

Million Cool Roofs

Study of Passive Cooling Strategies | Results Summary

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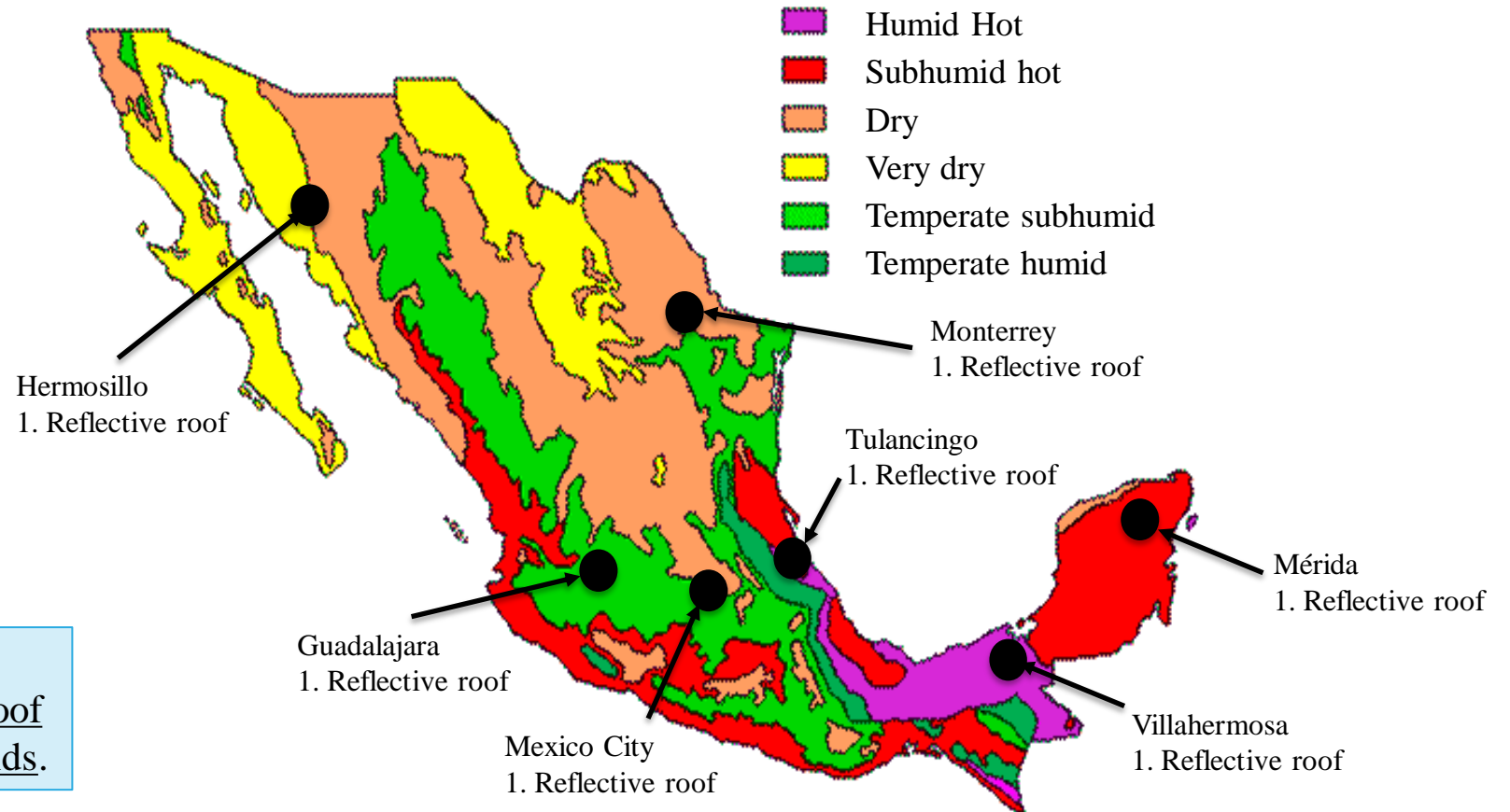
Executive Summary

Reflective roofs (high albedo) are the most effective strategy for reducing heat stress in each region.

The higher the albedo, i.e. the more reflective the surface, the greater the cooling effect and the more comfortable the internal conditions.

While we didn't explicitly study the results in combination, the results are consistent with previous studies.

This suggests the most effective combination of strategies is reflective roof + increased window size + external blinds.



Background and Approach

As part of the Million Cool Roofs Challenge, a range of passive cooling strategies were investigated to determine the impact each has on the thermal conditions of a prototype emergency shelter during peak summer conditions. Performance in seven different climate zones was studied to understand whether the benefits of these strategies are transferrable to other contexts (e.g. locations and construction methodologies).

The strategies investigated were:

1. Reflective roofs
2. Increased window size (20%)
3. House orientation
4. Roof pitch (flat roof and x2 pitch)
5. Insulation
6. Steel sheet roofing (as compared to fibre cement)
7. Flat on ground (as compared to raised foundations)

The strategies listed were individually compared to the base case.

The investigation was conducted using the Arup-developed software BEANS (Building Environment Analysis Suite). All cases are modelled with no wind present for conservatism.

Base Case

The base case is modelled after the emergency shelter designed and used by the non-profit Techo in Mexico.

Figure 1 shows the structure and materiality of the shelter. Certain simplifying assumptions were made. The synthetic fibre cement sheets that make up the walls and the roof have an albedo of 0.27 to represent unpainted panels.

The structure has window openings without glazing, which can either be open (to allow light and ventilation) or closed (to prevent both). The models assume these are open from 7am to 7pm and closed otherwise. The front wall has two windows and a door, and the back wall has one window.

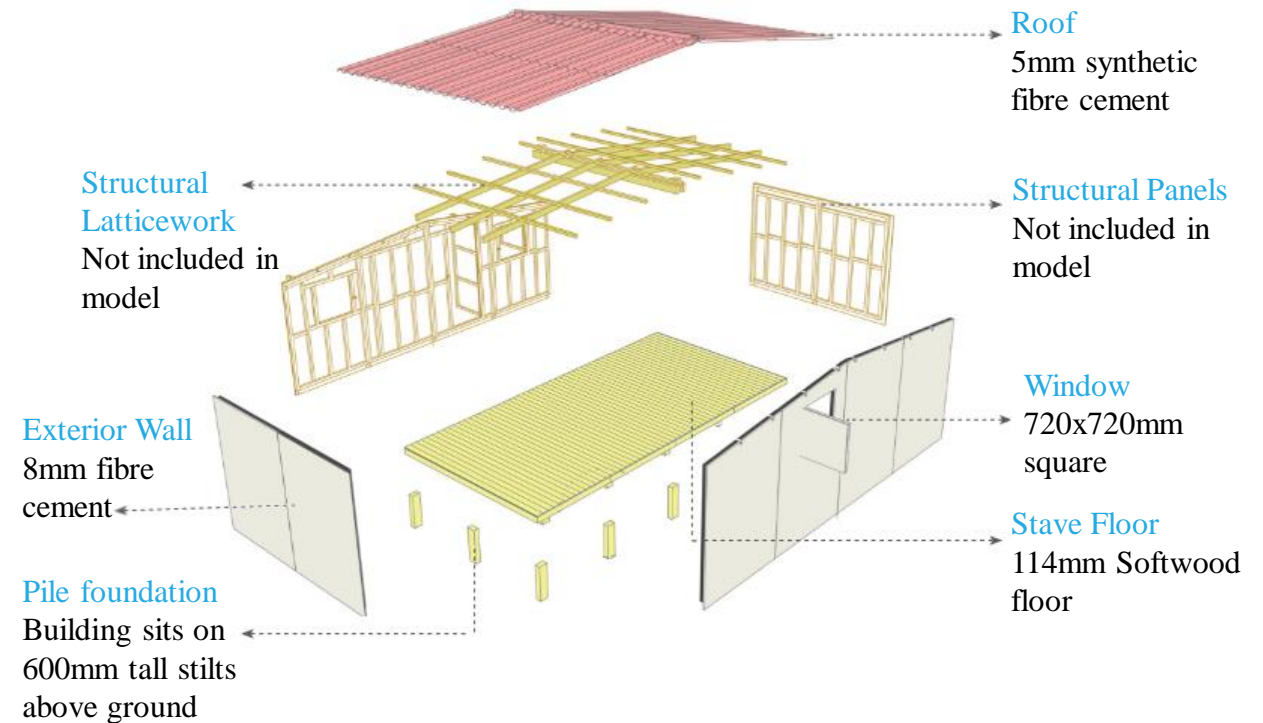


Figure 1: Exploded view of building for base case

Base Case

The building is oriented such that the sun crosses parallel to the roof direction (Figure 2). As the building is elevated 0.6m above the ground due to the pile foundation, the bottom of the floor layer is modelled to have a high albedo to prevent unrealistic heat absorption of the floor from the ground. This assumption was used as a raised, stilted structure could not be directly implemented in BEANS.

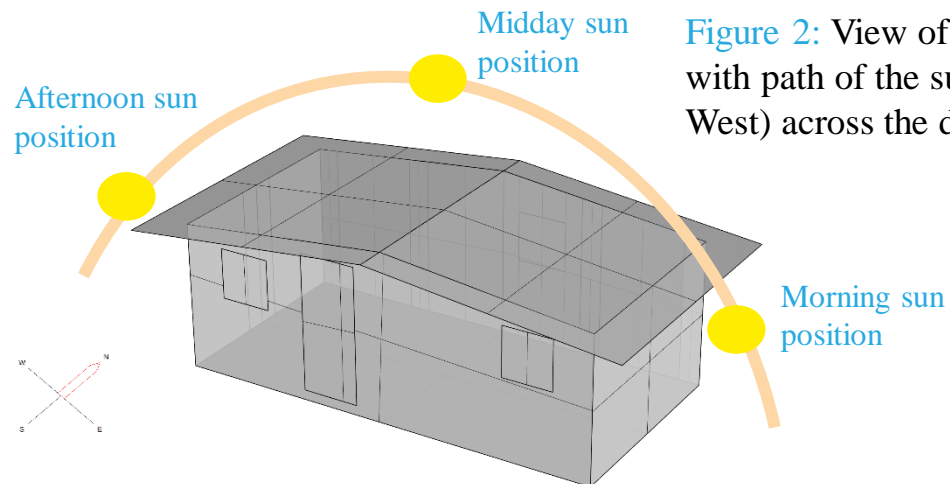


Figure 2: View of building base case with path of the sun (from East to West) across the day

Description of Strategies

Reflective roof

A reflective roof strategy was modelled by increasing the roof albedo from 0.27 to 0.75, 0.85, and 0.95. This strategy should reduce internal temperatures by reducing the surface temperature of the roof. Doing so would also reduce the temperature difference between the internal and external spaces, reducing the air change rate.

Increased window size

Increased window size was modelled by upsizing the existing windows by 20%. This strategy should allow higher ventilation rates. Because external spaces are typically cooler than internal spaces, this would reduce internal temperature. The amount of ventilation is quantified in air changes per hour. This is driven by the temperature difference between the interior and exterior: a greater temperature difference drives more ventilation.

House orientation

A range of orientations from the base case were considered in 45° intervals. Building orientation can be chosen before construction to control the amount and timing of solar gains entering the house through the windows and door. A building will experience lower internal temperatures if it is oriented so the windows and door face away from the trajectory of the sun.

Roof pitch

The structure modelled in the base case (pitch = 6°) features a roof with a gentle slope. Two alternatives were modelled: a flat roof (pitch = 0°) and a steeper roof (pitch = 12°). At a given time of day, a flat roof generally exposes more of its surface to direct sunlight than a pitched roof. Therefore, roof pitch is expected to reduce solar gains, roof surface temperature, and internal temperature.

Description of Strategies

Insulation

The internal insulation strategy used 25mm thick mineral wool and 10mm plasterboard. Internal insulation should increase internal temperatures in both summer and winter. This is because the interior is usually warmer than the exterior, and insulation prevents this heat from escaping outdoors. This should have a negative effect on thermal comfort in summer.

Blinds

Blinds (external and internal) were not modelled due to complexities related to the operability of window coverings in the base case. Previous modelling has shown external blinds to be highly effective at reducing temperatures in areas of the house near windows that are exposed to sun. This strategy allows occupants significant flexibility to control internal conditions. It can be implemented on existing buildings and is relatively inexpensive.

In addition, we wanted to study the effect of two design features of the Techo emergency shelter: the fibre cement roof material and the raised foundation. The study considers more common approaches, like the use of metal sheet roofing (new and weathered) and flat-on-ground construction.

Steel sheet roofing

To study the thermal performance of a common roofing material, a structural steel roof panel was modelled. Two cases were modelled, with albedo values to represent both polished steel (albedo number = 0.8) and weathered/matte steel (albedo number = 0.25). The weathered roof is more representative of real conditions and is expected to show poor thermal performance.

Flat on ground

The building is moved to be directly on the ground. This is to assess the impact of the piled foundation. With no wind modelled, this is not expected to have a significant effect.

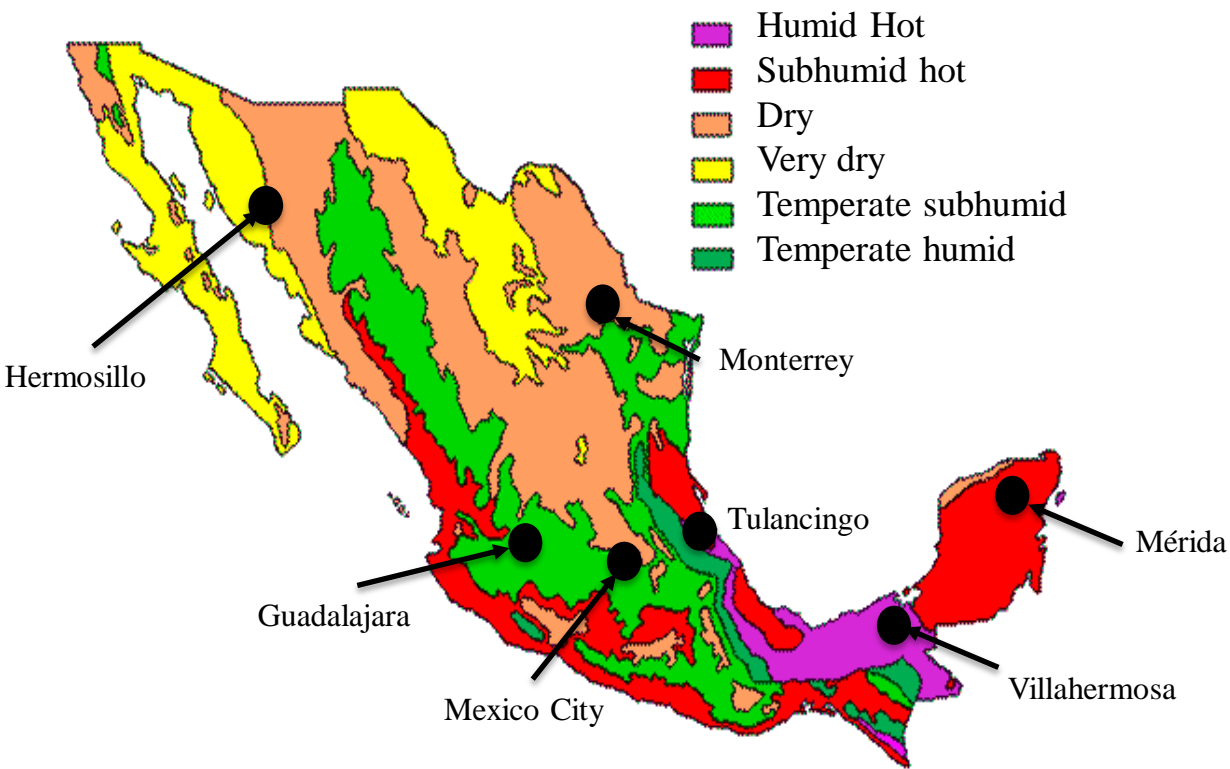
Climate Zones

All cases were tested for the following climate zones:

- 1. Tropical monsoon (Am) –Villahermosa
- 2. Tropical savannah (Aw) – Mérida
- 3. Semi-arid (BSh) – Monterrey
- 4. Hot desert (BWh) – Hermosillo
- 5. Oceanic (Cfb) – Tulancingo
- 6. Humid subtropical (Cwa) – Guadalajara
- 7. Subtropical highland (Cwb) – Mexico City

The hottest month of the year was run for all climates. The coldest month was also run for the temperate climates (3-7) to ensure strategies did not have a large negative impact in winter.

	Villahermosa	Mérida	Monterrey	Hermosillo	Tulancingo	Guadalajara	Mexico City
Summer case	✓	✓	✓	✓	✓	✓	✓
Winter case	✗	✗	✓	✓	✓	✓	✓



Measuring Performance

Numerical values presented from the report are taken with respect to the centre of the house. Spatial plots show the temperature variation around the house. Strategies such as reflective roofs, increased window size, insulation and roof pitch affect temperatures throughout the house generally, so the central point gives a good indication of the effectiveness of these methods. Strategies such as orientation and blinds chiefly reduce temperatures in areas affected by direct solar gain through windows and door. In these cases, spatial plots are more useful.

Roof surface temperatures

Roof surface temperatures have been included in the results due to their significant influence on the space temperatures in the room. The roof surface temperatures also directly demonstrate the effect of the reflective roof, steel roofing and roof pitch strategies.

Indicative comfort

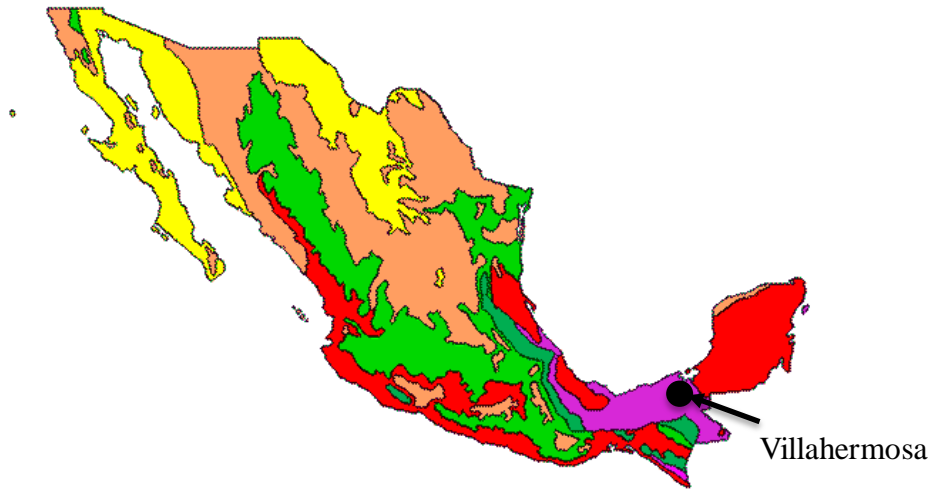
PMV (predicted mean vote) and THI (temperature humidity index) were calculated to show the thermal comfort and heat stress respectively. THI is calculated from temperature and humidity, and values correspond to the level of stress as such:

THI	Indicative heat stress
< 70	No stress
70-79	Mild stress
80-89	Severe stress
90-99	Very severe stress
> 99	Extreme danger

THI does not give insight to stress level or comfort during cold weather in the winter months.

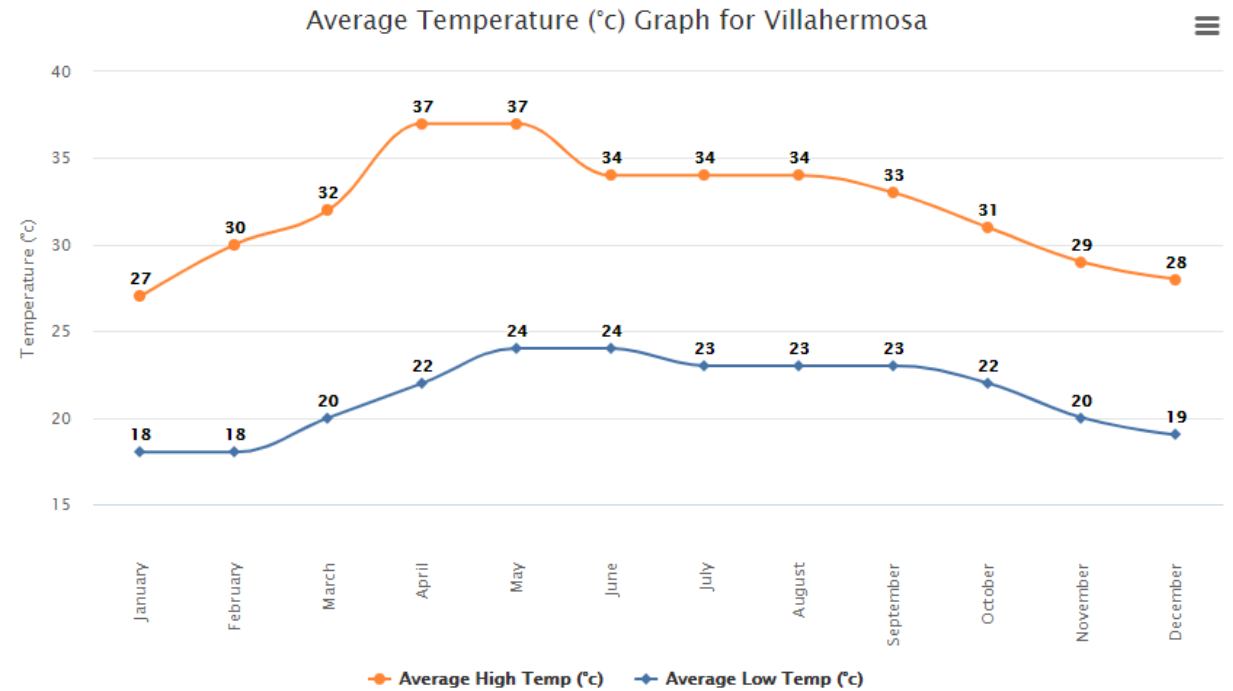
Regional Results

Villahermosa Summer



Tropical monsoon climate (Am)

Monthly Average Temperature



Villahermosa Average values (difference from base in May)

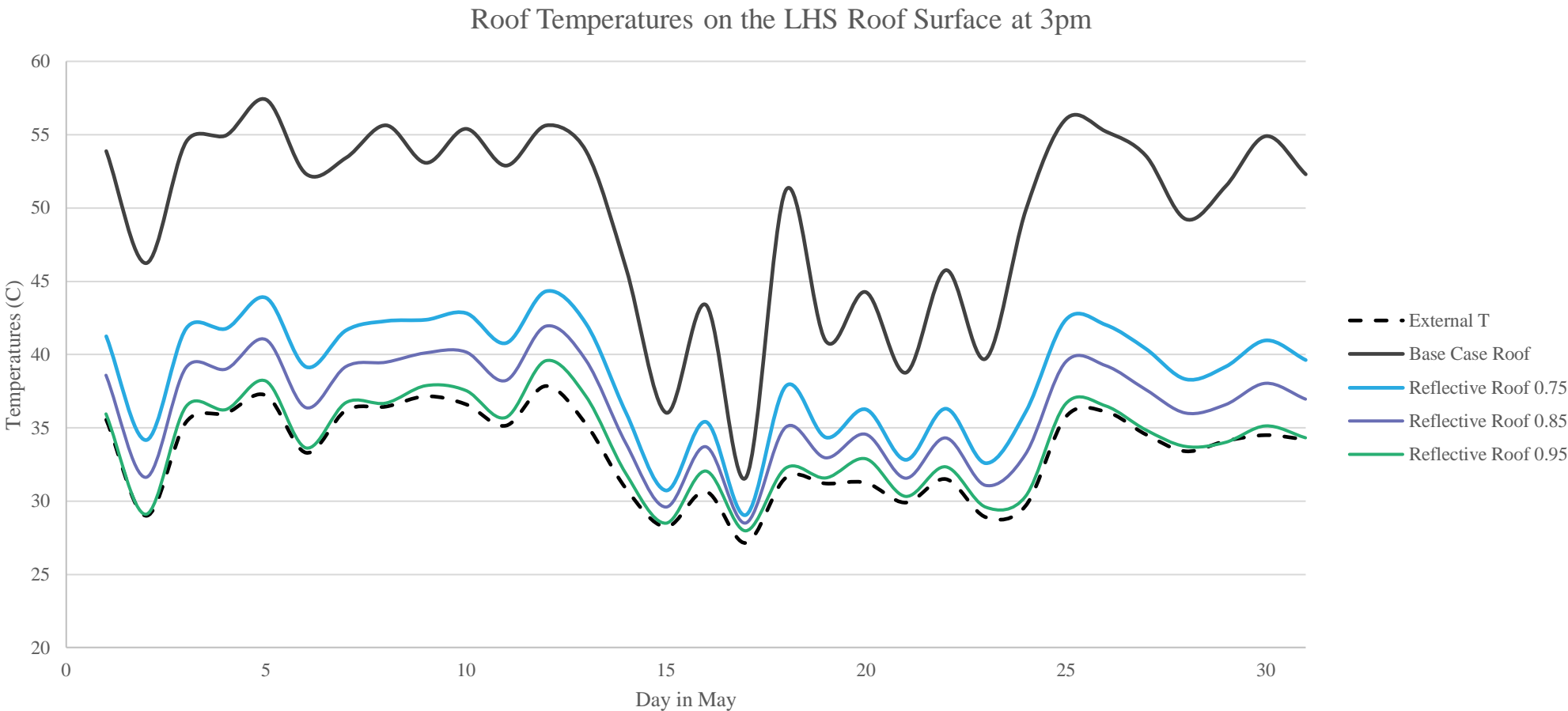
	Average Difference from base across May								
	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp	
	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left side	Right side
	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)
Base									
Reflective Roof (0.75)	-0.55	-0.99	-0.29	-1.22	1.93	1.93	-1.93	-4.08	-4.07
Reflective Roof (0.85)	-0.68	-1.20	-0.35	-1.48	2.40	2.40	-2.47	-4.93	-4.92
Reflective Roof (0.95)	-0.81	-1.42	-0.41	-1.74	2.90	2.90	-3.09	-5.79	-5.78
Larger Window	-0.05	-0.04	-0.01	-0.03	0.18	0.18	0.65	0.00	0.00
Orientation +45°	0.14	0.26	0.08	0.32	-0.49	-0.49	0.38	0.14	0.05
Orientation +90°	0.20	0.42	0.12	0.53	-0.72	-0.72	0.58	0.23	0.09
Orientation +135°	0.14	0.28	0.08	0.35	-0.50	-0.50	0.42	0.16	0.06
Orientation +180°	0.01	0.02	0.01	0.02	-0.03	-0.03	0.03	0.02	0.01
Orientation +225°	0.14	0.28	0.08	0.34	-0.51	-0.51	0.39	0.06	0.15
Orientation +270°	0.19	0.41	0.12	0.51	-0.69	-0.69	0.55	0.09	0.21
Orientation +315°	0.12	0.25	0.07	0.31	-0.45	-0.45	0.39	0.05	0.14
Flat Roof	0.00	0.02	0.01	0.03	0.00	0.00	0.36	-0.12	
Steeper Roof	0.03	0.00	0.00	-0.02	-0.09	-0.09	-0.61	0.10	0.08
Insulation	0.17	0.21	0.06	0.22	-0.65	-0.65	0.09	0.08	0.08
Steel sheet roofing (polished)	-0.59	-1.06	-0.31	-1.31	2.11	2.11	-2.13	-4.38	-4.37
Steel sheet roofing (weathered)	0.07	0.13	0.04	0.16	-0.22	-0.22	0.19	0.28	0.27
Flat on Ground	0.03	0.03	0.01	0.04	-0.06	-0.06	0.00	0.01	0.01

Villahermosa Average values (absolute averages over all hours in May)

Absolute Values averaged over May											
	External	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp		Temp diff
	Tdry	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left Side	Right Side	
	(°C)	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)	(°C)
Base	29.12	30.51	31.30	2.27	84.07	74.76	74.76	9.63	34.61	34.60	
Reflective Roof (0.75)	29.12	29.97	30.31	1.99	82.85	76.69	76.69	7.70	30.53	30.53	-0.99
Reflective Roof (0.85)	29.12	29.84	30.10	1.93	82.59	77.16	77.16	7.17	29.67	29.68	-1.20
Reflective Roof (0.95)	29.12	29.70	29.88	1.86	82.33	77.66	77.66	6.54	28.82	28.83	-1.42
Larger Window	29.12	30.46	31.26	2.26	84.05	74.94	74.94	10.28	34.61	34.60	-0.09
Orientation +45°	29.12	30.65	31.56	2.35	84.39	74.27	74.27	10.01	34.75	34.65	0.26
Orientation +90°	29.12	30.72	31.72	2.39	84.60	74.04	74.04	10.21	34.84	34.70	0.42
Orientation +135°	29.12	30.65	31.58	2.36	84.43	74.26	74.26	10.06	34.77	34.66	0.28
Orientation +180°	29.12	30.52	31.32	2.28	84.10	74.73	74.73	9.66	34.63	34.61	0.02
Orientation +225°	29.12	30.65	31.58	2.35	84.42	74.25	74.25	10.03	34.67	34.75	0.28
Orientation +270°	29.12	30.71	31.70	2.39	84.58	74.07	74.07	10.19	34.70	34.82	0.41
Orientation +315°	29.12	30.64	31.55	2.34	84.38	74.31	74.31	10.02	34.66	34.74	0.25
Flat Roof	29.12	30.52	31.32	2.28	84.10	74.76	74.76	10.00	34.49		0.02
Steeper Roof	29.12	30.54	31.30	2.27	84.06	74.67	74.67	9.02	34.71	34.69	0.00
Insulation	29.12	30.68	31.51	2.33	84.29	74.11	74.11	9.72	34.68	34.68	0.21
Steel sheet roofing (polished)	29.12	29.92	30.24	1.96	82.76	76.87	76.87	7.51	30.23	30.23	-1.06
Steel sheet roofing (weathered)	29.12	30.58	31.43	2.31	84.23	74.53	74.53	9.82	34.88	34.88	0.13
Flat on Ground	29.12	30.54	31.33	2.28	84.11	74.70	74.70	9.63	34.62	34.61	-0.04

Reflective Roof

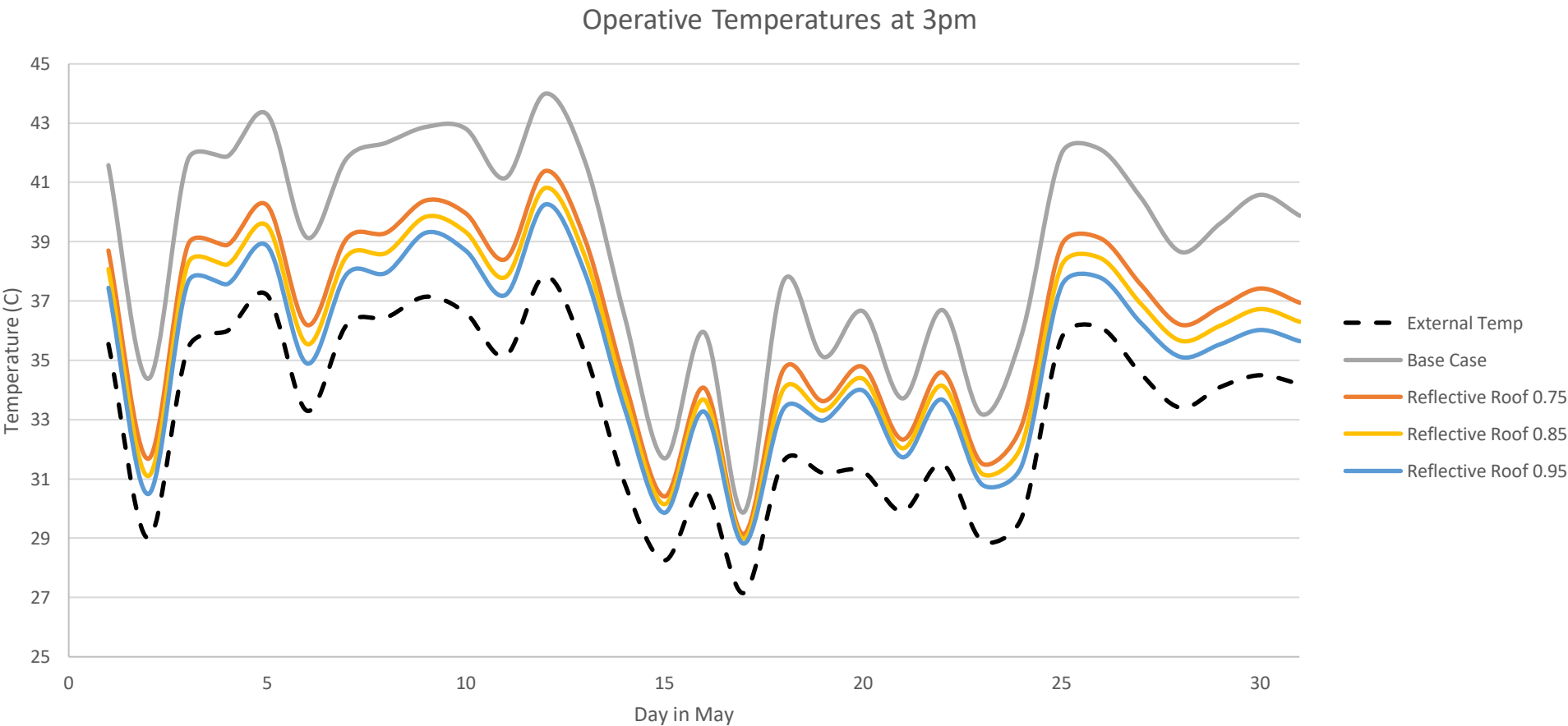
Reflective Roof – Roof Surface Temperatures



The base case has an albedo of 0.27. The painted roofs with higher albedo, reflect more sunlight than the base case, so less heat is absorbed by the roof. This reduces the roof surface temperature and in turn reduces the internal temperature of the house.

Figure 3: Roof surface temperatures for 3pm in May, comparing the reflective roof strategies against the base case.

Reflective Roof – Internal Operative Temperatures

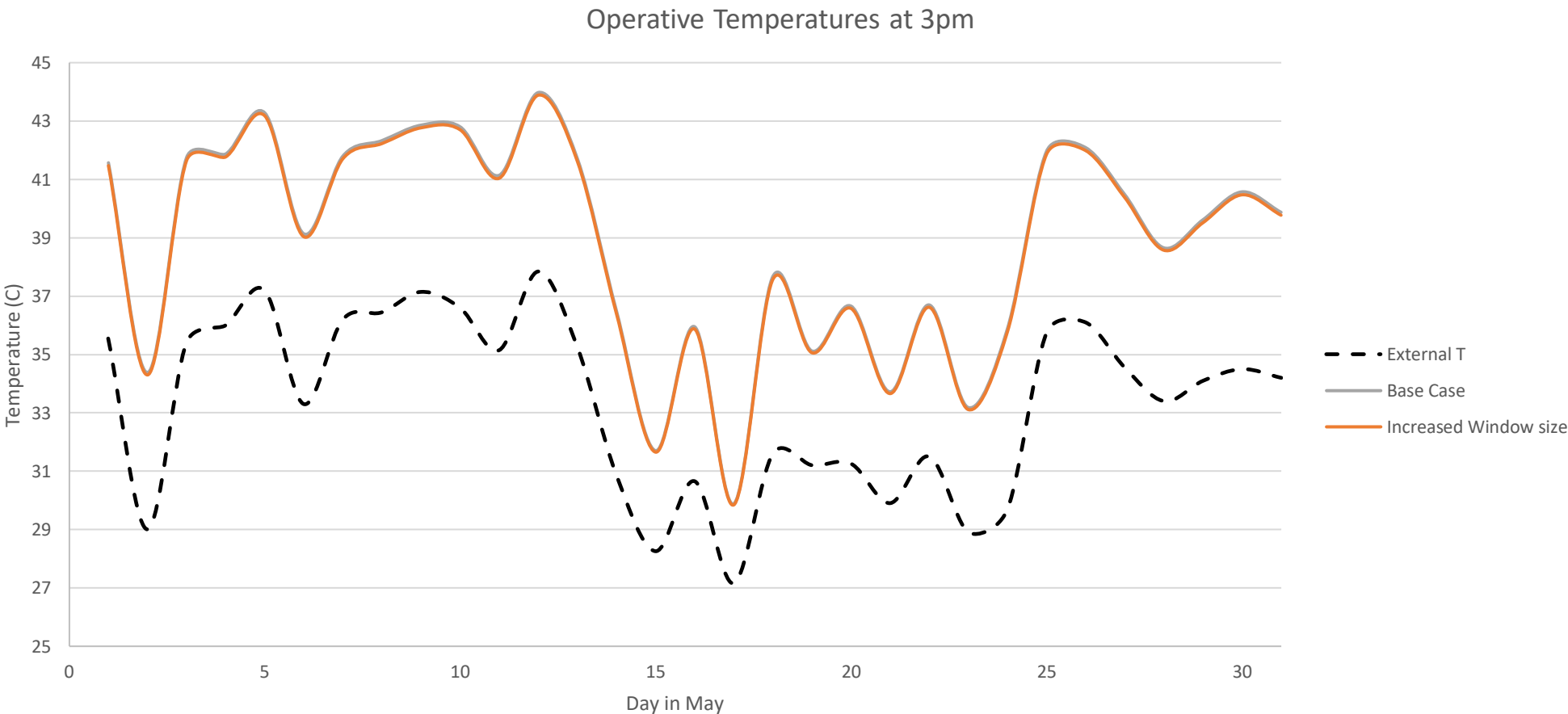


The reduction of the roof surface temperature due to the high albedo surfaces, reduces the internal temperature of the house.

Figure 4: Internal operative temperatures for 3pm in May, comparing the reflective roof strategies against the base case.

Increased Window Size

Increased Window Size – Internal Operative Temperatures

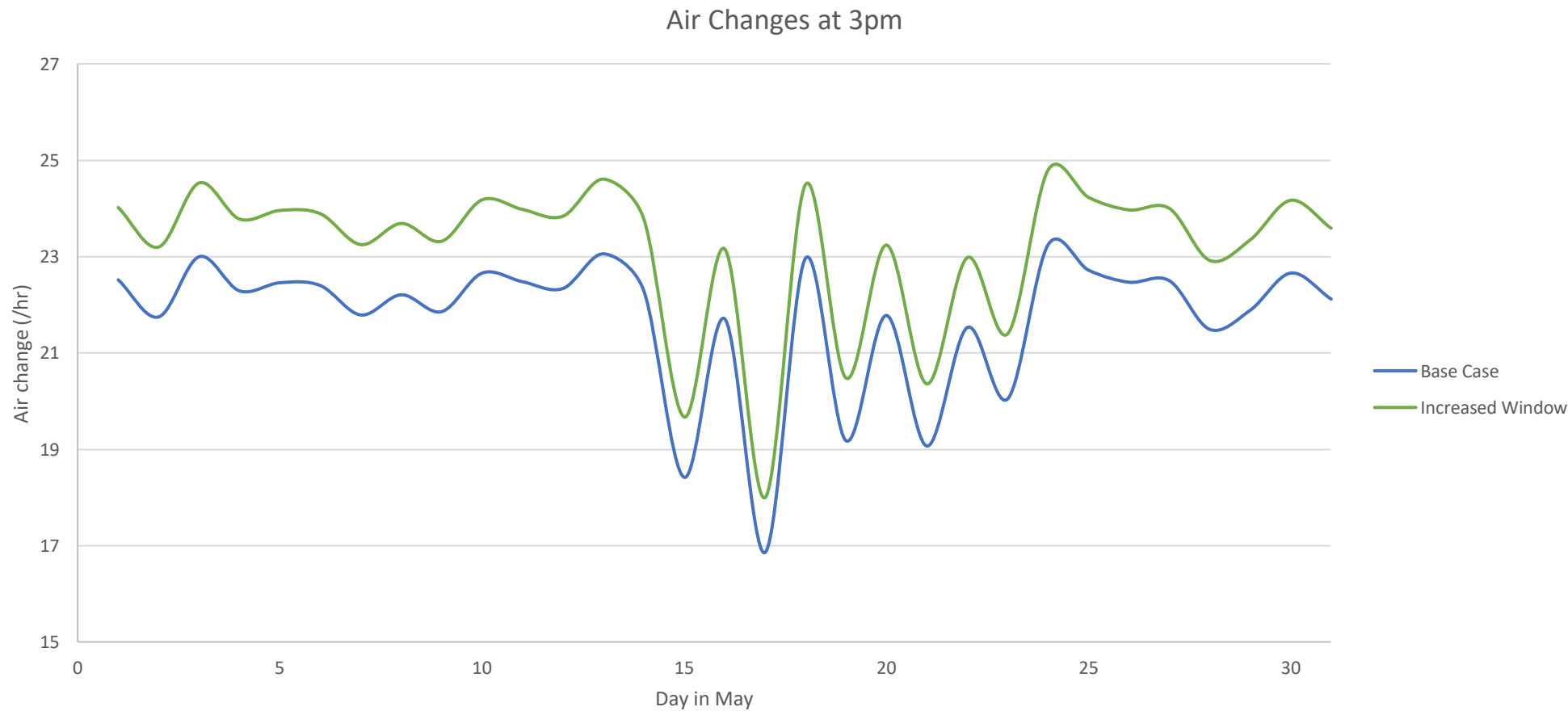


Increasing the window size gives a slightly cooler internal operative temperature due to an increase in ventilation. Since the external temperature is cooler than internal temperatures increasing the ventilation decreases the internal temperatures.

However, increased windows also allow greater solar gains into the room which can cause higher temperatures depending on time of day and building orientation.

Figure 5: Internal operative temperatures for 3pm in May, comparing the increased window strategy against the base case.

Increased Window Size - Air change rates



The air change rate is higher for the increased window case than the base case, as expected due to an increase in ventilation. While the difference in air change rate between the cases is notable, the difference in temperatures is much less so.

It is important to note that our models do not account for wind/wind speeds so the improvement in air change shown is conservative.

It is likely that, on a breezy day the increased window size would be more effective at cooling the space and increasing air change rate.

Figure 6: Air change for base case and increased window cases at 3pm in May.

Orientation

Building Orientation – 9.30am

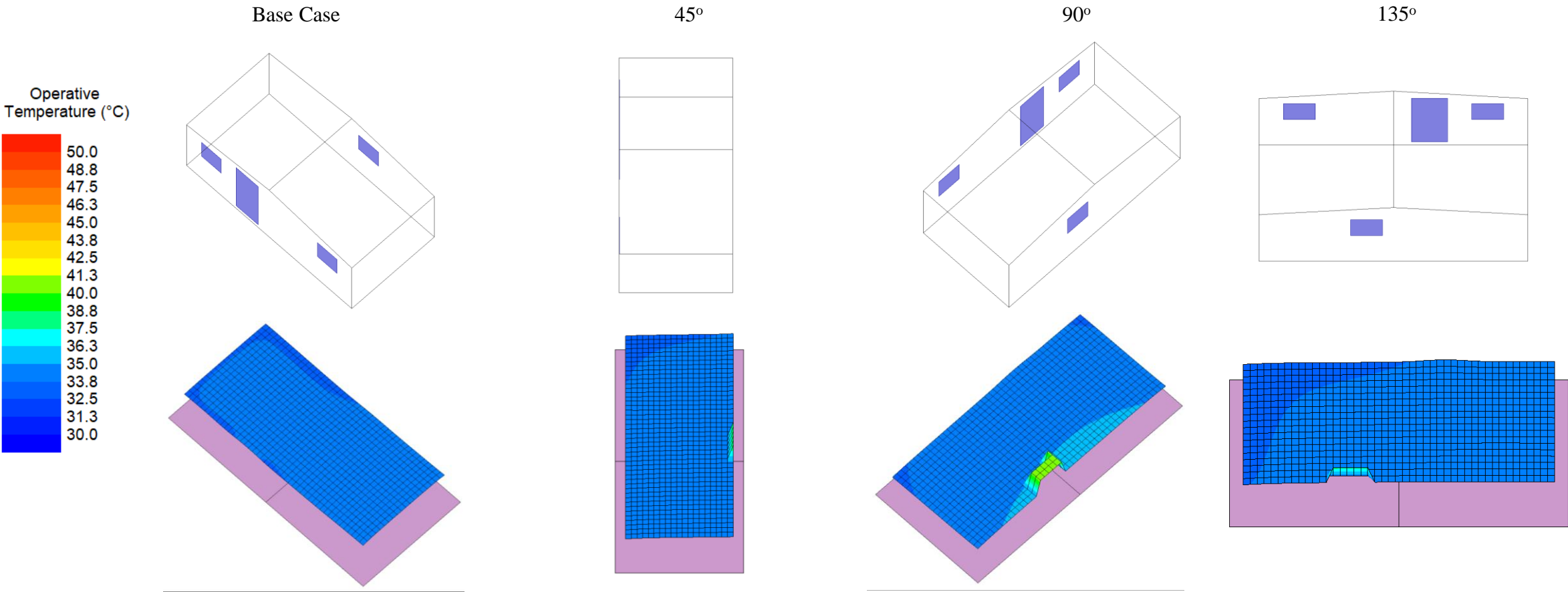
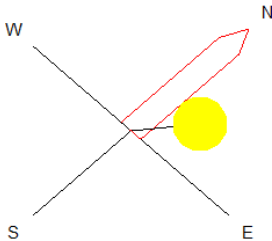


Figure 7a: Spatial operative temperatures for 9.30am in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 27.5°C.

Building Orientation – 9.30am

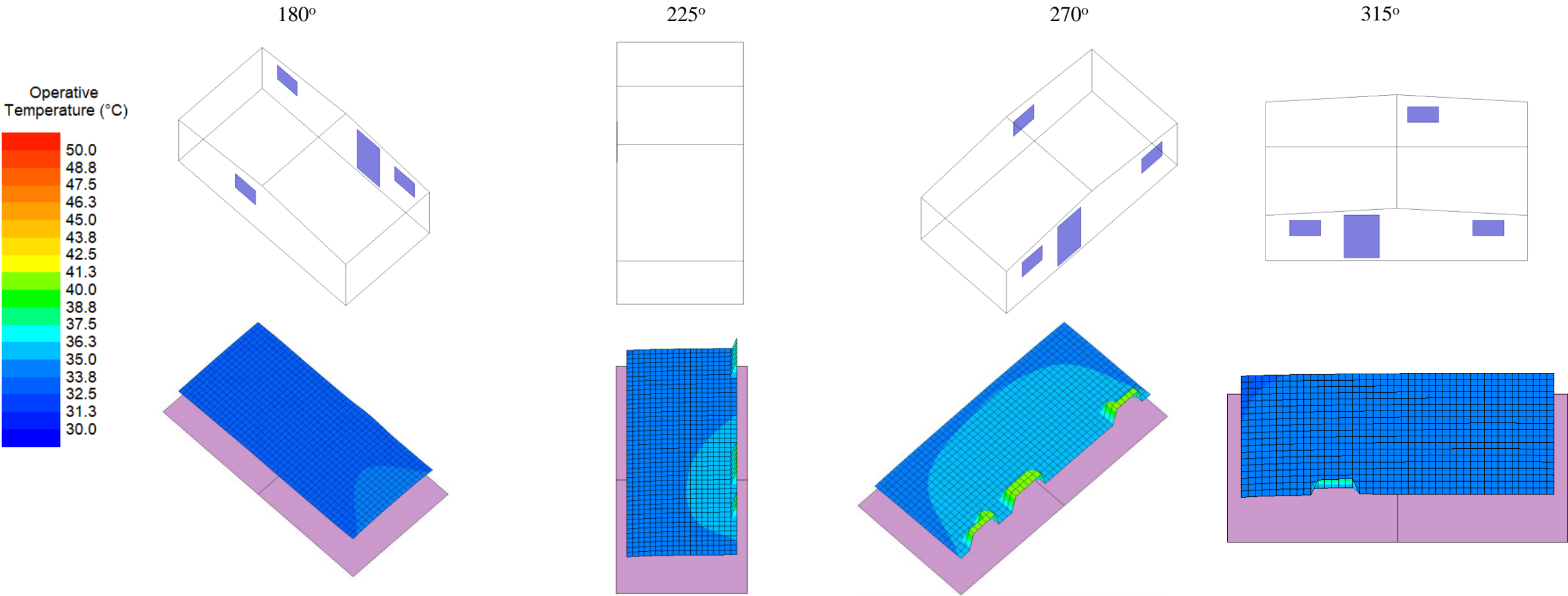
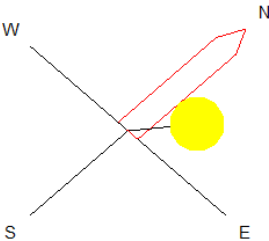


Figure 7b: Spatial operative temperatures for 9.30am in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 27.5°C.

Building Orientation – 4.30pm

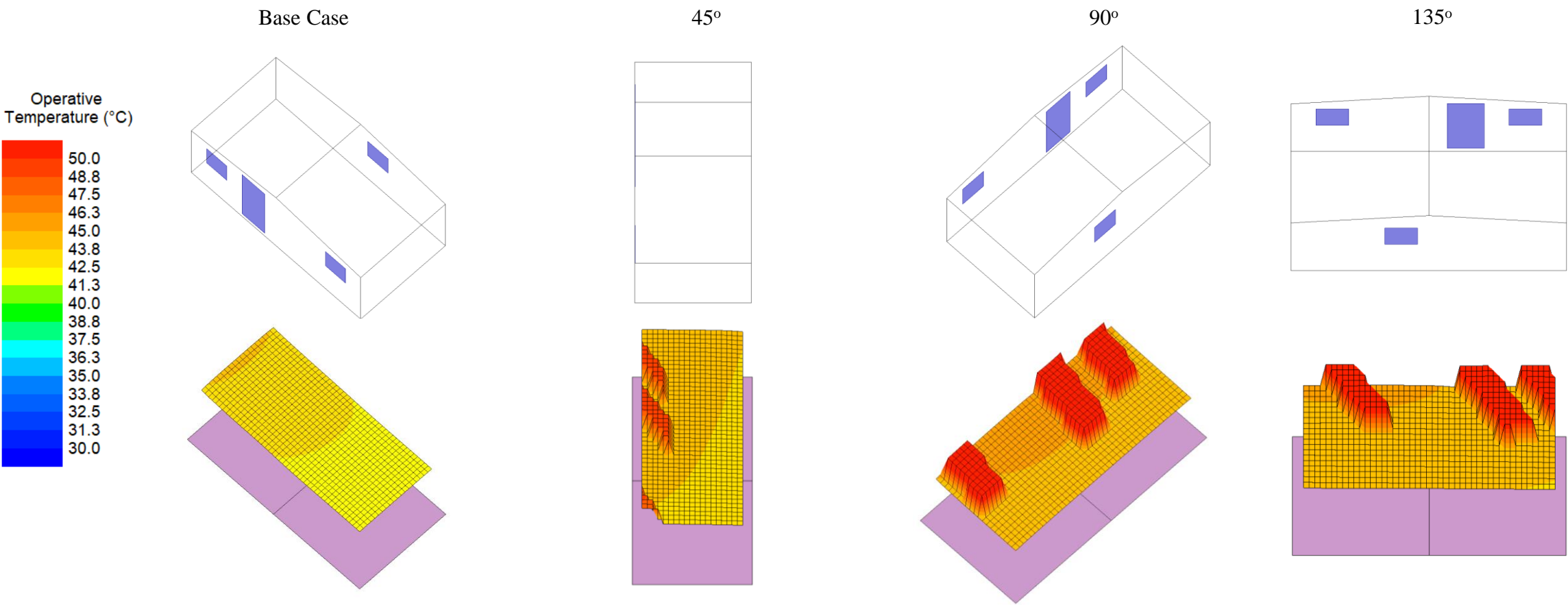
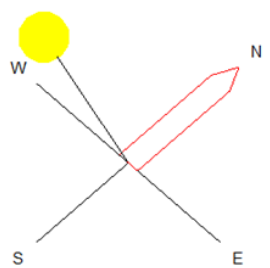
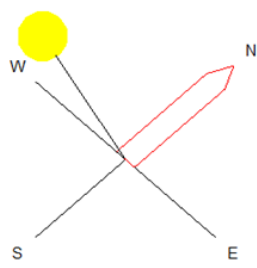


Figure 8a: Spatial operative temperatures for 4.30pm in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 38.0°C.



Building Orientation – 4.30pm

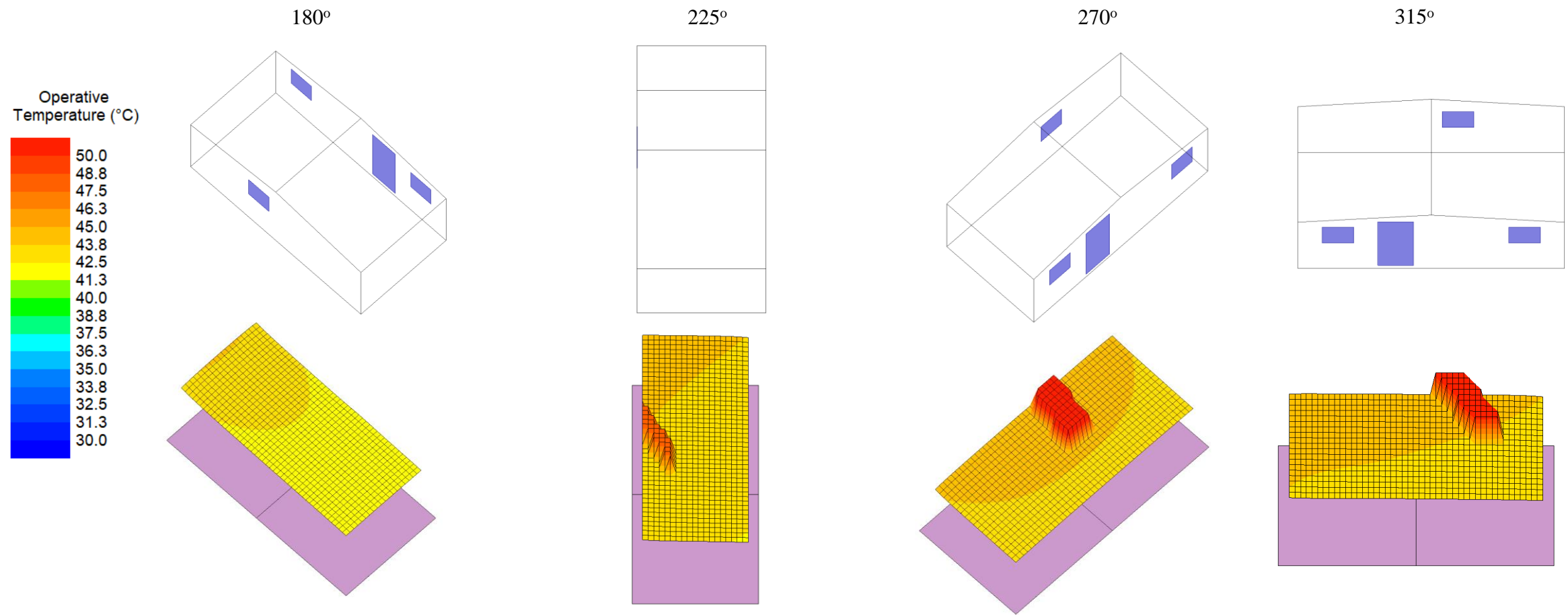


Figure 8b: Spatial operative temperatures for 4.30pm in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 38.0°C.

Building Orientation

The base case in Figure 7a, 8a shows lower temperatures than the other orientations at both 9.30am and 4.30pm. This is because there are no windows facing east or west during the day, to let in sunlight and cause higher solar gain.

Looking at the 90° case in Figure 8a, it is clear that the heat spikes inside the building are due to the window positioning which allows high solar gain at the hottest part of the day. This is further demonstrated in Figure 9, where the base case consistently has the lowest temperatures, while the 90° case has the highest temperatures.

The results of examining building orientation on temperature highlight the effectiveness of interventions that reduce solar gains. Using blinds would also improve internal temperatures by reducing solar gains, regardless of building orientation.

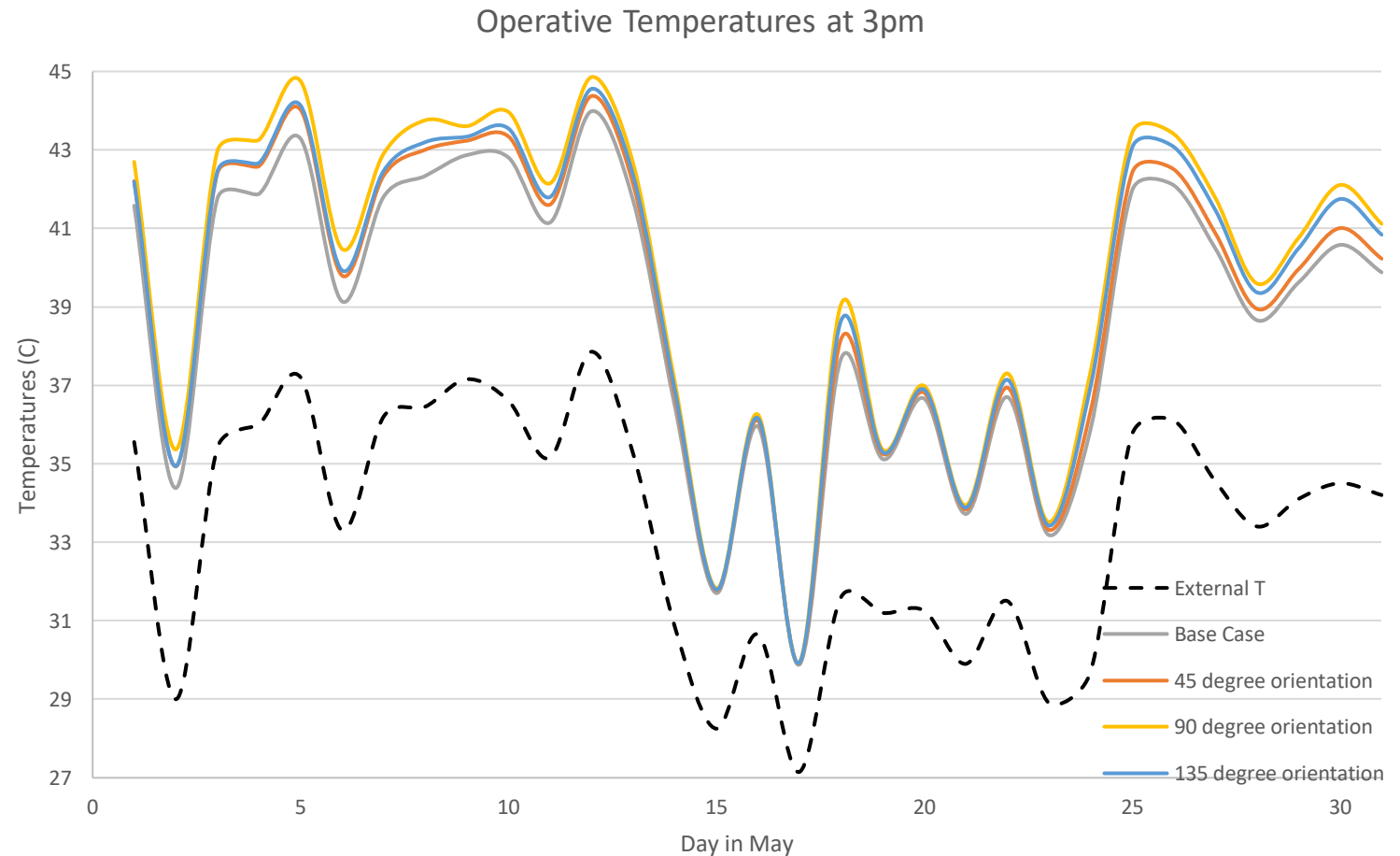


Figure 9: Internal operative temperatures for 3pm in May, comparing different building orientations.

Steeper Roof & Flat Roof

Roof Pitch

For the base case, the roof is orientated parallel to the path of the sun during the day, with the windows perpendicular to the sun. This means that changing the roof pitch has little effect on the roof temperatures and therefore the internal temperatures as the sun is heating the roof all day regardless of pitch.

Later, we will investigate the impact of roof pitch on the building oriented perpendicular to the path of the sun.

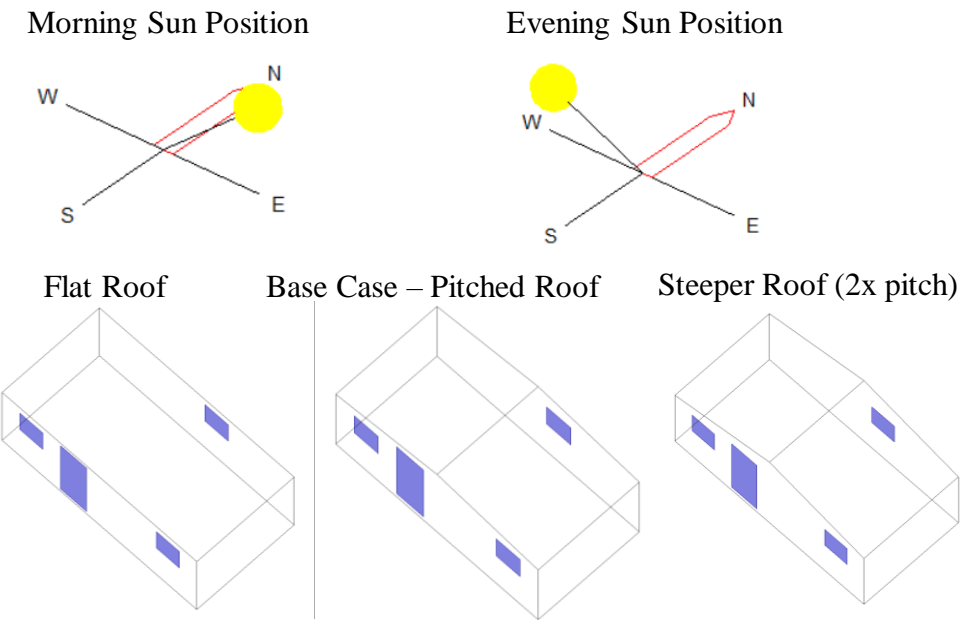


Figure 10: Models of flat roof, base case and steeper roof.

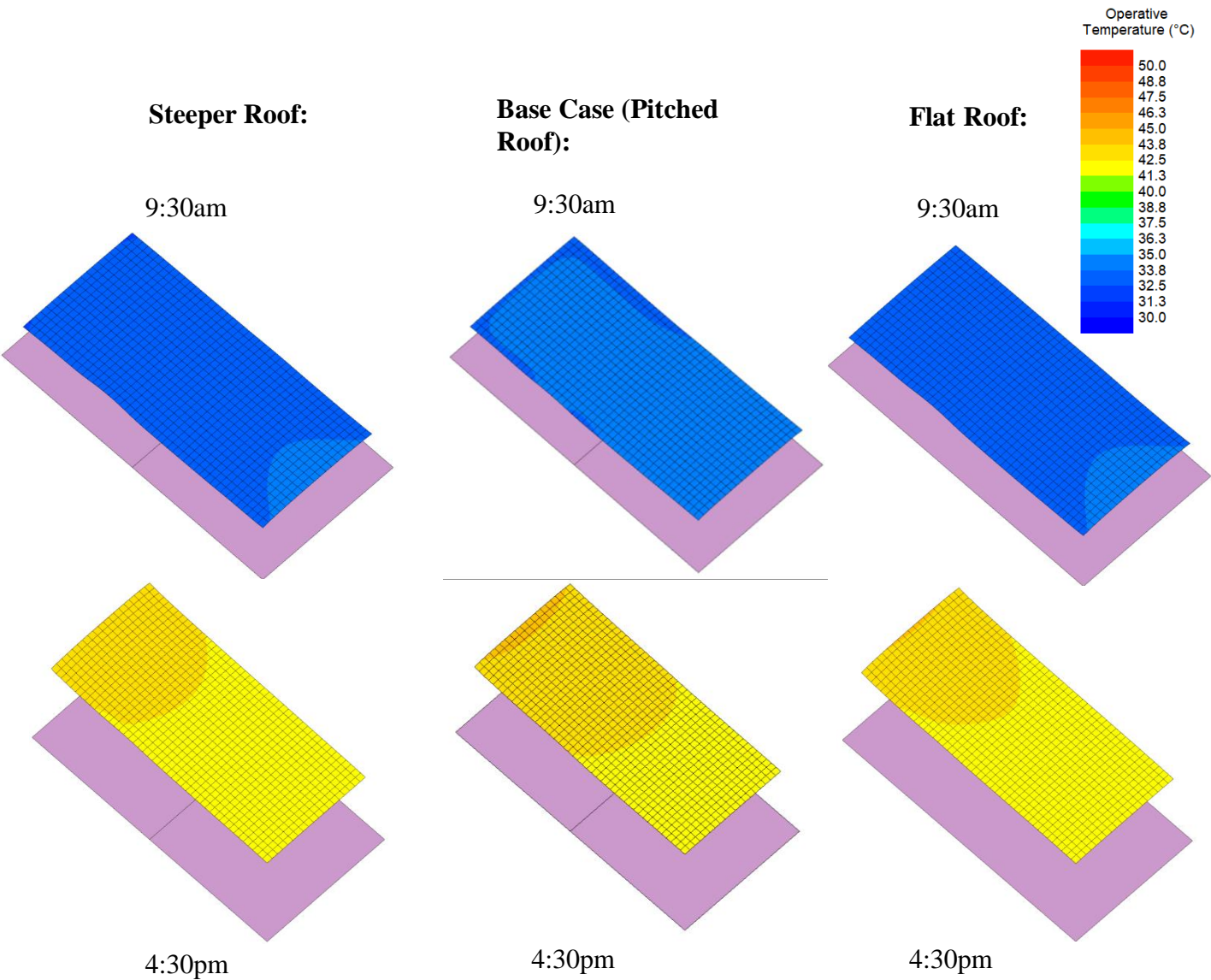
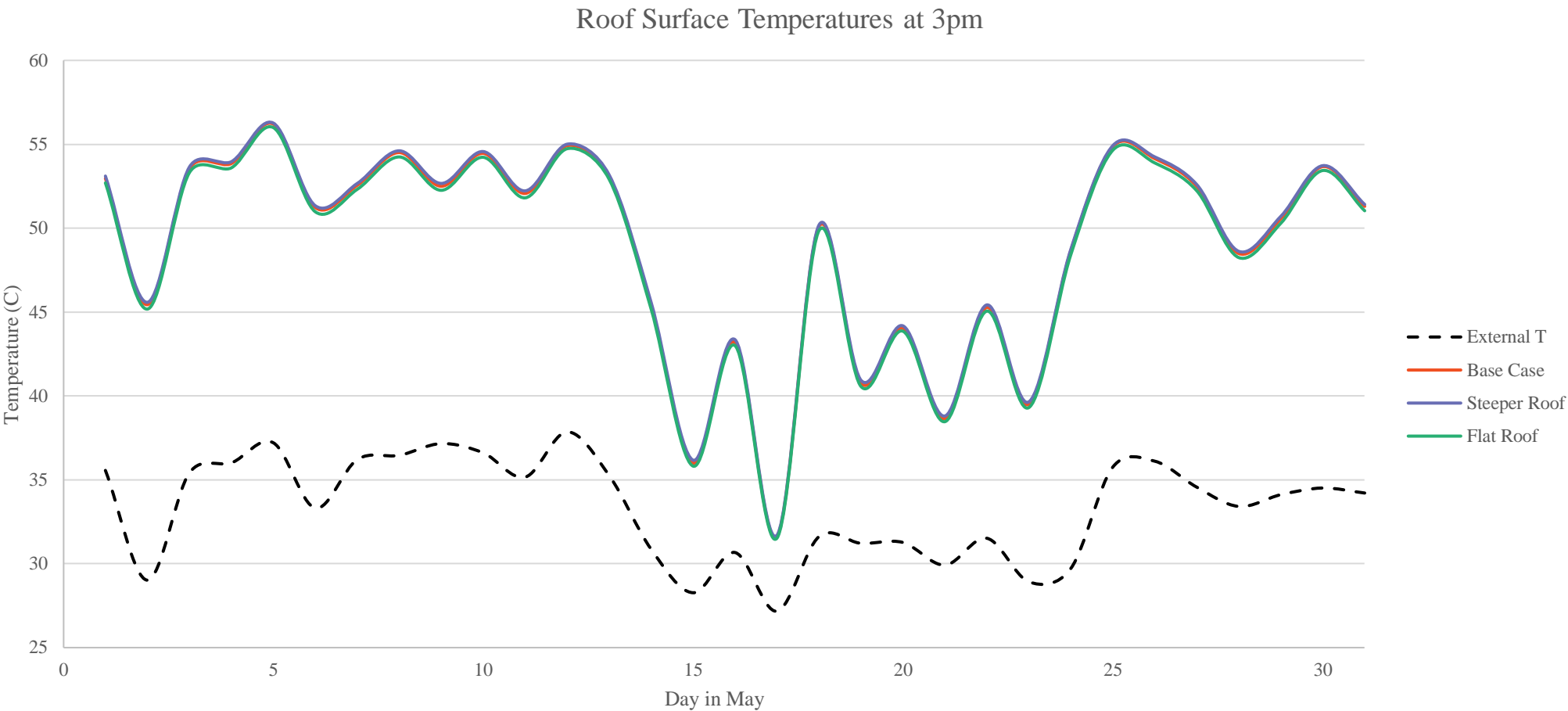


Figure 11: Spatial operative temperatures for 9:30am and 4:30pm in May.

