Microclimatic responses to greenhouse covers

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CERTH
CENTRE FOR RESEARCH & TECHNOLOGY HELLAS

iBO
Agri-Technology & Bio-Economy

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CENTRE FOR
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HELLAS

iti
Information
Technologies
Institute

iBO
Agri-Technology & Bio-Economy

INAB

Hellenic Institute
of Transport (H.I.T.)

30 YEARS
CPERI
Chemical
Process and
Energy
Resources
Institute

https://youtu.be/Go2it2ZXhfs

CPERI
Chemical Process & Energy Resources Institute

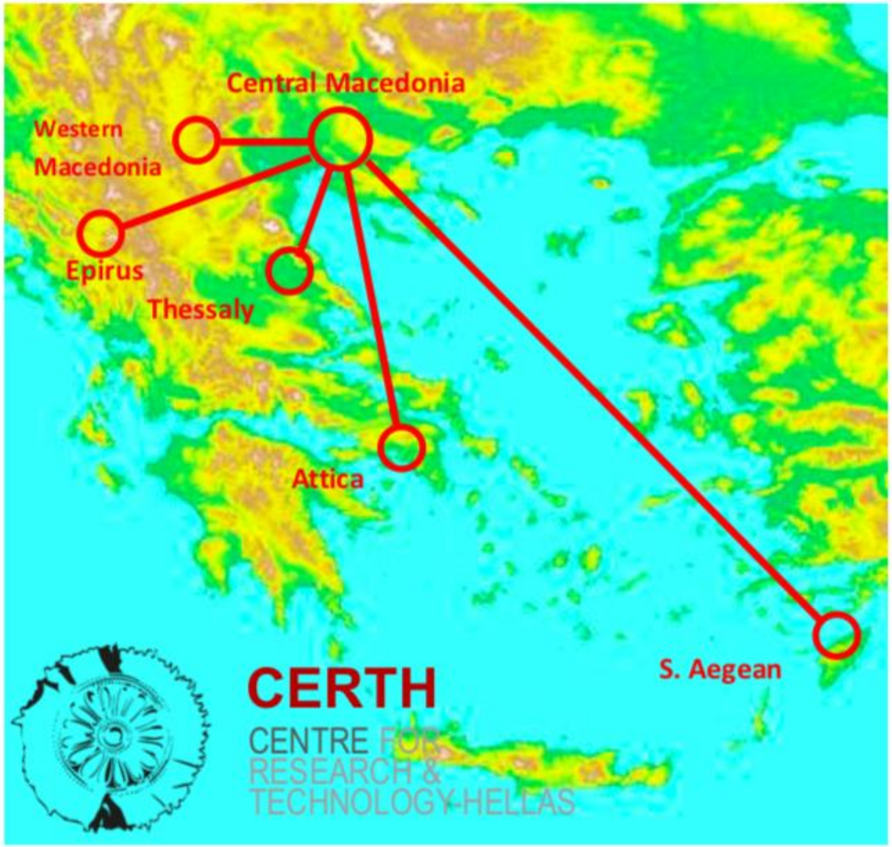
ITI
Informatics & Telecommunications Institute

HIT
Hellenic Institute of Transport

INAB
Institute of Applied Biosciences

iBO
Institute of Bio-economy and Agri-technology

- 5 Institutes & Annexes in 6 Regions
- Emphasis on RTD & Innovation
- Strong collaboration with international industry
- Strong co-operation with Universities and Research Institutes worldwide
- Unique Infrastructures at the lab, pilot and demonstration scales in Energy, Environment, Sustainable Mobility, ICT, Processes & Manufacturing, Agritech, Biosciences/Biotech



CERTH AT A GLANCE

- **Established**: in 2000 (CPERI existing since 1985). 2013 IBO (ex-IRETETH) joined CERTH.
- **Personnel** : 700+ with majority being engineers and scientists
- **Annual Turnover:** € 25+ Million yearly average for the last 10 years (2017 – 35 M €)
  - ✓ >20% from bilateral industrial research contracts/
  - ✓ >70% from competitive research projects and
  - ✓ <10% as government institutional funding (2016-17: 13%)
- **Publications:** >500/year - Heterocitations: >7000/year
- **Return-on-Investment:** Highest among greek RCs. >12:1 for each € of institutional government funding. 63% of competitive EU grants in Central Macedonia.
- **Center of Excellence:** *Top-20 (10th) EU Research Centers in number of competitive grants (2007-today), 300+ active projects/year (>5000 total)*
- **Numerous awards and distinctions** (including *EU Descartes Prize, ERC Advanced Grant, REG-POT Grant, Trading Agent Competition Award,* and many more)
- **Digital Innovation Hubs:** Near Zero Energy-Smart House, Circular Economy-Industrial Symbiosis (applied)
- **Startups:** 10

Evolution of Research Organizations

Stage 1:
Islands of Excellence
(driven by individuality)

Stage 2:
Centers of Competence
(driven by specialization)

Stage 3:
Co-Evolving Ecosystems
(driven by synergy)

CERTH is at Stage 2 preparing to move into Stage 3

INSTITUTE OF BIO-ECONOMY & AGRITECHNOLOGY

iBO

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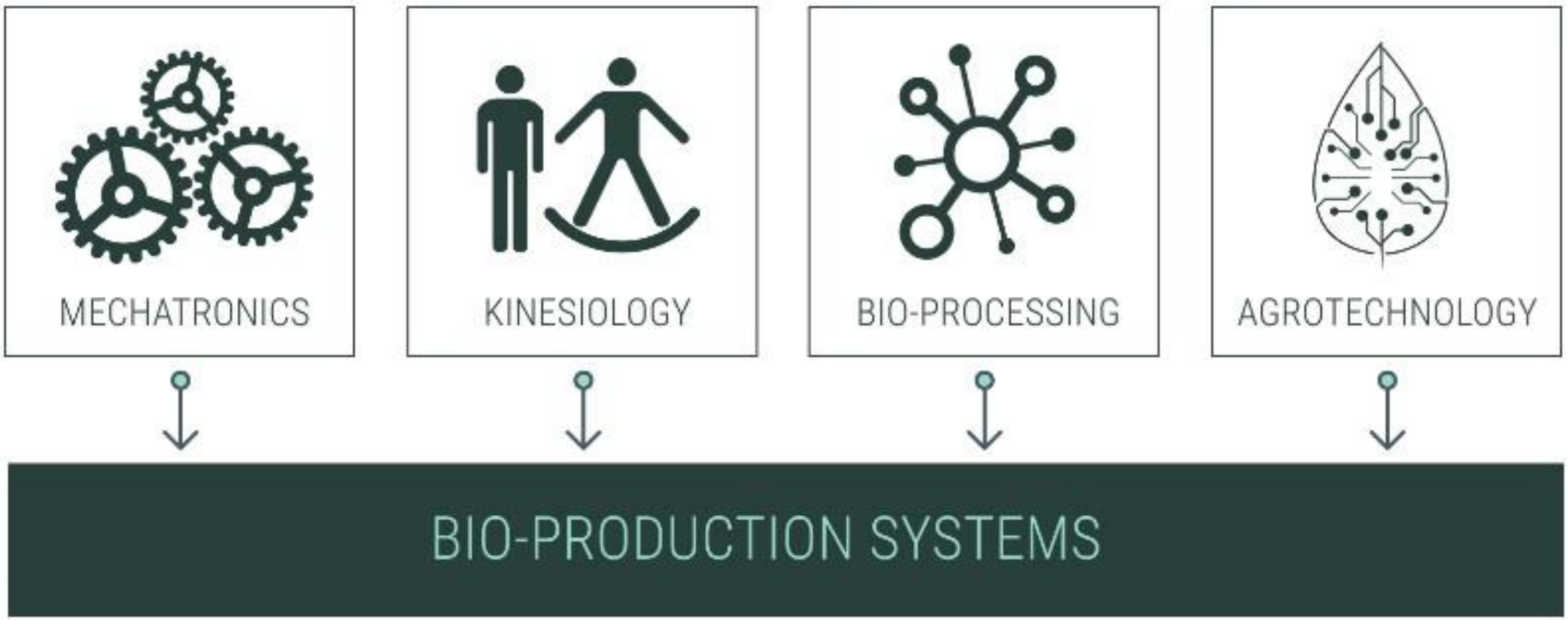
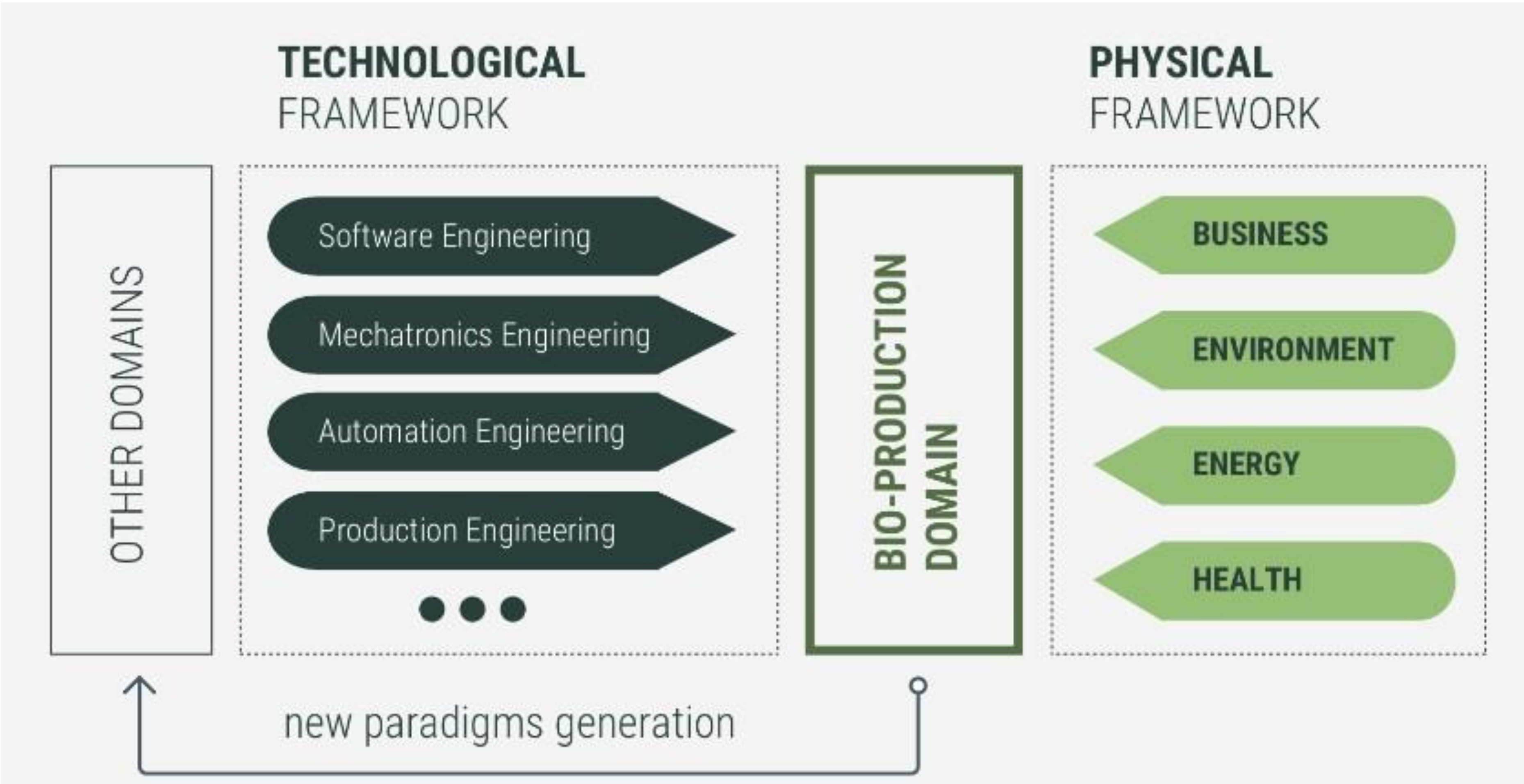
THE INSTITUTE



PHILOSOPHY



TECHNOLOGICAL
FRAMEWORK
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Software Engineering
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PERSONNEL


6
permanent researchers
18
collaborating researchers
2
auxiliary staff
8
administration
14
collaborating technical staff
11
collaborating academics
6
PhD fellows
65

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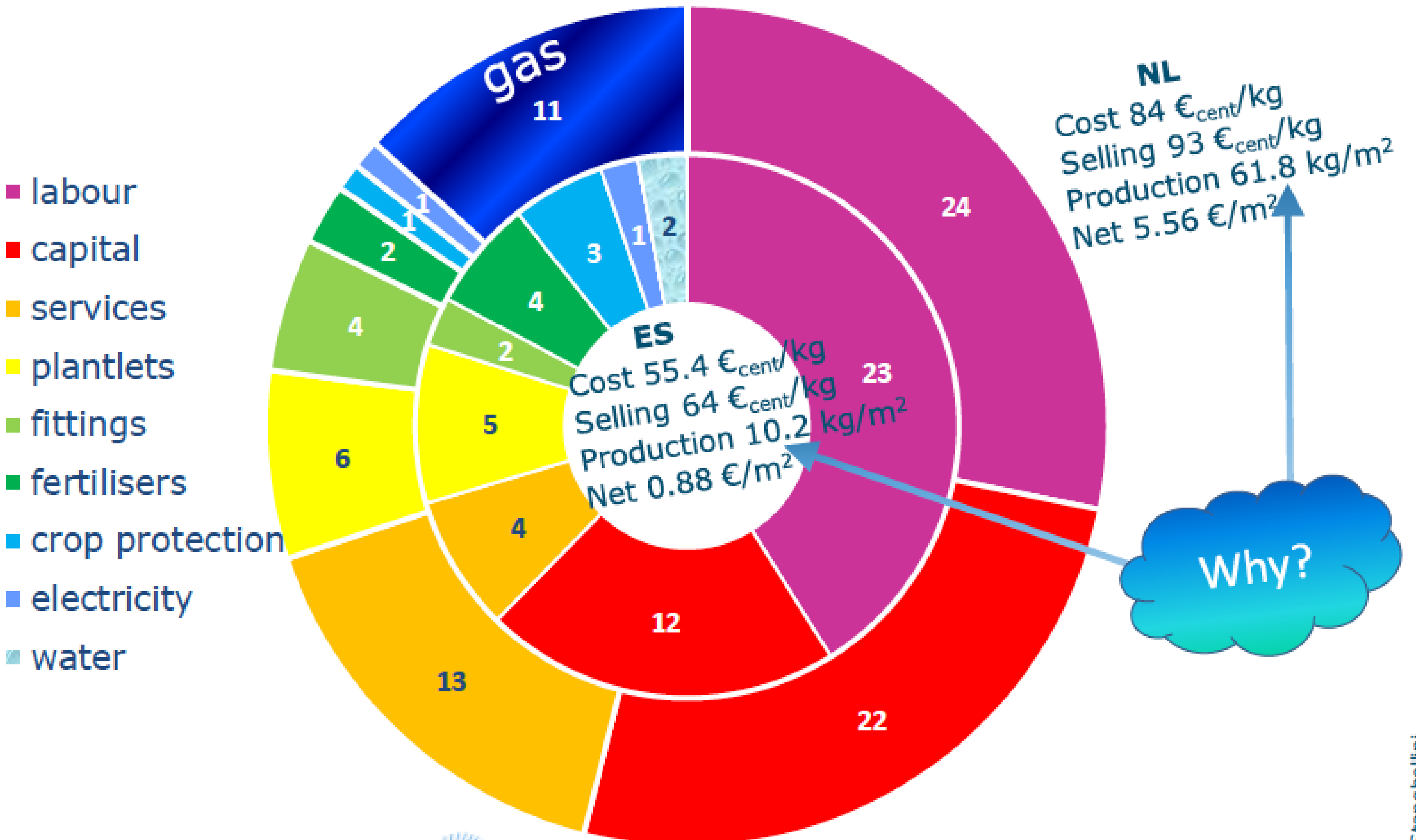
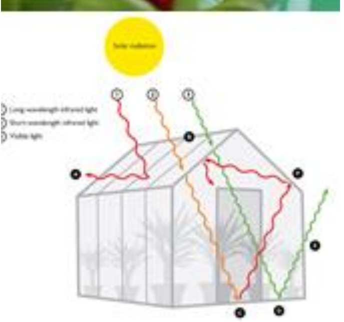
Production costs 2016 ($€_{cent}/kg_{truss\ tomato}$)



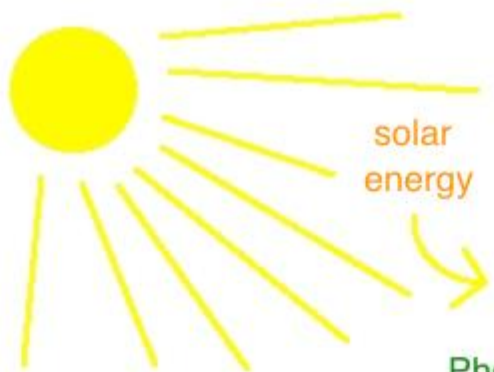
Sources: Fundación Cajamar
Wageningen Greenhouse Horticulture







Greenhouse transmittance is critical



Photosynthesis

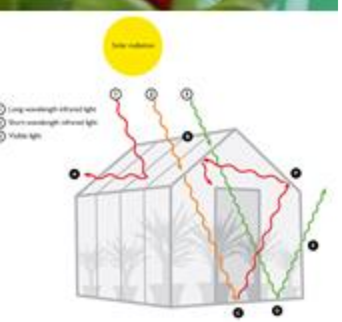
$$6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 6O_2$$

carbon dioxide | water | glucose | oxygen

Production of 1 kg tomato:

Sunlight: 90 mol PAR + 0.5 m³ natural gas

Illumination: 15 kWh = 3.75 m³ natural gas



Effects of light intensity

yield increase per % light increase

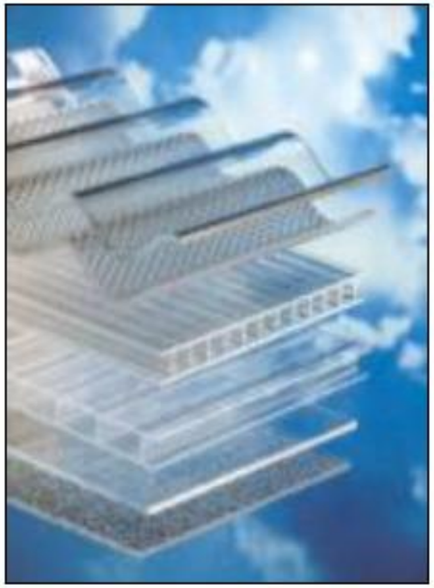
Crop	% Yield increase
Lettuce	0.8
Radish	1
Cucumber	0.7–1
Tomato	0.7–1
Rose	0.8–1
Chrysanthemum	0.6
Pointsettia	0.5–0.7
Ficus benjamina	0.6

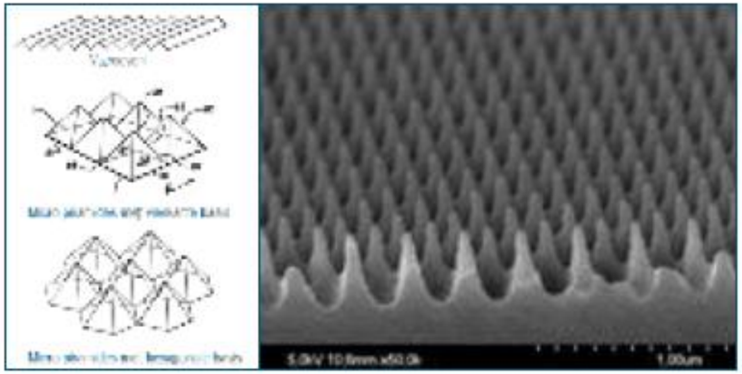
Source: Marcelis et al., 2006

Greenhouse transparency is a key factor

Covering material

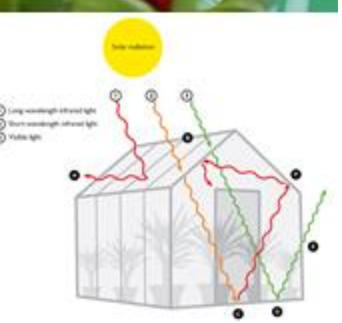
- Base material
  Standard glass
  Low iron glass
  Plastics (PC, PMMA, PE, ETFE...)
  Single/multilayer
- AR coatings
  Single/multilayer coating
  Surface treatment
- Diffuse
  Structures (grooves, bubble, pyramids)
  Random (etching, sandblast)
  macro, micro, nano
  pigments, masterbatches











Importance of light scattering

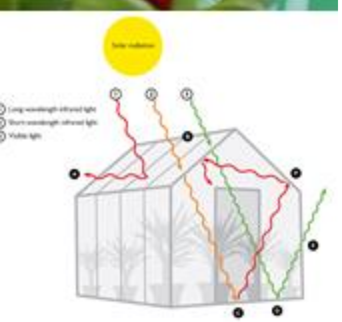
Scattering materials convert direct sunlight into (partially) diffuse light

This results in:

- Higher photosynthesis
- More light interception
- Lower crop temperature
- Less photo inhibition
- Better micro climate at high radiation
- Higher yield for cucumber (5-10%)
- Higher growth rate for pot plants (5-25%)





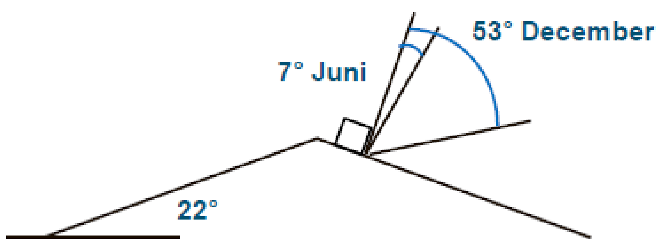


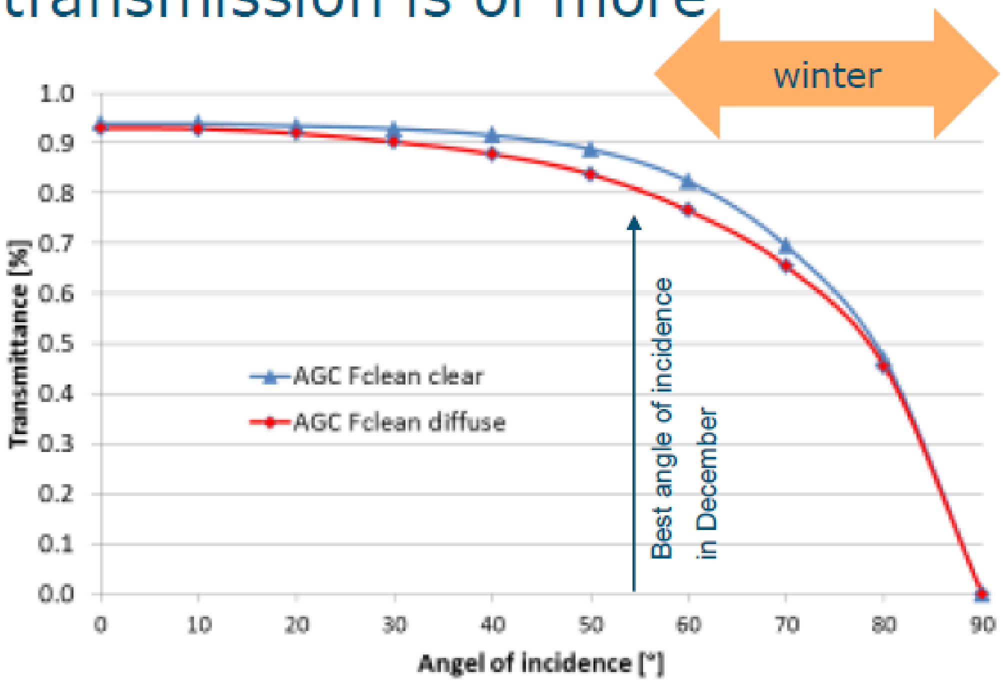
How we can increase light transmission

- Improve covering material e.g.
  - White (low iron) glass (+1-2%)
  - AR coatings (+5-7%)
- Lighter construction (max +1-3%)
- Roof slope (~1%)
- Roof orientation (+3-4% year round)
  - Differs per season (25% January)
- Clean roof (up to 10% or more)
- Less installations (max +1-3%)

