4.401/4.464 Environmental Technologies in Buildings

Christoph Reinhart

4.401 Thermal Comfort and Case Studies

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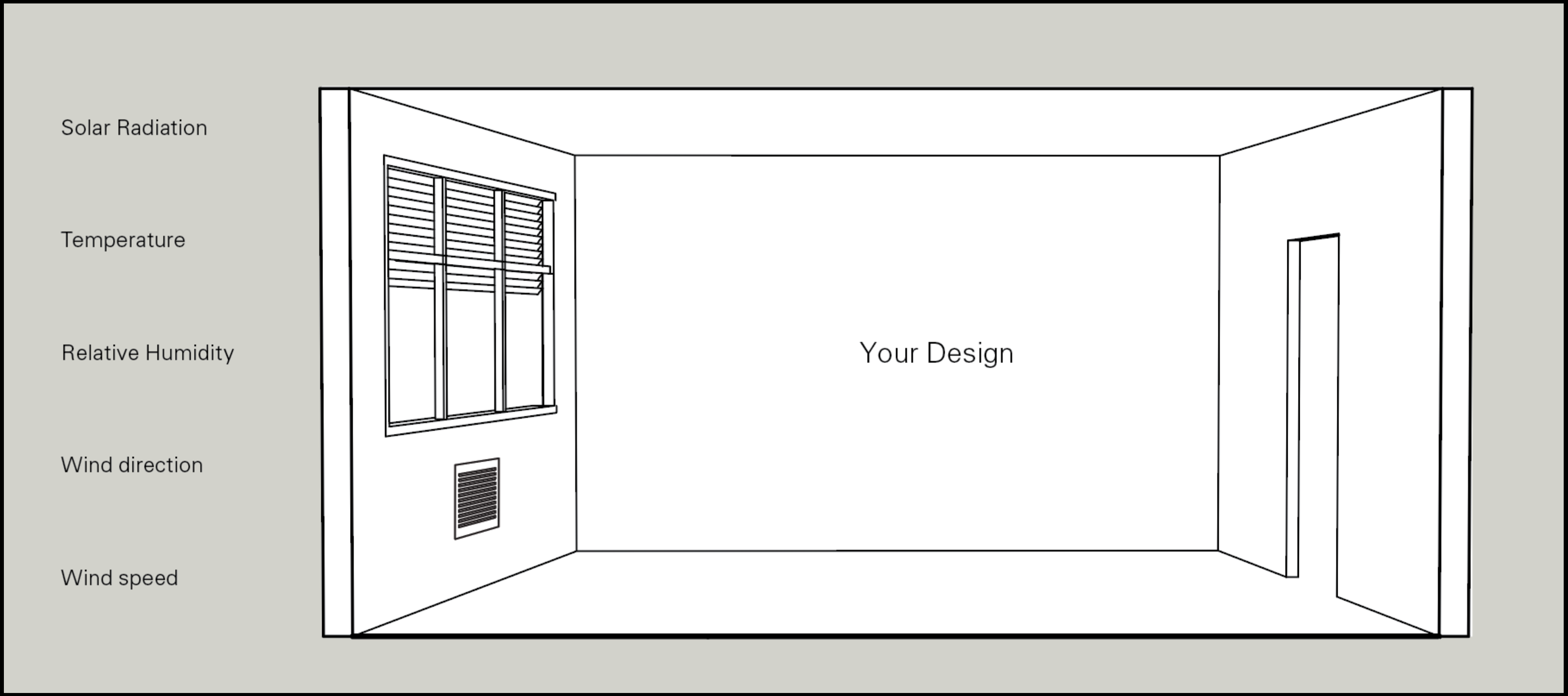
Future Climate Files

Bioclimatic Design



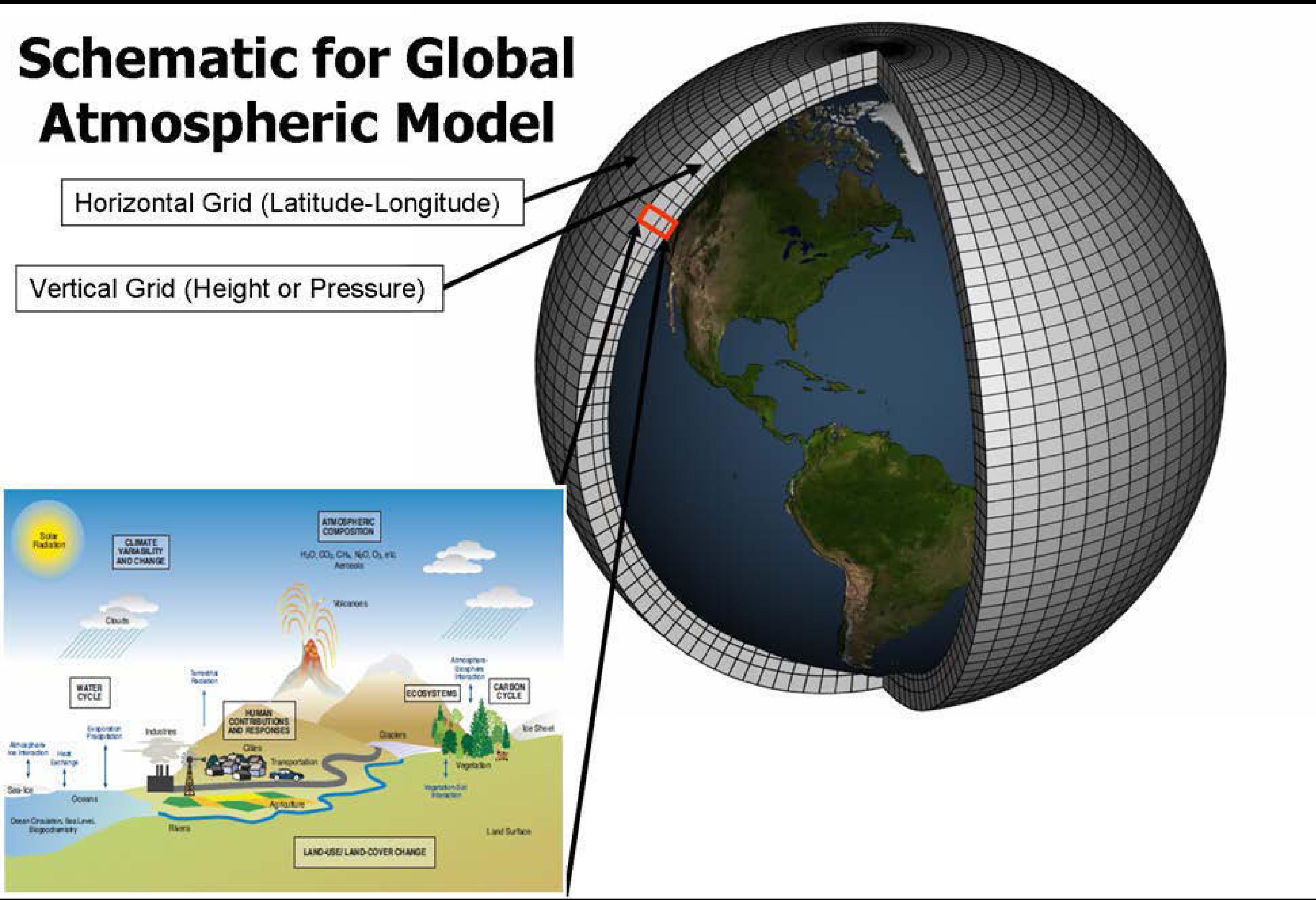
For a thermal analysis of a building we need local hourly climate data from a weather file including direct and diffuse solar radiation, wind speed and direction, as well as temperature and relative humidity.

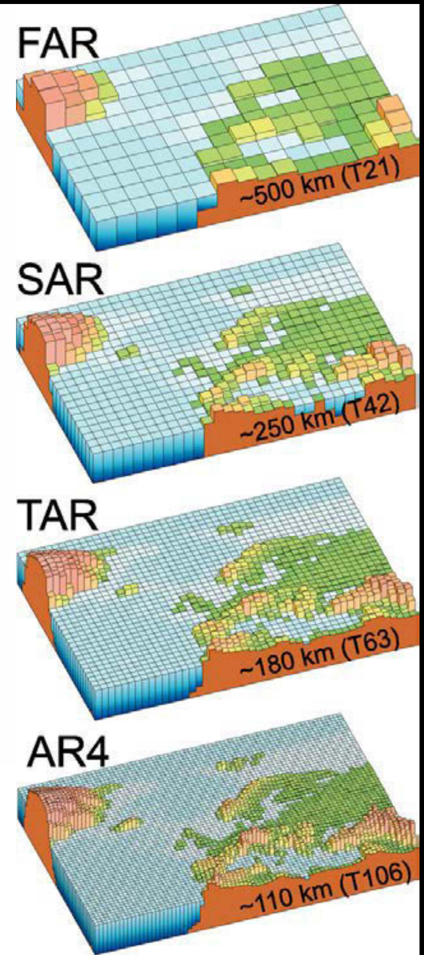
Historic Weather Fluctuations and Resulting Building Energy Use

See Figures 3-9 and 3-10, Drury B. Crawley, “Building Performance Simulation: A Tool for Policy Making," PhD thesis, University of Strathclyde, 2008 (PDF).

How can we consider climate change in our designs?

Future Climate Files





Left: public domain image courtesy of National Oceanic and Atmospheric Administration (NOAA)

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Climate Change Weather File Generator

http://www.energy.soton.ac.uk/ccworldweathergen/

Generates future climate files for locations worldwide (with limitations) with a specific focus on the UK. It is based on the ‘morphing’ methodology.

Belcher SE, Hacker JN, Powell DS. “Constructing design weather data for future climates.” *Building Services Engineering Research and Technology* 2005; 26 (1): 49-61.

Jentsch MF, Bahaj AS, James PAB. “Climate change future proofing of buildings - Generation and assessment of building simulation weather files.” *Energy and Buildings* 2008; 40 (12): 2148-2168.

Climate Change Weather File Generator

CCWorldWeatherGen climate change weather file generator V1.5 manual

For transforming EPW weather files into climate change TMY2/EPW files. (Acknowledgements & disclaimer of warranties below)

Specify the HadCM3 data file p C:\CCWorldWeatherGen\HadCM3data

Summary of combined HadCM3 A2 ensemble climate change predictions for the selected weather site

Selected scenario: A2 scenario ensemble for the 2080's

			JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Daily mean temperature	**TEMP**	(°C)	4.10	4.43	4.16	4.32	4.73	4.95	5.81	5.84	5.50	5.09	4.43	3.97	4.78
Maximum temperature	**TMAX**	(°C)	3.92	4.48	4.30	4.07	4.76	5.56	6.46	6.07	5.36	4.79	4.48	4.08	4.86
Minimum temperature	**TMIN**	(°C)	4.39	4.56	3.83	4.42	4.77	4.62	5.52	5.88	5.68	5.27	4.30	4.02	4.77
Horizontal solar irradiation	**DSWF**	W/m²	-3.96	-6.05	-4.22	-0.51	11.77	17.59	14.20	10.09	11.50	6.57	-1.14	-2.35	4.46
Total cloud cover	**TCLW**	% points	-0.25	-0.50	-0.88	-0.13	-2.00	-3.00	-5.25	-5.00	-5.63	-4.38	-0.63	-0.88	-2.38
Total precipitation rate	**PREC**	%	13.41	22.11	24.97	28.96	14.52	6.39	12.84	24.38	-8.16	2.82	12.59	15.63	14.21
Relative humidity	**RHUM**	% points	-2.59	-4.54	-4.91	-3.85	-5.21	-7.54	-7.09	-4.63	-4.16	-3.27	-3.17	-3.15	-4.51
Mean sea level pressure	**MSLP**	hpa	-1.61	-1.02	-2.48	-0.52	-1.22	-1.68	-2.09	-2.54	-1.09	-0.87	-0.21	-0.95	-1.36
Wind speed*	**WIND**	%	-1.40	-2.22	0.70	-0.58	-1.41	-2.39	-1.79	-7.25	-6.52	-5.72	-1.20	-2.52	-2.69

* Please note that wind speed resides on a 96x72 grid whilst all the other data is on a 96x73 grid

EPW weather file selection

(1) Please specify the EPW file you want to transform

Select EPW File for Morphing

Current EPW baseline weather file for morphing:

Baltimore Blt Washngtn Intl ***Latitude:*** 39.17 N
Longitude: ##### W
Elevation: 45 m

HadCM3 scenario timeframe selection

(2) Please select a HadCM3 A2 scenario ensembe timeframe

2020's 2050's 2080's Load Scenario

Closest four HadCM3 96x73 grid points to Baltimore Blt Washngtn

A2 scenario for the 208

	Latitude:	***Longitude:***
A	40.00 N	##### W
B	40.00 N	##### W
C	37.50 N	##### W
D	37.50 N	##### W

EPW weather file morphing

(3) Click button to start morphing procedure

Start Morphing Procedure

Current morphed EPW weather file:

Morphed EPW file for: Baltimore Blt Washngtn Intl, USA
HadCM3 A2 emissions senario ensemble for the 2080's

EPW/TMY2 weather file generation

(4) Click the appropriate button for EPW / TMY2 file generation

Generate Climate Change EPW Weather File

Generate Climate Change TMY2 Weather File

To create a TMY2 file of the original EPW file click the button below:

Generate Present-Day TMY2 Weather File form EPW data

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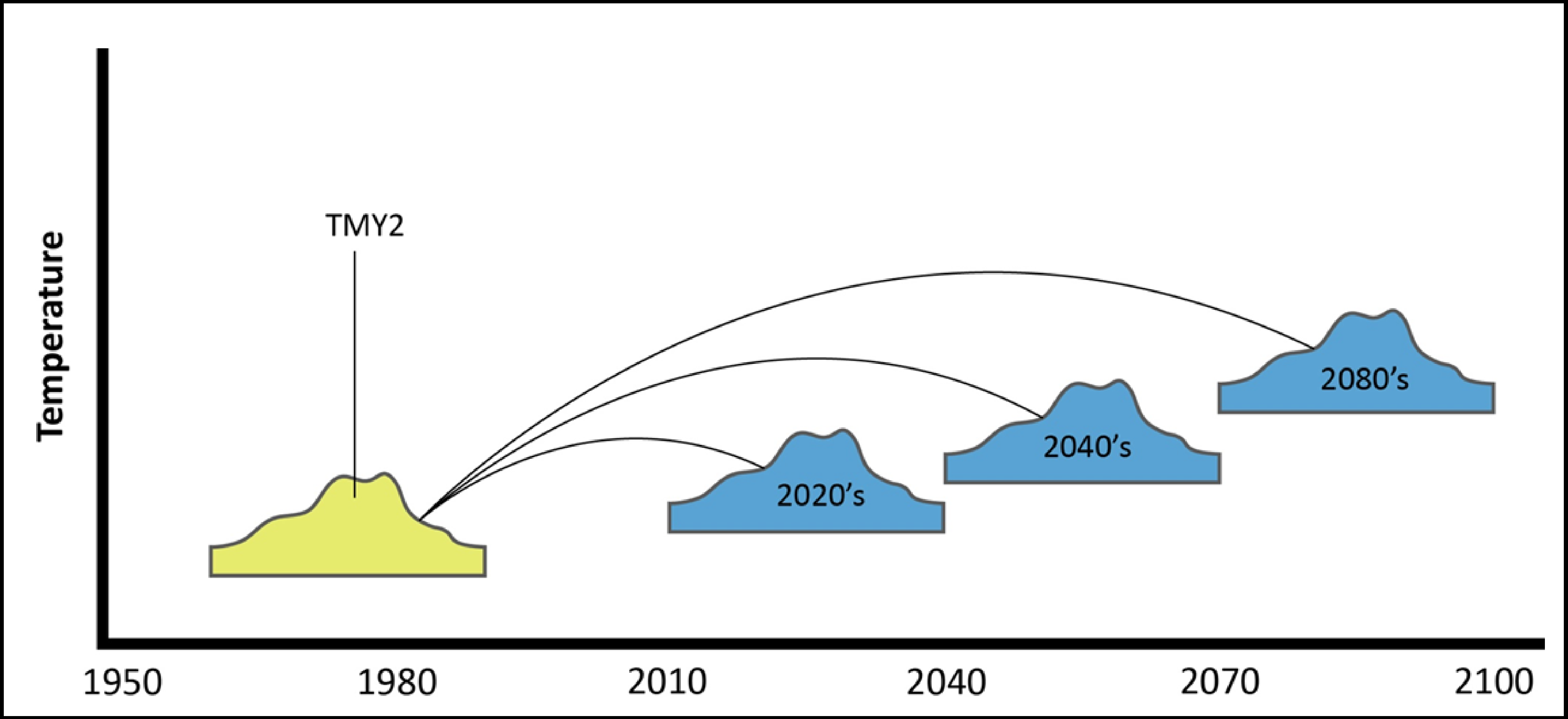
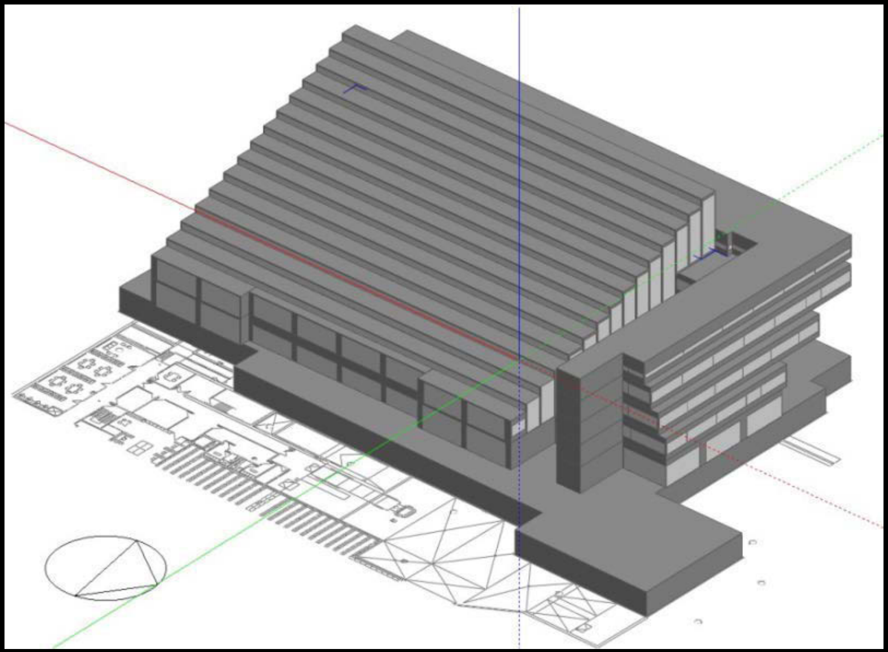
TMY2 Into The Future



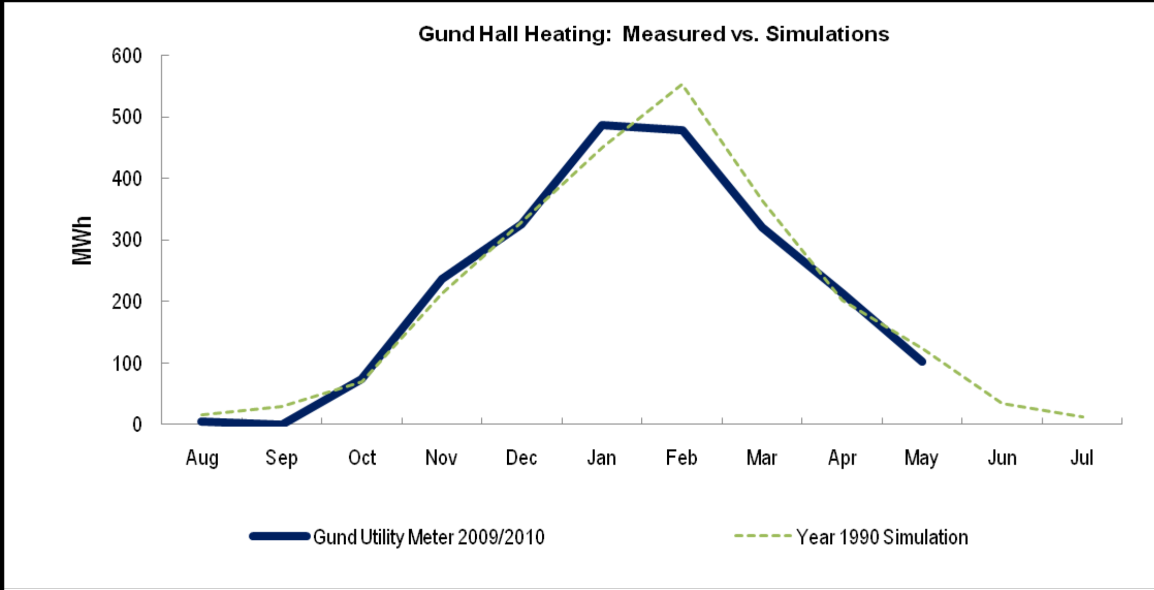
How large is the effect?

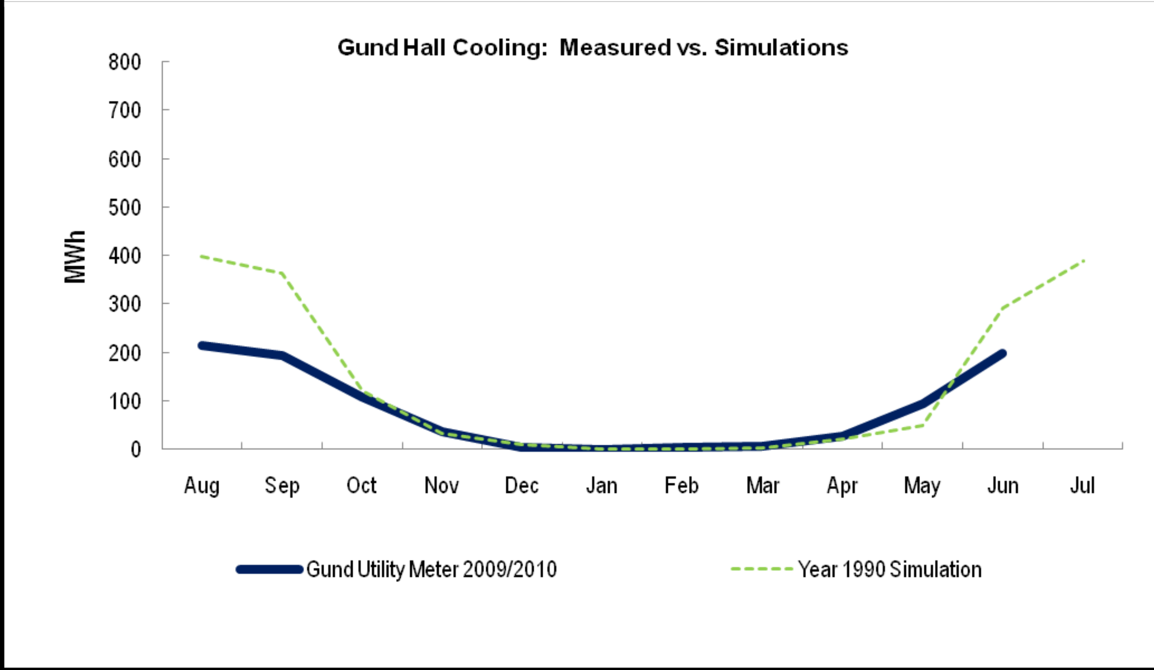
Harvard University – Gund Hall

DesignBuilder model



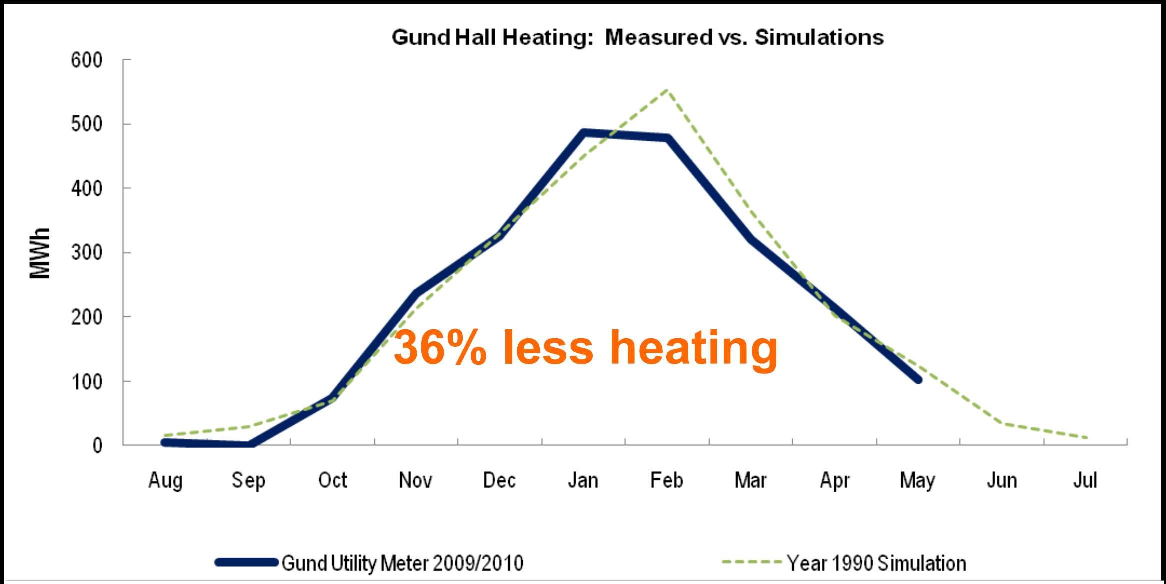
Gund Hall now

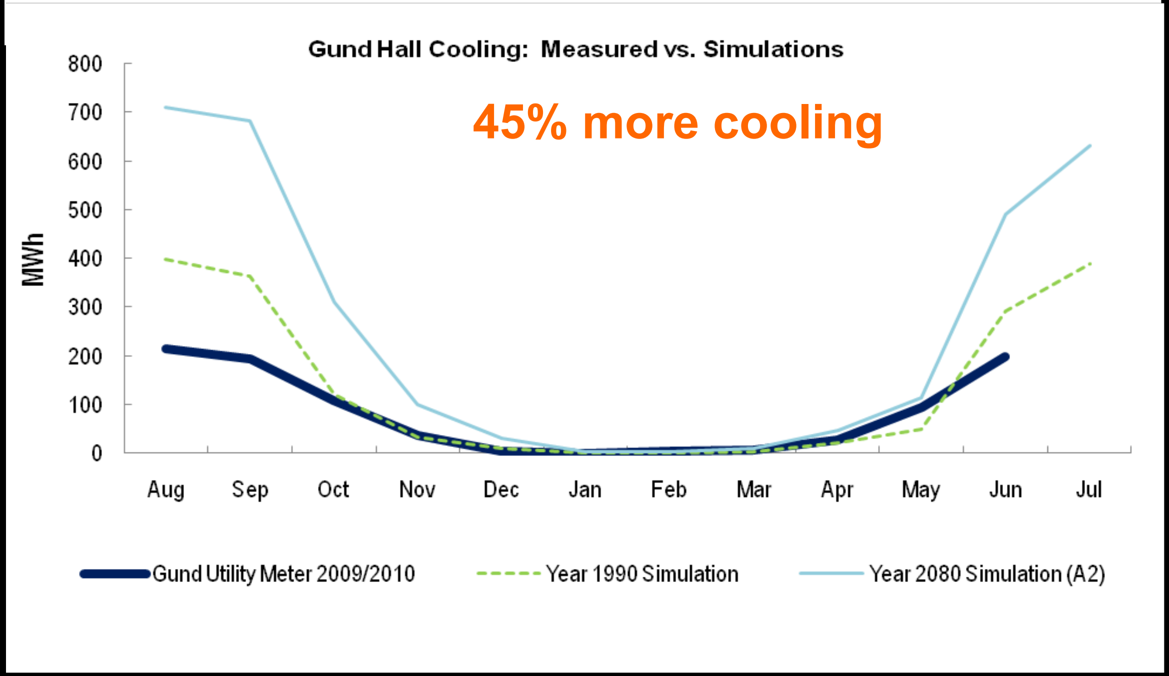




- ❑ 33 Zone E+ model
- ❑ 1990 TMY2 weather data for Boston

Case Study I : Gund Hall now and then





- 33 Zone E+ model
- 1990 TMY2 weather data for Boston
- predicted 2080 weather data for the IPCCCA2 scenario (medium to high emissions scenario).

