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	136 °F (58 °C)
45%	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	87 °F (31 °C)	89 °F (32 °C)	93 °F (34 °C)	96 °F (36 °C)	100 °F (38 °C)	104 °F (40 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)	
50%	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	99 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	113 °F (45 °C)	118 °F (48 °C)	124 °F (51 °C)	131 °F (55 °C)	137 °F (58 °C)		
55%	81 °F (27 °C)	84 °F (29 °C)	86 °F (30 °C)	89 °F (32 °C)	93 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	106 °F (41 °C)	112 °F (44 °C)	117 °F (47 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)			
60%	82 °F (28 °C)	84 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	110 °F (43 °C)	116 °F (47 °C)	123 °F (51 °C)	129 °F (54 °C)	137 °F (58 °C)				
65%	82 °F (28 °C)	85 °F (29 °C)	89 °F (32 °C)	93 °F (34 °C)	98 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	114 °F (46 °C)	121 °F (49 °C)	128 °F (53 °C)	136 °F (58 °C)					
70%	83 °F (28 °C)	86 °F (30 °C)	90 °F (32 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	112 °F (44 °C)	119 °F (48 °C)	126 °F (52 °C)	134 °F (57 °C)						
75%	84 °F (29 °C)	88 °F (31 °C)	92 °F (33 °C)	97 °F (36 °C)	103 °F (39 °C)	109 °F (43 °C)	116 °F (47 °C)	124 °F (51 °C)	132 °F (56 °C)							
80%	84 °F (29 °C)	89 °F (32 °C)	94 °F (34 °C)	100 °F (38 °C)	106 °F (41 °C)	113 °F (45 °C)	121 °F (49 °C)	129 °F (54 °C)								
85%	85 °F (29 °C)	90 °F (32 °C)	96 °F (36 °C)	102 °F (39 °C)	110 °F (43 °C)	117 °F (47 °C)	126 °F (52 °C)	135 °F (57 °C)								
90%	86 °F (30 °C)	91 °F (33 °C)	98 °F (37 °C)	105 °F (41 °C)	113 °F (45 °C)	122 °F (50 °C)	131 °F (55 °C)									
95%	86 °F (30 °C)	93 °F (34 °C)	100 °F (38 °C)	108 °F (42 °C)	117 °F (47 °C)	127 °F (53 °C)										
100%	87 °F (31 °C)	95 °F (35 °C)	103 °F (39 °C)	112 °F (44 °C)	121 °F (49 °C)	132 °F (56 °C)										

Key to colors:  Caution  Extreme caution  Danger  Extreme danger

For example, if the air temperature is 96 °F (36 °C) and the relative humidity is 65%, the heat index is 121 °F (49 °C)

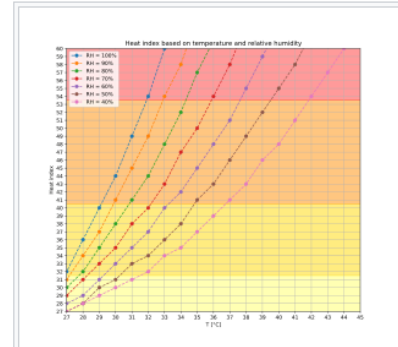
# ARC

## Architecture for resilient communities

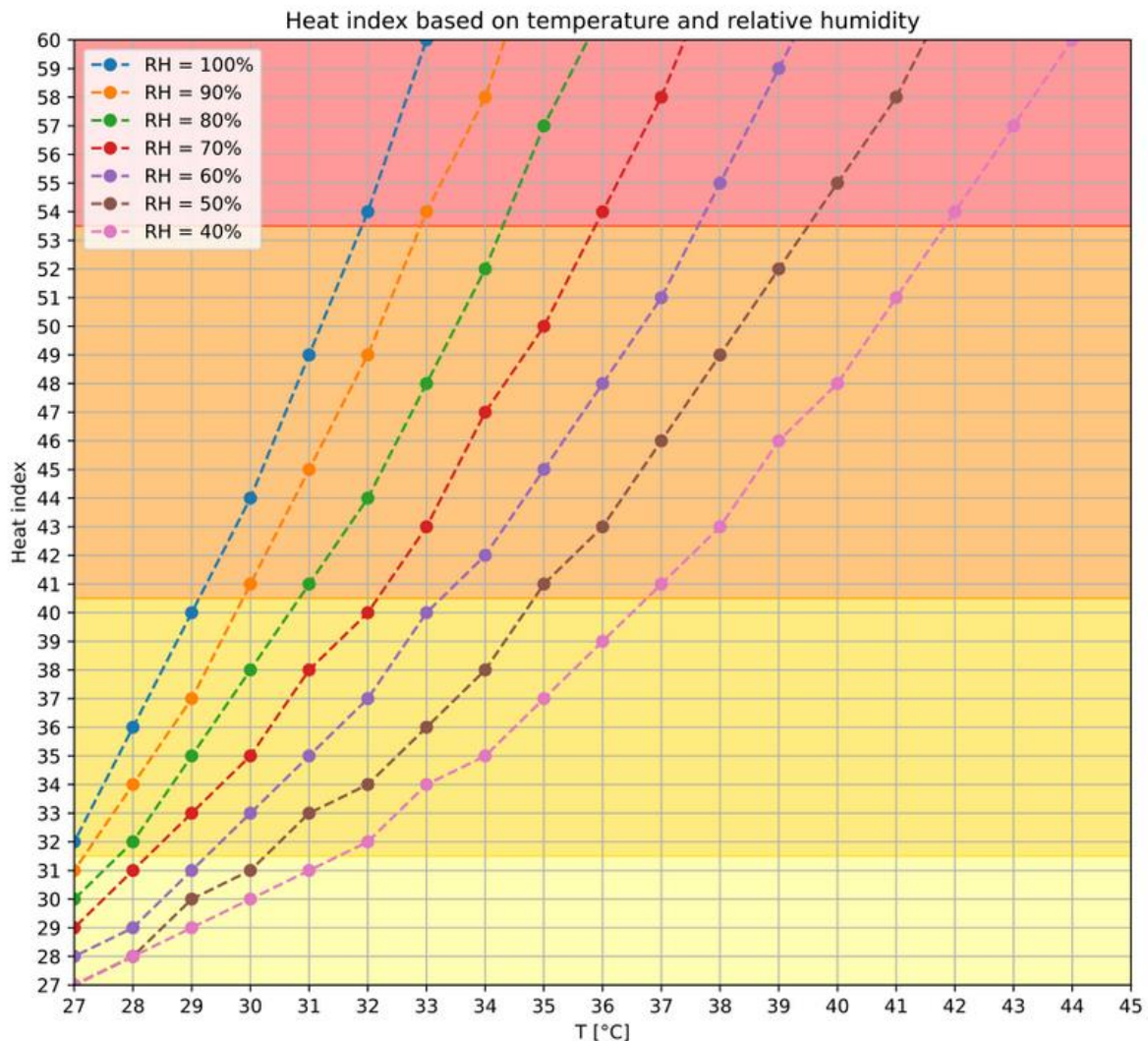
For example, if the air temperature is 96 °F (36 °C) and the relative humidity is 65%, the heat index is 121 °F (49 °C)