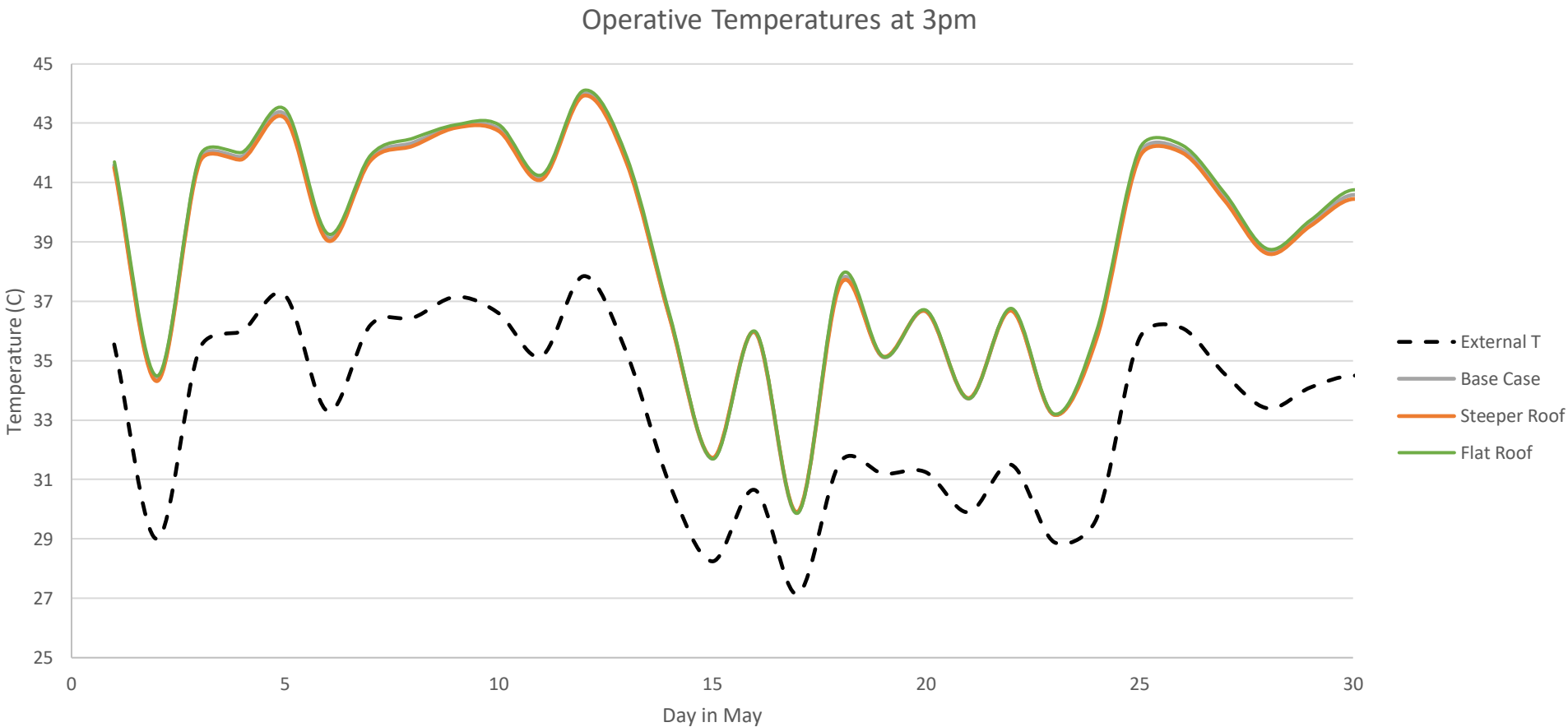
Roof Pitch – Roof Surface Temperatures



Due to the buildings in all cases being oriented with roofs parallel to the path of the sun during the day, the roof pitch has little impact on the roof surface temperature.

Figure 12: Roof surface temperatures for 3pm in May, comparing the flat roof, steeper roof and base cases.

Roof Pitch – Internal Operative Temperatures

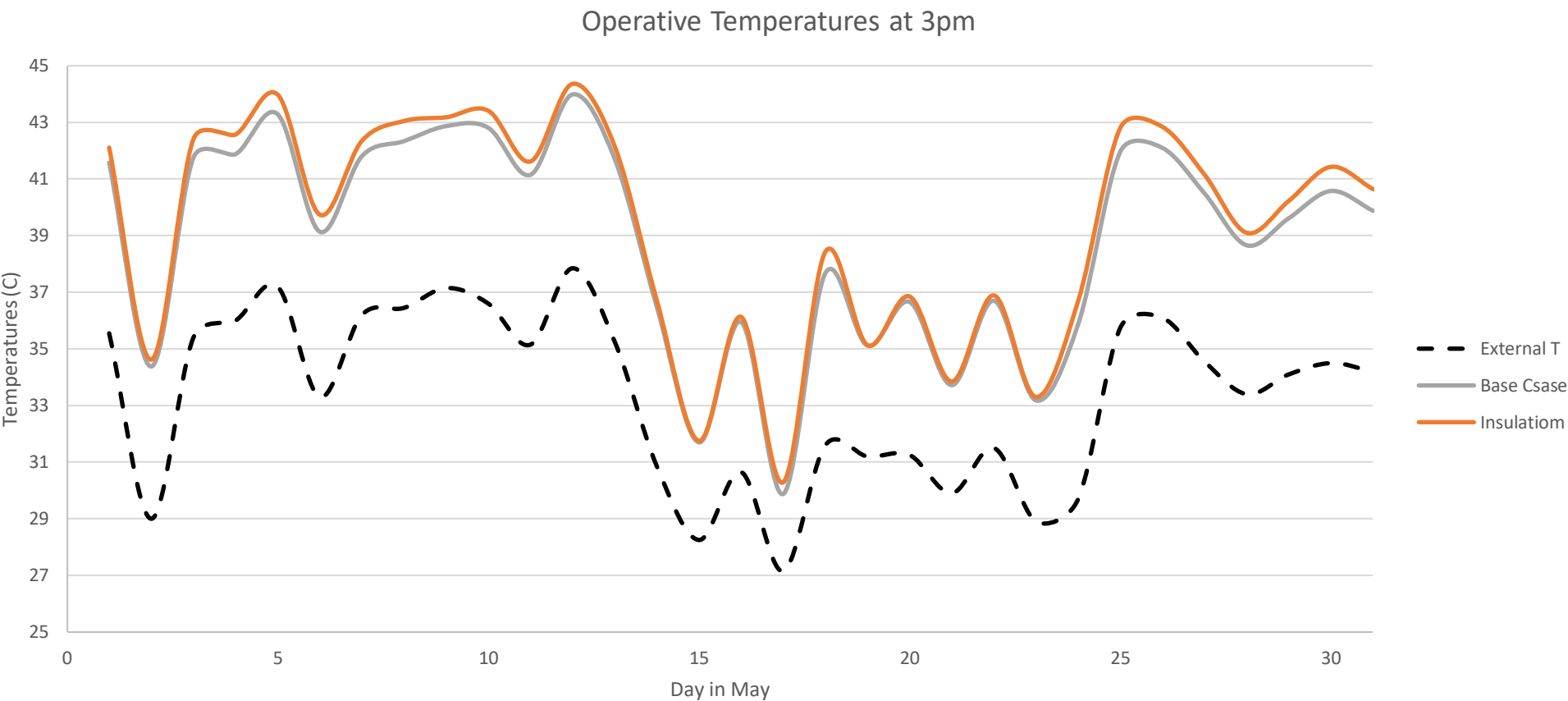


Internal temperatures are similar regardless of roof pitch as roof pitch has little effect on roof surface temperature.

Figure 13: Internal operative temperatures for 3pm in May, comparing the flat roof, steeper roof and base cases.

Insulation

Insulation – Internal Operative Temperatures



Insulation prevents heat loss from the internal space causing slightly higher internal temperatures, as expected.

Figure 14: Internal operative temperatures for 3pm in May, comparing the insulation strategy against the base case.

Steel Sheet Roofing

Steel Sheet Roofing – Internal Operative Temperatures

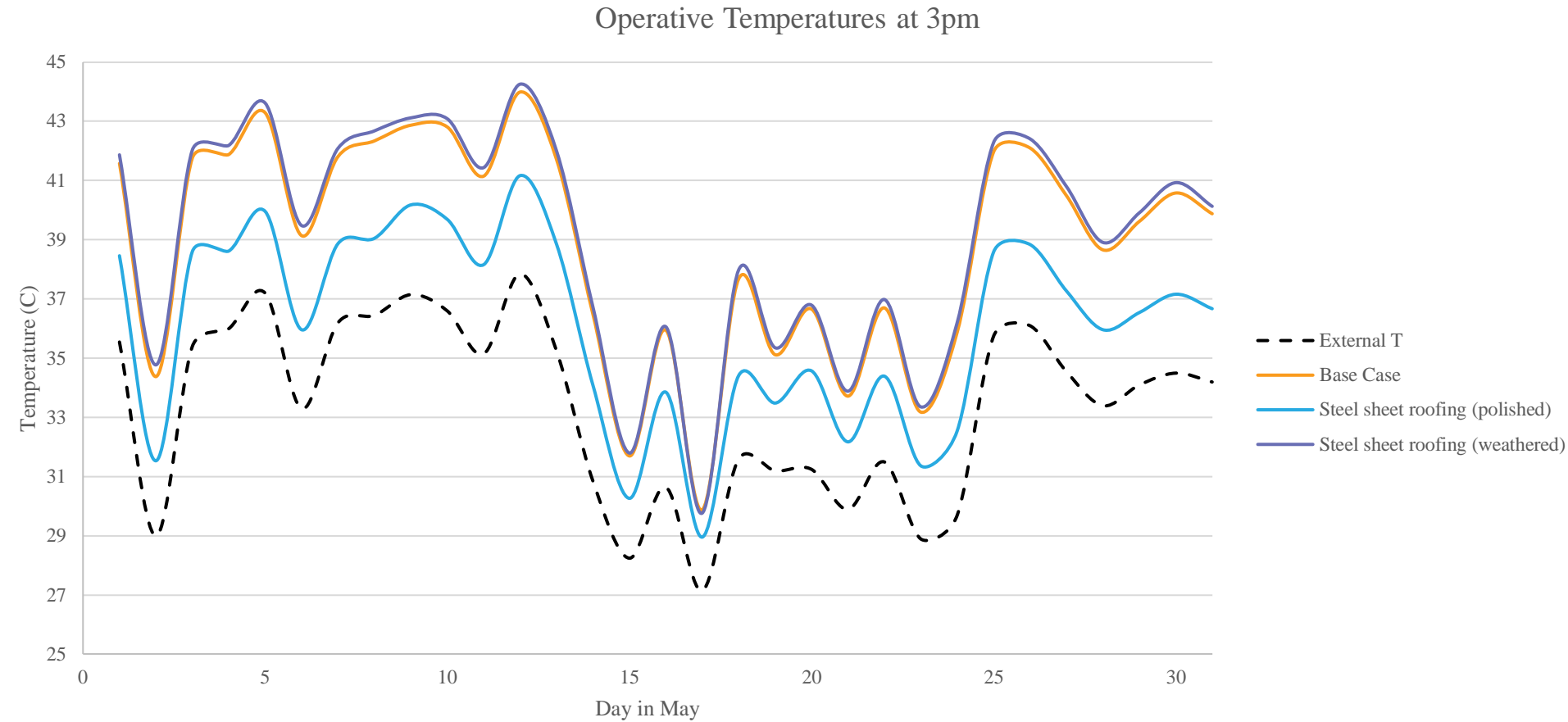


Figure 15: Internal operative temperatures for 3pm in May, comparing the roof materials.

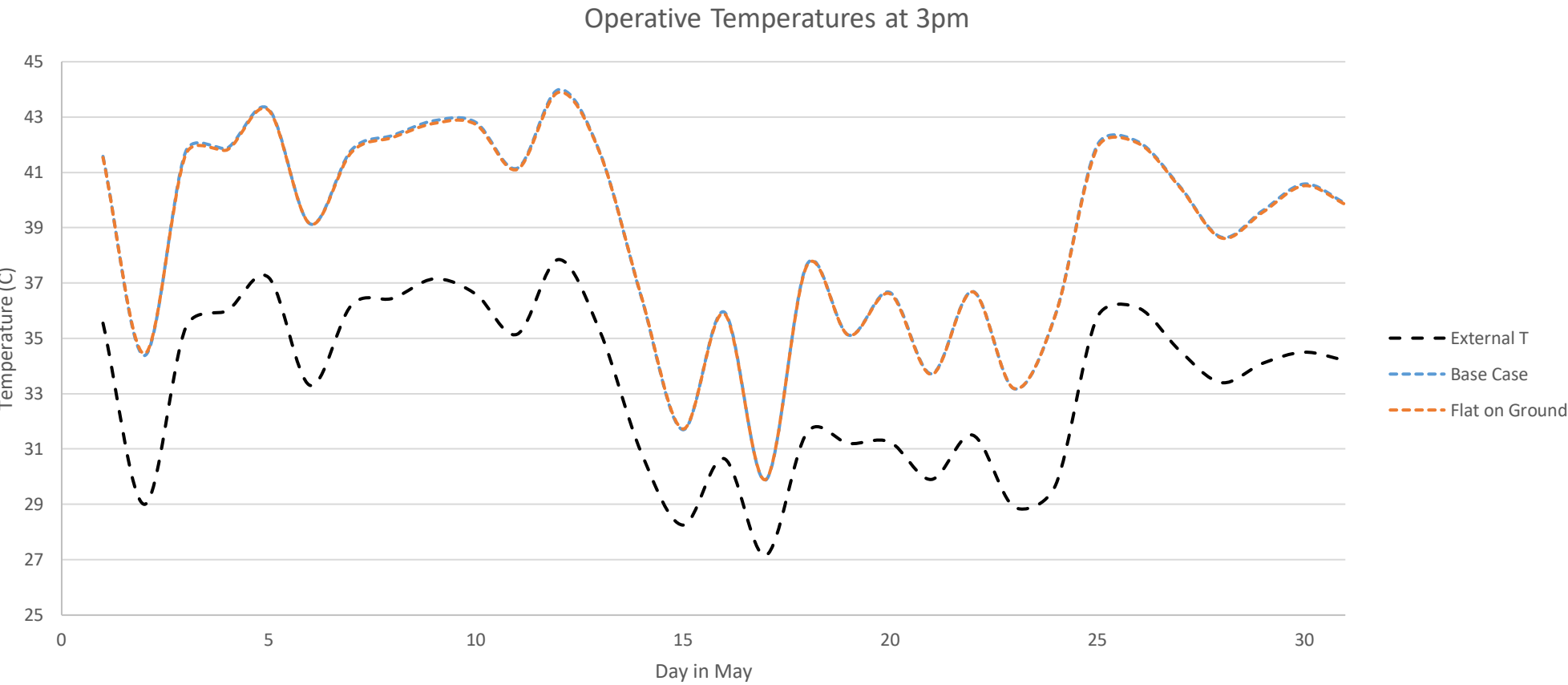
The base case is made up of fibre cement boards with an albedo of 0.27, while the steel sheet roofing has albedos of: 0.25 for weathered and 0.8 for polished.

The weathered steel roof has higher thermal conductivity than the base case roof which gives higher roof surface temperatures and therefore higher internal temperatures. While the polished has a much higher albedo than the other cases causing more sunlight to be reflected away from the roof, reducing roof temperatures and thus internal temperatures.

The weathered steel more closely represents a steel sheet roofing than the polished steel.

Flat on Ground

Flat on Ground – Internal Operative Temperatures



Moving building to be flat on the ground, rather than elevated on stilts (as in the base case) should increase temperatures due to lack of ventilation underneath the building. The ventilation would carry cooler external air underneath the building reducing the temperature.

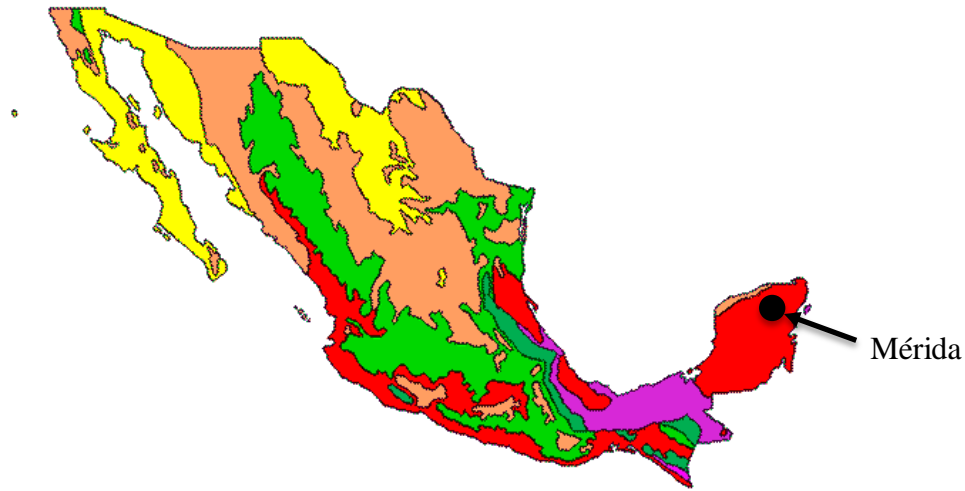
However, possibly due to no wind being modelled, the two cases have little to no difference in internal temperature..

Figure 16: Internal operative temperatures for 3pm in May, comparing the flat on ground strategy against the base case.

Villahermosa Summary

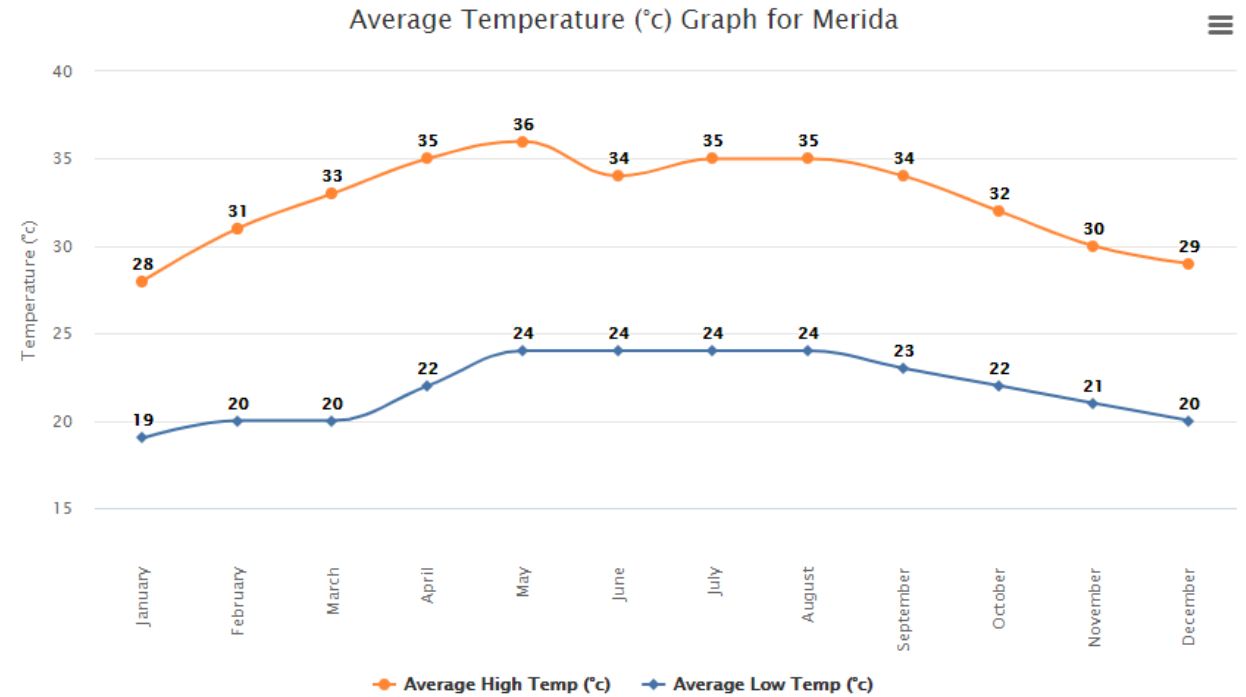
The most effective strategy for Villahermosa is the reflective roof, where a higher albedo gives a greater cooling effect. Limited improvement was seen for the polished steel roof material, increased window size and steeper roof.

Mérida Summer



Tropical savannah climate (Aw)

Monthly Average Temperature



MÉRIDA Average values (difference from base in May)

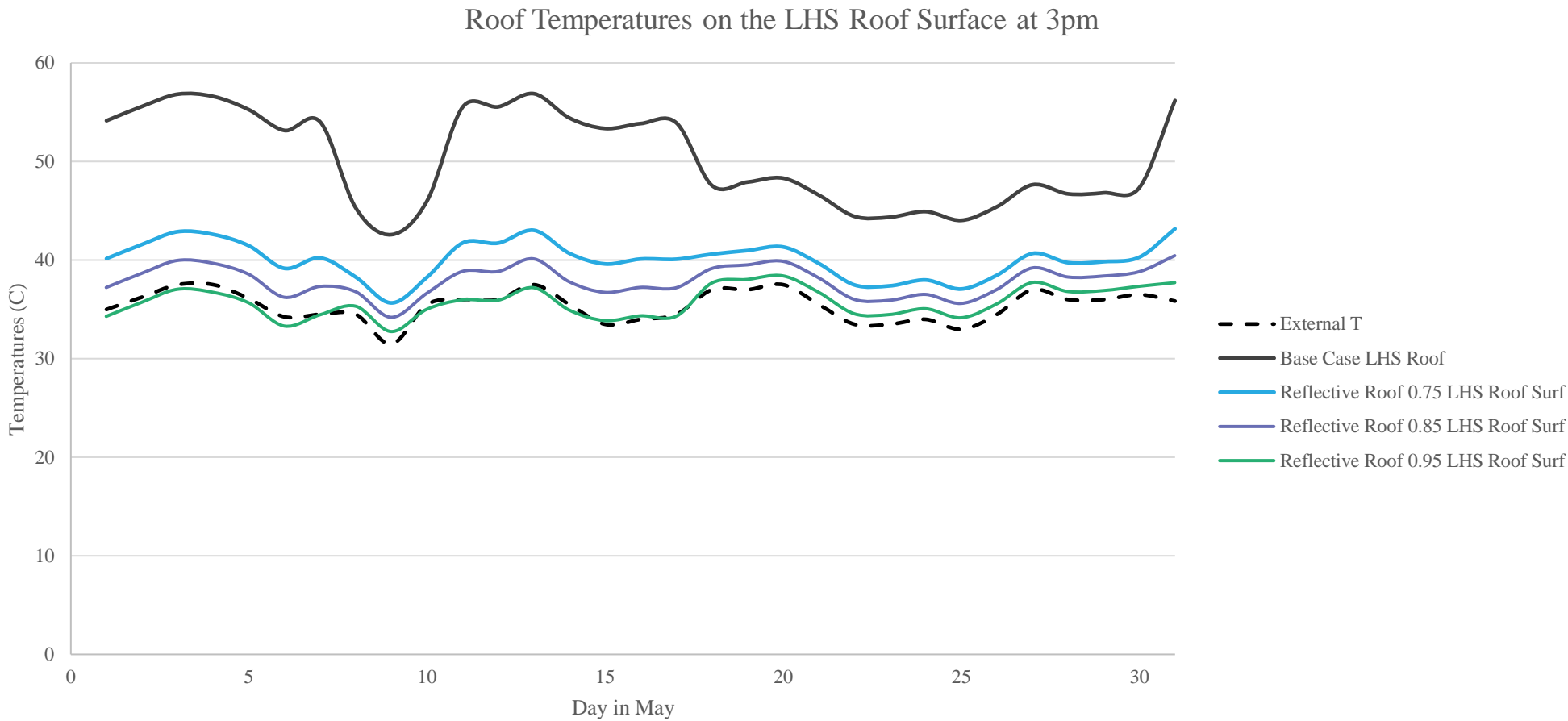
Average difference from base across May									
	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp	
	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left side	Right Side
	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)
Base									
Reflective Roof (0.75)	-0.56	-1.01	-0.29	-1.18	1.40	1.40	-2.04	-4.22	-4.21
Reflective Roof (0.85)	-0.70	-1.24	-0.36	-1.43	1.75	1.75	-2.62	-5.10	-5.10
Reflective Roof (0.95)	-0.84	-1.46	-0.42	-1.69	2.13	2.13	-3.32	-5.98	-5.98
Larger Window	-0.05	-0.04	-0.01	-0.02	0.16	0.16	0.64	0.00	0.00
Orientation +45°	0.12	0.25	0.07	0.28	-0.33	-0.33	0.36	0.11	0.07
Orientation +90°	0.18	0.38	0.11	0.45	-0.46	-0.46	0.53	0.17	0.11
Orientation +135°	0.13	0.26	0.07	0.30	-0.30	-0.30	0.39	0.13	0.07
Orientation +180°	0.01	0.01	0.00	0.01	-0.02	-0.02	0.02	0.02	0.00
Orientation +225°	0.12	0.25	0.07	0.29	-0.35	-0.35	0.36	0.08	0.10
Orientation +270°	0.17	0.38	0.11	0.44	-0.46	-0.46	0.51	0.12	0.16
Orientation +315°	0.12	0.24	0.07	0.28	-0.30	-0.30	0.36	0.07	0.10
Flat Roof	0.00	0.02	0.01	0.03	0.05	0.05	0.35	-0.13	
Steeper Roof	0.03	0.00	0.00	-0.02	-0.12	-0.12	-0.60	0.08	0.10
Insulation	0.21	0.26	0.08	0.27	-0.52	-0.52	0.17	0.09	0.09
Steel sheet roofing (polished)	-0.61	-1.09	-0.32	-1.27	1.45	1.45	-2.24	-4.51	-4.50
Steel sheet roofing (weathered)	0.07	0.14	0.04	0.15	-0.25	-0.25	0.20	0.31	0.31
Flat on Ground	0.02	0.02	0.01	0.00	-0.14	-0.14	-0.01	0.00	0.00

Mérida Average values (absolute averages over all hours in May)

Absolute Values averaged over May											
	External	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp		Op Tdiff
	Tdry	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left Side	Right Side	
	(°C)	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)	(°C)
Base	29.22	30.53	31.29	2.28	81.24	58.08	58.08	9.44	34.69	34.69	
Reflective Roof (0.75)	29.22	29.96	30.27	1.98	80.06	59.48	59.48	7.40	30.47	30.47	-1.01
Reflective Roof (0.85)	29.22	29.83	30.05	1.92	79.81	59.83	59.83	6.82	29.59	29.59	-1.24
Reflective Roof (0.95)	29.22	29.69	29.83	1.85	79.55	60.21	60.21	6.11	28.70	28.71	-1.46
Larger Window	29.22	30.48	31.25	2.26	81.22	58.24	58.24	10.07	34.68	34.69	-0.04
Orientation +45°	29.22	30.65	31.53	2.35	81.52	57.75	57.75	9.79	34.80	34.76	0.25
Orientation +90°	29.22	30.71	31.67	2.39	81.69	57.62	57.62	9.97	34.86	34.80	0.38
Orientation +135°	29.22	30.65	31.54	2.35	81.54	57.78	57.78	9.82	34.81	34.76	0.26
Orientation +180°	29.22	30.53	31.30	2.28	81.25	58.06	58.06	9.45	34.71	34.69	0.01
Orientation +225°	29.22	30.65	31.54	2.35	81.52	57.73	57.73	9.79	34.77	34.79	0.25
Orientation +270°	29.22	30.70	31.66	2.38	81.68	57.62	57.62	9.95	34.81	34.84	0.38
Orientation +315°	29.22	30.64	31.52	2.34	81.51	57.78	57.78	9.80	34.76	34.79	0.24
Flat Roof	29.22	30.53	31.30	2.28	81.27	58.13	58.13	9.79	34.55		0.02
Steeper Roof	29.22	30.56	31.28	2.27	81.21	57.96	57.96	8.83	34.77	34.79	0.00
Insulation	29.22	30.74	31.55	2.35	81.51	57.56	57.56	9.61	34.78	34.78	0.26
Steel sheet roofing (polished)	29.22	29.92	30.20	1.96	79.96	59.53	59.53	7.20	30.18	30.19	-1.09
Steel sheet roofing (weathered)	29.22	30.60	31.42	2.32	81.38	57.83	57.83	9.63	34.99	34.99	0.14
Flat on Ground	29.22	30.54	31.31	2.28	81.24	57.94	57.94	9.42	34.69	34.69	0.02

Reflective Roof

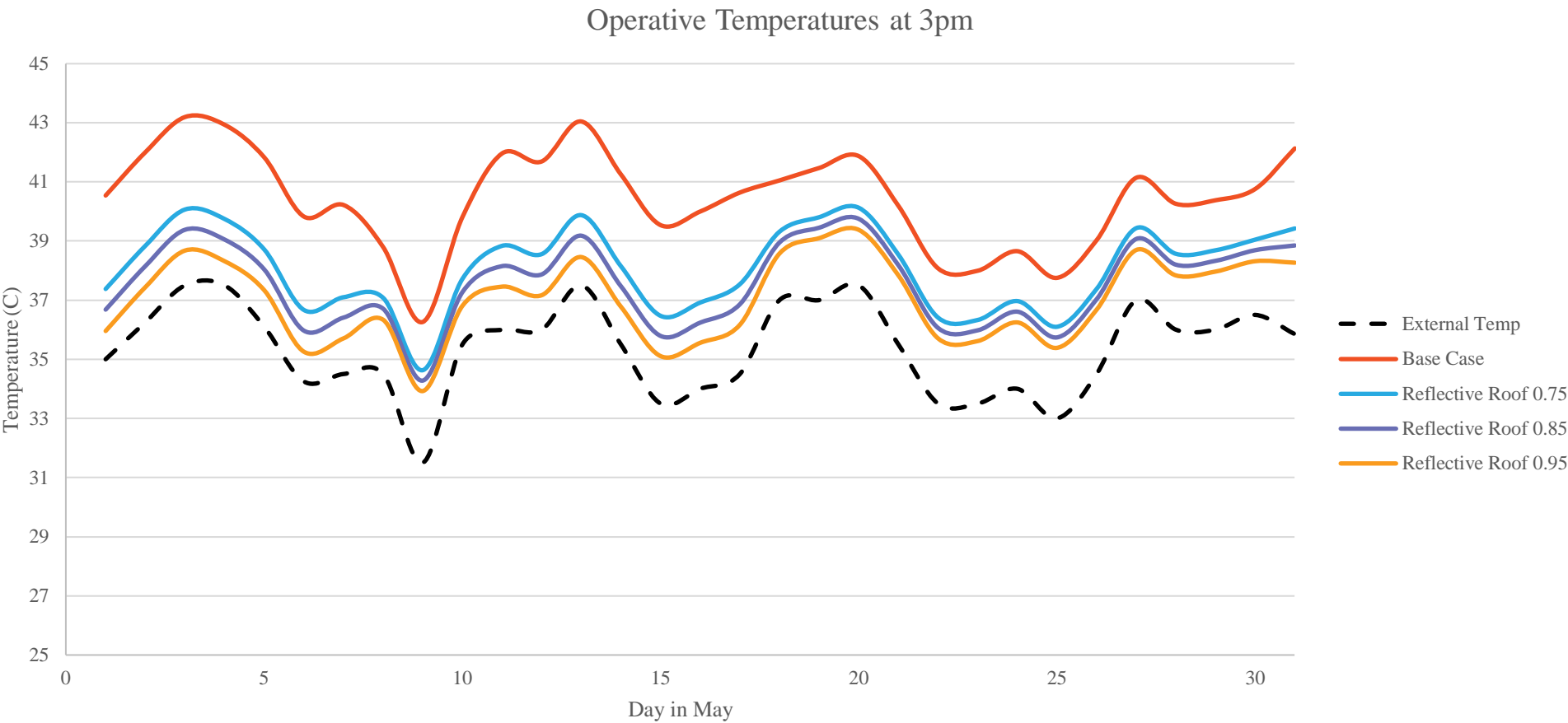
Reflective Roof – Roof Surface Temperatures



The base case has an albedo of 0.27. The painted roofs with higher albedo, reflect more sunlight than the base case, so less heat is absorbed by the roof. This reduces the roof surface temperature and in turn reduces the internal temperature of the house.

Figure 17: Roof surface temperatures for 3pm in May comparing the reflective roof strategies against the base case.

Reflective Roof – Internal Operative Temperatures

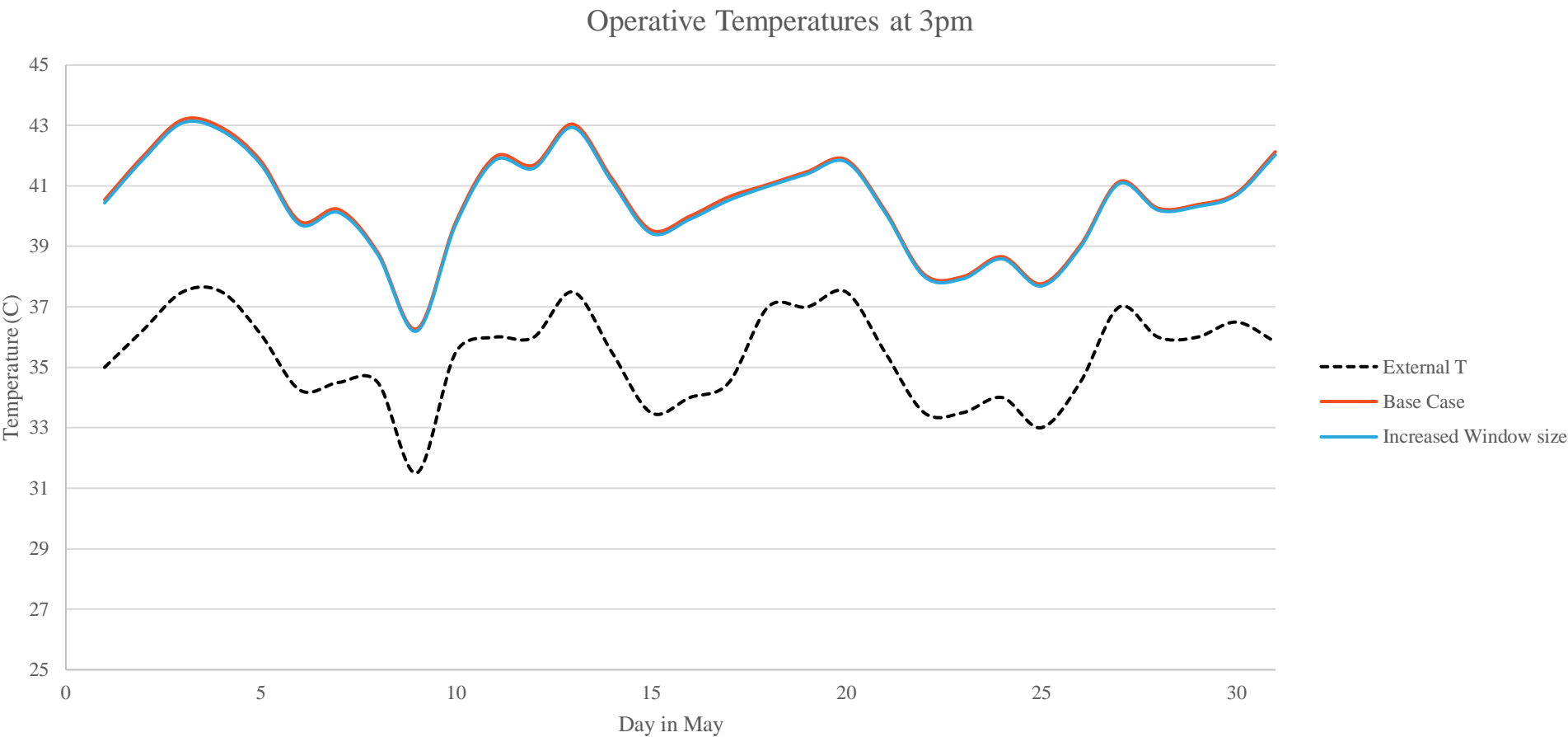


The reduction of the roof surface temperature due to the high albedo surfaces, reduces the internal temperature of the house.

Figure 18: Internal operative temperatures for 3pm in May, comparing the reflective roof strategies against the base case.

Increased Window Size

Increased Window Size – Internal Operative Temperatures

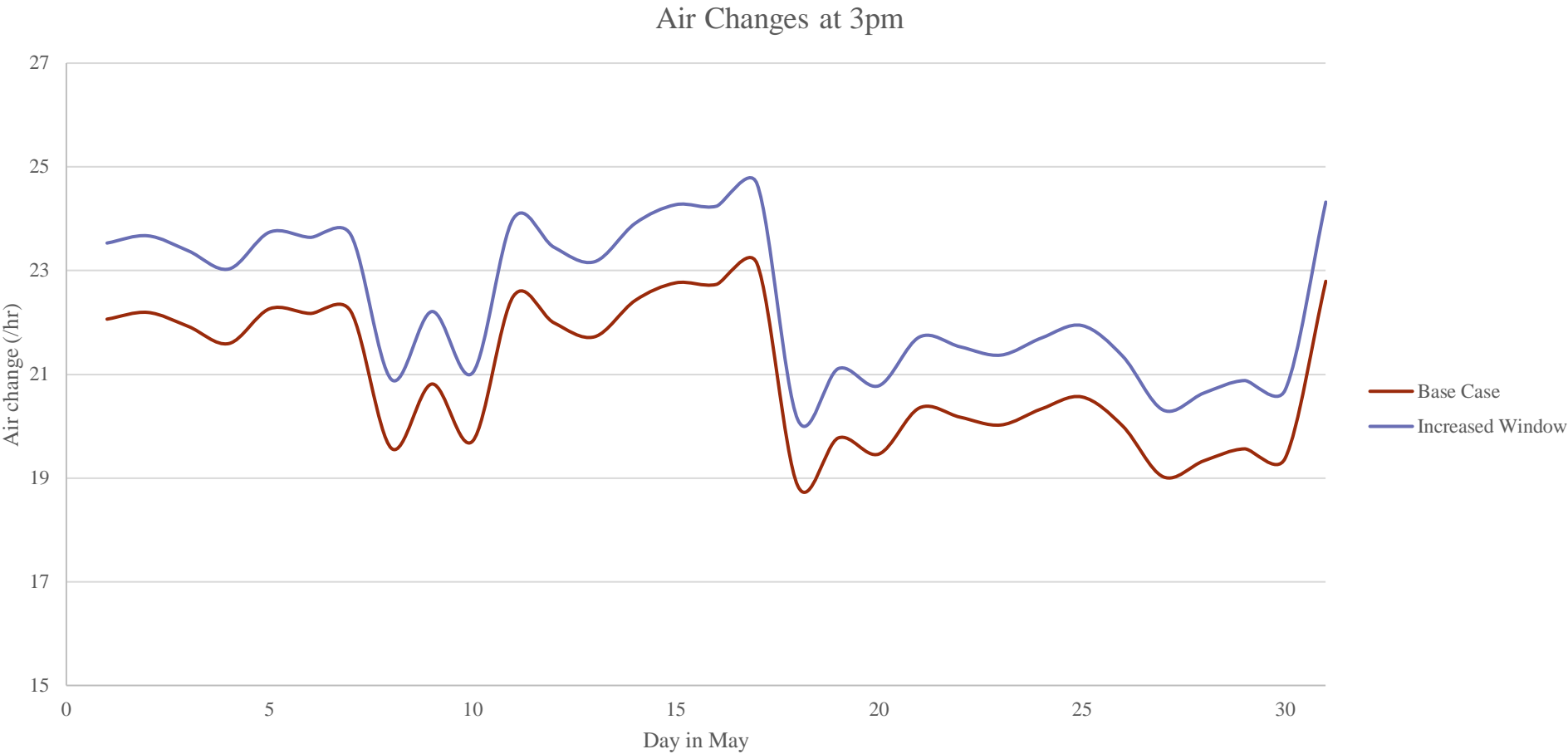


Increasing the window size gives a slightly cooler internal operative temperature due to an increase in ventilation. Since the external temperature is cooler than internal temperatures increasing the ventilation decreases the internal temperatures.

However, increased windows also allow greater solar gains into the room which can cause higher temperatures depending on time of day and building orientation.

Figure 19: Internal operative temperatures for 3pm in May, comparing the increased window strategy against the base case.

Increased Window Size - Air change rates



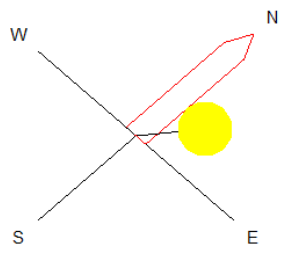
The air change rate is higher for the increased window case than the base case, as expected due to an increase in ventilation. While the difference in air change rate between the cases is notable, the difference in temperatures is much less so.

It is important to note that our models do not account for wind/wind speeds so the improvement in air change shown is conservative.

It is likely that, on a breezy day the increased window size would be more effective at cooling the space and increasing air change rate.

Figure 20: Air change rate for base case and increased window cases at 3pm in May.

Orientation



Building Orientation – 9.30am

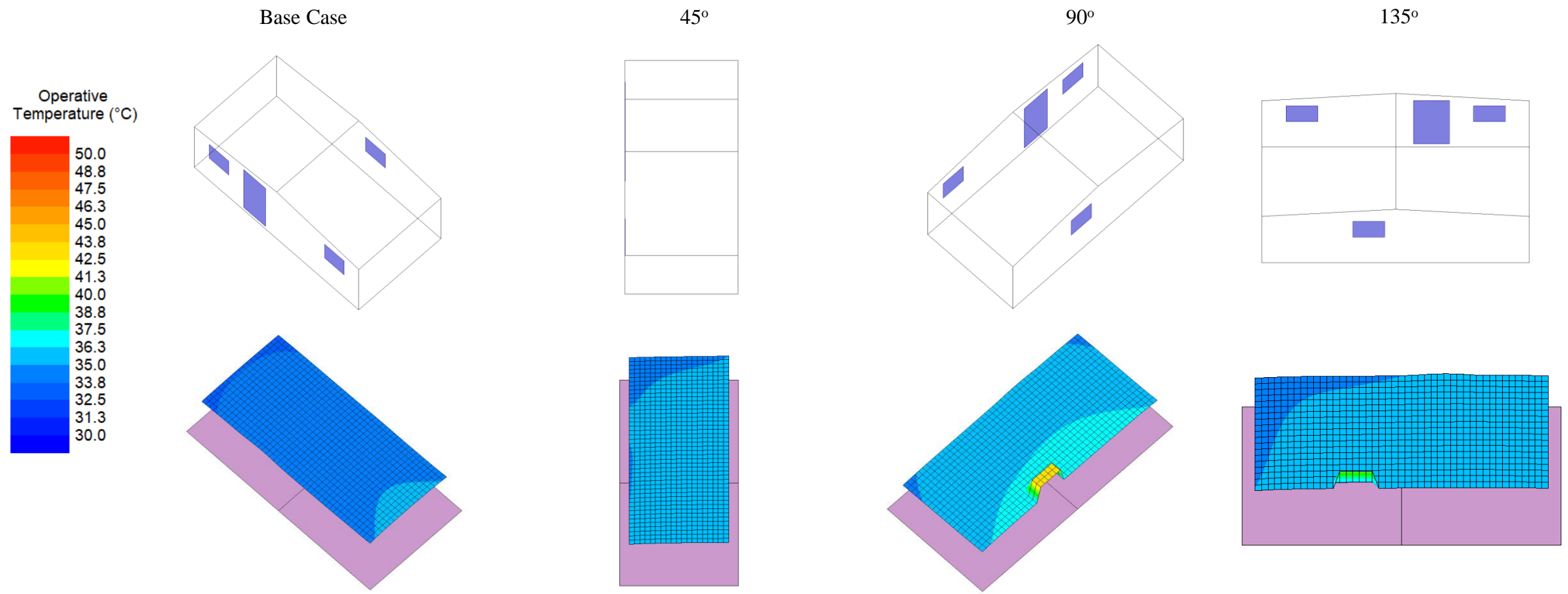
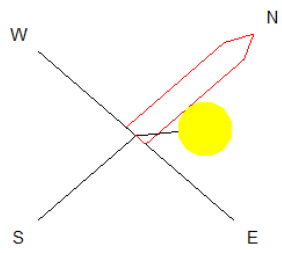


Figure 21a: Spatial operative temperatures for 9.30am in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 27.3°C.



Building Orientation – 9.30am

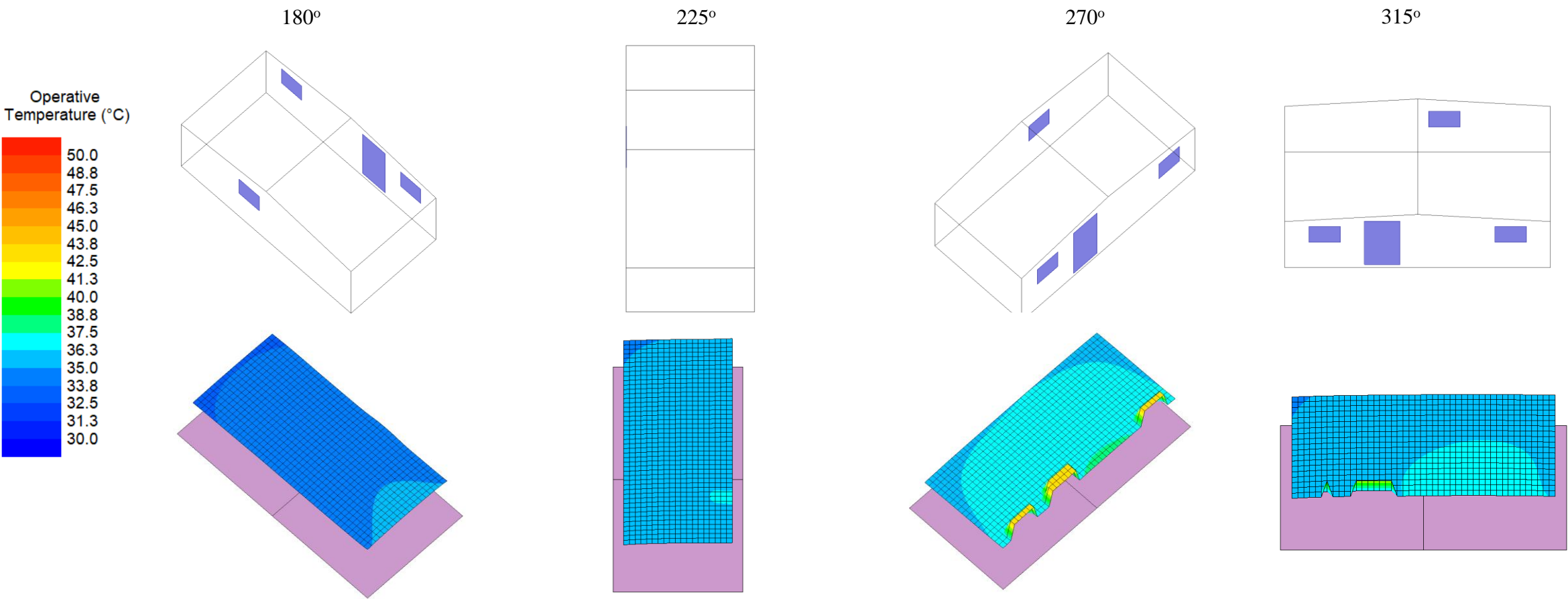
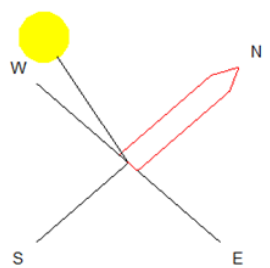


Figure 21b: Spatial operative temperatures for 9.30am in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 27.3°C.



Building Orientation – 4.30pm

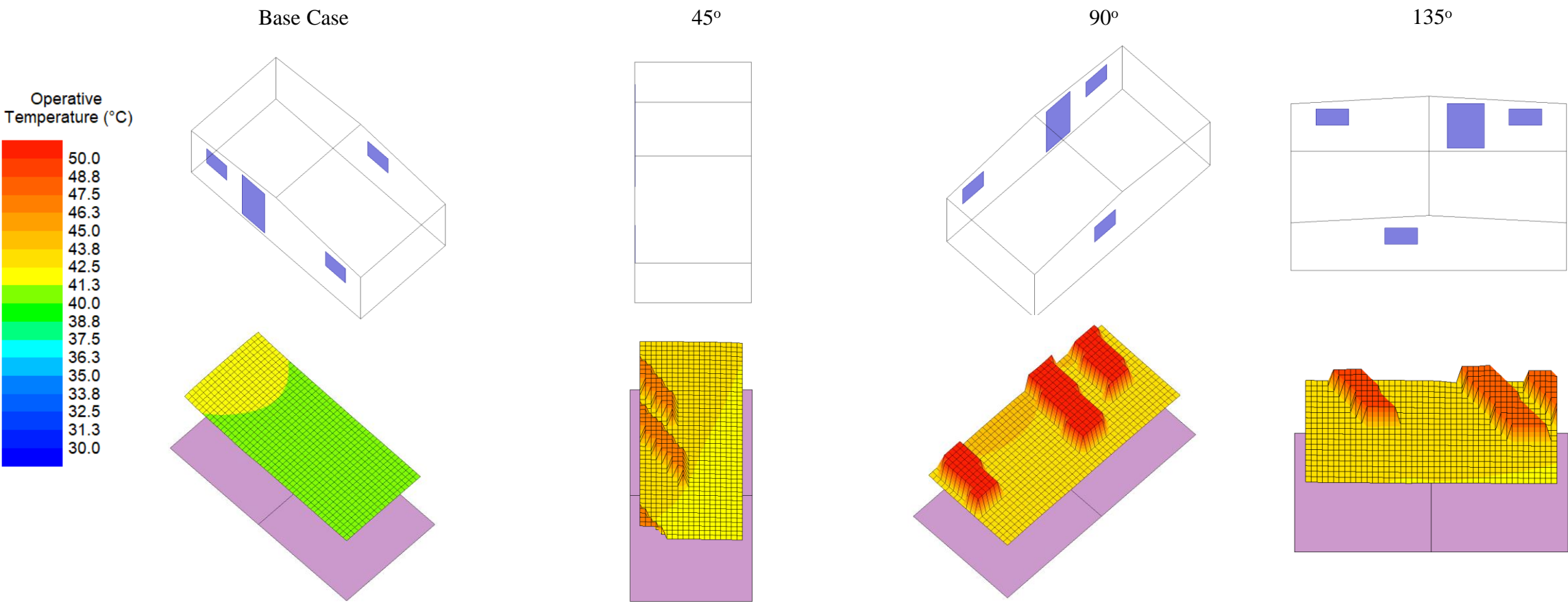
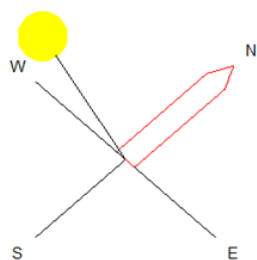


Figure 22a: Spatial operative temperatures for 4.30pm in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 37.4°C.



Building Orientation – 4.30pm

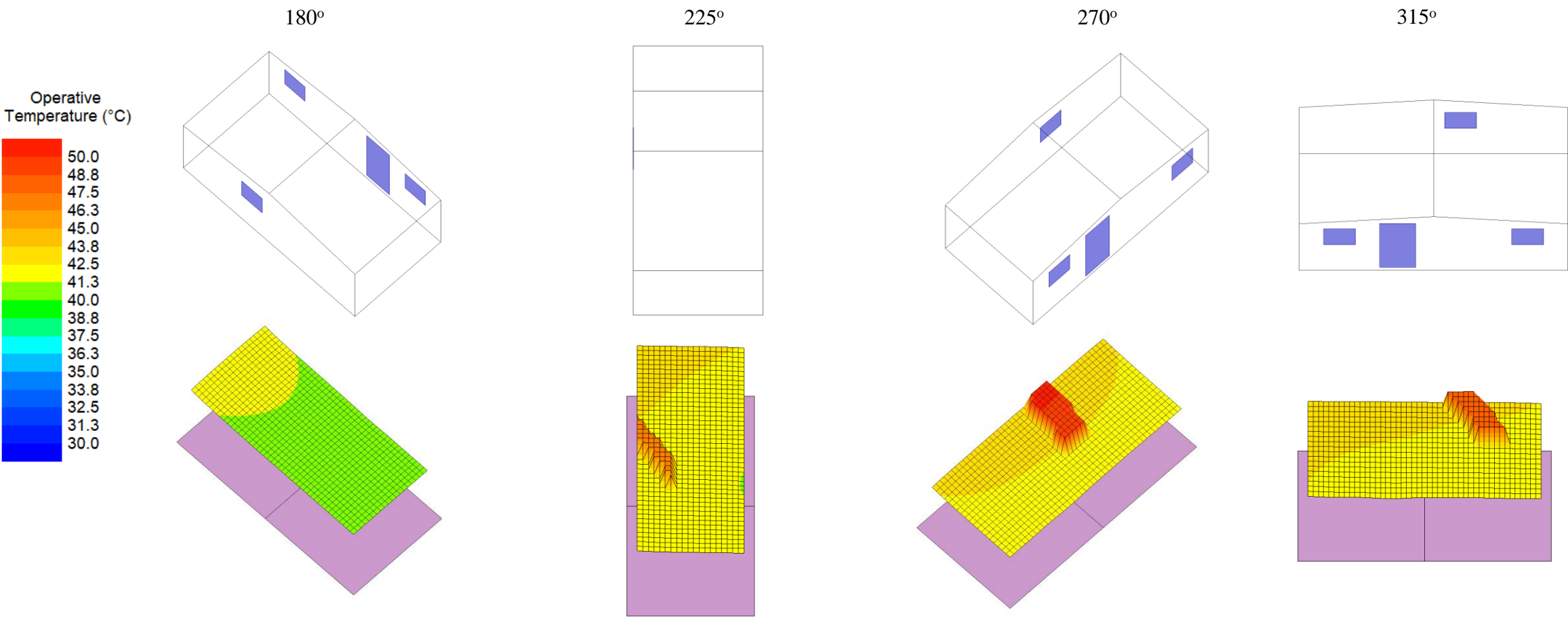


Figure 22b: Spatial operative temperatures for 4.30pm in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 37.4°C.

Building Orientation

The base case in Figure 21a, 22a shows lower temperatures than the other orientations at both 9.30am and 4.30pm. This is because there are no windows facing east or west during the day, to let in sunlight and cause higher solar gain.

Looking at the 90° case in Figure 22a, it is clear that the heat spikes inside the building are due to the window positioning which allows high solar gain at the hottest part of the day. This is further demonstrated in Figure 23, where the base case consistently has the lowest temperatures, while the 90° case has the highest temperatures.

The results of examining building orientation on temperature highlight the effectiveness of interventions that reduce solar gains. Using blinds would also improve internal temperatures by reducing solar gains, regardless of building orientation.

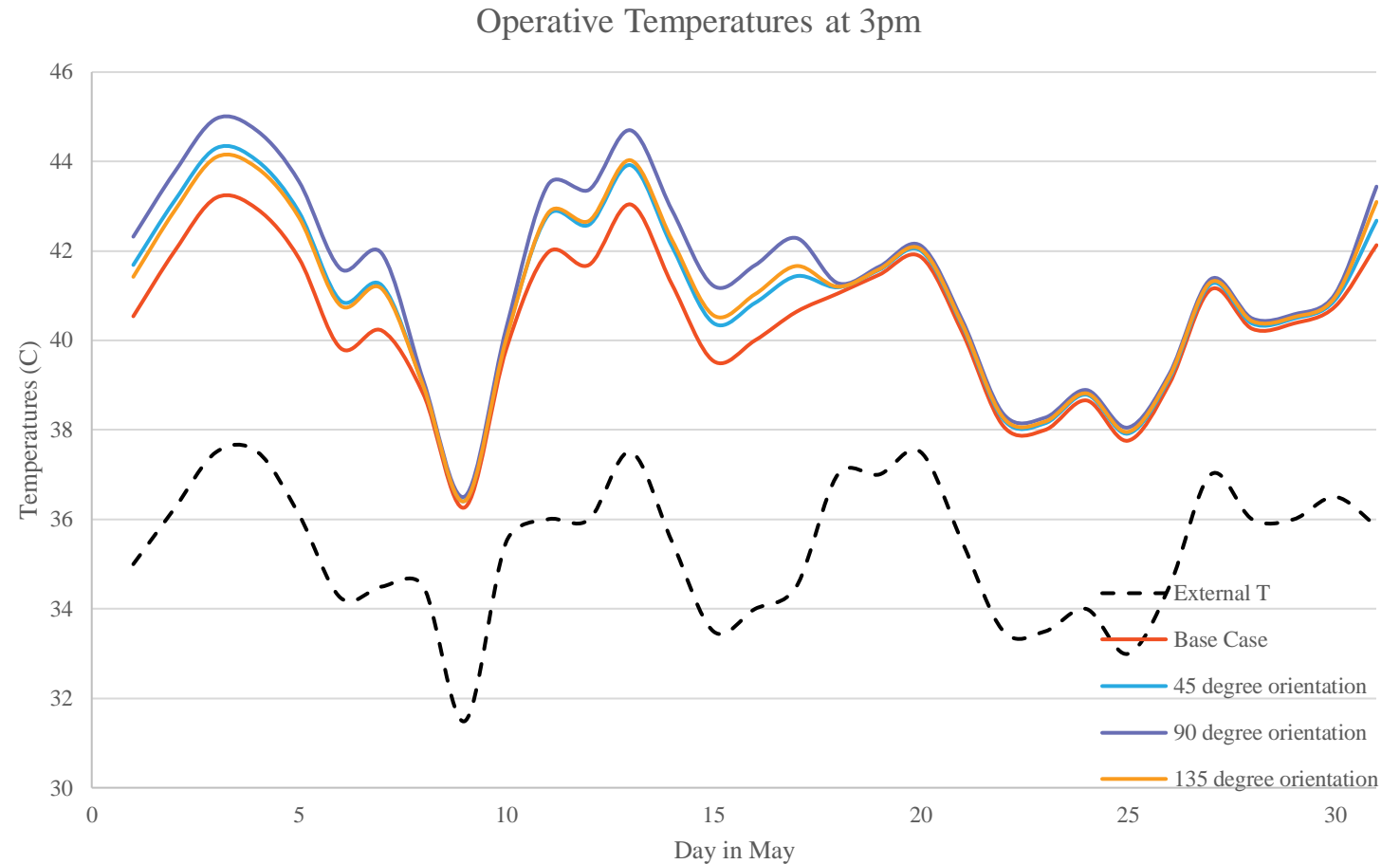


Figure 23: Internal operative temperatures for 3pm in May, comparing different building orientations.

Steeper Roof & Flat Roof

Roof Pitch

For the base case, the roof is orientated parallel to the path of the sun during the day, with the windows perpendicular to the sun. This means that changing the roof pitch has little effect on the roof temperatures and therefore the internal temperatures as the sun is heating the roof all day regardless of pitch.

Later, we will investigate the impact of roof pitch on the building oriented perpendicular to the path of the sun.

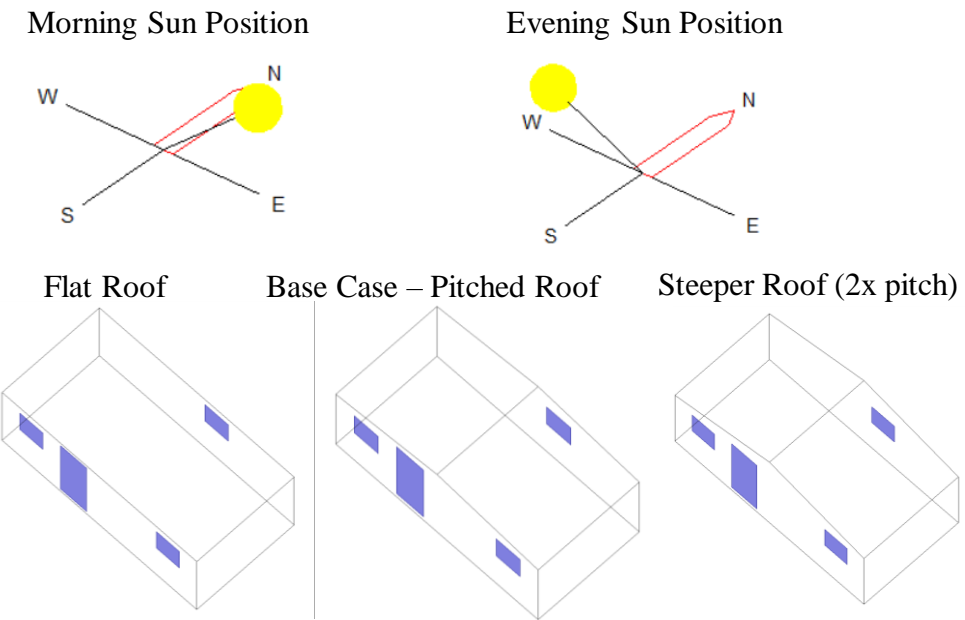


Figure 24: Models of flat roof, base case and steeper roof.