Transmission of covering material

- Transmission of transparent materials is depending of angle of incidence
  - Perpendicular (in this case the same)
  - Hemispherical 87/82%
    - Hemispherical transmission is of more importance

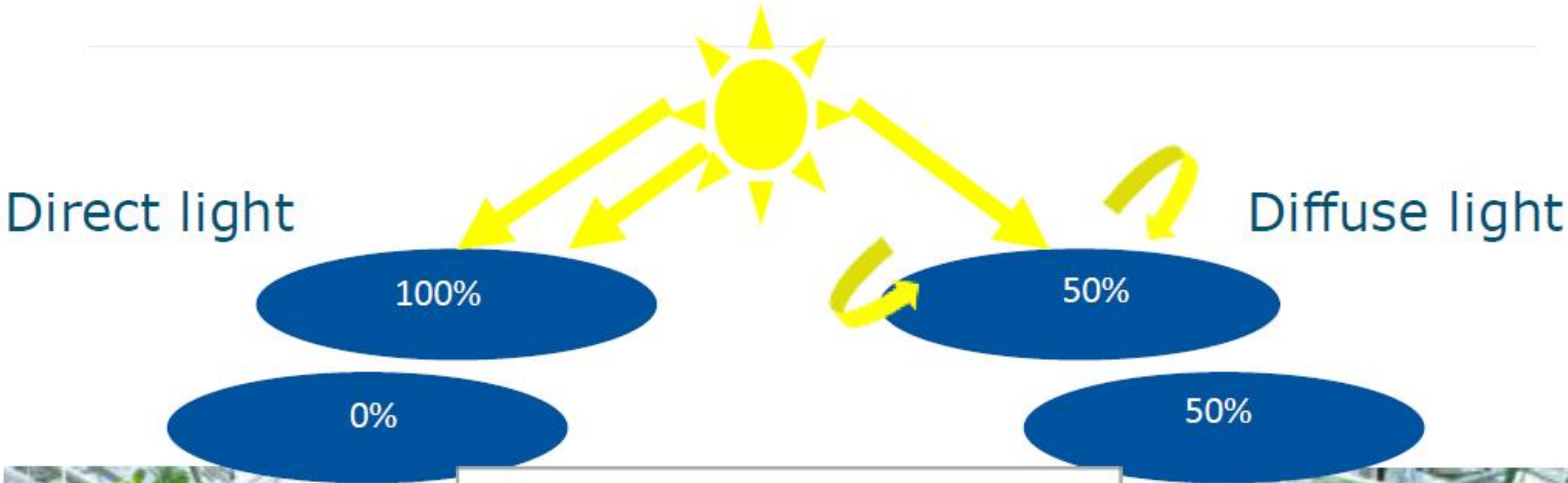


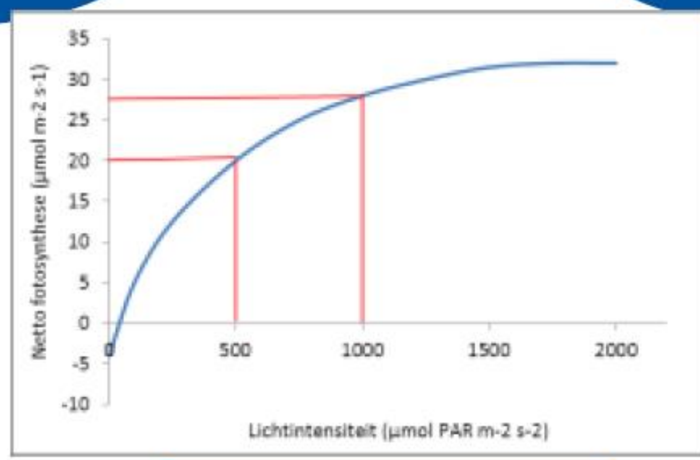


Transmission losses by condensation

- In winter our cover is wet

Light quality → diffuse



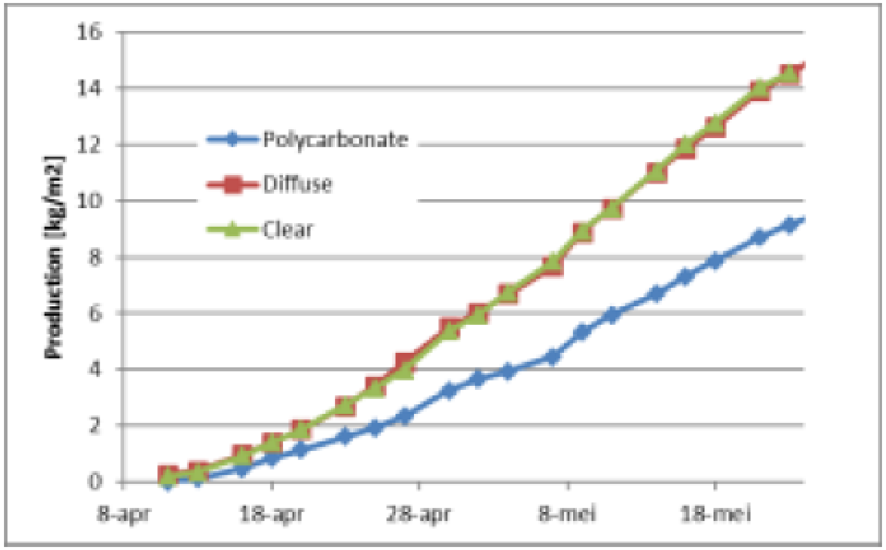


More photosynthesis
+ different micro climate
= more production

Source: Dueck, 2011

Some results from experiments

- Average production till 23rd of May 2017 was 9.2 kg/m2 under the polycarbonate,14.5 kg/m2 under the diffuse cover and 14.6 kg/m2 under clear
- 58% more is produced in the diffuse greenhouse compared to the polycarbonate
- No difference between clear and diffuse covering



4 mixed gutters	Production Kg/m2	St. deviation
Polycarbonate	9.15	0.31
Diffuse	14.51	0.66
Clear	14.55	0.80

Source, Campen 2018

Some results from experiments

Overall production	Total Production [kg]	total light [mol]	light efficiency [g/mol]
M3 (polycarbonate)	9.15	995.88	9.2
M4 (diffuse)	14.51	1690.39	8.6
M5 (clear)	14.55	1703.22	8.5

- Light measurement done by PAR sensors in the greenhouse, corrected for the screen position if not 100% closed
- The light use efficiency for the difference coverings is similar showing more light gives indeed more production!

Source, Campen 2018

Effects of a PE film with high reflectance and absorption in near infrared radiation (NIR) and of a PE film with low transmittance in IR, on th greenhouse microclimate, energy consumption and on growth and yield of a hydroponic tomato crop.

The NIR-PE film **reflects 39% more than the C-PE and 33% more** than the IR-PE film in the wavelengths range between 400 nm and 1100 nm (total). The **NIR-PE film has 13% lower transmissivity** in total radiation band than the other two films. Finally, the **NIR-PE film has 57%** higher absorbtivity than the C- PE film.

Mean values of air temperature and vapour pressure deficit in the three tested greenhouses and ambient environment during March 2009 (NIR-PE: PE film high reflectance and absorption in NIR radiation, IR-PE: PE film with low transmittance in IR (IR-PE, PE: standard PE film, Out: ambient environment).

	Day (08:00-20:00)		Night (20:00-08:00)	
	Air temperature (°C)	Air vapour pressure deficit (kPa)	Air temperature (°C)	Air vapour pressure deficit (kPa)
NIR-PE	16.5 ± 0.7	0.68 ± 0.3	15.2 ± 0.7	0.28 ± 0.1
IR-PE	15.4 ± 0.6	0.59 ± 0.3	15 ± 0.6	0.26 ± 0.1
C-PE	15.3 ± 0.6	0.58 ± 0.3	15.1 ± 0.6	0.25 ± 0.1
Out	12.5 ± 0.7	1.2 ± 0.4	5.5 ± 0.3	0.5 ± 0.2

Net radiation losses were 35% less in the IR-PE covered greenhouse than in the C-PE covered greenhouse. Based on the energy consumption for the winter period observed in the experimental greenhouses, the mean daily energy consumption calculated for a 1 ha greenhouse would be: 3620 MJ in the C-PE greenhouse, 3270 MJ in the NIR-PE greenhouse and 3160 MJ in the IR-PE greenhouse. This represents a total energy saving of about 12% when using the NIR-PE or the IR-PE films compared to the C-PE film.

Effects of Anti-Drip Polyethylene Covering Films on Microclimate and Crop Production

A standard polyethylene (PE) film covered one of the three greenhouses **(C-PE).**

The other two greenhouses were covered:

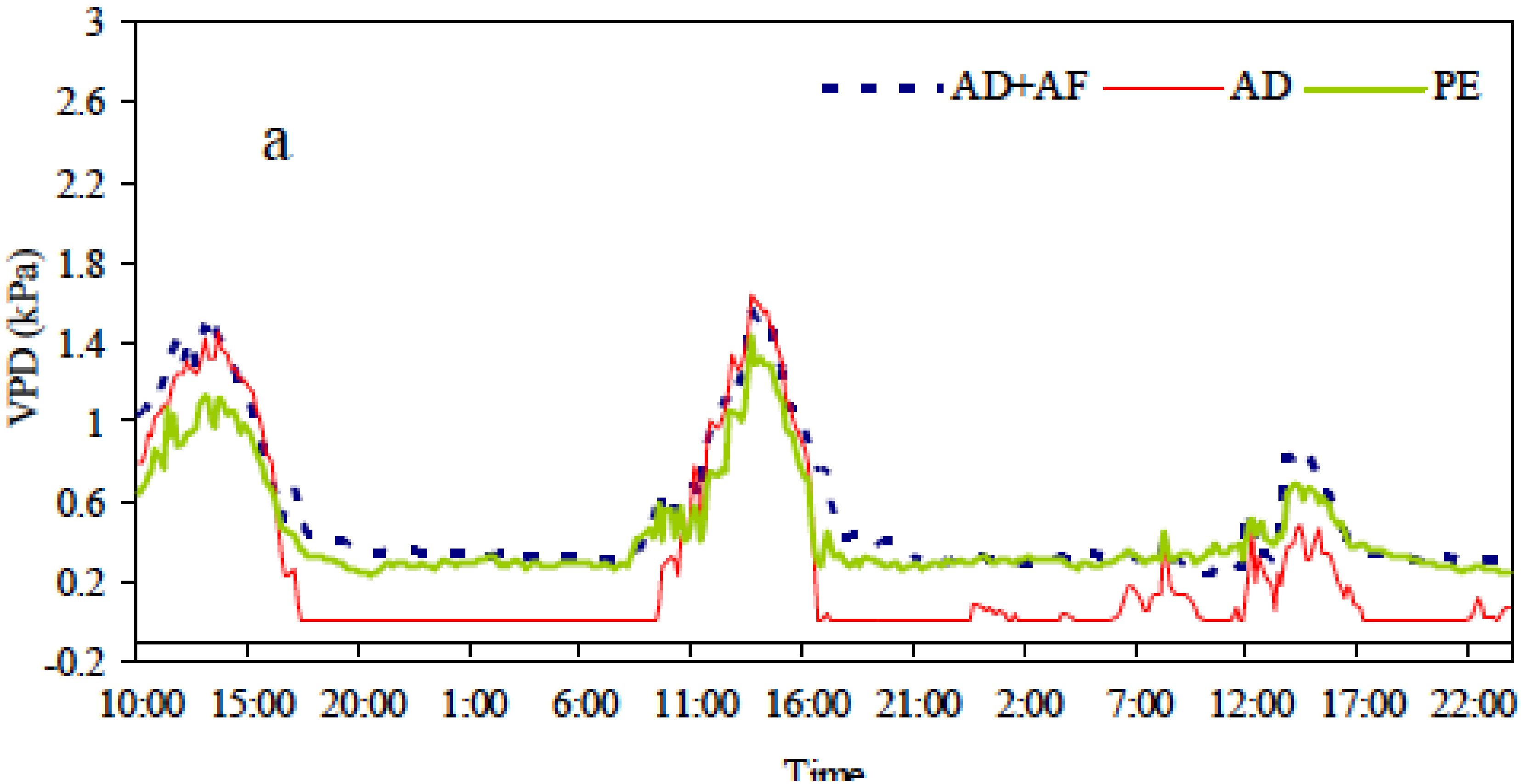
- the first by a PE film with anti-drip (AD) and anti-fog (AF) properties **(AD+AF-PE) and**
- the second one by a PE film with AD properties (**AD-PE**). The

Mean values of plants' total dry matter (g m^{-2}).

Date	Crop total dry matter (g m^{-2})		
	Greenhouse		
	C-PE	AD-PE	AD+AF-PE
	Cucumber		
10/10/2006	21.5a*	25.4a	17.0a
25/10/2006	78.8a	85.1a	88.8a
09/11/2006	112.9b	110.6b	159.8a
24/11/2006	137.0a	137.6a	119.2a
08/12/2006	116.3a	97.2a	92.4a
19/12/2006	120.8a	109.4a	128.8a
	Tomato		
18/1/2007	0.2b	0.2b	0.9a
1/2/2007	1.3b	1.8a	1.5ab
16/2/2007	8.8b	11.5a	11.6a
3/3/2007	30.2b	42.2a	36.0ab
16/3/2007	78.1a	90.6a	81.3a
31/3/2007	128.8a	143.1a	157.6a
18/4/2007	248.6b	264.0ab	289.3a
25/4/2007	222.6a	285.7a	277.3a

*Different letters in the same line indicate statistically significant differences.

The air vapor pressure deficit (VPD) inside the AD+AF-PE covered greenhouse was very low, reaching values near 0 kPa for many hours during the night during winter period, while VPD levels were higher in the C-PE and AD-PE covered greenhouses and during spring experimental period for all three greenhouses



Plant biomass expressed as fresh and dry matter.

Covering materials	Fresh biomass (g plant^{-1})			
	Stem	Leaves	Fruits	Total
Polyethylene film	411	393	1950	2754
Insect net	323	415	2124	2862
Photo-selective film	328	360	1707	2396
LSD	*41.5*	*35.3*	*331*	*376*
	Dry biomass (g plant^{-1})			
	Stem	Leaves	Fruits	Total
Polyethylene film	66	55	123	244
Insect net	52	58	134	244
Photo-selective film	53	50	108	211
LSD	*6.6*	*4.9*	*20.9*	*28.4*

Source: Leonardi et al. 2004, Acta Hort. 659

Yield level and fruit production per plant.

Covering materials	Marketable yield (t ha^{-1})	Unit weight (g)	Fruit number (n plant^{-1})	Unmarketable fruit number (%)
Polyethylene film	45.8	85.4	24.5	26.7
Insect net	55.1	116.5	21.8	27.6
Photo-selective film	42.1	90.7	20.1	23.5
LSD	*12.4*	*10.2*	*2.9*	

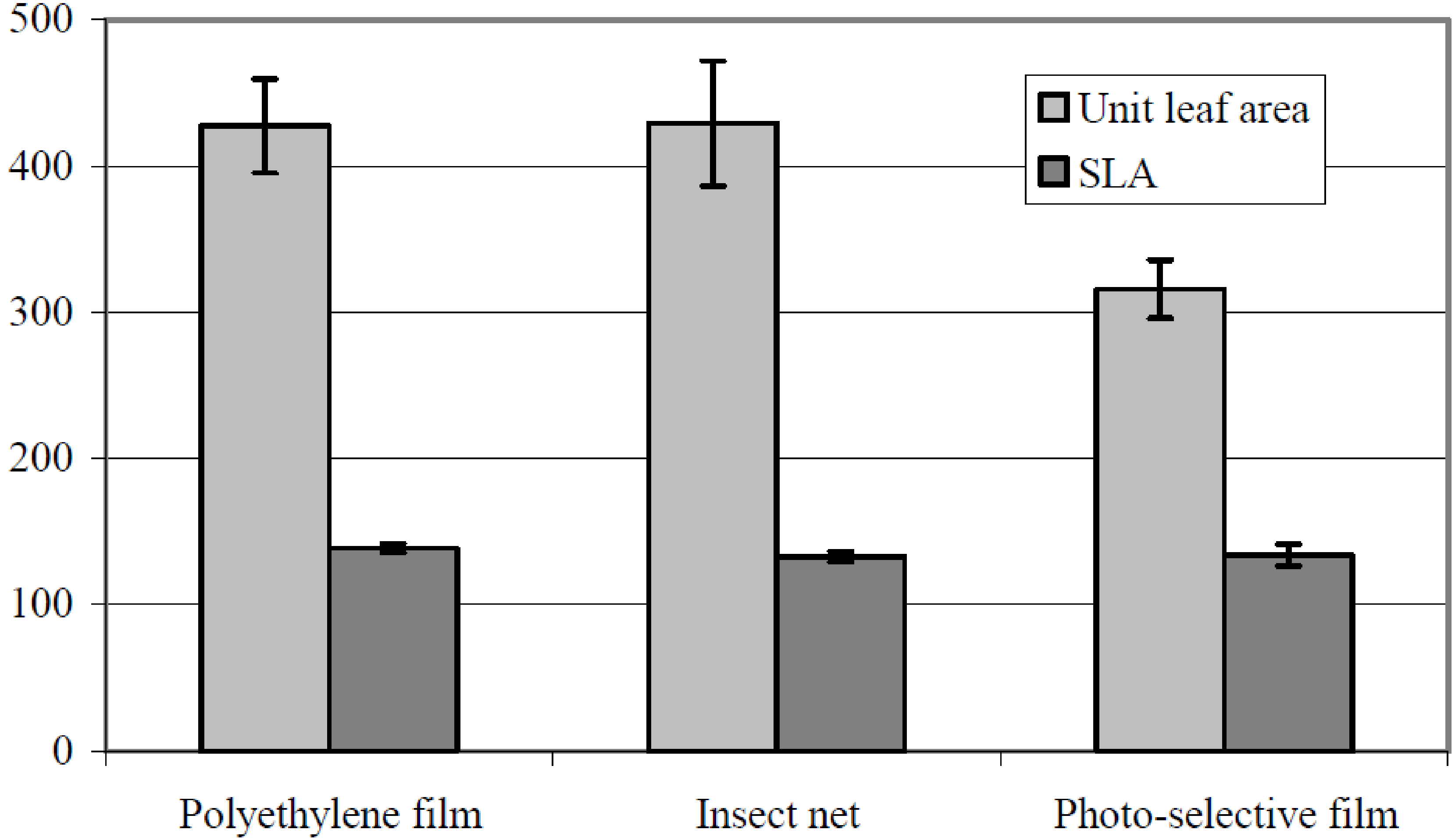
Fruit quality characteristics.

Covering materials	Polar diameter (cm)	Shape [(1)]	Firmness (g/2 mm)	Chromatic coordinates			Soluble solids (°brix)	Dry matter (%)
				L	a*	b*		
Polyethylene film	6.72	1.41	2317	54.8	9.2	22.9	3.74	4.62
Insect net	6.70	1.30	2114	51.4	11.2	23.8	3.56	4.20
Photo-selective film	6.68	1.39	2331	57.1	8.8	21.2	3.53	4.60
LSD	*n.s.*	*0.05*	*n.s.*	*n.s.*	*3.03*	*n.s.*	*n.s.*	*0.31*

(1) (polar / equatorial diameter)

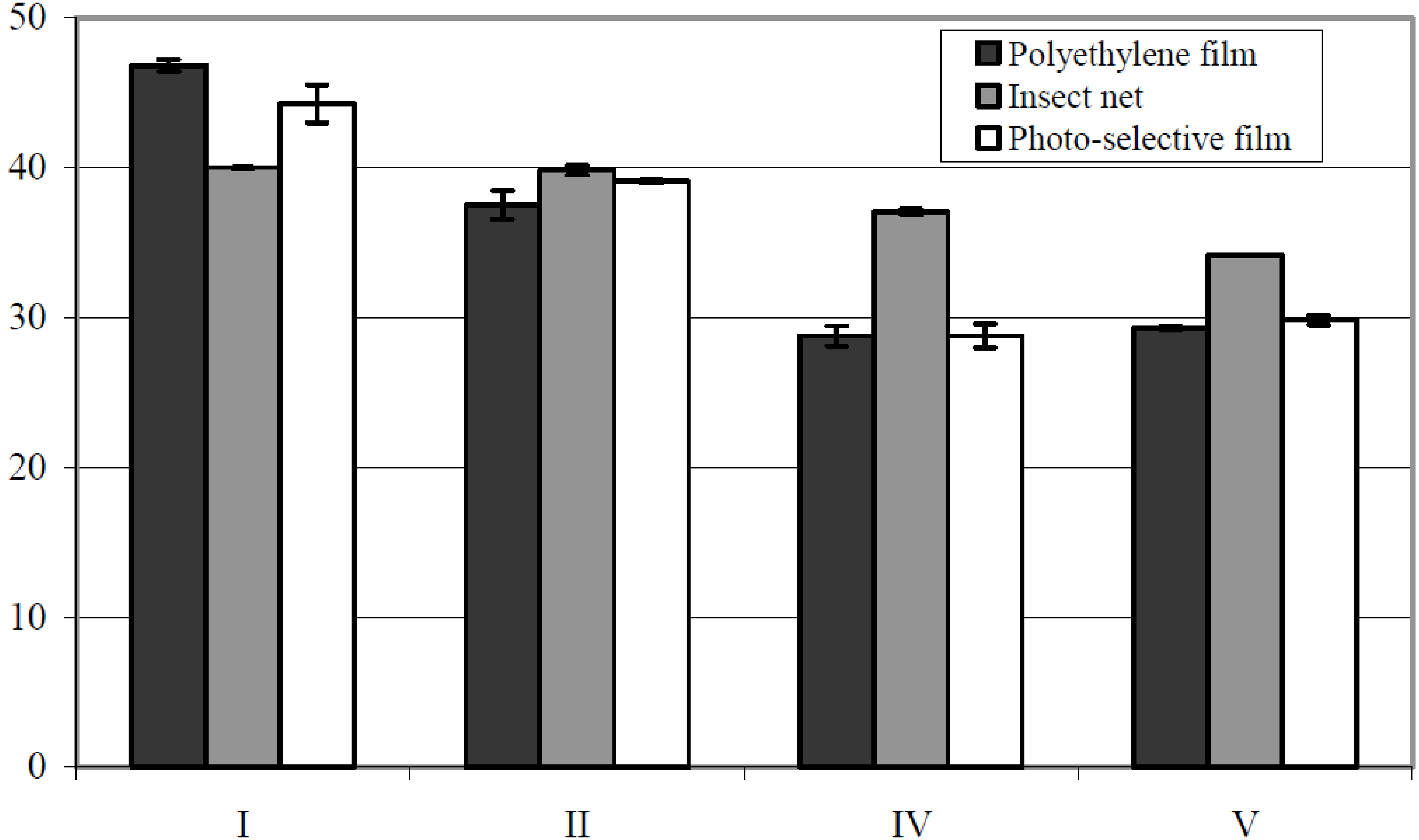
Source: Leonardi et al. 2004, Acta Hort. 659

Unit leaf area (cm2) and specific leaf area (cm2 g-1) [data concerning the leaves comprised between the 3rd and 4th truss]. (in this and in the following table vertical bars represent standard error).