### Effects of the heat index (shade values) [\[edit\]](#)

Heat index	Notes
27–32 °C (81–90 °F)	Caution: fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps.
32–41 °C (90–106 °F)	Extreme caution: heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke.
41–54 °C (106–129 °F)	Danger: heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity.
over 54 °C (129 °F)	Extreme danger: heat stroke is imminent.



Heat index for temperature in °C with shaded caution/danger ranges



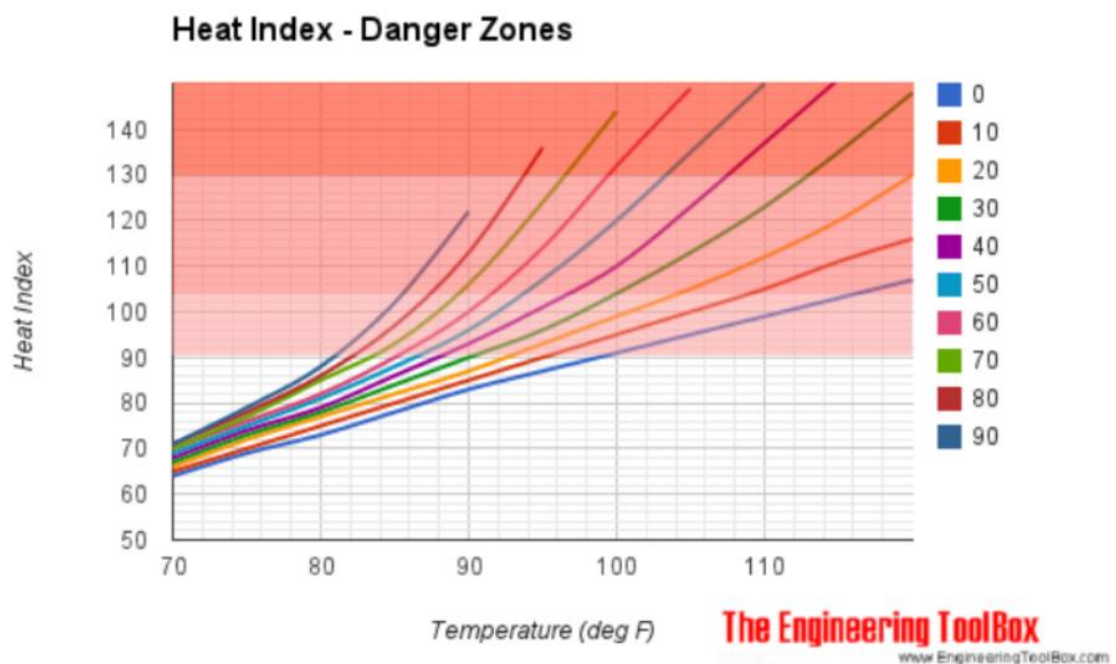
Key to colors:  Caution  Extreme caution  Danger  Extreme danger

## Heat and Humidity Index Danger Zones

- **90 - 104** : Heat cramps or heat exhaustion possible
- **105 - 130** : Heat cramps or heat exhaustion likely, heatstroke possible
- **130 and more** : Heat stroke highly likely

## Example - Apparent Temperature

From the table - with dry temperature  $85^{\circ}\text{F}$  and relative humidity  $80\%$  - the apparent temperature - or Heat Index - is 97  $^{\circ}\text{F}$ .



