A LARGE CLIMATE-MODERATING ENCLOSURE SUITABLE FOR HOT ARID CLIMATES

Christopher G.H. Jofeh
Ove Arup & Partners
13 Fitzroy Street
London W1P 6BQ
United Kingdom

The purpose of this work is to design a large volume ($>10^5$ m^3) climate-moderating enclosure suitable for hot arid climates. Without air-conditioning or any other powered mechanical cooling device it is to maintain an internal temperature significantly cooler than outside ambient. The interior is to be naturally lit. Potential uses of such an enclosure include agriculture, shopping centres, office parks and manufacturing.

The background to this work is diverse: Buckminster Fuller's one mile diameter dome over Manhattan (3); the one hundred acre roof of the Haj Terminal at Jeddah airport; the visionary ideas of Nikolaus Laing (6); and the pioneering computations of a group at the Oak Ridge National Laboratories (8).

A mathematical model has been constructed on a Macintosh microcomputer of the energy flows within a hypothetical large climate-moderating enclosure (LCME) situated near Tucson, Arizona. The LCME is very simple and is shown in Figure 1. It consists of a shallow depression in the ground surrounded by tall earth walls. The roof canopy is made of a durable and reflective architectural fabric arranged in large scale louvres, supported by a widely spaced regular grid of steel or timber masts.

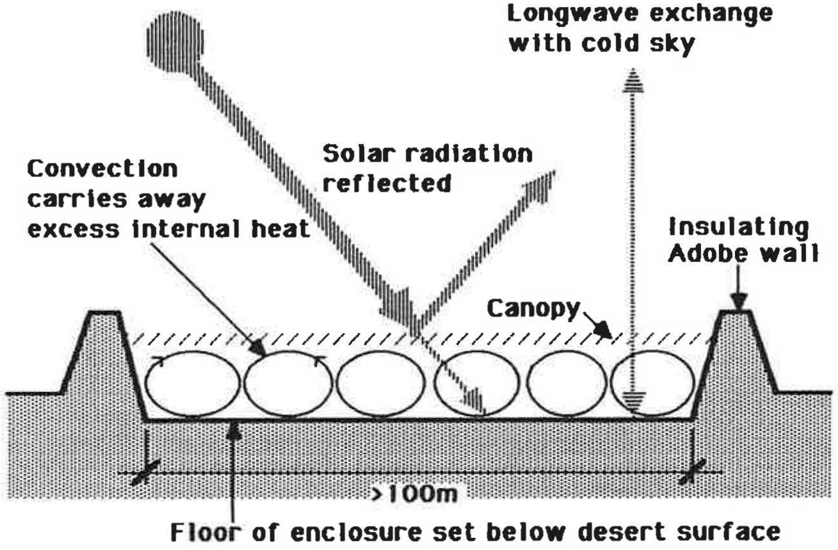


Fig. 1. Prototype Large Climate-Moderating Enclosure

The principles behind the design are also very simple. The canopy reflects most of the incident solar radiation. At the same time it is also open to the sky which permits an exchange of longwave radiation between the interior of the enclosure and the sky, which acts as a radiative sink. The massive earth walls insulate the sides of the enclosure. The roof is set below the top of the walls to discourage the mixing of wind-driven hot outside air with the cooler air within the enclosure. In this way a pool of cool air is maintained at the bottom of the enclosure. Natural convection ensures that the bottom of the enclosure tends to remain its coolest part.

The energy flows that are accounted for in the model are as follows:

1.Longwave and shortwave radiation, both inside and outside. The basic radiative exchanges are shown in figure 2. The symbol R means either longwave or shortwave radiation. R14, R15 and R16 represent emissions from the upper and lower surfaces of the canopy and from the ground and are therefore only longwave. R1 represents either shortwave radiation from the sun or longwave radiation from the sky. The radiative temperature of the sky is calculated using relationships devised by Berdahl and Fromberg (2). The dewpoint temperature is calculated from the dry bulb air temperature and relative humidity.