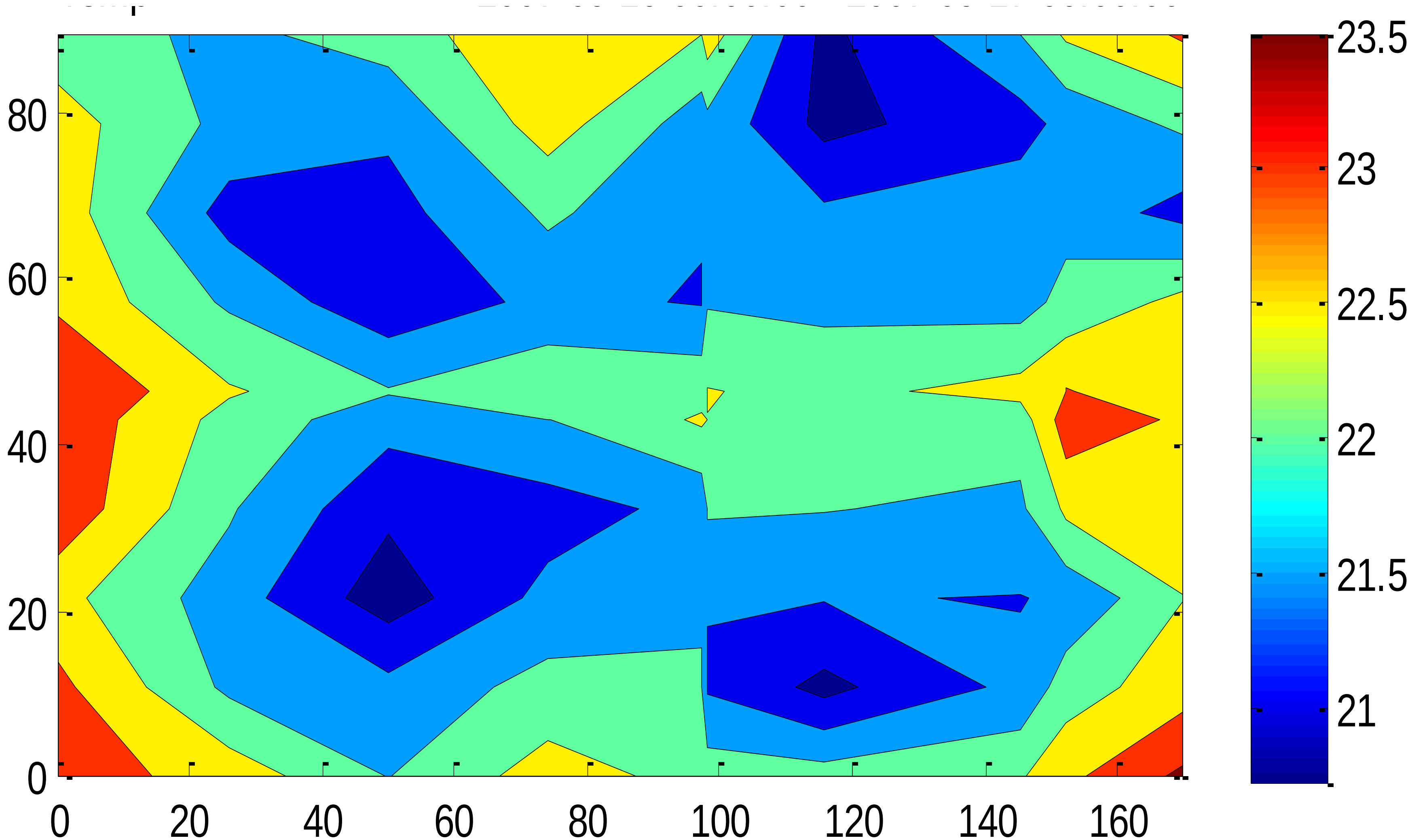
Source: Leonardi et al. 2004, Acta Hort. 659

Setting – ripening interval (day) of third fruit of different trusses

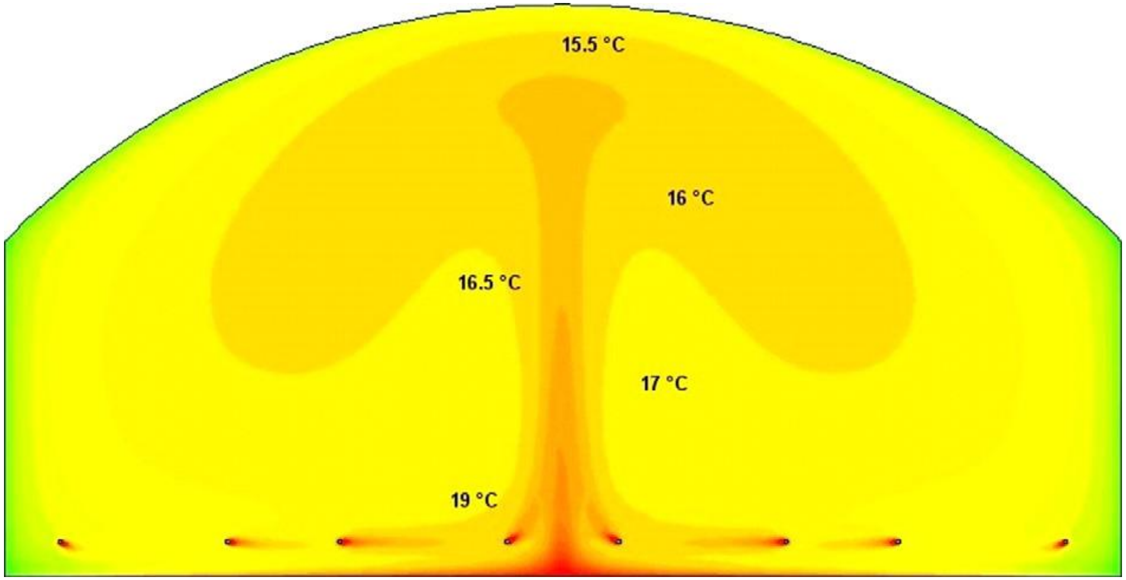


Climate heterogeneity

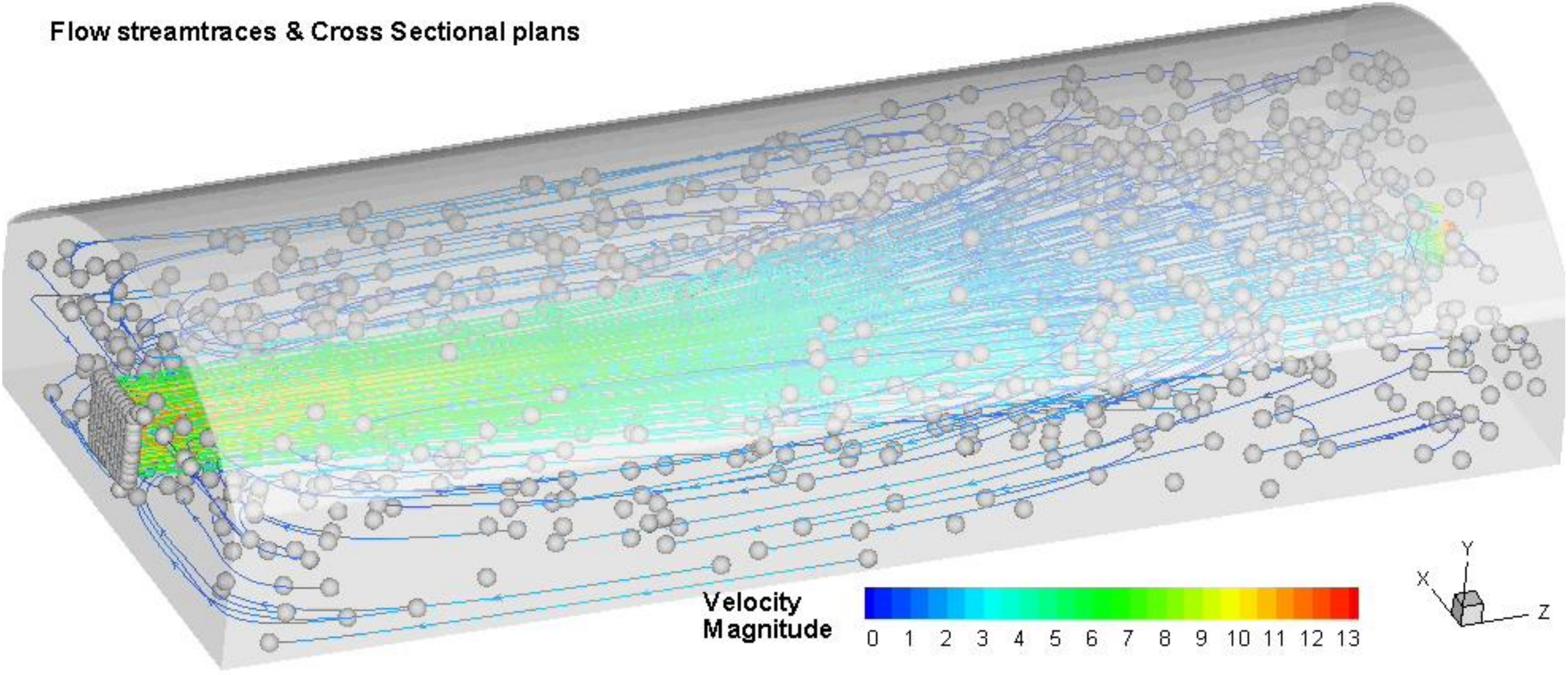
Cucumber with 100 sensors at 1.5 m height, grid:10 x 24m^2, 1 hourly average



Sapounas et al. 2011



No climatological variables are homogeneous in a greenhouse



Why CFD modelling in horticulture?

Experiments

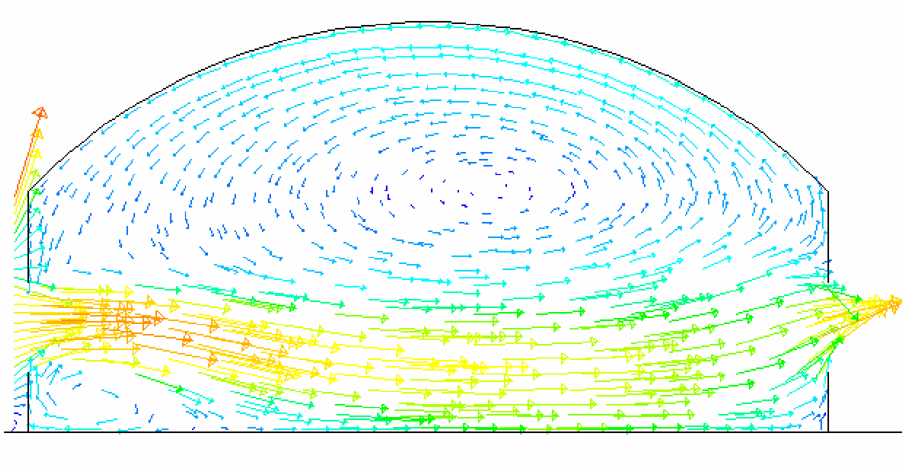
- ❑ Allows accurate measurements
- ❑ No need for modelling assumptions

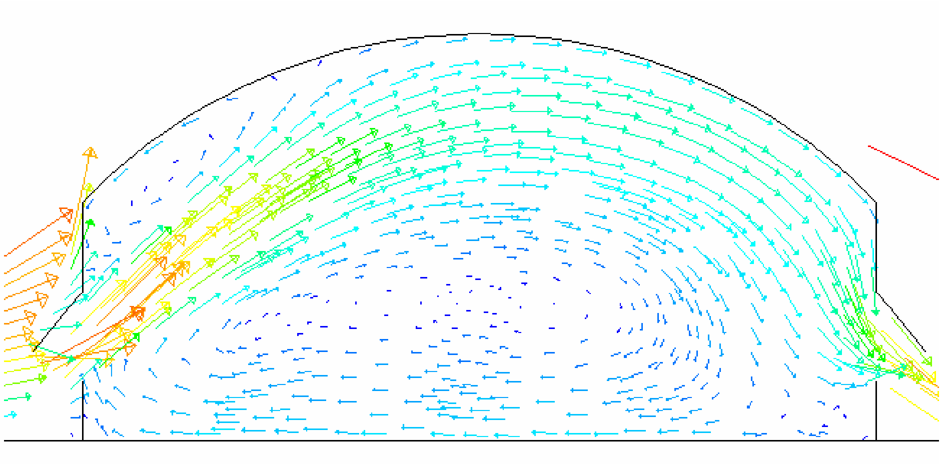
Demands for

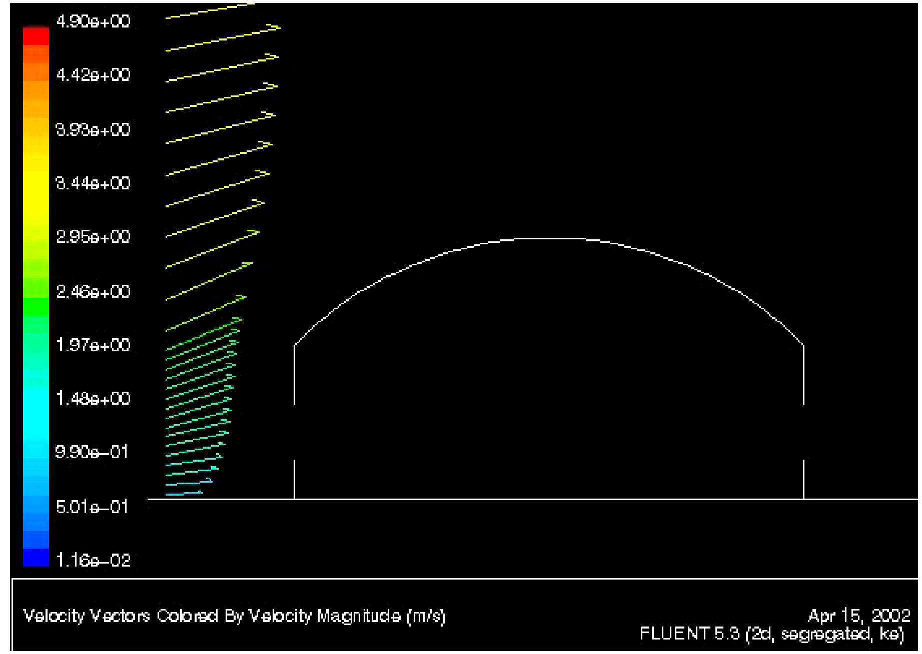
- ❑ Lab Expensive equipment
- ❑ or
- ❑ Time

Has to cope with

- ❑ Climate conditions
- ❑ Different structures and equipment designs



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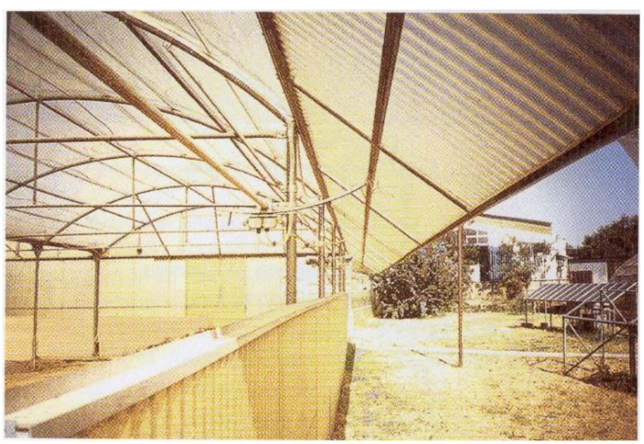
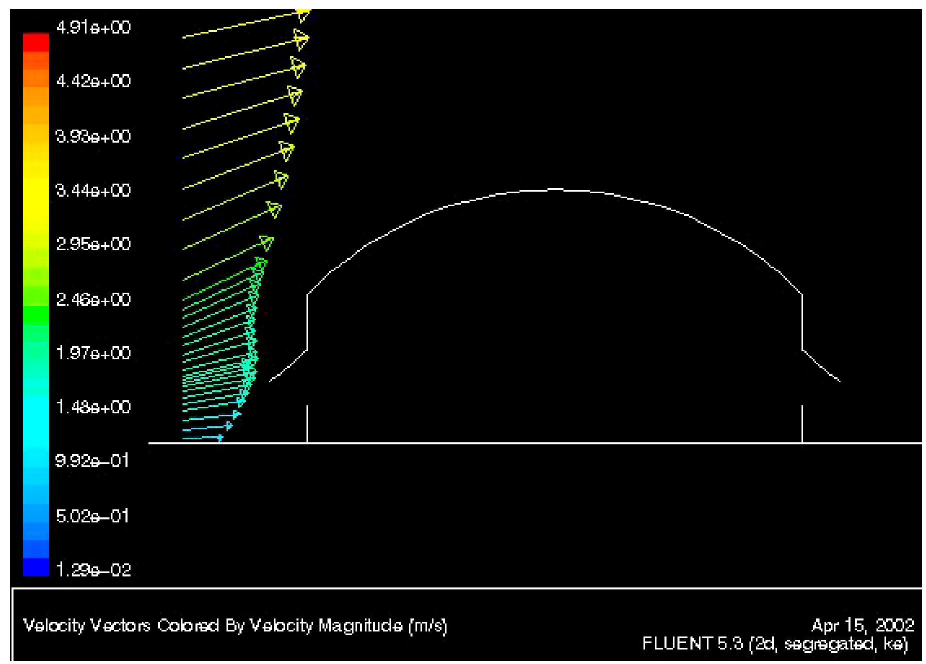
Velocity Vectors Colored By Velocity Magnitude (m/s)
Apr 15, 2002
FLUENT 5.3 (2d, segregated, ke)

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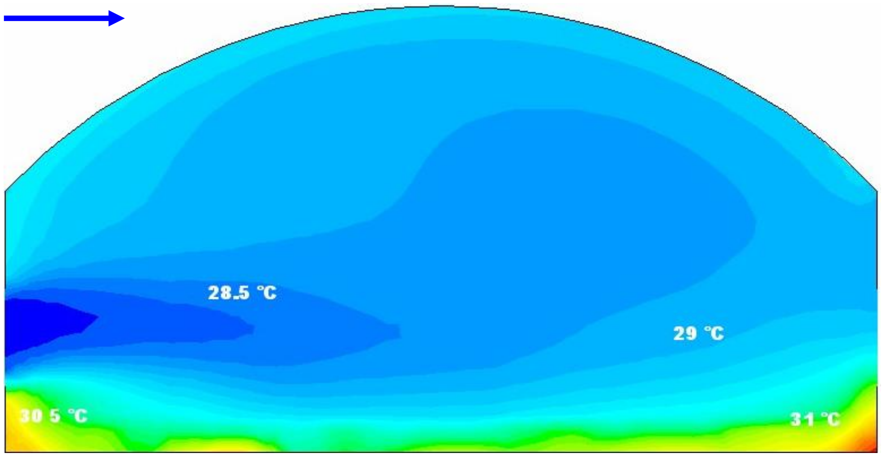
Velocity Vectors Colored By Velocity Magnitude (m/s)
Apr 15, 2002
FLUENT 5.3 (2d, segregated, ke)

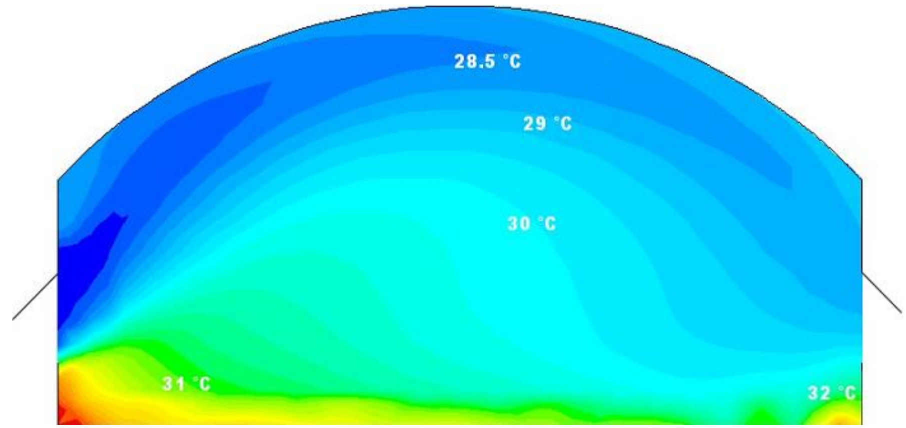
CFD models – improving natural ventilation systems
Air temperature distribution for different vent openings