Note: ###

## Further discussions on factoring in Humidity to air temperature

From TC 1.8.25, Claude AI:

"Feels like" temperature (also called apparent temperature, heat index, or wind chill) is calculated using formulas that account for how environmental factors affect human perception of temperature.

There are different calculations depending on conditions:

**Heat Index (hot weather):** Used when it's hot and humid, typically above 80°F (27°C). The most common formula incorporates air temperature and relative humidity:

$$HI = -42.379 + 2.04901523T + 10.14333127R - 0.22475541TR - 6.83783 \times 10^{-3}T^2 - 5.481717 \times 10^{-2}R^2 + 1.22874 \times 10^{-3}T^2R + 8.5282 \times 10^{-4}TR^2 - 1.99 \times 10^{-6}T^2R^2$$

Where T = temperature in °F and R = relative humidity as a percentage.

**Wind Chill (cold weather):** Used in cold conditions with wind, typically below 50°F (10°C):

$$WC = 35.74 + 0.6215T - 35.75(V^{0.16}) + 0.4275T(V^{0.16})$$

Where T = air temperature in °F and V = wind speed in mph.

**The reasoning behind these calculations:**

**Toby Cambray 10:04**

- High humidity makes you feel hotter because sweat doesn't evaporate as efficiently
- Wind makes you feel colder because it increases heat loss from your body
- Both formulas are based on studies of human physiology and how the body regulates temperature

Weather services use these formulas to give you a more accurate sense of how the weather will actually feel on your skin, rather than just the air temperature measured in shade.

## Heatwave advice

During a heatwave the following advice is recommended.

- Siestas

Siestas lower your metabolic rate and therefore you produce less heat.

- Changing location

Larger houses with courtyards typically have thermal diversity, which means temperatures are different in different parts of the house. Occupants can utilise this by moving to a cooler area in the building, for example north eastern rooms could be cooler during evenings.

- Taking a shower



Taking a shower helps cool the body through evaporative cooling. However, a study showed that this impact is temporary and goes away within 20 minutes. The water must be tepid or lukewarm to avoid the body responding by constricting your blood vessels, which prevents you from releasing your heat<sup>8</sup>.

- Evaporative cooling

Evaporative cooling works in hot dry climates as it increases the humidity in the air, which lowers the dry bulb temperature. This only works where there is a difference between wet and dry bulb temperature, and the maximum performance depends on what the wet bulb temperature is. Evaporative cooling could be through an evaporative cooling air conditioner, sprinklers and misters, or a fountain. This is because the water droplets need to be agitated and dispersed into the air to be more effective. Additionally, still water poses risks like becoming a mosquito breeding ground.

- Fans

Fans increase air speeds, which aids in sweating. This is further explored in the air speed section of thermal comfort. A key consideration is ensuring the occupant is facing the middle of the fan, as air speeds are significantly lower when the person isn't directly in front of the fan. This could require using stand/ desk fans in addition to the ceiling fan.

- Closing windows and curtains during the day

While people in hot climates are used to closing windows and heavy curtains during midday, this adaptive behaviour is not intuitive in milder climates. Curtains limit the amount of solar gain entering the space. However, ideally, you want to stop the solar gain before it gets into the building through external shading. This is because once it is inside, it is harder to lose that heat.

- Opening windows overnight and evenings

As temperatures cool down in the evening, its important to open the windows to allow the thermal mass in the building to release its stored heat. If this process doesn't happen, the building will be hotter the next day.

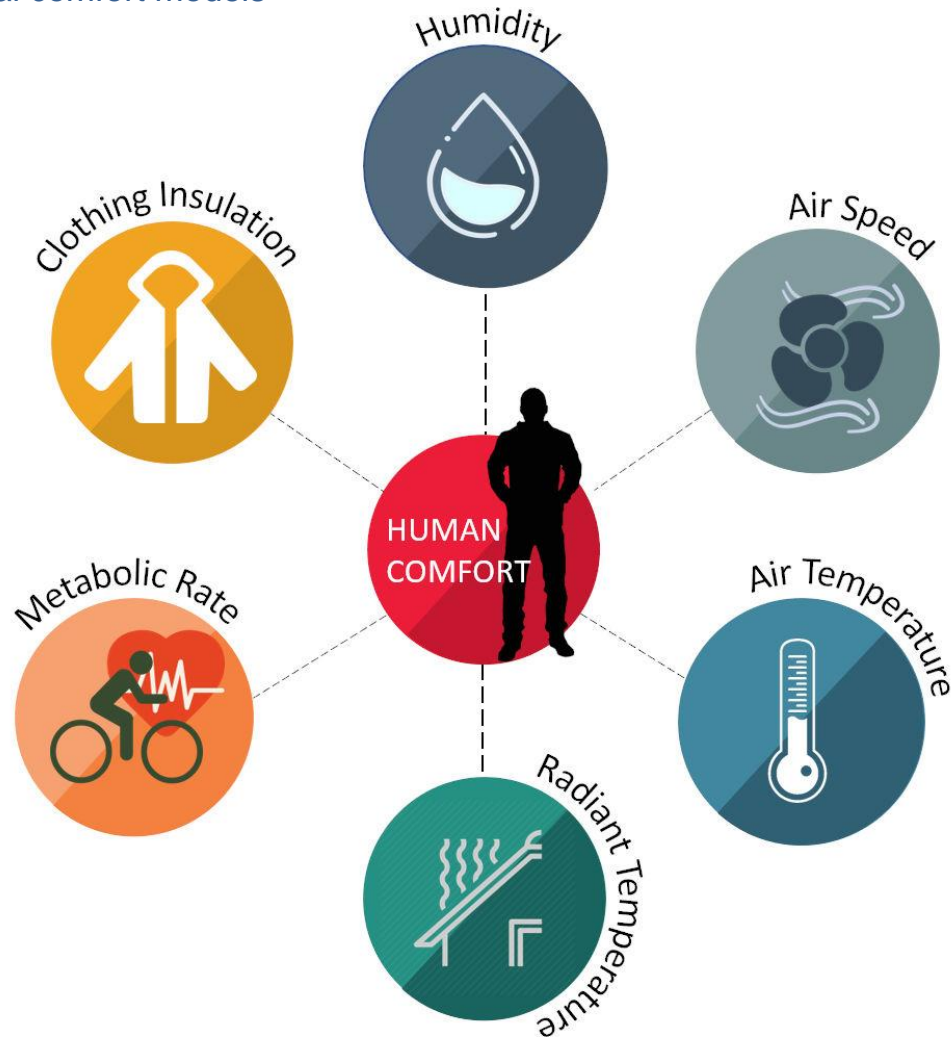
- Creating a shelter with batteries and solar panels