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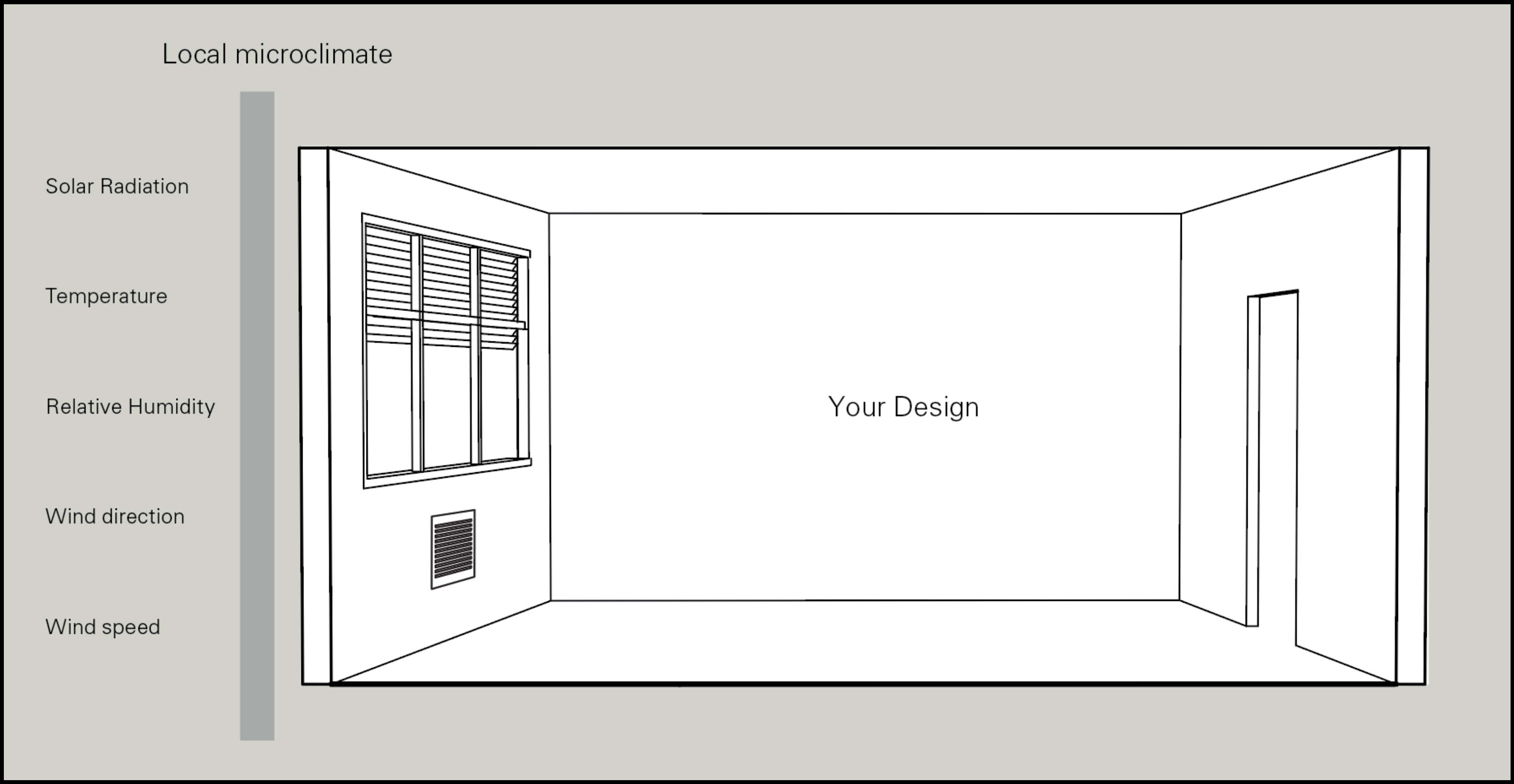
Microclimate

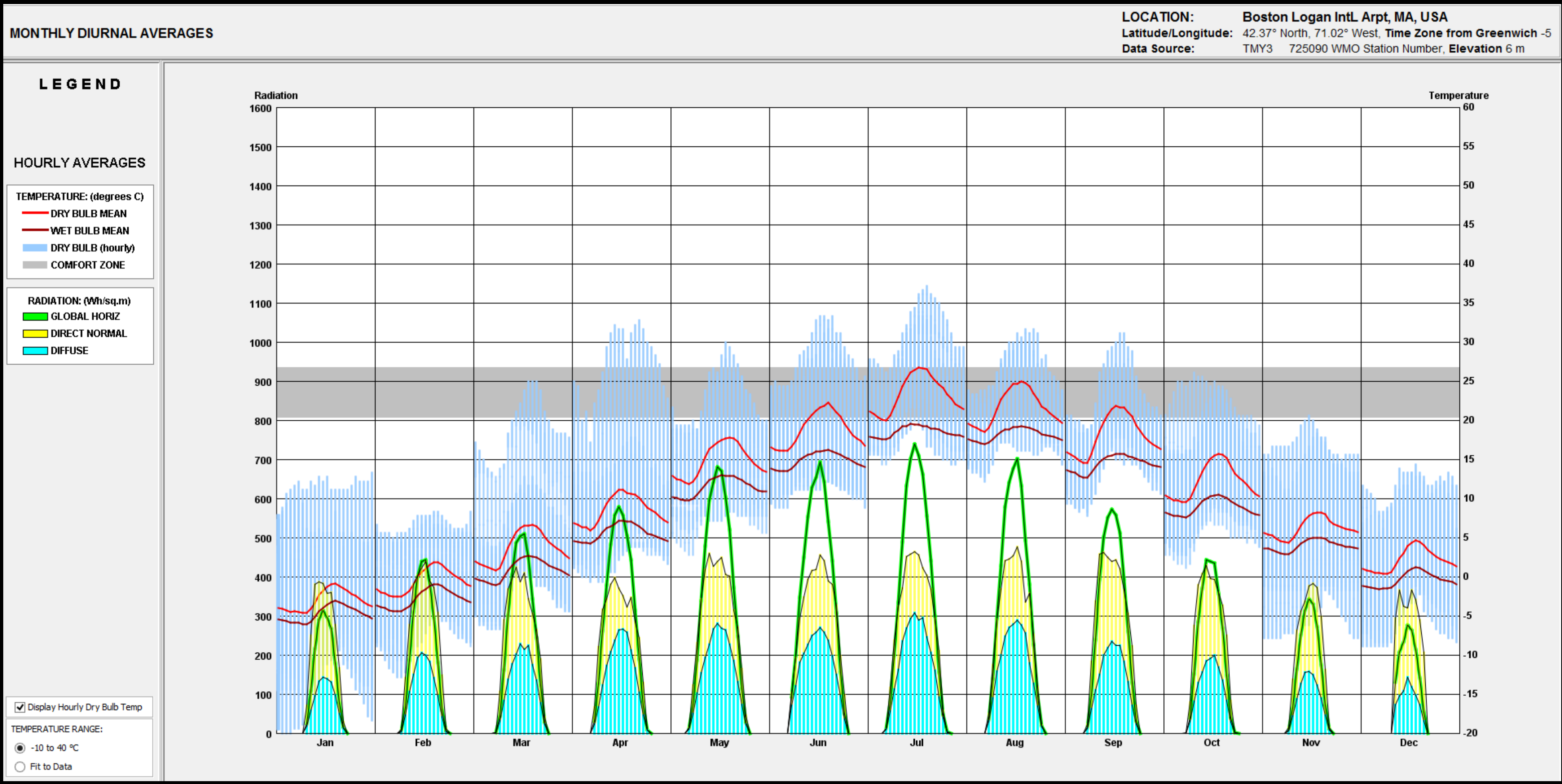


You should also consider local microclimatic conditions:

- Local shading is considered by all major thermal simulation programs
- Other microclimatic effects are climate change, urban heat island, and local wind patterns.

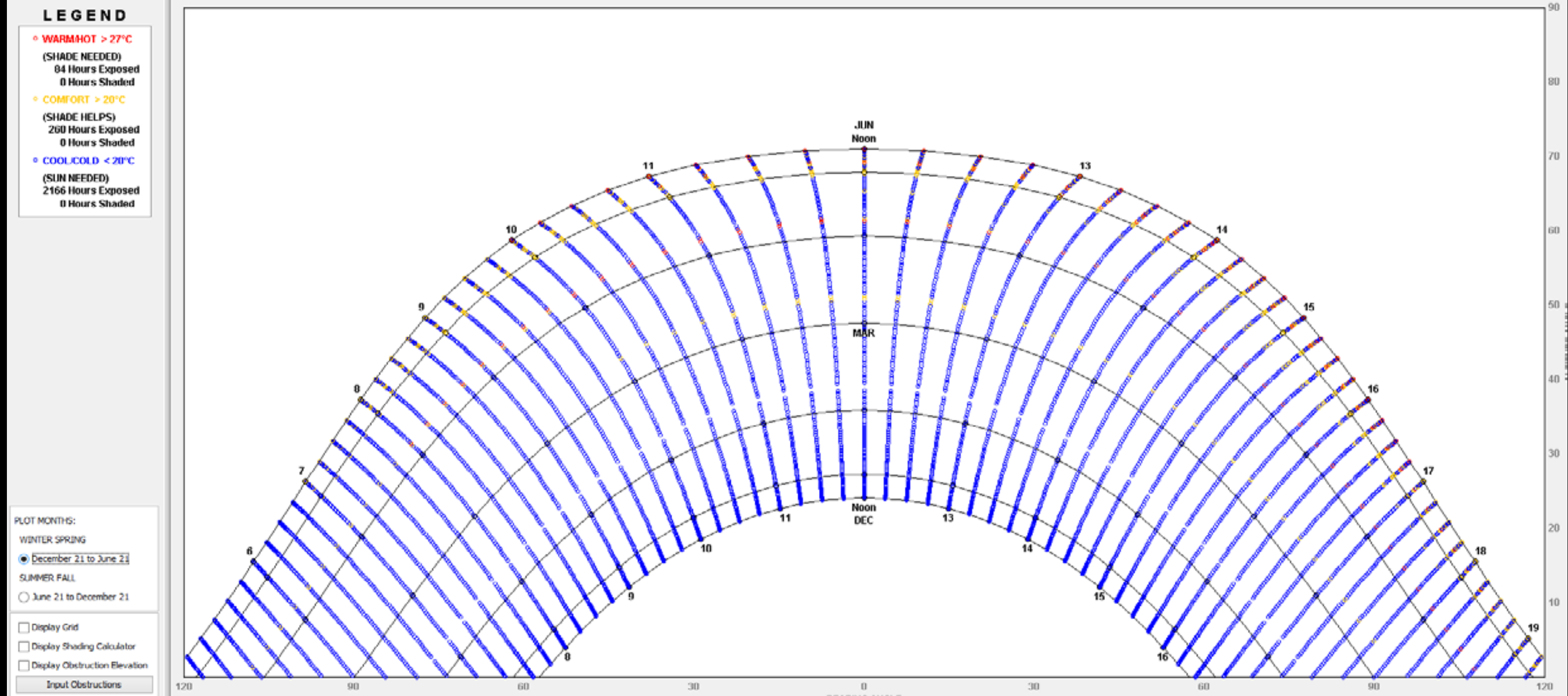
Climate Consultant

Boston

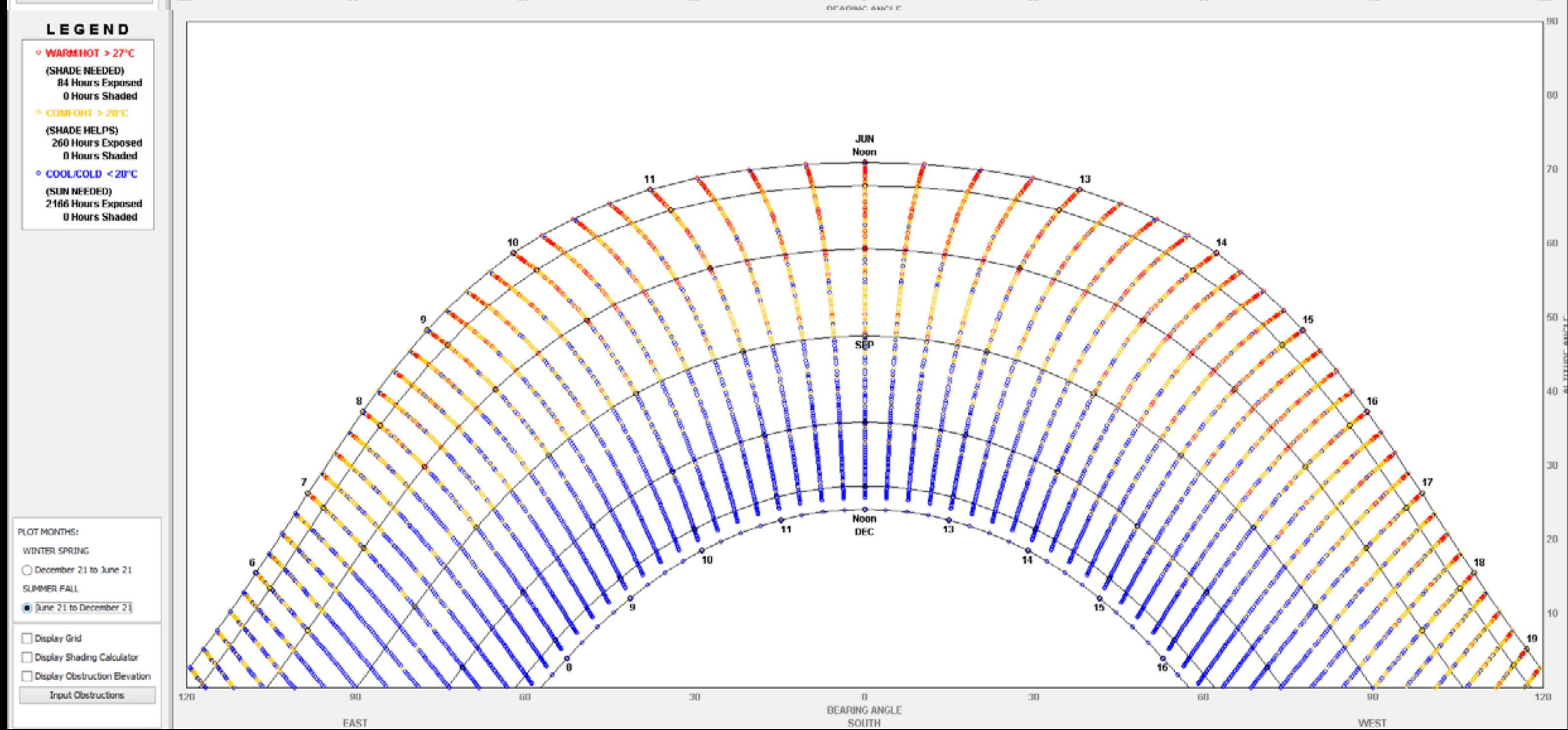


SDLAB

Boston



LEGEND
WARM/HOT > 27°C
(SHADE NEEDED)
84 Hours Exposed
0 Hours Shaded
COMFORT > 20°C
(SHADE HELPS)
260 Hours Exposed
0 Hours Shaded
COOL/COLD < 20°C
(SUN NEEDED)
2166 Hours Exposed
0 Hours Shaded
PLOT MONTHS:
WINTER SPRING
December 21 to June 21
SUMMER FALL
June 21 to December 21
Display Grid
Display Shading Calculator
Display Obstruction Elevation
Input Obstructions
JUN Noon
MAR
Noon DEC