WD

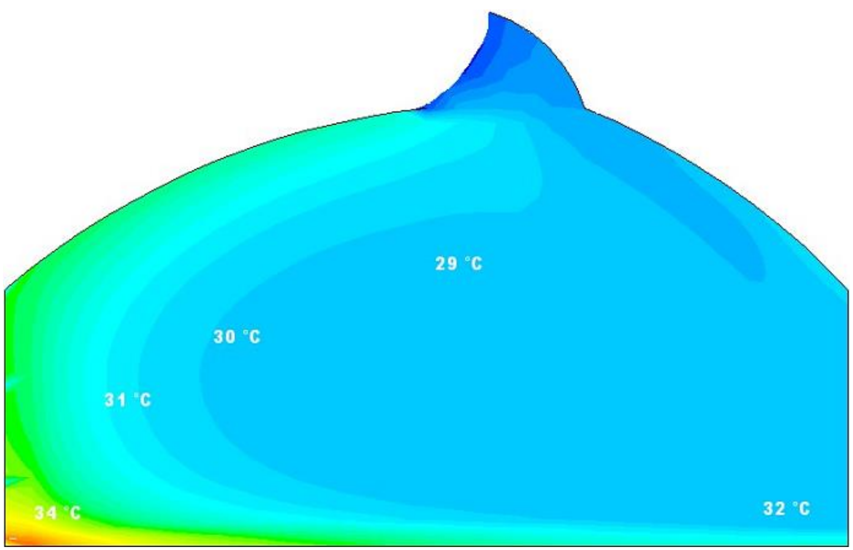
Roll –up type vents



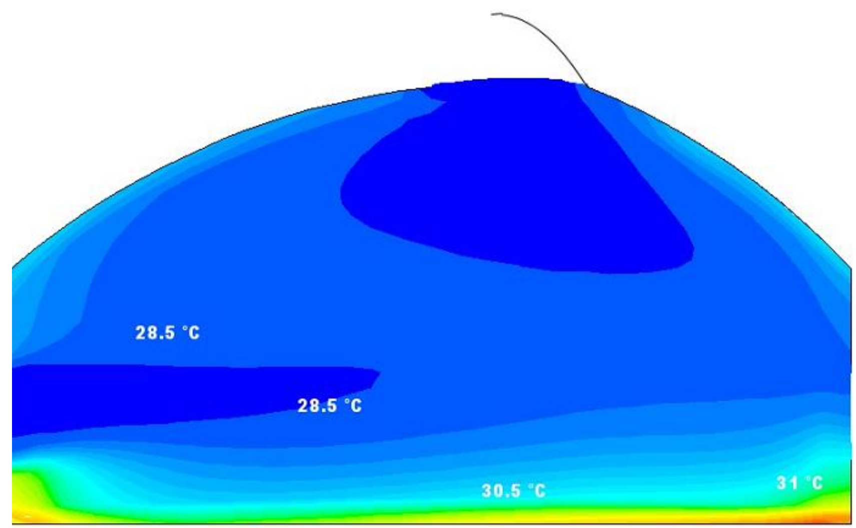
Sliding door type vents



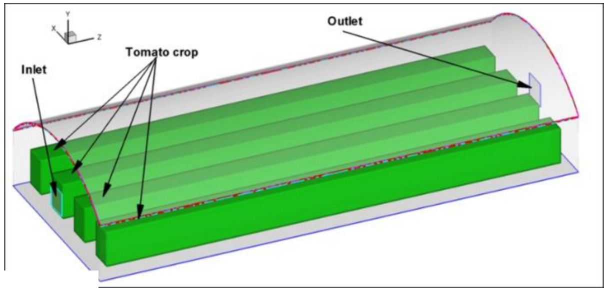
Roof only

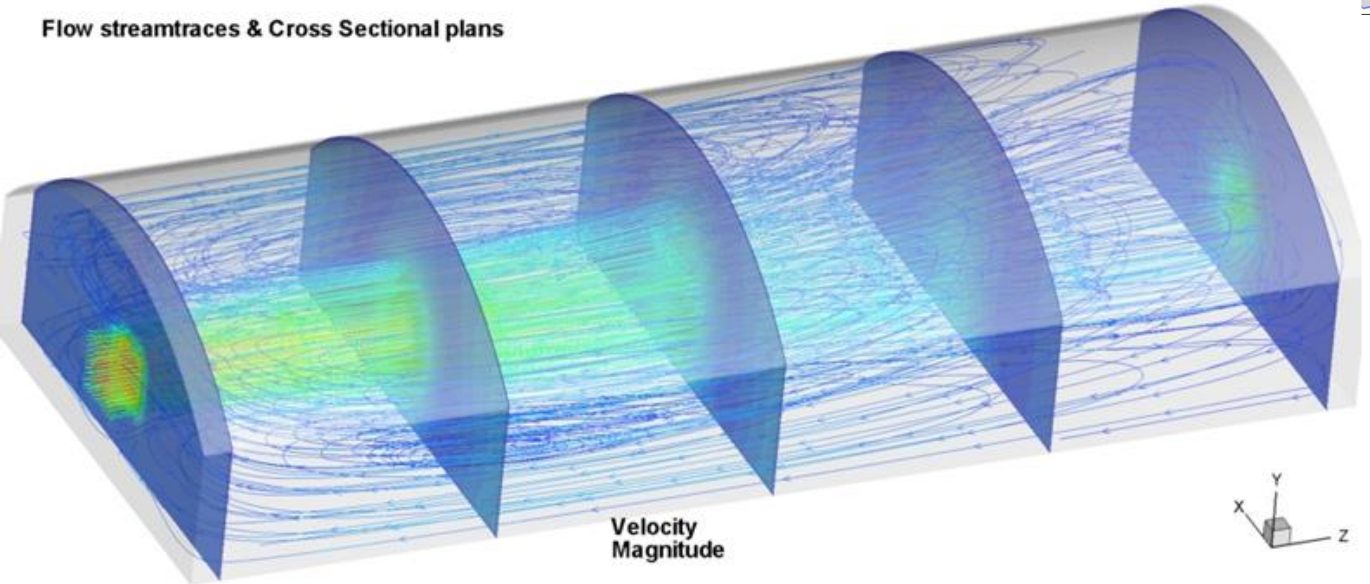


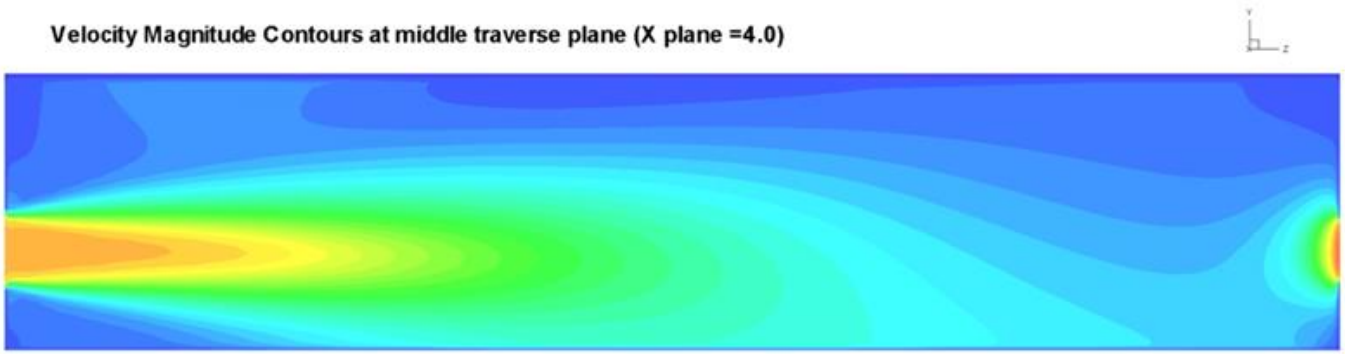
Side & Roof

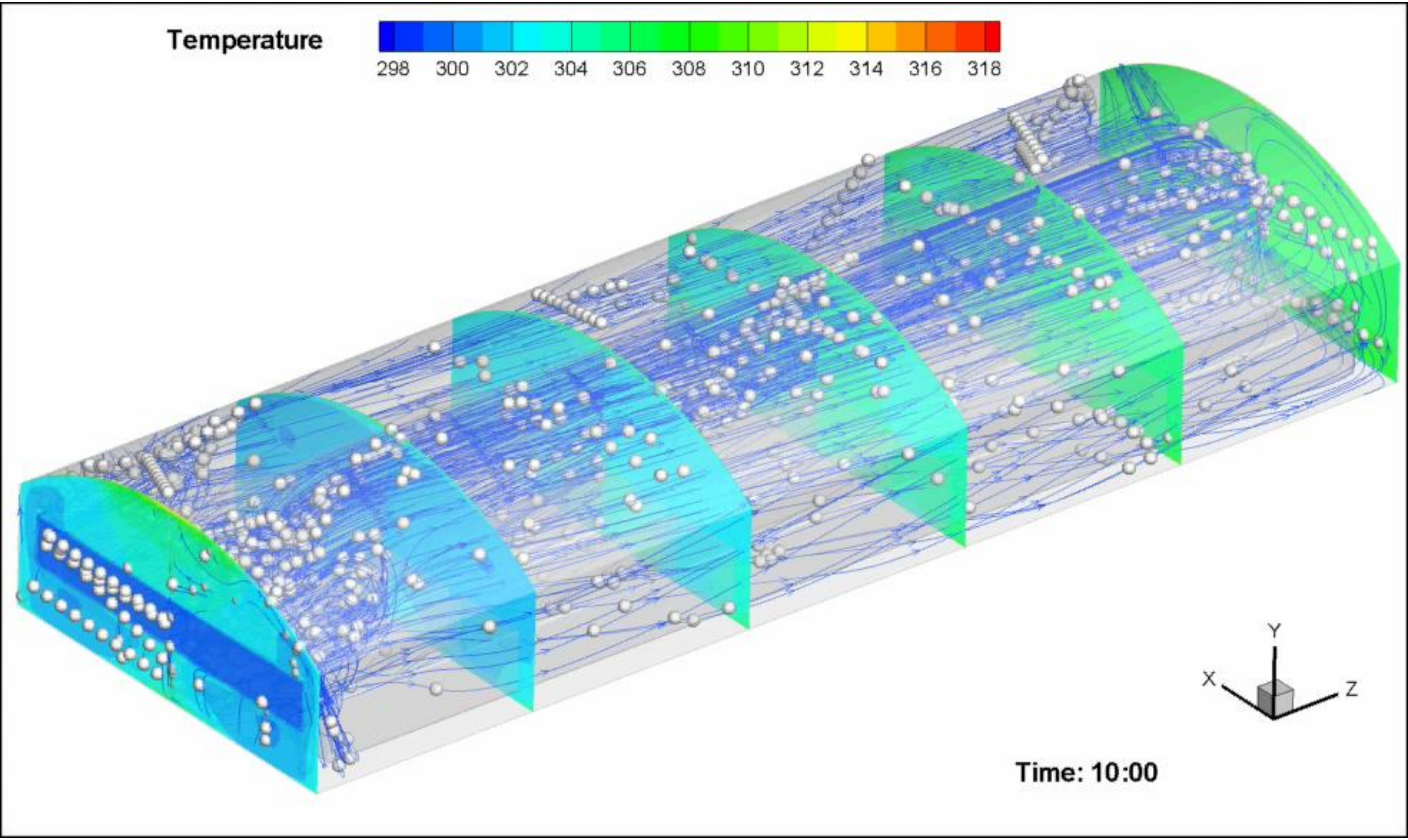


CFD models – Improve the uniformity of evaporative cooling








Temperature
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304
306
308
310
312
314
316
318
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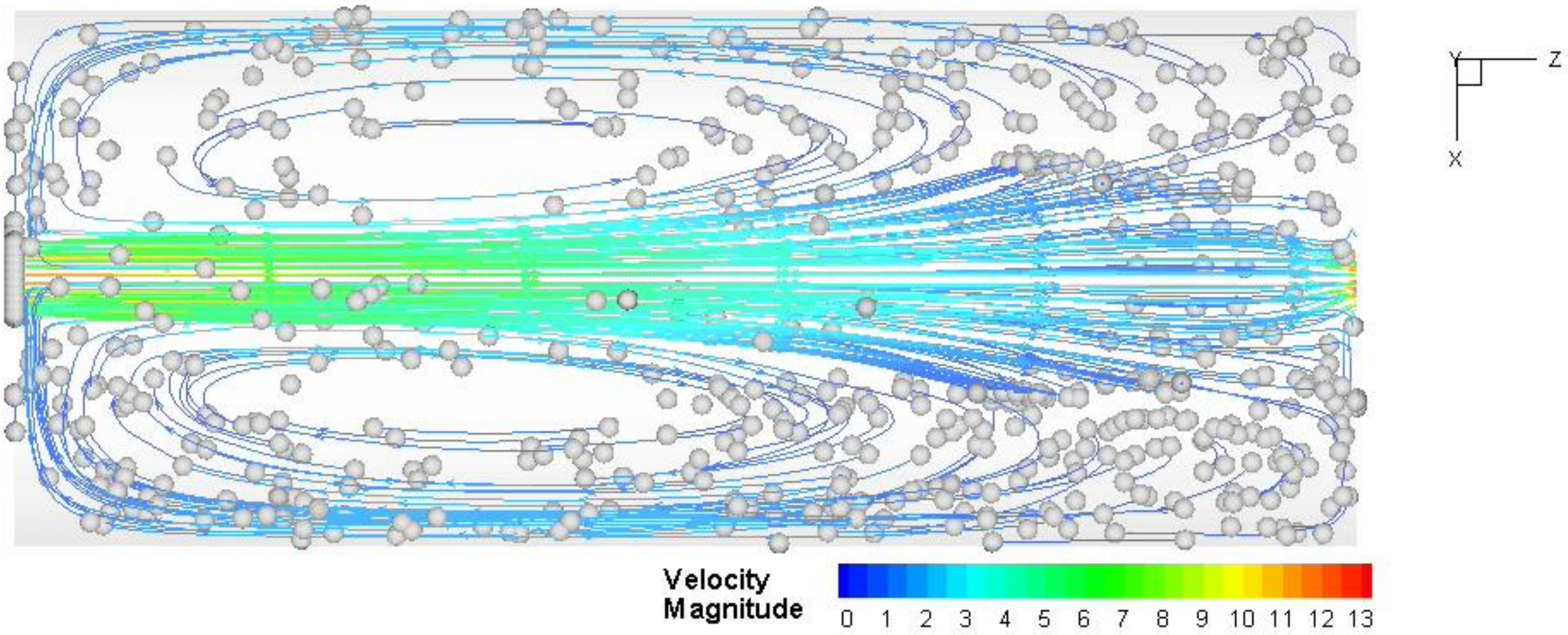
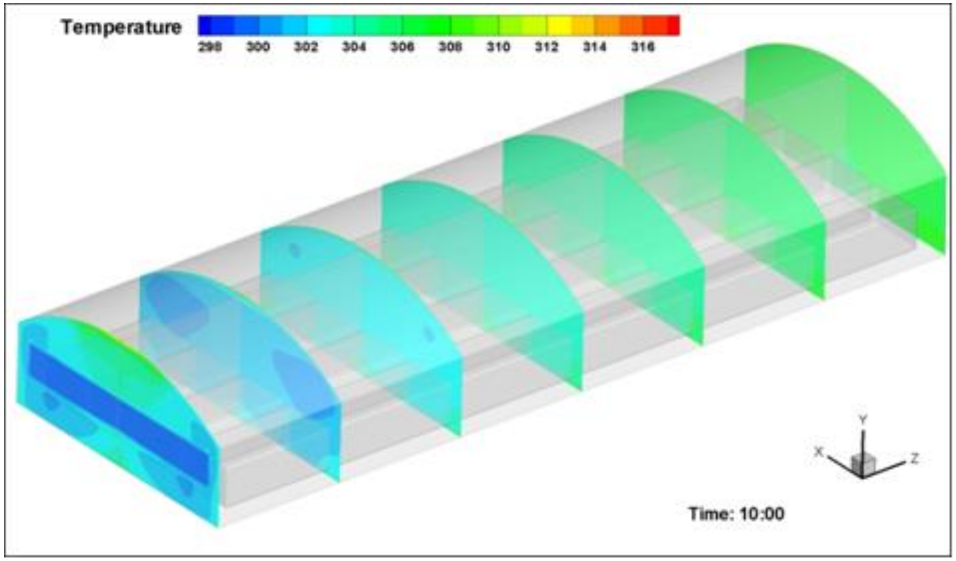
X
Z
Time: 10:00

Flow streamtraces

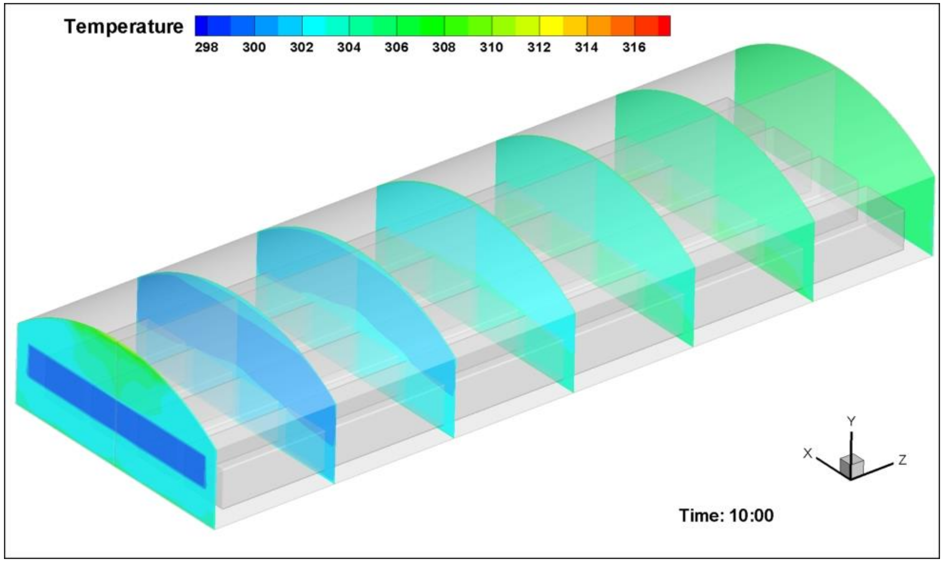


Modelling greenhouse systems / Fan & pad cooling



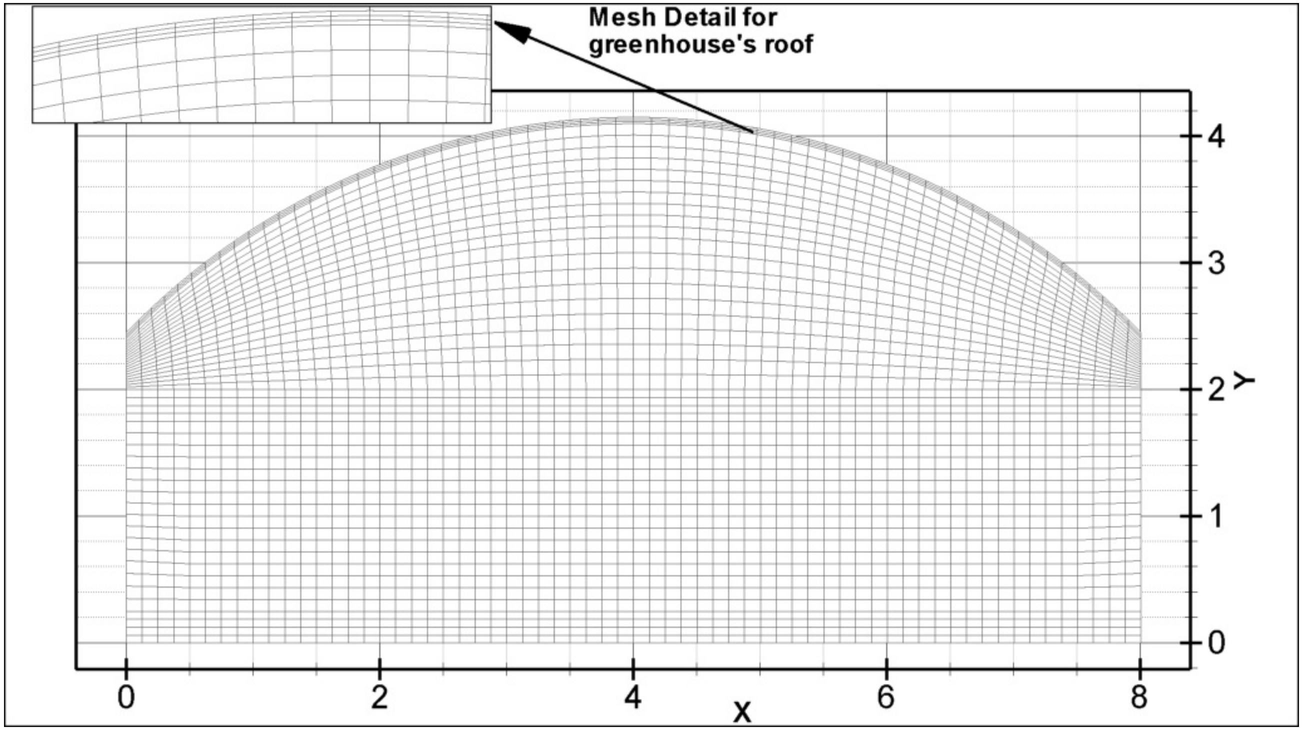
Flow rate 30 m³ / h

Flow rate 35 m³ / h



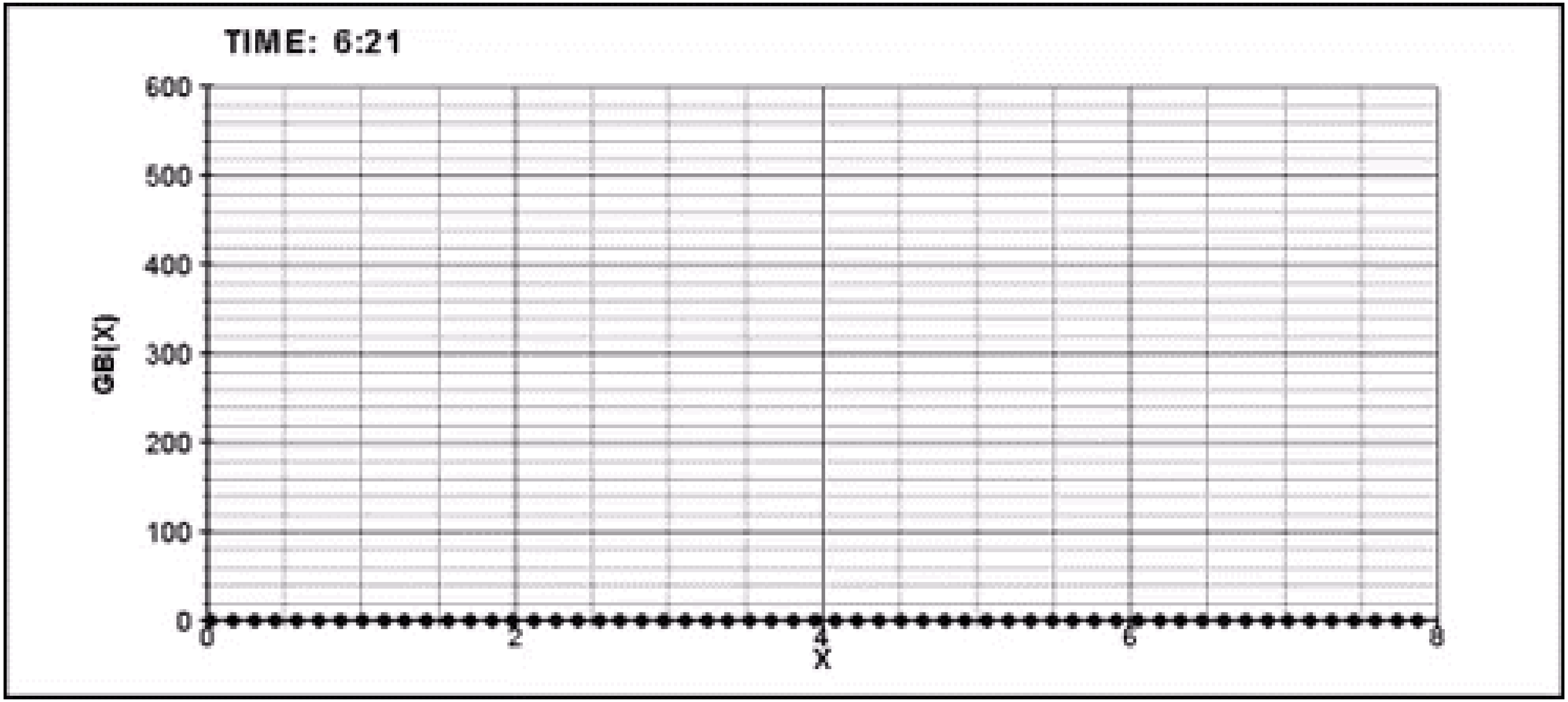
Temperature contours in an evaporative cooled greenhouse with 2 different flow rates (Bartzanas et al., 2012.)