In many cases, due to power cuts, its necessary to rely on solar panels to power one space that acts as a shelter. The panel/ battery need to be connected to a socket, a light source and a fan.

---

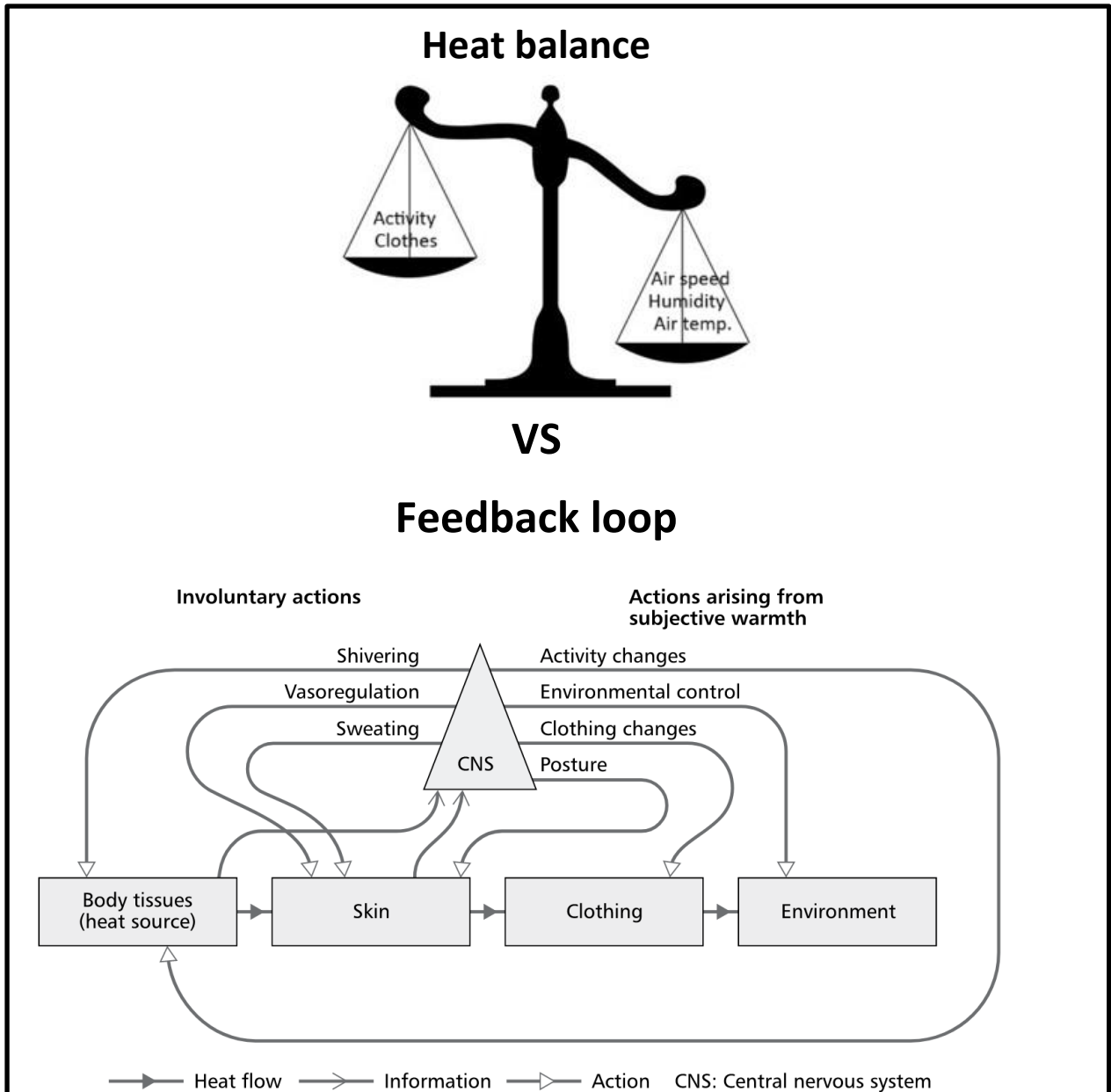
<sup>8</sup> <https://theconversation.com/why-taking-a-cold-shower-on-a-hot-day-might-be-a-bad-idea-259074>