LEGEND
WARM/HOT > 27°C
(SHADE NEEDED)
84 Hours Exposed
0 Hours Shaded
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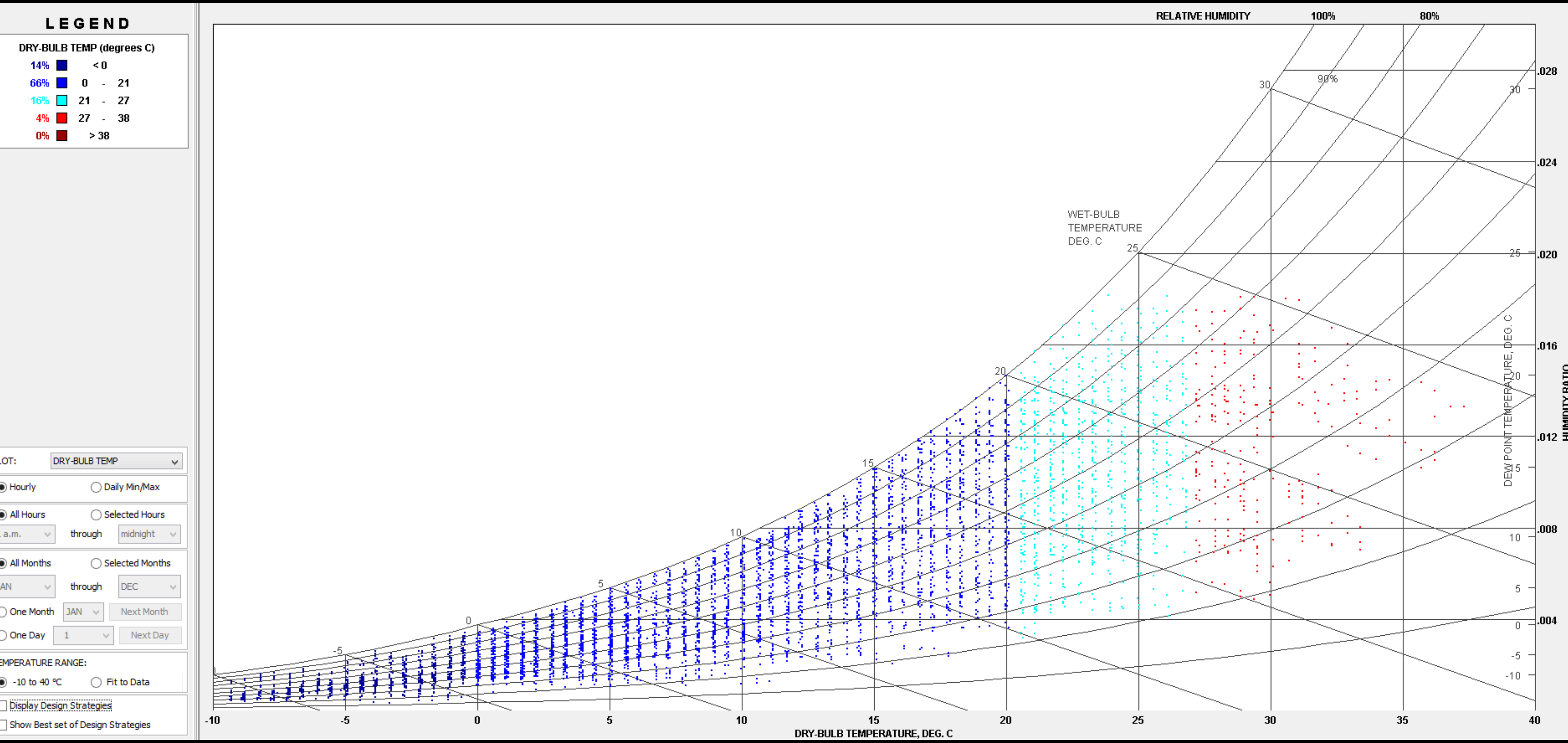
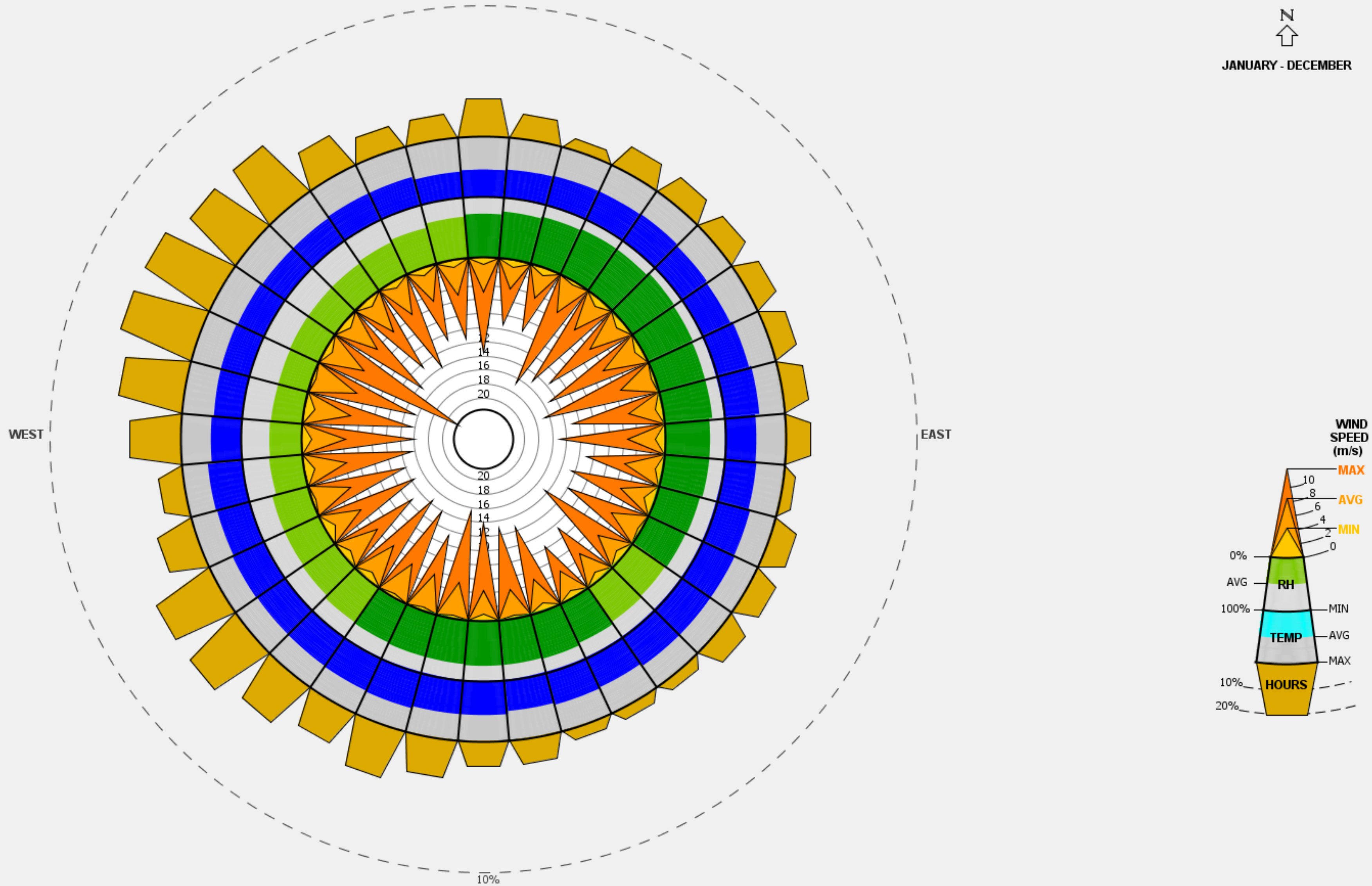
JUN Noon
SEP
Noon DEC
BEARING ANGLE
EAST
SOUTH
WEST

Boston



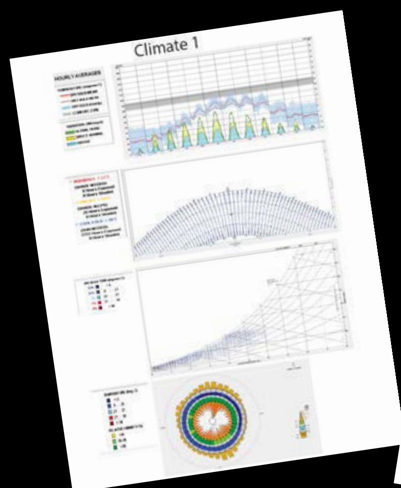
SDLAB

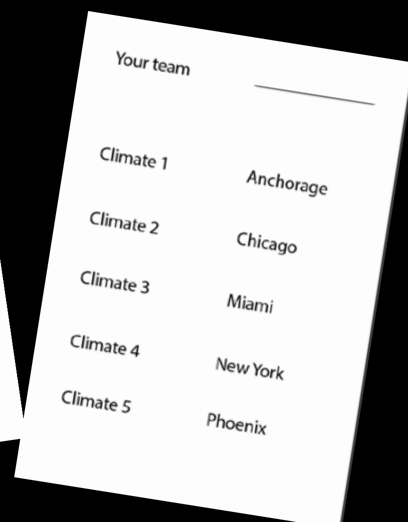
Boston



N
JANUARY - DECEMBER
WEST
EAST
10%
WIND SPEED (m/s)
MAX
AVG
MIN
10
8
6
4
2
0
0%
AVG
RH
100%
MIN
TEMP
AVG
MAX
10%
HOURS
20%

Climate File Board Game





Climate File Board Game

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Thermal Comfort

How much of our time do we spend indoors?

Over 90%.

Thermal Comfort - History

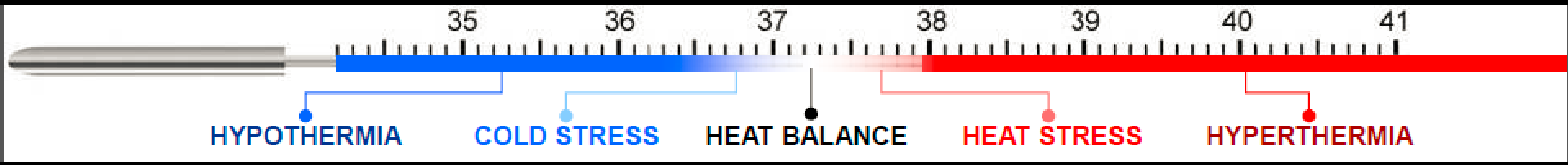
- ❑ Baldwin 1898: "It is usual to maintain a room temperature of 70^o F."
- ❑ Le Corbusier: "Maintain 18^o C in buildings all over the world."
- ❑ While temperature was early recognized to have a strong (the only) impact of thermal comfort, relative humidity was not a recognized concept. Instead, researchers used other descriptors such as stuffiness, smell, draught.
- ❑ This was partly due to our inability at the time to measure CO_2 or relative humidity.

Migration and Adaptation

Left: public domain photo courtesy of Library of Congress.
Center: public domain photo courtesy of National Parks Service. Right: photo by instructor.

Thermal Sensation - Regulation

Humans and many other mammals have efficient internal temperature regulating systems that automatically maintain stable core body temperatures at about 37.0° C. Individual differences in metabolism, hormone levels, physical activity can cause a variation of 0.6° C.



Basal metabolic rate +	Basal metabolic rate -
Muscular activity +	Muscular activity -
Dietary intake	Drink cool fluids
Vasoconstriction	Thermal sweating
Postural changes	Vasodilation (red skin)
Adjust clothing level	Adjust clothing level

How can we adapt when we are too hot or too cold?

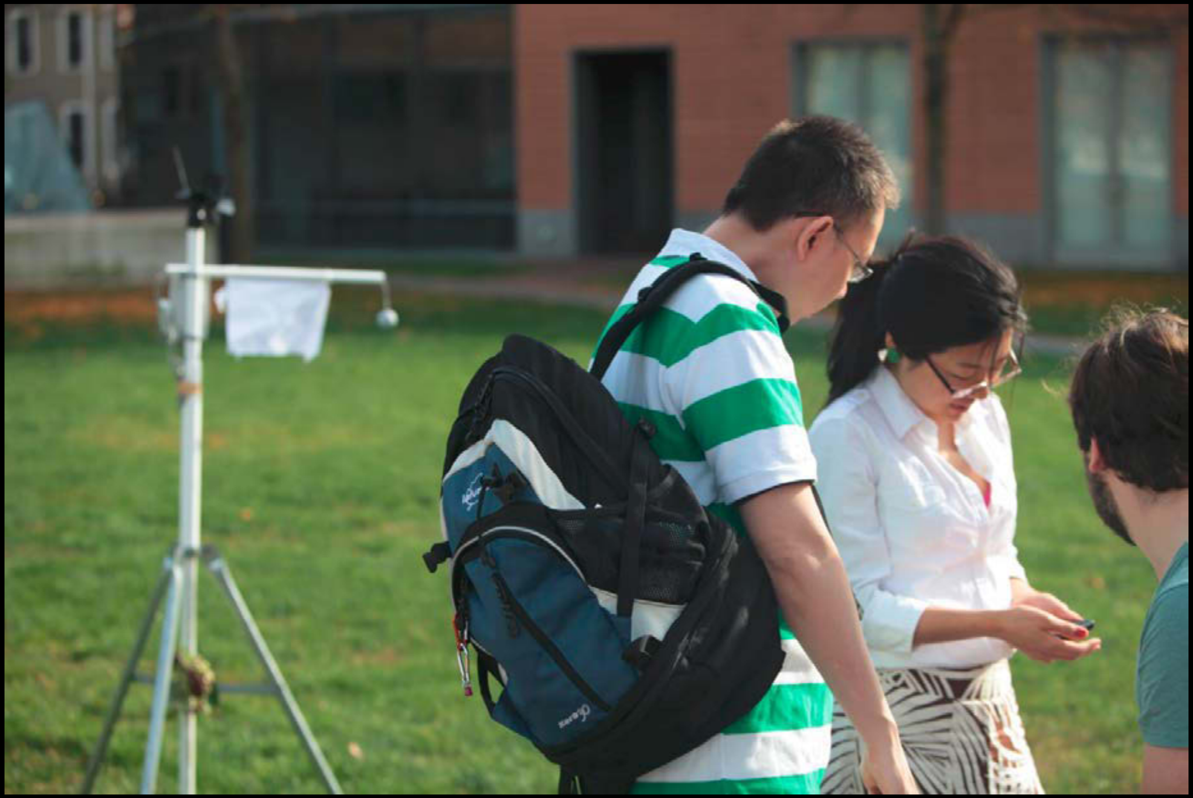
Define "thermal comfort"

Thermal Comfort - Definitions

Definition 1: Conditions wherein the average person does not experience the feeling of discomfort (Olgyay).