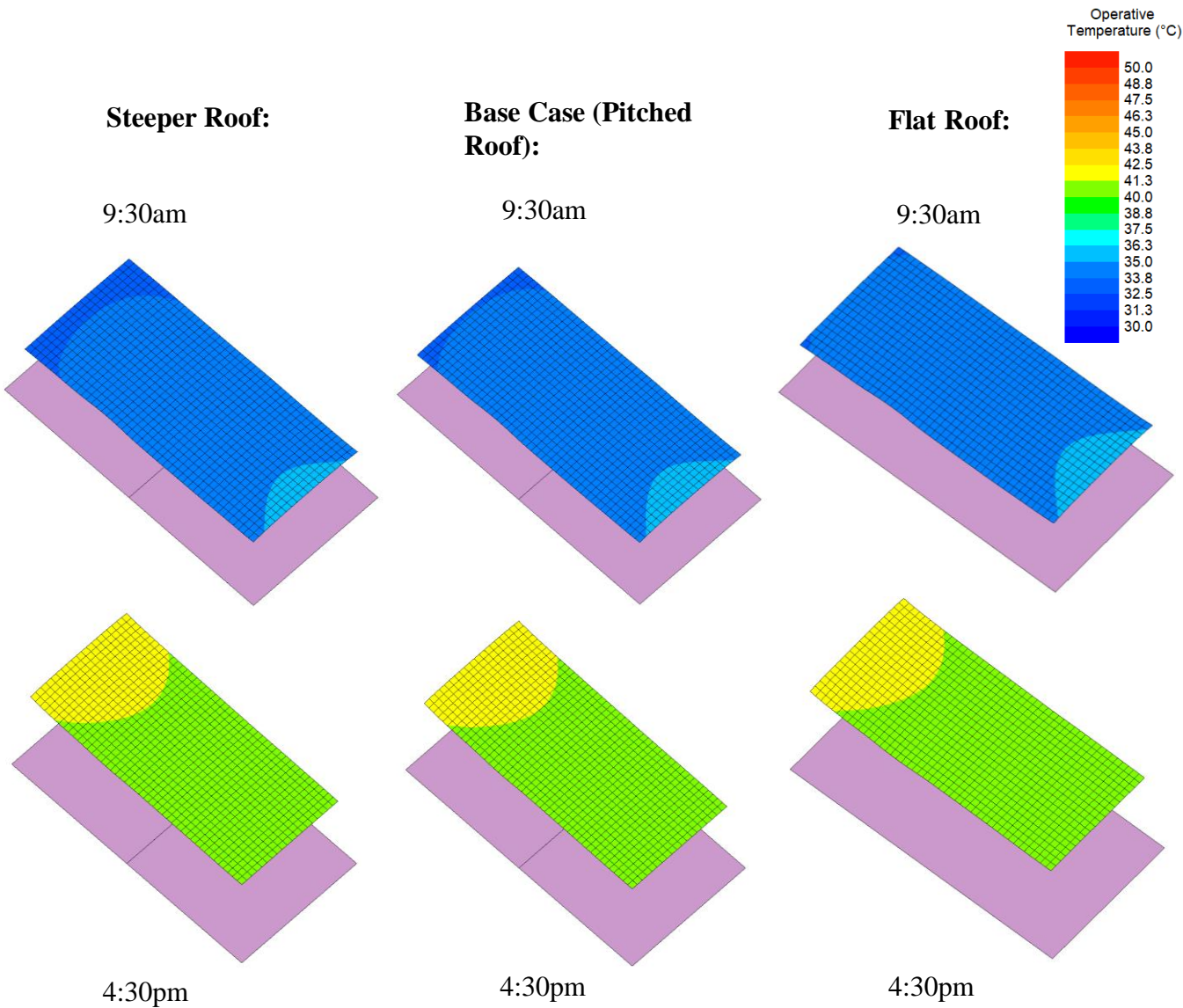
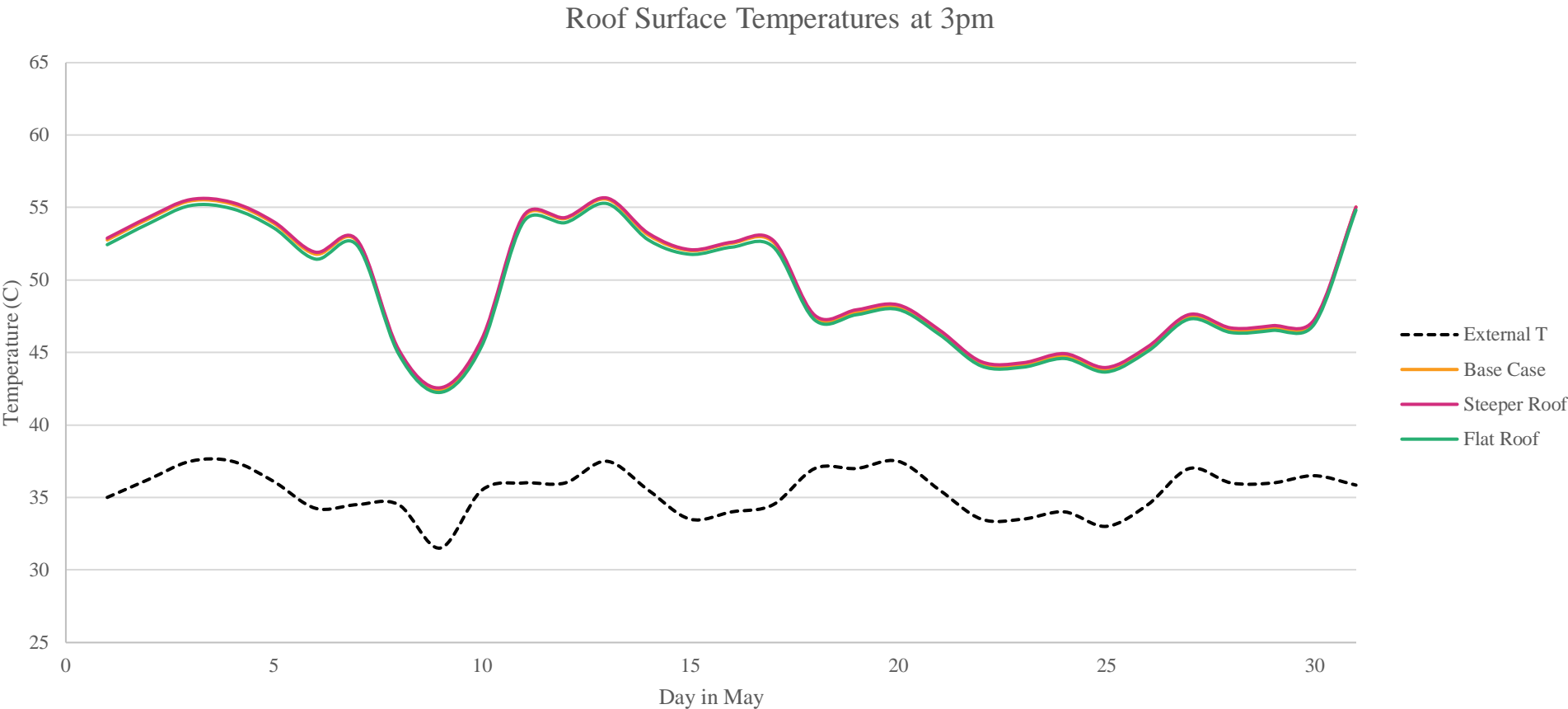


Figure 25: Spatial operative temperatures for 9:30am and 4:30pm in May.

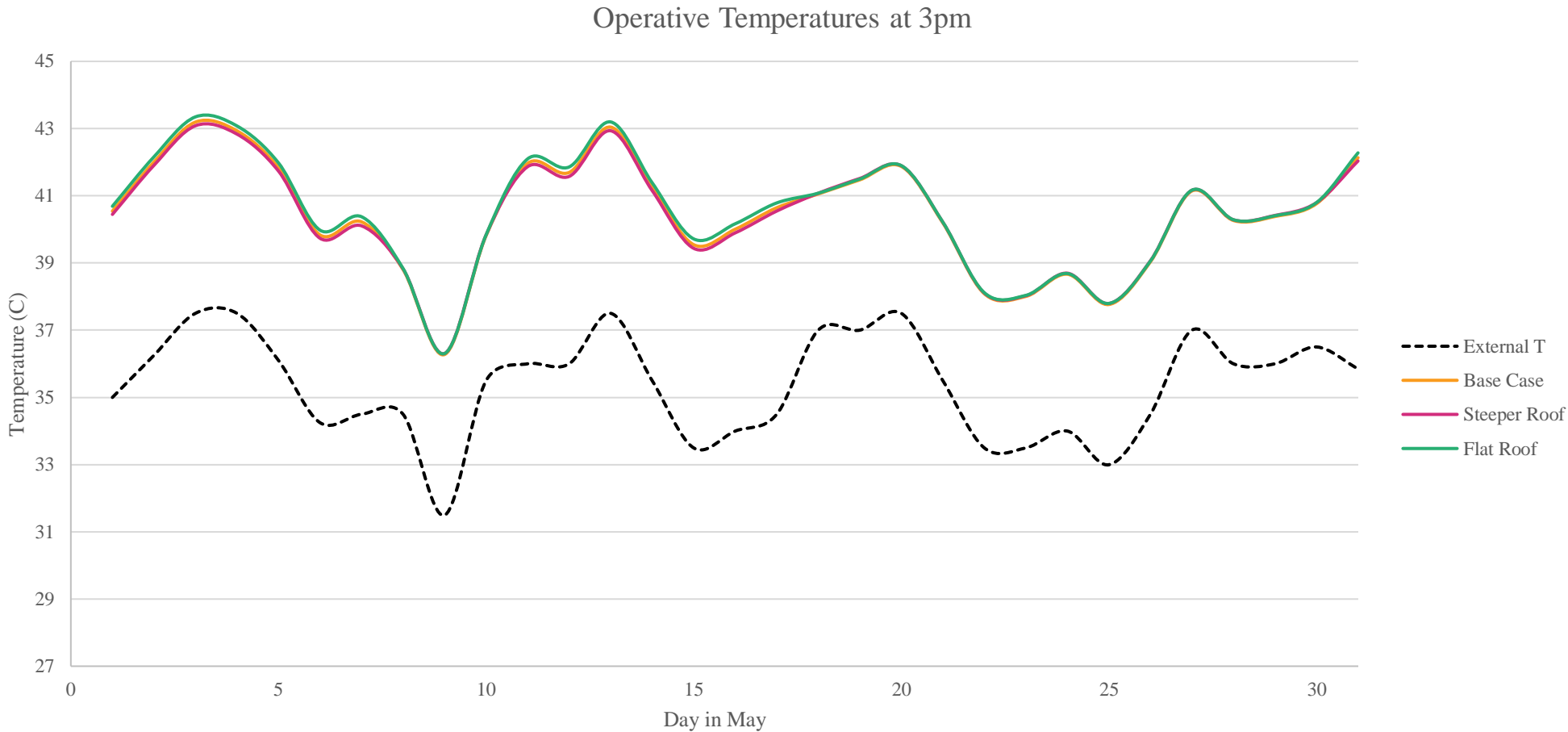
Roof Pitch – Roof Surface Temperatures



Due to the buildings in all cases being oriented with roofs parallel to the path of the sun during the day, the roof pitch has little impact on the roof surface temperature.

Figure 26: Roof surface temperatures for 3pm in May, comparing the flat roof, steeper roof and base cases.

Roof Pitch – Internal Operative Temperatures

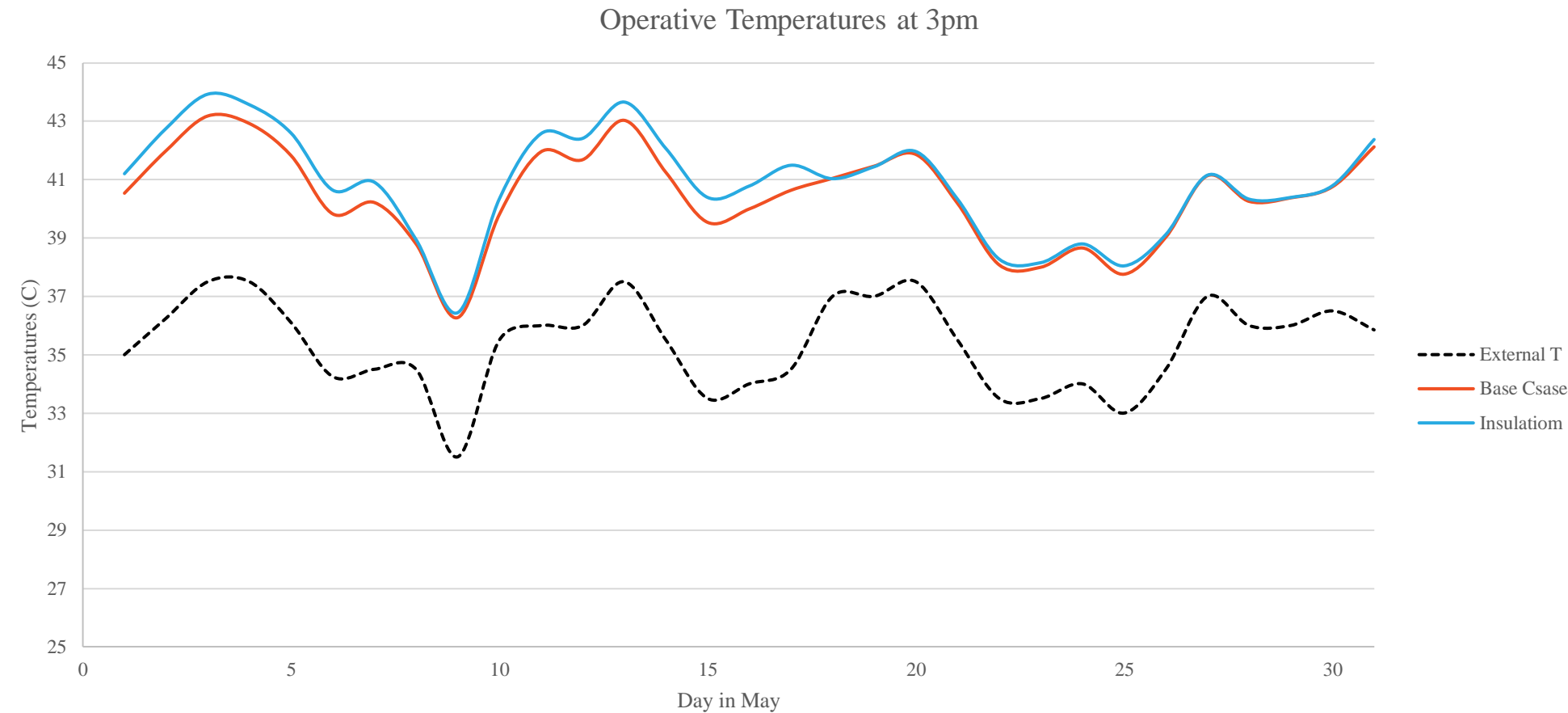


Internal temperatures are similar regardless of roof pitch as roof pitch has little effect on roof surface temperature.

Figure 27: Internal operative temperatures for 3pm in May, comparing the flat roof, steeper roof and base cases.

Insulation

Insulation – Internal Operative Temperatures



Insulation prevents heat loss from the internal space causing slightly higher internal temperatures, as expected.

Figure 28: Internal operative temperatures for 3pm in May, comparing the insulation strategy against the base case.

Steel Sheet Roofing

Steel Sheet Roofing – Internal Operative Temperatures

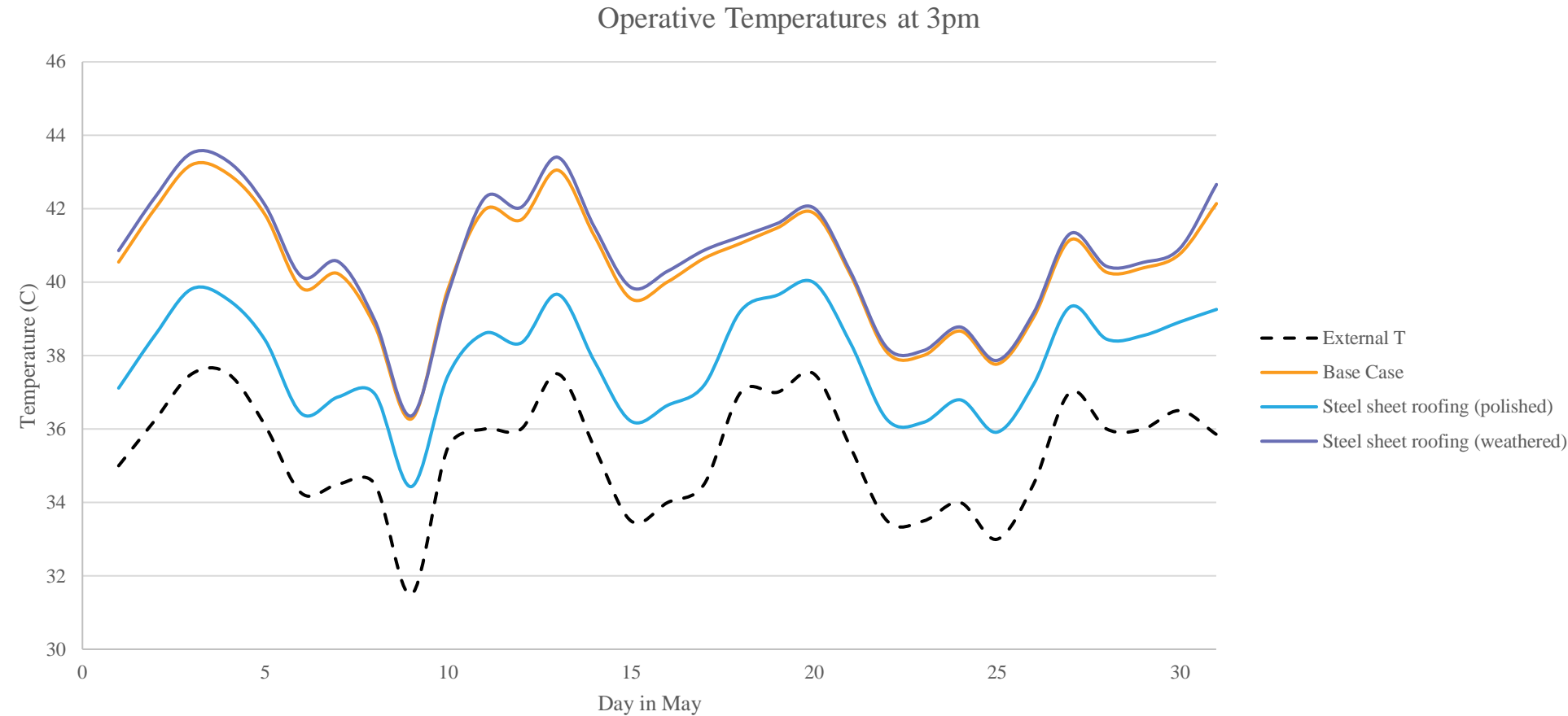


Figure 29: Internal operative temperatures for 3pm in May, comparing the roof materials.

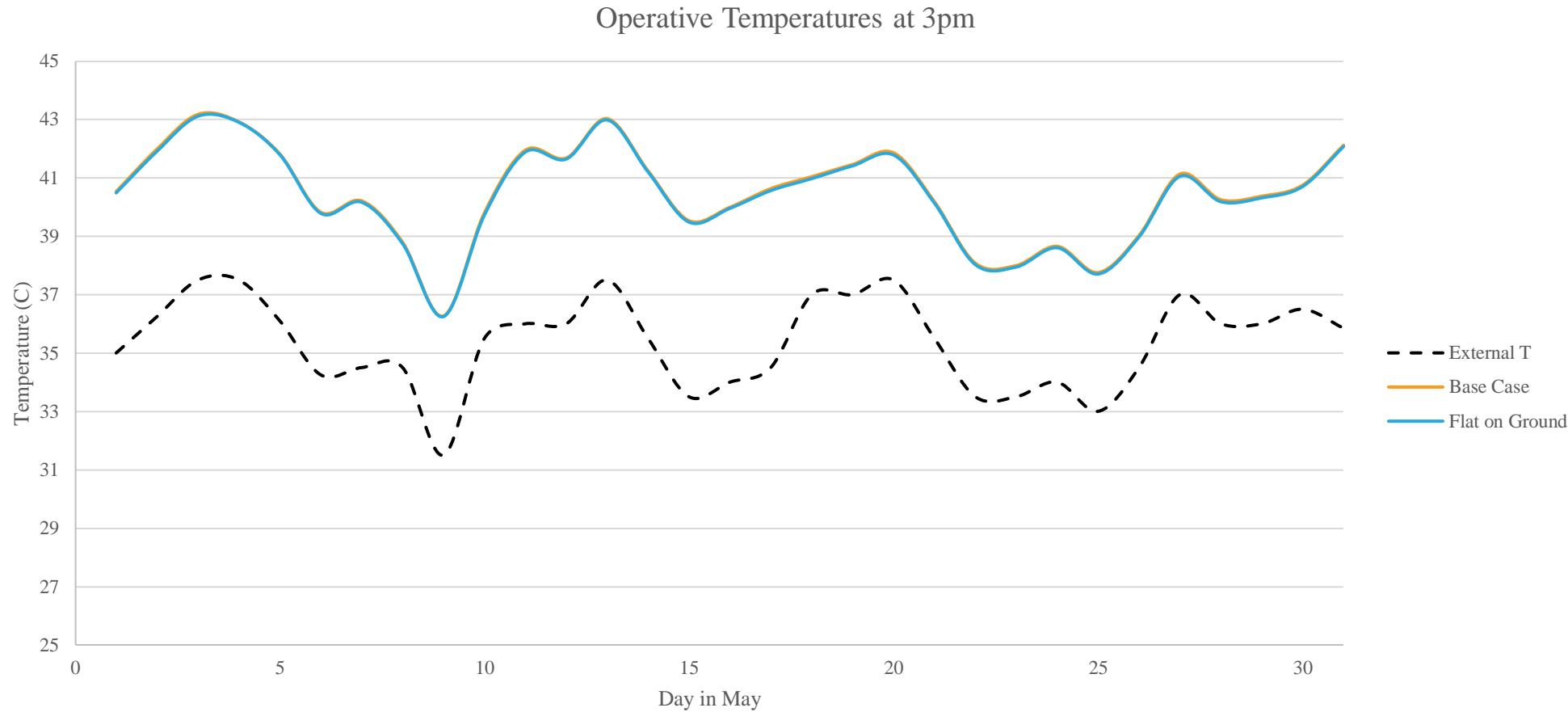
The base case is made up of fibre cement boards with an albedo of 0.27, while the steel sheet roofing has albedos of: 0.25 for weathered and 0.8 for polished.

The weathered steel roof has higher thermal conductivity than the base case roof which gives higher roof surface temperatures and therefore higher internal temperatures. While the polished has a much higher albedo than the other cases causing more sunlight to be reflected away from the roof, reducing roof temperatures and thus internal temperatures.

The weathered steel more closely represents a steel sheet roofing than the polished steel.

Flat on Ground

Flat on Ground – Internal Operative Temperatures



Moving building to be flat on the ground, rather than elevated on stilts (as in the base case) should increase temperatures due to lack of ventilation underneath the building. The ventilation would carry cooler external air underneath the building reducing the temperature.

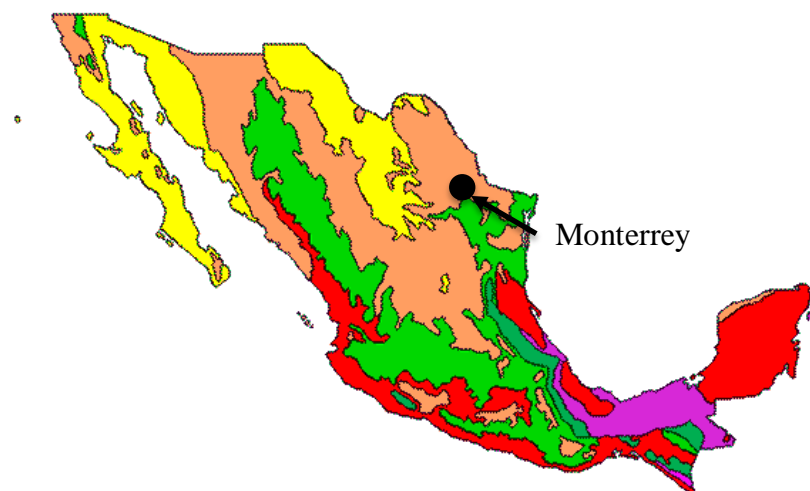
However, possibly due to no wind being modelled, the two cases have little to no difference in internal temperature.

Figure 30: Internal operative temperatures for 3pm in May, comparing the flat on ground strategy against the base case.

Mérida Summary

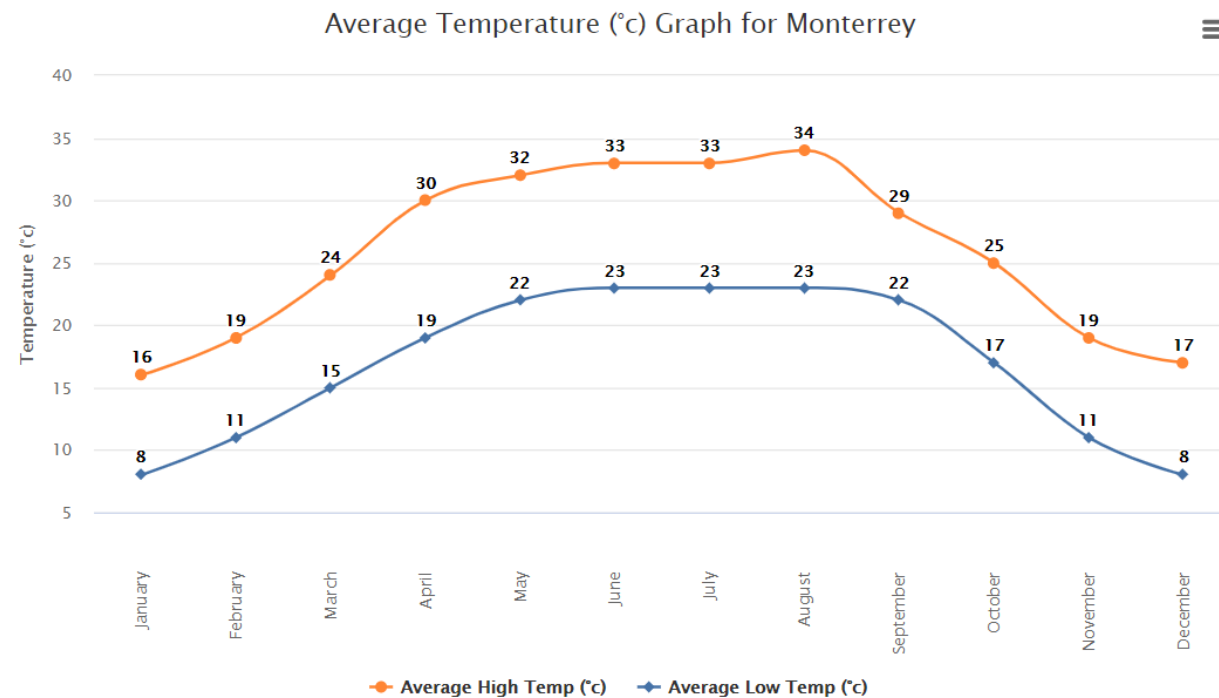
The most effective strategy for Mérida is the reflective roof, where a higher albedo gives a greater cooling effect. Limited improvement was seen for the polished steel roof material, increased window size and steeper roof.

Monterrey Summer



Semi-arid climate (BSh)

Monthly Average Temperature



Monterrey Average values (difference from base for June)

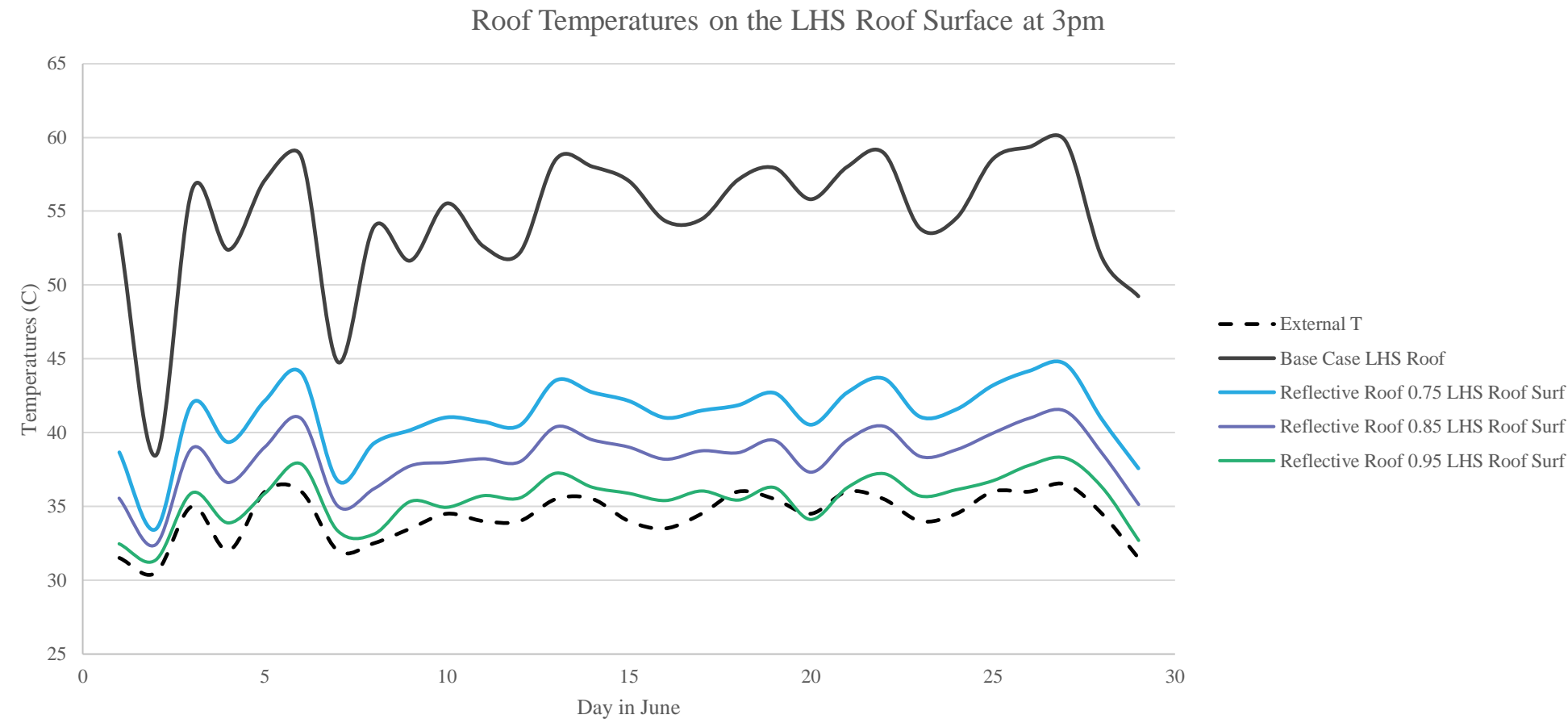
Average difference from base across June									
	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp	
	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left side	Right Side
	(°C)	(°C)	-		%	%	/hr	(°C)	(°C)
Base									
Reflective Roof (0.75)	-0.64	-1.12	-0.33	-1.30	1.57	1.57	-2.04	-4.63	-4.63
Reflective Roof (0.85)	-0.78	-1.37	-0.40	-1.58	1.95	1.95	-2.62	-5.60	-5.59
Reflective Roof (0.95)	-0.94	-1.62	-0.47	-1.87	2.37	2.37	-3.31	-6.57	-6.56
Larger Window	-0.06	-0.04	-0.01	-0.03	0.16	0.16	0.68	0.00	0.00
Orientation +45°	0.17	0.32	0.09	0.37	-0.44	-0.44	0.41	0.16	0.06
Orientation +90°	0.27	0.55	0.16	0.63	-0.66	-0.66	0.63	0.27	0.12
Orientation +135°	0.18	0.35	0.10	0.42	-0.41	-0.41	0.43	0.19	0.07
Orientation +180°	0.01	0.02	0.01	0.02	-0.03	-0.03	0.02	0.02	0.00
Orientation +225°	0.17	0.34	0.10	0.39	-0.48	-0.48	0.44	0.08	0.17
Orientation +270°	0.25	0.53	0.15	0.61	-0.66	-0.66	0.63	0.12	0.25
Orientation +315°	0.16	0.31	0.09	0.37	-0.37	-0.37	0.41	0.06	0.16
Flat Roof	0.01	0.04	0.01	0.05	-0.02	-0.02	0.40	-0.11	
Steeper Roof	0.02	-0.02	-0.01	-0.04	-0.07	-0.07	-0.65	0.08	0.06
Insulation	0.27	0.34	0.10	0.32	-0.83	-0.83	0.06	0.11	0.11
Steel sheet roofing (polished)	-0.70	-1.23	-0.36	-1.41	1.75	1.75	-2.25	-5.03	-5.03
Steel sheet roofing (weathered)	0.06	0.13	0.04	0.15	-0.13	-0.13	0.20	0.25	0.24
Flat on Ground	0.01	0.01	0.00	-0.01	-0.12	-0.12	0.00	0.00	0.00

Monterrey Average values (absolute averages over all hours in June)

Absolute Values											
	External	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp		Tdiff
	Tdry	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left Side	Right Side	
	(°C)	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)	(°C)
Base	28.27	30.05	30.92	2.17	80.58	57.15	57.15	9.97	34.93	34.93	
Reflective Roof (0.75)	28.27	29.41	29.80	1.85	79.28	58.72	58.72	7.93	30.30	30.30	-1.12
Reflective Roof (0.85)	28.27	29.26	29.55	1.78	79.00	59.11	59.11	7.35	29.33	29.34	-1.37
Reflective Roof (0.95)	28.27	29.10	29.30	1.71	78.71	59.52	59.52	6.66	28.36	28.37	-1.62
Larger Window	28.27	29.98	30.88	2.16	80.55	57.31	57.31	10.64	34.92	34.93	-0.04
Orientation +45°	28.27	30.21	31.24	2.27	80.94	56.71	56.71	10.37	35.09	34.99	0.32
Orientation +90°	28.27	30.31	31.46	2.33	81.21	56.49	56.49	10.60	35.20	35.05	0.55
Orientation +135°	28.27	30.22	31.27	2.28	80.99	56.74	56.74	10.40	35.12	35.00	0.35
Orientation +180°	28.27	30.06	30.94	2.18	80.60	57.12	57.12	9.99	34.95	34.93	0.02
Orientation +225°	28.27	30.22	31.26	2.27	80.97	56.68	56.68	10.40	35.01	35.10	0.34
Orientation +270°	28.27	30.30	31.45	2.33	81.19	56.50	56.50	10.60	35.05	35.18	0.53
Orientation +315°	28.27	30.20	31.23	2.27	80.94	56.78	56.78	10.37	34.99	35.09	0.31
Flat Roof	28.27	30.06	30.96	2.19	80.63	57.14	57.14	10.36	34.82		0.04
Steeper Roof	28.27	30.07	30.90	2.17	80.54	57.09	57.09	9.31	35.01	34.99	-0.02
Insulation	28.27	30.32	31.25	2.27	80.90	56.32	56.32	10.03	35.04	35.04	0.34
Steel sheet roofing (polished)	28.27	29.35	29.69	1.82	79.16	58.91	58.91	7.71	29.90	29.90	-1.22
Steel sheet roofing (weathered)	28.27	30.11	31.05	2.21	80.73	57.02	57.02	10.17	35.17	35.17	0.13
Flat on Ground	28.27	30.06	30.93	2.18	80.57	57.04	57.04	9.96	34.93	34.93	0.01

Reflective Roof

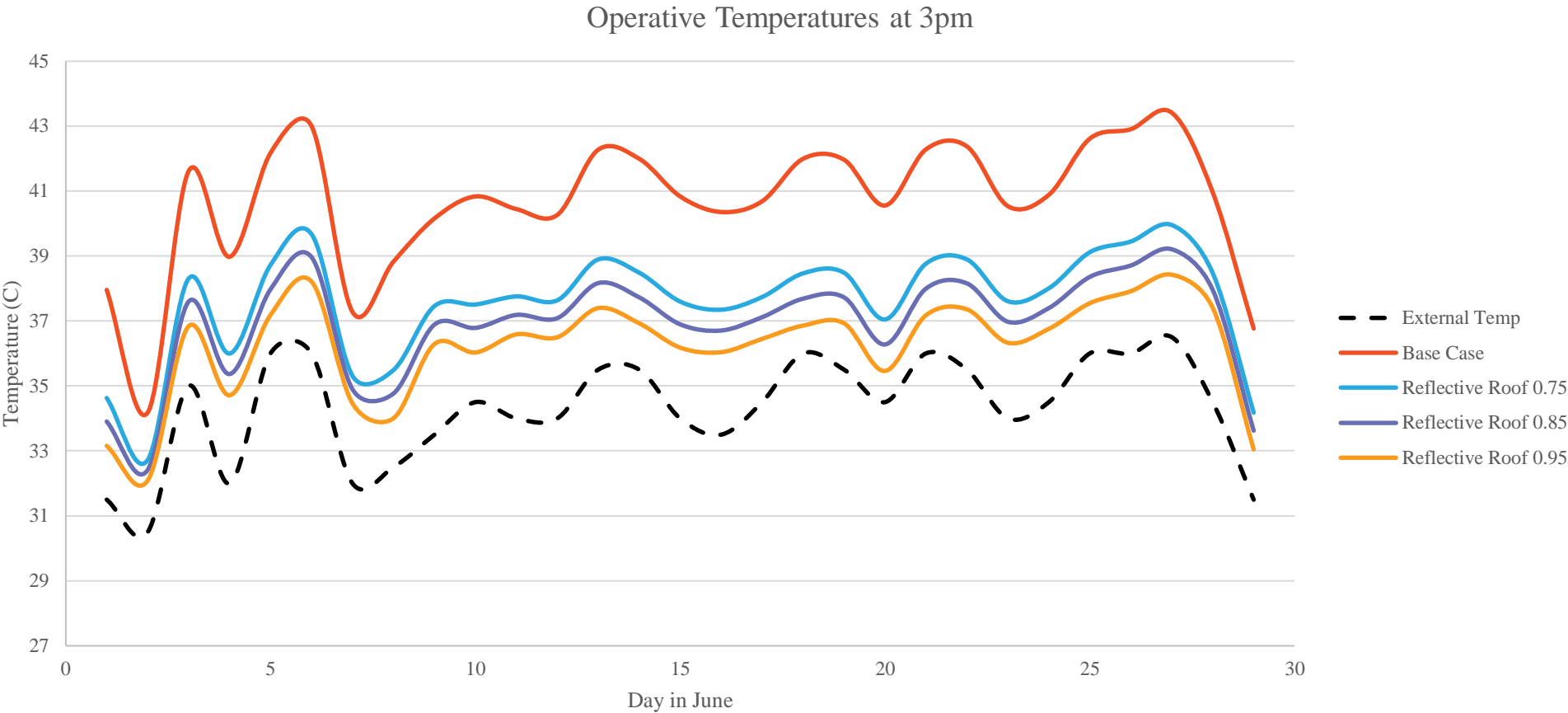
Reflective Roof – Roof Surface Temperatures



The base case has an albedo of 0.27. The painted roofs with higher albedo, reflect more sunlight than the base case, so less heat is absorbed by the roof. This reduces the roof surface temperature and in turn reduces the internal temperature of the house.

Figure 31: Roof surface temperatures for 3pm in May comparing the reflective roof strategies against the base case.

Reflective Roof – Internal Operative Temperatures

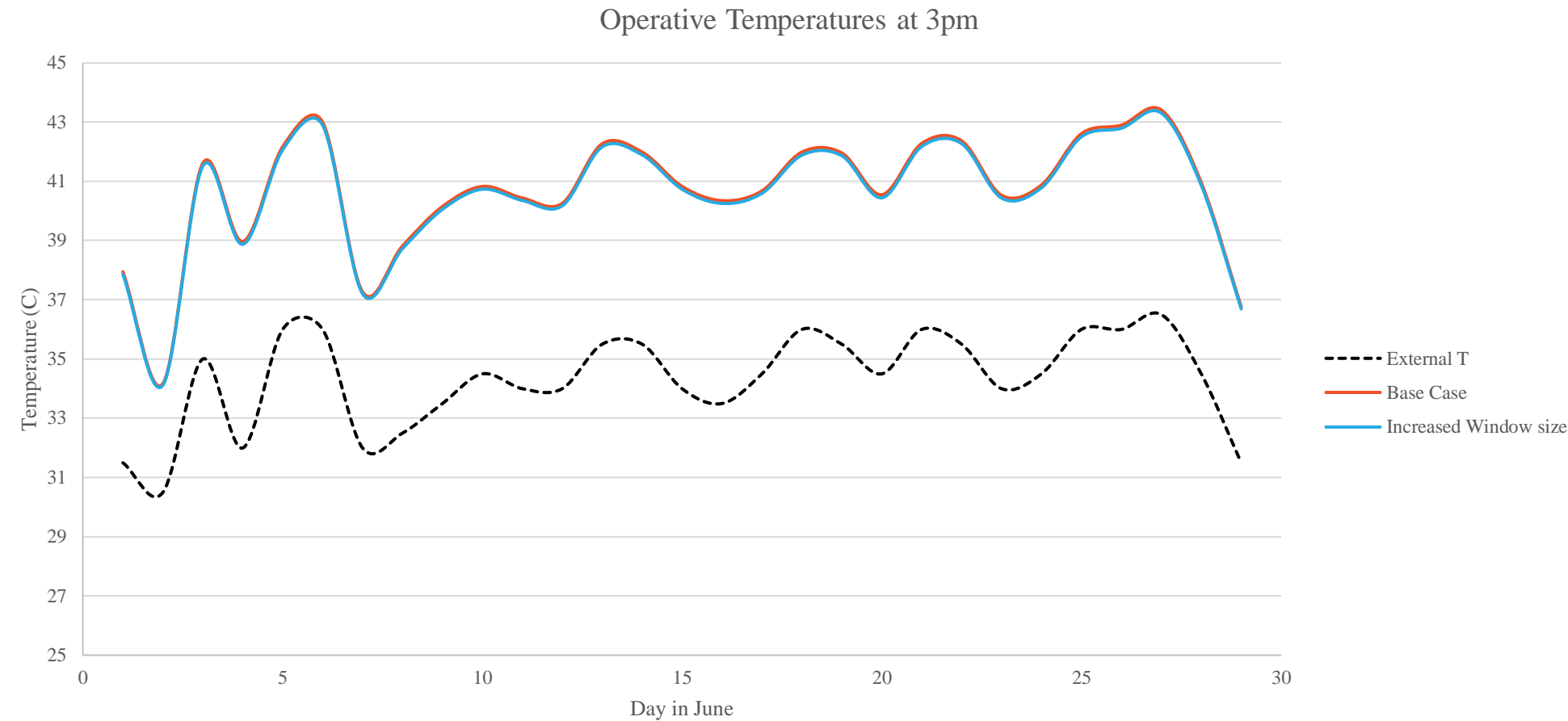


The reduction of the roof surface temperature due to the high albedo surfaces, reduces the internal temperature of the house.

Figure 32: Internal operative temperatures for 3pm in June, comparing the reflective roof strategies against the base case.

Increased Window Size

Increased Window Size – Internal Operative Temperatures

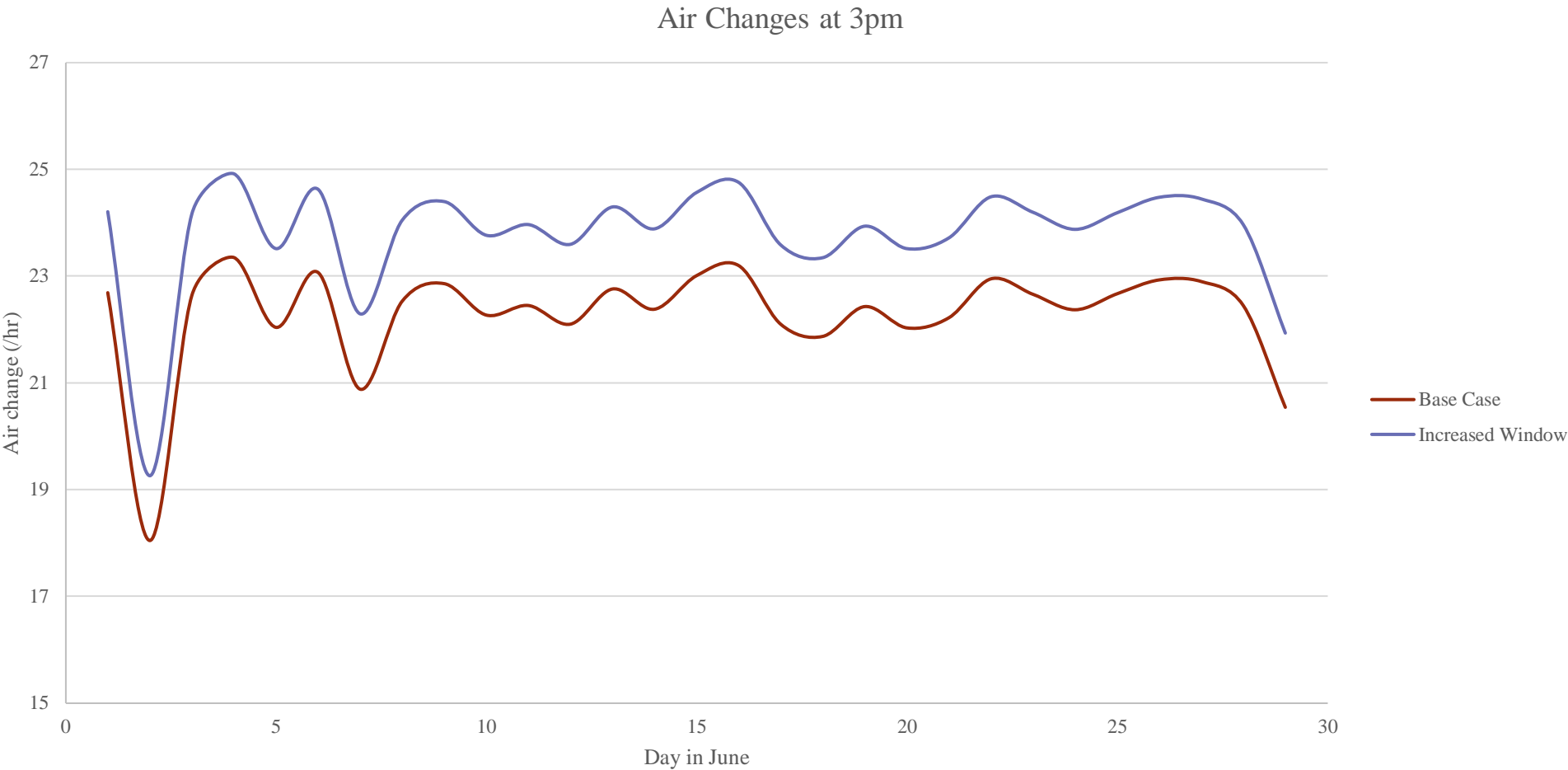


Increasing the window size gives a slightly cooler internal operative temperature due to an increase in ventilation. Since the external temperature is cooler than internal temperatures increasing the ventilation decreases the internal temperatures.

However, increased windows also allow greater solar gains into the room which can cause higher temperatures depending on time of day and building orientation.

Figure 33: Internal operative temperatures for 3pm in June, comparing the increased window strategy against the base case.

Increased Window Size - Air change rates



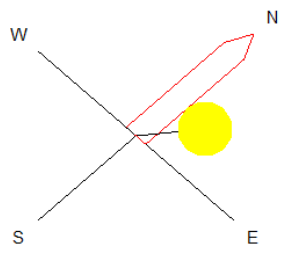
The air change rate is higher for the increased window case than the base case, as expected due to an increase in ventilation. While the difference in air change rate between the cases is notable, the difference in temperatures is much less so.

It is important to note that our models do not account for wind/wind speeds so the improvement in air change shown is conservative.

It is likely that, on a breezy day the increased window size would be more effective at cooling the space and increasing air change rate.

Figure 34: Air change rate for 3pm in June.

Orientation



Building Orientation – 9.30am

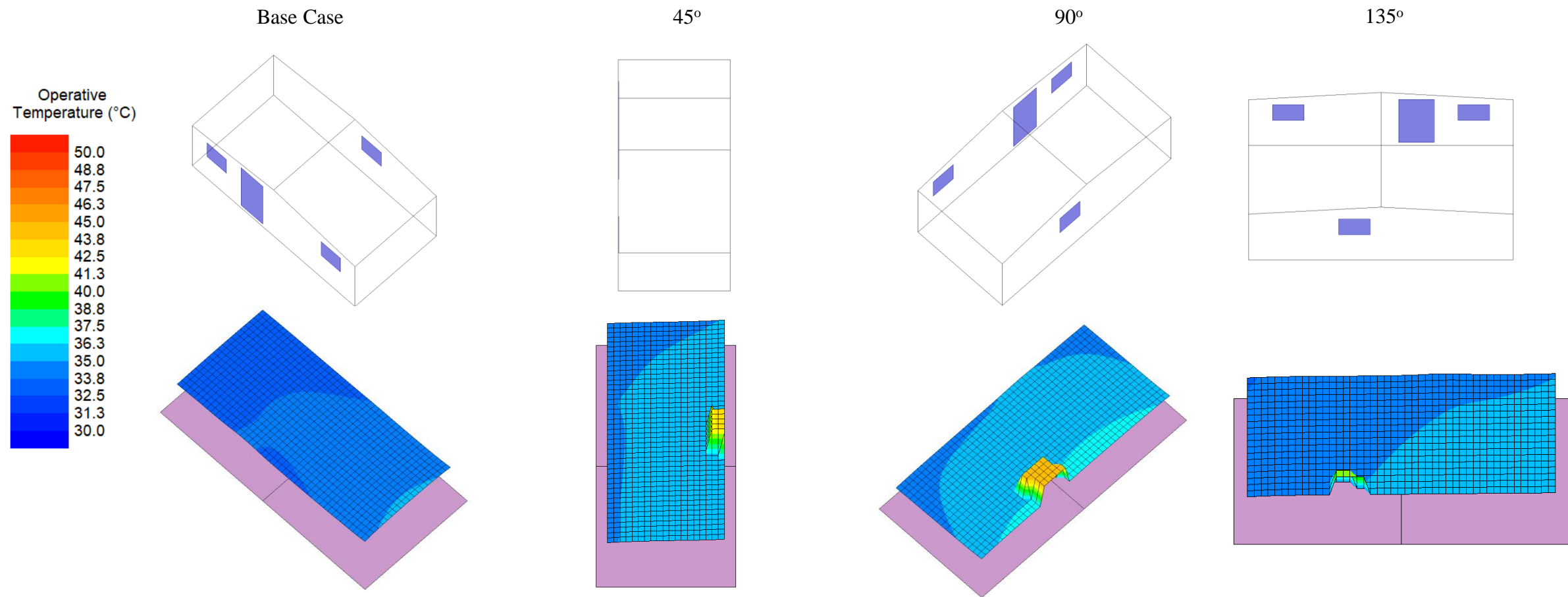


Figure 35a: Spatial operative temperatures for 9.30am in June for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 27.8°C.

Building Orientation – 4.30pm

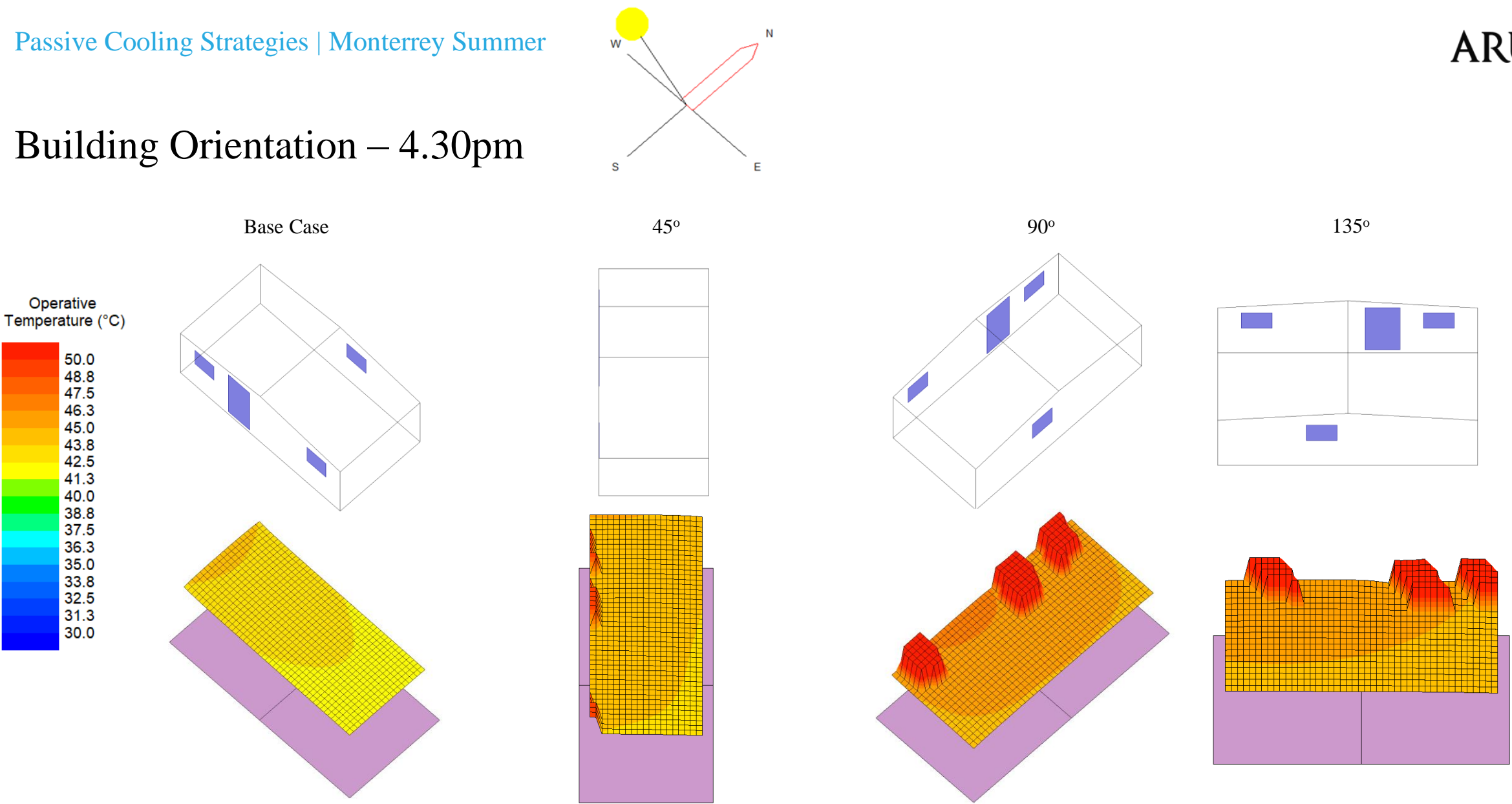
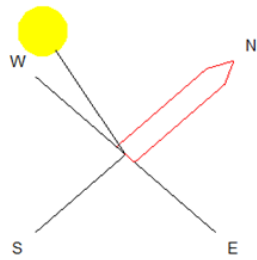


Figure 36a: Spatial operative temperatures for 4.30pm in June for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 37°C.



Building Orientation – 4.30pm

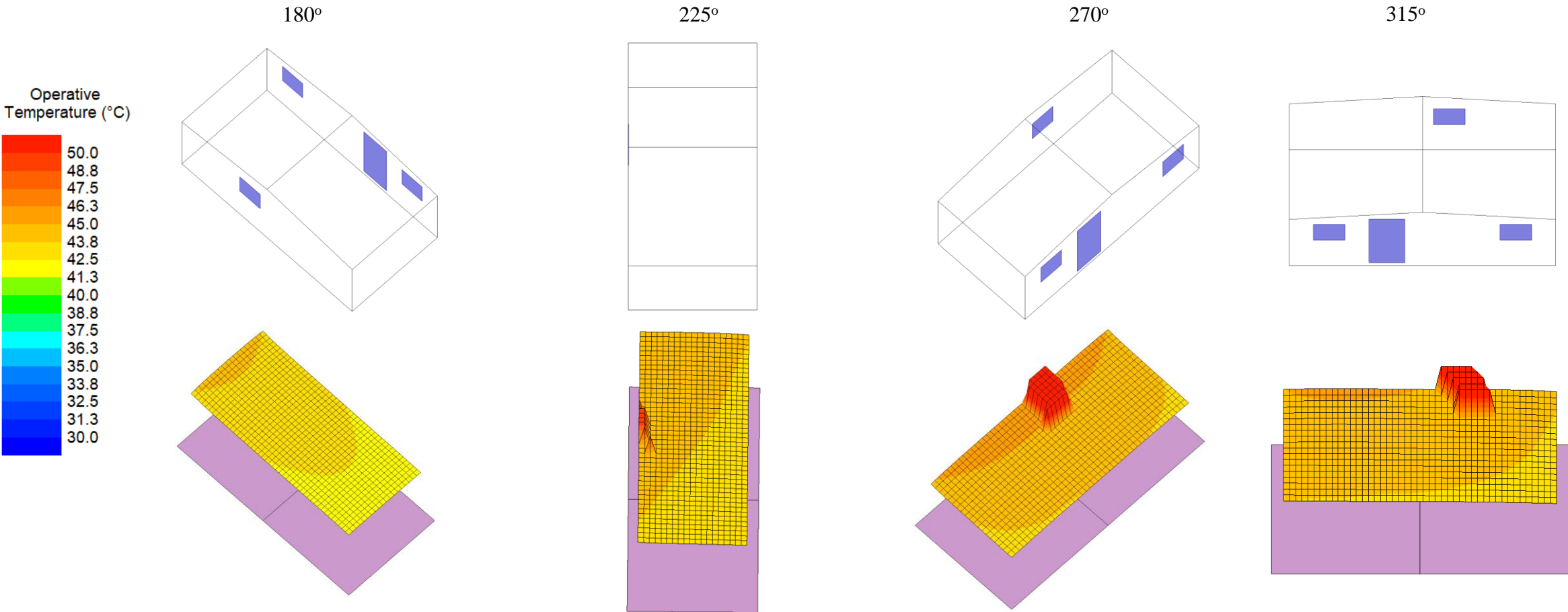


Figure 36b: Spatial operative temperatures for 4.30pm in June for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 37°C.

Building Orientation

The base case in Figure 35a, 36a shows lower temperatures than the other orientations at both 9.30am and 4.30pm. This is because there are no windows facing east or west during the day, to let in sunlight and cause higher solar gain.

Looking at the 90° case in Figure 36a, it is clear that the heat spikes inside the building are due to the window positioning which allows high solar gain at the hottest part of the day. This is further demonstrated in Figure 37, where the base case consistently has the lowest temperatures, while the 90° case has the highest temperatures.

The results of examining building orientation on temperature highlight the effectiveness of interventions that reduce solar gains. Using blinds would also improve internal temperatures by reducing solar gains, regardless of building orientation.

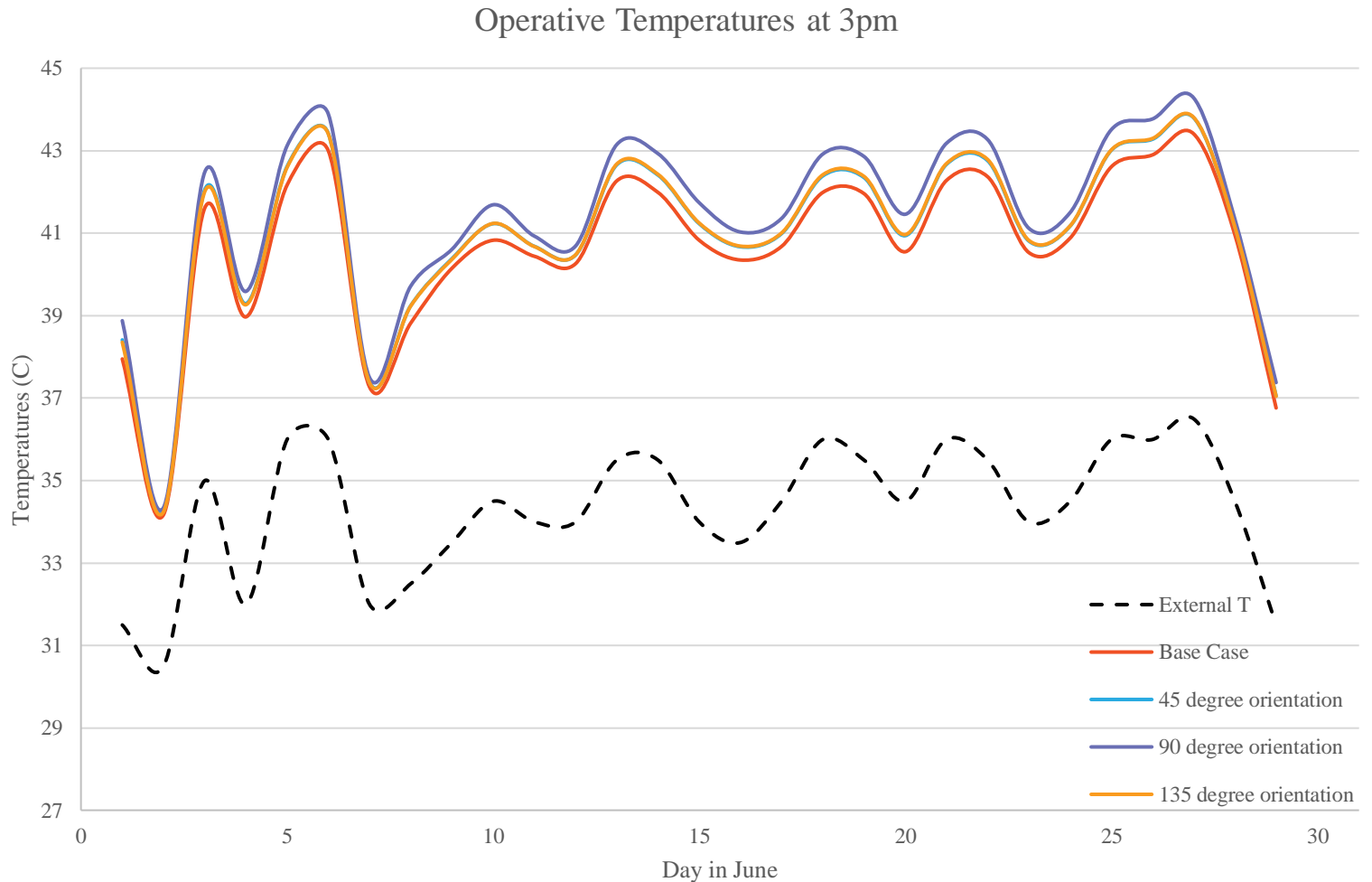


Figure 37: Internal operative temperatures for 3pm in June, comparing different orientations.

Steeper Roof & Flat Roof

Roof Pitch

For the base case, the roof is orientated parallel to the path of the sun during the day, with the windows perpendicular to the sun. This means that changing the roof pitch has little effect on the roof temperatures and therefore the internal temperatures as the sun is heating the roof all day regardless of pitch.

Later, we will investigate the impact of roof pitch on the building oriented perpendicular to the path of the sun.

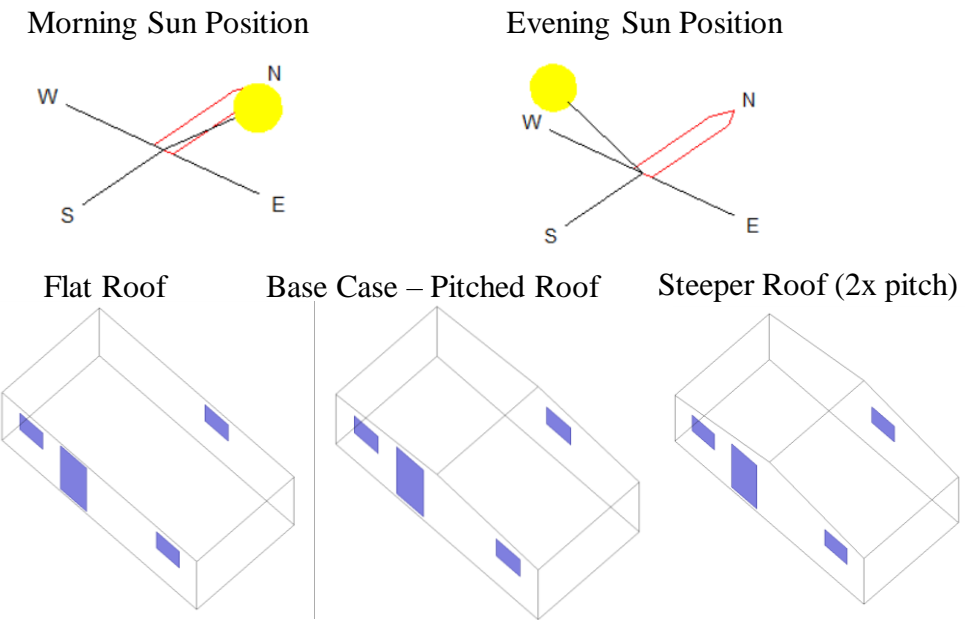


Figure 38: Models of flat roof, base case and steeper roof.

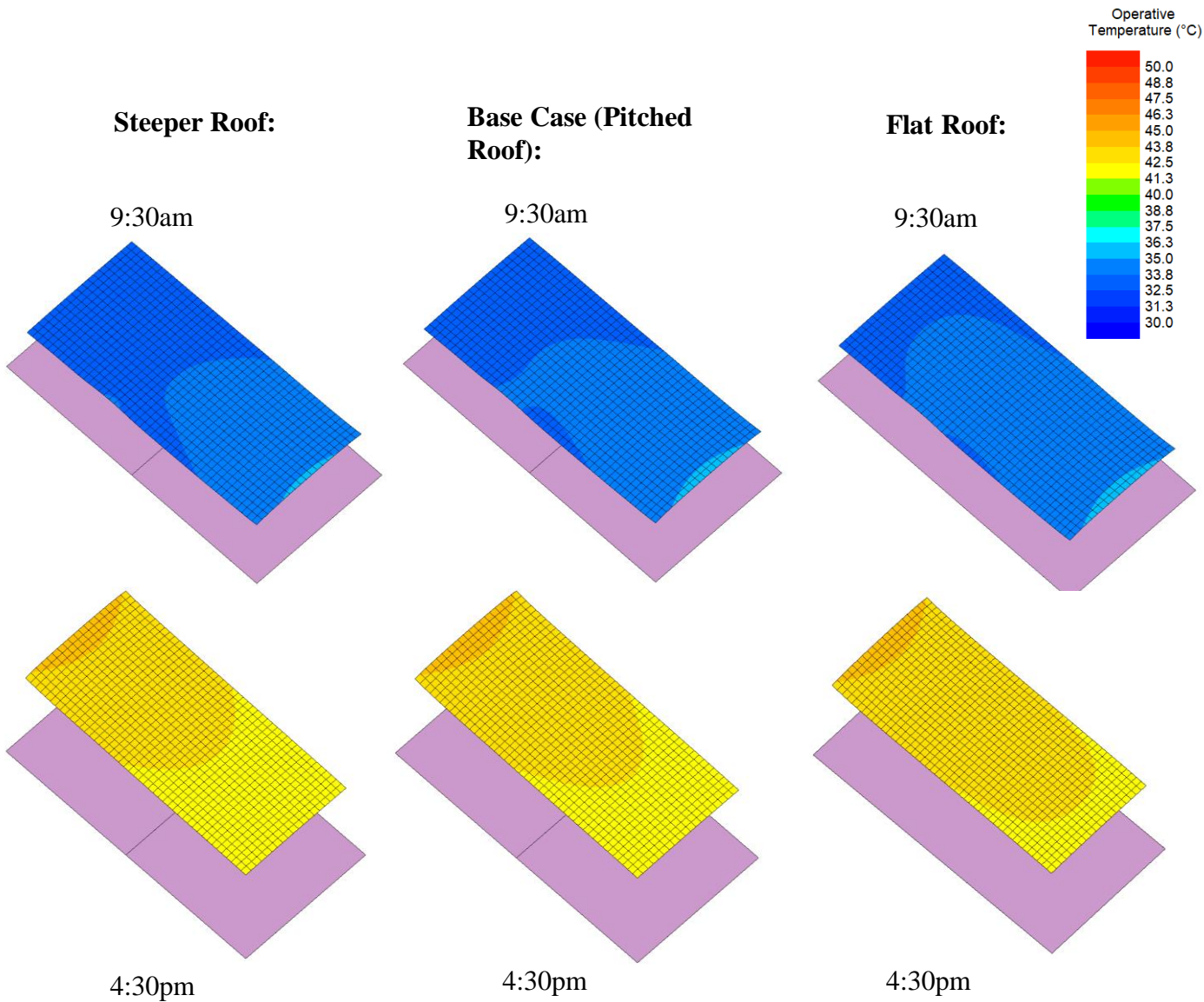
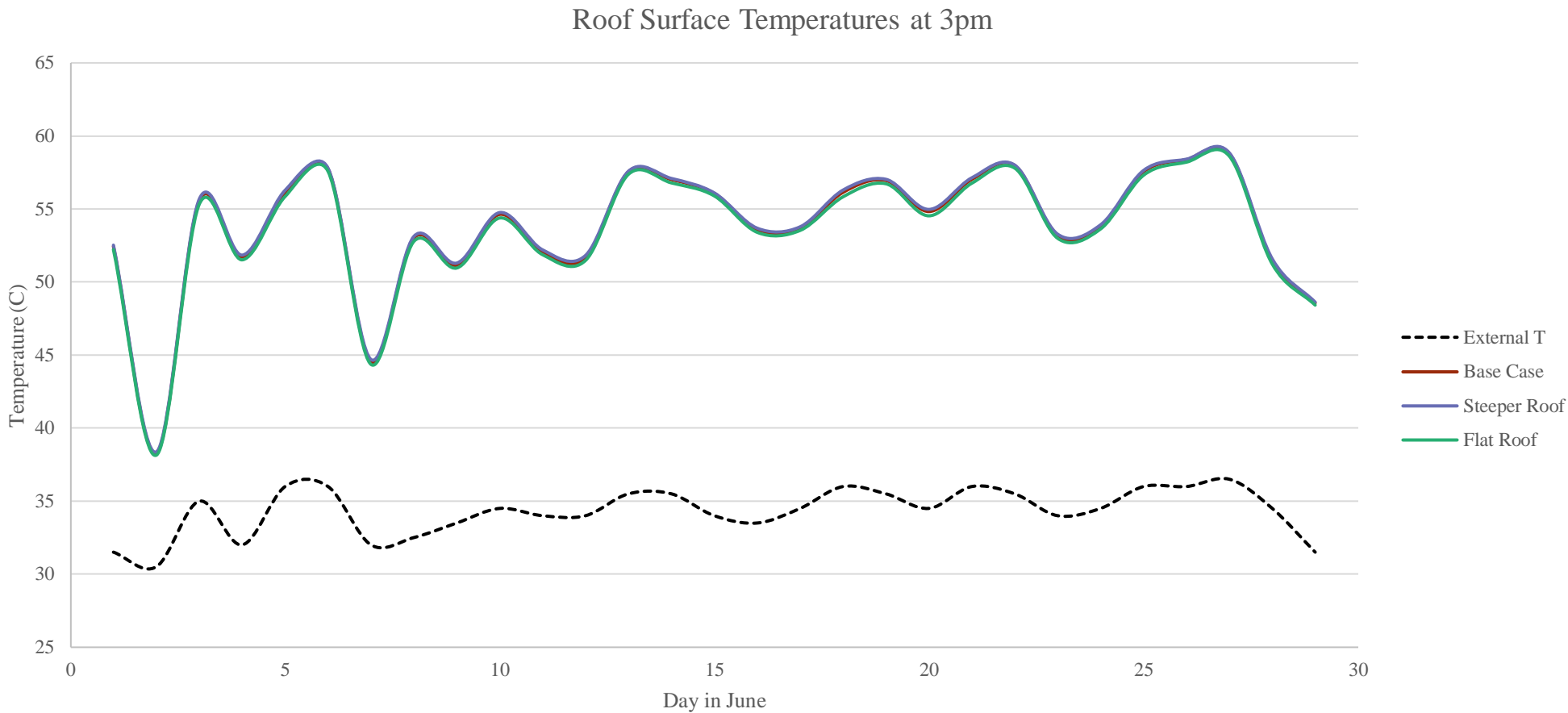


Figure 39: Spatial operative temperatures for 9:30am and 4:30pm in June.