## Thermal comfort models



According to the ISO standard 7730 definition, thermal comfort is the “condition of mind which expresses satisfaction with the thermal environment”. There are currently two main models that most standards are built upon: The steady-state heat balance model and the Adaptive comfort model. The steady state heat balance model theorises that a person’s thermal comfort can be measured by calculating the impact of specific factors (shown in the image above) on the ‘thermal load’ that impacts people’s own internal thermal regulation systems. By distilling it into tangible things that you can measure, this model makes it easy of HVAC engineers to size their heating and cooling systems. However, field research has shown that people are comfortable in much larger ranges than the mathematical model predicted. Thus the adaptive comfort model was born, its based on the idea that in addition to the factors above, people actively (and subconsciously) change their behaviour and environment to aid the thermal regulation process. So instead of viewing comfort as a simple balancing scale, it’s more a continuous feedback loop (shown below).





What the feedback loop diagram is saying is that your body changes the situation at all 4 levels of heat transfer from your internal body, to skin, to the clothes you wear and finally the environment surrounding you. At the body level, you can shiver to produce heat or rub your hands to create some heat from the movement. At the skin level, you can sweat, change the blood flow rates to different parts of the body or change your posture. For example, when its very cold, you huddle and curl up into a ball, to preserve your heat, but when its hot you might spread out while lying down on the bed. Your clothing can be added or removed to adapt to the surrounding temperatures. Finally, you can change your environment by opening windows, finding a better space, or closing the curtains for example.

### Clothing

According to the ASHRAE 55-2010 and the BS ISO 9920. The clothing level can be estimated in measurements of 'clo'. The table below shows the clo equivalent to typical ensembles. Where people wear traditional clothes like turbans and saris, some local studies offer equivalent clos. For a typical designer the key benefit in understanding this, is to check that any local surveys were based on clo levels typical of the project they are working on. For example, if a local survey was conducted in people's homes, it would mean people were likely wearing less clothes than they would in an office with a suit and tie policy. You can use the clo values in climate consultant to help you assess the strategies available to achieve comfort.

Description	Insulation level / clo
Underpants plus:	
— shirt (short sleeves), lightweight trousers, light socks, shoes	0.5
— shirt, lightweight trousers, socks, shoes	0.6
— boiler suit, socks, shoes	0.7
— shirt, trousers, socks, shoes	0.75
— shirt, boiler suit, socks, shoes	0.8
— shirt, trousers, jacket, socks, shoes	0.85
— shirt, trousers, smock, socks, shoes	0.9
Underwear (short sleeves/legs) plus:	
— tracksuit (sweater and trousers), long socks, training shoes	0.75
— shirt, trousers, jacket or sweater, socks, shoes	1.0
— shirt, trousers, boiler suit, socks, shoes	1.1
— shirt, trousers, jacket, insulated jacket, socks, shoes	1.25
— boiler suit, insulated jacket and trousers, socks, shoes	1.4
— shirt, trousers, jacket, insulated jacket and trousers, socks, shoes	1.55
— shirt, trousers, jacket, quilted jacket and overalls, socks, shoes	1.85
— shirt, trousers, jacket, quilted jacket and overalls, socks, shoes, cap, gloves	2.0
Underwear (long sleeves/legs) plus:	
— shirt, trousers, pullover, jacket, socks, shoes	1.3
— insulated jacket and trousers, insulated jacket and trousers, socks, shoes	2.2
— insulated jacket and trousers, quilted parka, quilted overalls, socks, shoes, cap, gloves	2.55
Bra and pants plus:	
— T-shirt, shorts, light socks, sandals	0.3
— petticoat, stockings, lightweight dress (with sleeves), sandals	0.45
— stockings, blouse (short sleeves), skirt, sandals	0.55
— petticoat, stockings, dress, shoes	0.7
— petticoat, shirt, skirt, thick socks (long), shoes	0.8
— shirt, skirt, sweater, thick socks (long), shoes	0.9
— shirt, trousers, jacket, socks, shoes	1.0
— blouse (long sleeves), long skirt, jacket, stockings, shoes	1.1
Pyjamas (long sleeves/legs), bath robe, slippers (no socks)	0.95

### Activities

How much heat you emit from the surface of your body depends on what you're doing. Heat will transfer from a warmer body with higher temperature to a colder body with lower temperature. Activity level is measured in 'met' units, which is 60 Watts per square metre

# ARC

Architecture for resilient communities

(W/m<sup>2</sup>). That specific number comes from the amount of energy you produce sitting, which is the most common activity. During heatwaves, taking a nap is an effective way to reduce your metabolic rate and help cool down. On the other hand, moving can help keep you warm in colder weather.



## Humidity

Air that is more humid, makes it harder to sweat. This is why people can tolerate higher temperatures in hot dry climates.

## Air speed

Higher air velocities help you sweating by making evaporation happen faster. This is especially important in humid areas. However, after if the air temperatures exceed a certain

point, the fan can no longer provide a cooling effect<sup>9</sup>. This cut off point is around 32°C-35°C for hot dry climates and up to 40°C for hot humid climates.