Definition 2: A condition of mind which expresses satisfaction with the thermal environment as assessed by subjective evaluation (ASHRAE 55 - 2004).

ASHRAE 7-point scale



Outdoor Thermal Comfort Study
(Photo courtesy of Jianxiang Huang. Used with permission.)

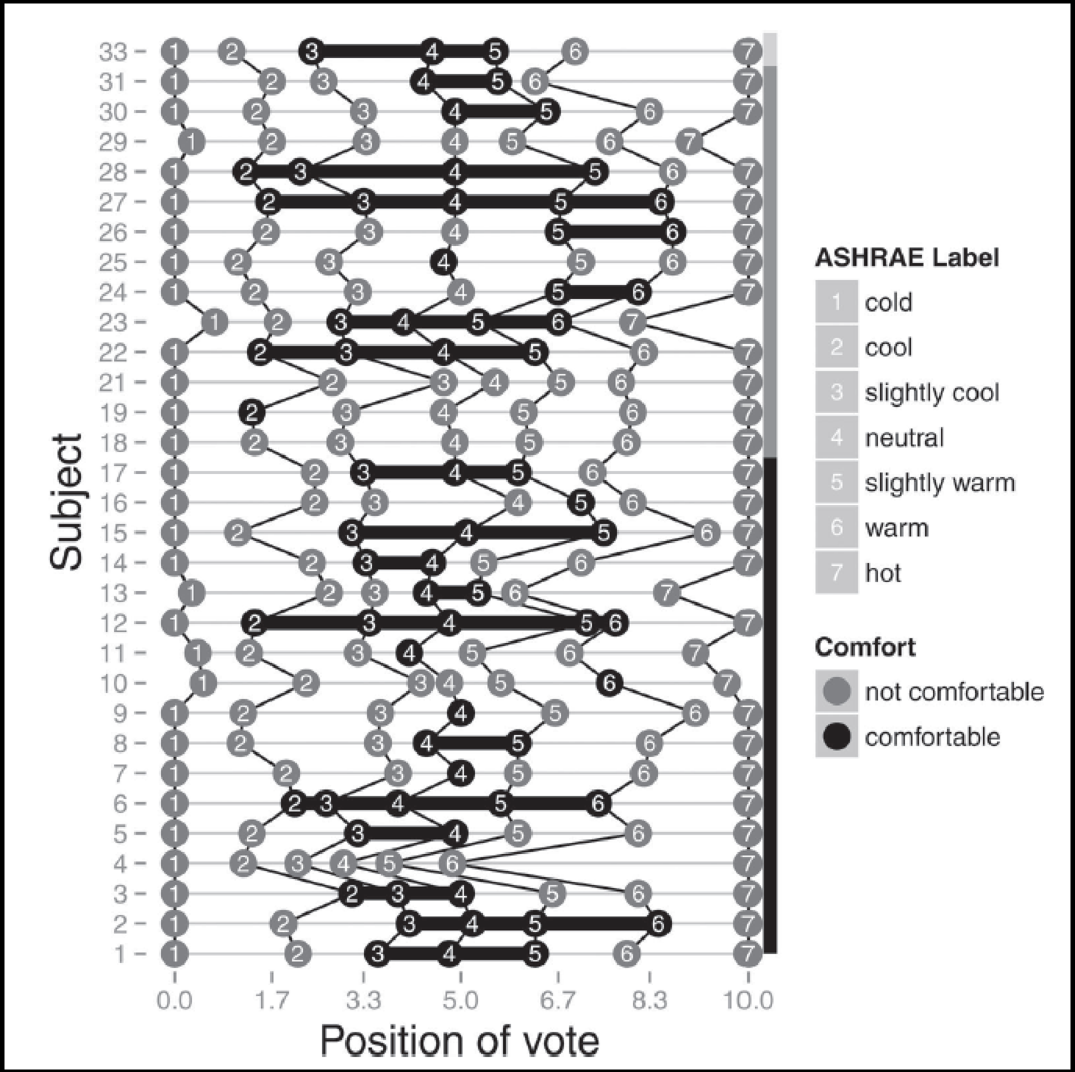
+3 Very Hot
+2 Hot

Comfort Range

+1 Warm
0 Neutral
-1 Cool

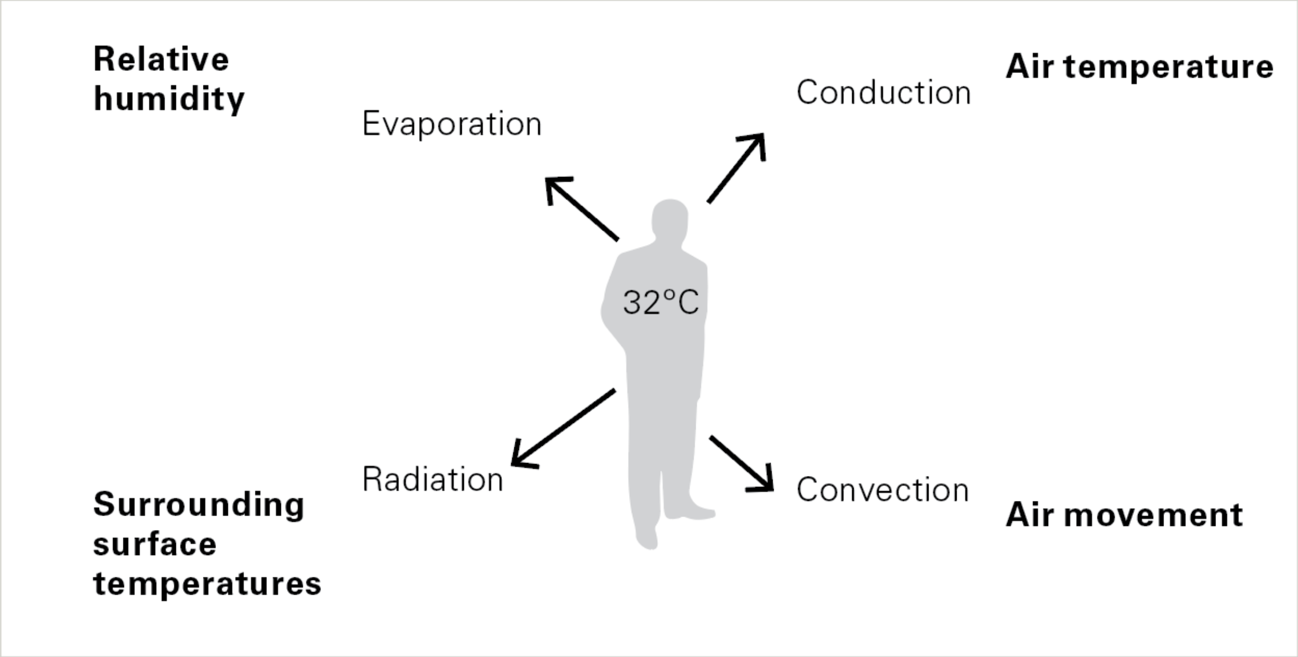
-2 Cold
-3 Very Cold

ASHRAE 7-point scale



Source: M Schweiker, X Fuchs, S Becker, M Shukuya, M Dovjak, M Hawighorst and J Kolarik, "Challenging the assumptions for thermal sensation scales," *Building Research and information*, 45:5,pp. 572-589, 2016.

What variables are influencing thermal comfort?



Personal factors: Clothing and activity

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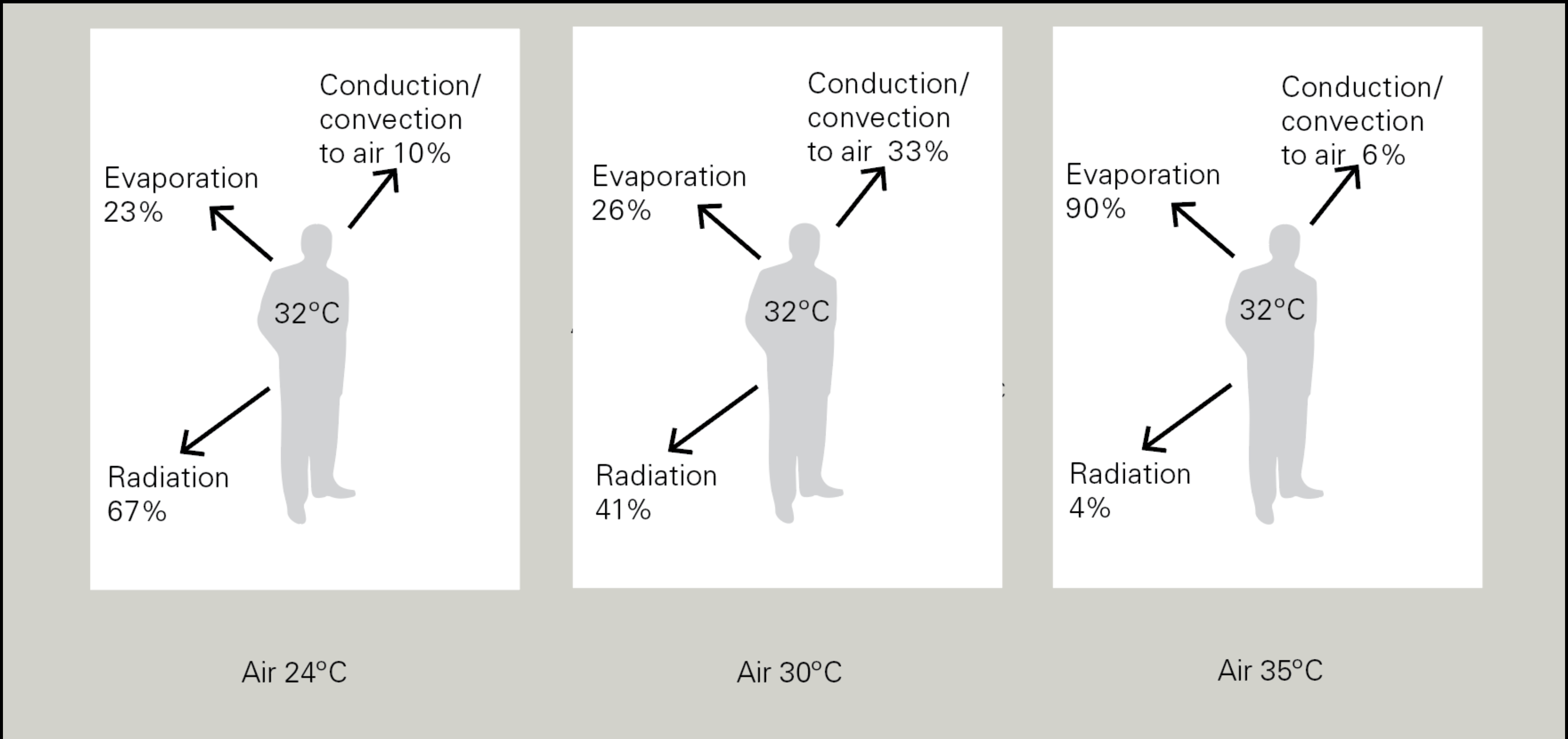
How do we regulate our body temperature?



Comfort Range

Depends on individuals' metabolism, clothing and activity level, season, and to a smaller degree on food and drink intake, body shape, age, and gender.

Relative humidity:

30% to 65%	little effect
<30%	dry skin and mucous membranes
>65%	restricted evaporation

Air velocity:

<0.1 m/s	stuffy
0.2 to 0.5	pleasant
0.5 to 1	awareness
1 to 1.5	drafty

Metabolic Rates

The metabolic rate, or human body heat production, is often measured in the unit "Met". The metabolic rate of a relaxed seated person is 1 Met, where 1 Met = 58 W/m2.

Activity	*W/m²*	*W**	*Btu/hr*	*Met*
Seated relaxed	58	104	356	1.0
Standing relaxed	70	126	430	1.2
Standing, light activity	93	167	571	1.6
Walking on the level, 2 km/h	110	198	675	1.9
Walking on the level, 5 km/h	200	360	1228	3.4
Sports - Running in 15 km/h	550	990	3377	9.5

Source: ASHRAE 55 – 2004 (page 15).

Metabolic rates are given in W per area of skin. A "typical" adult has an effective skin surface area of 1.8 m^2. => 1 person radiates about 100 W (an incandescent light bulb).

Clothing

TABLE B1

Clothing Insulation Values for Typical Ensembles[a]

Clothing Description	Garments Included[b]	I_{cl} (clo)
Trousers	1) Trousers, short-sleeve shirt	0.57
	2) Trousers, long-sleeve shirt	0.61
	3) #2 plus suit jacket	0.96

Source: ASHRAE 55 – 2004 (page 15)

Thermal Comfort Index

Thermal comfort indices are assessment methods of thermal sensation and comfort. More than 100 thermal comfort indices have been developed over the last 100 years.