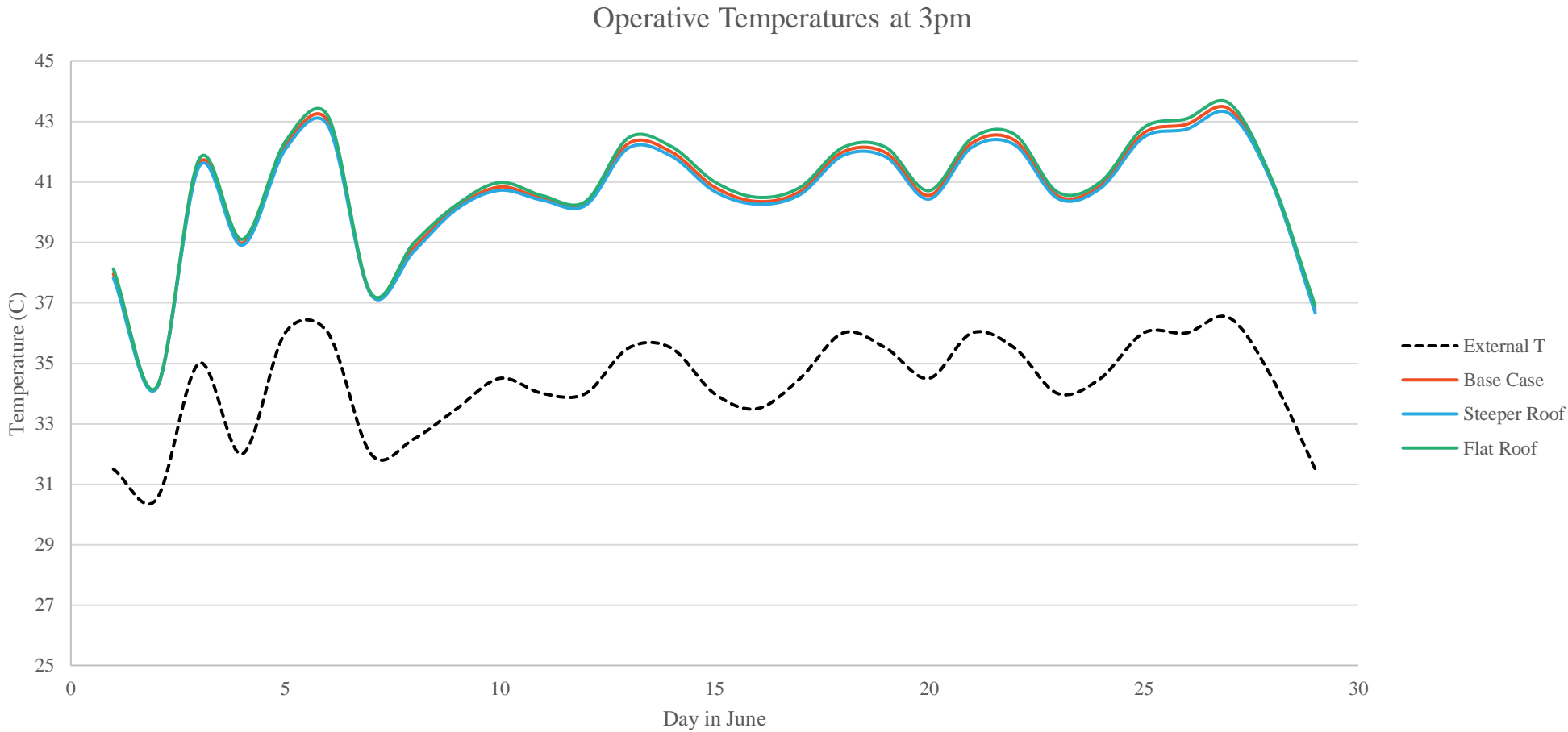
Roof Pitch – Roof Surface Temperatures



Due to the buildings in all cases being oriented with roofs parallel to the path of the sun during the day, the roof pitch has little impact on the roof surface temperature.

Figure 40: Roof surface temperatures for 3pm in June, comparing the flat roof, steeper roof and base cases.

Roof Pitch – Internal Operative Temperatures

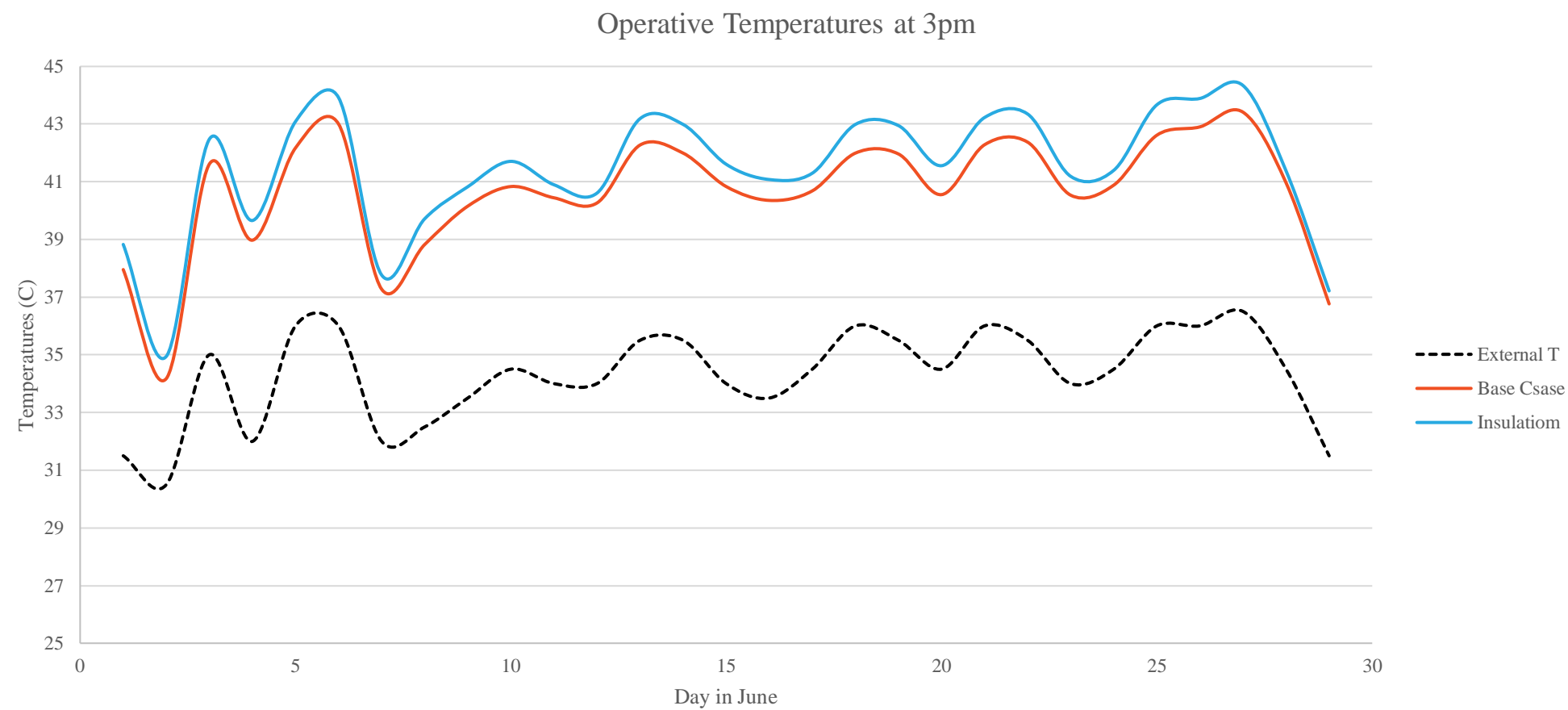


Internal temperatures are similar regardless of roof pitch as roof pitch has little effect on roof surface temperature.

Figure 41: Internal operative temperatures for 3pm in June, comparing the flat roof, steeper roof and base cases.

Insulation

Insulation – Internal Operative Temperatures



Insulation prevents heat loss from the internal space causing slightly higher internal temperatures, as expected.

Figure 42: Internal operative temperatures for 3pm in June, comparing the insulation strategy against the base case.

Steel Sheet Roofing

Steel Sheet Roofing – Internal Operative Temperatures

Operative Temperatures at 3pm

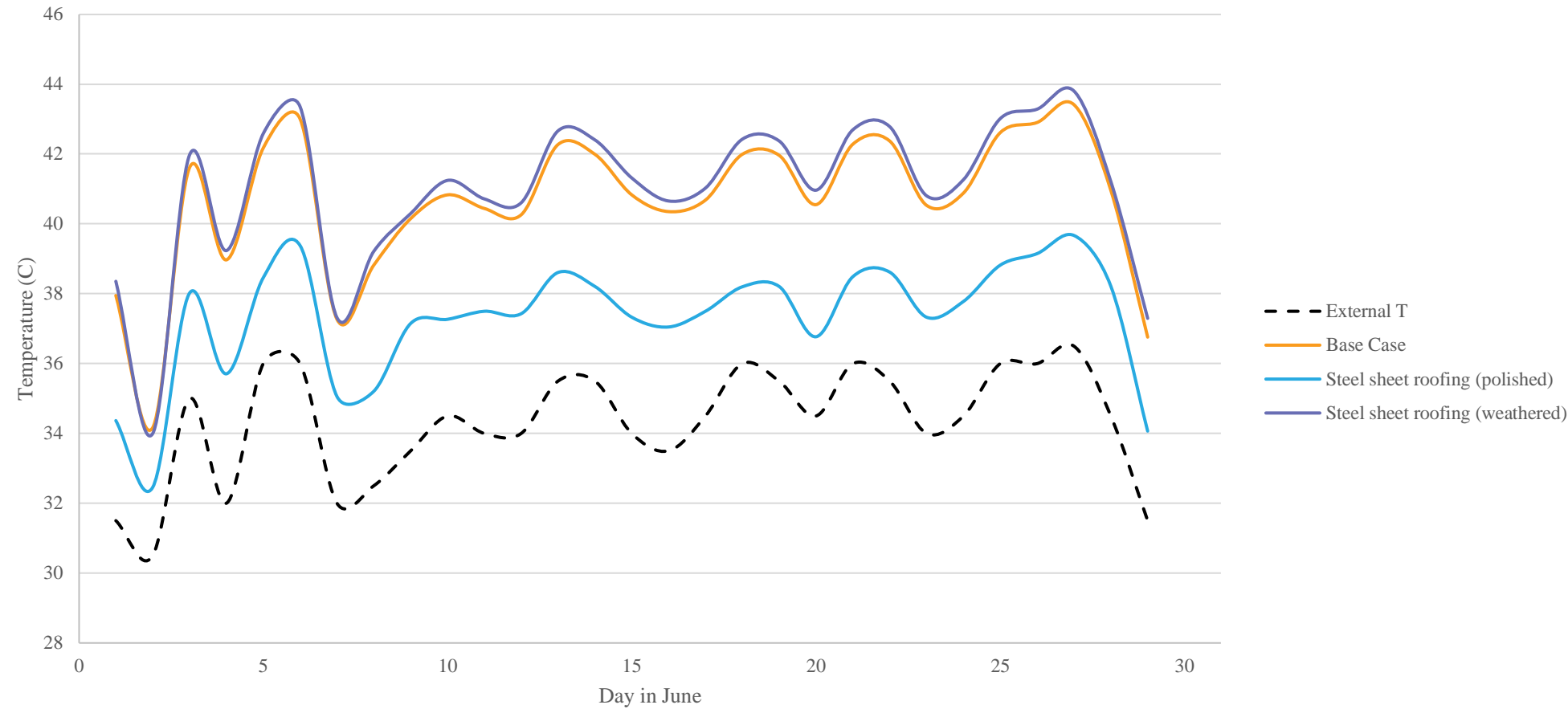


Figure 43: Internal operative temperatures for 3pm in June, comparing the roof materials.

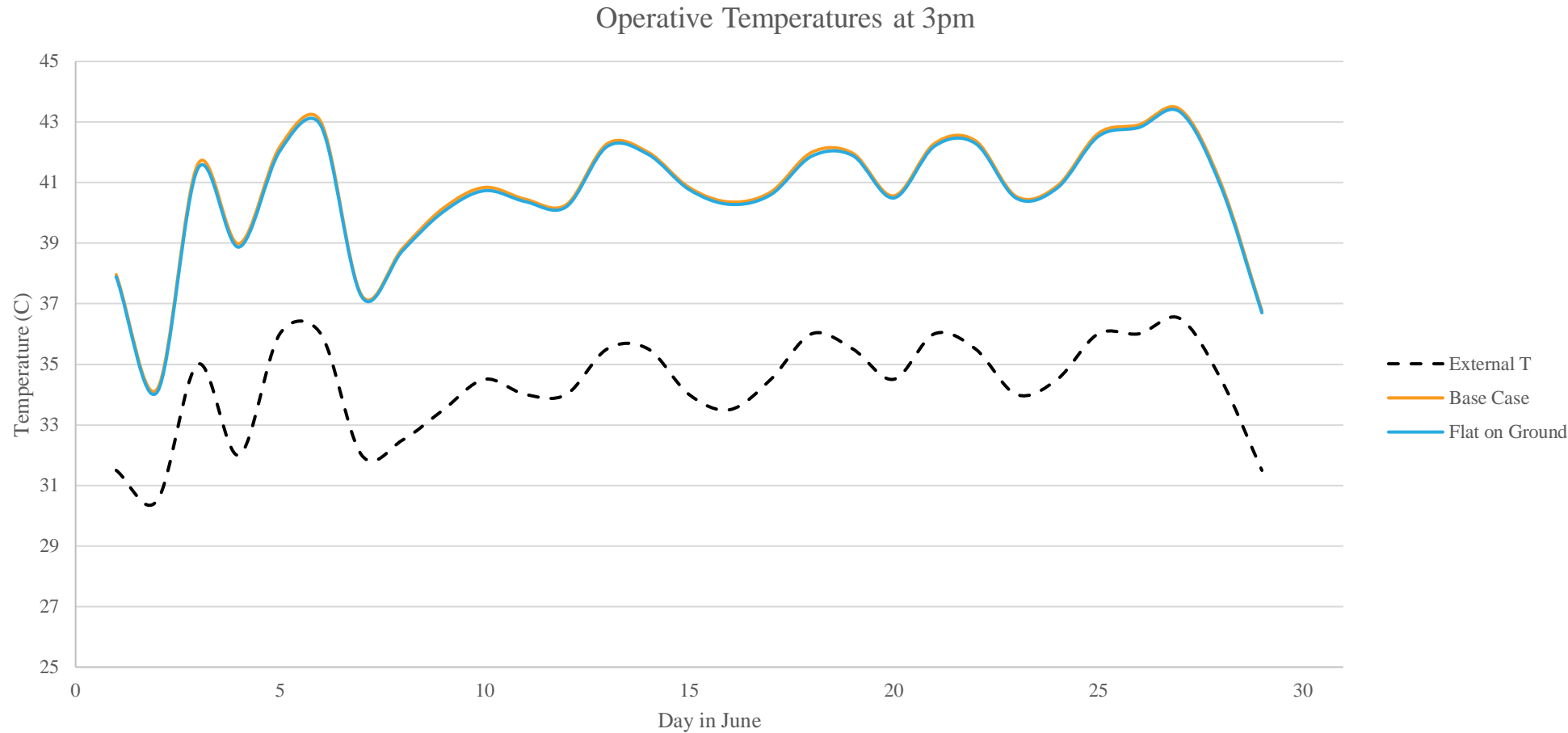
The base case is made up of fibre cement boards with an albedo of 0.27, while the steel sheet roofing has albedos of: 0.25 for weathered and 0.8 for polished.

The weathered steel roof has higher thermal conductivity than the base case roof which gives higher roof surface temperatures and therefore higher internal temperatures. While the polished has a much higher albedo than the other cases causing more sunlight to be reflected away from the roof, reducing roof temperatures and thus internal temperatures.

The weathered steel more closely represents a steel sheet roofing than the polished steel.

Flat on Ground

Flat on Ground – Internal Operative Temperatures

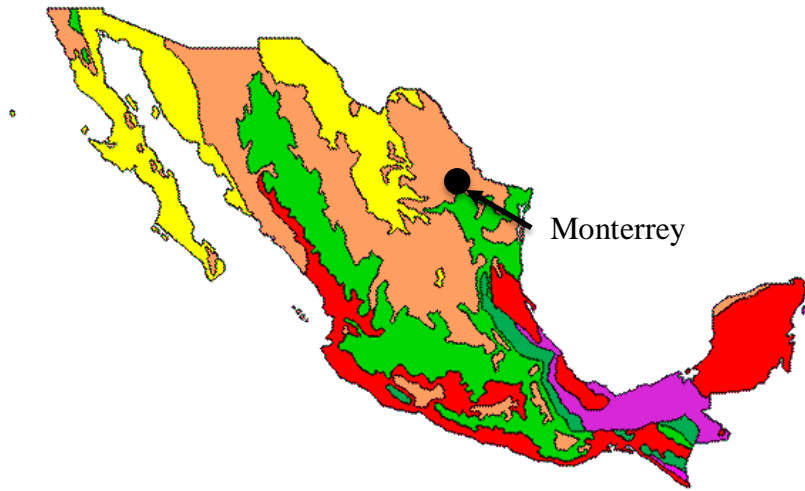


Moving building to be flat on the ground, rather than elevated on stilts (as in the base case) should increase temperatures due to lack of ventilation underneath the building. The ventilation would carry cooler external air underneath the building reducing the temperature.

However, possibly due to no wind being modelled, the two cases have little to no difference in internal temperature..

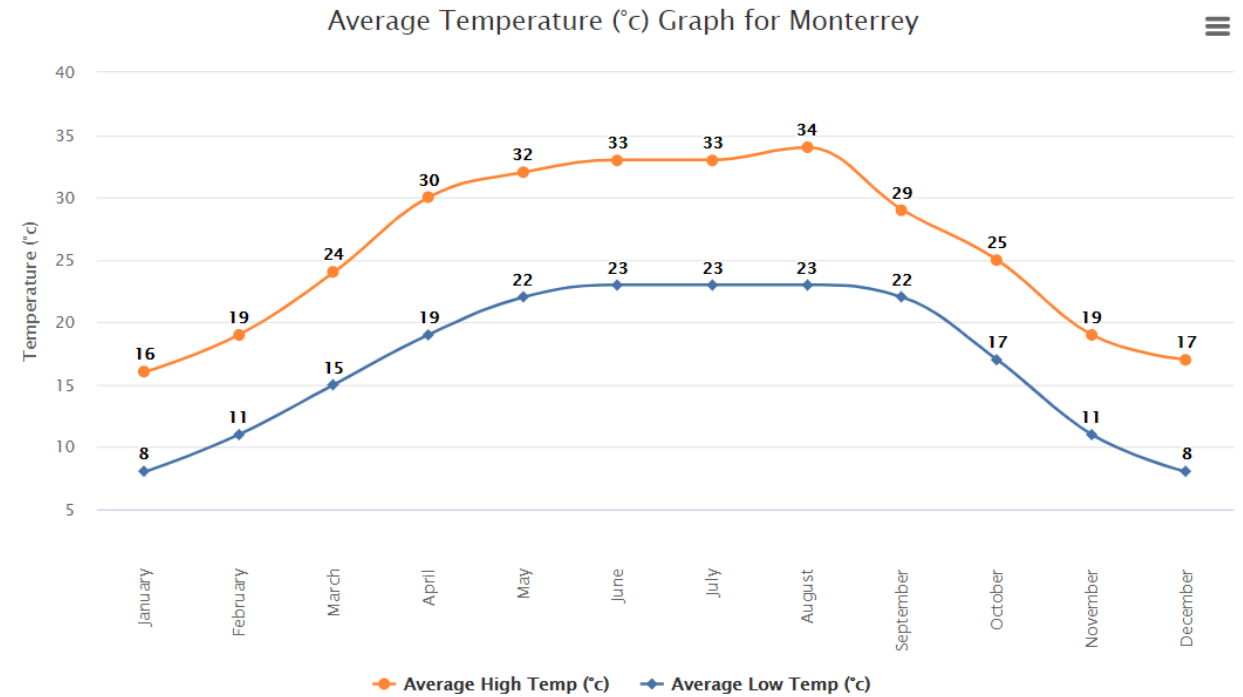
Figure 44: Internal operative temperatures for 3pm in June, comparing the flat on ground strategy against the base case.

Monterrey Winter



Semi-arid climate (BSh)

Monthly Average Temperature



Monterrey Average values (difference from base for January)

Average difference from base across January							
	Space temperatures		Indicative Comfort		Relative humidity		Air changes
	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural
	(°C)	(°C)	-	-	%	%	/hr
Base							
Reflective Roof (0.75)	-0.29	-0.54	-0.14	-0.78	0.92	0.92	-1.10
Reflective Roof (0.85)	-0.36	-0.65	-0.17	-0.95	1.13	1.13	-1.36
Reflective Roof (0.95)	-0.42	-0.77	-0.20	-1.11	1.34	1.34	-1.65
Larger Window	-0.04	-0.02	-0.01	-0.03	0.12	0.12	0.58
Orientation +45°	-0.11	-0.27	-0.07	-0.39	0.32	0.32	-0.35
Orientation +90°	-0.11	-0.32	-0.08	-0.46	0.31	0.31	-0.32
Orientation +135°	-0.12	-0.31	-0.08	-0.45	0.37	0.37	-0.39
Orientation +180°	-0.08	-0.22	-0.06	-0.33	0.25	0.25	-0.23
Orientation +225°	-0.15	-0.39	-0.10	-0.57	0.47	0.47	-0.48
Orientation +270°	-0.11	-0.28	-0.08	-0.41	0.29	0.29	-0.29
Orientation +315°	-0.07	-0.13	-0.04	-0.19	0.20	0.20	-0.22
Flat Roof	-0.02	-0.05	-0.01	-0.07	0.07	0.07	0.24
Steeper Roof	0.04	0.05	0.01	0.06	-0.11	-0.11	-0.49
Insulation	0.14	0.13	0.03	0.17	-0.64	-0.64	0.02
Steel sheet roofing (polished)	-0.32	-0.58	-0.15	-0.84	1.00	1.00	-1.22
Steel sheet roofing (weathered)	0.03	0.06	0.02	0.09	-0.09	-0.09	0.10
Flat on Ground	0.14	0.18	0.05	0.25	-0.61	-0.61	0.16

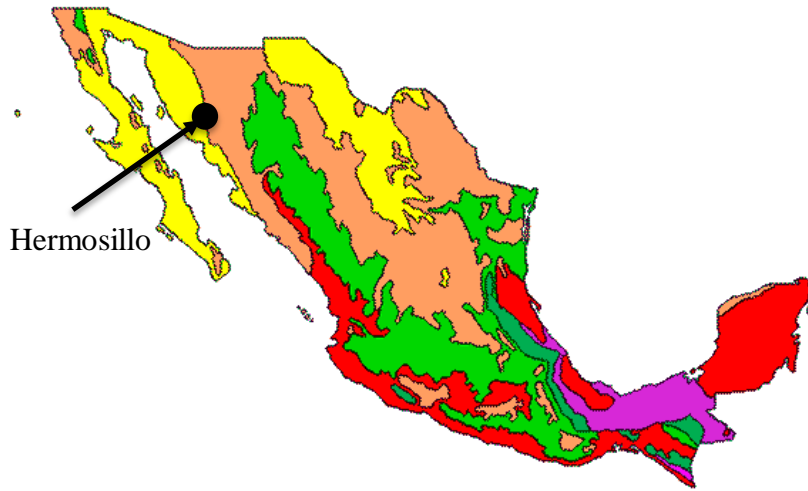
Monterrey Average values (absolute averages over all hours in January)

Absolute Values									
	External	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Op Tdiff
	Tdry	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	
	(°C)	(°C)	(°C)	-	-	%	%	/hr	(°C)
Base	15.26	16.38	17.12	-1.62	61.97	68.68	68.68	8.46	
Reflective Roof (0.75)	15.26	16.09	16.58	-1.77	61.19	69.59	69.59	7.37	-0.54
Reflective Roof (0.85)	15.26	16.02	16.47	-1.80	61.02	69.81	69.81	7.10	-0.65
Reflective Roof (0.95)	15.26	15.96	16.36	-1.83	60.85	70.02	70.02	6.81	-0.77
Larger Window	15.26	16.34	17.10	-1.63	61.94	68.80	68.80	9.04	-0.02
Orientation +45°	15.26	16.27	16.85	-1.69	61.58	69.00	69.00	8.11	-0.27
Orientation +90°	15.26	16.27	16.80	-1.71	61.50	68.99	68.99	8.14	-0.32
Orientation +135°	15.26	16.26	16.82	-1.71	61.52	69.04	69.04	8.07	-0.31
Orientation +180°	15.26	16.30	16.90	-1.68	61.64	68.93	68.93	8.23	-0.22
Orientation +225°	15.26	16.23	16.73	-1.73	61.40	69.15	69.15	7.98	-0.39
Orientation +270°	15.26	16.28	16.84	-1.70	61.56	68.97	68.97	8.17	-0.28
Orientation +315°	15.26	16.31	16.99	-1.66	61.78	68.87	68.87	8.24	-0.13
Flat Roof	15.26	16.36	17.07	-1.64	61.90	68.75	68.75	8.71	-0.05
Steeper Roof	15.26	16.42	17.17	-1.61	62.03	68.57	68.57	7.97	0.05
Insulation	15.26	16.52	17.25	-1.59	62.14	68.04	68.04	8.48	0.13
Steel sheet roofing (polished)	15.26	16.06	16.54	-1.78	61.12	69.68	69.68	7.24	-0.58
Steel sheet roofing (weathered)	15.26	16.41	17.18	-1.61	62.06	68.59	68.59	8.56	0.06
Flat on Ground	15.26	16.53	17.30	-1.58	62.22	68.07	68.07	8.62	0.18

Monterrey Summary

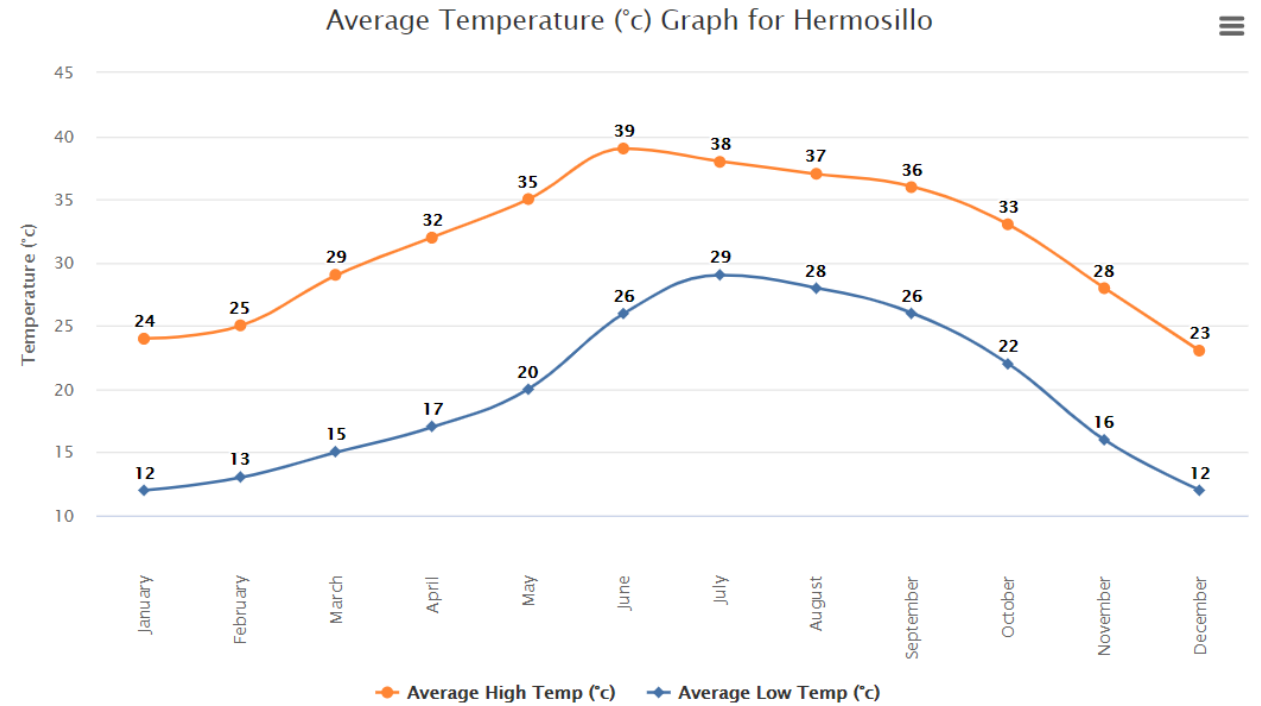
The most effective strategy in Monterrey is the reflective roof, where a higher albedo gives a greater cooling effect. Limited improvement was seen for the polished steel roof material, increased window size and steeper roof. Benefits of the strategies in summer exceed the penalty in winter, as the winter condition is not significantly worsened, while the summer condition is significantly improved.

Hermosillo Summer



Hot desert climate (BWh)

Monthly Average Temperature



Hermosillo Average values (difference from base for July)

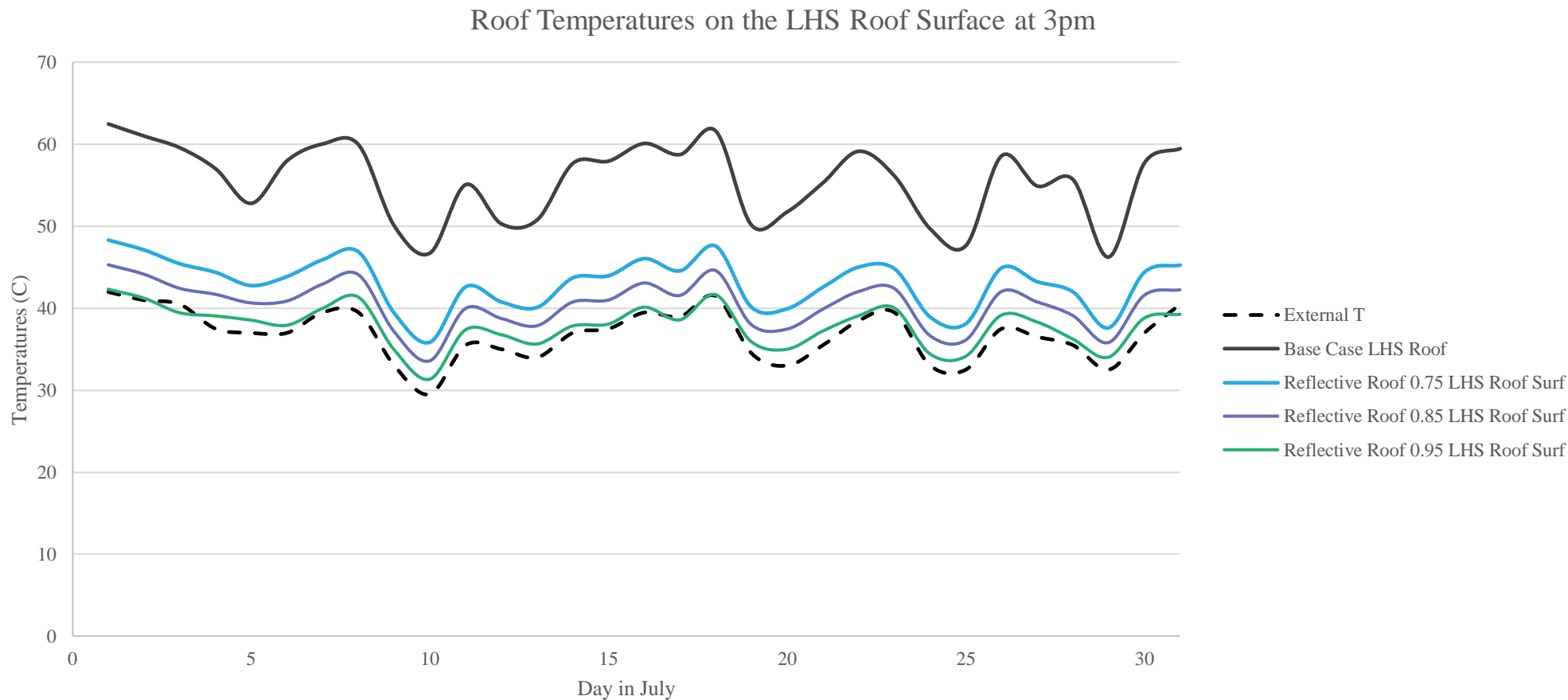
Average difference from base across July									
	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp	
	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left side	Right Side
	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)
Base									
Reflective Roof (0.75)	-0.60	-1.06	-0.32	-1.12	1.31	1.31	-2.00	-4.23	-4.31
Reflective Roof (0.85)	-0.74	-1.29	-0.38	-1.36	1.63	1.63	-2.56	-5.11	-5.22
Reflective Roof (0.95)	-0.89	-1.52	-0.45	-1.60	1.97	1.97	-3.26	-6.00	-6.12
Larger Window	-0.06	-0.04	-0.01	-0.02	0.13	0.13	0.64	0.00	0.00
Orientation +45°	0.18	0.34	0.10	0.36	-0.41	-0.41	0.48	0.15	0.10
Orientation +90°	0.24	0.49	0.15	0.52	-0.52	-0.52	0.64	0.26	0.10
Orientation +135°	0.15	0.30	0.09	0.32	-0.31	-0.31	0.45	0.25	-0.03
Orientation +180°	0.00	0.01	0.00	0.01	-0.01	-0.01	0.01	0.16	-0.15
Orientation +225°	0.19	0.36	0.11	0.38	-0.45	-0.45	0.48	0.26	0.00
Orientation +270°	0.24	0.50	0.15	0.54	-0.55	-0.55	0.64	0.26	0.11
Orientation +315°	0.15	0.30	0.09	0.33	-0.33	-0.33	0.45	0.14	0.09
Flat Roof	0.02	0.04	0.01	0.05	-0.03	-0.03	0.38	-0.02	
Steeper Roof	0.02	-0.02	-0.01	-0.03	-0.04	-0.04	-0.63	0.01	0.12
Insulation	0.26	0.34	0.10	0.31	-0.62	-0.62	0.25	0.12	0.11
Steel sheet roofing (polished)	-0.66	-1.15	-0.34	-1.22	1.45	1.45	-2.21	-4.59	-4.69
Steel sheet roofing (weathered)	0.06	0.13	0.04	0.14	-0.14	-0.14	0.18	0.23	0.23
Flat on Ground	-0.02	-0.03	-0.01	-0.04	0.01	0.01	-0.05	-0.01	-0.01

Hermosillo Average values (absolute averages over all hours in July)

	Absolute Values										
	External	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp		Op Tdiff
	Tdry	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left Side	Right Side	
	(°C)	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)	(°C)
Base	31.87	33.57	34.37	3.17	83.77	49.41	49.41	9.56	38.00	38.14	
Reflective Roof (0.75)	31.87	32.97	33.32	2.86	82.65	50.72	50.72	7.56	33.77	33.83	-1.06
Reflective Roof (0.85)	31.87	32.83	33.09	2.79	82.41	51.04	51.04	6.99	32.88	32.93	-1.29
Reflective Roof (0.95)	31.87	32.68	32.85	2.72	82.16	51.38	51.38	6.30	32.00	32.03	-1.52
Larger Window	31.87	33.51	34.33	3.16	83.74	49.54	49.54	10.20	37.99	38.14	-0.04
Orientation +45°	31.87	33.75	34.72	3.27	84.13	49.00	49.00	10.03	38.15	38.24	0.34
Orientation +90°	31.87	33.81	34.86	3.32	84.29	48.89	48.89	10.20	38.26	38.24	0.49
Orientation +135°	31.87	33.72	34.67	3.26	84.09	49.10	49.10	10.01	38.24	38.12	0.30
Orientation +180°	31.87	33.57	34.38	3.17	83.77	49.40	49.40	9.56	38.15	37.99	0.01
Orientation +225°	31.87	33.75	34.73	3.28	84.14	48.96	48.96	10.04	38.26	38.15	0.36
Orientation +270°	31.87	33.81	34.87	3.32	84.30	48.86	48.86	10.20	38.26	38.26	0.50
Orientation +315°	31.87	33.72	34.68	3.26	84.09	49.08	49.08	10.01	38.13	38.24	0.30
Flat Roof	31.87	33.58	34.41	3.18	83.81	49.38	49.38	9.94	37.98		0.04
Steeper Roof	31.87	33.58	34.35	3.16	83.73	49.37	49.37	8.93	38.00	38.27	-0.02
Insulation	31.87	33.83	34.71	3.27	84.07	48.79	48.79	9.81	38.12	38.26	0.34
Steel sheet roofing (polished)	31.87	32.90	33.22	2.83	82.55	50.86	50.86	7.35	33.40	33.46	-1.15
Steel sheet roofing (weathered)	31.87	33.63	34.50	3.21	83.90	49.27	49.27	9.74	38.22	38.37	0.13
Flat on Ground	31.87	33.54	34.34	3.16	83.73	49.41	49.41	9.51	37.99	38.14	-0.03

Reflective Roof

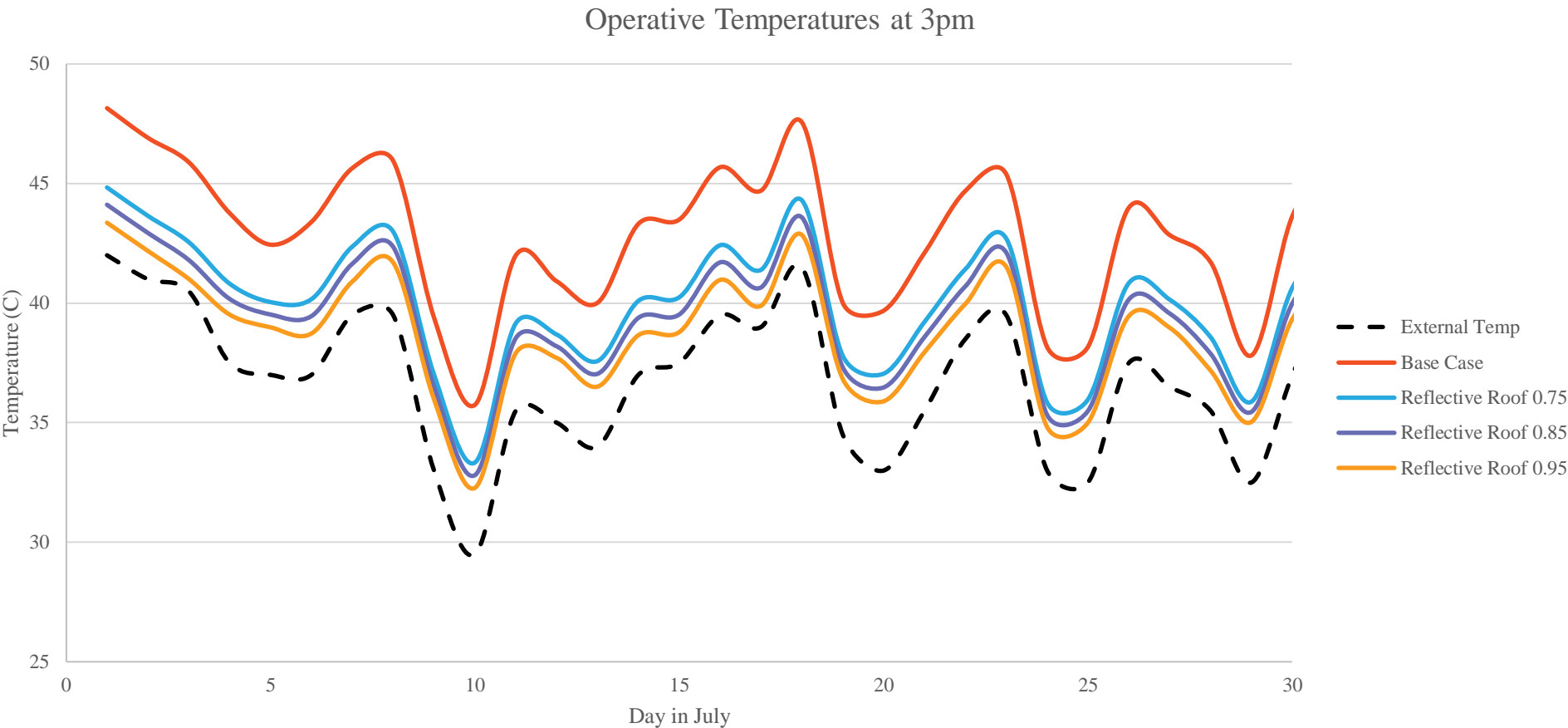
Reflective Roof – Roof Surface Temperatures



The base case has an albedo of 0.27. The painted roofs with higher albedo, reflect more sunlight than the base case, so less heat is absorbed by the roof. This reduces the roof surface temperature and in turn reduces the internal temperature of the house.

Figure 46: Roof surface temperatures for 3pm in July, comparing the reflective roof strategies against the base case.

Reflective Roof – Internal Operative Temperatures



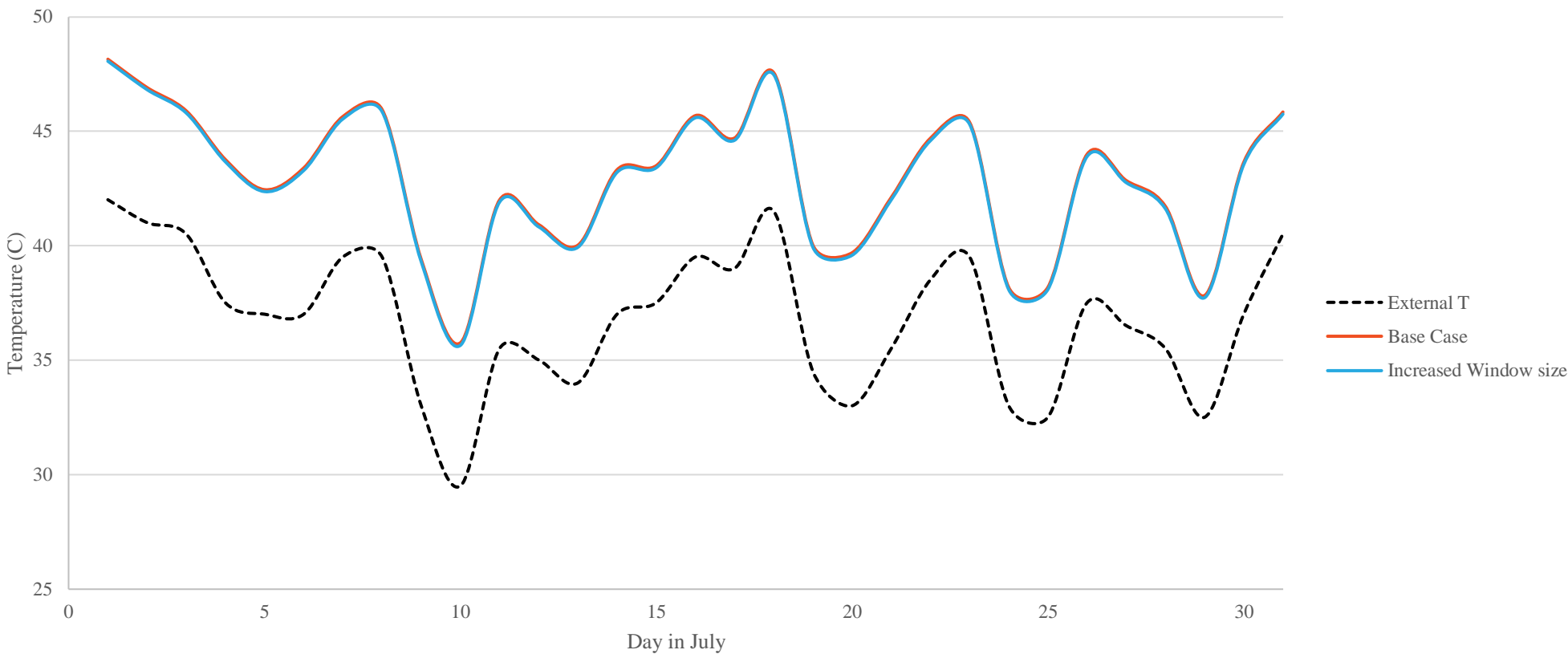
The reduction of the roof surface temperature due to the high albedo surfaces, reduces the internal temperature of the house.

Figure 45: Internal operative temperatures for 3pm in July, comparing the reflective roof strategies against the base case.

Increased Window Size

Increased Window Size – Internal Operative Temperatures

Operative Temperatures at 3pm



Increasing the window size gives a slightly cooler internal operative temperature due to an increase in ventilation. Since the external temperature is cooler than internal temperatures increasing the ventilation decreases the internal temperatures.

However, increased windows also allow greater solar gains into the room which can cause higher temperatures depending on time of day and building orientation.

Figure 47: Internal operative temperatures for 3pm in July, comparing the increased window strategy against the base case.

Increased Window Size - Air change rates

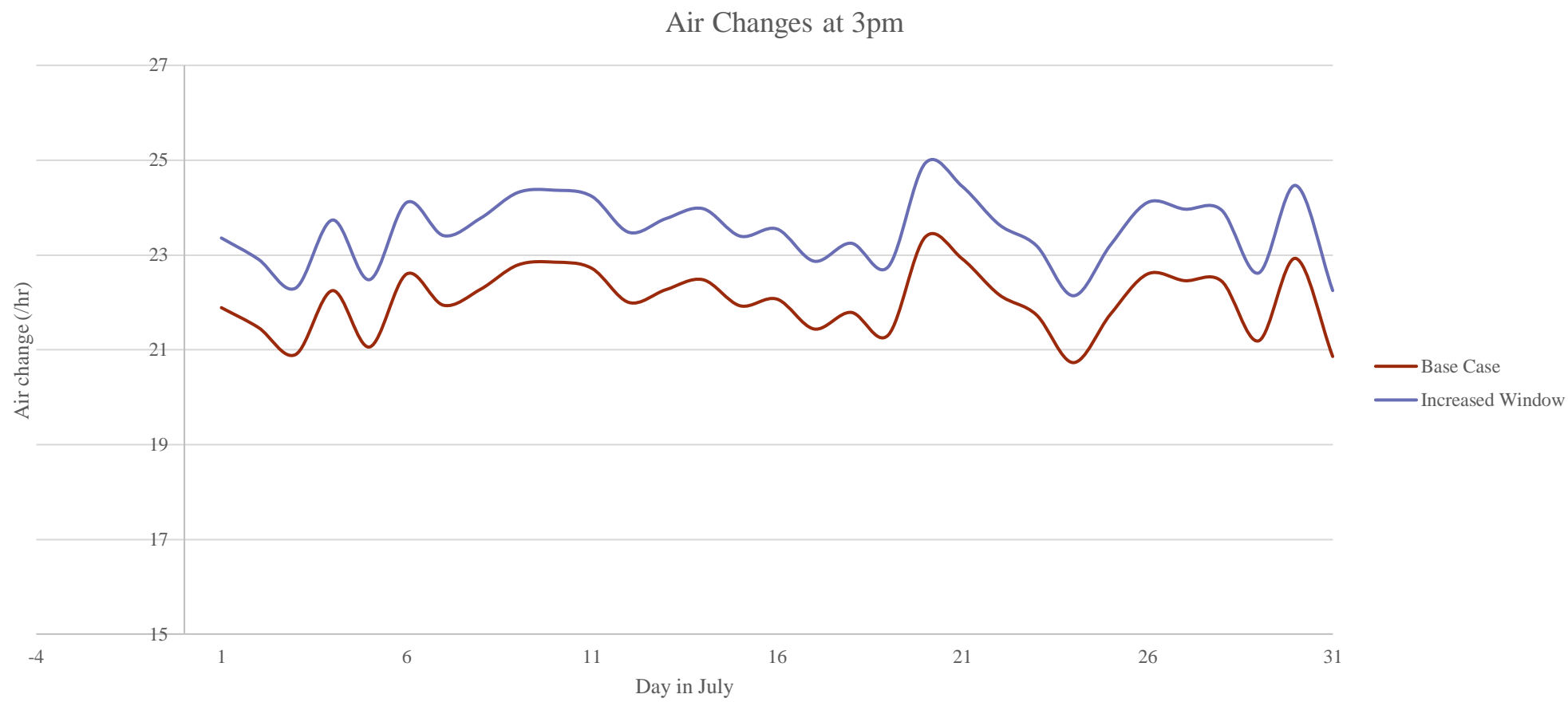


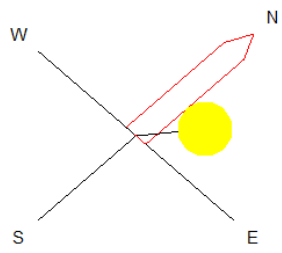
Figure 48: Air change rate for 3pm in July, comparing the increased window strategy against the base case.

The air change rate is higher for the increased window case than the base case, as expected due to an increase in ventilation. While the difference in air change rate between the cases is notable, the difference in temperatures is much less so.

It is important to note that our models do not account for wind/wind speeds so the improvement in air change shown is conservative.

It is likely that, on a breezy day the increased window size would be more effective at cooling the space and increasing air change rate.

Orientation



Building Orientation – 9.30am

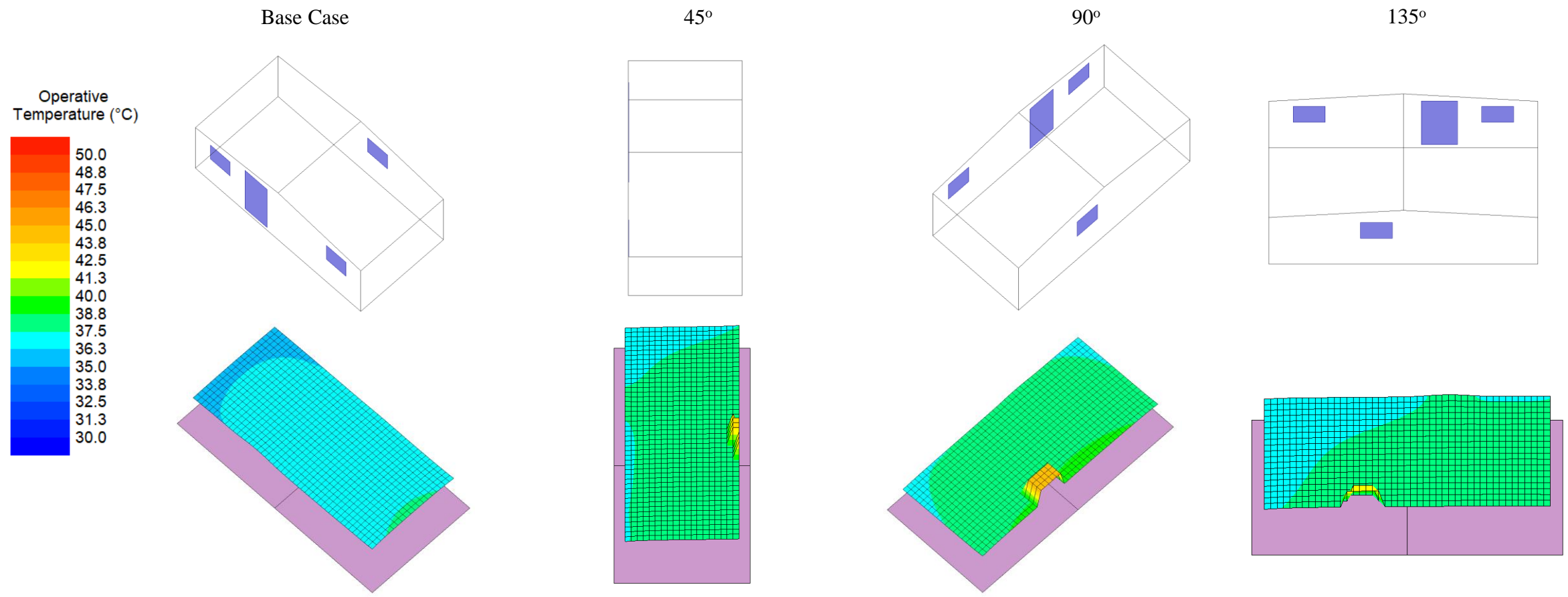
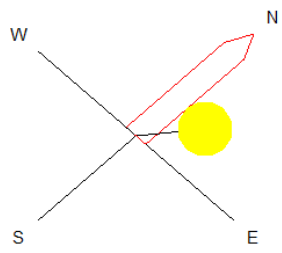


Figure 49a: Spatial operative temperatures for 9.30am in July for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 30.8°C.



Building Orientation – 9.30am

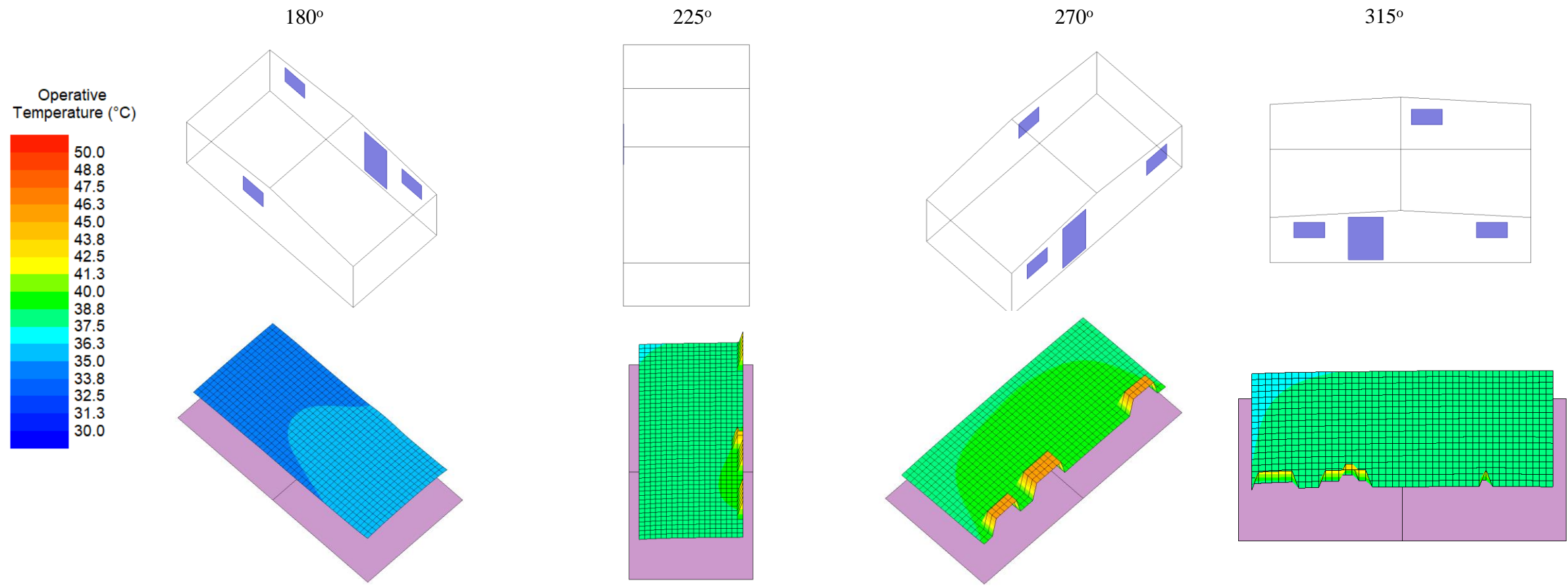


Figure 49b: Spatial operative temperatures for 9.30am in July for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 30.8°C.

Building Orientation – 4.30pm

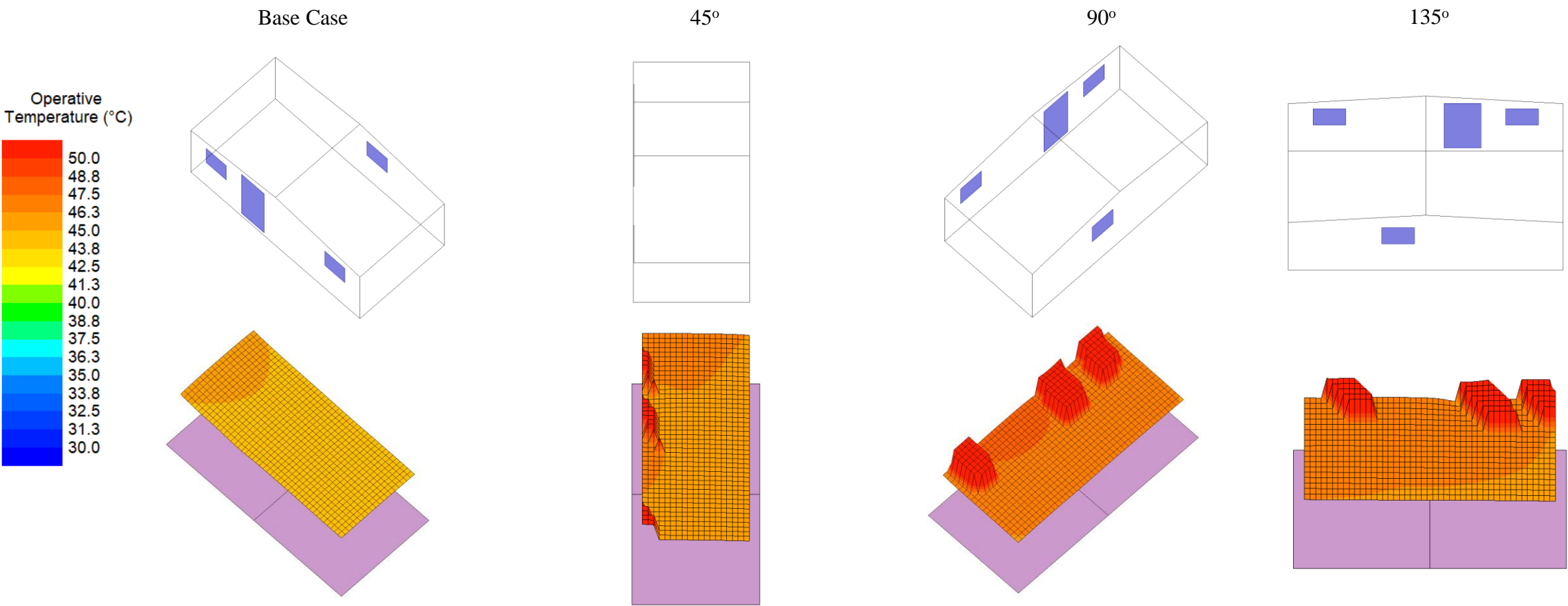
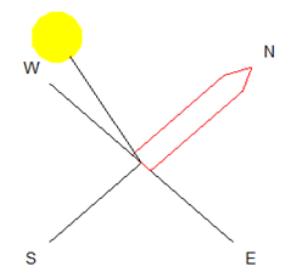
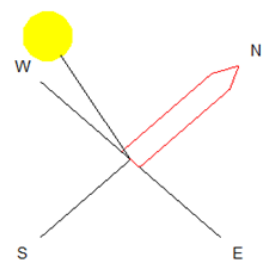


Figure 50a: Spatial operative temperatures for 4.30pm in July for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 40.8°C.



Building Orientation – 4.30pm

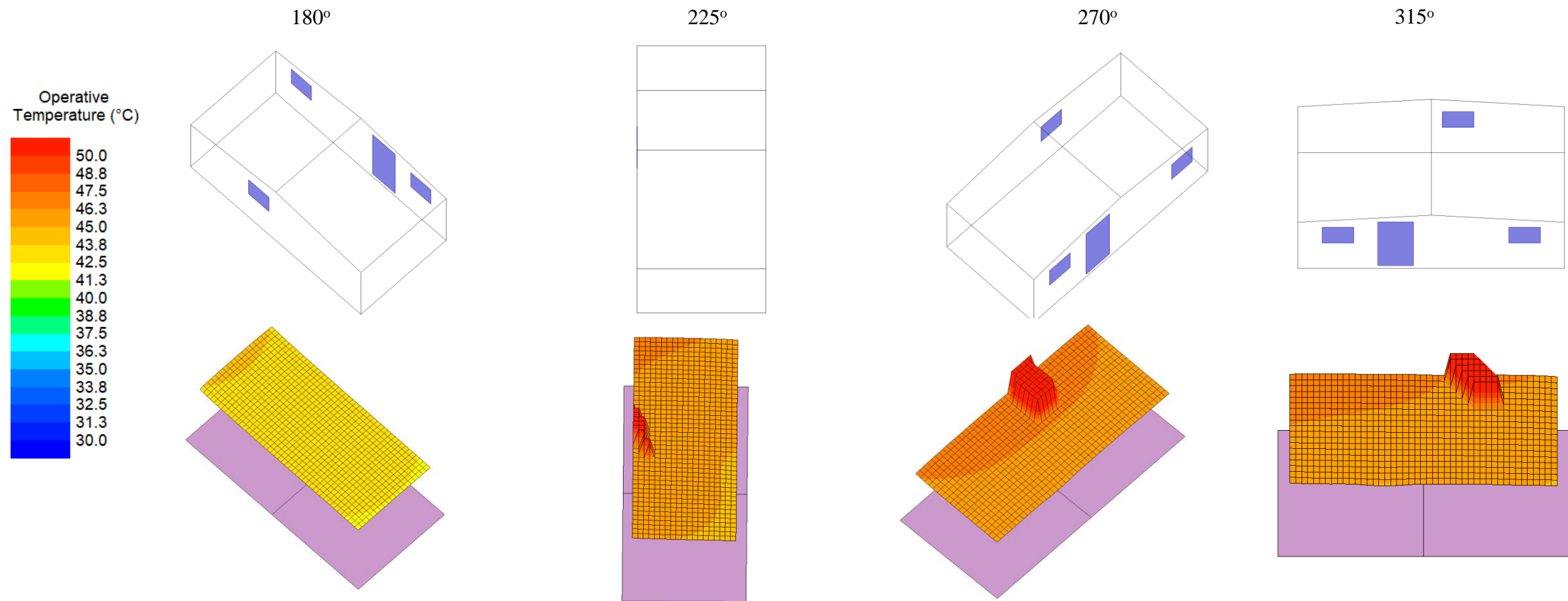


Figure 50b: Spatial operative temperatures for 4.30pm in July for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 40.8°C.

Building Orientation

The base case in Figure 49a, 50a shows lower temperatures than the other orientations at both 9.30am and 4.30pm. This is because there are no windows facing east or west during the day, to let in sunlight and cause higher solar gain.

Looking at the 90° case in Figure 50a, it is clear that the heat spikes inside the building are due to the window positioning which allows high solar gain at the hottest part of the day. This is further demonstrated in Figure 51, where the base case consistently has the lowest temperatures, while the 90° case has the highest temperatures.

The results of examining building orientation on temperature highlight the effectiveness of interventions that reduce solar gains. Using blinds would also improve internal temperatures by reducing solar gains, regardless of building orientation.