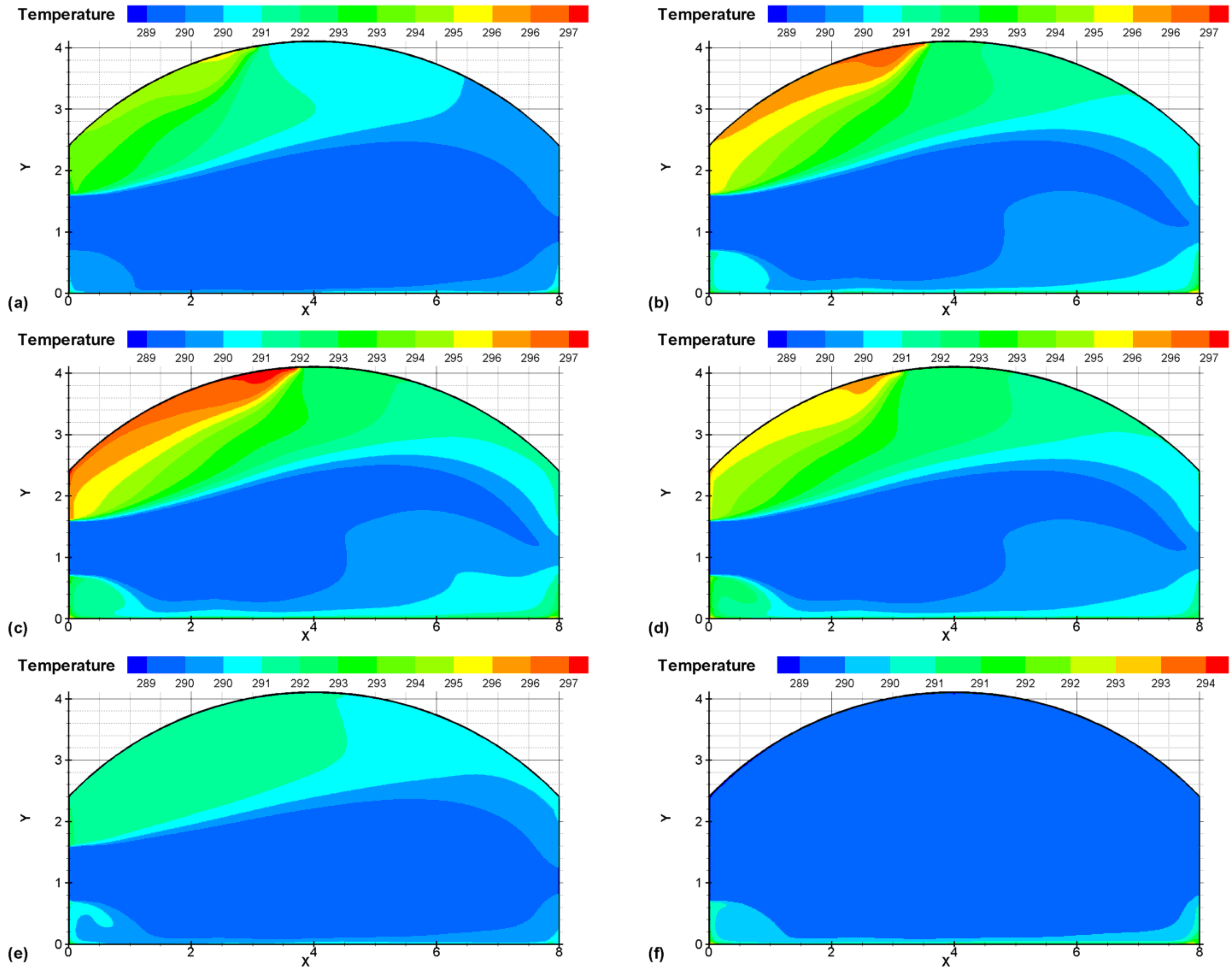
Radiation modelling



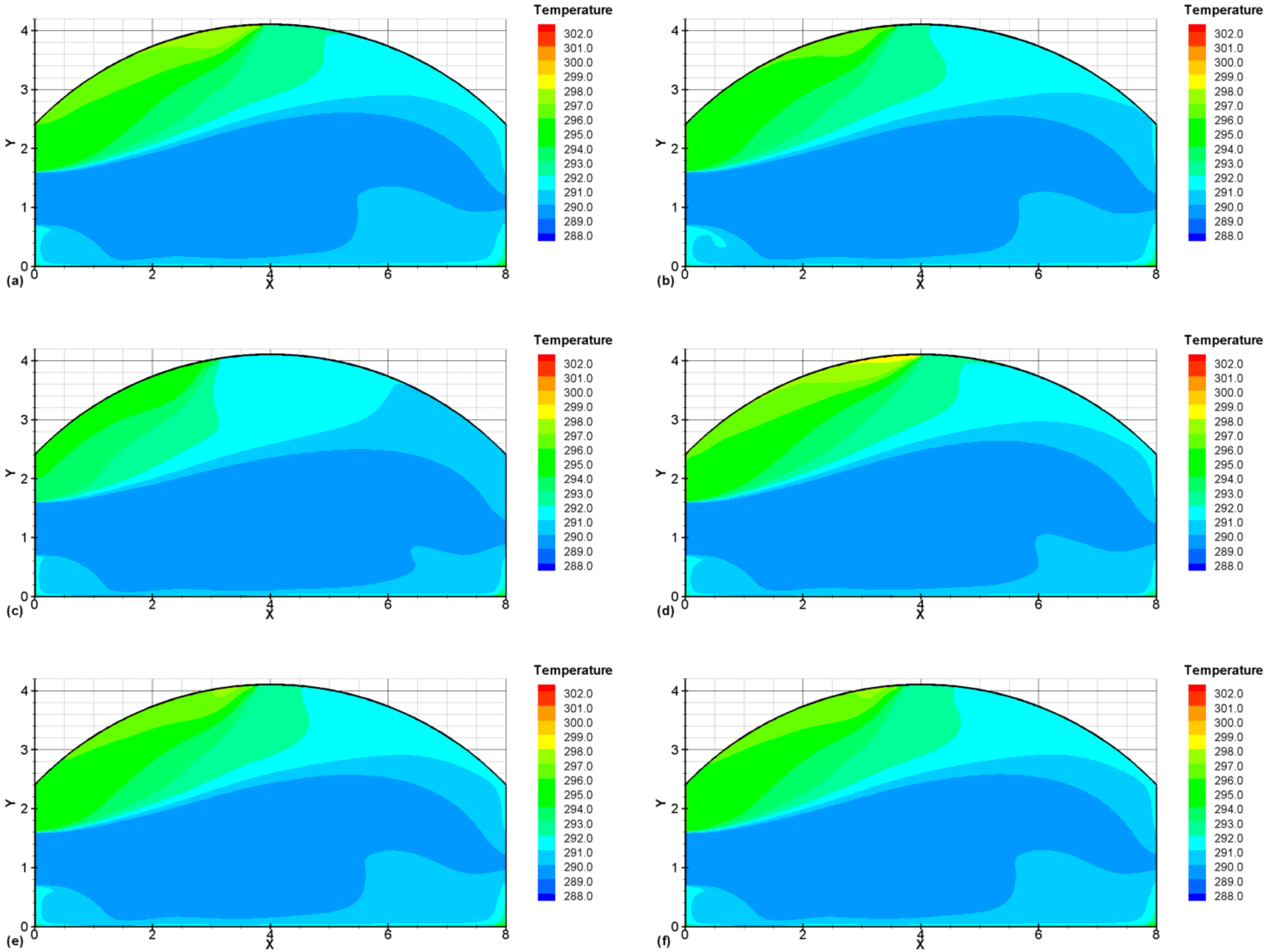
The cover is a solid zone composed by 4 rows of cells where the **conduction thermal equation** is being solved.

A **mixed heat transfer boundary condition** (combination of radiation and convection) is applied at the external boundary of the solid region. The same boundary condition is imposed at the internal margin **where the solid and the fluid zones are coupled**, restoring a **conjugated** heat transfer treatment at the specific area

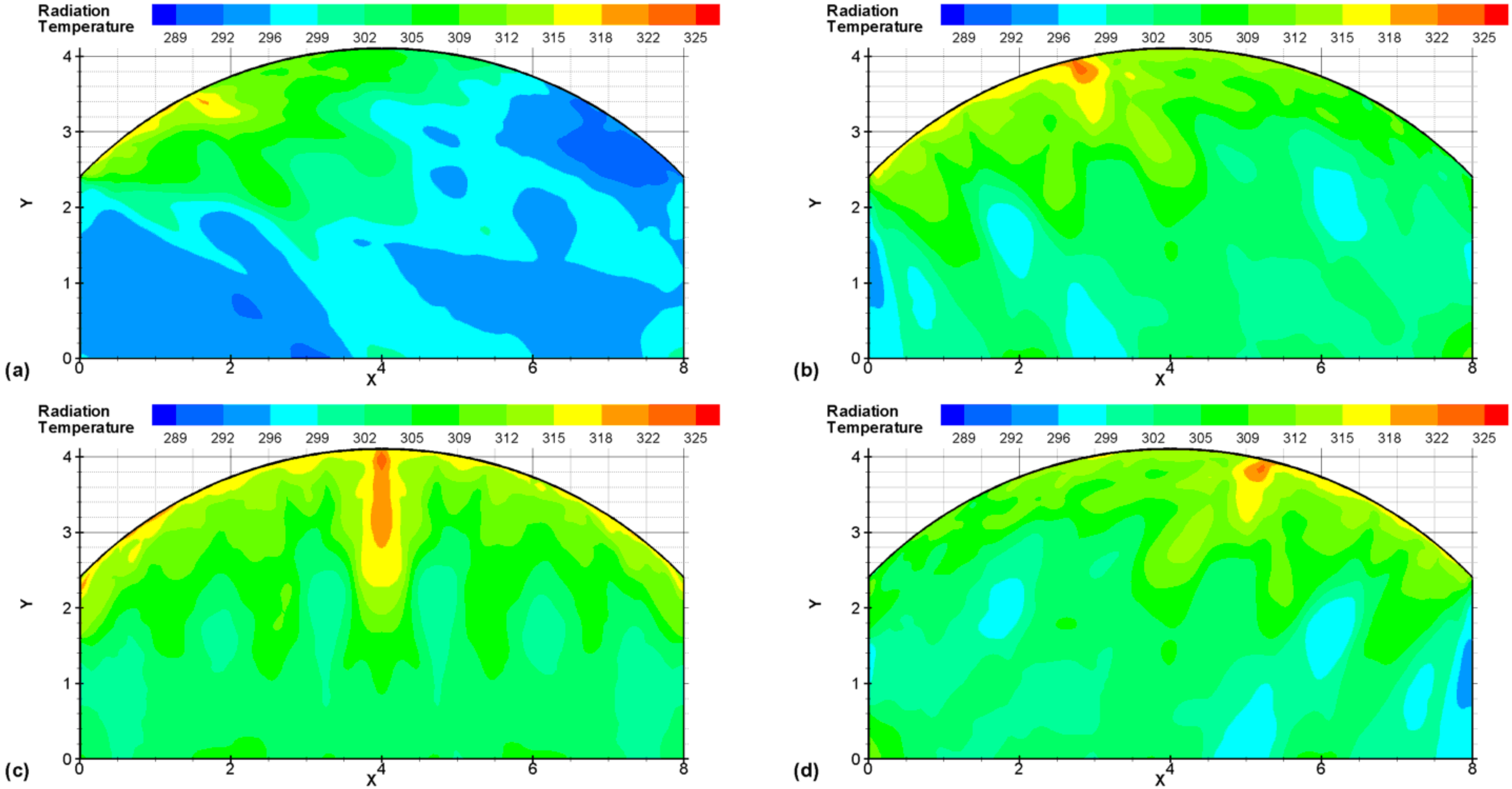

TIME: 6:21
600
500
400
300
200
100
0
GB(X)
0
2
4
6
8
X

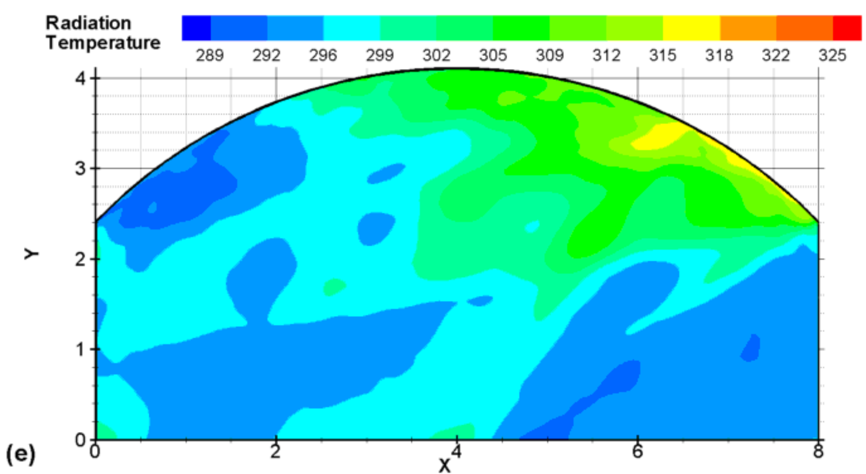


Temperature distributions for different inclinations of the incident solar radiation (a-e) and with no radiation effect (f): a) 30, b) 60, c) 90, d) 120, e) 150 degrees and f) No radiation model applied

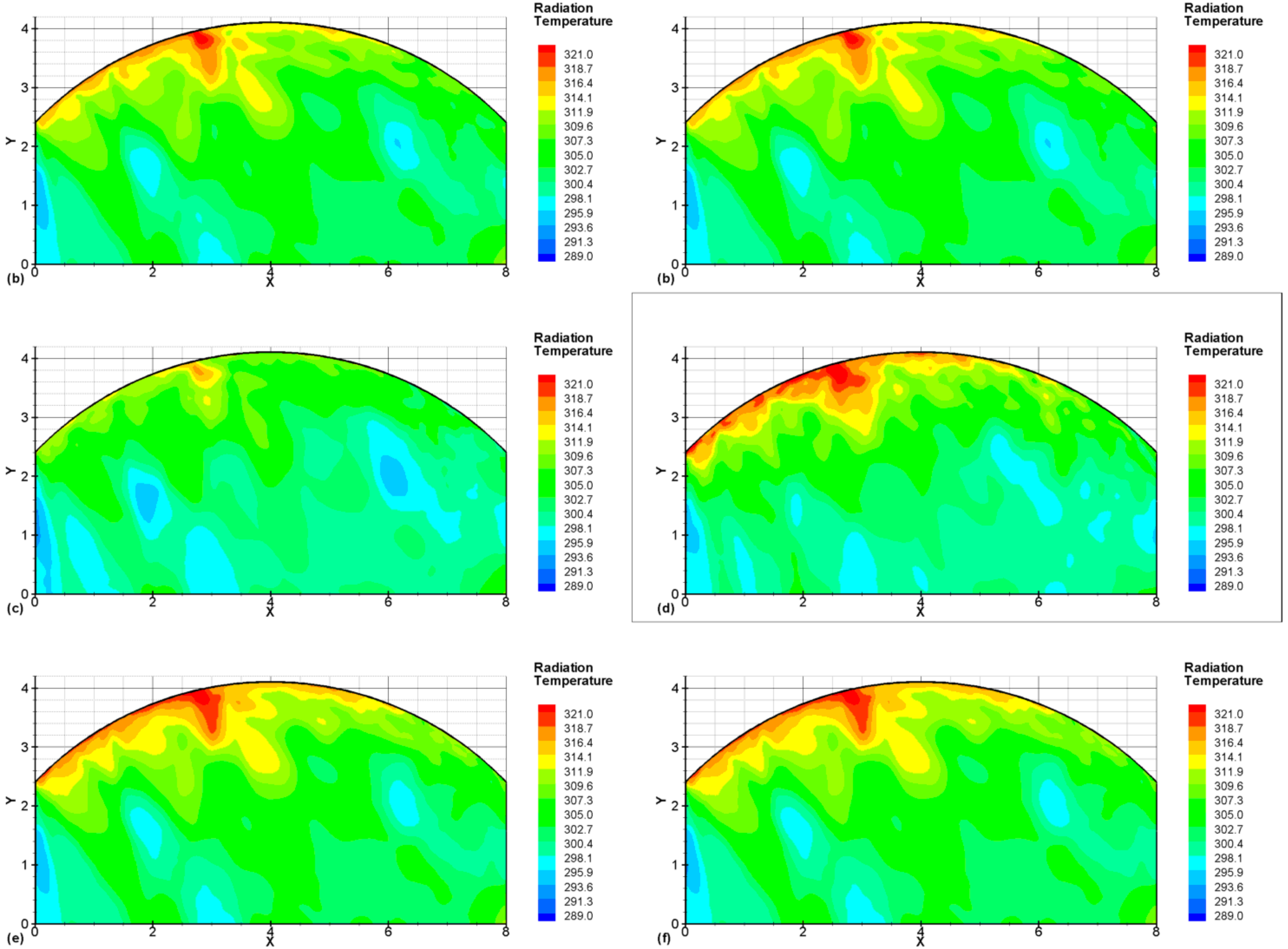


Temperature distributions inside the greenhouse for the six different types of the covering materials (a-f) a) material 1 b) material 2 c) material 3 d) material 4 e) material 5 f) material 6

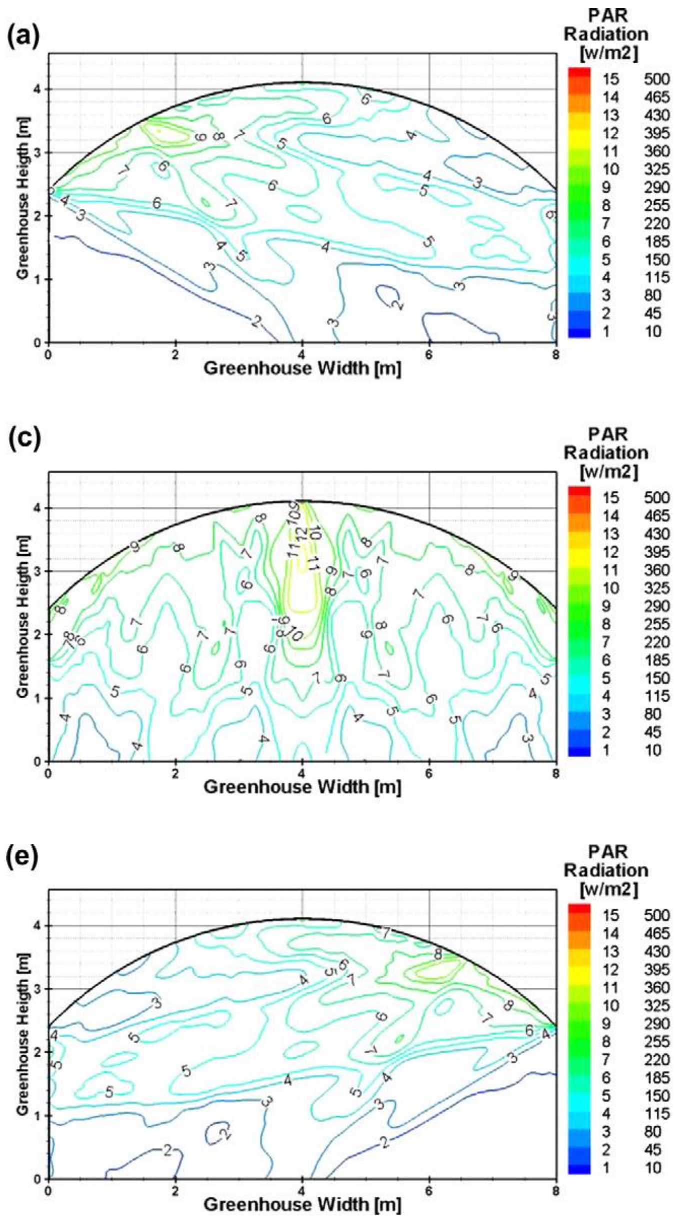




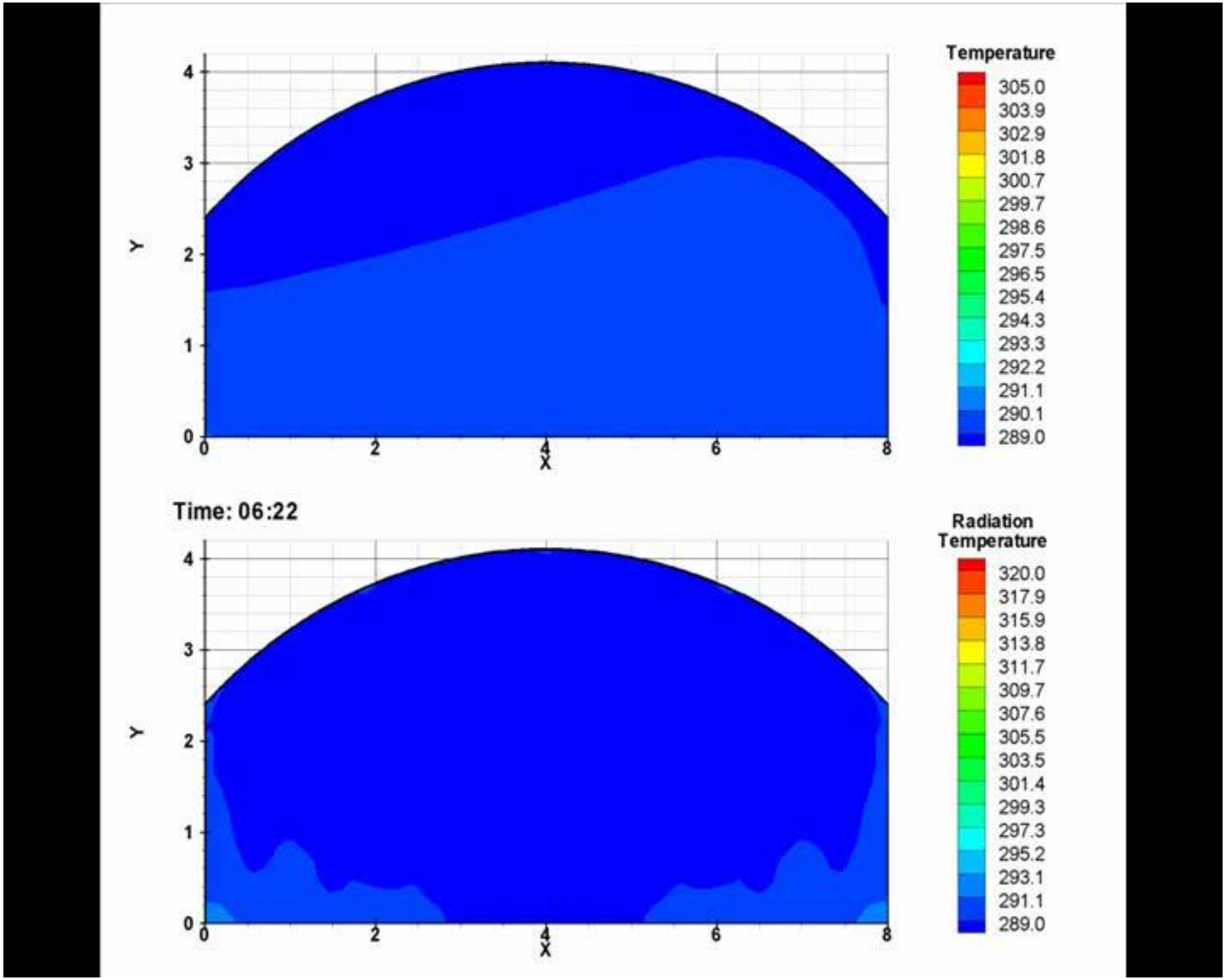
Radiation temperature distributions for different inclinations of the incident solar radiation (a-e) a) 30, b) 60, c) 90, d) 120 and e) 150 degrees.