Actual Sensation Vote (Nikolopoulou, 2004); **Adaptive Thermal Index** (Humphrey, 1975); Apparent Temperature (Steadman, 1979); Discomfort Index (Thom, 1959); **Effective Temperature Scale** (Houghton et al.1923); **ETU** (Nagano& Horikoshi, 2011); **ETF**(Kurazumi et al., 2010); **Humid Operative Temperature** (Horikoshi et al., 1991); **Local_SET** (Kohri and Mochida, 2003); **New Effective Temperature ET*** (Gagge at al. 1971) **Outdoor Standard Effective Temperature** (Spagnolo and de Dear 2003); **Perceived Temperature** (Tinz and Jendritzky 2003); **Perceived Temperature** (Staiger, et al, 2011); **Physiologically Equivalent Temperature** (Höppe 1999); **Predicted Mean Vote, Predicted Percentage Dissatisfied** (Fanger, 1972); **Standard Effective Temperature** (Gagge et al. 1986); **Seven-Point Thermal Comfort Scale** (Bedford, 1936); **Temperature-Humidity Index** (Clarke & Bach, 1971) **UTCI** (ISB, 2009); Thermal Comfort Zone (Houghton & Yagloglou, 1923) **Wind Chill Index** (Steadman, 1971); **Wind Chill Temperature Index** (OFCM, *2003*);

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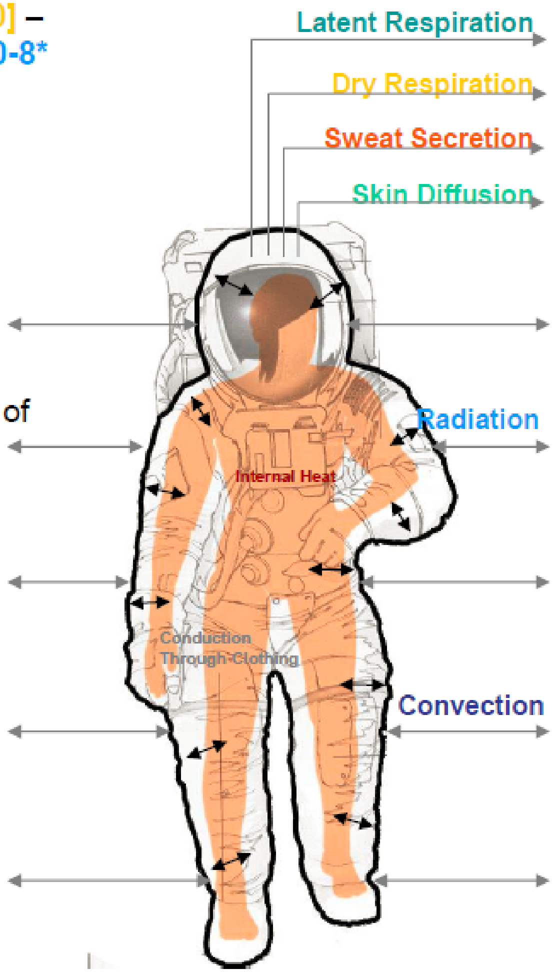
Predicted Mean Vote

$$(0.352 \cdot \exp(-0.042 \cdot M/A_{Du}) + 0.032) \cdot \{ M/A_{Du} \cdot (1 - \eta) - 0.35 [43 - 0.061 \cdot M/A_{Du} \cdot (1 - \eta) - p_a] - 0.42 [M/A_{Du} \cdot (1 - \eta) - 50] - 0.0023\, M/A_{Du} \cdot (44 - p_a) - 0.0014 \cdot M/A_{Du} \cdot (34 - t_a) - 3.4 \cdot 10^{-8} \cdot f_{cl}[(t_{cl} + 273)^4 - (t_{mrt} + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\}$$

- **M** Metabolism rate (kcal/ hr)
- **A_{Du}** Surface area of the nude body (m^2)
- **η** W/M body movement work / heat ratio
- **p_a** Water vapor pressure (mmHg)
- **f_{cl}** Ratio of surface area of the clothed body to the surface area of nude body
- **I_{cl}** Thermal resistance of the clothing (0 ~ 1)
- **t_a** Air temperature °C
- **t_{mrt}** Mean radiant temperature °C
- **t_{cl}** Tempearture of clothes external surface °C
  $t_{cl} = 35.7 - 0.032 \cdot M / A_{Du} \cdot (1 - \eta) - 0.18\, I_{cl} \cdot [3.4 \cdot 10^{\wedge}(-8) \cdot f_{cl} \cdot [(t_{cl}+273)^4 - (t_{mrt}+273)^4] + fcl \cdot h_c \cdot (t_{cl} - t_a)]$
- **h_c** Heat transfer coefficient forced convection
  $h_c = 2.05 \cdot (t_{cl} - t_a)^{0.25}$ if $2.05 \cdot (t_{cl} - t_a)^{0.25} > 10.4 \cdot V^{0.5}$
  $h_c = 10.4 \cdot V^{0.5}$ if $2.05 \cdot (t_{cl} - t_a)^{0.25} < 10.4 \cdot V^{0.5}$
- **V** Relative wind speed

(Fanger, 1970)



Ole Fanger wanted to predict conditions for which the largest possible percentage of a given group experiences thermal comfort.

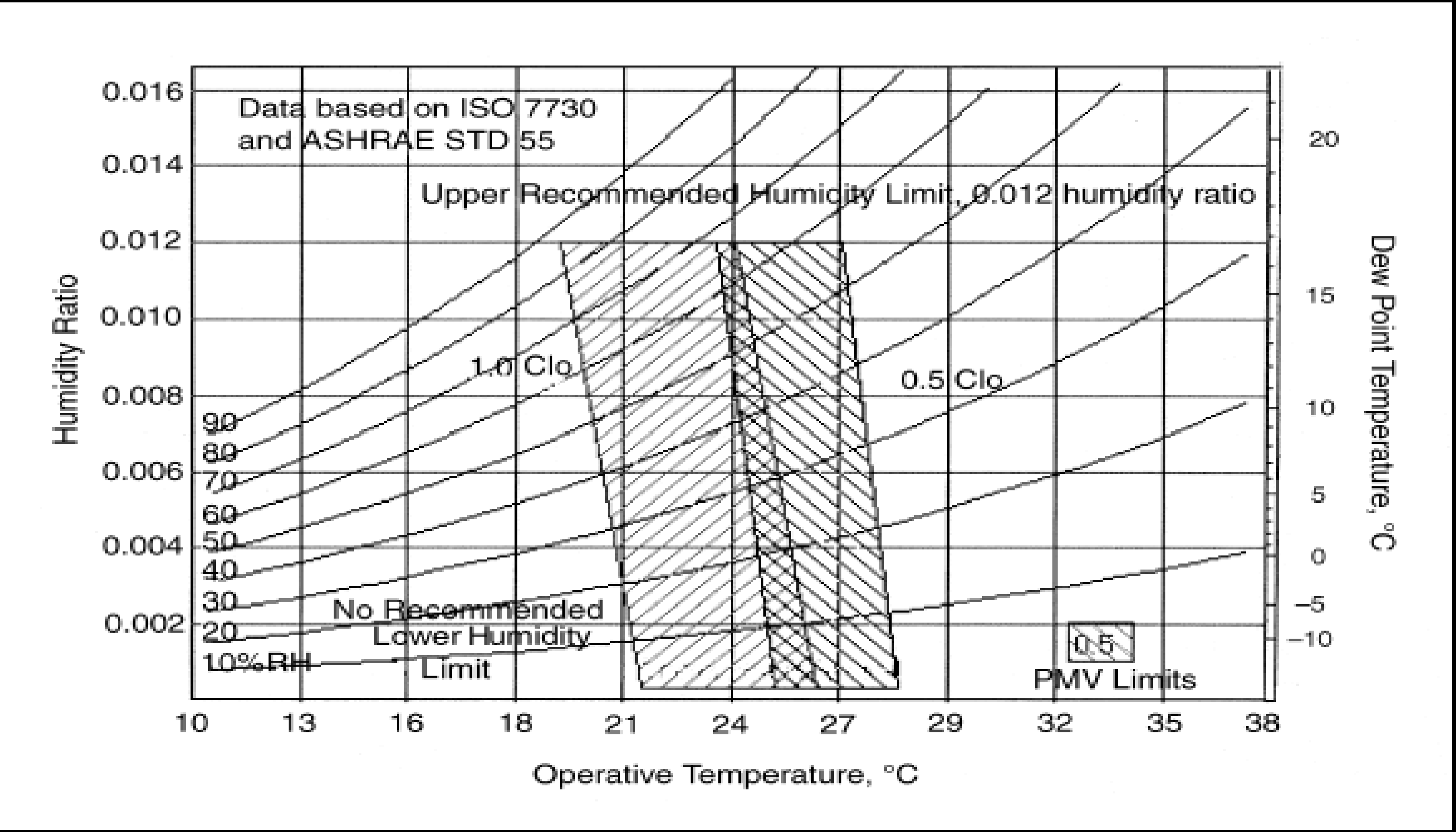
Predicted Mean Vote

According to Fanger, requirements for steady-state thermal comfort are:

- body is in heat balance
- mean skin temperature and sweat rate are within limits
- no local discomfort exists

PMV is based on experiments with Danish college students exposed to steady-state conditions for 3 hours in a climate chamber.

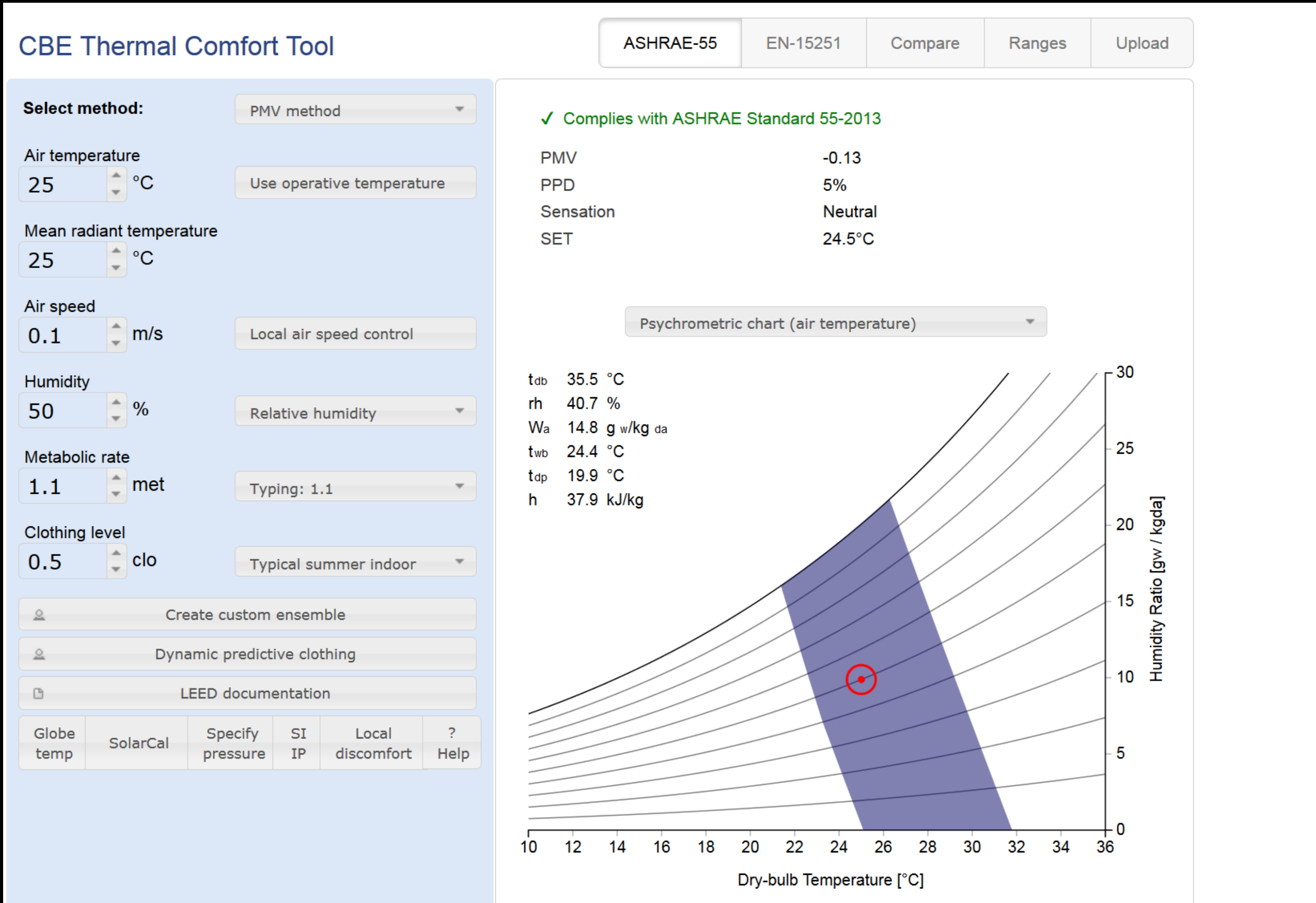
ASHRAE Comfort Range



- Note, the X-axis is provided in operative instead of dry bulb temperature.
- Figure applies for a metabolic rate of 1.0 to 1.3 met and a clothing level of 0.5 to 1.0 clo, air speed <0.2 m/s.

ASHRAE 55

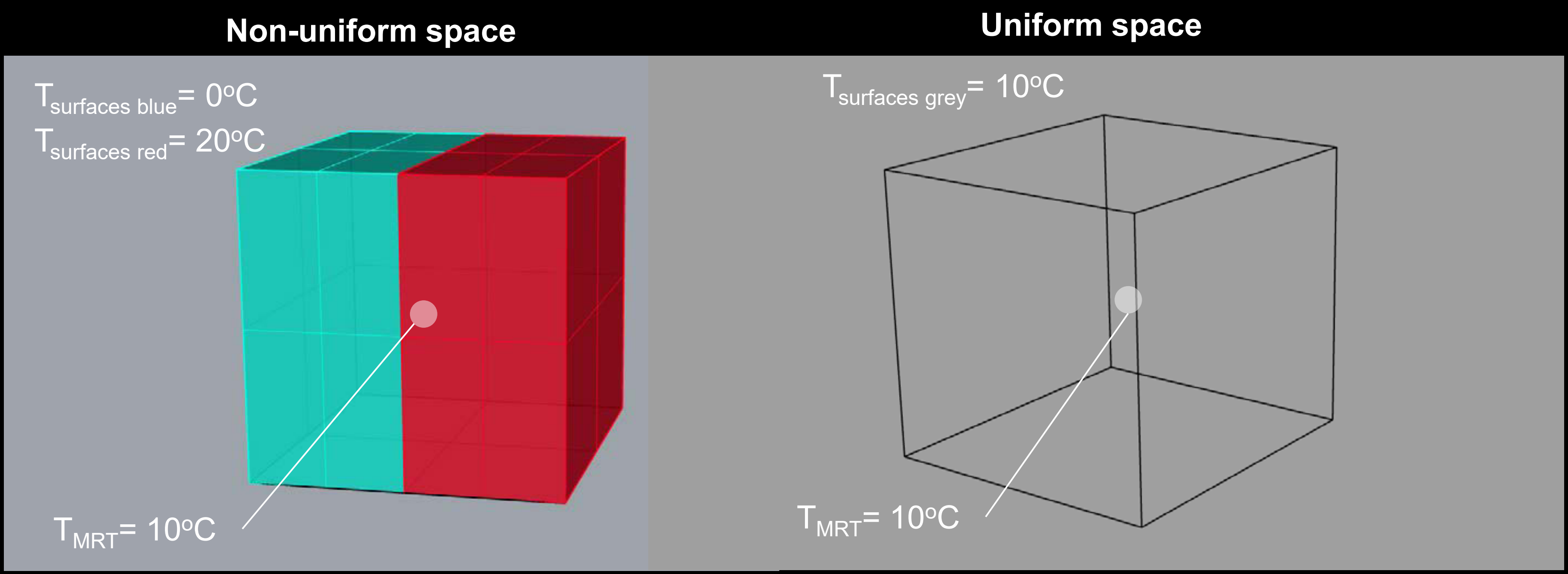
Compliance with PMV is required in air conditioned spaces.



http://comfort.cbe.berkeley.edu/

Mean Radiative Temperature [MRT]

The uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non uniform space. Source: ASHRAE 55