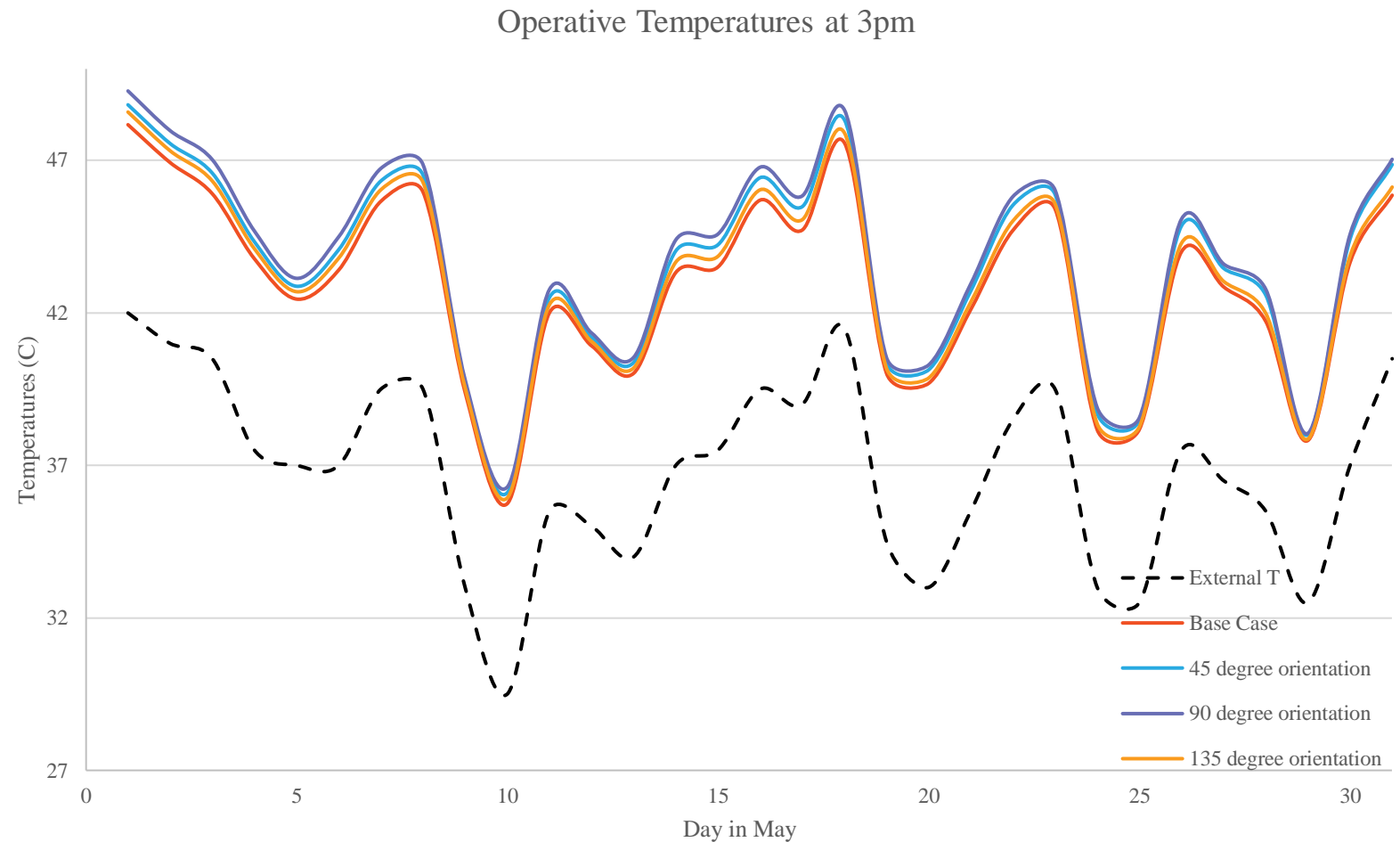


Figure 51: Internal operative temperatures for 3pm in July, comparing different orientations.

Steeper Roof & Flat Roof

Roof Pitch

For the base case, the roof is orientated parallel to the path of the sun during the day, with the windows perpendicular to the sun. This means that changing the roof pitch has little effect on the roof temperatures and therefore the internal temperatures as the sun is heating the roof all day regardless of pitch.

Later, we will investigate the impact of roof pitch on the building oriented perpendicular to the path of the sun.

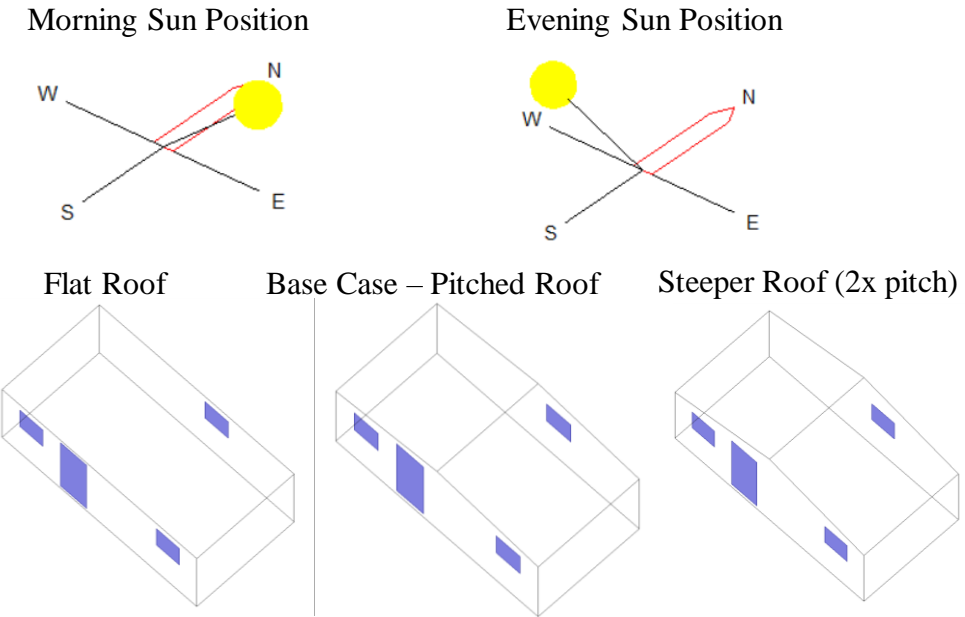


Figure 52: Models of flat roof, base case and steeper roof.

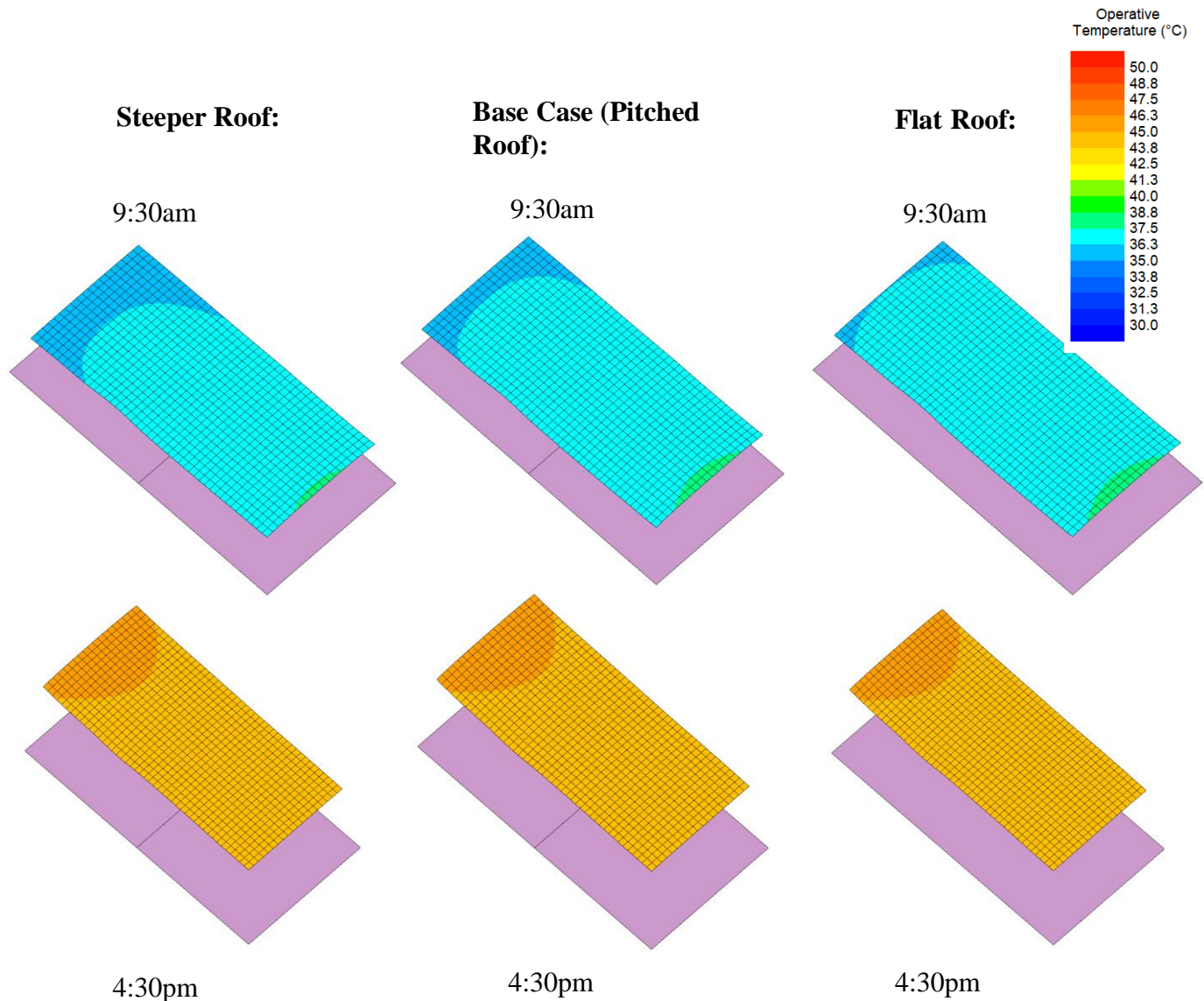
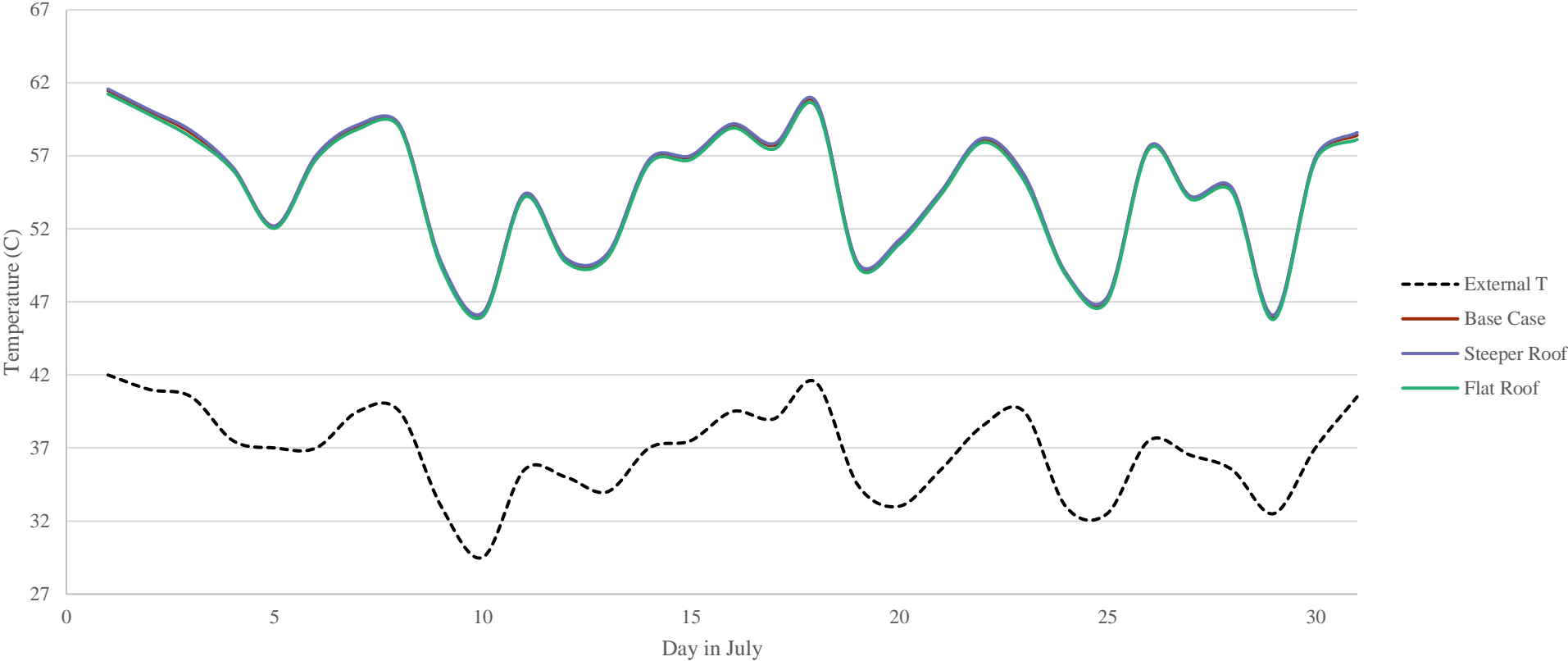


Figure 53: Spatial operative temperatures for 9:30 am and 4:30pm in July.

Roof Pitch – Roof Surface Temperatures

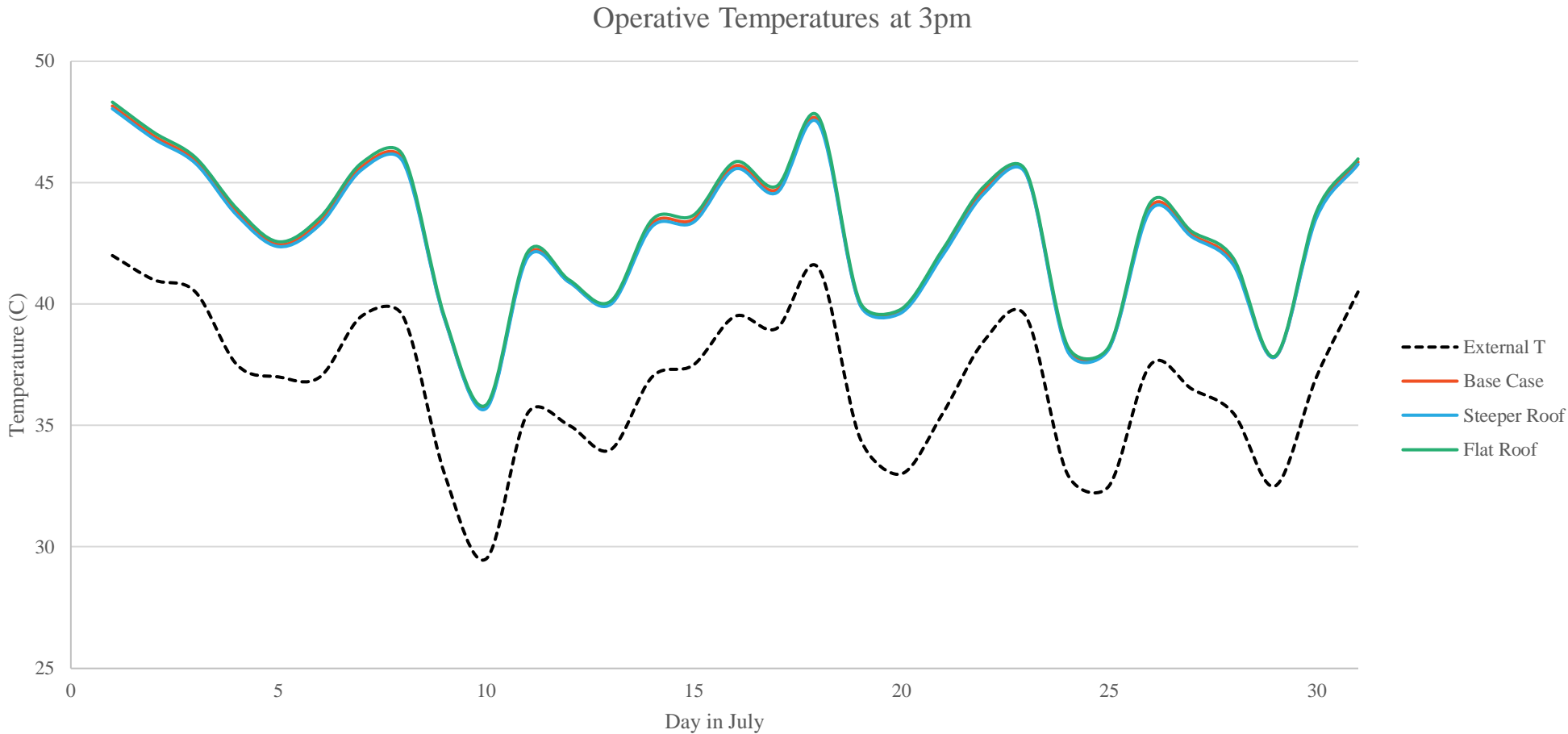
Roof Surface Temperatures at 3pm



Due to the buildings in all cases being oriented with roofs parallel to the path of the sun during the day, the roof pitch has little impact on the roof surface temperature.

Figure 54: Roof surface temperatures for 3pm in July, comparing the flat roof, steeper roof and base cases.

Roof Pitch – Internal Operative Temperatures

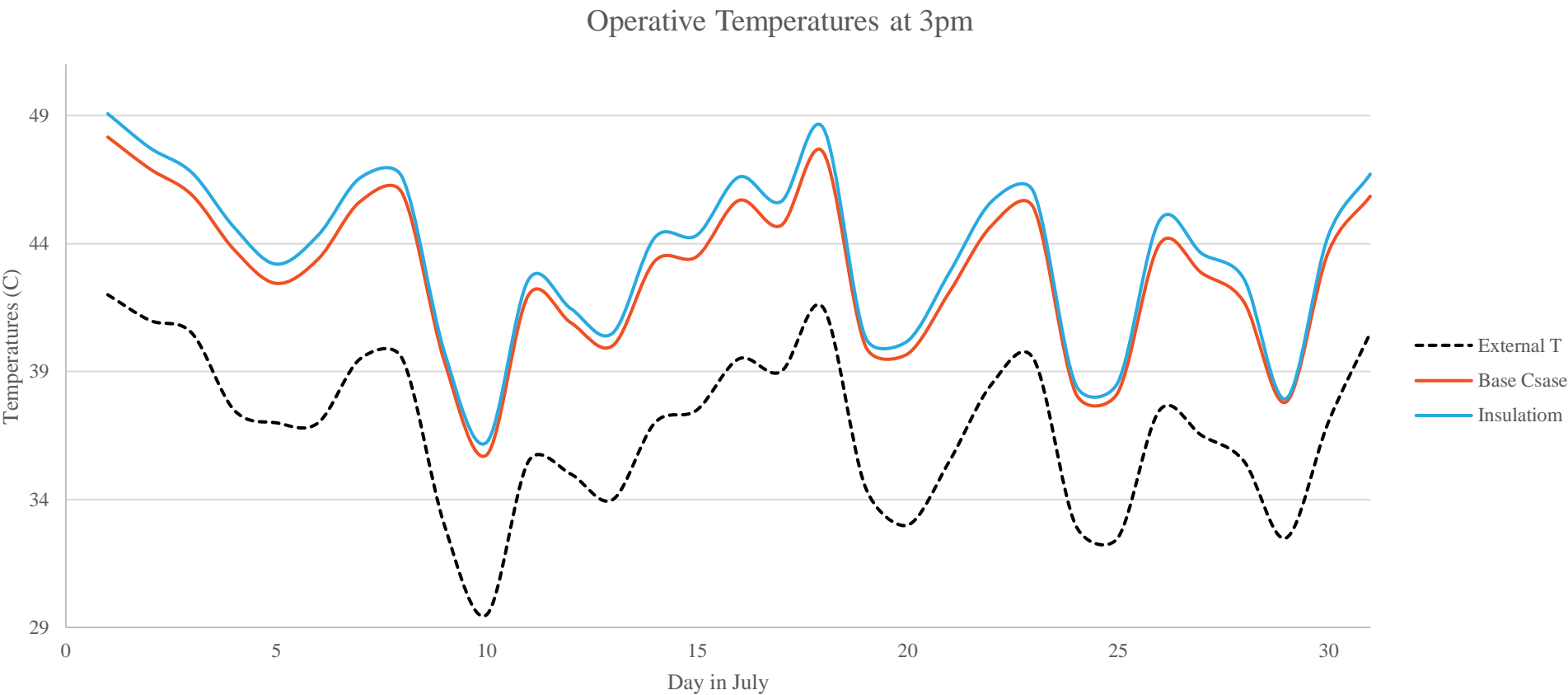


Internal temperatures are similar regardless of roof pitch as roof pitch has little effect on roof surface temperature.

Figure 55: Internal operative temperatures for 3pm in July, comparing the flat roof, steeper roof and base cases.

Insulation

Insulation – Internal Operative Temperatures



Insulation prevents heat loss from the internal space causing slightly higher internal temperatures, as expected.

Figure 56: Internal operative temperatures for 3pm in July, comparing the insulation strategy against the base case.

Steel Sheet Roofing

Steel Sheet Roofing – Internal Operative Temperatures

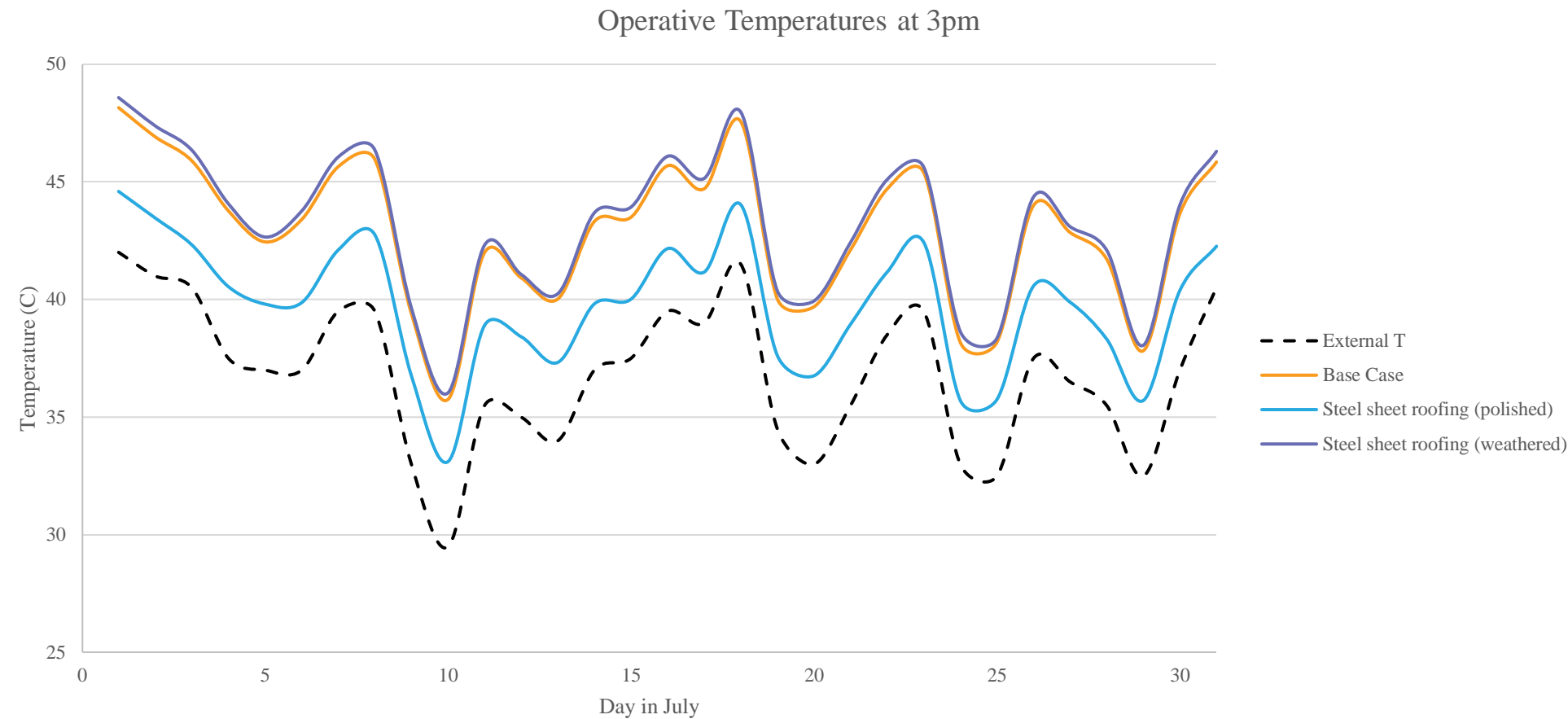


Figure 57: Internal operative temperatures for 3pm in July, comparing the roof material strategies with the base case.

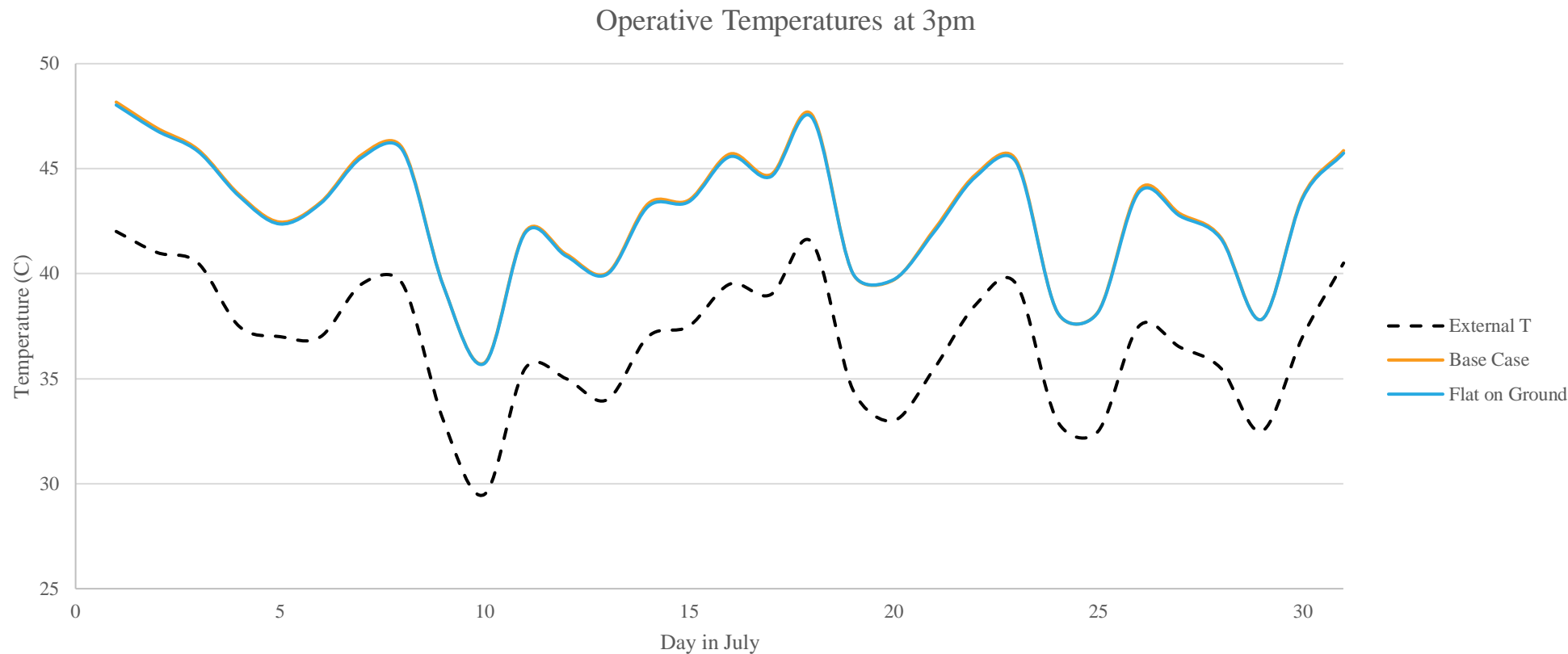
The base case is made up of fibre cement boards with an albedo of 0.27, while the steel sheet roofing has albedos of: 0.25 for weathered and 0.8 for polished.

The weathered steel roof has higher thermal conductivity than the base case roof which gives higher roof surface temperatures and therefore higher internal temperatures. While the polished has a much higher albedo than the other cases causing more sunlight to be reflected away from the roof, reducing roof temperatures and thus internal temperatures.

The weathered steel more closely represents a steel sheet roofing than the polished steel.

Flat on Ground

Flat on Ground – Internal Operative Temperatures

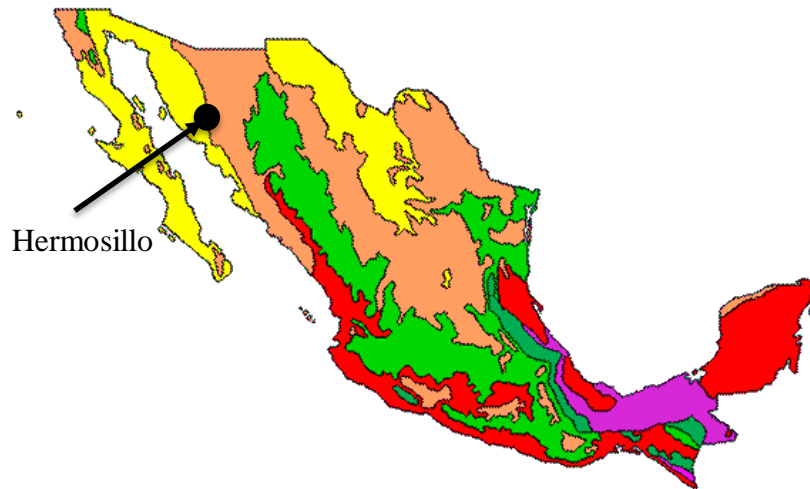


Moving building to be flat on the ground, rather than elevated on stilts (as in the base case) should increase temperatures due to lack of ventilation underneath the building. The ventilation would carry cooler external air underneath the building reducing the temperature.

However, possibly due to no wind being modelled, the two cases have little to no difference in internal temperature..

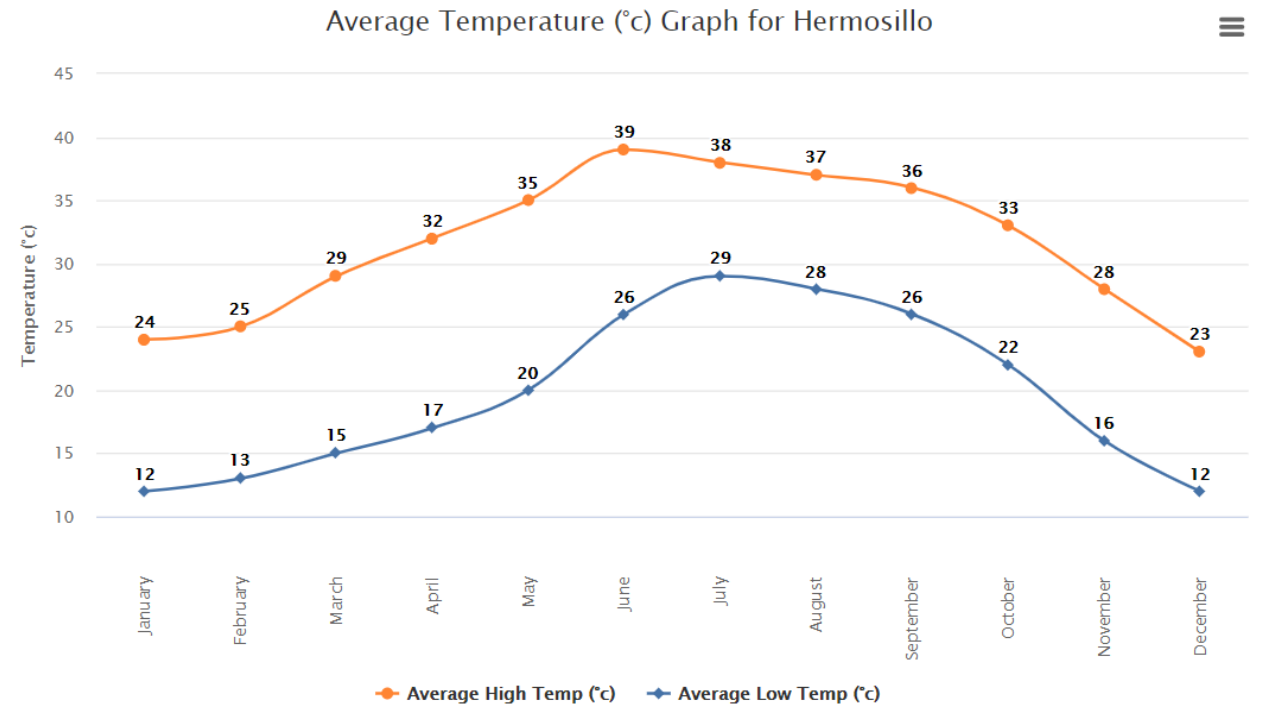
Figure 58: Internal operative temperatures for 3pm in July, comparing the flat on ground strategy with the base case.

Hermosillo Winter



Hot desert climate (BWh)

Monthly Average Temperature



Hermosillo Average values (difference from base for December)

Average difference from base across December							
	Space temperatures		Indicative Comfort		Relative humidity		Air changes
	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural
	(°C)	(°C)	-	-	%	%	/hr
Base							
Reflective Roof (0.75)	-0.41	-0.71	-0.19	-1.02	1.13	1.13	-1.16
Reflective Roof (0.85)	-0.50	-0.86	-0.23	-1.24	1.39	1.39	-1.44
Reflective Roof (0.95)	-0.60	-1.01	-0.27	-1.46	1.66	1.66	-1.75
Larger Window	-0.06	-0.03	-0.01	-0.04	0.14	0.14	0.63
Orientation +45°	-0.13	-0.27	-0.07	-0.39	0.42	0.42	-0.39
Orientation +90°	-0.13	-0.34	-0.09	-0.50	0.29	0.29	-0.30
Orientation +135°	-0.21	-0.47	-0.13	-0.68	0.51	0.51	-0.51
Orientation +180°	-0.11	-0.30	-0.08	-0.44	0.32	0.32	-0.28
Orientation +225°	-0.21	-0.48	-0.12	-0.69	0.63	0.63	-0.57
Orientation +270°	-0.14	-0.34	-0.09	-0.50	0.28	0.28	-0.29
Orientation +315°	-0.14	-0.26	-0.07	-0.38	0.29	0.29	-0.32
Flat Roof	-0.04	-0.07	-0.02	-0.11	0.10	0.10	0.27
Steeper Roof	0.06	0.08	0.02	0.11	-0.15	-0.15	-0.53
Insulation	0.21	0.19	0.05	0.26	-0.73	-0.73	-0.12
Steel sheet roofing (polished)	-0.44	-0.76	-0.20	-1.09	1.21	1.21	-1.28
Steel sheet roofing (weathered)	0.05	0.09	0.02	0.13	-0.13	-0.13	0.10
Flat on Ground	0.13	0.16	0.04	0.22	-0.39	-0.39	0.03

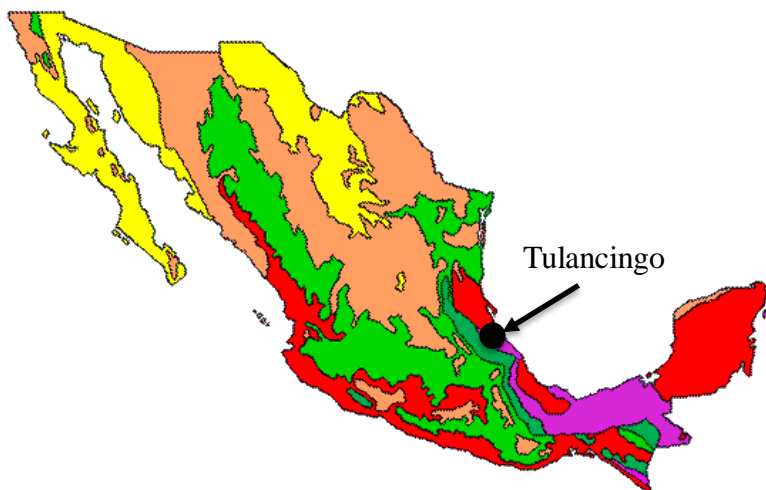
Hermosillo Average values (absolute averages over all hours in December)

Absolute Values									
	External	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Op Tdiff
	Tdry	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	
	(°C)	(°C)	(°C)	-	-	%	%	/hr	(°C)
Base	15.06	15.72	16.58	-1.77	61.13	67.07	67.07	9.07	
Reflective Roof (0.75)	15.06	15.31	15.88	-1.95	60.11	68.20	68.20	7.92	-0.71
Reflective Roof (0.85)	15.06	15.22	15.73	-1.99	59.89	68.46	68.46	7.63	-0.86
Reflective Roof (0.95)	15.06	15.12	15.58	-2.03	59.67	68.73	68.73	7.32	-1.01
Larger Window	15.06	15.67	16.56	-1.77	61.10	67.21	67.21	9.71	-0.03
Orientation +45°	15.06	15.59	16.32	-1.83	60.74	67.49	67.49	8.68	-0.27
Orientation +90°	15.06	15.59	16.24	-1.86	60.63	67.36	67.36	8.77	-0.34
Orientation +135°	15.06	15.51	16.11	-1.89	60.45	67.58	67.58	8.56	-0.47
Orientation +180°	15.06	15.61	16.28	-1.84	60.70	67.39	67.39	8.79	-0.30
Orientation +225°	15.06	15.51	16.11	-1.89	60.44	67.70	67.70	8.50	-0.48
Orientation +270°	15.06	15.58	16.24	-1.86	60.64	67.35	67.35	8.78	-0.34
Orientation +315°	15.06	15.58	16.32	-1.84	60.75	67.36	67.36	8.75	-0.26
Flat Roof	15.06	15.68	16.51	-1.78	61.03	67.17	67.17	9.34	-0.07
Steeper Roof	15.06	15.78	16.66	-1.75	61.24	66.92	66.92	8.55	0.08
Insulation	15.06	15.93	16.77	-1.71	61.39	66.34	66.34	8.95	0.19
Steel sheet roofing (polished)	15.06	15.28	15.83	-1.97	60.04	68.28	68.28	7.79	-0.76
Steel sheet roofing (weathered)	15.06	15.77	16.67	-1.74	61.26	66.94	66.94	9.17	0.09
Flat on Ground	15.06	15.85	16.74	-1.73	61.35	66.68	66.68	9.10	0.16

Hermosillo Summary

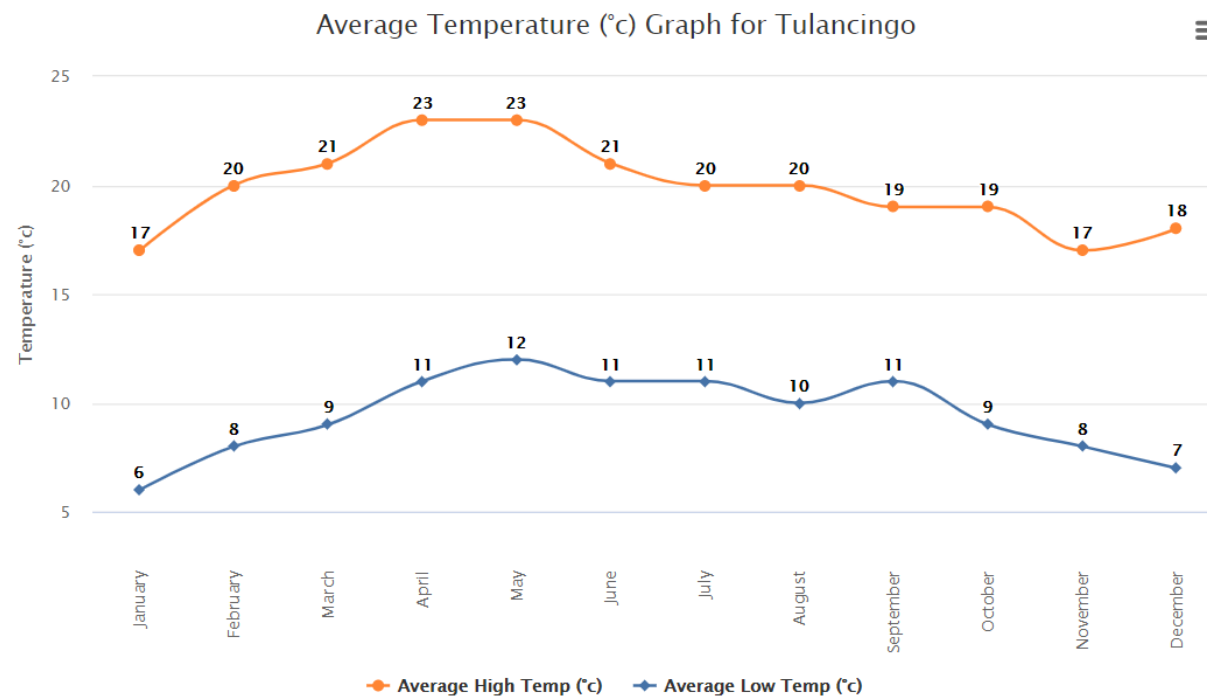
The most effective strategy in Hermosillo is the reflective roof, where a higher albedo gives a greater cooling effect. Limited improvement was seen for the polished steel roof material, increased window size and steeper roof. Benefits of the strategies in summer exceed the penalty in winter, as the winter condition is not significantly worsened, while the summer condition is significantly improved.

Tulancingo Summer



Oceanic climate (Cfb)

Monthly Average Temperature



Tulancingo Average values (difference from base for May)

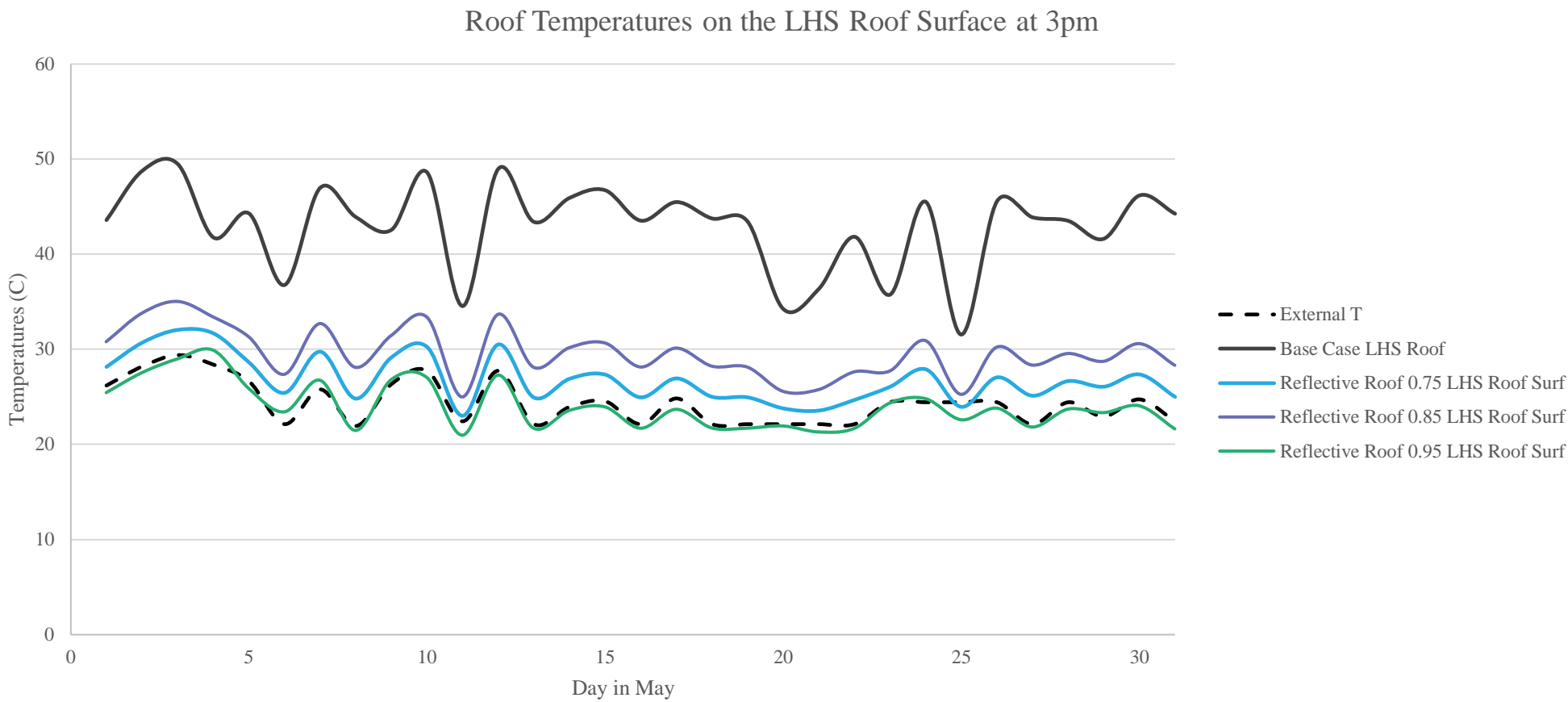
Average difference from base across May									
	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp	
	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left side	Right Side
	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)
Base									
Reflective Roof (0.75)	-0.79	-1.27	-0.34	-1.77	2.25	2.25	-2.16	-5.97	-6.08
Reflective Roof (0.85)	-0.98	-1.55	-0.41	-2.16	2.80	2.80	-2.80	-4.93	-5.03
Reflective Roof (0.95)	-1.19	-1.83	-0.49	-2.57	3.41	3.41	-3.63	-7.00	-7.13
Larger Window	-0.06	-0.04	-0.01	-0.06	0.16	0.16	0.63	-0.01	0.00
Orientation +45°	0.25	0.43	0.12	0.59	-0.84	-0.84	0.52	0.22	0.05
Orientation +90°	0.37	0.68	0.18	0.92	-1.19	-1.19	0.74	0.39	0.05
Orientation +135°	0.25	0.44	0.12	0.60	-0.79	-0.79	0.51	0.35	-0.06
Orientation +180°	0.01	0.02	0.01	0.03	-0.05	-0.05	0.02	0.18	-0.15
Orientation +225°	0.27	0.49	0.13	0.66	-0.90	-0.90	0.57	0.24	0.08
Orientation +270°	0.37	0.71	0.19	0.96	-1.19	-1.19	0.77	0.22	0.23
Orientation +315°	0.23	0.42	0.11	0.57	-0.74	-0.74	0.51	0.10	0.17
Flat Roof	0.00	0.02	0.01	0.03	0.00	0.00	0.35	-0.09	
Steeper Roof	0.04	0.00	0.00	0.00	-0.11	-0.11	-0.59	0.08	0.22
Insulation	0.22	0.29	0.08	0.39	-0.66	-0.66	0.03	0.09	0.09
Steel sheet roofing (polished)	-0.85	-1.35	-0.36	-1.88	2.41	2.41	-2.36	-5.23	-5.33
Steel sheet roofing (weathered)	0.10	0.17	0.05	0.24	-0.28	-0.28	0.24	0.41	0.41
Flat on Ground	0.04	0.04	0.01	0.06	-0.09	-0.09	0.00	0.01	0.01

Tulancingo Average values (absolute averages over all hours in May)

	Absolute Values										
	External	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp		Op Tdiff
	Tdry	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left Side	Right Side	
	(°C)	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)	(°C)
Base	17.61	19.33	20.02	-0.84	66.18	66.97	66.97	9.07	23.66	23.82	
Reflective Roof (0.75)	17.61	18.53	18.75	-1.18	64.42	69.22	69.22	6.92	17.70	17.75	-1.27
Reflective Roof (0.85)	17.61	18.34	18.48	-1.25	64.02	69.77	69.77	6.27	18.73	18.80	-1.55
Reflective Roof (0.95)	17.61	18.14	18.19	-1.33	63.62	70.38	70.38	5.44	16.66	16.69	-1.83
Larger Window	17.61	19.26	19.98	-0.85	66.13	67.13	67.13	9.70	23.66	23.82	-0.04
Orientation +45°	17.61	19.58	20.46	-0.72	66.77	66.13	66.13	9.59	23.88	23.88	0.43
Orientation +90°	17.61	19.69	20.70	-0.66	67.11	65.78	65.78	9.82	24.05	23.88	0.68
Orientation +135°	17.61	19.57	20.46	-0.72	66.78	66.18	66.18	9.59	24.01	23.77	0.44
Orientation +180°	17.61	19.34	20.04	-0.83	66.21	66.93	66.93	9.10	23.84	23.67	0.02
Orientation +225°	17.61	19.59	20.51	-0.71	66.84	66.08	66.08	9.64	23.90	23.90	0.49
Orientation +270°	17.61	19.69	20.73	-0.65	67.15	65.78	65.78	9.85	23.89	24.06	0.71
Orientation +315°	17.61	19.56	20.44	-0.73	66.75	66.23	66.23	9.58	23.76	23.99	0.42
Flat Roof	17.61	19.33	20.04	-0.83	66.22	66.97	66.97	9.42	23.57		0.02
Steeper Roof	17.61	19.36	20.02	-0.84	66.18	66.86	66.86	8.48	23.74	24.05	0.00
Insulation	17.61	19.54	20.31	-0.76	66.57	66.31	66.31	9.11	23.76	23.91	0.29
Steel sheet roofing (polished)	17.61	18.48	18.67	-1.20	64.30	69.38	69.38	6.72	18.44	18.49	-1.35
Steel sheet roofing (weathered)	17.61	19.43	20.20	-0.79	66.42	66.69	66.69	9.31	24.07	24.23	0.17
Flat on Ground	17.61	19.37	20.06	-0.83	66.24	66.88	66.88	9.07	23.67	23.83	0.04

Reflective Roof

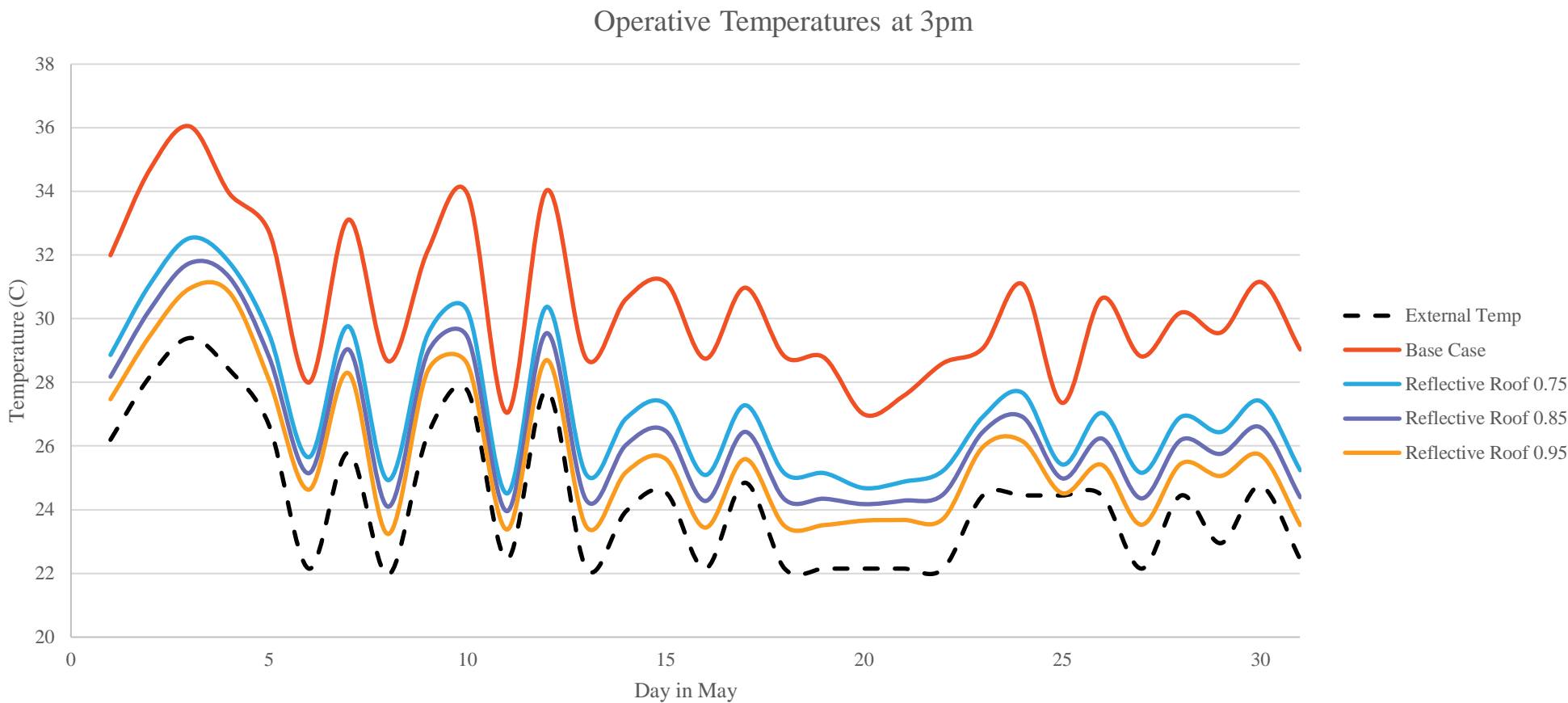
Reflective Roof – Roof Surface Temperatures



The base case has an albedo of 0.27. The painted roofs with higher albedo, reflect more sunlight than the base case, so less heat is absorbed by the roof. This reduces the roof surface temperature and in turn reduces the internal temperature of the house.

Figure 59: Roof surface temperatures for 3pm in May comparing the reflective roof strategies against the base case.

Reflective Roof – Internal Operative Temperatures



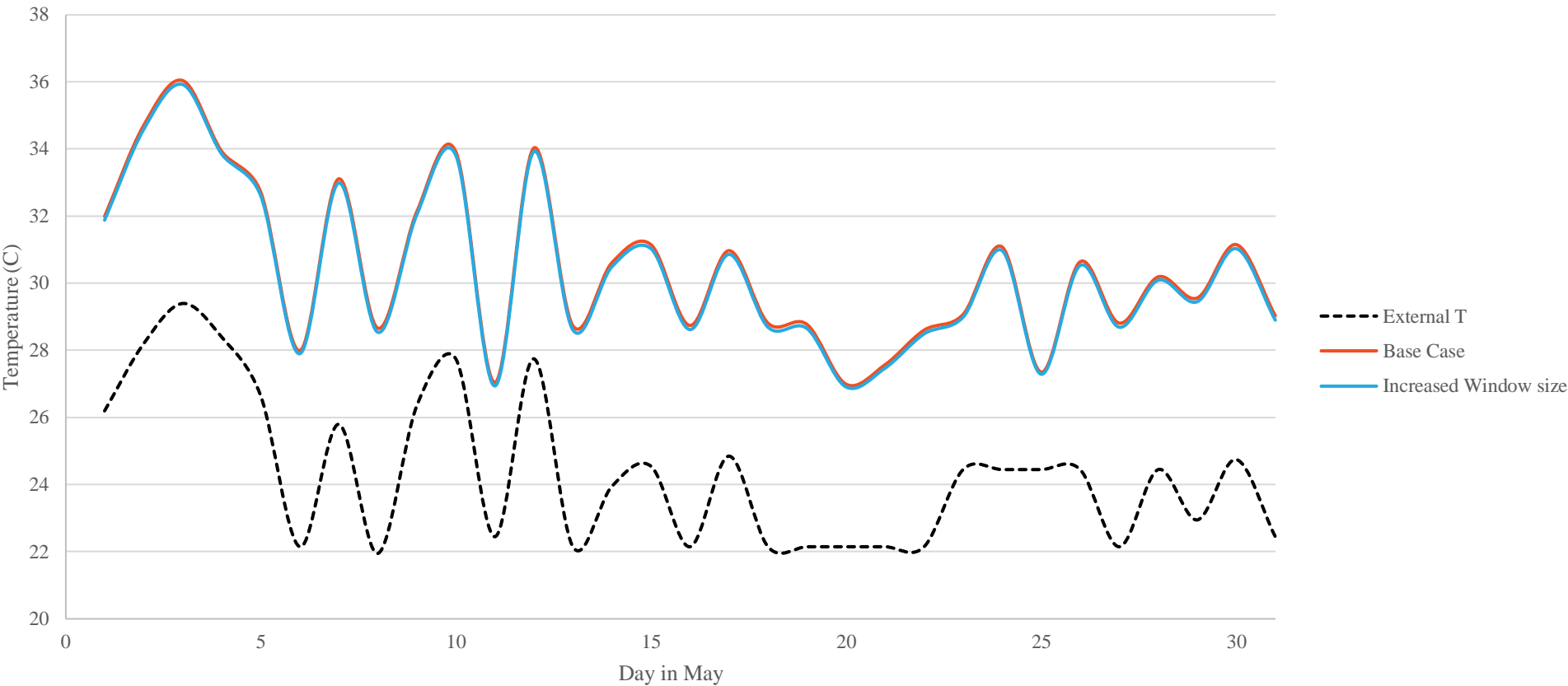
The reduction of the roof surface temperature due to the high albedo surfaces, reduces the internal temperature of the house.

Figure 60: Internal operative temperatures for 3pm in May, comparing the reflective roof strategies against the base case.

Increased Window Size

Increased Window Size – Internal Operative Temperatures

Operative Temperatures at 3pm

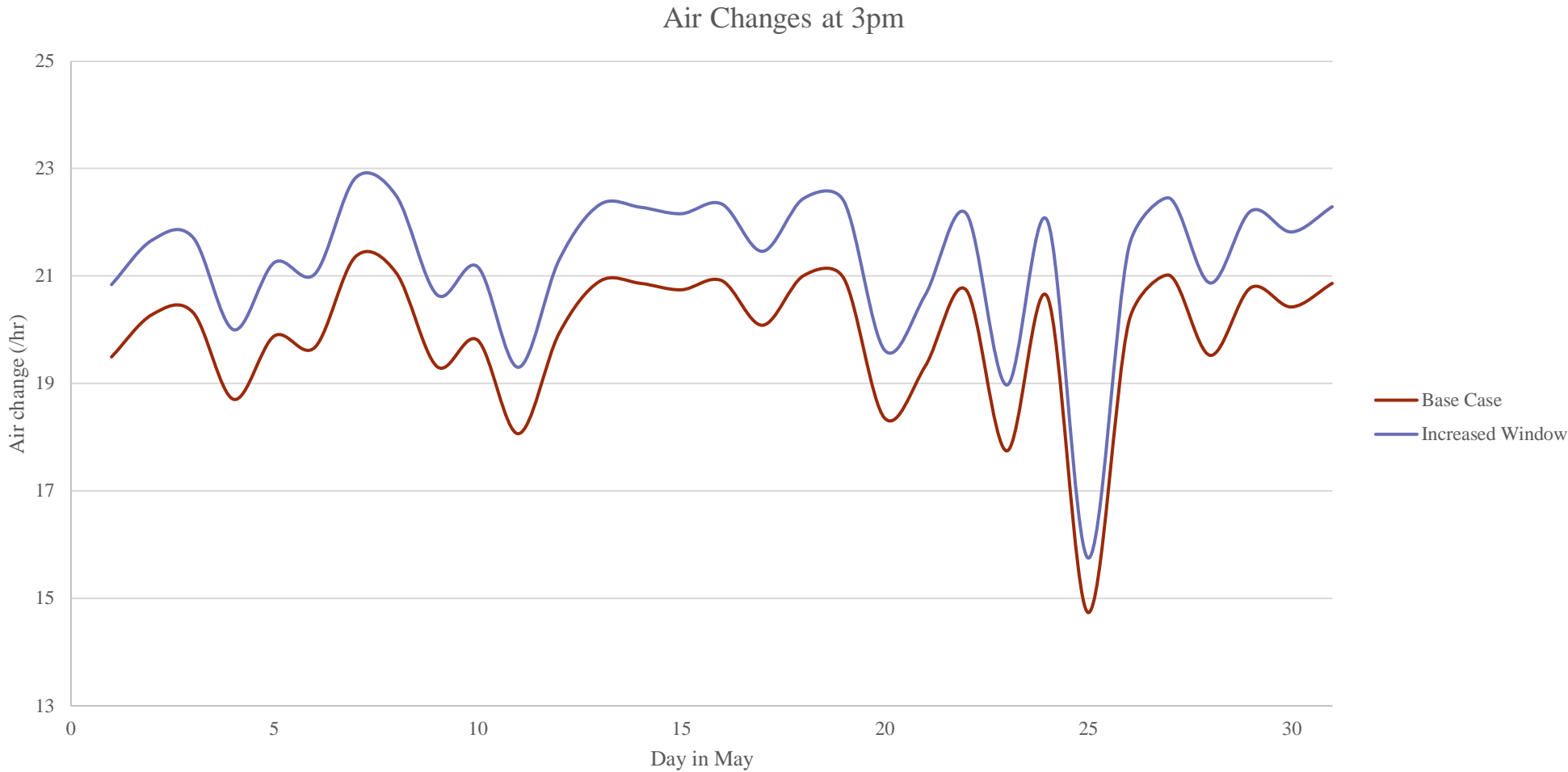


Increasing the window size gives a slightly cooler internal operative temperature due to an increase in ventilation. Since the external temperature is cooler than internal temperatures increasing the ventilation decreases the internal temperatures.

However, increased windows also allow greater solar gains into the room which can cause higher temperatures depending on time of day and building orientation.

Figure 61: Internal operative temperatures for 3pm in May, comparing the increased window strategy against the base case.

Increased Window Size - Air change rates



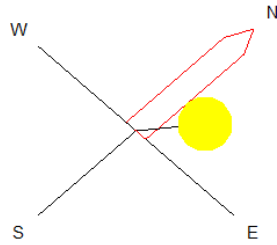
The air change rate is higher for the increased window case than the base case, as expected due to an increase in ventilation. While the difference in air change rate between the cases is notable, the difference in temperatures is much less so.

It is important to note that our models do not account for wind/wind speeds so the improvement in air change shown is conservative.

It is likely that, on a breezy day the increased window size would be more effective at cooling the space and increasing air change rate.

Figure 62: Air change rate for 3pm in May. Increasing the window size increases the air change rate but has a smaller effect on operative temperature.

Orientation



Building Orientation – 9.30am

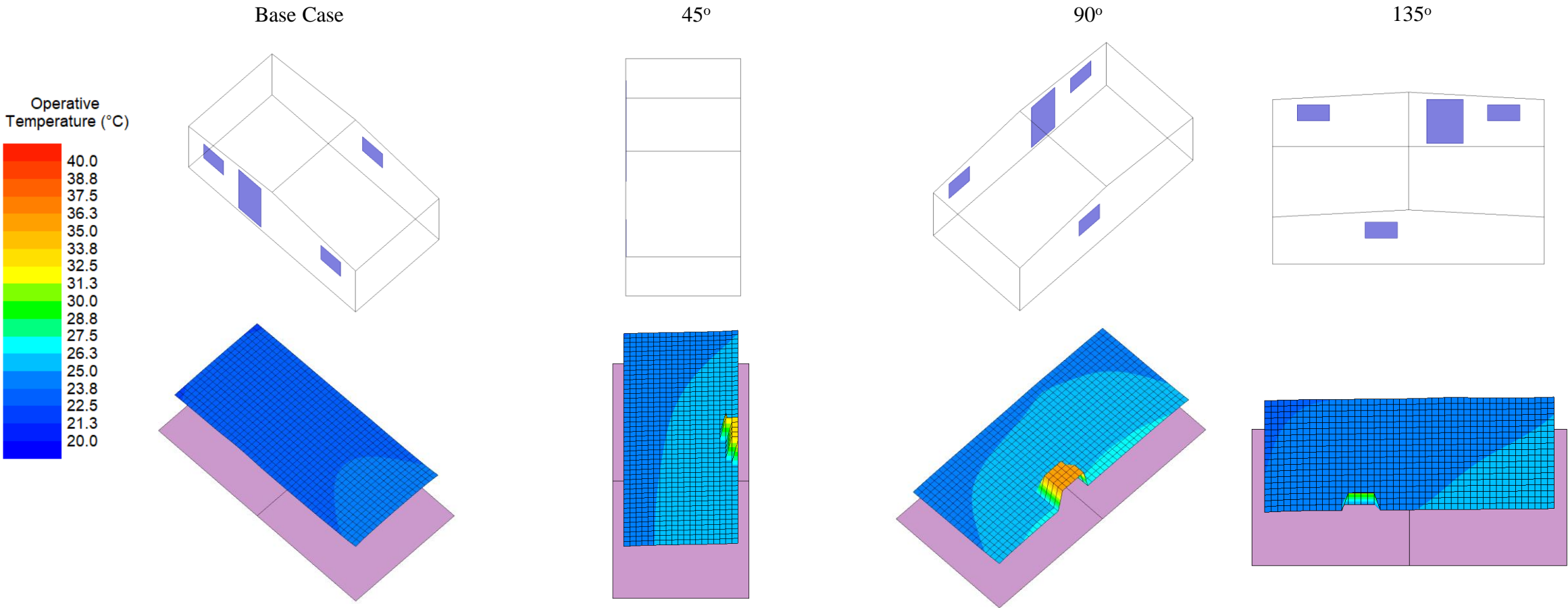
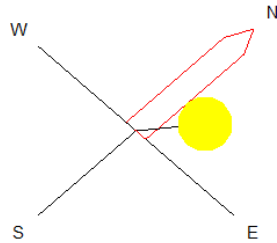


Figure 63a: Spatial operative temperatures for 9.30am in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 17°C.