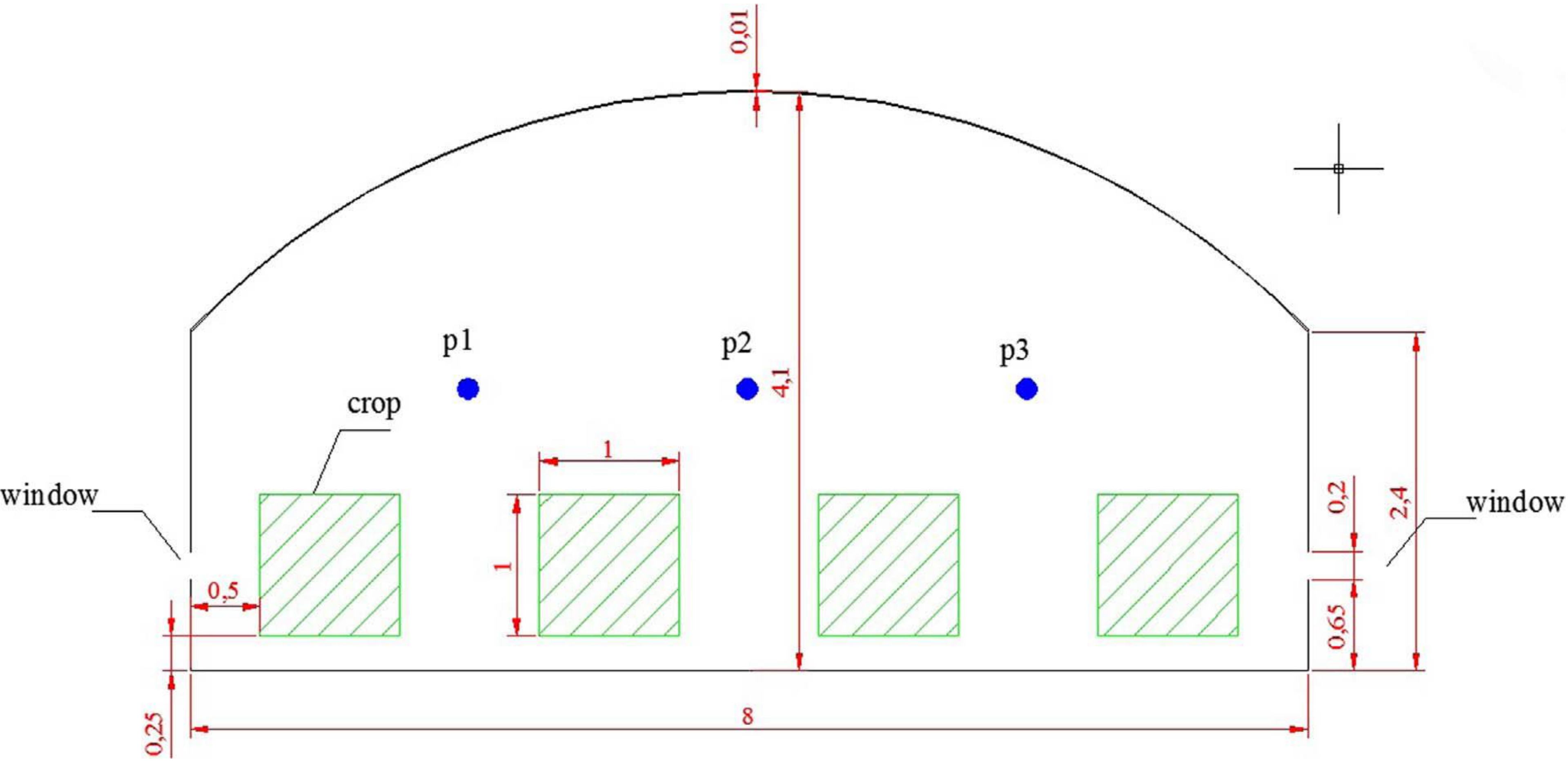


Radiation temperature distributions in the interior of the greenhouse for the six different types of covering materials (a-f) a) material 1 b) material 2 c) material 3 d) material 4 e) material 5 f) material 6



PAR distributions for different inclinations of the incident solar radiation (a–e) (a) 60, (b) 30, (c) 0, (d) 30 and (e) 60 (Baxevanou et al., 2010).


Temperature
305.0
303.9
302.9
301.8
300.7
299.7
298.6
297.5
296.5
295.4
294.3
293.3
292.2
291.1
290.1
289.0
Y
X
0
1
2
3
4
0
2
4
6
8
Time: 06:22
Radiation Temperature
320.0
317.9
315.9
313.8
311.7
309.7
307.6
305.5
303.5
301.4
299.3
297.3
295.2
293.1
291.1
289.0



Examined geometry during winter (units are given in m).

Materials' thermal properties.

Material	Density, ρ[kg m^{-3}]	Thermal conductivity, k [W m^{-1} K^{-1}]	Specific heat capacity, C_p [J kg^{-1} K^{-1}]	Emissivity, ε [-]
Cover (3L, EVA, TPE)	923.000	0.380	2300.00	0.70
Cover VPVC	13.850	25.330	2300.00	0.70
Ground	1300.000	1.000	800.00	0.92
Air	1.225	0.042	1006.43	0.90
Tomato crop	700.000	0.173	2130.00	0.46

Parametric study

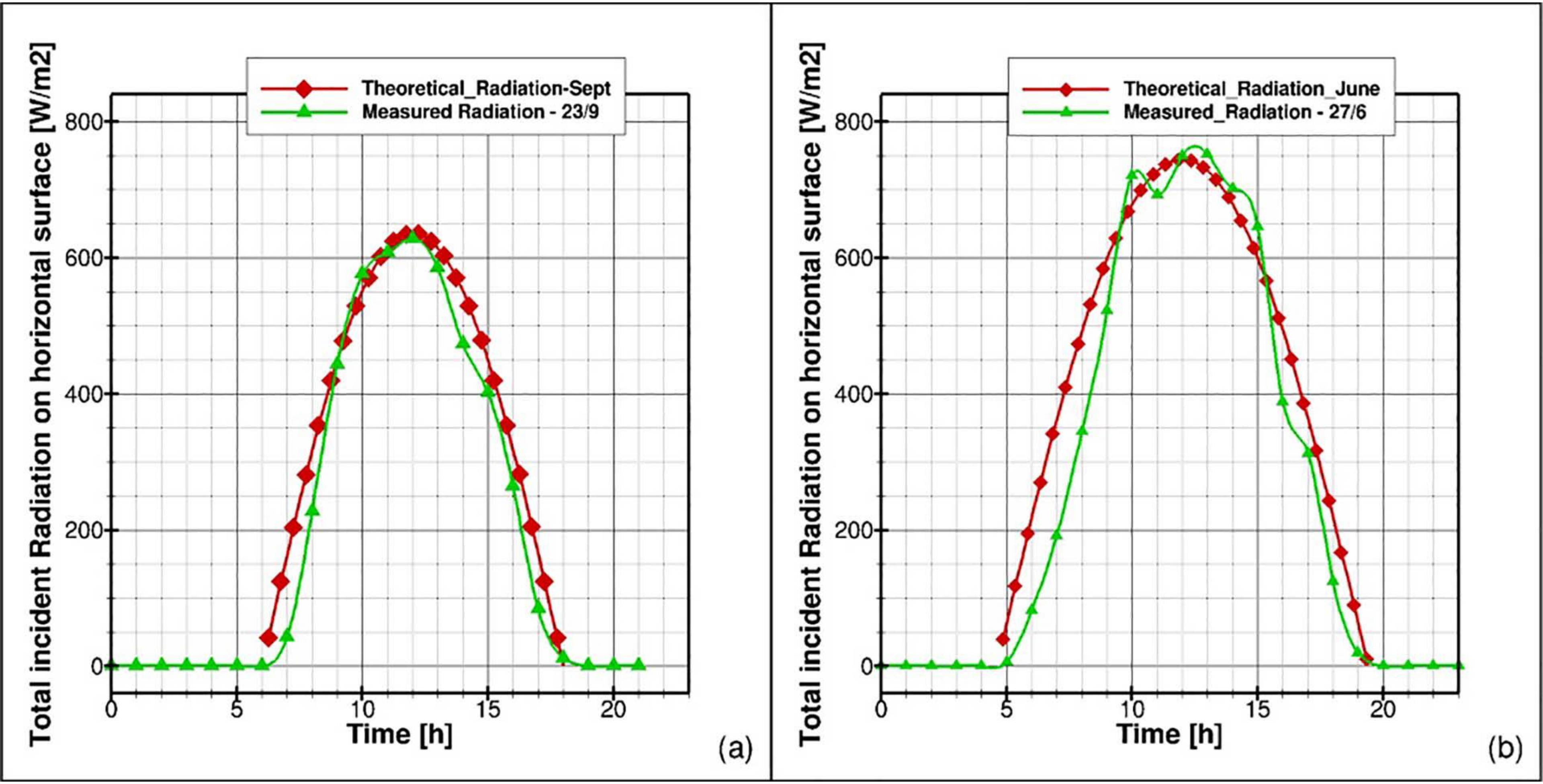
Day	H_{tot} [Wh m^{-2}]	H_d [Wh/m^{-2}]	T_{max} [°C]	T_{min} [°C]
6-Feb	2550	1082	12.2	1.3
21-Mar	3620	1574	14.9	3.3
6-May	6158	2652	25.8	11.0
21-June	7027	2877	31.1	15.3
6-Aug	6268	2368	32.7	17.4
21-Sep	4863	1813	28.5	14.1
6-Nov	2040	810	15.9	5.8
21-Dec	1542	635	11.0	1.9

Material's optical properties

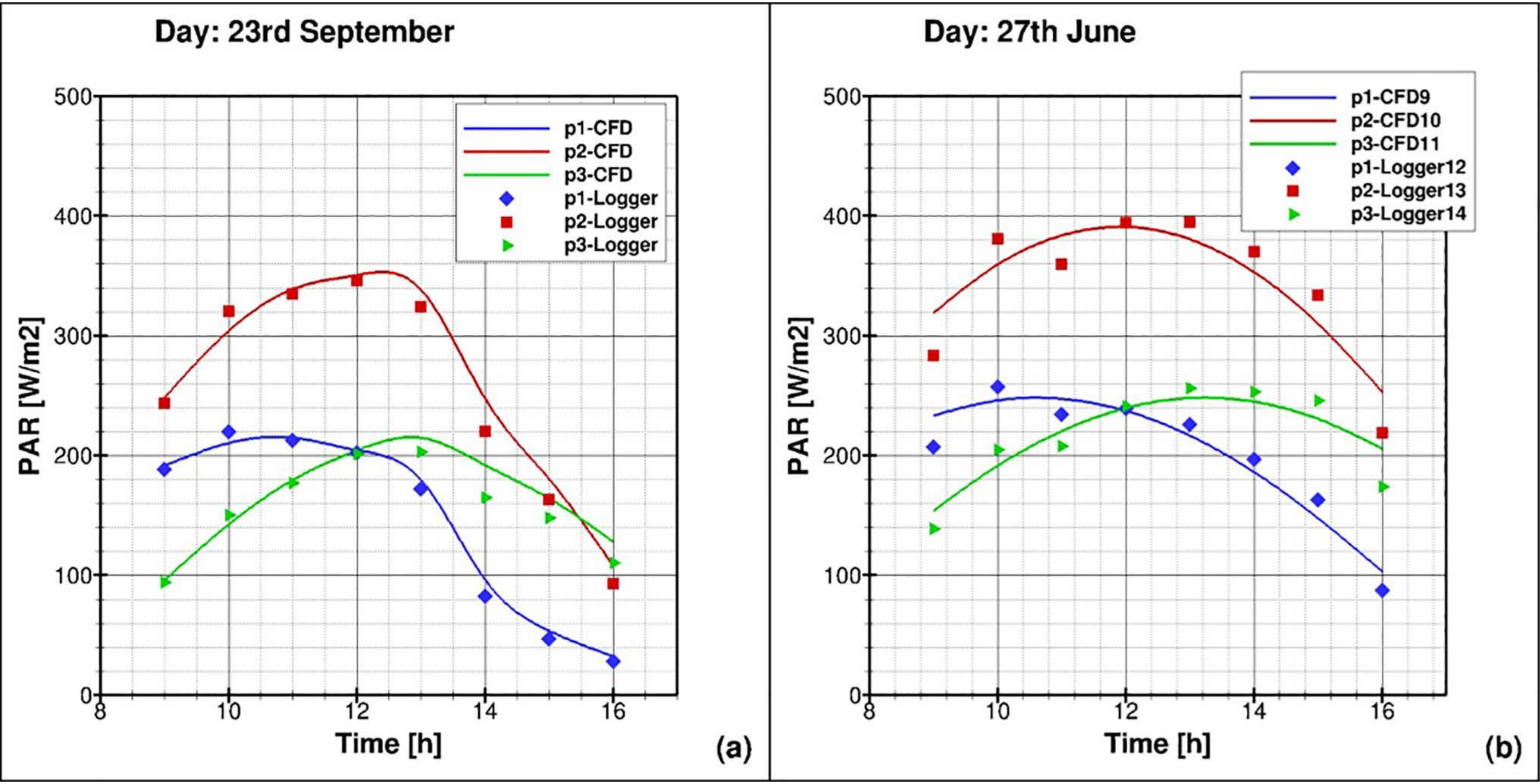
Material	Absorption coefficient, as, [m^{-1}]		
	UV	PAR	NIR-IR
TPE	244.44	83.38	61.88
EVA	134.70	203.00	272.10
3L	185.29	137.50	113.98
VPVC	51.08	73.40	17.43
Air	0.000582	0.000582	0.0015
Tomato crop	1.23	1.23	1.23

Material's optical properties

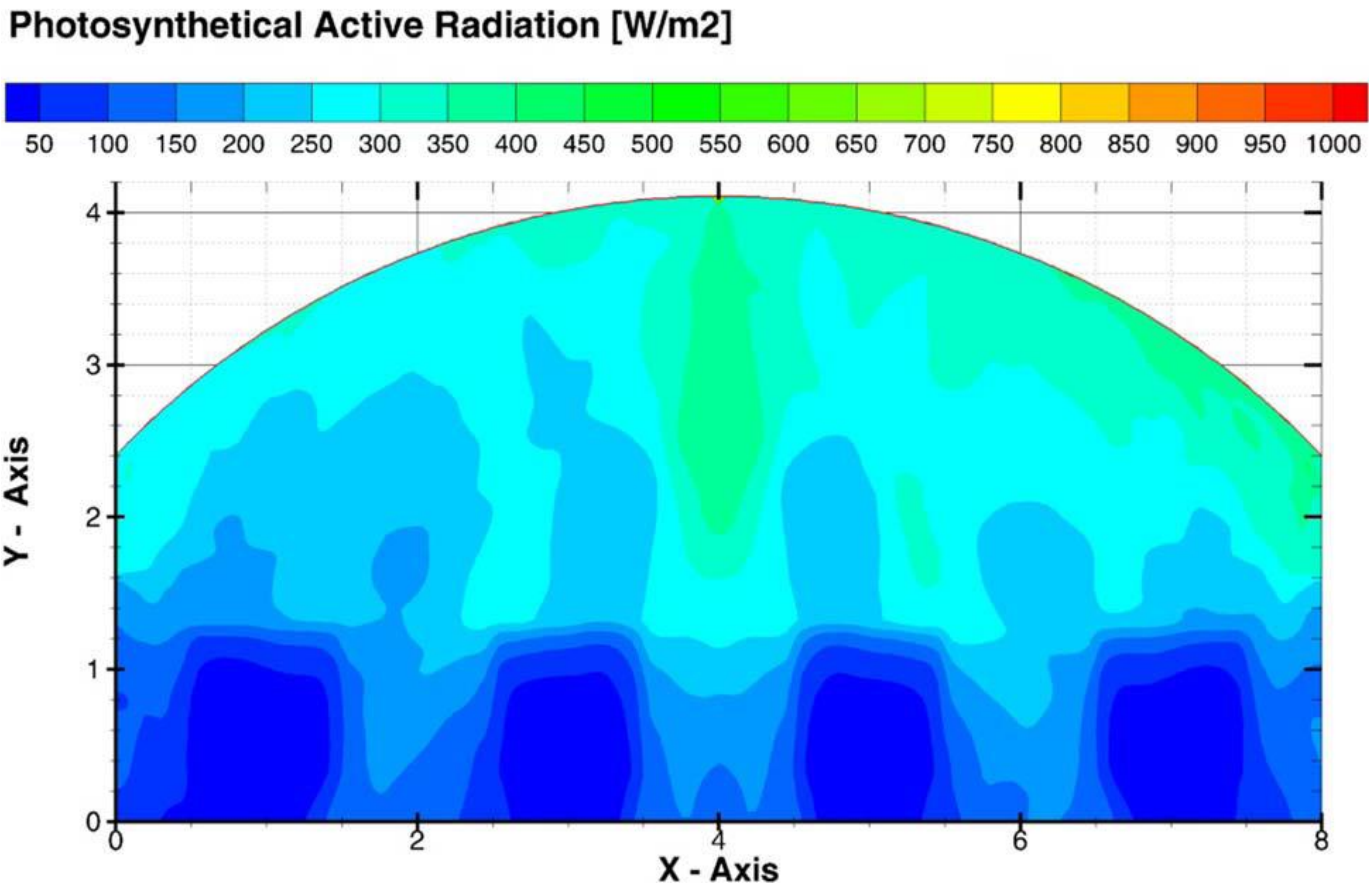
Material	Refractive index, n, [-]			Thickness [m]
	UV	PAR	NIR-IR	
TPE	1.79	1.86	1.86	0.00100
EVA	1.86	1.79	1.72	0.00015
3L	1.86	1.79	1.72	0.00045
VPVC	1.79	1.79	1.92	0.01000
Air	1.009	1.009	1.009	–
Tomato crop	2.77	2.77	2.77	–



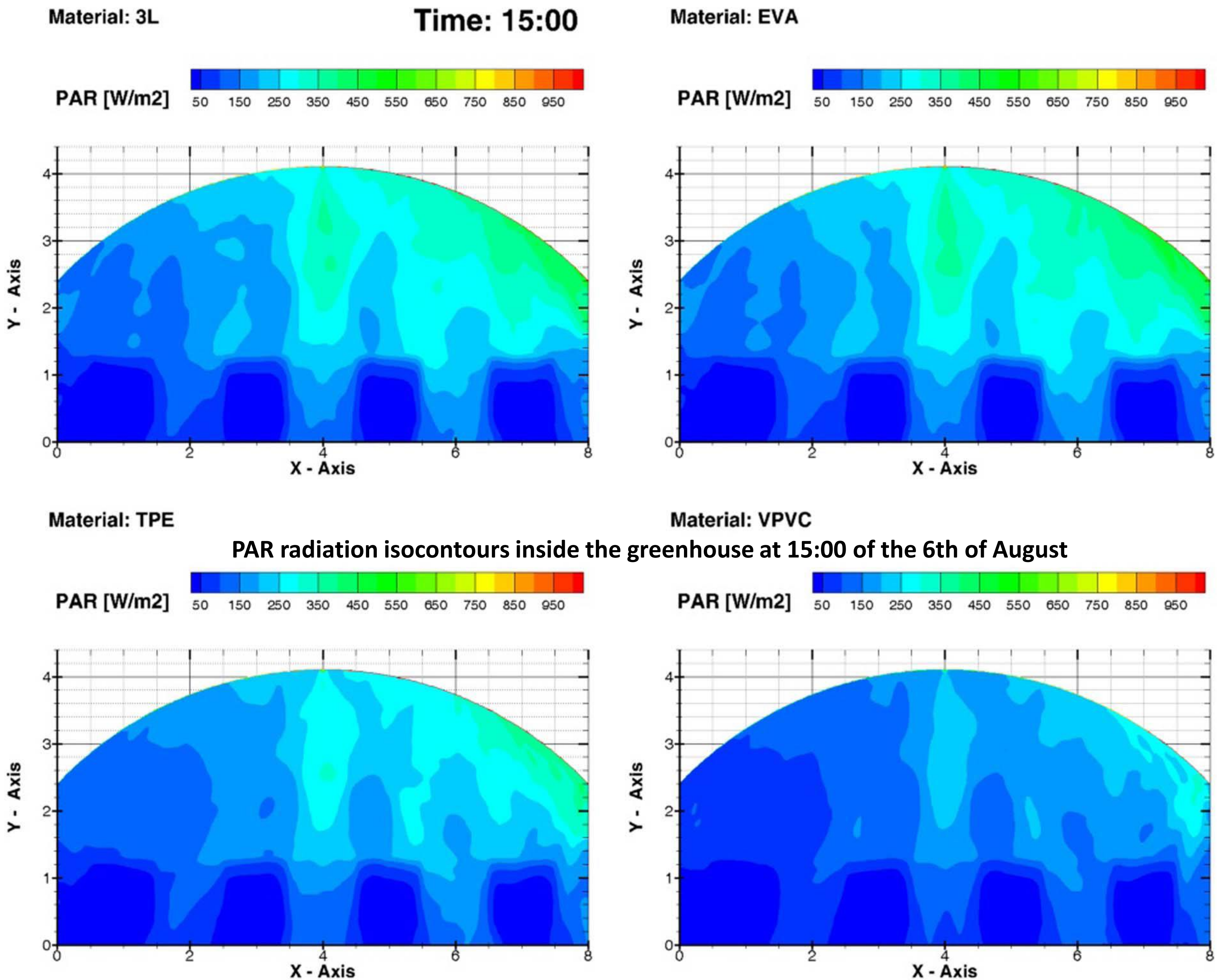
Measured and theoretical solar radiation incident on horizontal surface: (a) for September and (b) for June.