## Air and radiant temperatures

Air temperature is the temperature of the air around you, while radiant temperatures are impacted by solar radiation either directly or indirectly reaching you. The 'operative temperature', often used in comfort models, is a sort of average between the two. The air and radiant temperatures are weighted depending on a factor that is derived from the air speeds in the area. So for example, when you are inside, not near the window or any hot ceiling, and the air is still, the operative temperature is usually the same as air temperatures. That's why data loggers, which only log air temperature, need to be placed somewhere away from heat/coolth sources to be able to use the air temperatures as substitutes for operative temperature. Although, ideally you have a black globe thermometer to separately measure radiant temperatures. However, in a project with floor to wall windows for example, the radiant temperatures would be really high, therefore measuring just the air temperatures wouldn't accurately reflect what the occupants are experiencing.

---

<sup>9</sup> <https://www.science.org/content/article/when-is-it-too-hot-use-fan>

## Appendix 2: heat waves and climate change in the global south: definitions, monitoring, and organizations

### WMO Official Definition

World Meteorological Organization (WMO): Defines a heat wave as a period where local excess heat accumulates over a sequence of unusually hot days and nights.

### UK Met Office Definition

- In the UK, the Met Office defines a heat wave as a period of three or more consecutive days when the daily maximum temperature exceeds a set threshold.
- These thresholds vary by region to reflect differences in climate and are updated regularly in response to rising average temperatures caused by climate change.
- This provides a useful reference model for defining heat waves contextually in Tanzania, suggesting the importance of localised thresholds and climate sensitivity when setting criteria.

Ref: <https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/temperature/heatwave> & <https://www.metoffice.gov.uk/about-us/news-and-media/media-centre/weather-and-climate-news/2022/heatwave-threshold-changes>

IPCC: Describes a heat wave as a period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months.

### Temperature Thresholds

Heat wave definitions typically rely on high-temperature thresholds relative to local climate baselines:

- Absolute anomaly-based: e.g., exceed daily maximum by  $>5^{\circ}\text{C}$  over normal (1961–1990 baseline) for  $\geq 5$  days.
- Percentile-based: e.g., daily max exceeding 99th percentile of May–September historical distribution for  $\geq 3$  days.
- Locally defined fixed values: e.g.,  $\geq 32^{\circ}\text{C}$  for  $\geq 3$  days in specific areas.
- Country-specific figures: India & Pakistan consider plains at  $\geq 40^{\circ}\text{C}$ , mountains at  $\geq 30^{\circ}\text{C}$ , for  $\geq 5$  days.

### Monitoring and Recording

National Meteorological and Hydrological Services (NMHSs) select thresholds based on local climatological baselines and maintain records. Global organizations:

- WMO/WHO collaborate through the Global Heat Health Information Network (GHHIN).
- WMO issues the annual 'State of the Global Climate' report.
- IPCC references thresholds and observational trends in Assessment Reports.
- Countries operate formal Heat-Health Action Plans guided by WHO-WMO.

### Why It Matters for the Global South

Regions like East Africa, India, and Pakistan face heightened risks from climate change, with heat waves becoming more frequent and severe. Monitoring gaps remain significant, with WMO reporting that half the world's population lacks access to early-warning systems, particularly in the Global South.

### Central Coordinating Body

The World Meteorological Organization (WMO) is the primary authority for defining heat waves, setting guidelines, coordinating data collection, and partnering with WHO for heat-health warning systems through GHHIN.

### Summary

Aspect	Key Info
Definition	Heat wave = 2–3+ days of unusually high temp vs local baseline
Thresholds	Based on anomalies (e.g., $+5^{\circ}\text{C}$ ) or percentiles (90th/99th)

# ARC

## Architecture for resilient communities

Monitoring | NMHSs implement; WMO/WHO set global best practices  
Central Body | WMO, working via GHHIN/WHO  
Global South Issue | High vulnerability; warning systems often lacking

### Actionable Starting Points

1. Visit WMO's "Heatwave" page for official definitions and resources:  
<https://wmo.int/topics/heatwave>
2. Review the WMO-WHO Heat-Health Warning System guidance: [https://ghhin.org/wp-content/uploads/WMO\\_WHO\\_Heat\\_Health\\_Guidance\\_2015.pdf](https://ghhin.org/wp-content/uploads/WMO_WHO_Heat_Health_Guidance_2015.pdf)
3. Consult NMHS documentation or national Heat-Health Action Plans for region-specific thresholds.

## Appendix 3: technical R&D brief for air-conditioning and ventilation for hot and humid climates

---

### 1. Objective

Develop a prototype air-conditioning (AC) unit optimised for high-temperature, high-humidity environments such as those found in parts of Tanzania and similar regions. The system should:

- Cool indoor air effectively,
  - Remove excess humidity efficiently,
  - Introduce fresh outdoor air with minimal added energy load,
  - Operate reliably with minimal maintenance and energy input.
- 

### 2. Core Design Challenge

In hot and humid climates, thermal comfort depends on both temperature reduction and moisture removal. Standard AC units often:

- Overcool air to achieve dehumidification (wasting energy),
- Or fail to adequately remove humidity (leading to discomfort and mould growth).

The design must balance cooling and dehumidification efficiently.