Building Orientation – 9.30am

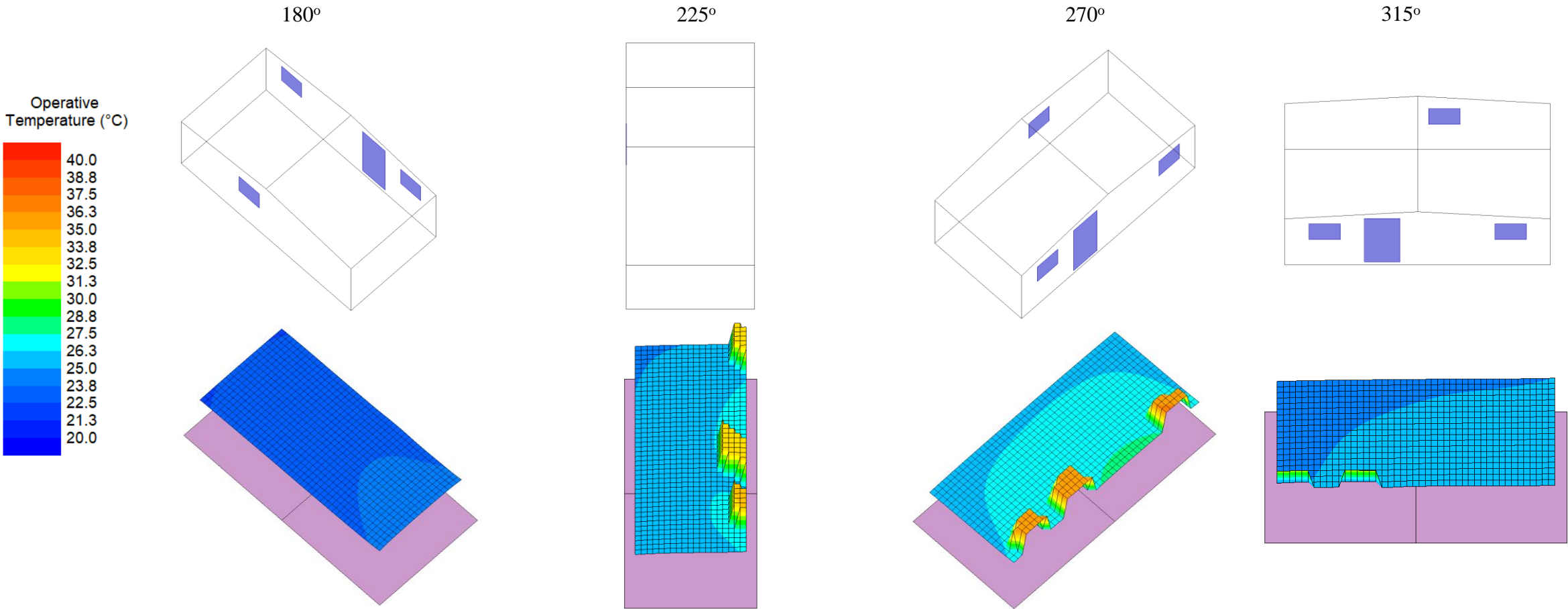
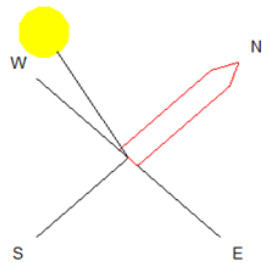


Figure 63b: Spatial operative temperatures for 9.30am in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 17°C.



Building Orientation – 4.30pm

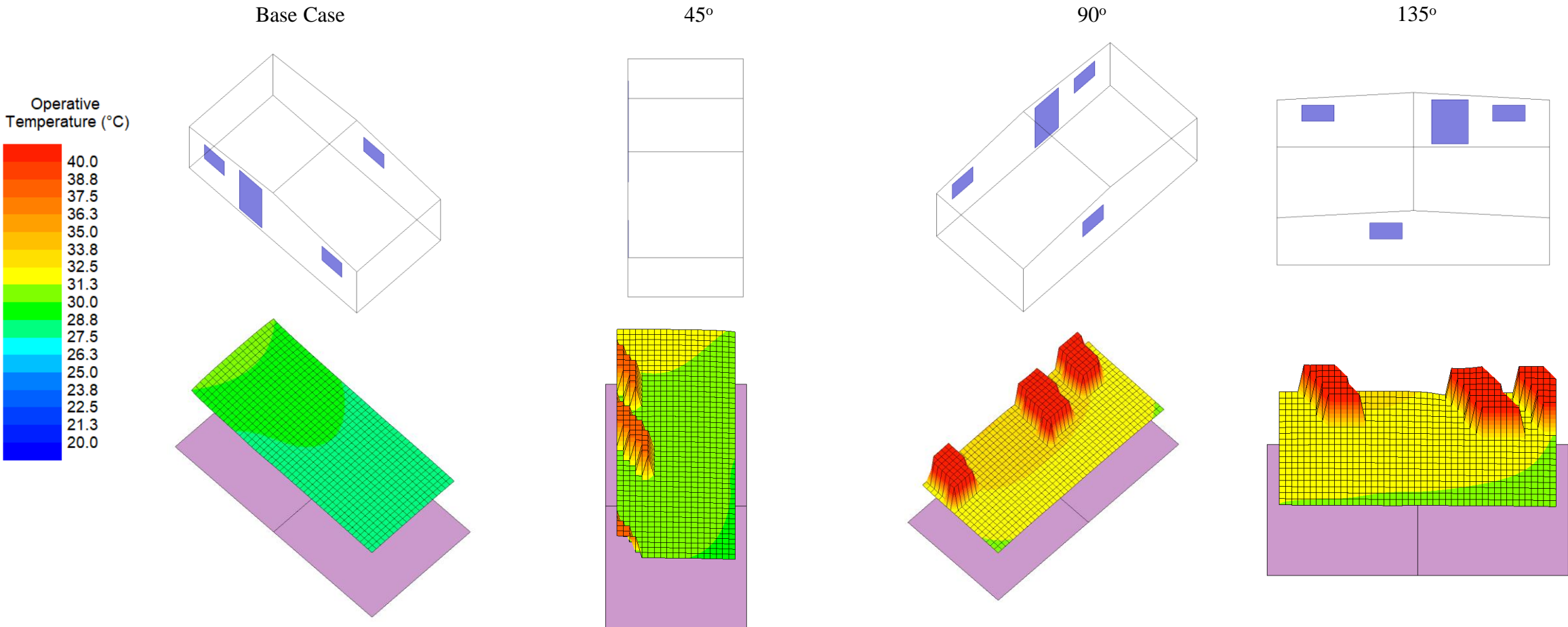
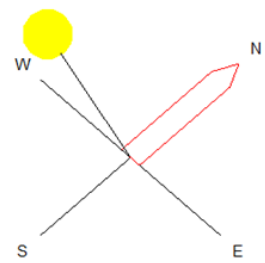


Figure 64a: Spatial operative temperatures for 5.30am in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 23.5°C.



Building Orientation – 4.30pm

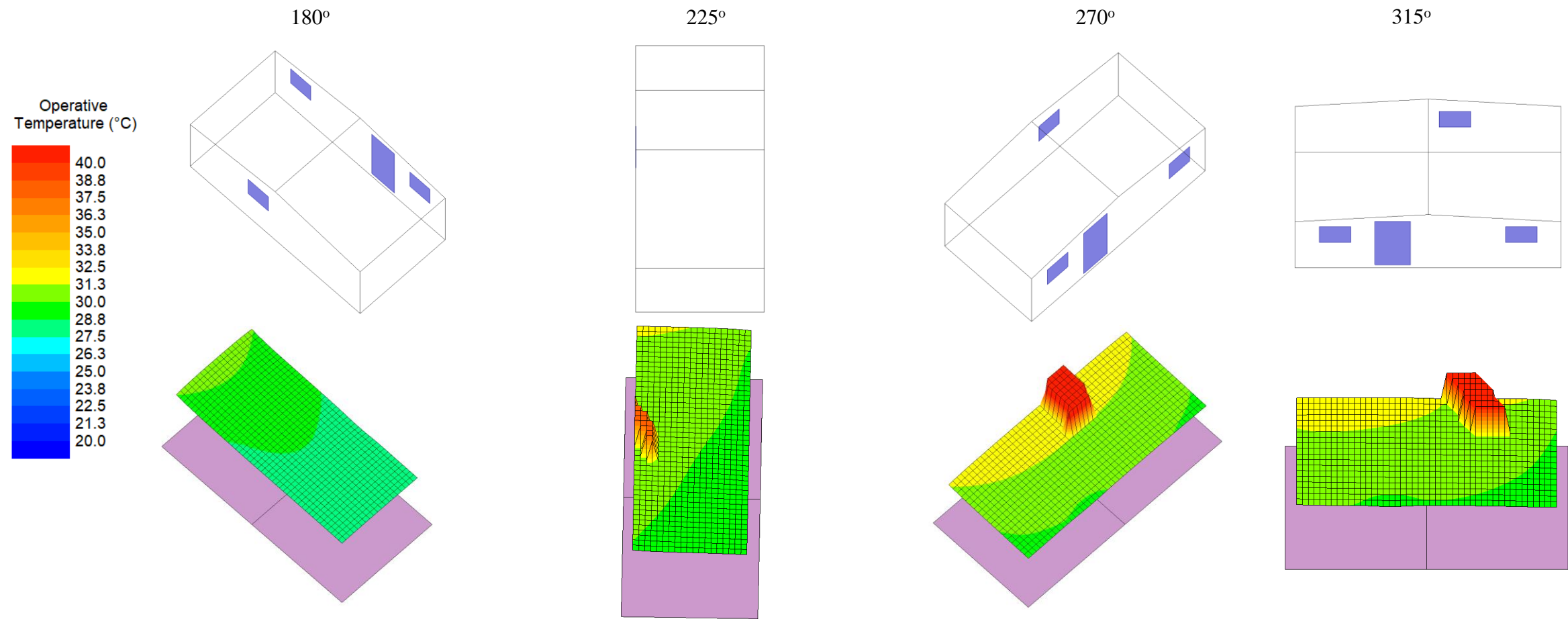


Figure 64b: Spatial operative temperatures for 5.30am in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 23.5°C.

Building Orientation

The base case in Figure 63a, 64a shows lower temperatures than the other orientations at both 9.30am and 4.30pm. This is because there are no windows facing east or west during the day, to let in sunlight and cause higher solar gain.

Looking at the 90° case in Figure 64a, it is clear that the heat spikes inside the building are due to the window positioning which allows high solar gain at the hottest part of the day. This is further demonstrated in Figure 65, where the base case consistently has the lowest temperatures, while the 90° case has the highest temperatures.

The results of examining building orientation on temperature highlight the effectiveness of interventions that reduce solar gains. Using blinds would also improve internal temperatures by reducing solar gains, regardless of building orientation.

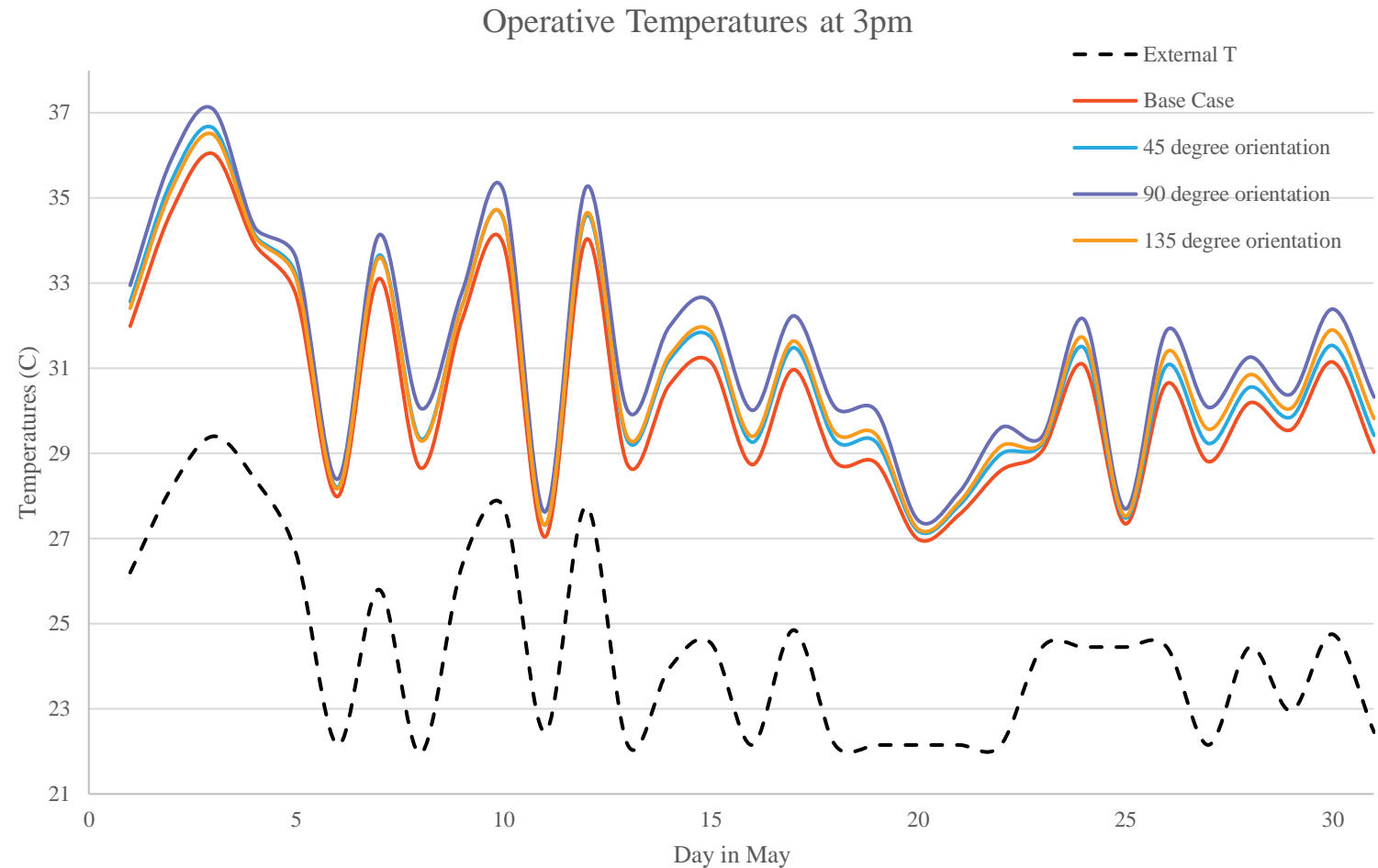


Figure 65: Internal operative temperatures for 3pm in May, comparing different orientations.

Steeper Roof & Flat Roof

Roof Pitch

For the base case, the roof is orientated parallel to the path of the sun during the day, with the windows perpendicular to the sun. This means that changing the roof pitch has little effect on the roof temperatures and therefore the internal temperatures as the sun is heating the roof all day regardless of pitch.

Later, we will investigate the impact of roof pitch on the building oriented perpendicular to the path of the sun.

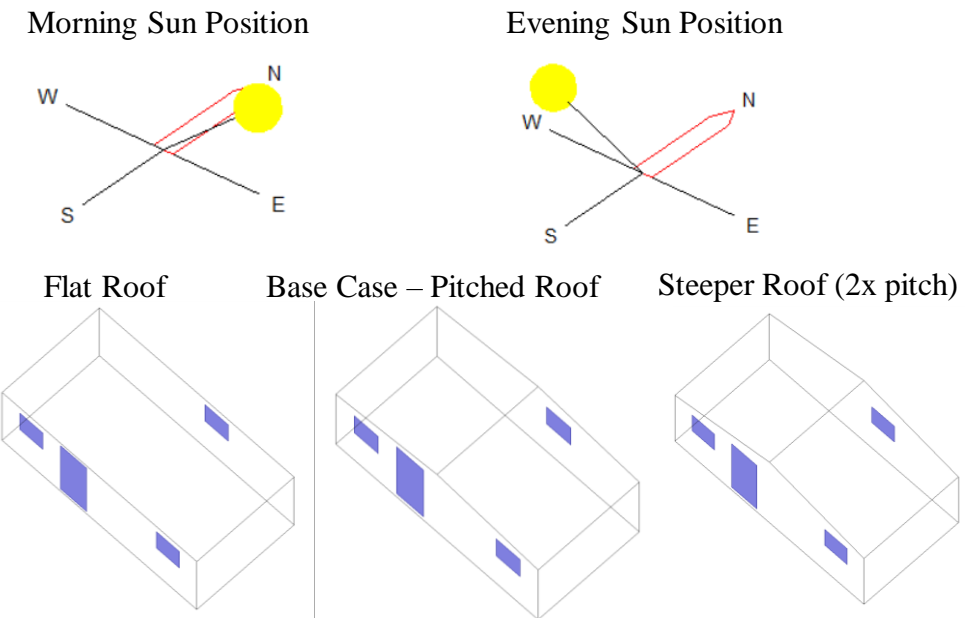


Figure 66: Models of flat roof, base case and steeper roof.

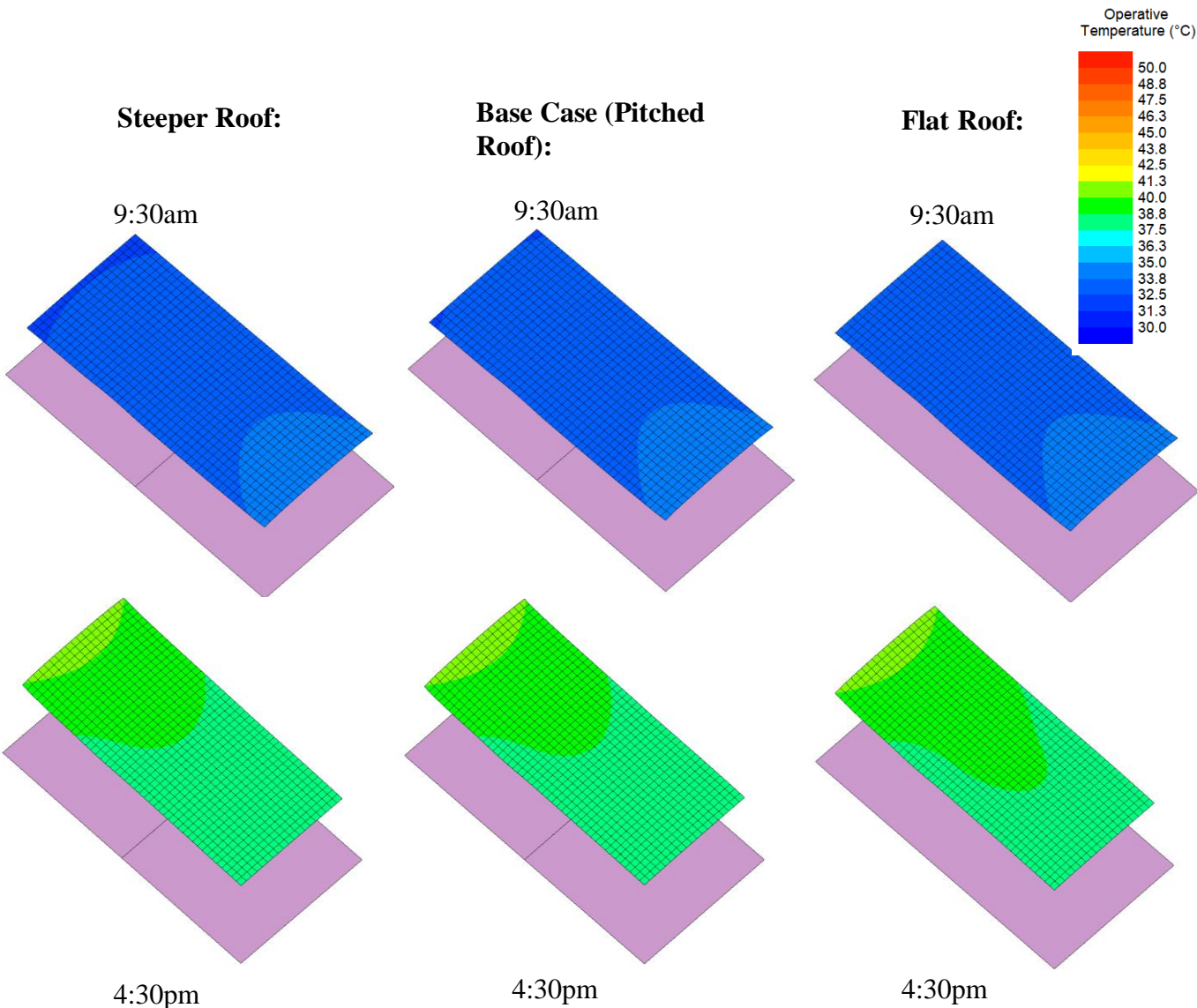
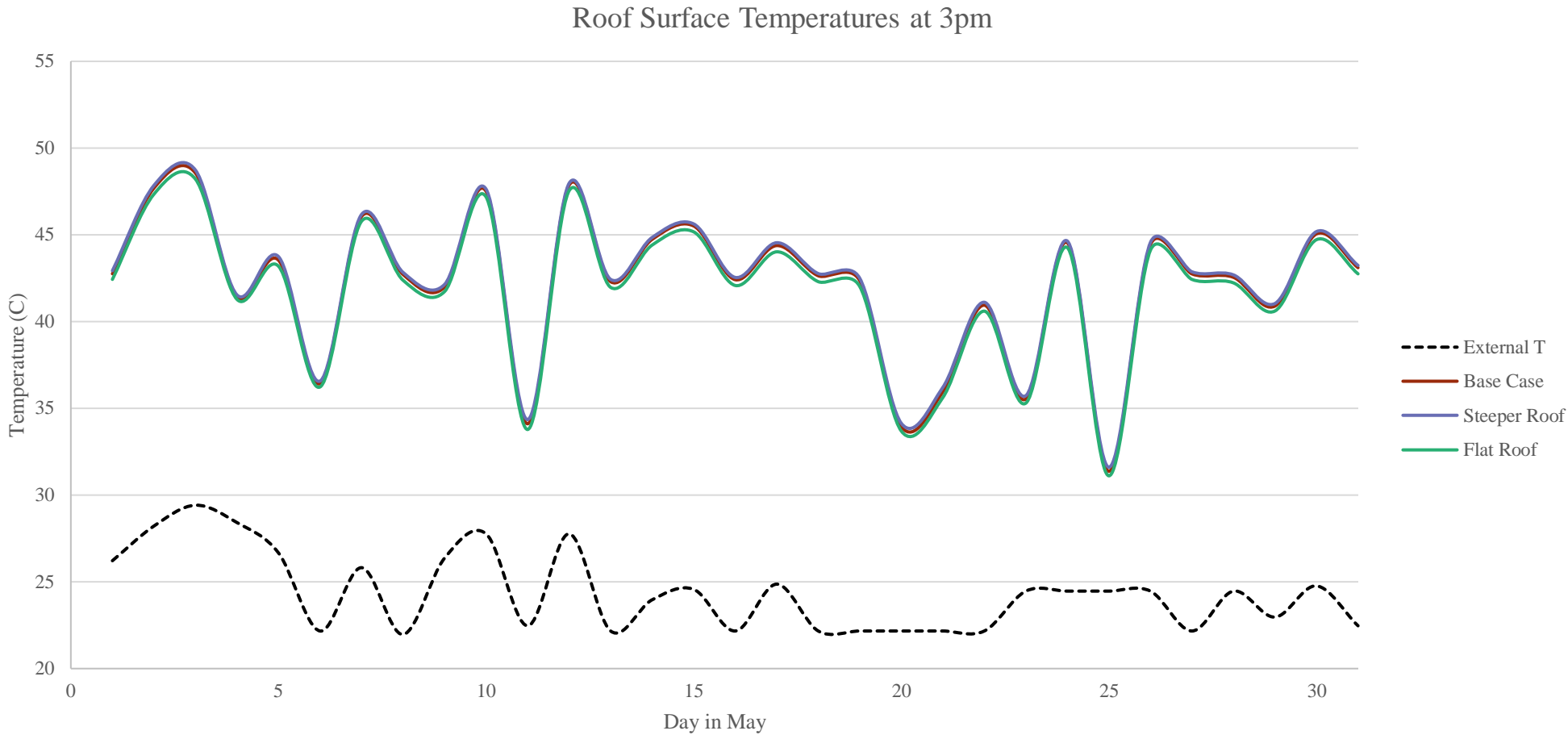


Figure 67: Spatial operative temperatures for 9:30 am and 4:30pm in May.

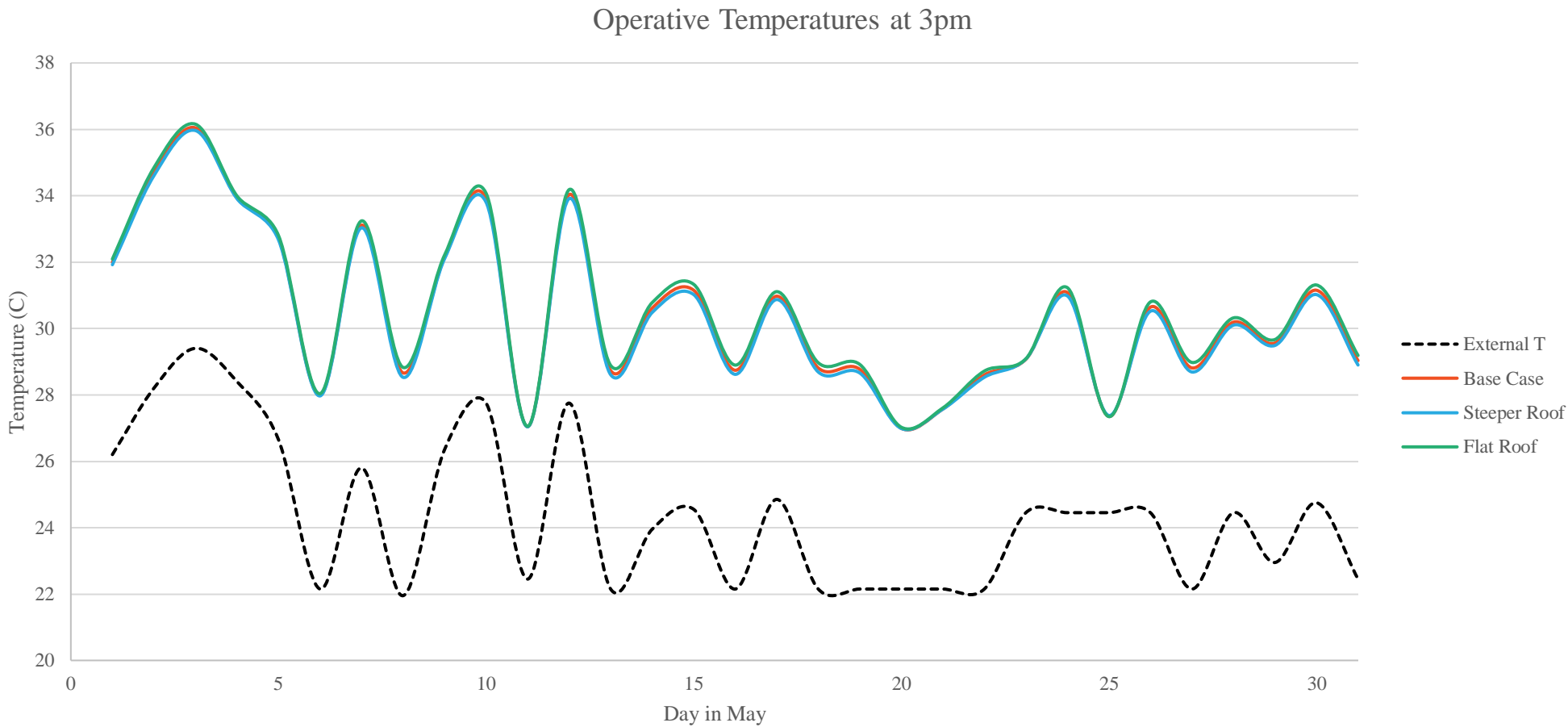
Roof Pitch – Roof Surface Temperatures



Due to the buildings in all cases being oriented with roofs parallel to the path of the sun during the day, the roof pitch has little impact on the roof surface temperature.

Figure 68: Roof surface temperatures for 3pm in May, comparing the flat roof, steeper roof and base cases.

Roof Pitch – Internal Operative Temperatures

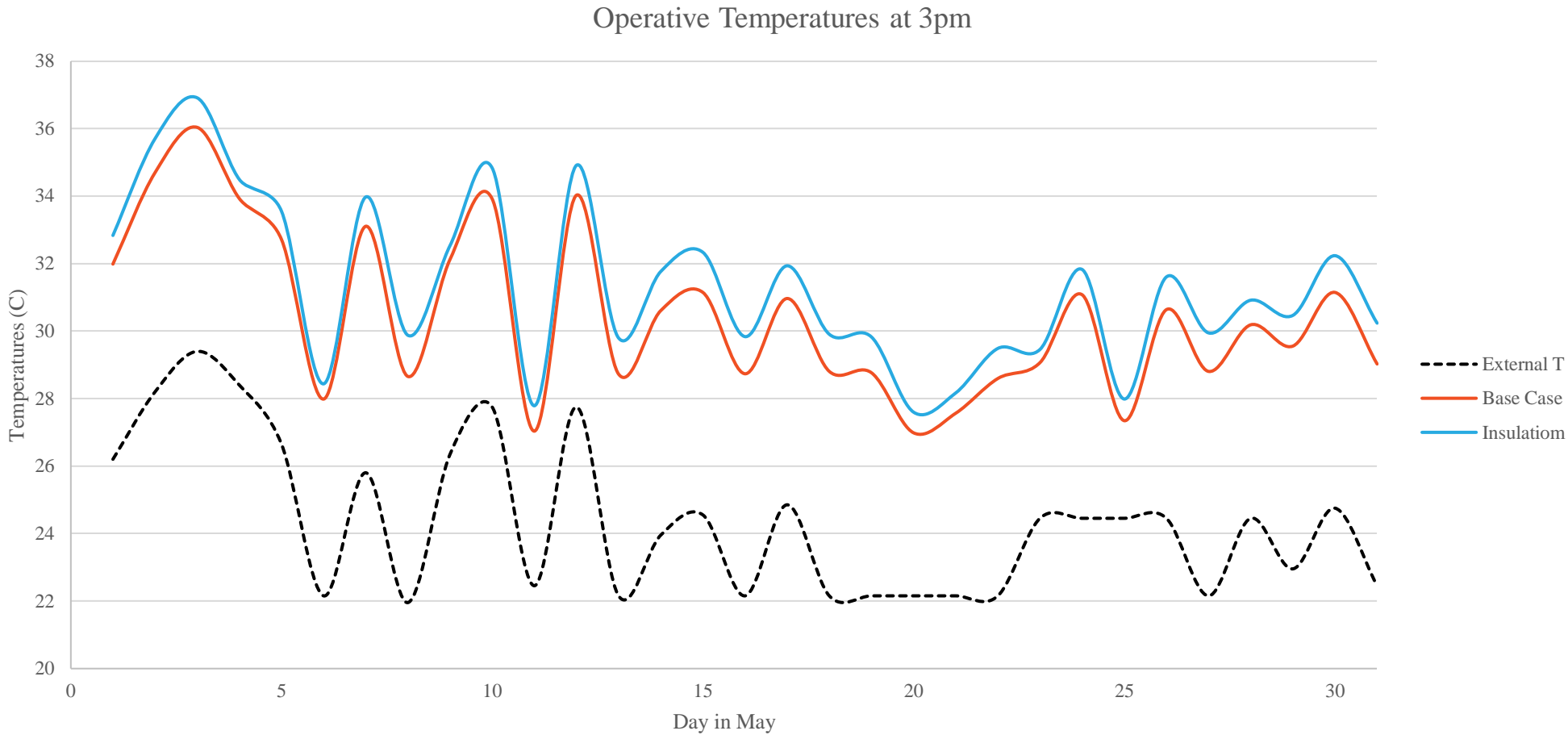


Internal temperatures are similar regardless of roof pitch as roof pitch has little effect on roof surface temperature.

Figure 69: Internal operative temperatures for 3pm in May, comparing the flat roof, steeper roof and base cases.

Insulation

Insulation – Internal Operative Temperatures



Insulation prevents heat loss from the internal space causing slightly higher internal temperatures, as expected.

Figure 70: Internal operative temperatures for 3pm in May, comparing the insulation strategy against the base case.

Steel Sheet Roofing

Steel Sheet Roofing – Internal Operative Temperatures

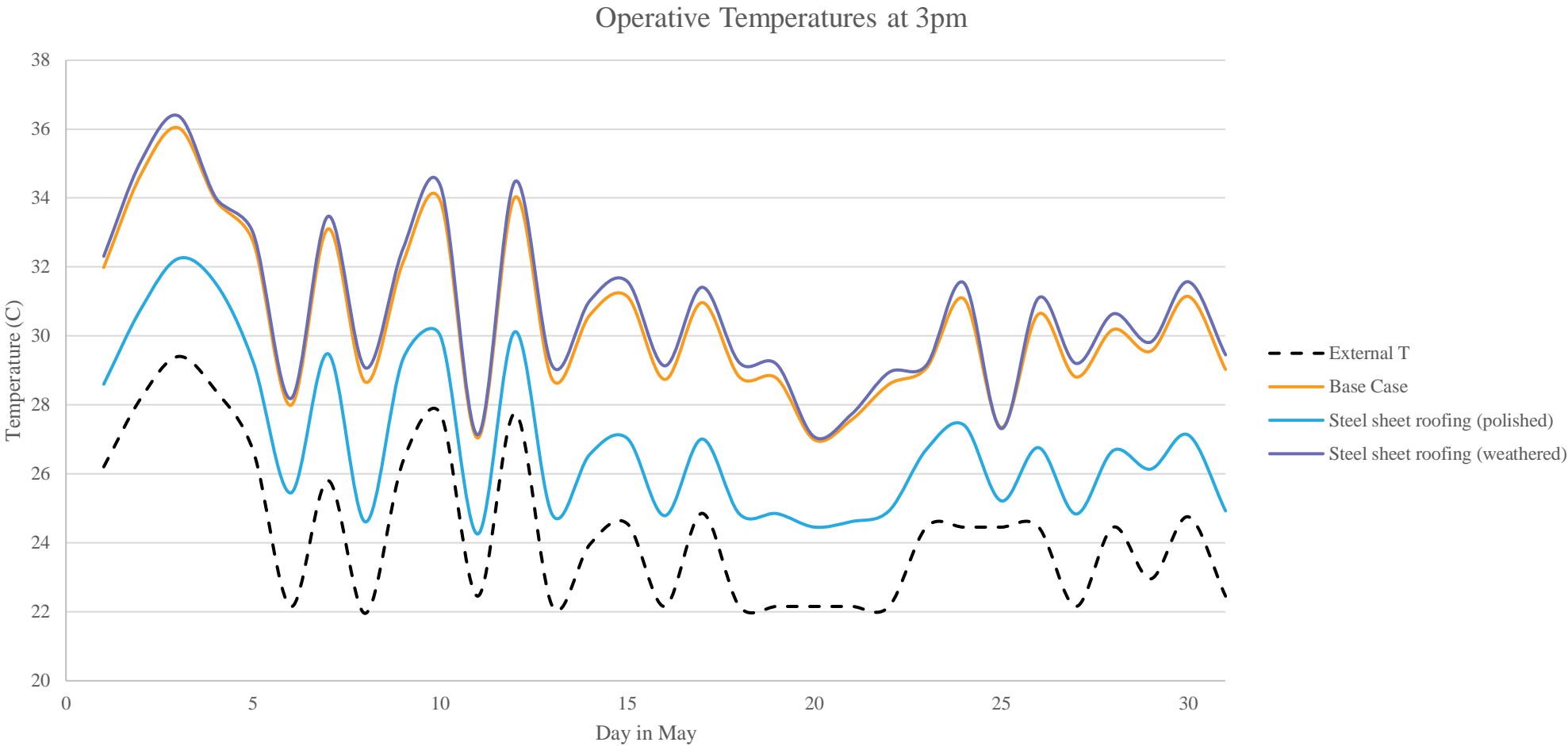


Figure 71: Internal operative temperatures for 3pm in May, comparing the roof material strategies with the base case.

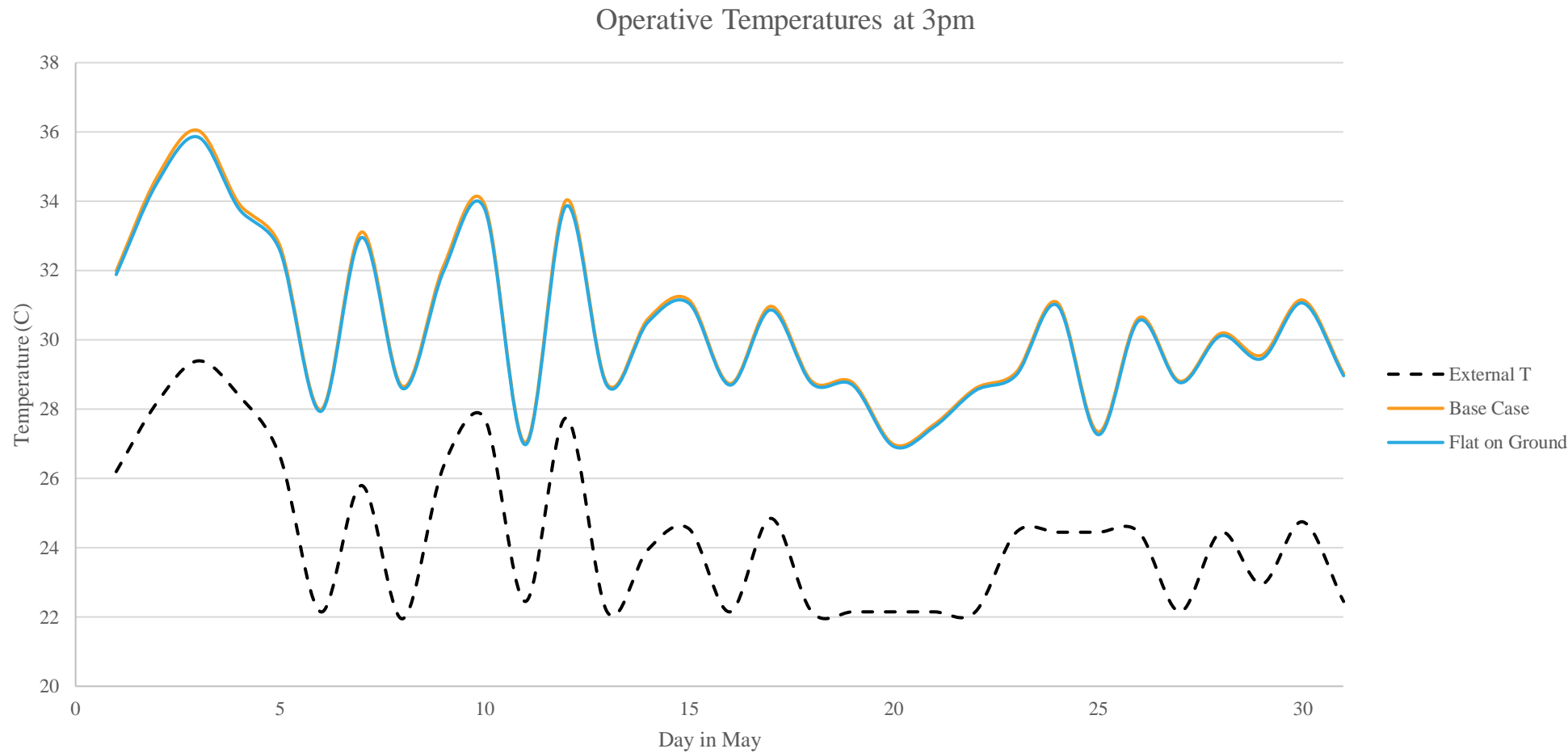
The base case is made up of fibre cement boards with an albedo of 0.27, while the steel sheet roofing has albedos of: 0.25 for weathered and 0.8 for polished.

The weathered steel roof has higher thermal conductivity than the base case roof which gives higher roof surface temperatures and therefore higher internal temperatures. While the polished has a much higher albedo than the other cases causing more sunlight to be reflected away from the roof, reducing roof temperatures and thus internal temperatures.

The weathered steel more closely represents a steel sheet roofing than the polished steel.

Flat on Ground

Flat on Ground – Internal Operative Temperatures

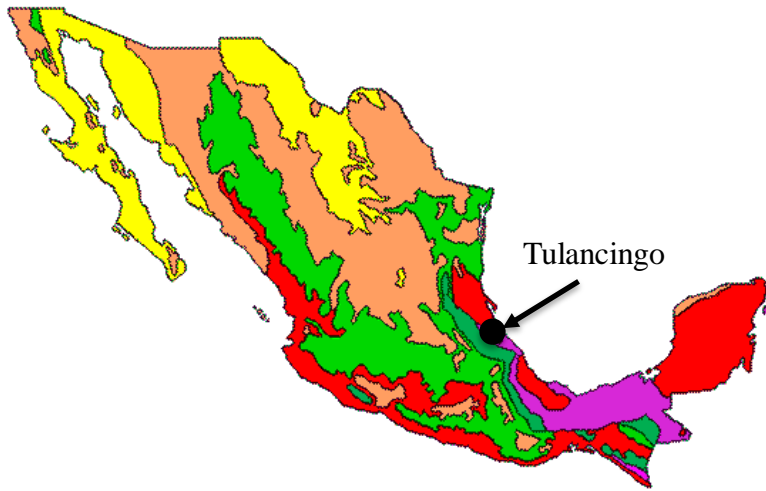


Moving building to be flat on the ground, rather than elevated on stilts (as in the base case) should increase temperatures due to lack of ventilation underneath the building. The ventilation would carry cooler external air underneath the building reducing the temperature.

However, possibly due to no wind being modelled, the two cases have little to no difference in internal temperature..

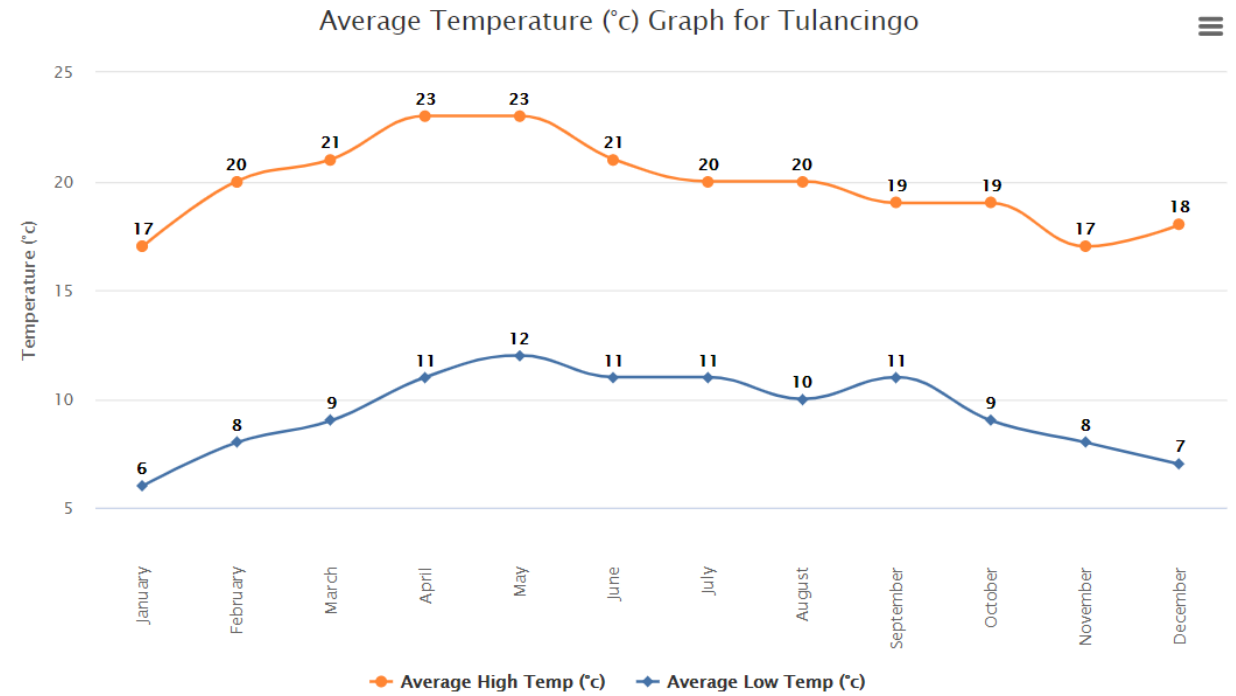
Figure 72: Internal operative temperatures for 3pm in May, comparing the flat on ground strategy against the base case.

Tulancingo Winter



Oceanic climate (Cfb)

Monthly Average Temperature



Tulancingo Average values (difference from base for January)

Average difference from base across January						
	Space temperatures		Indicative	Relative humidity		Air changes
	Dry bulb	Operative	PMV	Occupied	Upper	Natural
	(°C)	(°C)	-	%	%	/hr
Base						
Reflective Roof (0.75)	-0.47	-0.78	-0.20	0.93	0.93	-1.22
Reflective Roof (0.85)	-0.57	-0.94	-0.25	1.14	1.14	-1.53
Reflective Roof (0.95)	-0.68	-1.11	-0.29	1.37	1.37	-1.86
Larger Window	-0.06	-0.03	-0.01	0.12	0.12	0.62
Orientation +45°	-0.11	-0.23	-0.06	0.27	0.27	-0.30
Orientation +90°	-0.11	-0.29	-0.08	0.16	0.16	-0.20
Orientation +135°	-0.20	-0.44	-0.11	0.31	0.31	-0.42
Orientation +180°	-0.11	-0.29	-0.07	0.22	0.22	-0.25
Orientation +225°	-0.19	-0.44	-0.11	0.42	0.42	-0.47
Orientation +270°	-0.11	-0.28	-0.08	0.14	0.14	-0.19
Orientation +315°	-0.57	-0.94	-0.25	1.14	1.14	-1.53
Flat Roof	-0.05	-0.09	-0.02	0.16	0.16	0.26
Steeper Roof	0.07	0.09	0.02	-0.18	-0.18	-0.51
Insulation	0.12	0.12	0.03	-0.30	-0.30	-0.03
Steel sheet roofing (polished)	-0.48	-0.81	-0.21	0.88	0.88	-1.34
Steel sheet roofing (weathered)	0.08	0.12	0.03	-0.23	-0.23	0.11
Flat on Ground	0.11	0.13	0.03	-0.49	-0.49	0.01

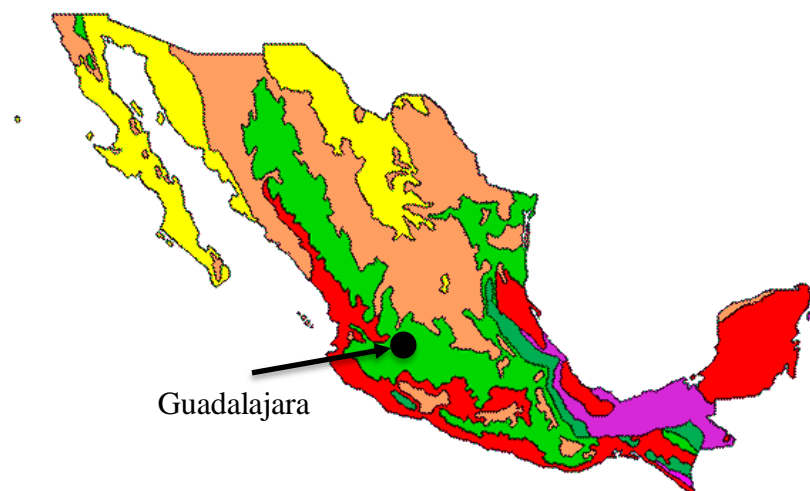
Tulancingo Average values (absolute averages over all hours in January)

Absolute Values									
	External	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Op Tdiff
	Tdry	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	
	(°C)	(°C)	(°C)	-	-	%	%	/hr	(°C)
Base	12.04	13.28	14.07	-2.44	57.47	54.77	54.77	8.77	
Reflective Roof (0.75)	12.04	12.81	13.29	-2.65	56.42	55.70	55.70	7.55	-0.78
Reflective Roof (0.85)	12.04	12.70	13.13	-2.69	56.19	55.92	55.92	7.24	-0.94
Reflective Roof (0.95)	12.04	12.59	12.96	-2.73	55.96	56.14	56.14	6.91	-1.11
Larger Window	12.04	13.22	14.04	-2.45	57.43	54.89	54.89	9.39	-0.03
Orientation +45°	12.04	13.17	13.84	-2.50	57.17	55.04	55.04	8.47	-0.23
Orientation +90°	12.04	13.17	13.78	-2.52	57.09	54.93	54.93	8.57	-0.29
Orientation +135°	12.04	13.08	13.63	-2.56	56.88	55.08	55.08	8.35	-0.44
Orientation +180°	12.04	13.16	13.78	-2.52	57.08	54.99	54.99	8.52	-0.29
Orientation +225°	12.04	13.08	13.63	-2.55	56.88	55.19	55.19	8.30	-0.44
Orientation +270°	12.04	13.16	13.79	-2.52	57.09	54.91	54.91	8.58	-0.28
Orientation +315°	12.04	12.70	13.13	-2.69	56.19	55.92	55.92	7.24	-0.94
Flat Roof	12.04	13.22	13.98	-2.46	57.35	54.94	54.94	9.03	-0.09
Steeper Roof	12.04	13.34	14.16	-2.42	57.60	54.59	54.59	8.26	0.09
Insulation	12.04	13.40	14.18	-2.41	57.63	54.47	54.47	8.74	0.12
Steel sheet roofing (polished)	12.04	12.79	13.26	-2.65	56.37	55.65	55.65	7.43	-0.81
Steel sheet roofing (weathered)	12.04	13.35	14.19	-2.41	57.63	54.54	54.54	8.88	0.12
Flat on Ground	12.04	13.38	14.20	-2.41	57.65	54.28	54.28	8.78	0.13

Tulancingo Summary

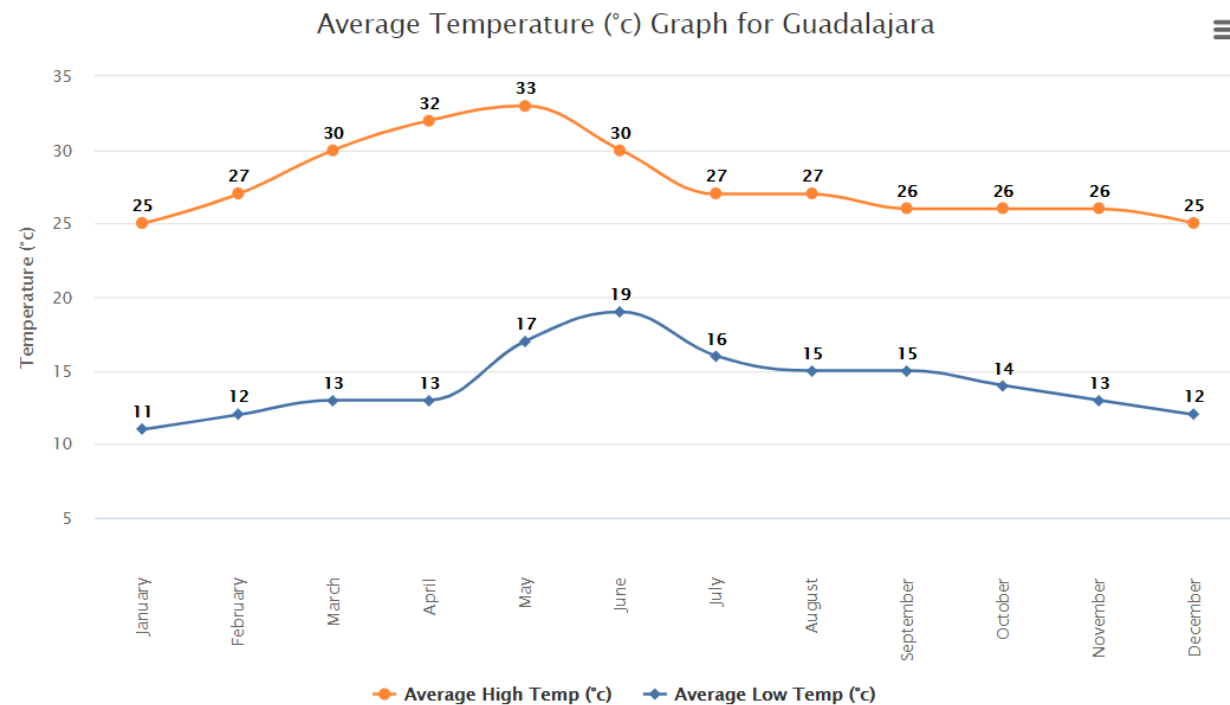
The most effective strategy in Tulancingo is the reflective roof, where a higher albedo gives a greater cooling effect. Limited improvement was seen for polished steel roof material, increased window size and steeper roof. Benefits of the strategies in summer exceed the penalty in winter, as the winter condition is not significantly worsened, while the summer condition significantly improved.

Guadalajara Summer



Humid subtropical climate (Cwa)

Monthly Average Temperature



Guadalajara Average values (difference from base for June)

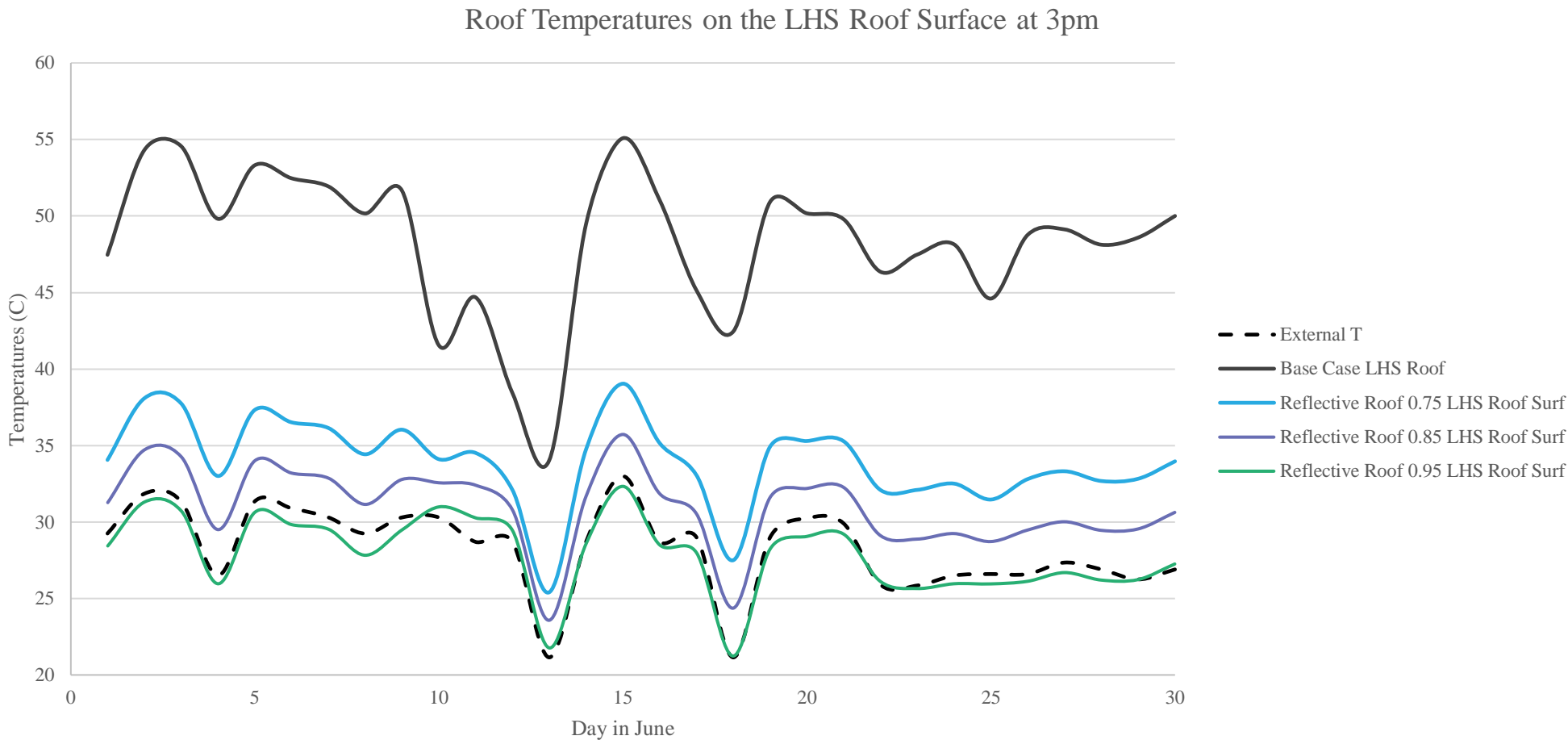
Average difference from base across June									
	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp	
	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left side	Right Side
	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)
Base									
Reflective Roof (0.75)	-0.73	-1.19	-0.33	-1.50	1.91	1.91	-2.10	-4.78	-4.75
Reflective Roof (0.85)	-0.90	-1.45	-0.40	-1.83	2.39	2.39	-2.73	-5.78	-5.74
Reflective Roof (0.95)	-1.08	-1.72	-0.48	-2.17	2.89	2.89	-3.51	-28.56	-28.52
Larger Window	-0.06	-0.04	-0.01	-0.04	0.16	0.16	0.63	0.00	0.00
Orientation +45°	0.16	0.30	0.08	0.38	-0.44	-0.44	0.39	0.16	0.02
Orientation +90°	0.29	0.56	0.16	0.71	-0.76	-0.76	0.63	0.28	0.09
Orientation +135°	0.20	0.38	0.11	0.48	-0.52	-0.52	0.41	0.19	0.08
Orientation +180°	0.02	0.03	0.01	0.04	-0.05	-0.05	0.04	-0.01	0.05
Orientation +225°	0.17	0.36	0.10	0.45	-0.51	-0.51	0.46	0.01	0.22
Orientation +270°	0.27	0.55	0.15	0.69	-0.74	-0.74	0.65	0.05	0.31
Orientation +315°	0.17	0.32	0.09	0.40	-0.44	-0.44	0.38	0.02	0.19
Flat Roof	0.00	0.03	0.01	0.04	0.01	0.01	0.35	-0.18	
Steeper Roof	0.02	-0.02	0.00	-0.03	-0.06	-0.06	-0.60	0.09	0.07
Insulation	0.32	0.38	0.11	0.42	-1.07	-1.07	0.00	0.12	0.12
Steel sheet roofing (polished)	-0.79	-1.29	-0.36	-1.62	2.07	2.07	-2.29	-5.13	-5.09
Steel sheet roofing (weathered)	0.08	0.14	0.04	0.18	-0.20	-0.20	0.25	0.33	0.33
Flat on Ground	0.02	0.03	0.01	0.02	-0.14	-0.14	0.01	0.01	0.01

Guadalajara Average values (absolute averages over all hours in June)

Absolute Values											
	External	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp		Op Tdiff
	Tdry	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left Side	Right Side	
	(°C)	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)	(°C)
Base	22.19	23.99	24.72	0.44	72.42	60.54	60.54	9.13	28.56	28.52	
Reflective Roof (0.75)	22.19	23.27	23.53	0.11	70.92	62.45	62.45	7.02	23.78	23.78	-1.19
Reflective Roof (0.85)	22.19	23.10	23.27	0.04	70.59	62.92	62.92	6.40	22.79	22.78	-1.45
Reflective Roof (0.95)	22.19	22.91	23.00	-0.03	70.25	63.43	63.43	5.61	0.00	0.00	-1.72
Larger Window	22.19	23.93	24.68	0.43	72.38	60.70	60.70	9.76	28.56	28.52	-0.04
Orientation +45°	22.19	24.15	25.02	0.52	72.80	60.10	60.10	9.51	28.72	28.54	0.30
Orientation +90°	22.19	24.28	25.28	0.60	73.13	59.78	59.78	9.75	28.84	28.61	0.56
Orientation +135°	22.19	24.20	25.10	0.55	72.90	60.02	60.02	9.53	28.76	28.60	0.38
Orientation +180°	22.19	24.01	24.75	0.45	72.46	60.49	60.49	9.16	28.55	28.57	0.03
Orientation +225°	22.19	24.17	25.08	0.54	72.87	60.03	60.03	9.58	28.57	28.75	0.36
Orientation +270°	22.19	24.26	25.27	0.59	73.12	59.80	59.80	9.78	28.61	28.83	0.55
Orientation +315°	22.19	24.16	25.04	0.53	72.82	60.10	60.10	9.51	28.58	28.71	0.32
Flat Roof	22.19	24.00	24.75	0.45	72.46	60.55	60.55	9.47	28.39		0.03
Steeper Roof	22.19	24.01	24.70	0.44	72.39	60.48	60.48	8.53	28.65	28.59	-0.02
Insulation	22.19	24.32	25.10	0.55	72.84	59.47	59.47	9.12	28.68	28.64	0.38
Steel sheet roofing (polished)	22.19	23.20	23.43	0.09	70.80	62.61	62.61	6.84	23.44	23.43	-1.29
Steel sheet roofing (weathered)	22.19	24.07	24.86	0.48	72.61	60.34	60.34	9.37	28.89	28.85	0.14
Flat on Ground	22.19	24.02	24.74	0.45	72.44	60.40	60.40	9.14	28.57	28.53	0.03

Reflective Roof

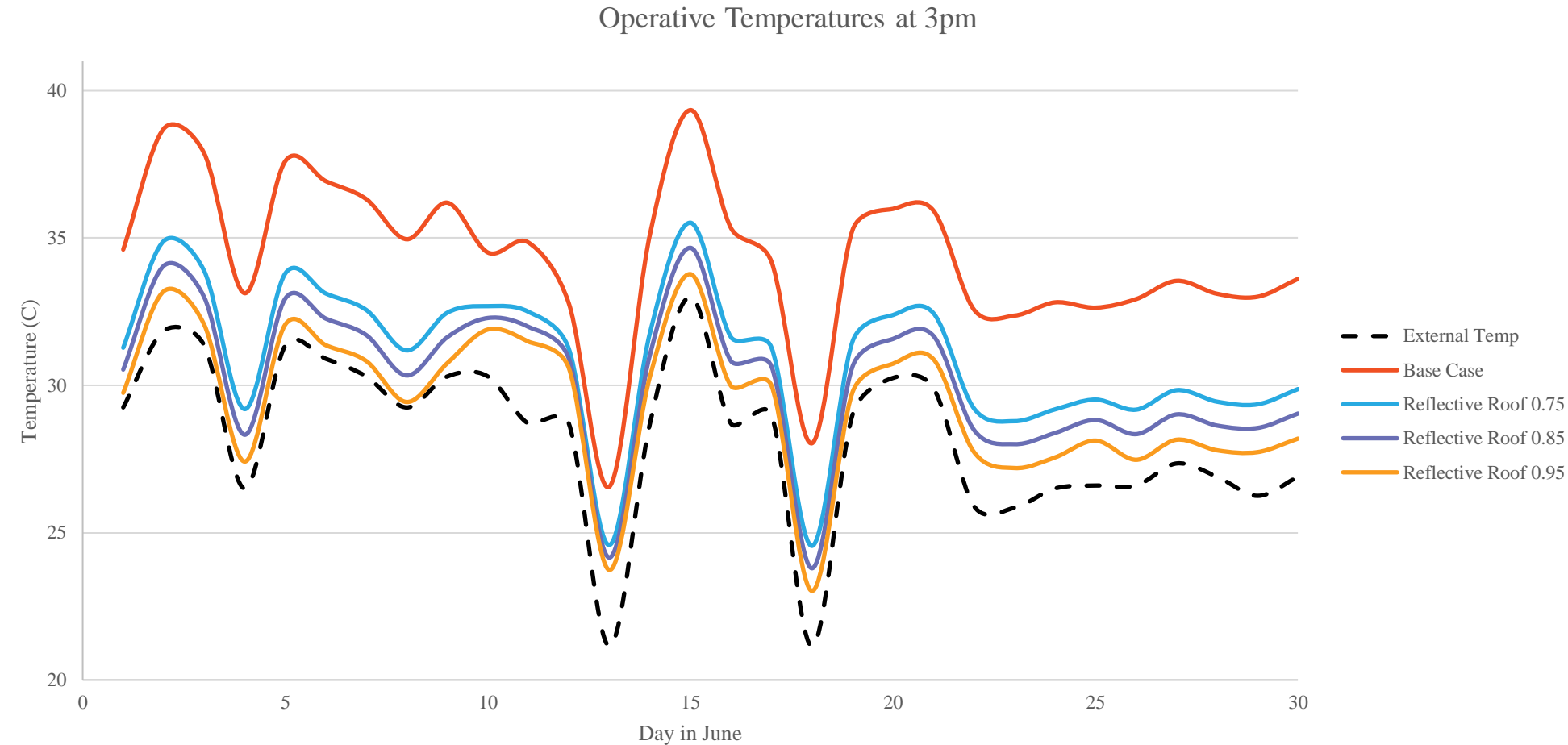
Reflective Roof – Roof Surface Temperatures



The base case has an albedo of 0.27. The painted roofs with higher albedo, reflect more sunlight than the base case, so less heat is absorbed by the roof. This reduces the roof surface temperature and in turn reduces the internal temperature of the house.

Figure 74: Roof surface temperatures for 3pm in June, comparing the reflective roof strategies against the base case.

Reflective Roof – Internal Operative Temperatures

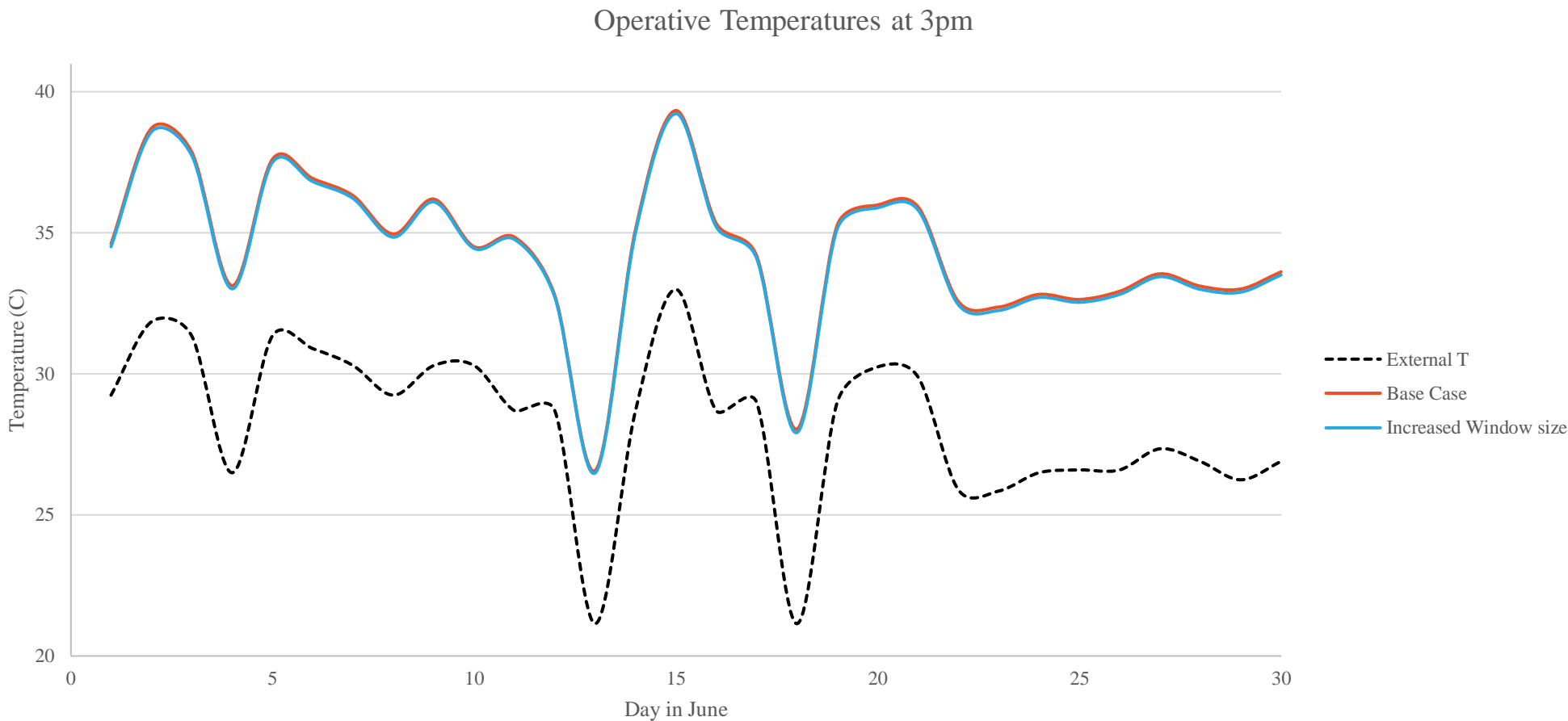


The reduction of the roof surface temperature due to the high albedo surfaces, reduces the internal temperature of the house.