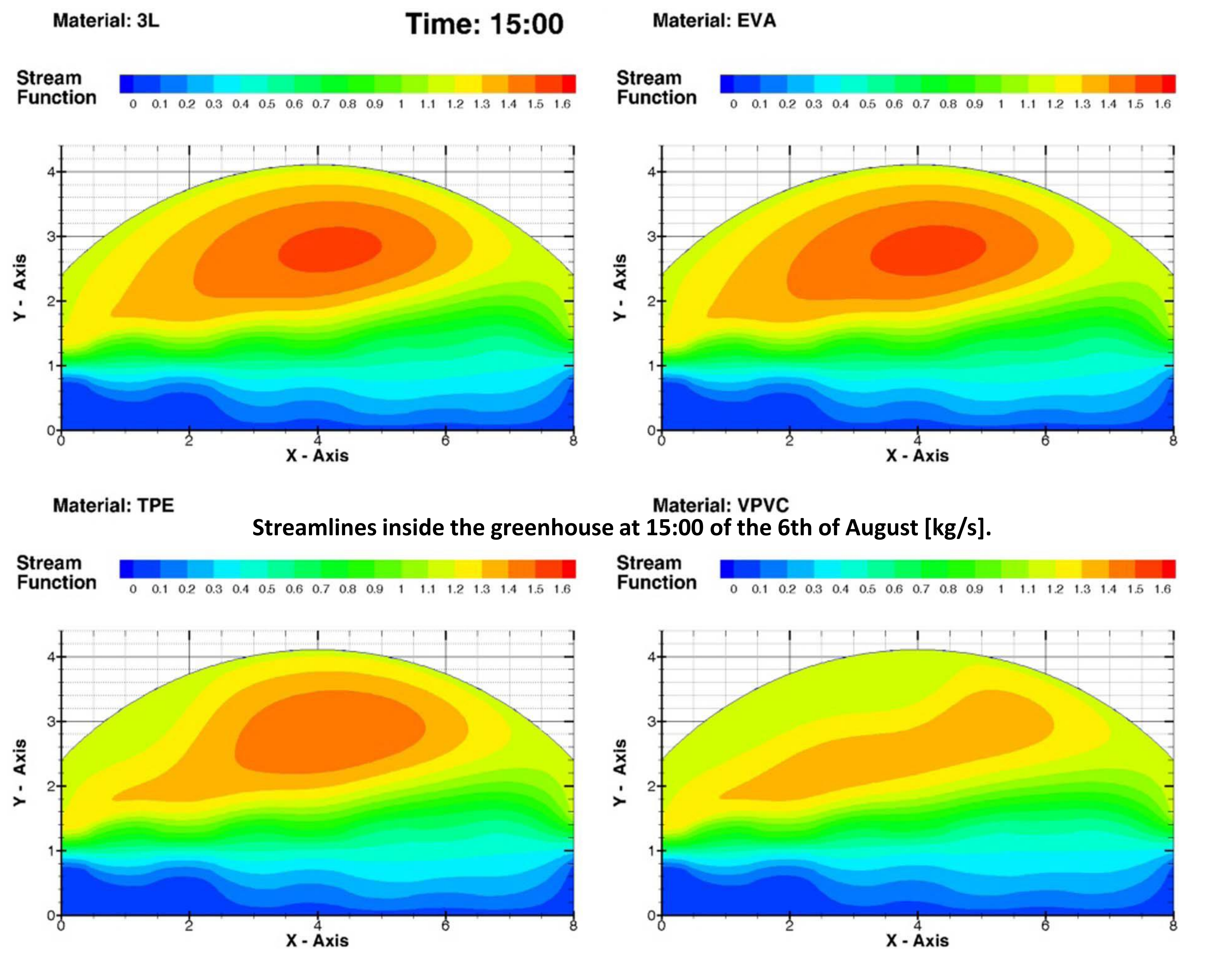
Simulated and measured PAR for: (a) the September day and (b) the June day. Notation: blue solid line for point P1 from CFD, red solid line for point P2 from CFD, green solid line for point P3 from CFD, blue rhombus for point P1 from measurements, red square for point P2 from measurements and green triangle for point P3 from measurements



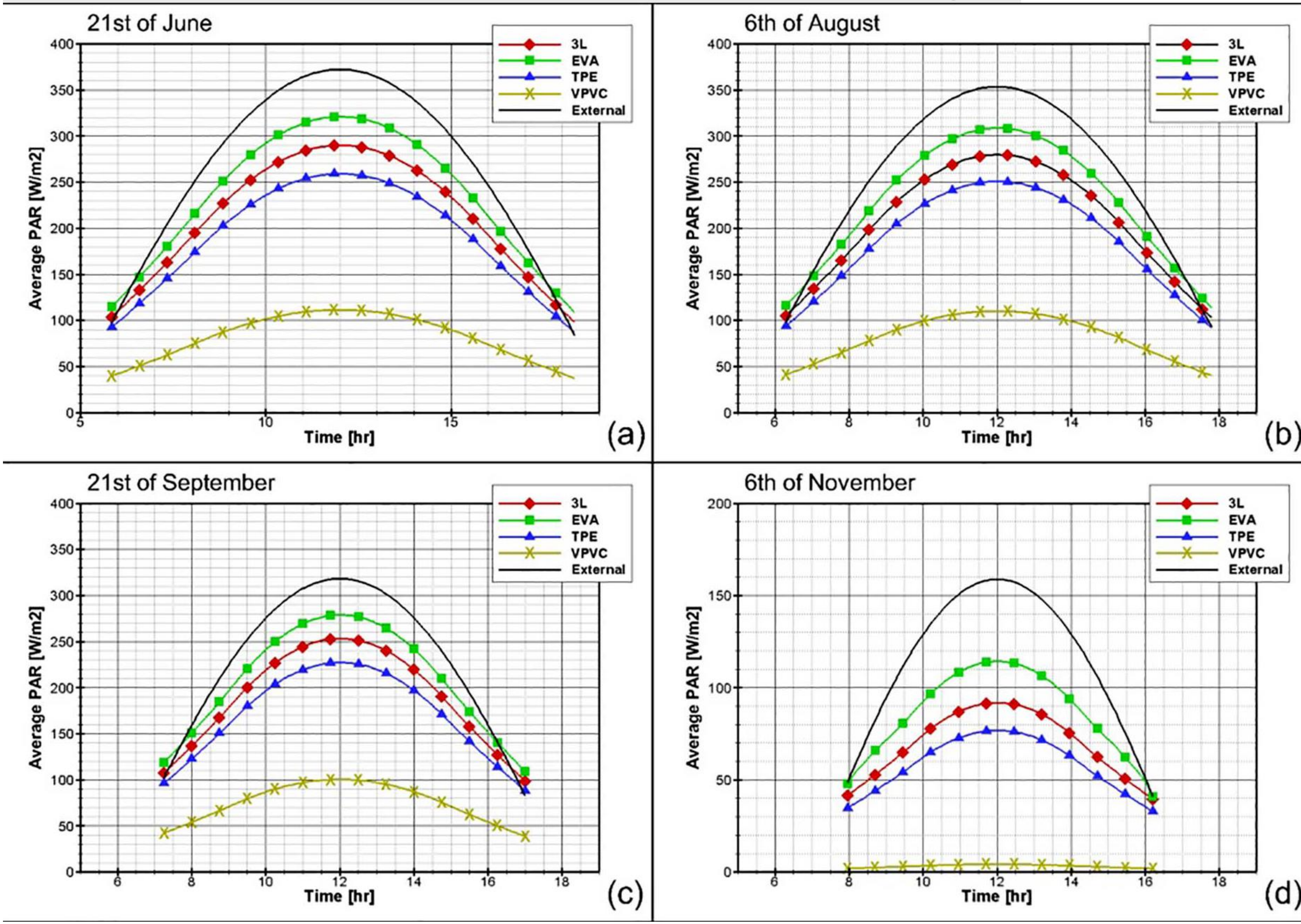
PAR radiation isocontours inside the greenhouse with TPE cover material at 13:00 of the 21st of June



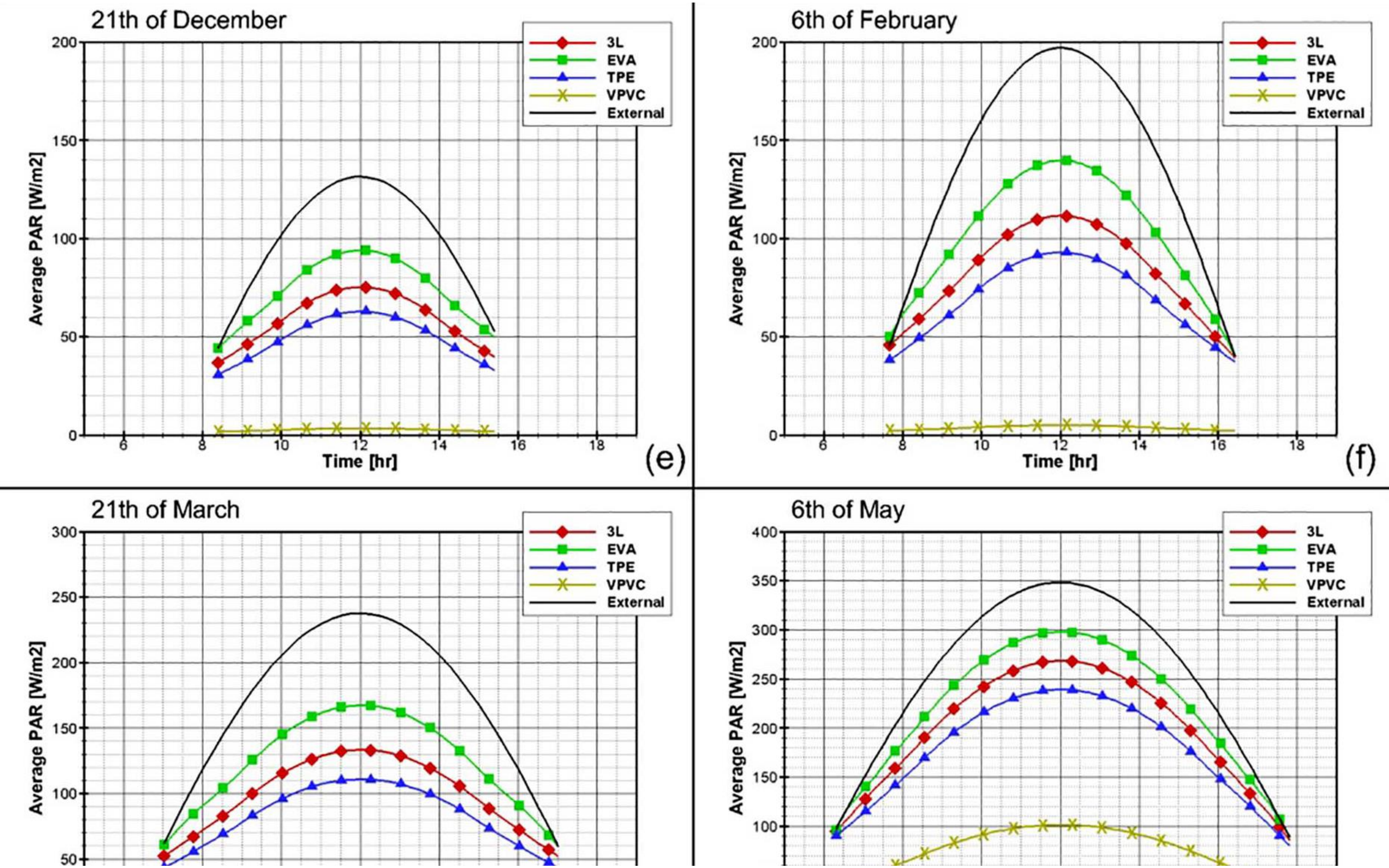
PAR radiation isocontours inside the greenhouse at 15:00 of the 6th of August



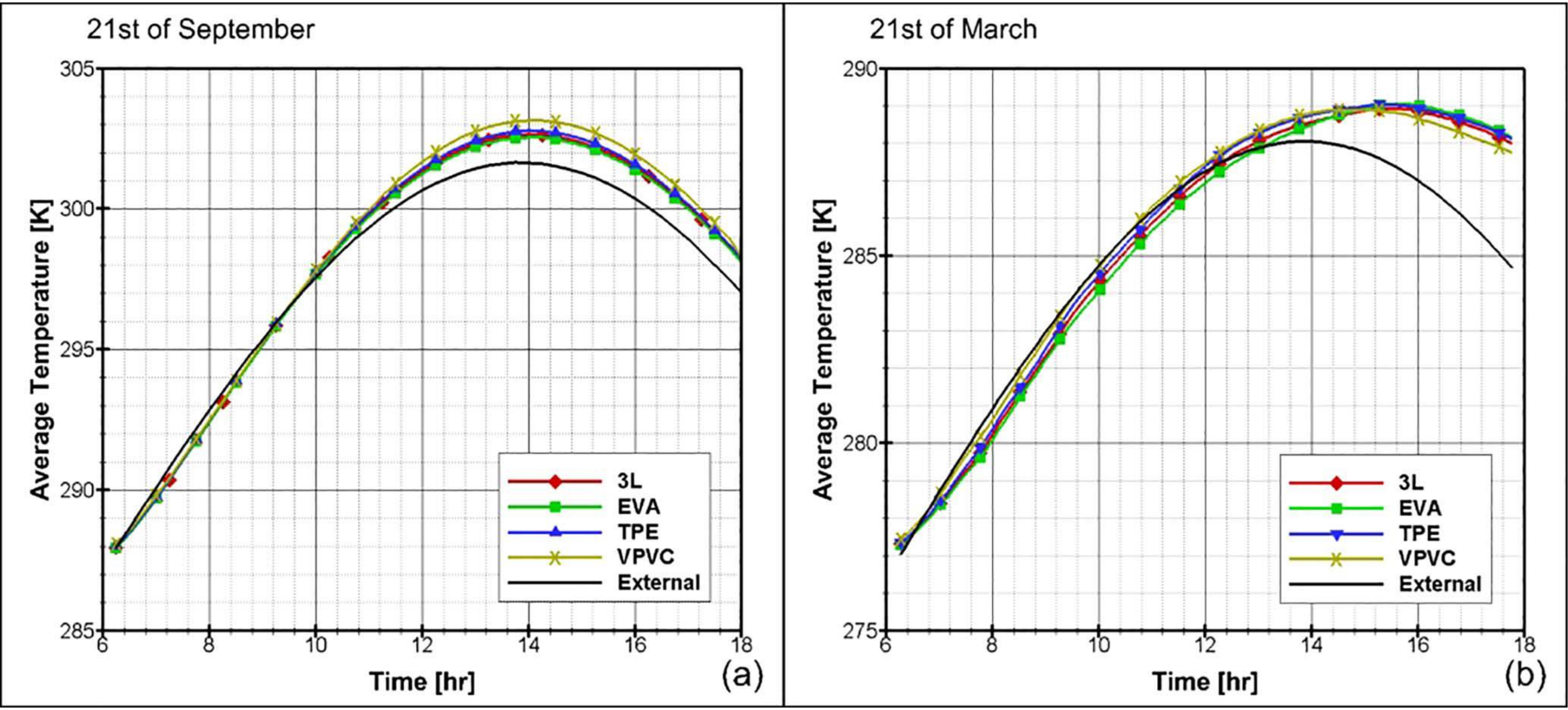
Streamlines inside the greenhouse at 15:00 of the 6th of August [kg/s].



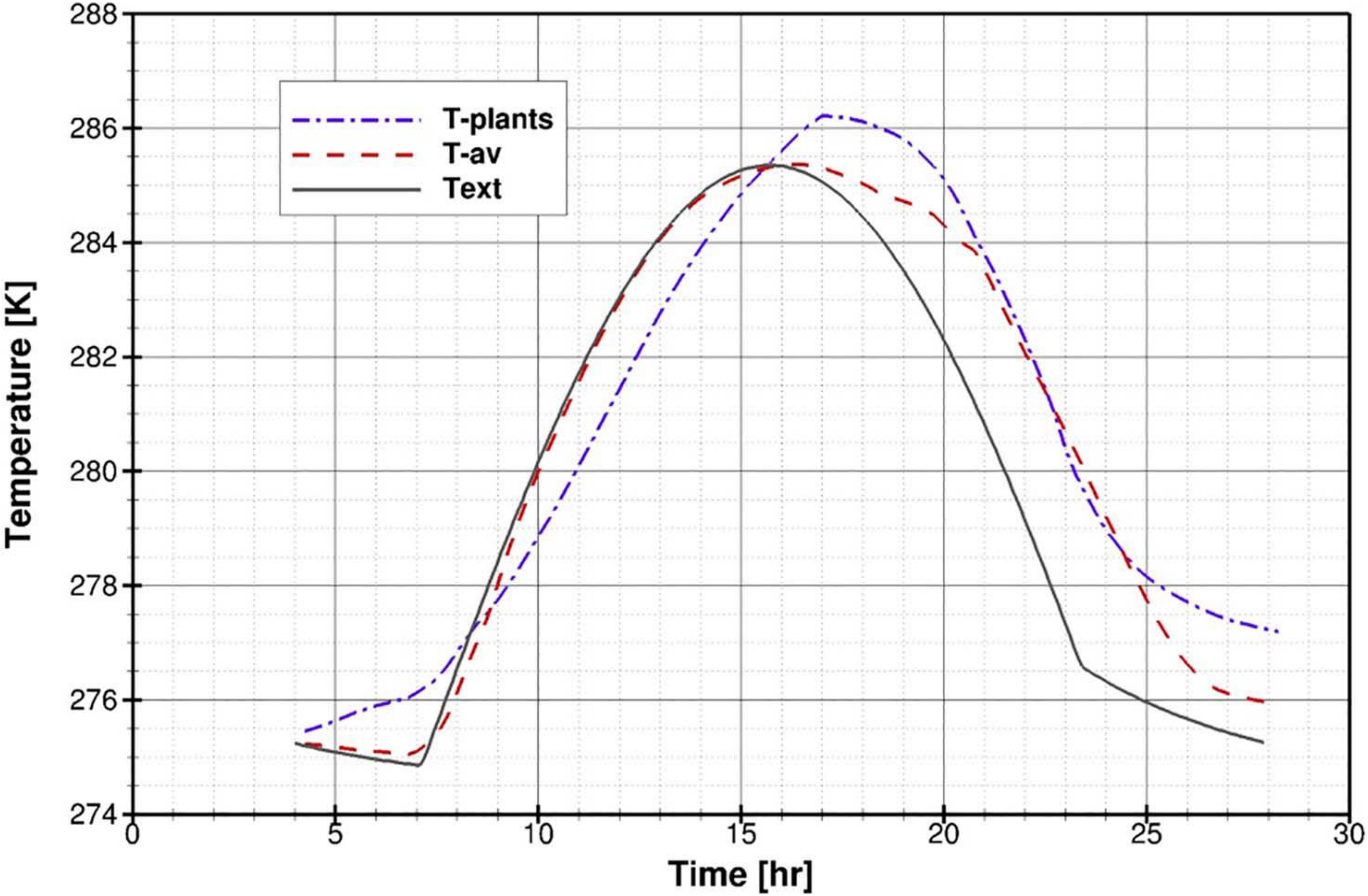
Average available PAR evolution during the examined solar day at plant level.



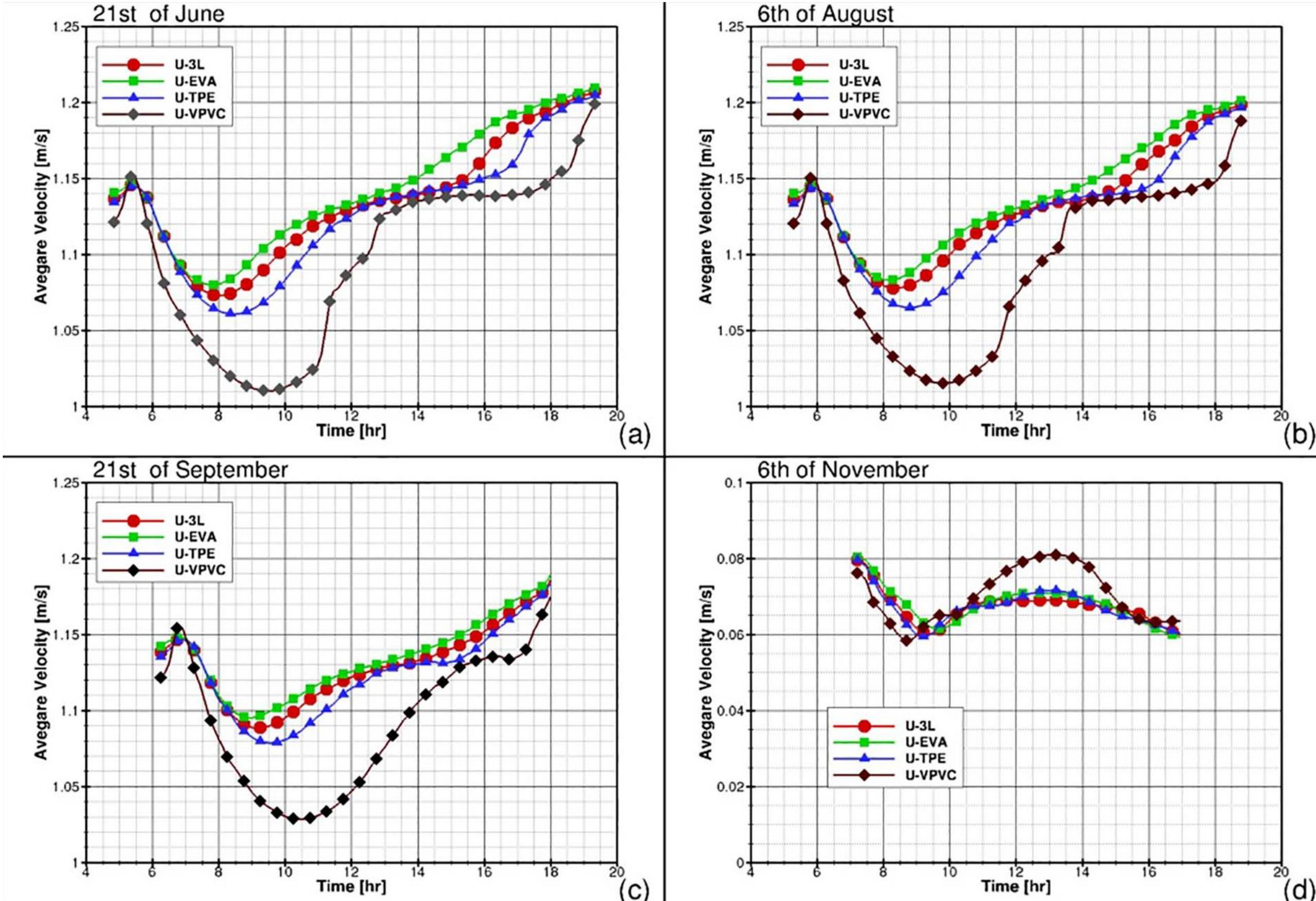
Average available PAR evolution during the examined solar day at plant level.



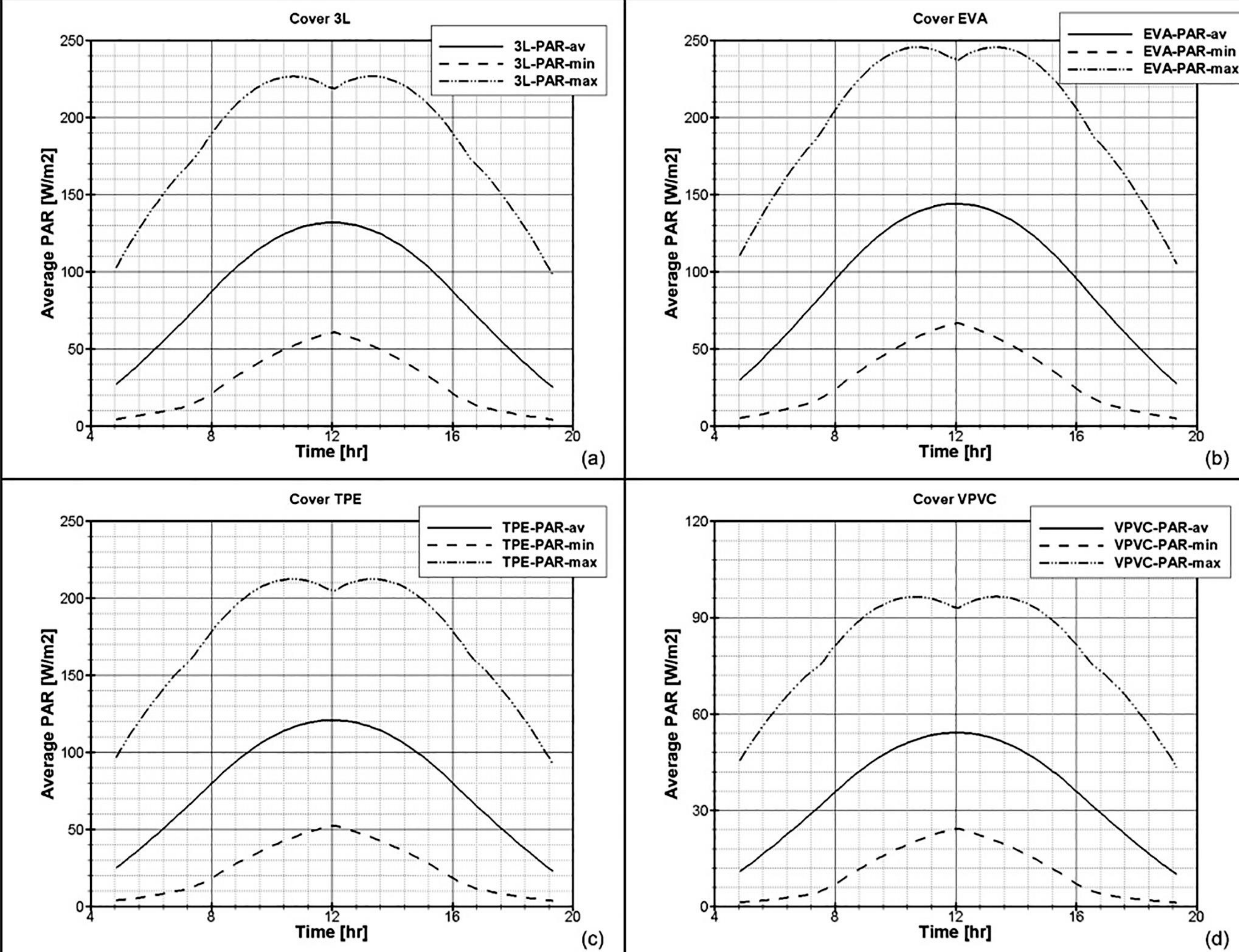
Average temperature evolution in the greenhouse interior during the examined solar day



Temperature for 24 h simulation at 6th of February for EVA cover.