---

### 3. R&D Focus Areas

#### A. Cooling and Dehumidification Balance

- Design for independent control of temperature (sensible load) and humidity (latent load).
- Investigate two-stage cooling systems:
  - Stage 1: Moisture removal using cold coils or desiccant systems.
  - Stage 2: Reheat to deliver comfortable air temperature supply.
- Use variable-speed fans and compressors for energy-efficient modulation.

*Target Performance:* - Indoor air temperature: 26–28°C - Relative humidity: 50–60%  
- Lower energy use than typical single-stage systems

#### B. Fresh Air Ventilation with Low Energy Penalty

Fresh air is essential for indoor air quality but increases the cooling and dehumidification load.

*Ventilation Options:* 1. **Integrated into AC Unit:** - Use heat and moisture recovery ventilators (HMRVs) or desiccant-based intake systems. 2. **Separate Systems:** - Trickle vents (possibly with moisture control features), - Stand-alone energy recovery ventilators (ERVs), - Solar-powered extract and intake fans.



*Ventilation Target:* - Supply 10–20 m<sup>3</sup>/h per person of fresh air - Minimise additional cooling and moisture load

---

#### 4. Context and Practical Constraints

**Environmental Conditions:** - Outdoor air: 30–35°C, 70–90% RH - Power supply: Intermittent or expensive - Maintenance: Should be low-frequency and simple - Noise: Quiet operation is preferred in domestic spaces

**Materials and Build:** - Corrosion-resistant components - Modular, repairable parts - Suitable for potential local assembly in East Africa

---

#### 5. Outputs Required

- Concept drawings and control schematics
  - Thermal and energy performance simulations
  - Bill of Materials (BOM) with approximate costing
  - Working prototype for field testing
  - Maintenance and installation guides suitable for non-specialist users
- 

#### 6. Success Criteria

- Indoor climate: 26–28°C, 50–60% RH
- Fresh air provision: 10–20 m<sup>3</sup>/h per person
- Energy use: At least 30% less than conventional AC
- Ease of use and maintenance
- Robustness and reliability in local conditions

## ARC technical meeting: Cooling individual rooms in a Tanzanian context

Date: 1.8.25

**Participants:** Andy Simmonds, Toby Cambray

**Meeting was recorded:** <https://zoom.us/rec/share/vu-obfsl4ZcwOuEZ08lhnjlzRE3aXxpv6aku-nOdCZlxdzqaf7bwyBrYQWOcAgCn.SwoZd7R5RBVYryGd>

Passcode: thD\$Np6\$

### Basic architectural unit for cooling brief

- Agreed to focus on individual rooms as the basic unit in the ARC three-zone model.
- This aligns with how people already manage thermal comfort in hot climates—cooling individual rooms, particularly during heat waves.

### Scenario Development

- Develop a scenario with a 10–15 year horizon, in line with:
  - Typical mechanical services lifespans
  - Copernicus climate projections
- Objective: Define a "worst-case" heat wave scenario for Tanzania, including:
  - Duration (e.g. two weeks)
  - External temperature and humidity extremes

### Comfort Threshold & Success Criteria

- Current success criteria are based on passive-only measures.
- Use current dry bulb threshold of <28°C, with a tentative proposal to incorporate 60% RH as a hard humidity target (since we are talking about equipment set points).
- Aim during heat waves: return indoor conditions to the comfort threshold using the simplest, minimal amount of equipment available locally, but also minimizing peak power and running costs to 'sustainable' levels for reduced community (electrical grid, heat island effects) and occupant benefit.

### Equipment Considerations

- Ideal solution:
  - Standard or higher-end mini-split air conditioning unit with both:
    - Sensible cooling (temperature)
    - Latent cooling (humidity control - ability to set room humidity)
- Investigate local availability of such units.
- Andy to ask Mahwah Mohabe to liaise with 'Uncle Gafur' to research units that are affordable and have dehumidification functionality.

### Ventilation & Airtightness

- Avoid using mechanical ventilation with heat recovery if possible.
- Explore:
  - Achievable airtightness levels in Tanzanian construction.

- Typical leakage paths (e.g. glass louvre or other types of windows, door gaps).<sup>10</sup>
- Use of dedicated "trickle vents" or accounting for cumulative construction gaps around windows and doors to allow fresh air supply.
- Consider mechanical extract ventilation:
  - Define required extract rates
  - Explore the use of standard locally available room extract fans
  - Investigate whether these can be wired to operate with AC units

### Modelling Needs

- Suggest modelling (PHPP or 'longhand'?) typical room types to:
  - Assess peak power demands
  - Estimate running costs during heat waves

### Adaptation vs. Heat Waves

- Produce educational text for science module on 'human adaptability to increased heat' versus 'human heat-stress':
  - Gradual adaptation to climate change over time
  - Inability to adapt rapidly to short-term heat wave extremes
- Develop scenarios explaining both but state that ARC is prioritising short-term heatwave measures with a longer-term approach to climate change requiring more extensive future adaptations.