Figure 73: Internal operative temperatures for 3pm in June, comparing the reflective roof strategies against the base case.

Increased Window Size

Increased Window Size – Internal Operative Temperatures

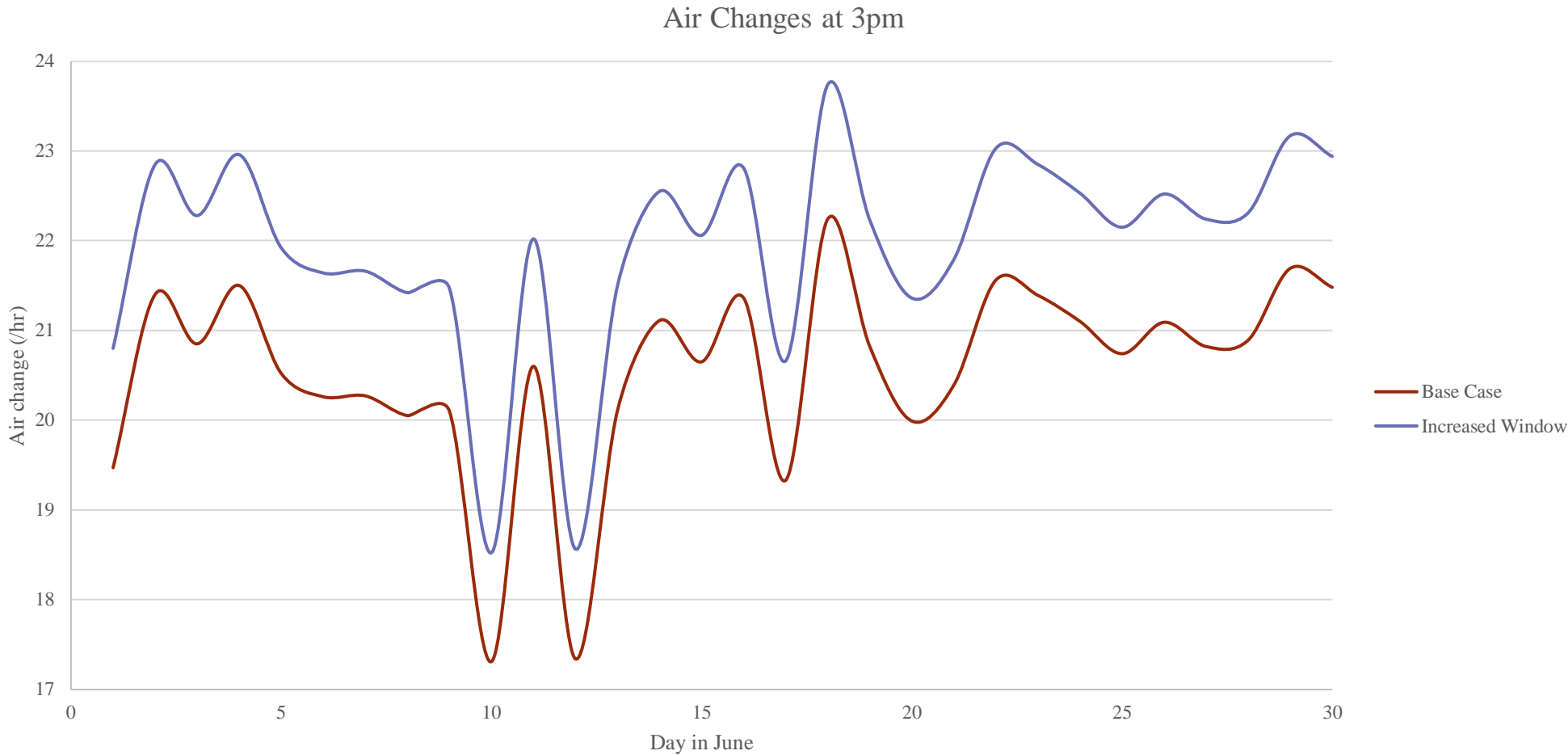


Increasing the window size gives a slightly cooler internal operative temperature due to an increase in ventilation. Since the external temperature is cooler than internal temperatures increasing the ventilation decreases the internal temperatures.

However, increased windows also allow greater solar gains into the room which can cause higher temperatures depending on time of day and building orientation.

Figure 75: Internal operative temperatures for 3pm in June, comparing the increased window strategy against the base case. Increasing the window size gives a slightly cooler internal operative temperature.

Increased Window Size - Air change rates



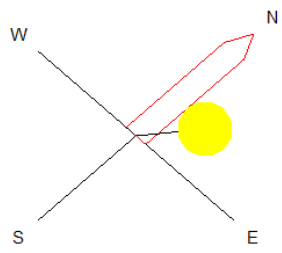
The air change rate is higher for the increased window case than the base case, as expected due to an increase in ventilation. While the difference in air change rate between the cases is notable, the difference in temperatures is much less so.

It is important to note that our models do not account for wind/wind speeds so the improvement in air change shown is conservative.

It is likely that, on a breezy day the increased window size would be more effective at cooling the space and increasing air change rate.

Figure 76: Air change rate for 3pm in June. Increasing the window size increases the air change rate but has a smaller effect on operative temperature.

Orientation



Building Orientation – 9.30am

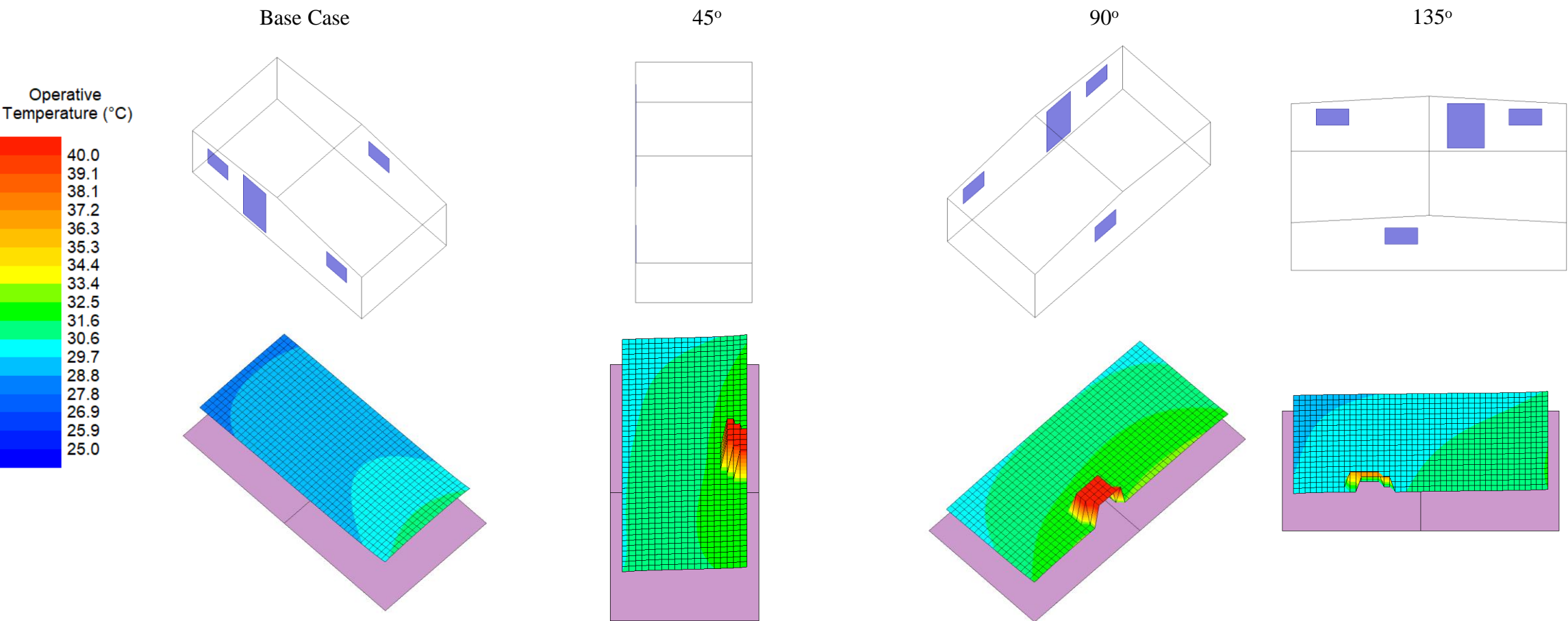


Figure 77a: Spatial operative temperatures for 9.30am in June for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 23.3°C.

Building Orientation – 9.30am

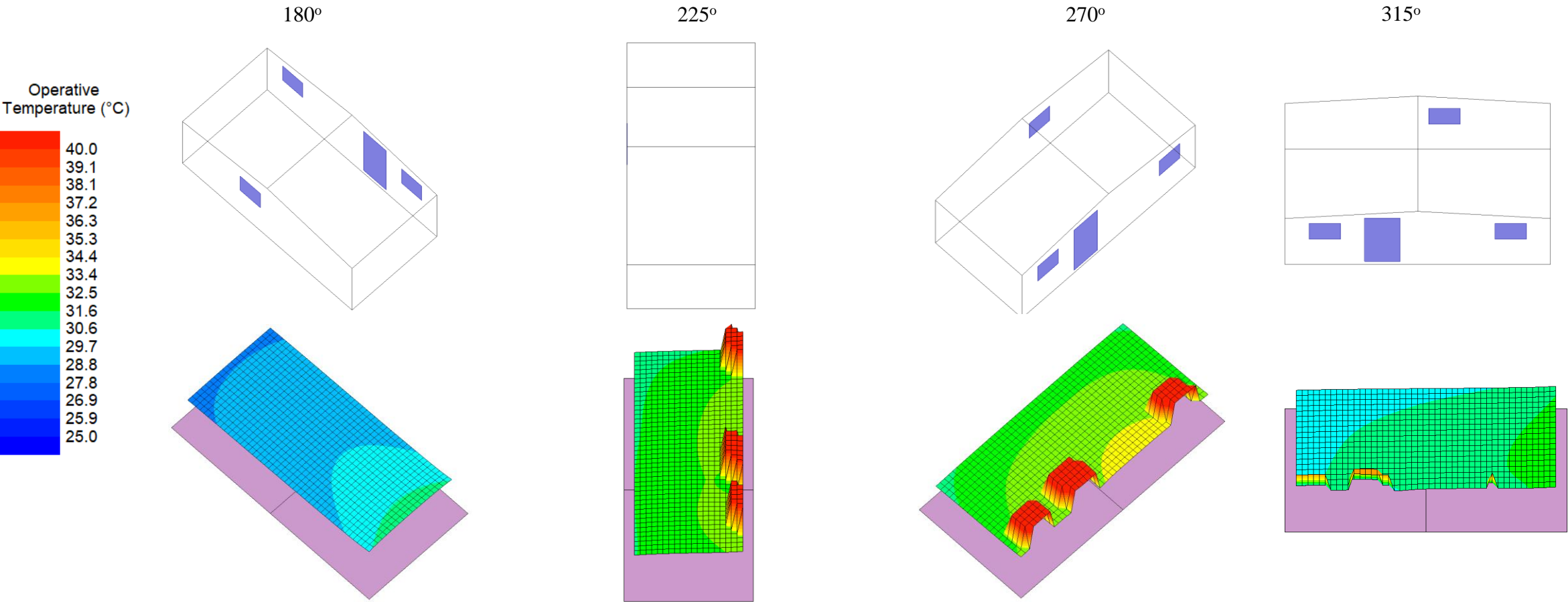
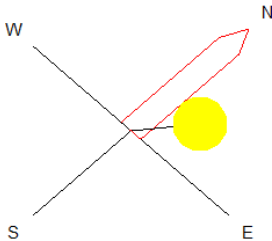
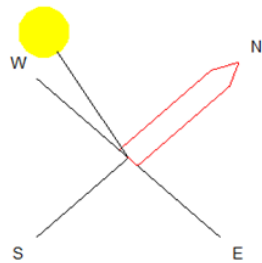


Figure 77b: Spatial operative temperatures for 9.30am in June for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 23.3°C.



Building Orientation – 4.30pm

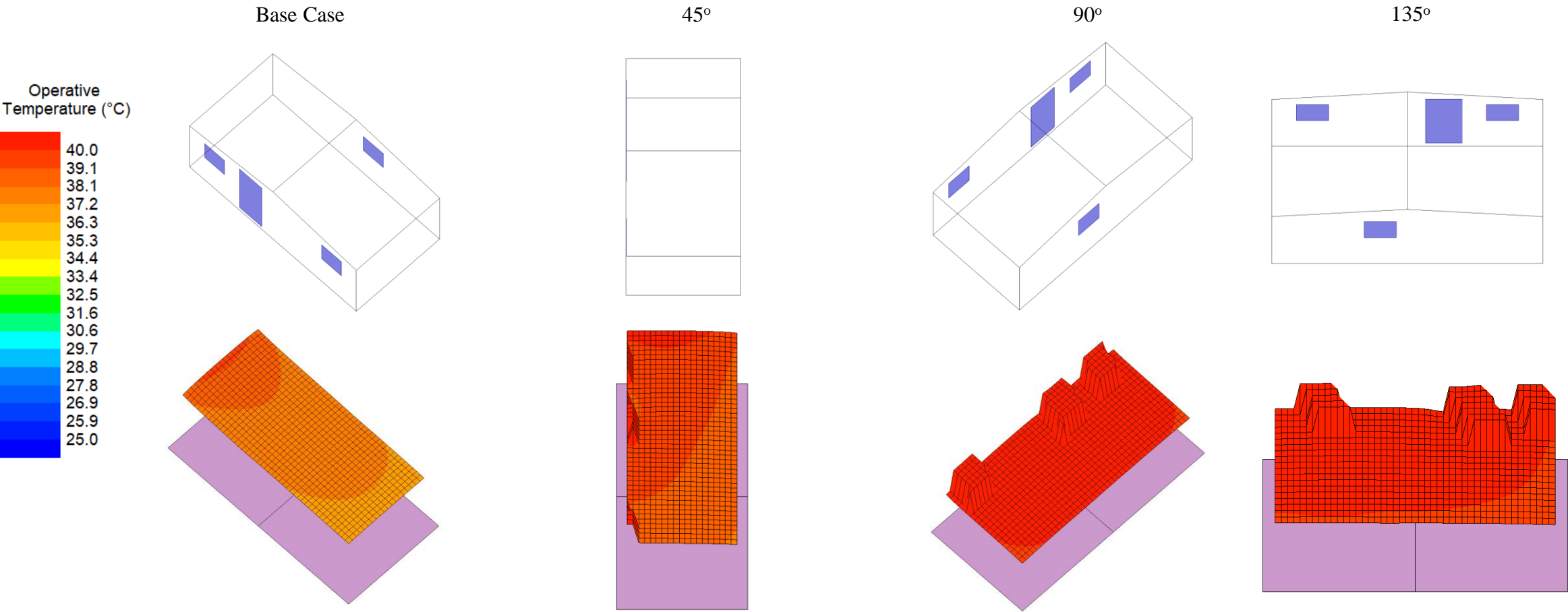
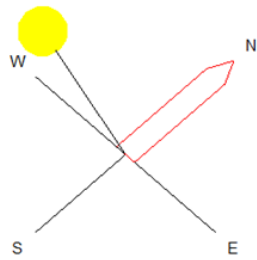


Figure 78a: Spatial operative temperatures for 4.30pm in June for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 31.7°C.



Building Orientation – 4.30pm

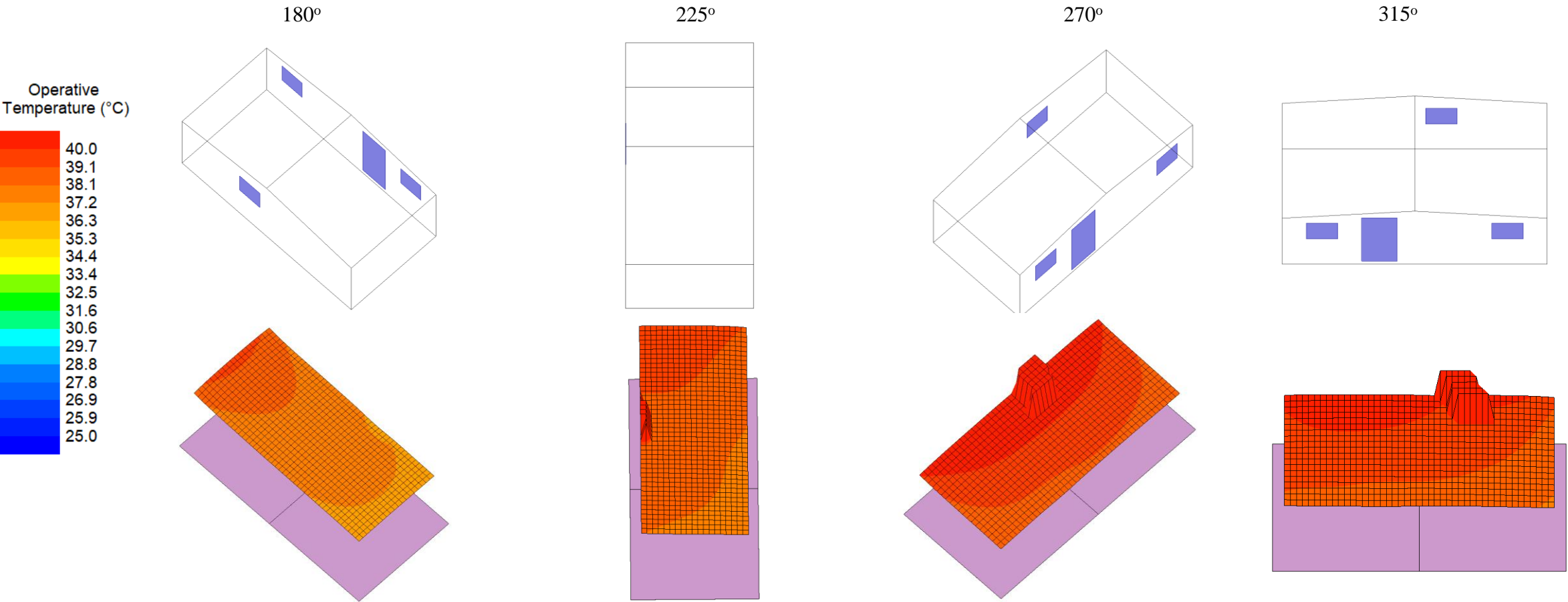


Figure 78b: Spatial operative temperatures for 4.30pm in June for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 31.7°C.

Building Orientation

The base case in Figure 77a, 78a shows lower temperatures than the other orientations at both 9.30am and 4.30pm. This is because there are no windows facing east or west during the day, to let in sunlight and cause higher solar gain.

Looking at the 90° case in Figure 78a, it is clear that the heat spikes inside the building are due to the window positioning which allows high solar gain at the hottest part of the day. This is further demonstrated in Figure 79, where the base case consistently has the lowest temperatures, while the 90° case has the highest temperatures.

The results of examining building orientation on temperature highlight the effectiveness of interventions that reduce solar gains. Using blinds would also improve internal temperatures by reducing solar gains, regardless of building orientation.

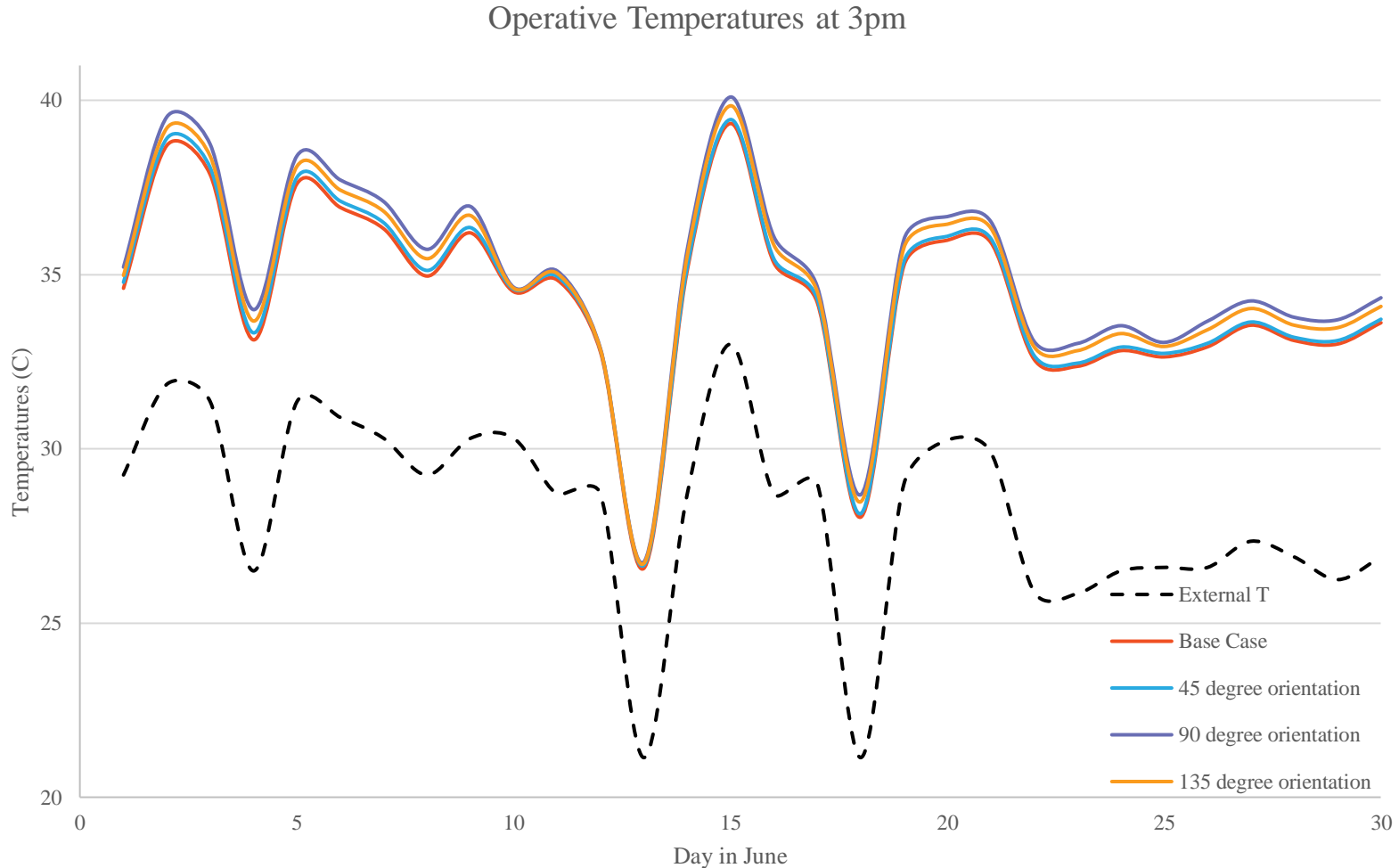


Figure 79: Internal operative temperatures for 3pm in June, comparing different orientations.

Steeper Roof & Flat Roof

Roof Pitch

For the base case, the roof is orientated parallel to the path of the sun during the day, with the windows perpendicular to the sun. This means that changing the roof pitch has little effect on the roof temperatures and therefore the internal temperatures as the sun is heating the roof all day regardless of pitch.

Later, we will investigate the impact of roof pitch on the building oriented perpendicular to the path of the sun.

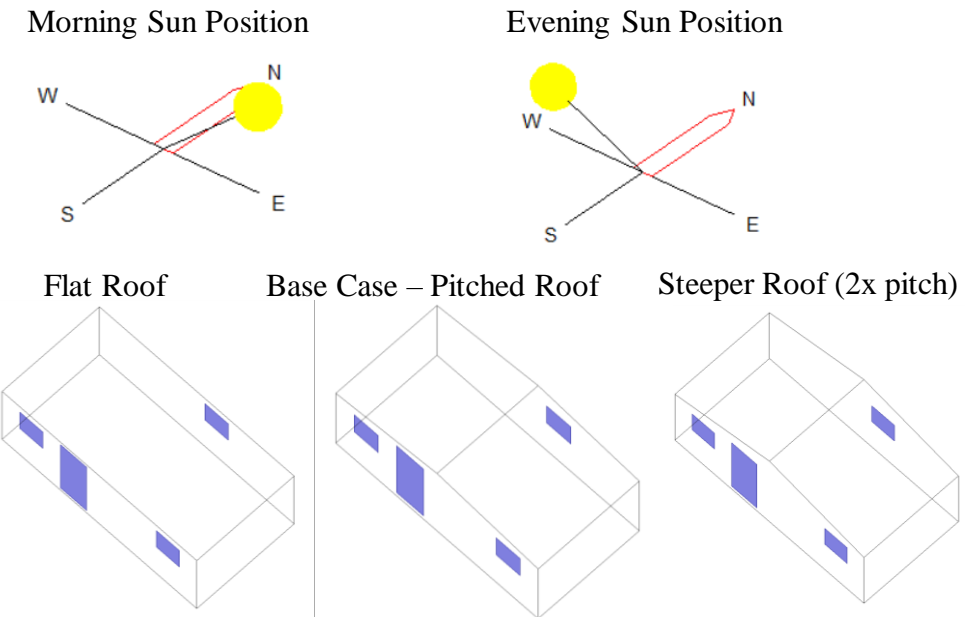


Figure 80: Models of flat roof, base case and steeper roof.

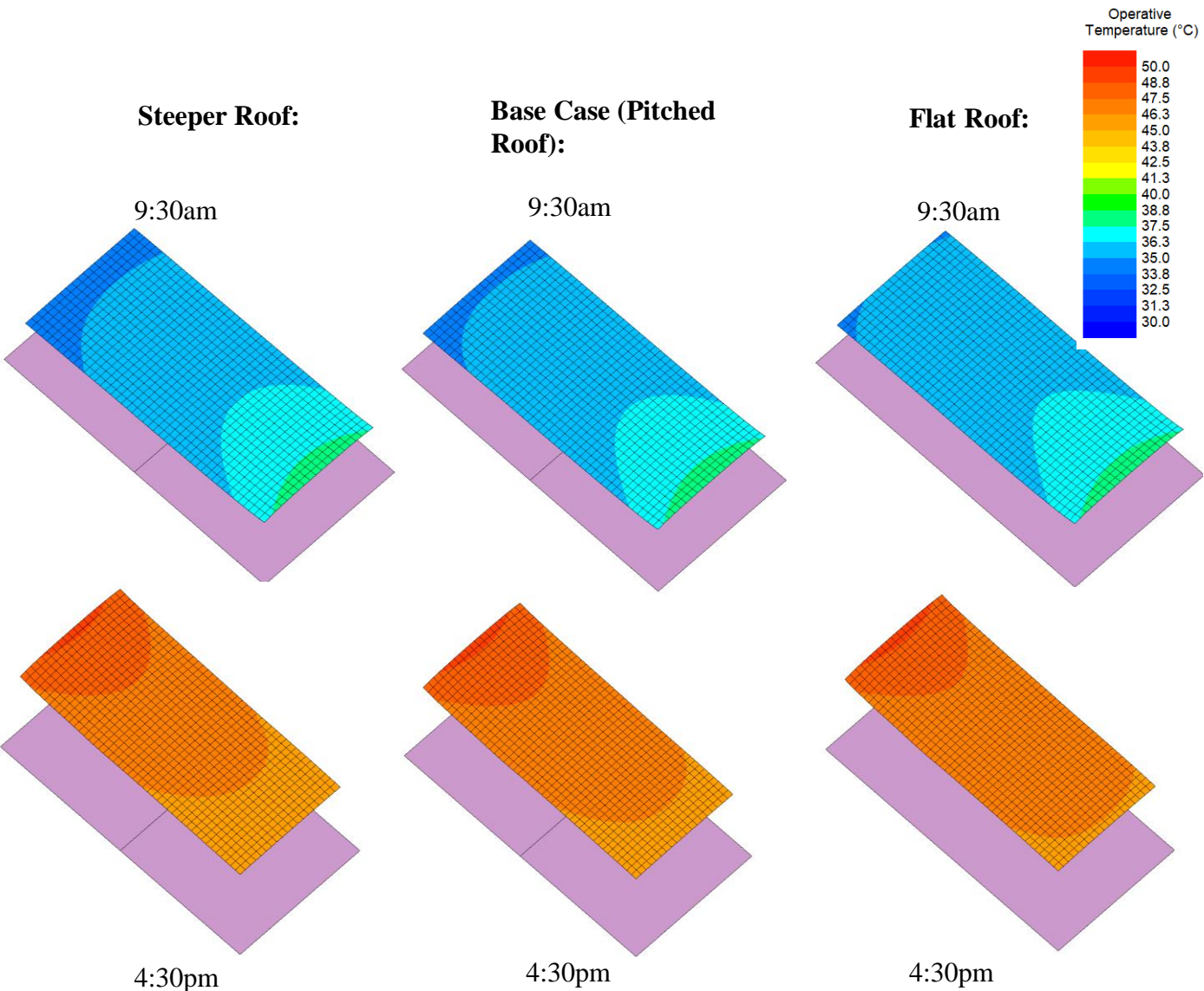
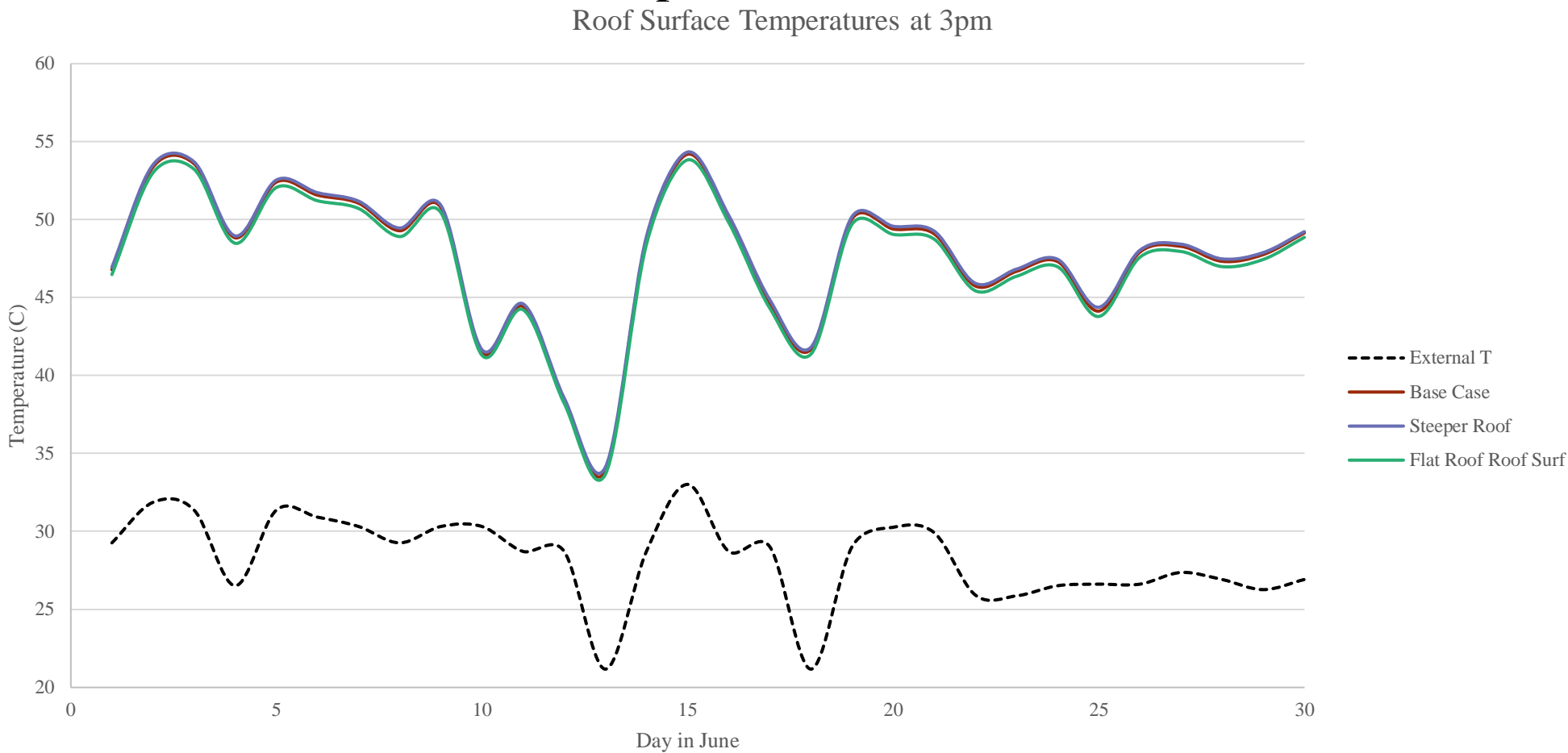


Figure 81: Spatial operative temperatures for 9:30 am and 4:30pm in June.

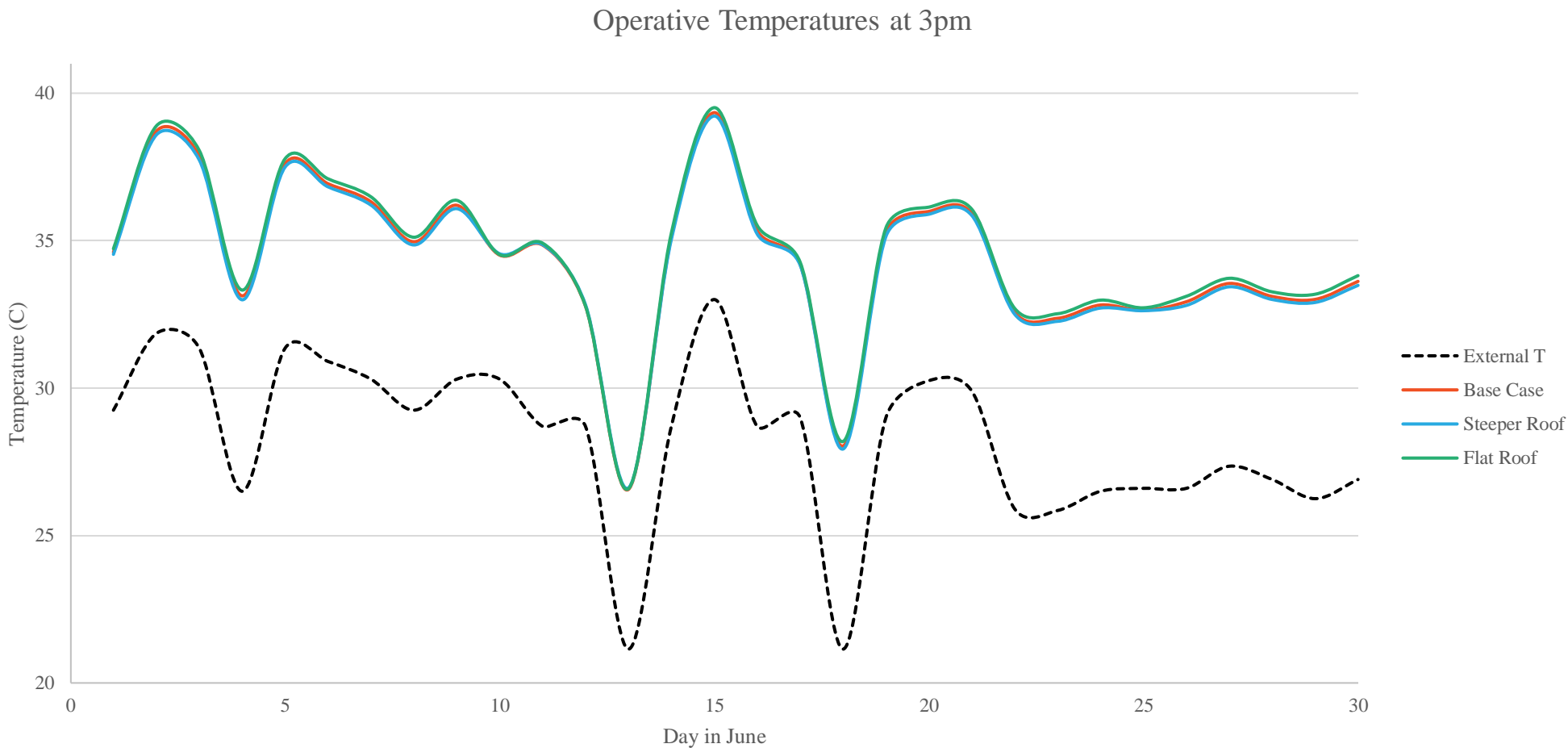
Roof Pitch – Roof Surface Temperatures



Due to the buildings in all cases being oriented with roofs parallel to the path of the sun during the day, the roof pitch has little impact on the roof surface temperature.

Figure 82: Roof surface temperatures for 3pm in June, comparing the flat roof, steeper roof and base cases.

Roof Pitch – Internal Operative Temperatures

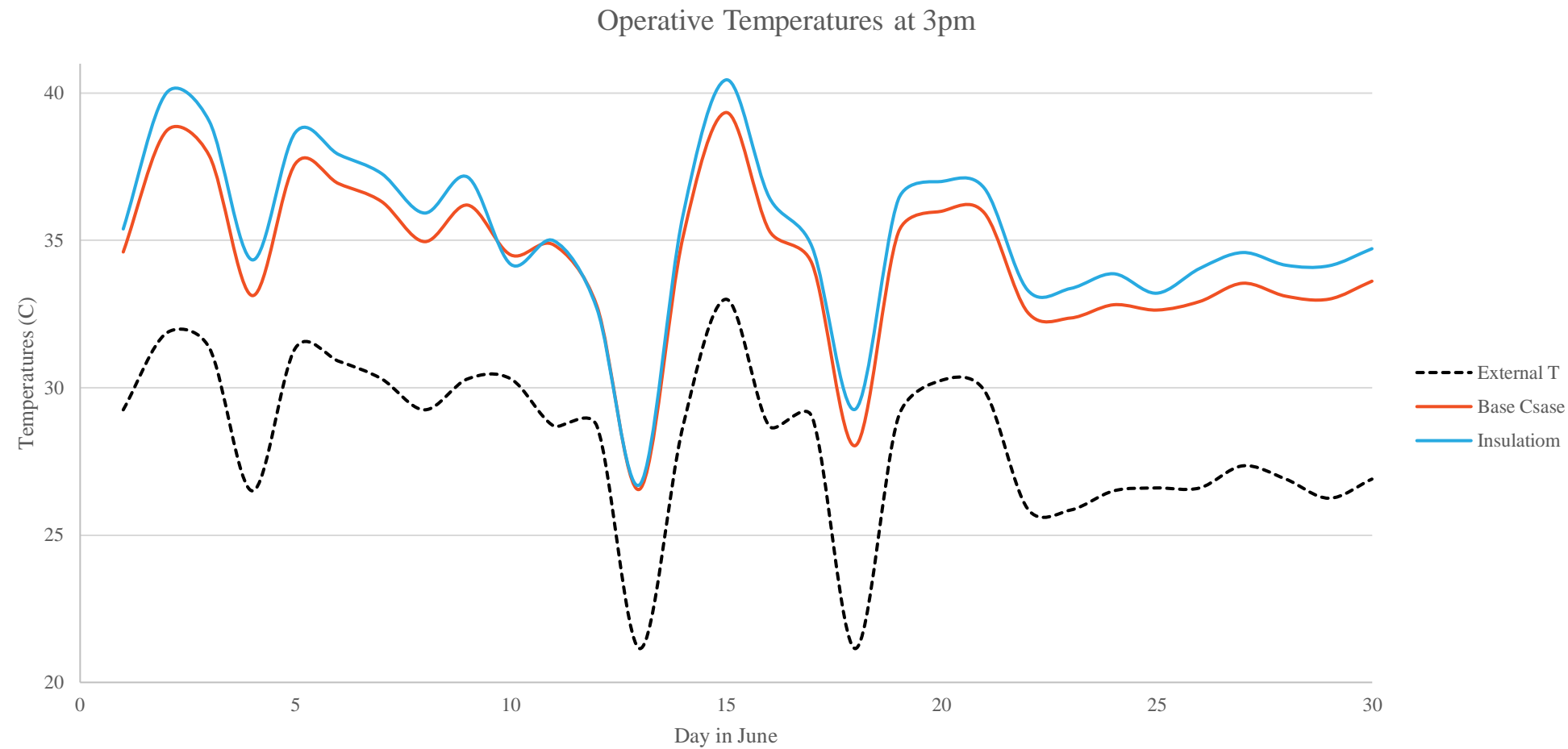


Internal temperatures are similar regardless of roof pitch as roof pitch has little effect on roof surface temperature.

Figure 83: Internal operative temperatures for 3pm in June, comparing the flat roof, steeper roof and base cases.

Insulation

Insulation – Internal Operative Temperatures

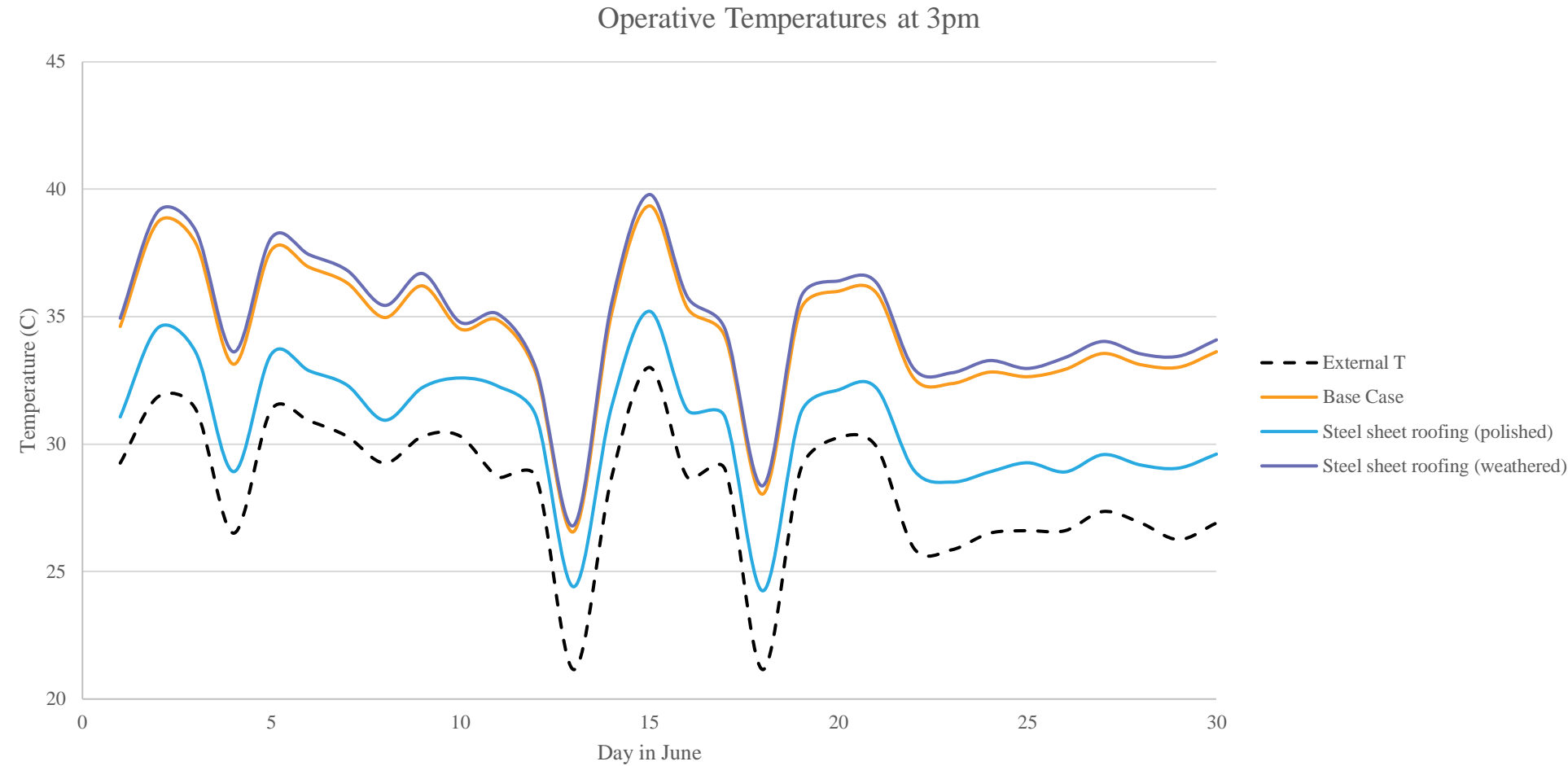


Insulation prevents heat loss from the internal space causing slightly higher internal temperatures, as expected.

Figure 84: Internal operative temperatures for 3pm in June, comparing the insulation strategy against the base case.

Steel Sheet Roofing

Steel Sheet Roofing – Internal Operative Temperatures



The base case is made up of fibre cement boards with an albedo of 0.27, while the steel sheet roofing has albedos of: 0.25 for weathered and 0.8 for polished.

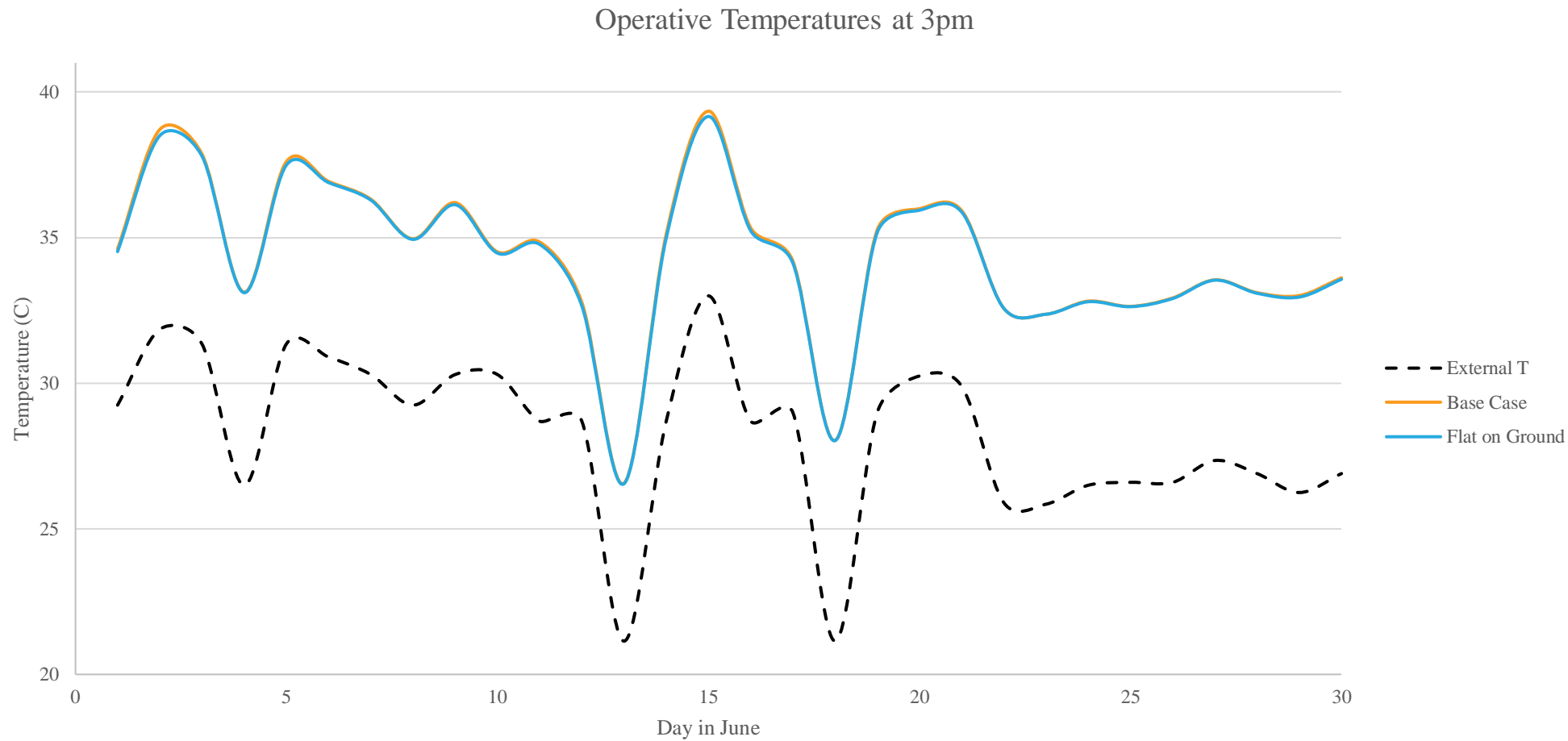
The weathered steel roof has higher thermal conductivity than the base case roof which gives higher roof surface temperatures and therefore higher internal temperatures. While the polished has a much higher albedo than the other cases causing more sunlight to be reflected away from the roof, reducing roof temperatures and thus internal temperatures.

The weathered steel more closely represents a steel sheet roofing than the polished steel.

Figure 85: Internal operative temperatures for 3pm in June, comparing the roof materials with the base case.

Flat on Ground

Flat on Ground – Internal Operative Temperatures

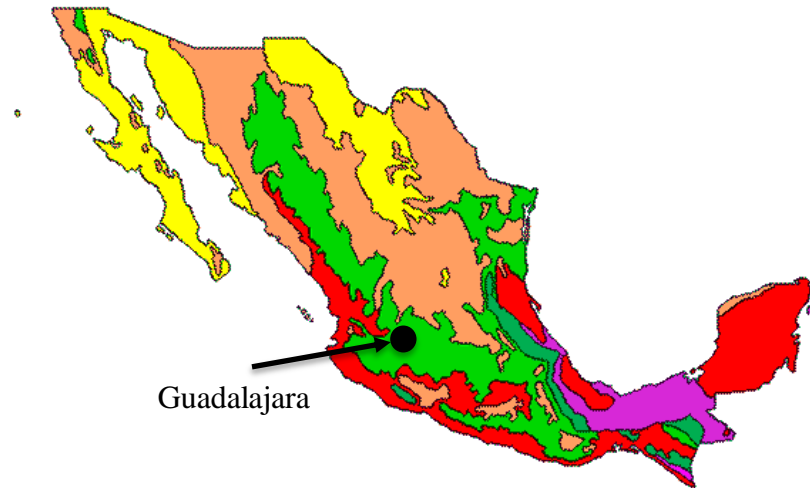


Moving building to be flat on the ground, rather than elevated on stilts (as in the base case) should increase temperatures due to lack of ventilation underneath the building. The ventilation would carry cooler external air underneath the building reducing the temperature.

However, possibly due to no wind being modelled, the two cases have little to no difference in internal temperature..

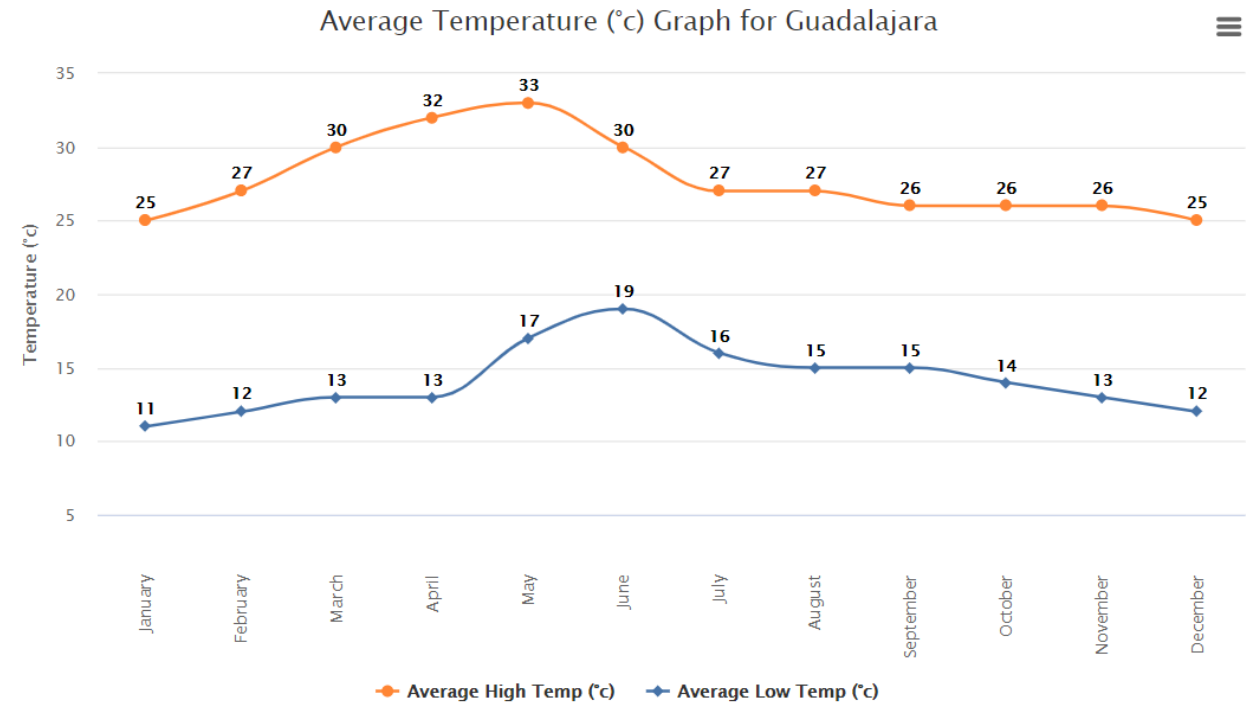
Figure 86: Internal operative temperatures for 3pm in June, comparing the flat on ground strategy against the base case.

Guadalajara Winter



Humid subtropical climate (Cwa)

Monthly Average Temperature



Guadalajara Average values (difference from base for June)

Average difference from base across December							
	Space temperatures		Indicative Comfort		Relative humidity		Air changes
	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural
	(°C)	(°C)	-	-	%	%	/hr
Base							
Reflective Roof (0.75)	-0.41	-0.71	-0.19	-1.02	1.13	1.13	-1.16
Reflective Roof (0.85)	-0.50	-0.86	-0.23	-1.24	1.39	1.39	-1.44
Reflective Roof (0.95)	-0.60	-1.01	-0.27	-1.46	1.66	1.66	-1.75
Larger Window	-0.06	-0.03	-0.01	-0.04	0.14	0.14	0.63
Orientation +45°	-0.13	-0.27	-0.07	-0.39	0.42	0.42	-0.39
Orientation +90°	-0.13	-0.34	-0.09	-0.50	0.29	0.29	-0.30
Orientation +135°	-0.21	-0.47	-0.13	-0.68	0.51	0.51	-0.51
Orientation +180°	-0.11	-0.30	-0.08	-0.44	0.32	0.32	-0.28
Orientation +225°	-0.21	-0.48	-0.12	-0.69	0.63	0.63	-0.57
Orientation +270°	-0.14	-0.34	-0.09	-0.50	0.28	0.28	-0.29
Orientation +315°	-0.14	-0.26	-0.07	-0.38	0.29	0.29	-0.32
Flat Roof	-0.04	-0.07	-0.02	-0.11	0.10	0.10	0.27
Steeper Roof	0.06	0.08	0.02	0.11	-0.15	-0.15	-0.53
Insulation	0.21	0.19	0.05	0.26	-0.73	-0.73	-0.12
Steel sheet roofing (polished)	-0.44	-0.76	-0.20	-1.09	1.21	1.21	-1.28
Steel sheet roofing (weathered)	0.05	0.09	0.02	0.13	-0.13	-0.13	0.10
Flat on Ground	0.13	0.16	0.04	0.22	-0.39	-0.39	0.03

Guadalajara Average values (absolute averages over all hours in December)

Absolute Values									
	External	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Tdiff
	Tdry	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	
	(°C)	(°C)	(°C)	-	-	%	%	/hr	(°C)
Base	14.26	15.72	16.58	-1.77	61.13	67.07	67.07	9.07	
Reflective Roof (0.75)	14.26	15.31	15.88	-1.95	60.11	68.20	68.20	7.92	-0.71
Reflective Roof (0.85)	14.26	15.22	15.73	-1.99	59.89	68.46	68.46	7.63	-0.86
Reflective Roof (0.95)	14.26	15.12	15.58	-2.03	59.67	68.73	68.73	7.32	-1.01
Larger Window	14.26	15.67	16.56	-1.77	61.10	67.21	67.21	9.71	-0.03
Orientation +45°	14.26	15.59	16.32	-1.83	60.74	67.49	67.49	8.68	-0.27
Orientation +90°	14.26	15.59	16.24	-1.86	60.63	67.36	67.36	8.77	-0.34
Orientation +135°	14.26	15.51	16.11	-1.89	60.45	67.58	67.58	8.56	-0.47
Orientation +180°	14.26	15.61	16.28	-1.84	60.70	67.39	67.39	8.79	-0.30
Orientation +225°	14.26	15.51	16.11	-1.89	60.44	67.70	67.70	8.50	-0.48
Orientation +270°	14.26	15.58	16.24	-1.86	60.64	67.35	67.35	8.78	-0.34
Orientation +315°	14.26	15.58	16.32	-1.84	60.75	67.36	67.36	8.75	-0.26
Flat Roof	14.26	15.68	16.51	-1.78	61.03	67.17	67.17	9.34	-0.07
Steeper Roof	14.26	15.78	16.66	-1.75	61.24	66.92	66.92	8.55	0.08
Insulation	14.26	15.93	16.77	-1.71	61.39	66.34	66.34	8.95	0.19
Steel sheet roofing (polished)	14.26	15.28	15.83	-1.97	60.04	68.28	68.28	7.79	-0.76
Steel sheet roofing (weathered)	14.26	15.77	16.67	-1.74	61.26	66.94	66.94	9.17	0.09
Flat on Ground	14.26	15.85	16.74	-1.73	61.35	66.68	66.68	9.10	0.16

Guadalajara Summary

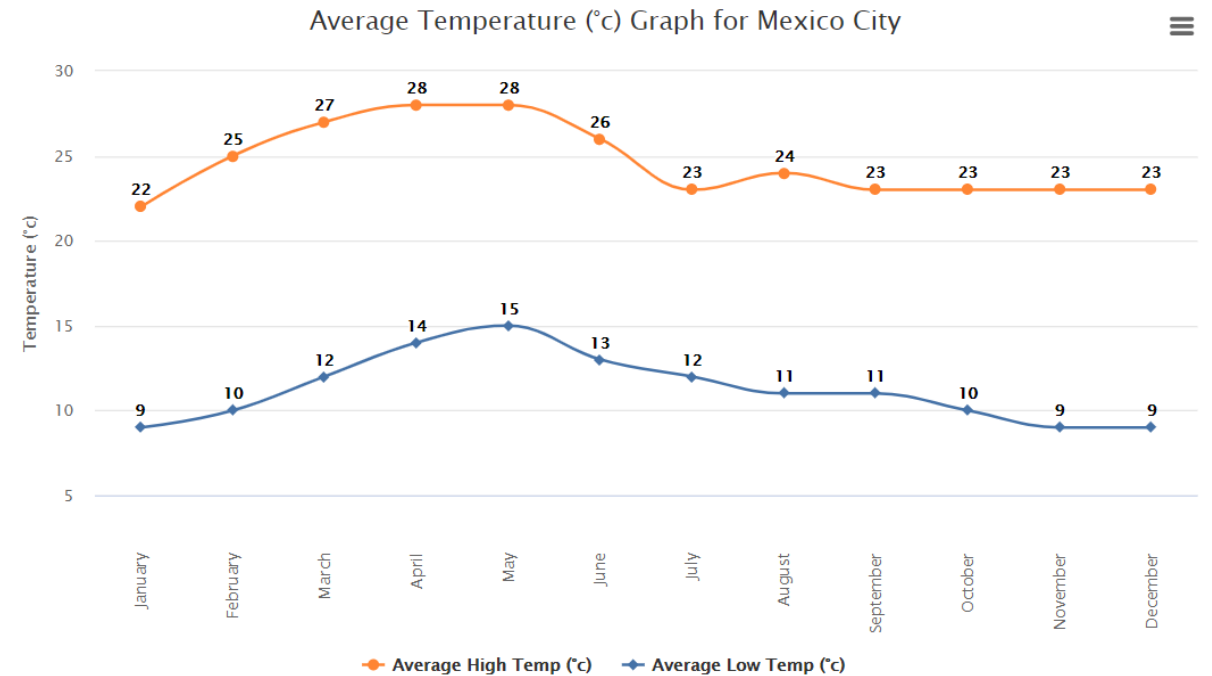
The most effective strategy in Guadalajara is the reflective roof, where a higher albedo gives a greater cooling effect. Limited improvement was seen for polished steel roof material, increased window size and steeper roof. Benefits of the strategies in summer exceed the penalty in winter, as the winter condition is not significantly worsened, while the summer condition is significantly improved.