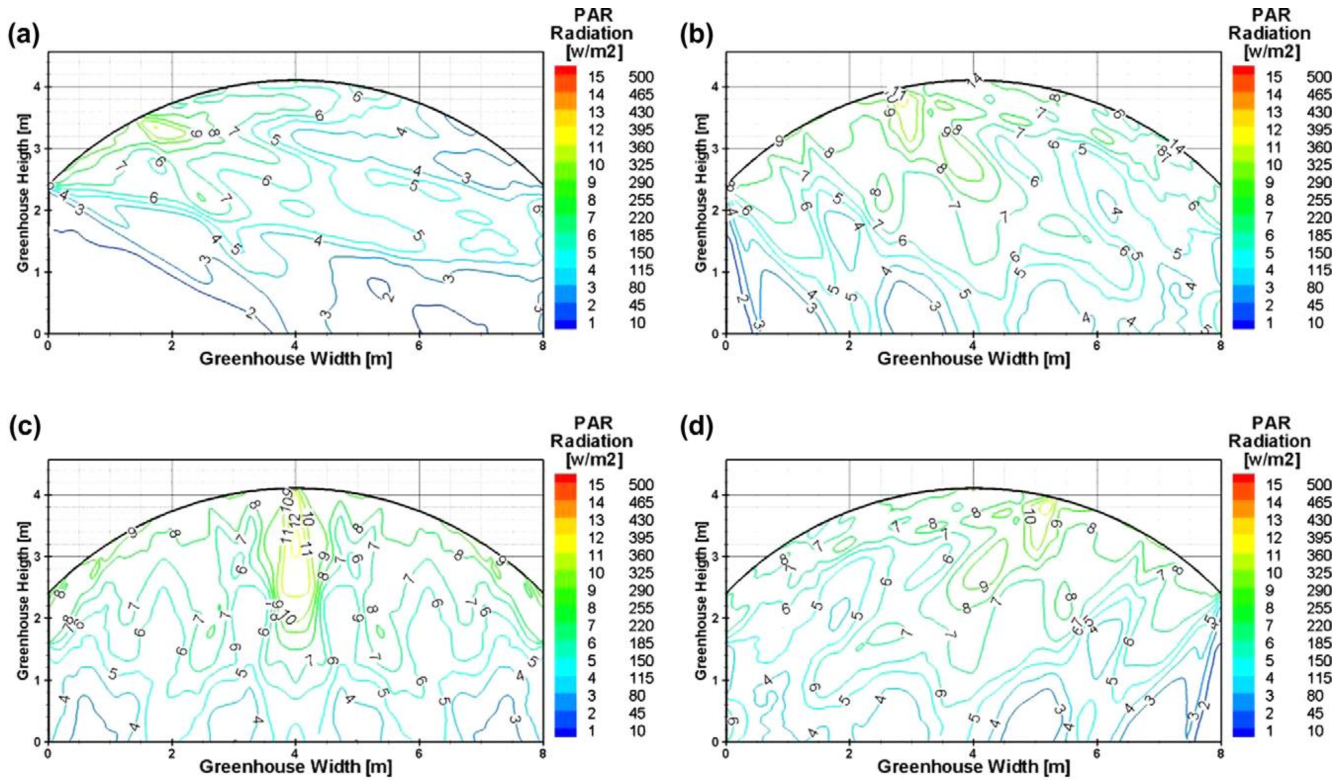


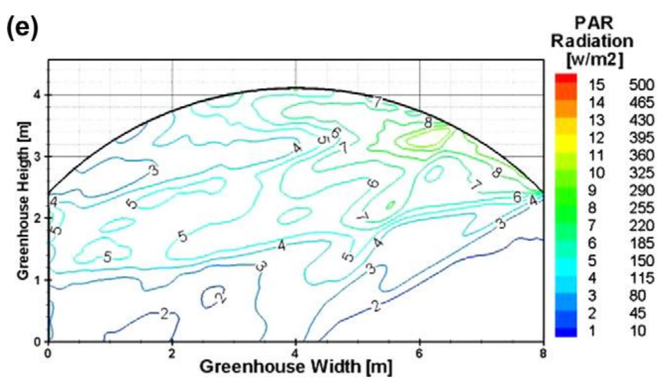
Average air velocity evolution during the examined solar day at plant level.



PAR radiation at plants base level at the 21st of June.

Modelling greenhouse systems / Solar radiation



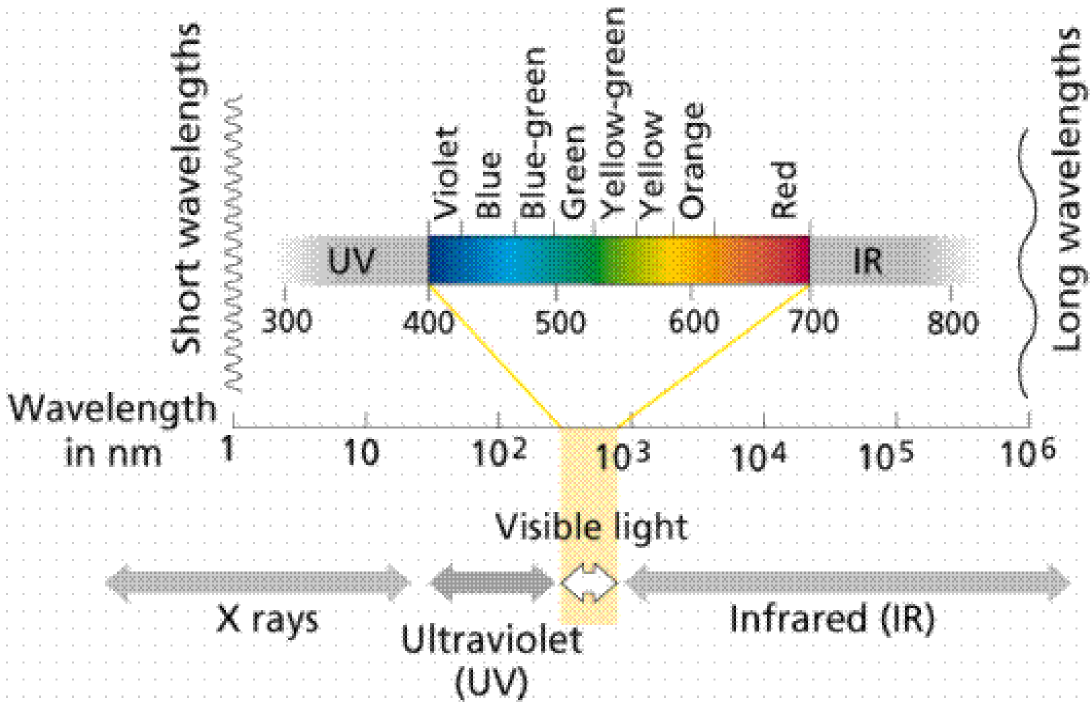


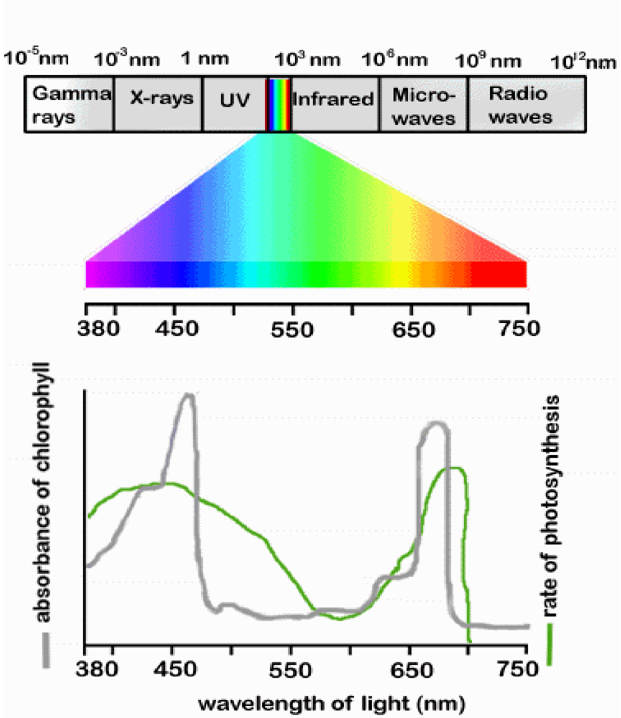
PAR distributions for different inclinations of the incident solar radiation (a–e) (a) 60, (b) 30, (c) 0, (d) 30 and (e) 60 (Baxevanou et al., 2010).

Covering materials

Use of photo selective covering materials

UV-absorbing cover materials started to spread recently after the observation that in greenhouses covered with those films, a reduction of insect populations and fungi diseases was obtained.



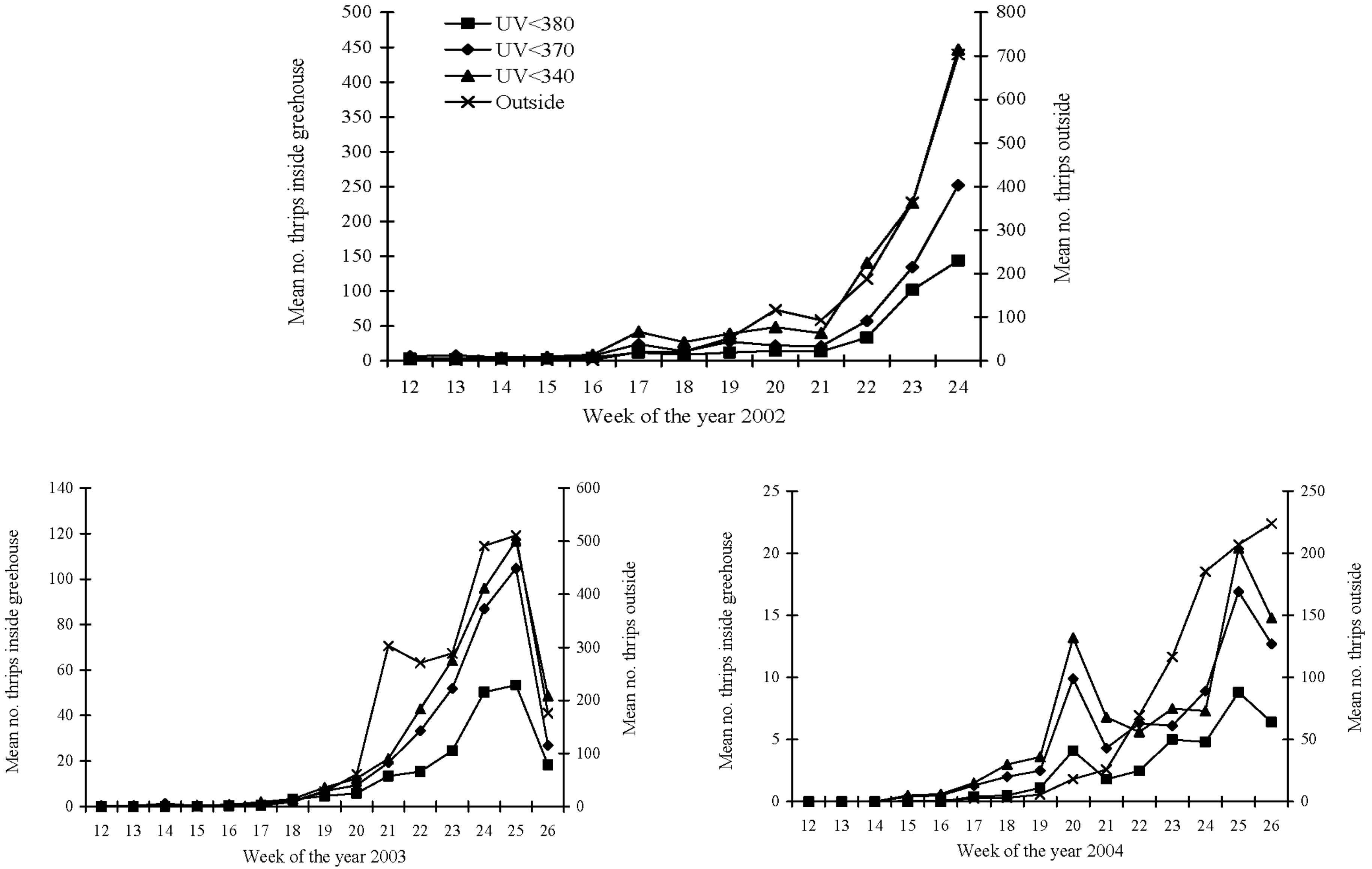


UV Covering materials

Covering materials with UV-absorbent (< 380 nm) can significantly reduce insects population

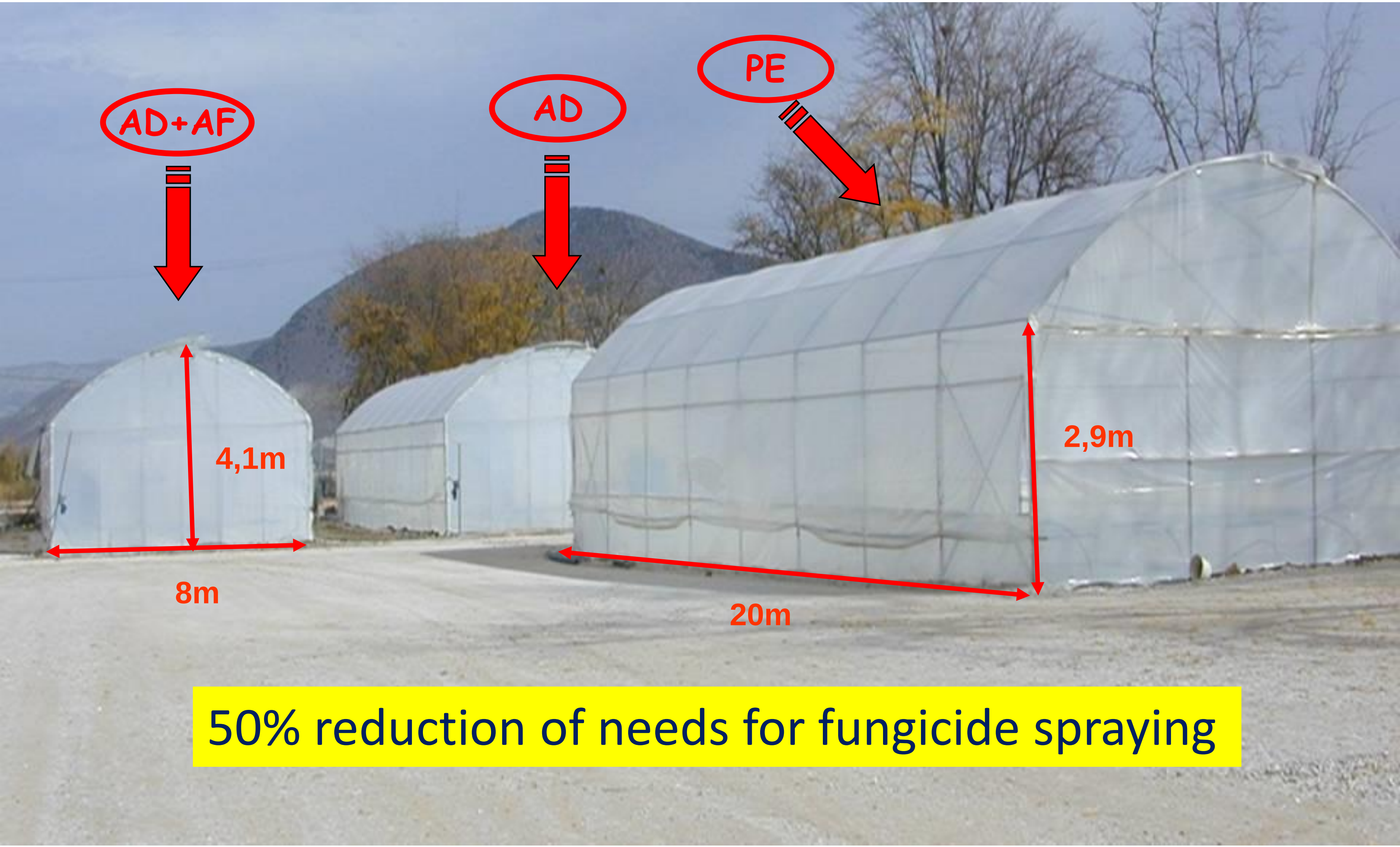
Hypericum calycinum , *Thomas Eisner Cornell University*

Number of thrips per sticky trap in greenhouses covered with plastics that blocked the entrance of UV light



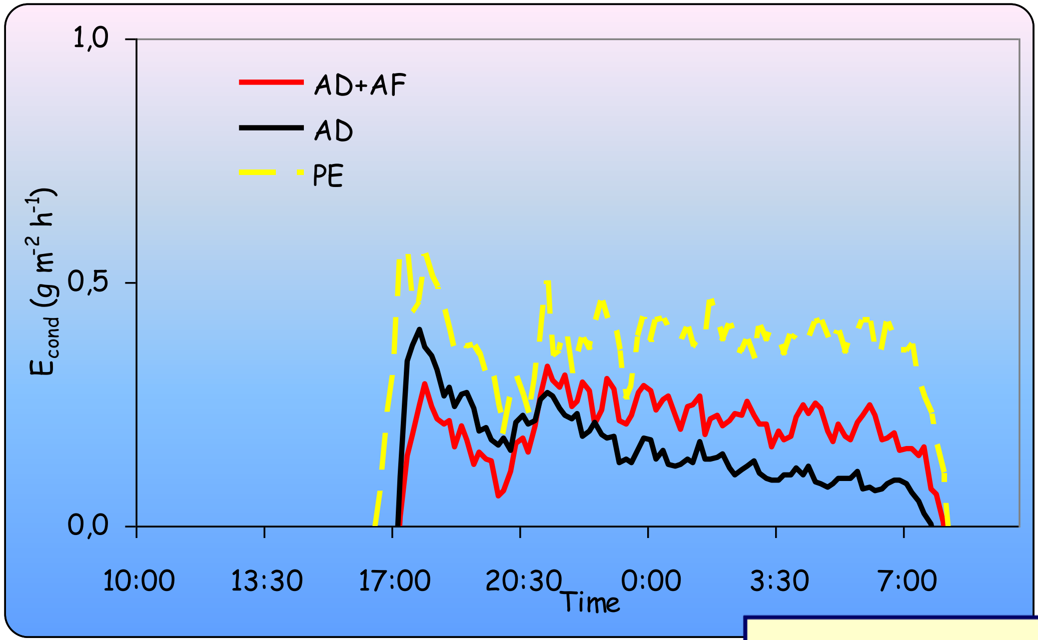

"ΘΕΡΜΟΛΟΥΞ" PLASTIKA KRITIS SA

Anti drop / fog covering materials



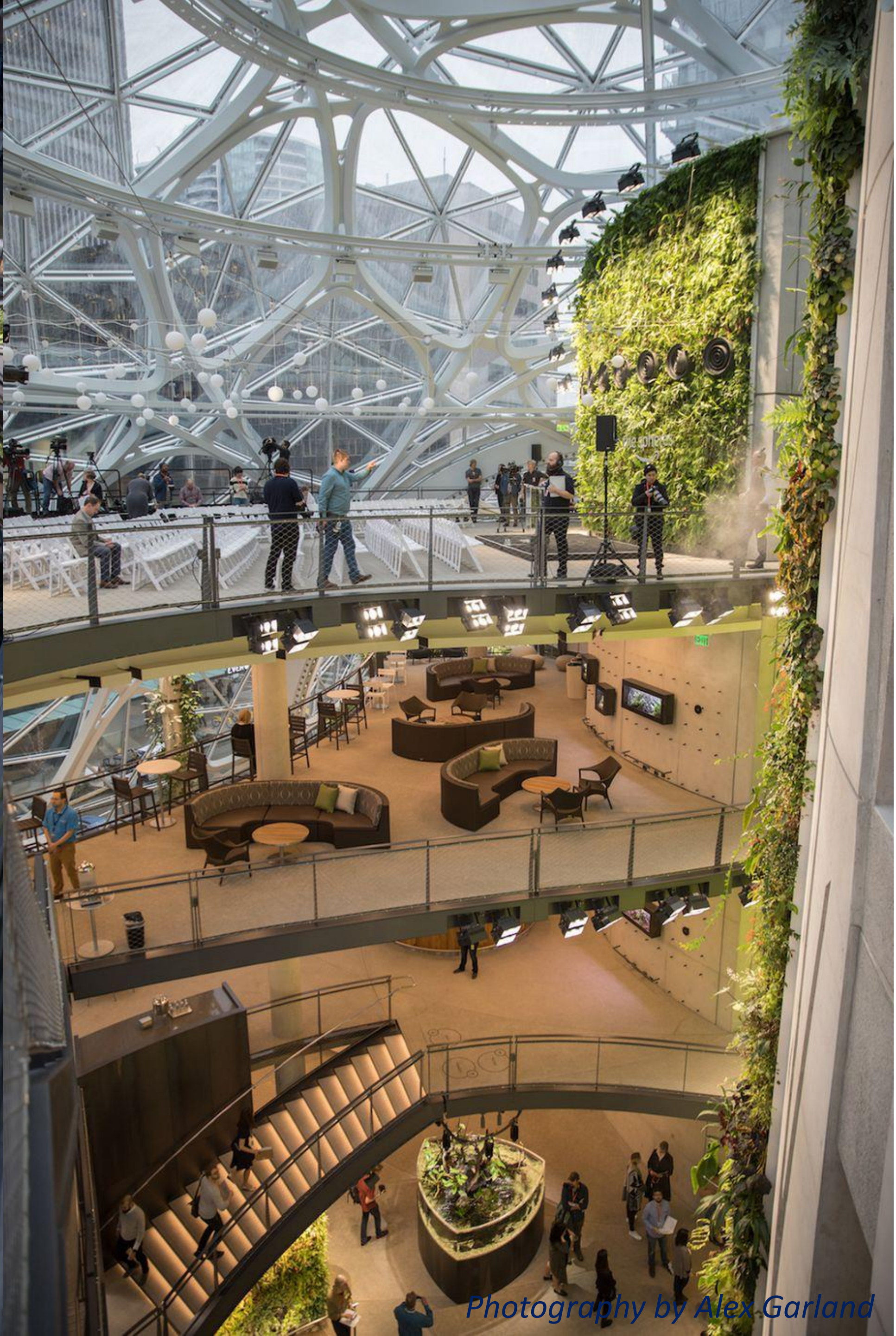
50% reduction of needs for fungicide spraying

Condensation



Crop production

Greenhouse	Total fruit production kg/plant	Total number of fruits per plant	Mean fruit weight (g)
AD+AF	2.8a	10.1a	374a
AD	2.4a	9.2a	345a
PE	2.6a	10.3a	358a



Photography by Alex Garland

Amazon Spheres, Seattle, USA

Photography by Alex Garland

Thank you!

Thomas Bartzanas

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Skype: thomas.Bartzanas

LinkedIn: thomas.bartzanas

Twitter: @bartzanas