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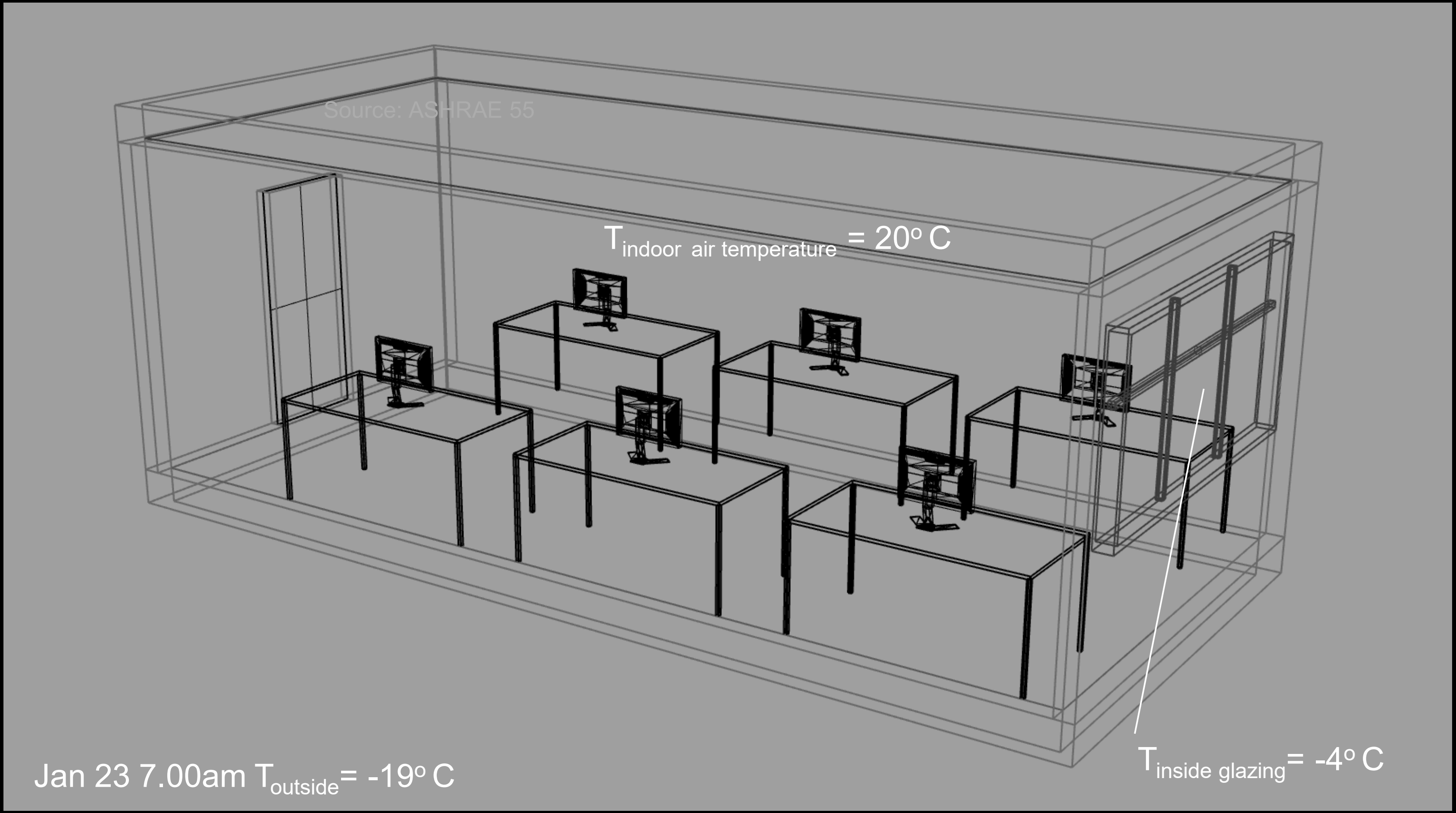
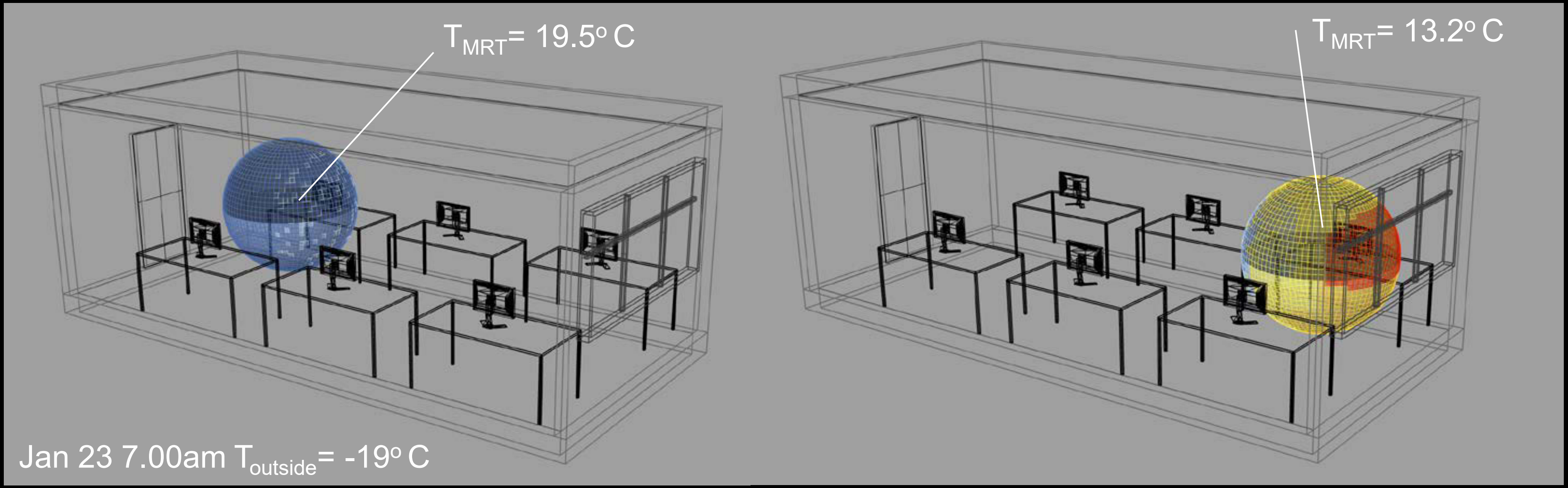
Mean Radiative Temperature Field



- ❑ The reference office is heated to 20° C.
- ❑ The surface of the single pane window is colder (-4° C) than the surfaces of the floor, ceiling and walls.

Mean Radiative Temperature Distribution



- ❑ The mean radiant temperature throughout the space depends on the exposure of a given point to the different surrounding surfaces.
- ❑ Even with an ideal forced-air heating/cooling system somebody sitting near the single pane window might get cold/hot.

How large is this effect over the course of the year?

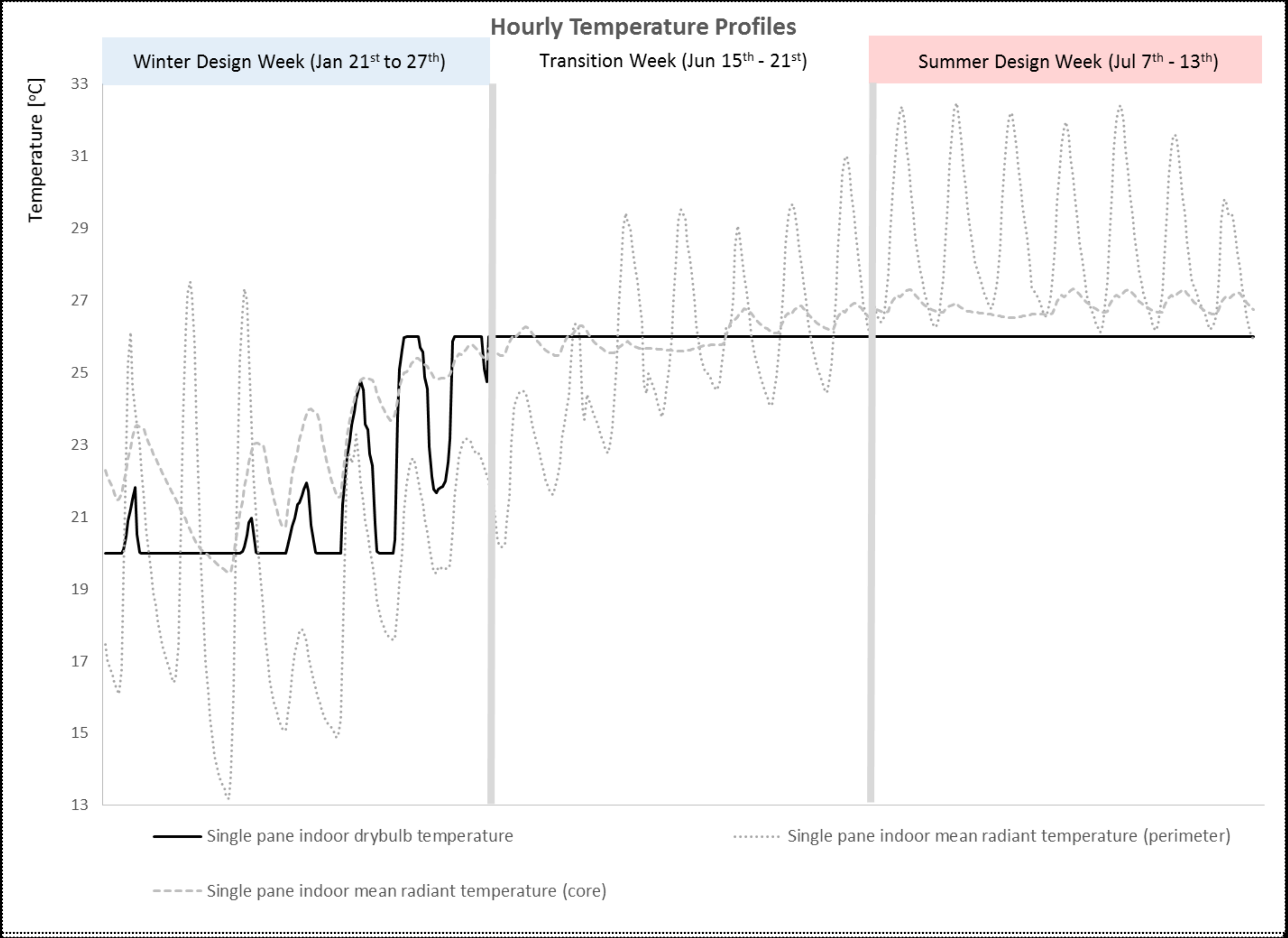
Winter/Summer Design Week

Winter design week - a week identified by the weather data translator as being the coldest of the year.

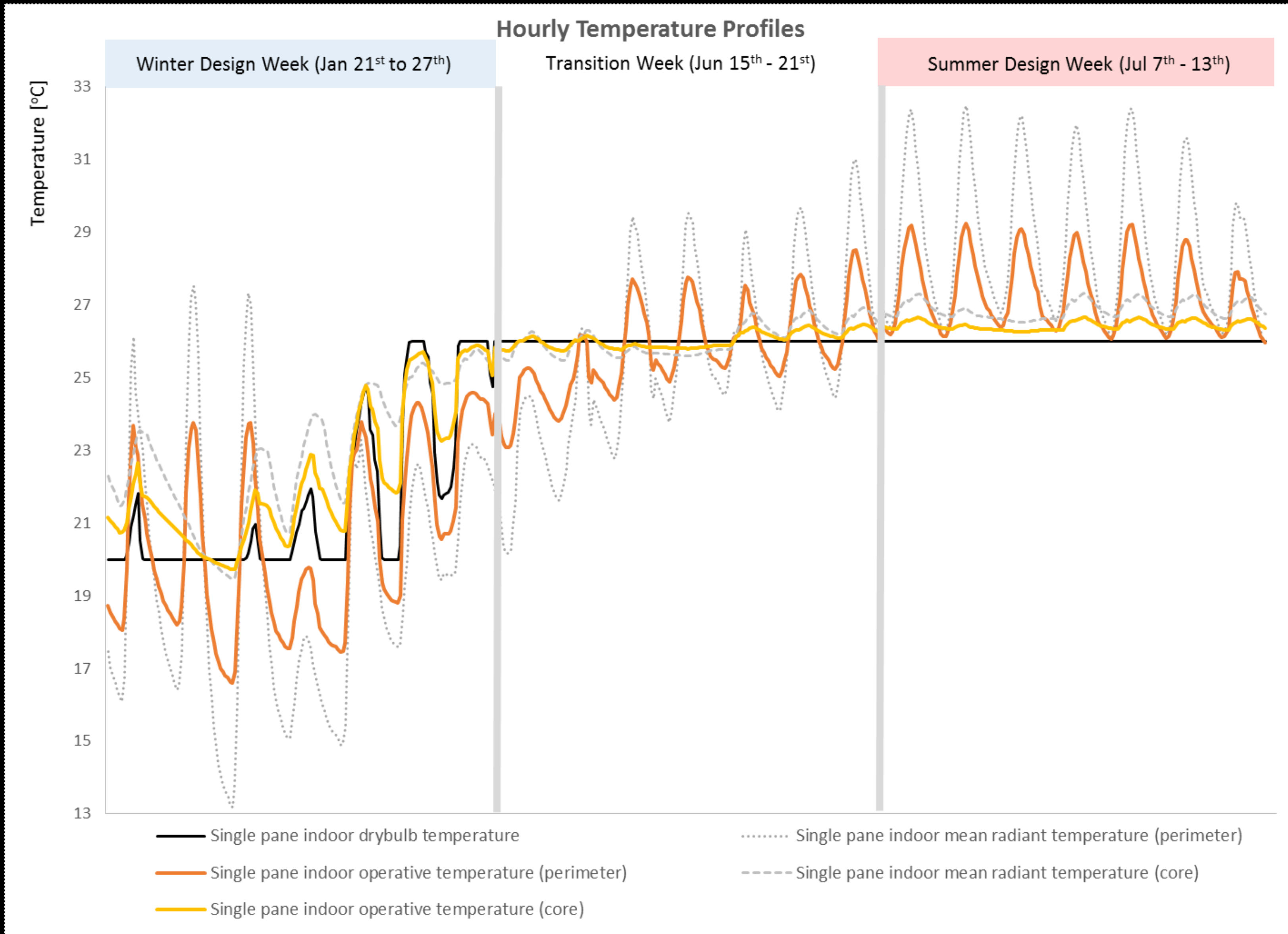
Summer design week - a week identified by the weather data translator as being the hottest of the year.

Transition period - a typical week between the heating and cooling periods.