Mexico City Summer



Subtropical highland climate (Cwb)

Monthly Average Temperature



Mexico City Average values (difference from base for May)

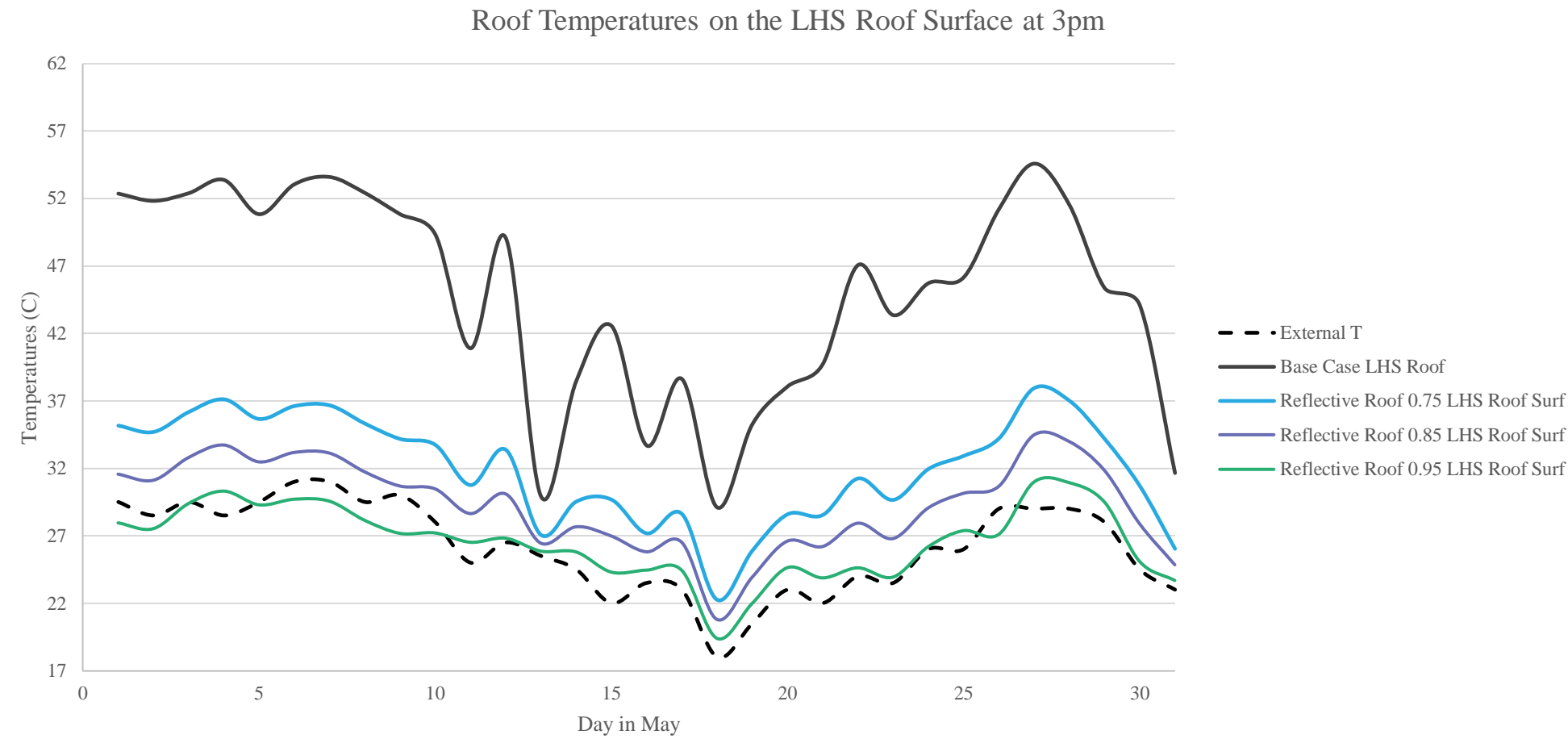
Average difference from base across May									
	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp	
	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left side	Right Side
	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)
Base									
Reflective Roof (0.75)	-0.72	-1.13	-0.31	-1.33	1.13	1.13	-1.96	-4.47	-4.39
Reflective Roof (0.85)	-0.89	-1.38	-0.38	-1.63	1.42	1.42	-2.55	-5.40	-5.31
Reflective Roof (0.95)	-1.08	-1.64	-0.45	-1.93	1.74	1.74	-3.21	-6.34	-6.23
Larger Window	-0.06	-0.04	-0.01	-0.04	0.09	0.09	0.60	0.00	0.00
Orientation +45°	0.18	0.31	0.08	0.36	-0.30	-0.30	0.41	0.13	0.08
Orientation +90°	0.29	0.52	0.14	0.61	-0.46	-0.46	0.59	0.19	0.17
Orientation +135°	0.21	0.36	0.10	0.43	-0.33	-0.33	0.42	0.08	0.18
Orientation +180°	0.01	0.02	0.01	0.02	-0.03	-0.03	0.02	-0.09	0.12
Orientation +225°	0.18	0.32	0.09	0.37	-0.31	-0.31	0.45	-0.03	0.24
Orientation +270°	0.27	0.51	0.14	0.59	-0.44	-0.44	0.62	0.05	0.28
Orientation +315°	0.19	0.32	0.09	0.38	-0.30	-0.30	0.41	0.05	0.16
Flat Roof	0.00	0.02	0.01	0.03	0.02	0.02	0.32	-0.20	
Steeper Roof	0.03	0.00	0.00	-0.01	-0.06	-0.06	-0.55	0.14	0.10
Insulation	0.28	0.34	0.09	0.36	-0.74	-0.74	0.06	0.10	0.11
Steel sheet roofing (polished)	-0.77	-1.21	-0.33	-1.43	1.21	1.21	-2.14	-4.77	-4.69
Steel sheet roofing (weathered)	0.09	0.14	0.04	0.17	-0.13	-0.13	0.24	0.33	0.32
Flat on Ground	0.04	0.04	0.01	0.03	-0.23	-0.23	0.03	0.01	0.01

Mexico City Average values (absolute averages over all hours in May)

Absolute Values											
	External	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Roof Surface temp		Op Tdiff
	Tdry	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	Left Side	Right Side	
	(°C)	(°C)	(°C)	-	-	%	%	/hr	(°C)	(°C)	(°C)
Base	19.41	21.07	21.73	-0.37	67.00	43.97	43.97	8.49	25.22	25.10	
Reflective Roof (0.75)	19.41	20.34	20.59	-0.68	65.67	45.10	45.10	6.52	20.75	20.71	-1.13
Reflective Roof (0.85)	19.41	20.17	20.34	-0.75	65.37	45.39	45.39	5.93	19.82	19.79	-1.38
Reflective Roof (0.95)	19.41	19.99	20.09	-0.82	65.07	45.70	45.70	5.28	18.88	18.87	-1.64
Larger Window	19.41	21.01	21.69	-0.38	66.96	44.06	44.06	9.08	25.21	25.10	-0.04
Orientation +45°	19.41	21.24	22.04	-0.29	67.36	43.67	43.67	8.90	25.35	25.18	0.31
Orientation +90°	19.41	21.35	22.25	-0.23	67.61	43.51	43.51	9.08	25.41	25.28	0.52
Orientation +135°	19.41	21.27	22.09	-0.27	67.43	43.63	43.63	8.90	25.30	25.28	0.36
Orientation +180°	19.41	21.08	21.75	-0.36	67.03	43.94	43.94	8.51	25.13	25.22	0.02
Orientation +225°	19.41	21.24	22.05	-0.28	67.38	43.66	43.66	8.93	25.19	25.34	0.32
Orientation +270°	19.41	21.33	22.23	-0.23	67.59	43.52	43.52	9.10	25.27	25.38	0.51
Orientation +315°	19.41	21.25	22.05	-0.28	67.38	43.67	43.67	8.90	25.27	25.26	0.32
Flat Roof	19.41	21.07	21.75	-0.36	67.03	43.98	43.98	8.81	25.02		0.02
Steeper Roof	19.41	21.10	21.73	-0.37	67.00	43.91	43.91	7.94	25.36	25.21	0.00
Insulation	19.41	21.34	22.06	-0.28	67.36	43.23	43.23	8.55	25.32	25.21	0.34
Steel sheet roofing (polished)	19.41	20.29	20.51	-0.70	65.57	45.18	45.18	6.35	20.45	20.41	-1.21
Steel sheet roofing (weathered)	19.41	21.15	21.87	-0.33	67.17	43.83	43.83	8.72	25.55	25.43	0.14
Flat on Ground	19.41	21.11	21.77	-0.36	67.04	43.74	43.74	8.52	25.23	25.11	0.04

Reflective Roof

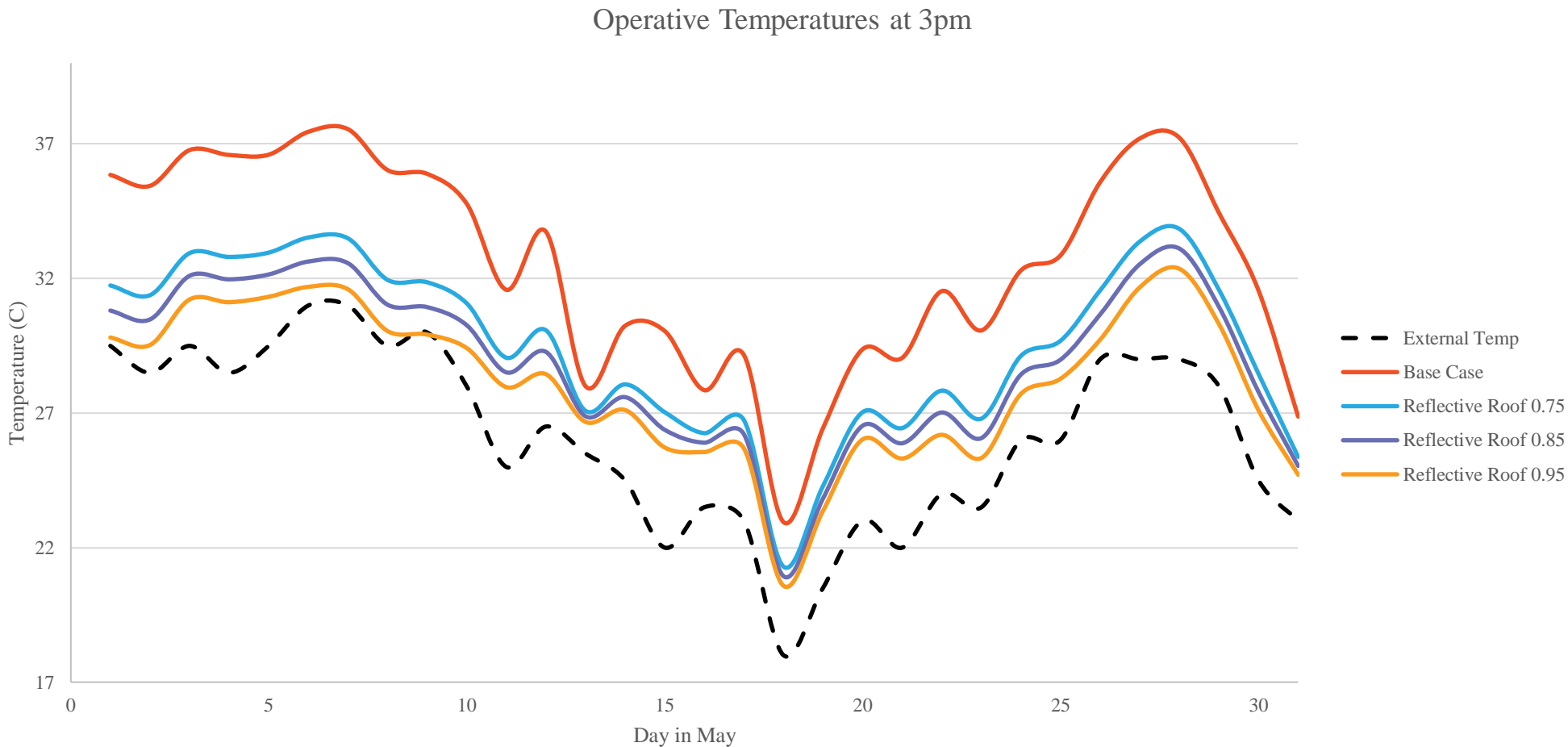
Reflective Roof – Roof Surface Temperatures



The base case has an albedo of 0.27. The painted roofs with higher albedo, reflect more sunlight than the base case, so less heat is absorbed by the roof. This reduces the roof surface temperature and in turn reduces the internal temperature of the house.

Figure 87: Roof surface temperatures for 3pm in May comparing the reflective roof strategies against the base case.

Reflective Roof – Internal Operative Temperatures

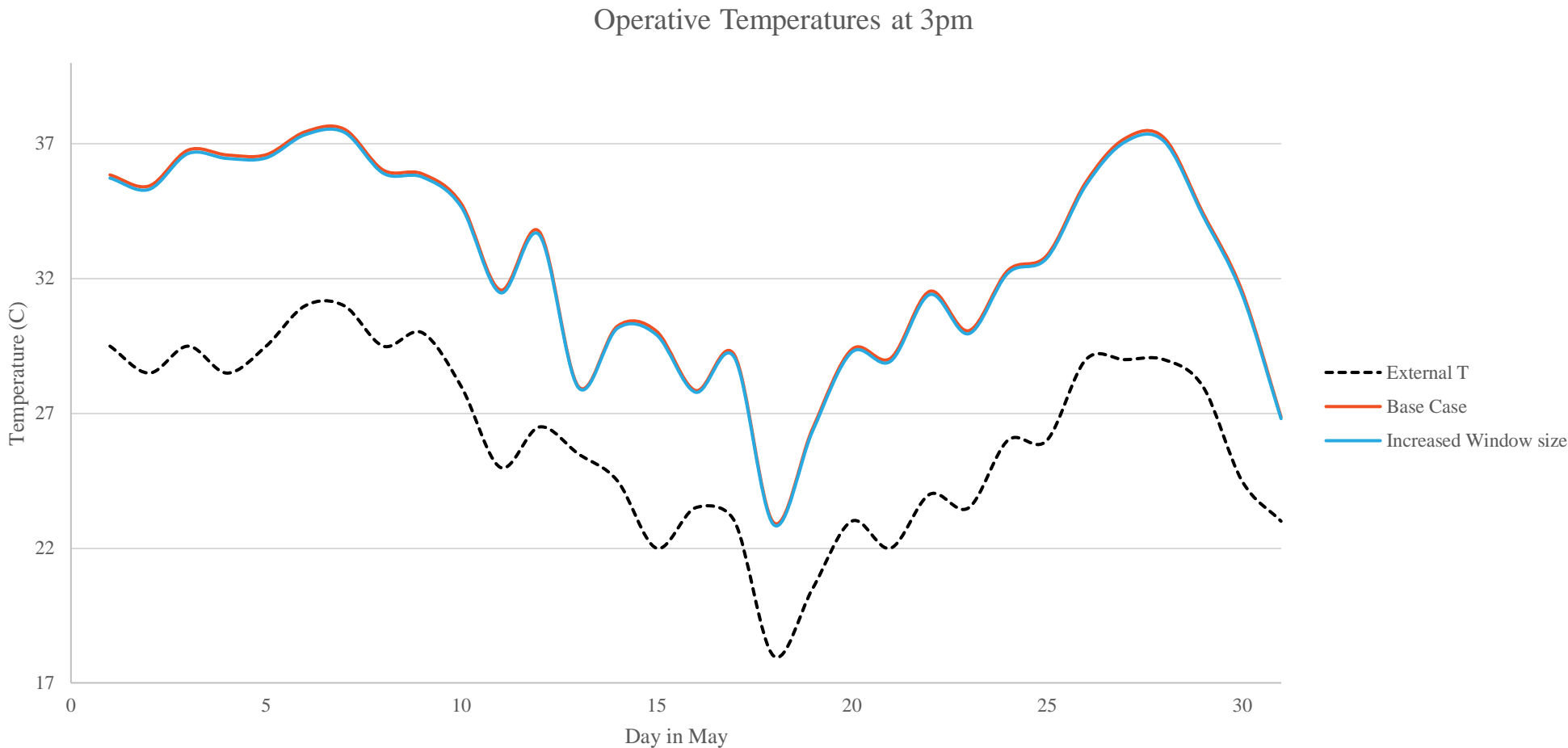


The reduction of the roof surface temperature due to the high albedo surfaces, reduces the internal temperature of the house.

Figure 88: Internal operative temperatures for 3pm in May, comparing the reflective roof strategies against the base case.

Increased Window Size

Increased Window Size – Internal Operative Temperatures

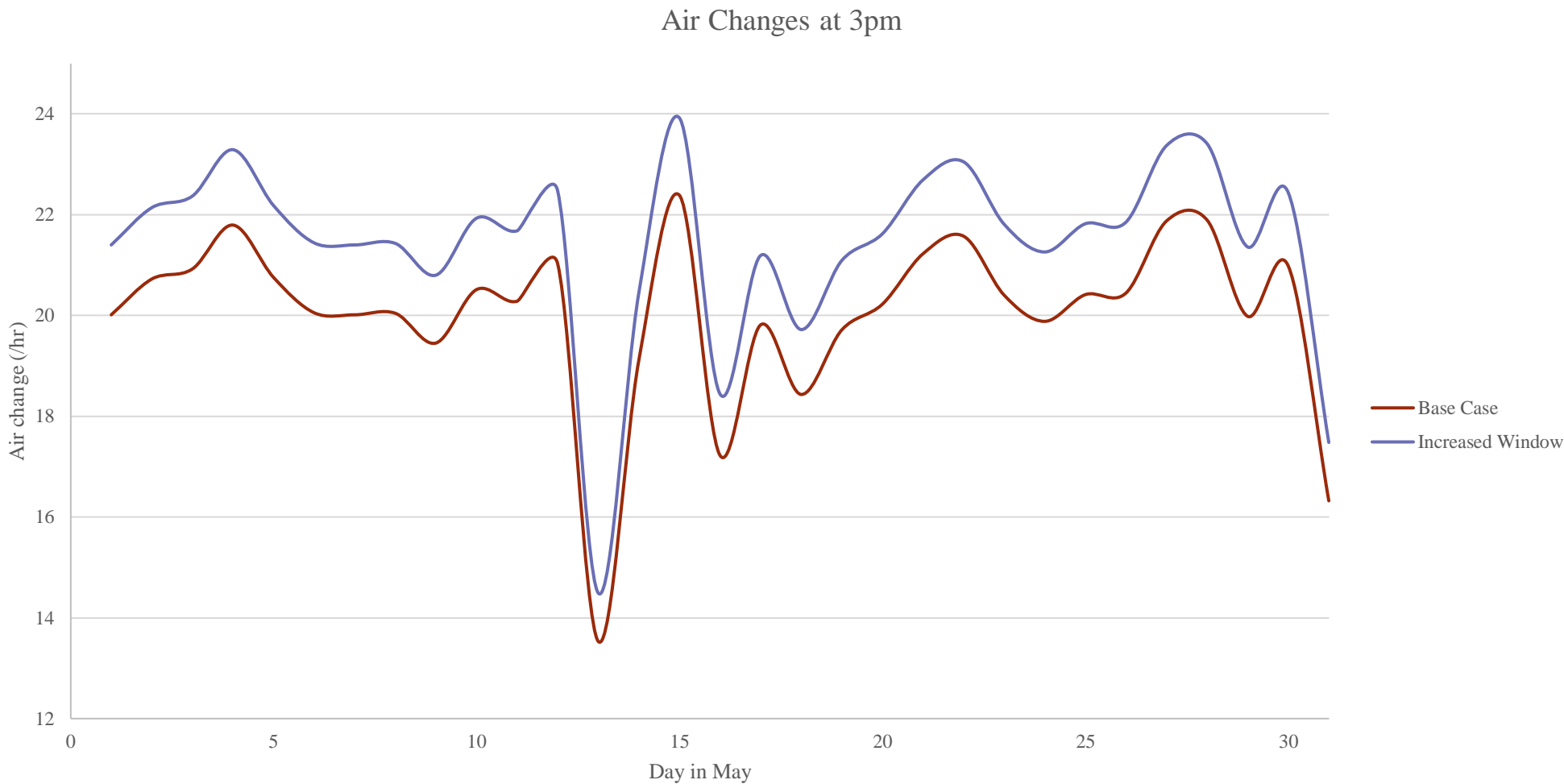


Increasing the window size gives a slightly cooler internal operative temperature due to an increase in ventilation. Since the external temperature is cooler than internal temperatures increasing the ventilation decreases the internal temperatures.

However, increased windows also allow greater solar gains into the room which can cause higher temperatures depending on time of day and building orientation.

Figure 89: Internal operative temperatures for 3pm in May, comparing the increased window strategy against the base case.

Increased Window Size - Air change rates



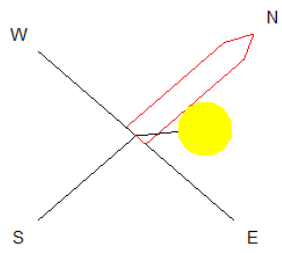
The air change rate is higher for the increased window case than the base case, as expected due to an increase in ventilation. While the difference in air change rate between the cases is notable, the difference in temperatures is much less so.

It is important to note that our models do not account for wind/wind speeds so the improvement in air change shown is conservative.

It is likely that, on a breezy day the increased window size would be more effective at cooling the space and increasing air change rate.

Figure 90: Air change rate for 3pm in May.

Orientation



Building Orientation – 9.30am

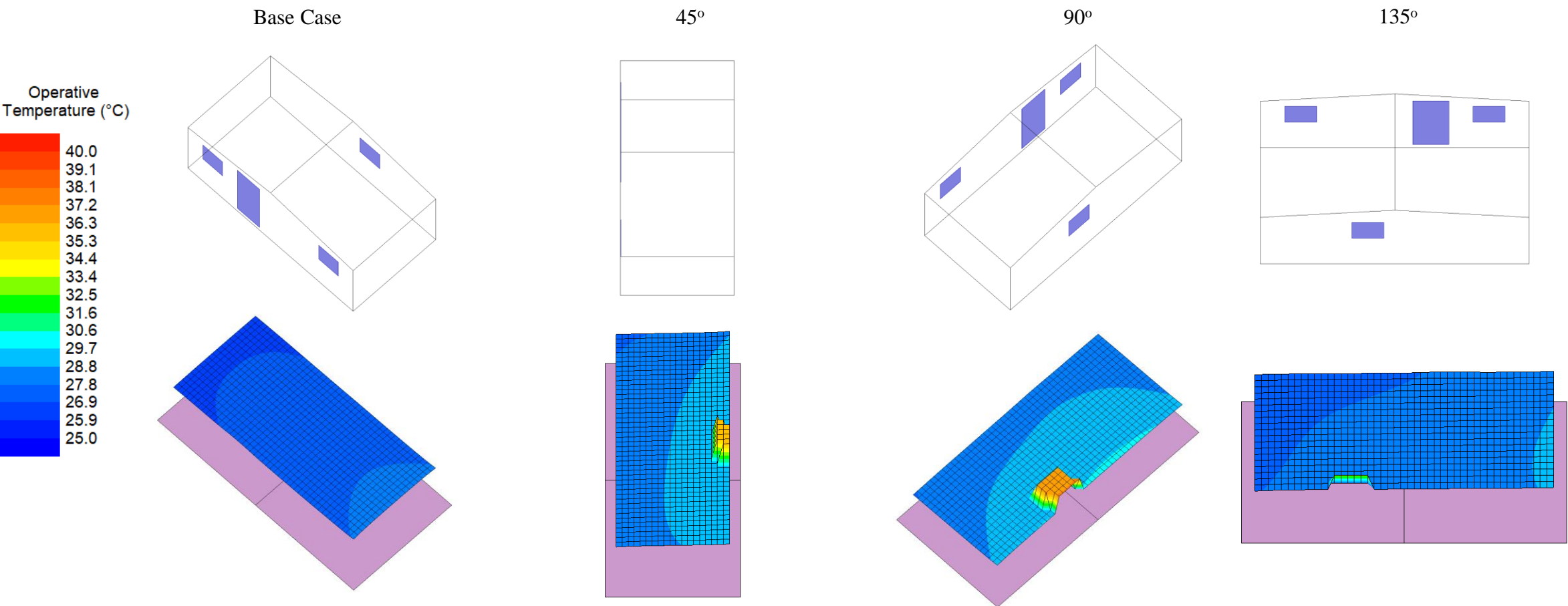
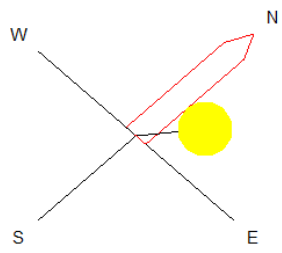


Figure 91a: Spatial operative temperatures for 9.30am in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 21.5°C.



Building Orientation – 9.30am

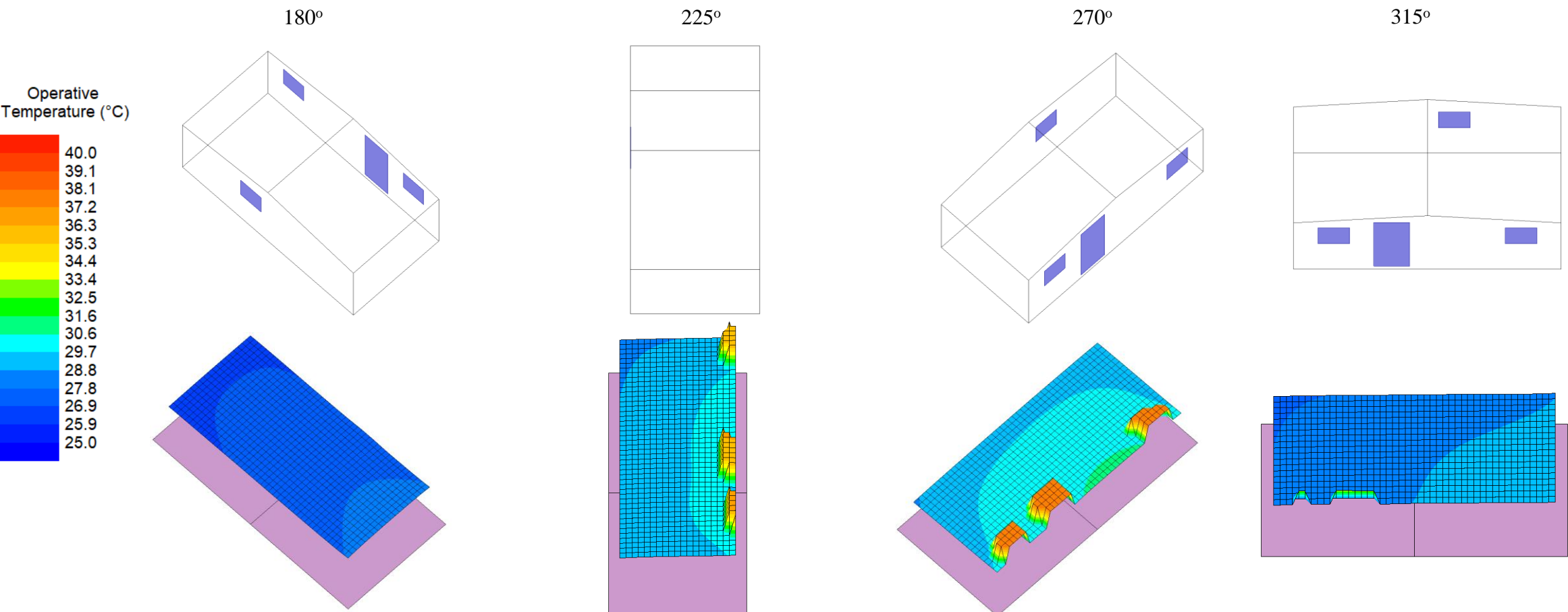
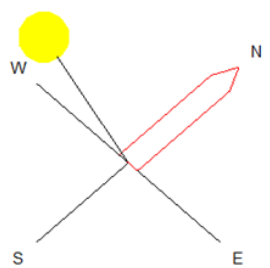


Figure 91b: Spatial operative temperatures for 9.30am in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 21.5°C.



Building Orientation – 4.30pm

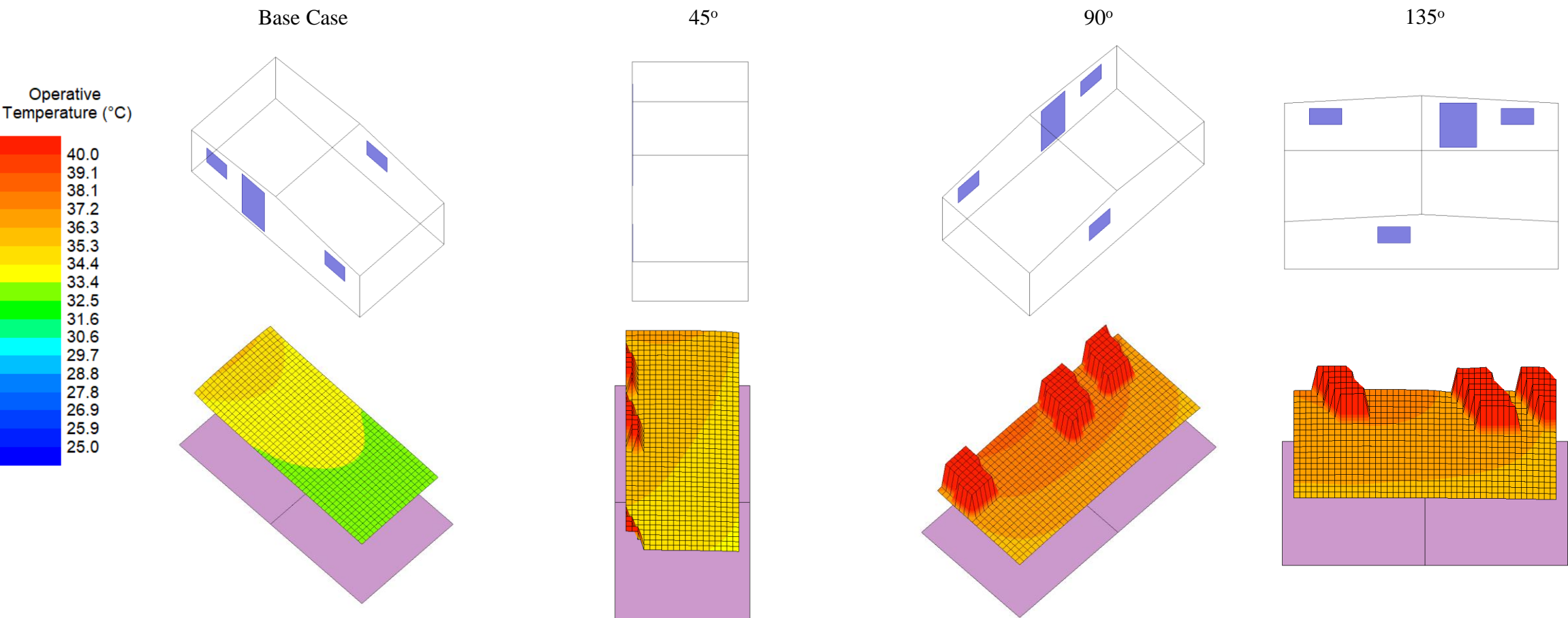
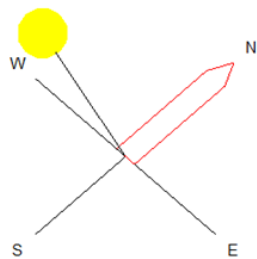


Figure 92a: Spatial operative temperatures for 4.30pm in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 27.5°C.



Building Orientation – 4.30pm

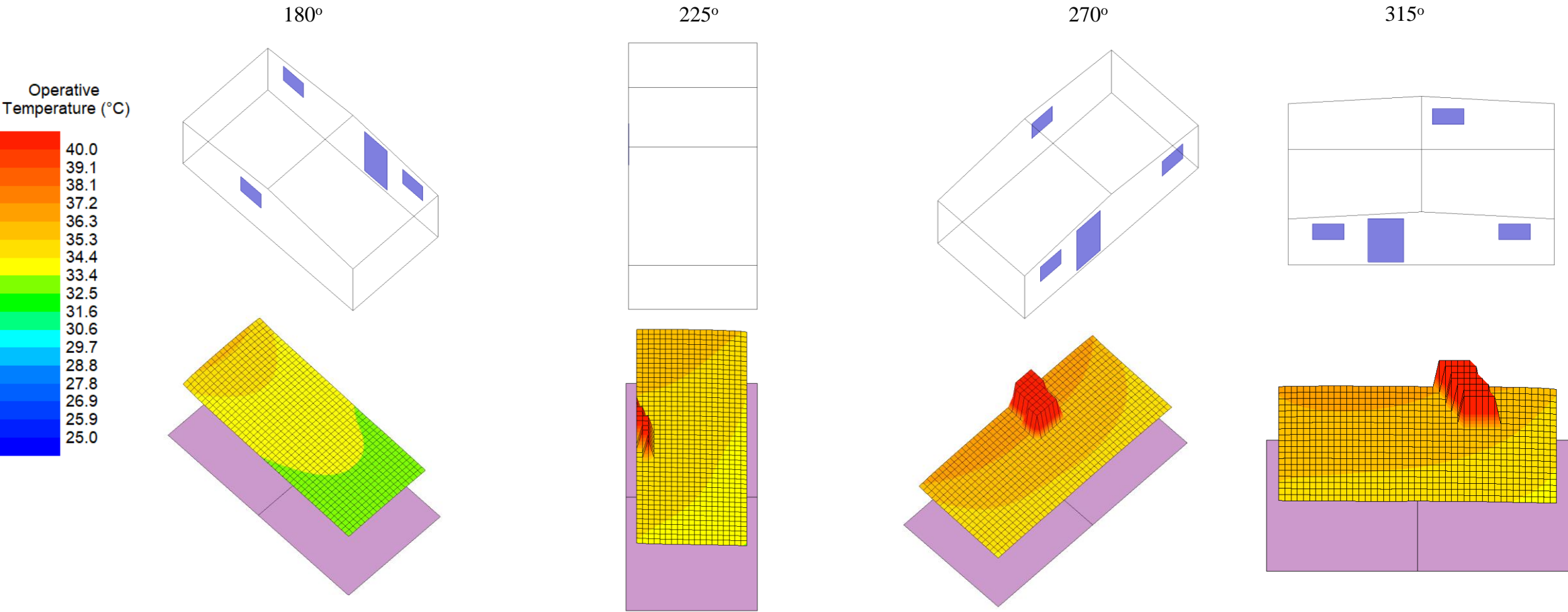


Figure 92b: Spatial operative temperatures for 4.30pm in May for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 27.5°C.

Building Orientation

The base case in Figure 91a, 92a shows lower temperatures than the other orientations at both 9.30am and 4.30pm. This is because there are no windows facing east or west during the day, to let in sunlight and cause higher solar gain.

Looking at the 90° case in Figure 92a, it is clear that the heat spikes inside the building are due to the window positioning which allows high solar gain at the hottest part of the day. This is further demonstrated in Figure 93, where the base case consistently has the lowest temperatures, while the 90° case has the highest temperatures.

The results of examining building orientation on temperature highlight the effectiveness of interventions that reduce solar gains. Using blinds would also improve internal temperatures by reducing solar gains, regardless of building orientation.

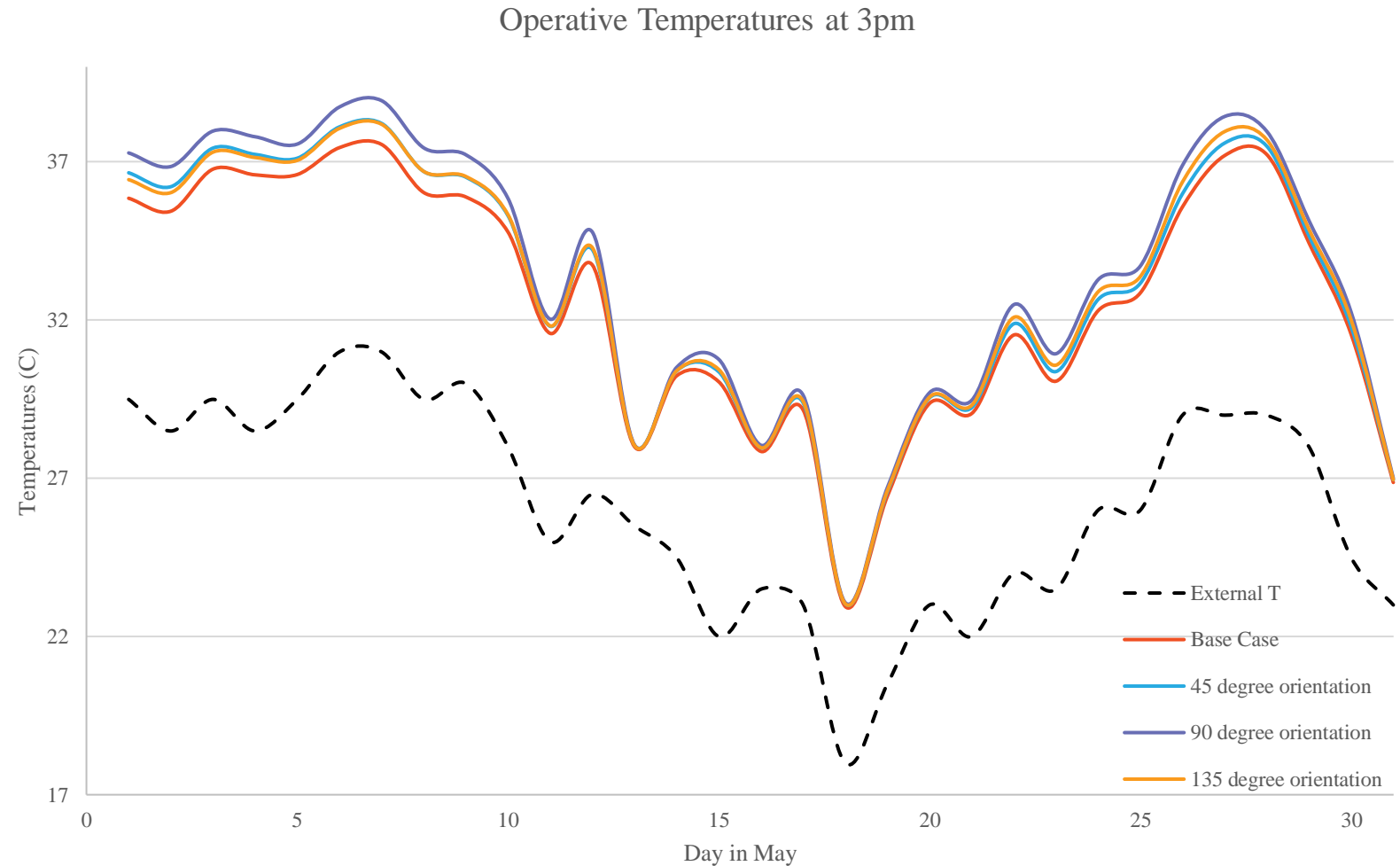


Figure 93: Internal operative temperatures for 3pm in May, comparing different building orientations.

Steeper Roof & Flat Roof

Roof Pitch

For the base case, the roof is orientated parallel to the path of the sun during the day, with the windows perpendicular to the sun. This means that changing the roof pitch has little effect on the roof temperatures and therefore the internal temperatures as the sun is heating the roof all day regardless of pitch.

Later, we will investigate the impact of roof pitch on the building oriented perpendicular to the path of the sun.

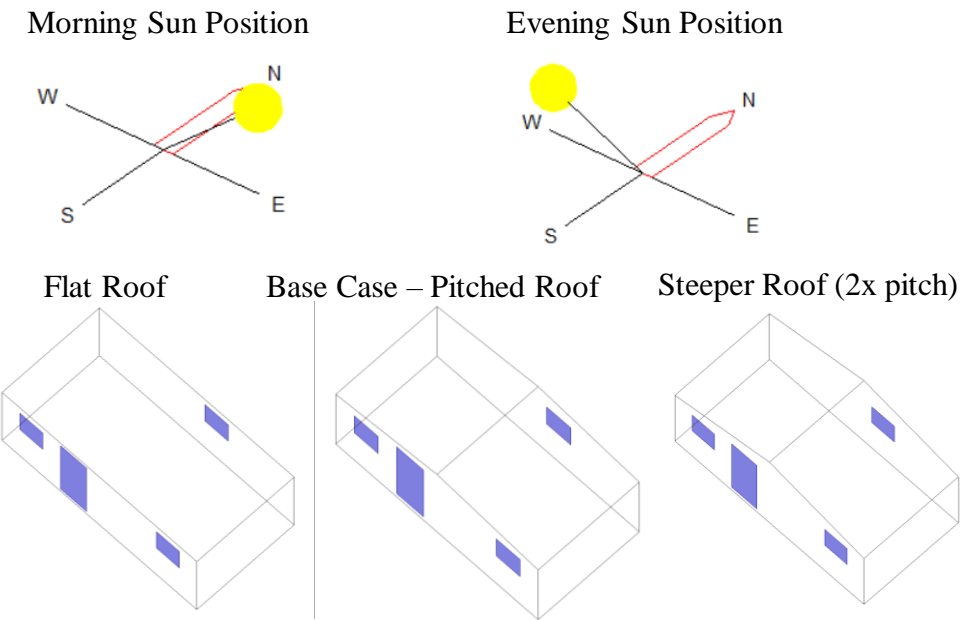


Figure 94: Models of flat roof, base case and steeper roof.

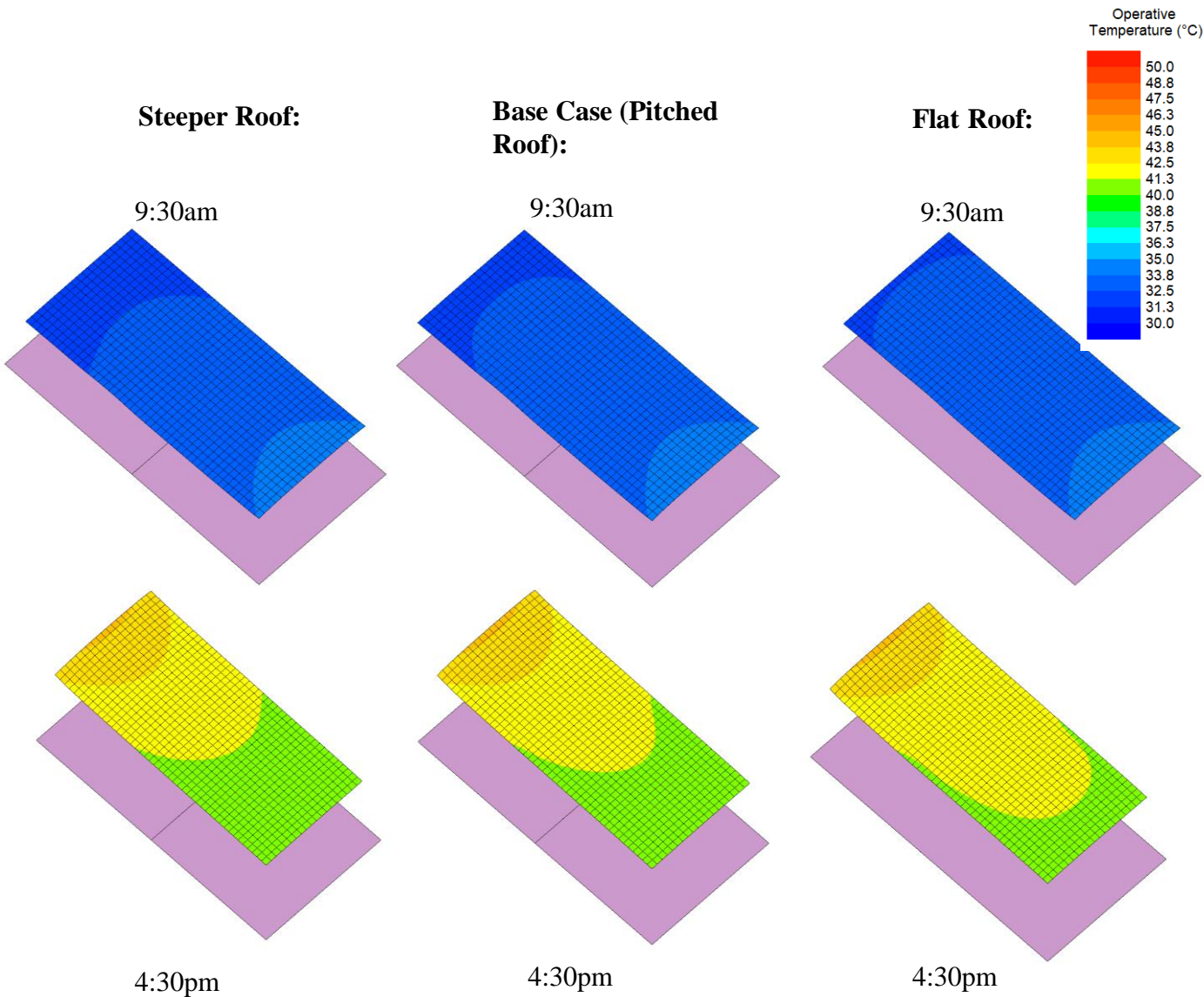
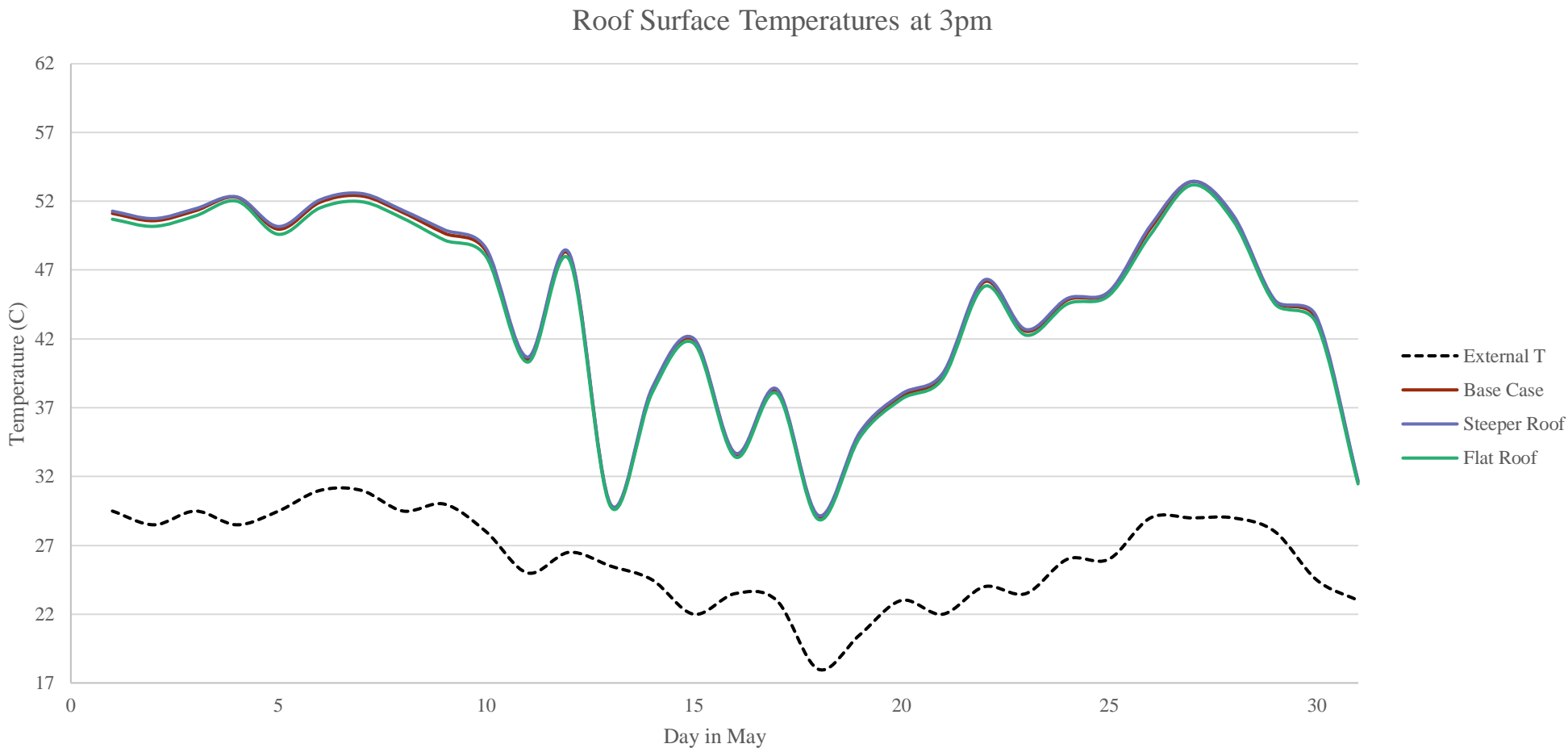


Figure 95: Spatial operative temperatures for 9:30 am and 4:30pm in May.

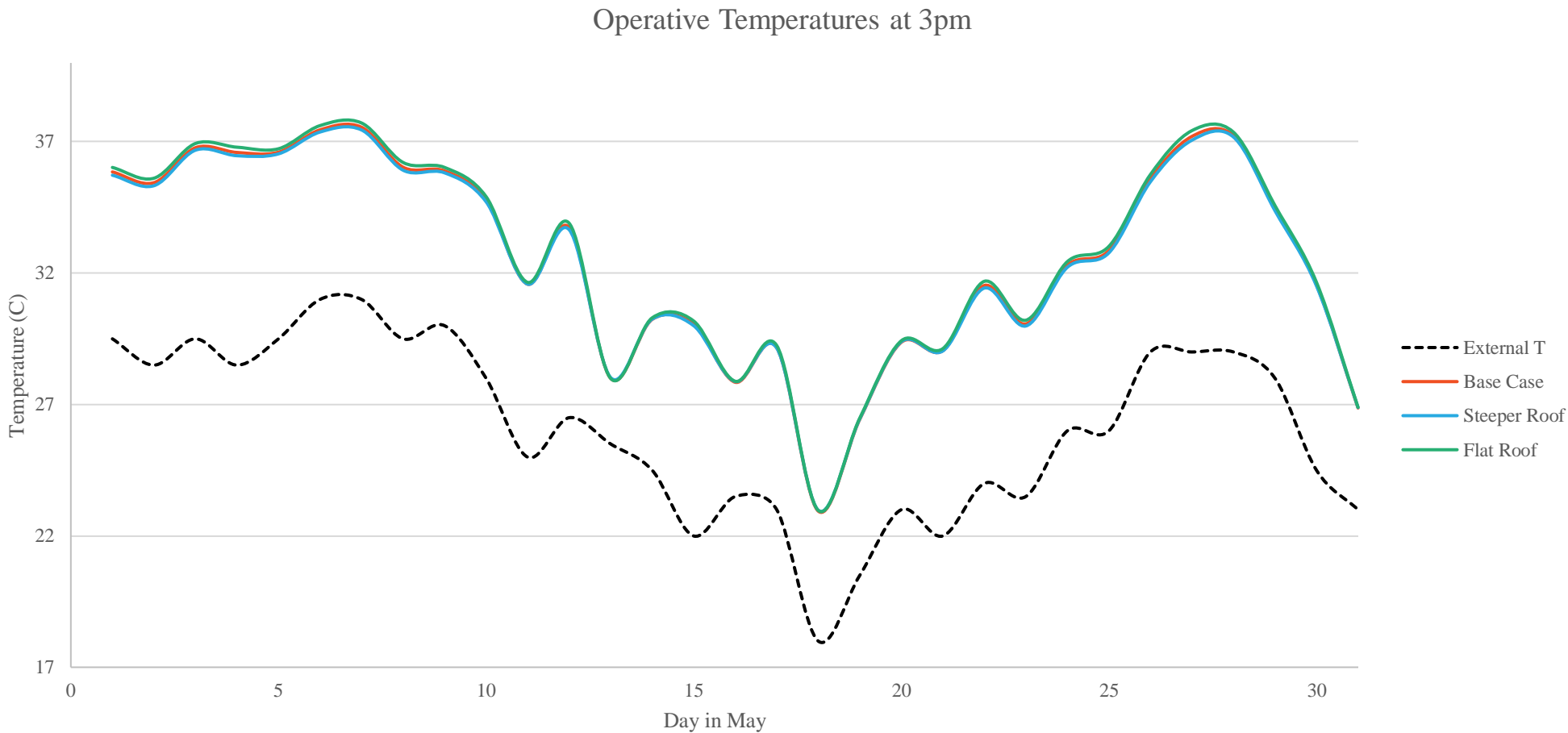
Roof Pitch – Roof Surface Temperatures



Due to the buildings in all cases being oriented with roofs parallel to the path of the sun during the day, the roof pitch has little impact on the roof surface temperature.

Figure 96: Roof surface temperatures for 3pm in May, comparing the flat roof, steeper roof and base cases.

Roof Pitch – Internal Operative Temperatures



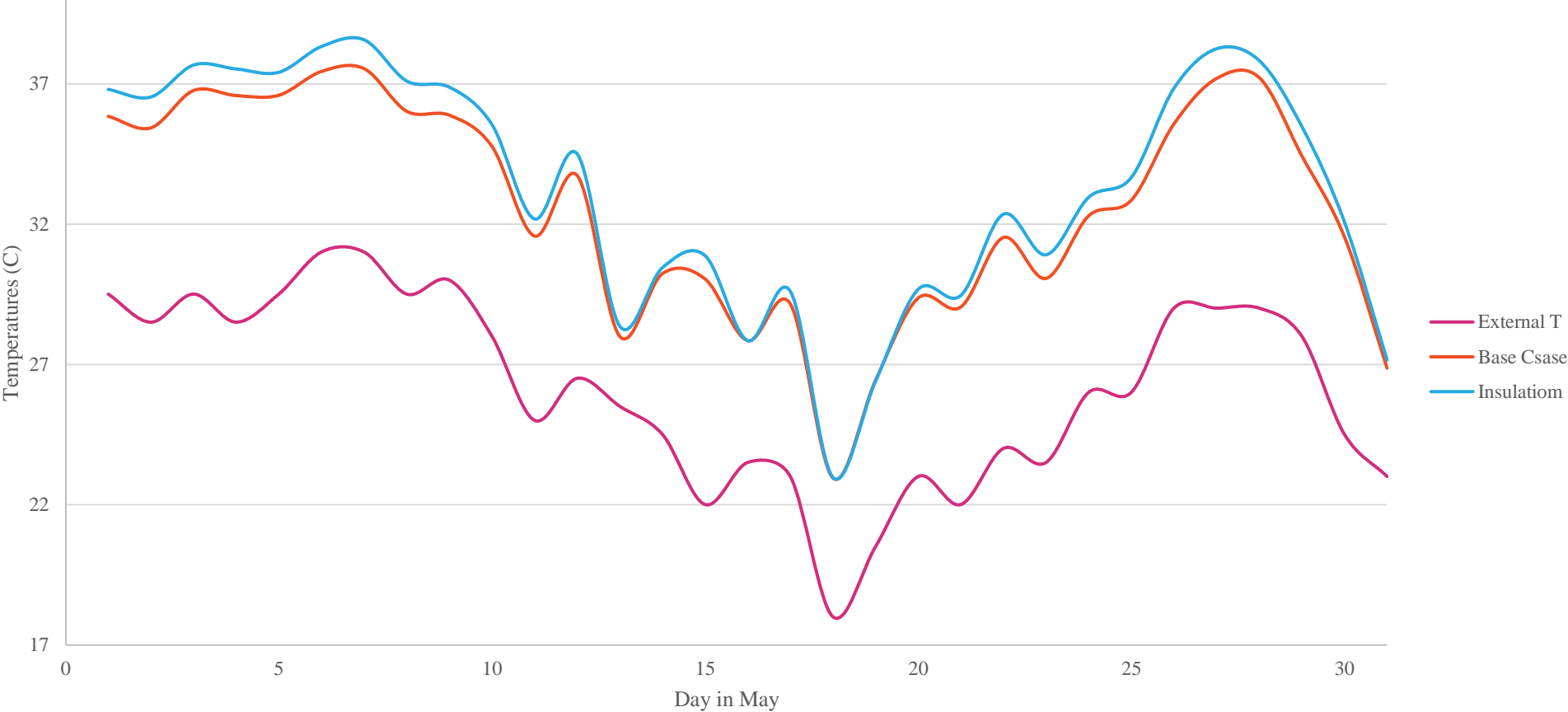
Internal temperatures are similar regardless of roof pitch as roof pitch has little effect on roof surface temperature.

Figure 97: Internal operative temperatures for 3pm in May, comparing the flat roof, steeper roof and base cases.

Insulation

Insulation – Internal Operative Temperatures

Operative Temperatures at 3pm



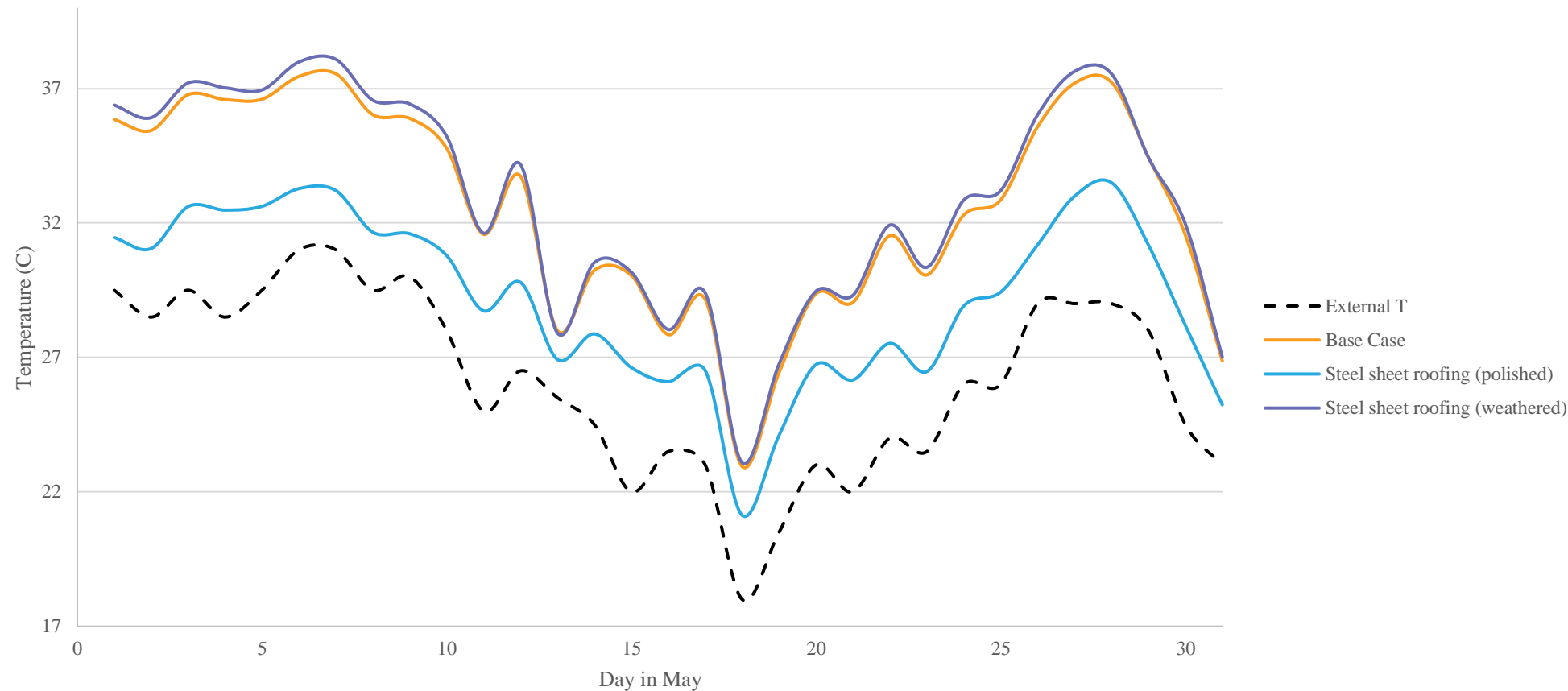
Insulation prevents heat loss from the internal space causing slightly higher internal temperatures, as expected.

Figure 98: Internal operative temperatures for 3pm in May, comparing the insulation strategy against the base case.

Steel Sheet Roofing

Steel Sheet Roofing – Internal Operative Temperatures

Operative Temperatures at 3pm



The base case is made up of fibre cement boards with an albedo of 0.27, while the steel sheet roofing has albedos of: 0.25 for weathered and 0.8 for polished.

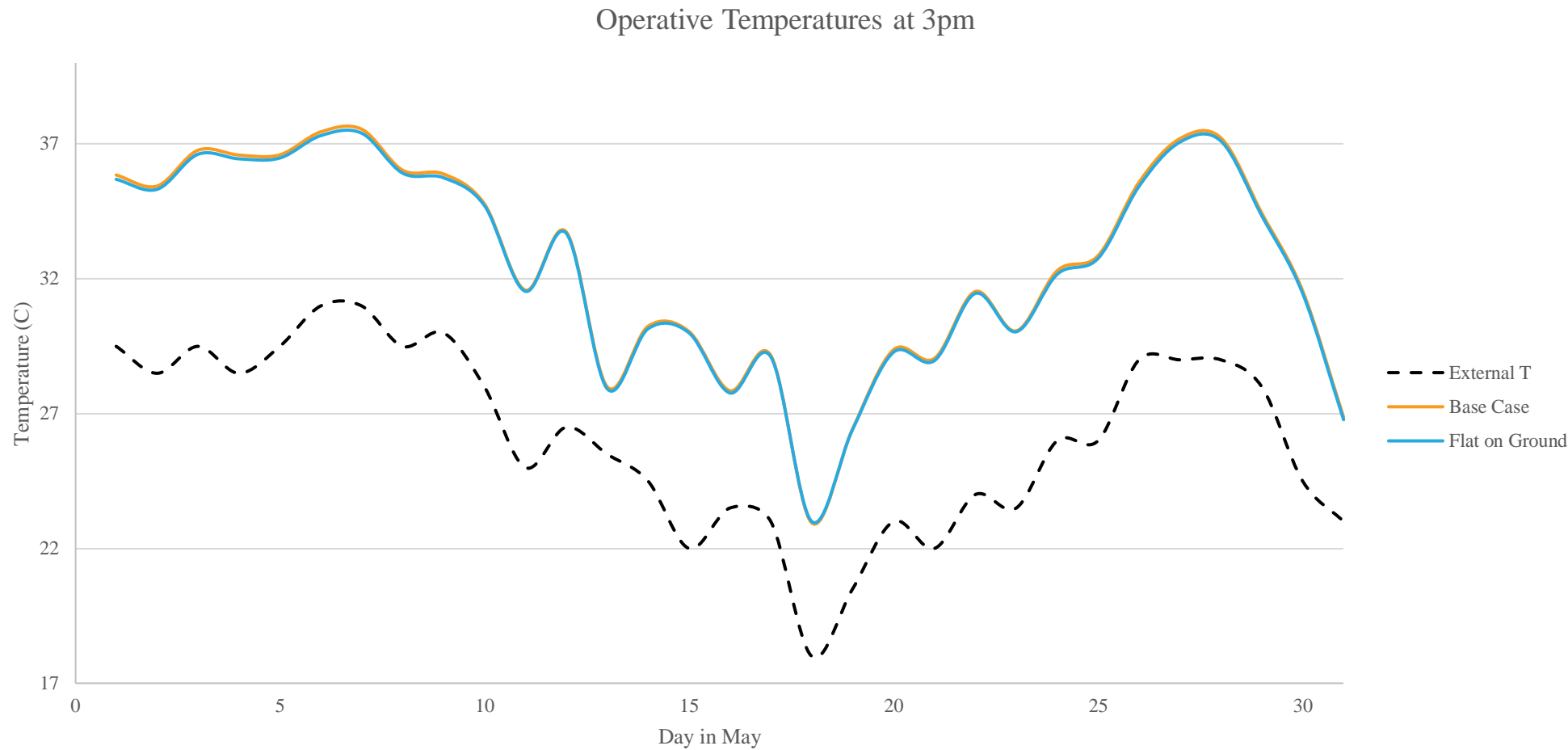
The weathered steel roof has higher thermal conductivity than the base case roof which gives higher roof surface temperatures and therefore higher internal temperatures. While the polished has a much higher albedo than the other cases causing more sunlight to be reflected away from the roof, reducing roof temperatures and thus internal temperatures.

The weathered steel more closely represents a steel sheet roofing than the polished steel.

Figure 99: Internal operative temperatures for 3pm in May, comparing the roof material strategies with the base case.

Flat on Ground

Flat on Ground – Internal Operative Temperatures



Moving building to be flat on the ground, rather than elevated on stilts (as in the base case) should increase temperatures due to lack of ventilation underneath the building. The ventilation would carry cooler external air underneath the building reducing the temperature.

However, possibly due to no wind being modelled, the two cases have little to no difference in internal temperature.

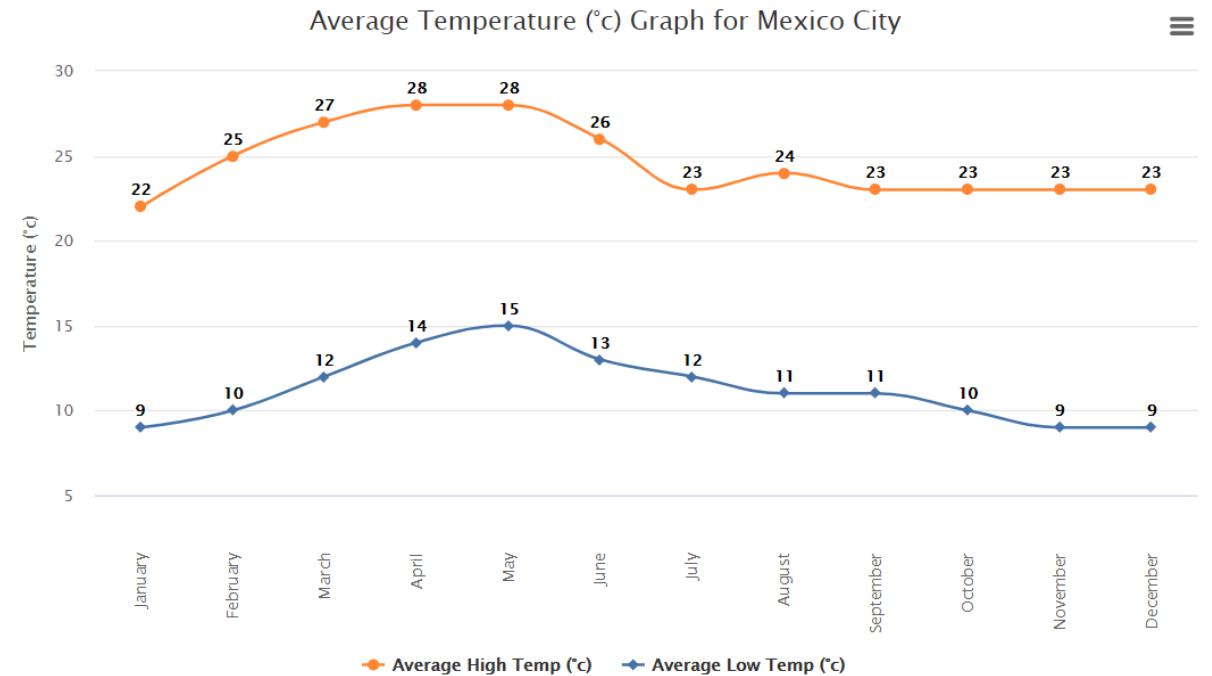
Figure 100: Internal operative temperatures for 3pm in May, comparing the flat on ground strategy against the base case.

Mexico City Winter



Subtropical highland climate (Cwb)

Monthly Average Temperature



Mexico City Average values (difference from base for December)

Average difference from base across December						
	Space temperatures		Indicative	Relative humidity		Air changes
	Dry bulb	Operative	PMV	Occupied	Upper	Natural
	(°C)	(°C)	-	%	%	/hr
Base						
Reflective Roof (0.75)	-0.46	-0.77	-0.21	0.89	0.89	-1.13
Reflective Roof (0.85)	-0.57	-0.93	-0.25	1.09	1.09	-1.41
Reflective Roof (0.95)	-0.67	-1.09	-0.29	1.30	1.30	-1.71
Larger Window	-0.06	-0.03	-0.01	0.11	0.11	0.62
Orientation +45°	-0.09	-0.16	-0.04	0.26	0.26	-0.28
Orientation +90°	-0.12	-0.32	-0.09	0.19	0.19	-0.26
Orientation +135°	-0.25	-0.55	-0.15	0.41	0.41	-0.50
Orientation +180°	-0.13	-0.32	-0.08	0.25	0.25	-0.26
Orientation +225°	-0.19	-0.42	-0.11	0.44	0.44	-0.48
Orientation +270°	-0.15	-0.38	-0.10	0.22	0.22	-0.28
Orientation +315°	-0.19	-0.38	-0.10	0.27	0.27	-0.34
Flat Roof	-0.04	-0.07	-0.02	0.11	0.11	0.26
Steeper Roof	0.07	0.09	0.02	-0.15	-0.15	-0.51
Insulation	0.22	0.21	0.06	-0.84	-0.84	-0.06
Steel sheet roofing (polished)	-0.50	-0.82	-0.22	0.91	0.91	-1.26
Steel sheet roofing (weathered)	0.05	0.09	0.02	-0.14	-0.14	0.11
Flat on Ground	0.12	0.15	0.04	-0.55	-0.55	0.05

Mexico City Average values (absolute averages over all hours in December)

Absolute Values									
	External	Space temperatures		Indicative Comfort		Relative humidity		Air changes	Tdiff
	Tdry	Dry bulb	Operative	PMV	Heat Stress	Occupied	Upper	Natural	
	(°C)	(°C)	(°C)	-	-	%	%	/hr	(°C)
Base	14.04	15.74	16.66	-1.74	60.89	51.39	51.39	8.78	
Reflective Roof (0.75)	14.04	15.28	15.89	-1.95	59.90	52.28	52.28	7.64	-0.77
Reflective Roof (0.85)	14.04	15.18	15.73	-1.99	59.68	52.48	52.48	7.37	-0.93
Reflective Roof (0.95)	14.04	15.07	15.57	-2.04	59.47	52.69	52.69	7.07	-1.09
Larger Window	14.04	15.68	16.63	-1.75	60.85	51.50	51.50	9.40	-0.03
Orientation +45°	14.04	15.66	16.50	-1.78	60.68	51.65	51.65	8.49	-0.16
Orientation +90°	14.04	15.62	16.34	-1.83	60.47	51.58	51.58	8.52	-0.32
Orientation +135°	14.04	15.49	16.11	-1.89	60.17	51.80	51.80	8.27	-0.55
Orientation +180°	14.04	15.62	16.34	-1.83	60.48	51.64	51.64	8.52	-0.32
Orientation +225°	14.04	15.55	16.24	-1.86	60.34	51.83	51.83	8.30	-0.42
Orientation +270°	14.04	15.59	16.28	-1.85	60.40	51.61	51.61	8.50	-0.38
Orientation +315°	14.04	15.56	16.28	-1.85	60.40	51.66	51.66	8.43	-0.38
Flat Roof	14.04	15.71	16.59	-1.76	60.79	51.50	51.50	9.03	-0.07
Steeper Roof	14.04	15.81	16.75	-1.72	61.00	51.24	51.24	8.27	0.09
Insulation	14.04	15.96	16.87	-1.69	61.14	50.55	50.55	8.72	0.21
Steel sheet roofing (polished)	14.04	15.25	15.84	-1.96	59.82	52.30	52.30	7.51	-0.82
Steel sheet roofing (weathered)	14.04	15.80	16.75	-1.72	61.01	51.25	51.25	8.89	0.09
Flat on Ground	14.04	15.87	16.81	-1.71	61.07	50.84	50.84	8.83	0.15

Mexico City Summary

The most effective strategy in Mexico City is the reflective roof, where a higher albedo gives a greater cooling effect. Limited improvement was seen for polished steel roof material, increased window size and steeper roof. Benefits of the strategies in summer exceed the penalty in winter, as the winter condition is not significantly worsened, while the summer condition is significantly improved.

Study of Passive Cooling Strategies

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ARUP