### Actions

- Toby to share:
  - TM52 and TM59 overheating criteria (CIBSE)
  - To inform development of teaching material on human adaptation to heat
- Andy to:
  - draft text based on CIBSE definitions of overheating criteria for Huda to draw on
  - draft text based on how we (might) define heatwaves for Huda to draw on
  - Ask ARC Tanzania to describe local understanding of heat waves
  - Ask Archie to analyse village monitoring data to:
- Identify potential past heat wave-like periods and compare with any current Tanzanian benchmarks, perhaps referencing the Copernicus site data: Use Copernicus Climate Change service, for CC projects and reference our own (weather station) data. To research – AW to use CC projection and make into heatwave scenario. <https://climate.copernicus.eu/>

---

<sup>10</sup> \*We are exploring local suppliers of magnetic strip insect mesh screens that can be applied to our (under design) steel framed window units, we can also explore the development of magnetic strip secondary glazing panels that could be used during heatwaves as an alternative to adding opening bifold or casement windows internally. This approach would likely provide quite an air-tight solution and would need to incorporate dedicated air inlet holes. Disadvantages are where to store the glazing when the building or room is in natural ventilation mode.

### Current state of standard technology - ChatGPT

Standard air conditioning (AC) units in Tanzania — typically split-system or window units used in homes, offices, and hotels — do **incorporate dehumidification** as a **byproduct** of their cooling function, but **not usually as a controllable, standalone feature**.

#### Key points:

1. **Passive dehumidification during cooling:**
  - When the AC cools the air, water vapor condenses on the cold evaporator coils.
  - This process **removes moisture** from the indoor air, thus reducing humidity.
  - The amount of dehumidification depends on factors like **coil temperature, air speed, and indoor humidity**.
2. **Lack of dedicated dehumidification mode:**
  - Most standard units **do not include** a "dry mode" or **humidity control setting** tailored to maintain a specific relative humidity (RH).
  - Higher-end or inverter models (often imported from brands like Daikin, LG, or Panasonic) **may include a "Dry" or "Dehumidify" mode**, which prioritizes moisture removal with limited cooling.
3. **Energy and design limitations:**
  - In humid coastal areas like Dar es Salaam, standard AC units may **not remove sufficient moisture** to maintain indoor RH in the **40–60% range** optimal for health and comfort.
  - Oversized or poorly controlled AC units often cycle on and off quickly, **limiting moisture removal** compared to steady-state operation.
4. **Installation practice:**
  - Many installations prioritize cost and cooling capacity over indoor air quality (IAQ), so **dehumidification is often incidental** rather than intentional.

#### Summary:

Yes, **some dehumidification occurs**, but **standard AC units in Tanzania are not typically designed or installed with deliberate humidity control in mind**. Where humidity is a serious concern — for comfort, mould control, or preservation of materials — **dedicated dehumidifiers or properly sized and controlled AC systems** (preferably with inverter drives and humidity sensors) are more appropriate.

Claude::

Mini split AC units are **deliberately designed** to dehumidify air as part of their cooling function, not just incidentally. This is especially important in hot, humid climates where latent heat removal (dehumidification) can account for 20-40% of the total cooling load.

#### How they're designed for dehumidification:

The evaporator coil is specifically sized and designed to operate at temperatures below the dew point of the incoming air. As humid air passes over the cold coil,

water vapor condenses out and drains away through the condensate system. This process removes latent heat from the air.

**Key design features:**

- **Variable speed compressors** allow the unit to run longer at lower speeds, which increases dehumidification effectiveness compared to simple on/off cycling
- **Condensate drainage systems** with pumps or gravity drains to handle the water removal
- **Coil design** optimized for both sensible cooling (temperature reduction) and latent cooling (moisture removal)
- 

**However, there's a balance issue:**

In very humid climates, mini splits can sometimes struggle with dehumidification when the sensible cooling load is low (like during mild but humid weather). The unit may satisfy the temperature setpoint before adequately dehumidifying, leading to a cool but clammy feeling.

**Solutions for high humidity:**

- Many newer units have dedicated "dry mode" settings
- Some have enhanced dehumidification features
- In extremely humid climates, supplemental dehumidifiers are sometimes needed

So, while dehumidification is an intentional design feature, the effectiveness varies by model and operating conditions. It's not just a happy accident of the cooling process.

## Technical reminders

- Mini-split systems:
  - Heat transfer is via Air to air (A2A) systems
  - One outdoor unit, one or more indoor units
  - Use refrigerant with pipes running inside the building'multi-split' systems can support several indoor units from one (larger) external unit, with more extensive refrigerant pipe runs.
- Mono-block systems:
  - Heat transfer is via Air to water (A2W) systems
  - Refrigerant remains outside the building envelope
  - Use air-to-water connection (e.g. UK systems)
- In Tanzania, dehumidification is typically a *byproduct* of cooling air, not a controlled function
- Our interest is in systems with deliberate, optimised latent cooling for dehumidification

## Misc. ARC expert comments

We used 40 mm black gloves (posh/expensive ping pong balls) in the Ghana test cells. Weirdly didn't get any difference between operative and air temperature. But the thermistors were encased, not exposed so perhaps why.

Ben

---

On Wed, 9 Jul 2025, 10:49 Andrew Simmonds, <[andy@simmondsmills.com](mailto:andy@simmondsmills.com)> wrote:  
Useful.

We are thinking that if we measure operative temperature the ping pong way, then also measure surface temps via the IR sensors, we can calculate the operative temps from the latter to compare to the ping pong results!

---

Yes could work. Assume there would need to be some correction factor as per CIBSE TM52

Ben

---



## Appendix 3 Definitions