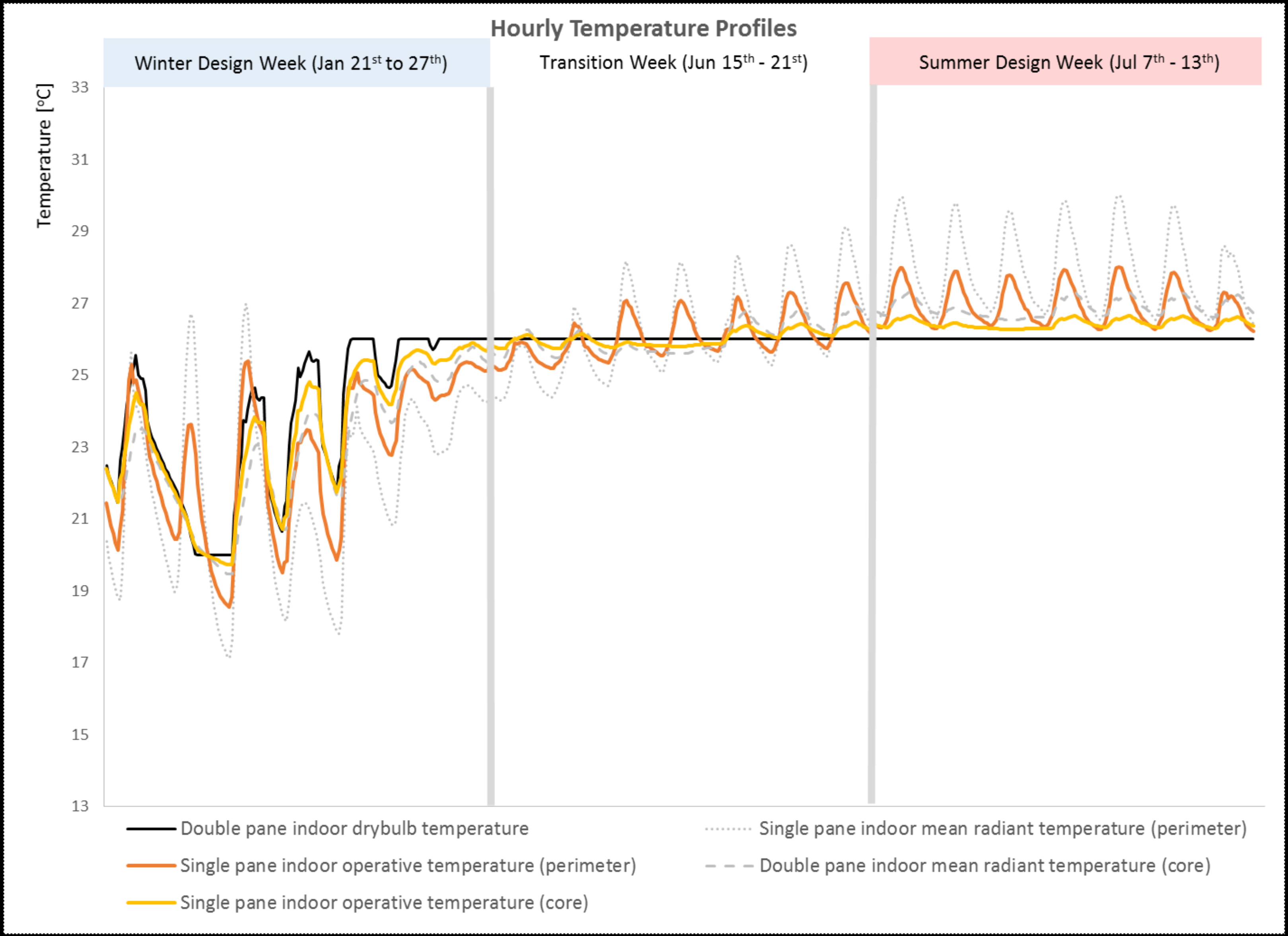
Conditioned Office with Single Pane Window



Conditioned Office with Single Pane Window



Conditioned Office with Double Pane Window



Measuring Radiative Temperature

Mean Radiative Temperature Calculation

To measure the mean radiant temperature at a particular reference point, x, you can use a spot thermometer to measure the surface temperature of all surfaces "seen" from x. You also need to estimate the Form Factor (FF) of each surface with respect to x. A form factor is the fraction of the solid angle that a given surfaces takes within the point of view of a point to the full solid angle (2π) surrounding the point. The sum of all form factors is 1.

$MRT^4 = Form\_Factor_1 \times MRT_1^4 + Form\_Factor_2 \times MRT_2^4 \ldots$

with MRT_i = temperature of surface i in Kelvin; FF_i = form factor of surface i

For the space below all surfaces except for the screen had a temperature of 26°C. The screen had a temperature of 43°C. Assuming that the screen takes up an estimated 7% of the surrounding surfaces from the position of a person seated at the desk, the MTR (in Kelvin) becomes:

$MRT^4 = 0.93 \times (273 + 26)\,K^4 + 0.07 \times (273 + 43)\,K^4 \Rightarrow MRT = 300.3\,K = 27.3\,^{o}C$

Operative Temperature

The operative temperature approximates how one "feels" in a given thermal environment.

Operative Temperature ~ 0.5 * MRT + 0.5 * DBT

Thermal Stress

Rule of Thumb

To maintain thermal comfort the difference between the MRT and DBT in a space should be no more than 3-4 K. For specific surfaces ASHRAE 55 allows for the following asymmetries for different surfaces:

TABLE 5.2.4.1
Allowable Radiant Temperature Asymmetry

Radiant Temperature Asymmetry °C (°F)			
Warm Ceiling	**Cool Wall**	**Cool Ceiling**	**Warm Wall**
< 5 (9.0)	< 10 (18.0)	< 14 (25.2)	< 23 (41.4)

Source: ASHRAE 55 – 2004 (page 7)

MIT SDLAB

Can we do better?

Thermal Neutrality vs. Preferred Thermal Sensation

Nobody on this photo is comfortable according to Thermal Comfort Indices.

Thermal neutrality is boring.

Thermal neutrality is influenced by season.

Individuals in air conditioned buildings are twice as sensitive as occupants of naturally ventilated buildings.

https://mitpress.mit.edu/books/thermal-delight-architecture

ASHRAE 55

Accepted temperature range depends on whether a space is ‘conditioned’ or not.

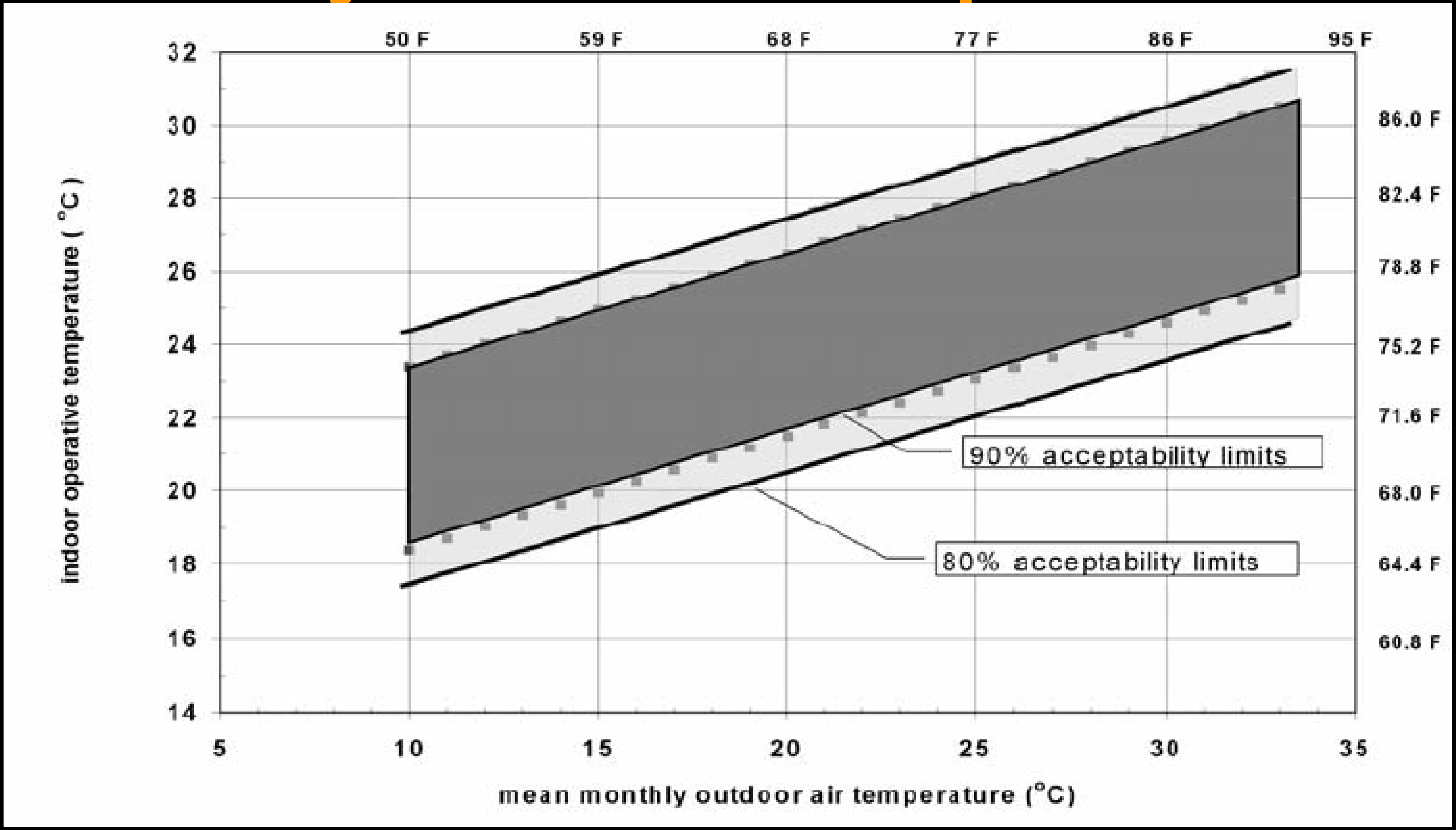
Two compliance paths:

- ❑ Predictive Mean Vote
- ❑ Adaptive Temperature

Mean Monthly Outdoor Temperature

Arithmetic average of the mean daily minimum and mean daily maximum outdoor (dry-bulb) temperatures for the month in question (ASHRAE 55).

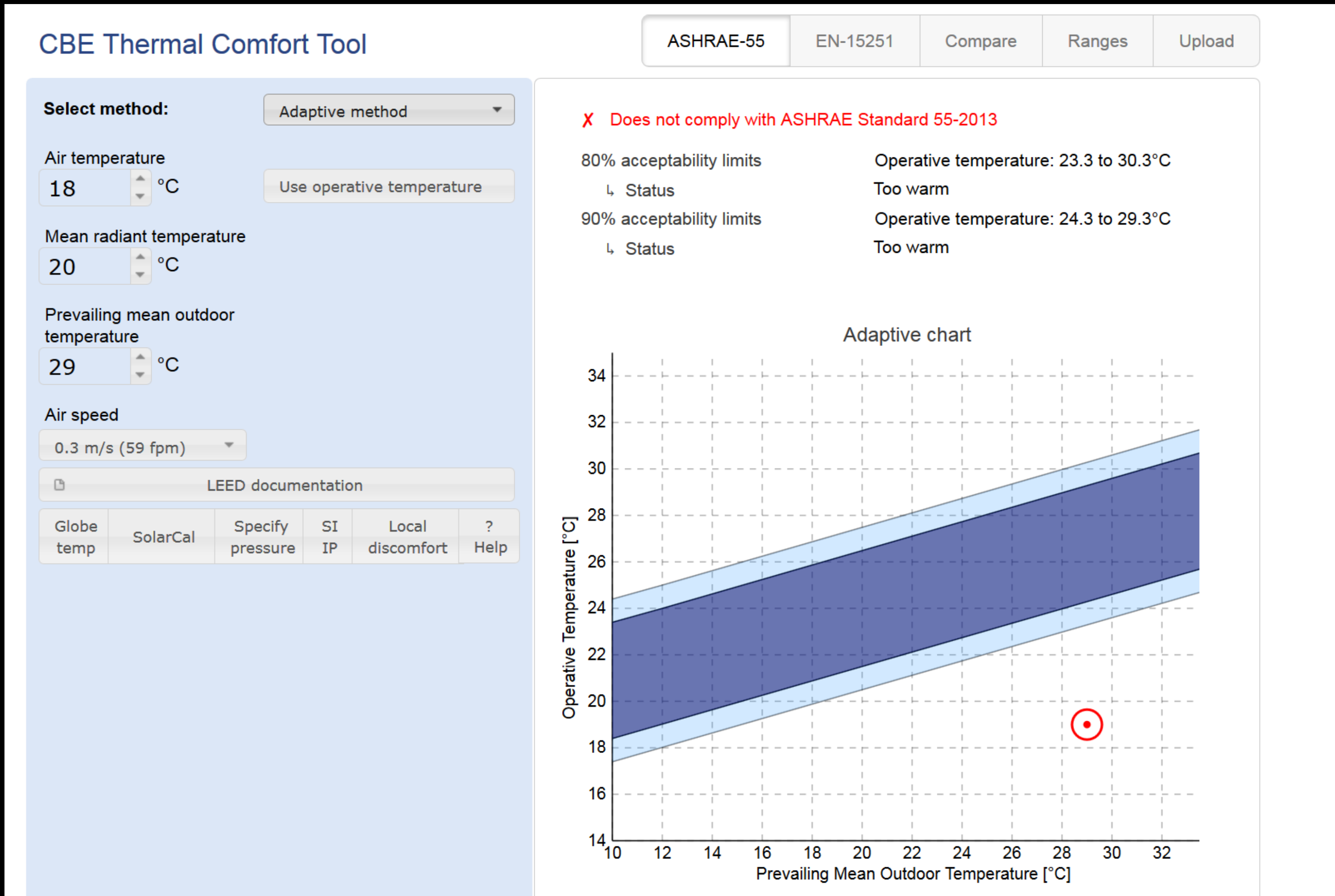
Acceptable operative temperature in naturally conditioned spaces



Source: ASHRAE 55 – 2004 (page 10)

Clothing level is assumed to vary 'naturally' with season. No humidity or air speed limits. Comment: Clarified legal implications for 'naturally conditioned' spaces in the US.

SDLAB



http://comfort.cbe.berkeley.edu/

Critique of Thermal Comfort Models

- Hypothesis has not been demonstrated

  How will an average person feel? = How will a large group respond?

- Model variation too large
  - group variance = 1.0 scale units
  - inter-individual variance = 1.0 scale unit
  - intra-individual variance 1.0 scale unit (season, mood, alertness)

- Model weak at the extremes of comfort

- Cultural differences
  - Thermal neutrality in Malaysia and London varies by 3 K

‘Enforcement’ of ASHRAE 55

- ❑ Declare exceedances such as 1% of time, 29 hours per year….
- ❑ Difficult to meet with large architectural glazings.
- ❑ Extra Credit under LEED.

Lessons for design

- Provide building occupants with thermal control over their environment (thermostats, fans, blinds, operable windows…).
- Allow occupants to dress as desired.

Questions?