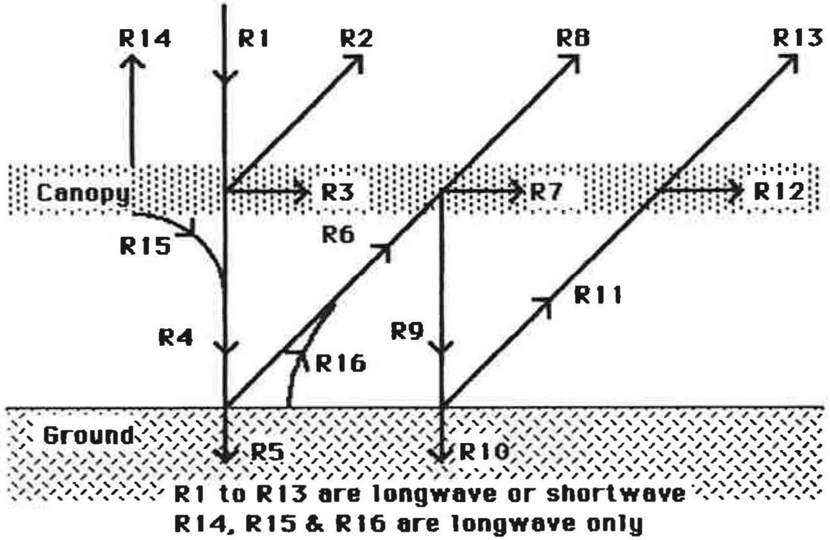
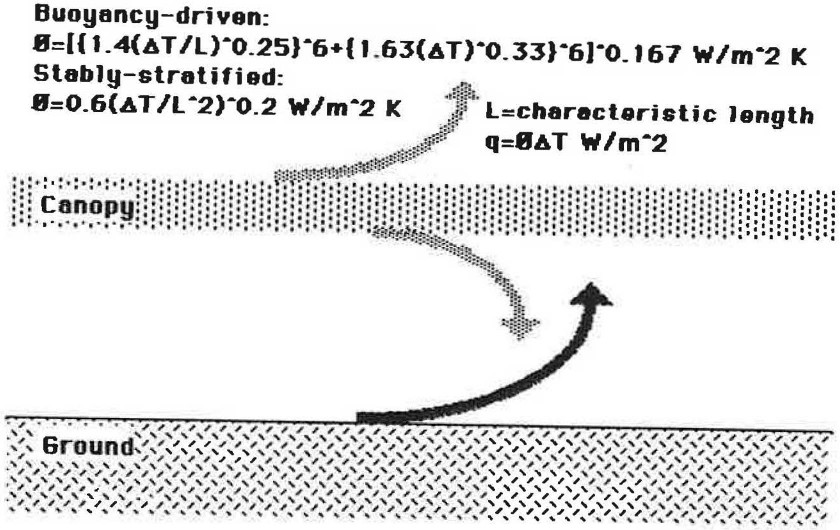


Fig. 2. Basic Radiation Exchanges

2.Convection from ground to air and from canopy to air. The basic convective exchanges are shown in figure 3. These are based upon correlations established by Alamdari and Hammond (1).

3.Conduction of heat in the soil beneath the floor of the enclosure. The sub-soil conduction of heat is calculated using the layered model shown in figure 4, taken from Ingersoll, Zobell and Ingersoll (4).



Buoyancy-driven:

$\varnothing=[\{1.4(\Delta T/L)^{0.25}\}^{6}+\{1.63(\Delta T)^{0.33}\}^{6}]^{0.167}$ W/m^2 K

Stably-stratified:

$\varnothing=0.6(\Delta T/L^{2})^{0.2}$ W/m^2 K

L=characteristic length

$q=\varnothing\Delta T$ W/m^2

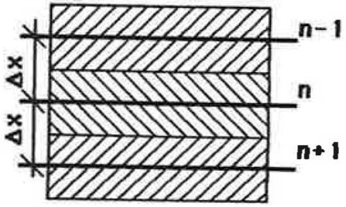
Fig. 3. Basic Convection Model.

During time Δt :

Heat flow from plane n-1 to plane n = Δt(Temp[n-1]-Temp[n])k/Δx

Heat flow from plane n to plane n+1 = Δt(Temp[n]-Temp[n+1])k/Δx

k: thermal conductivity
C: heat capacity
d: density



Net flow of heat into plane n = Δt(Temp[n-1]-2Temp[n]+Temp[n+1])k/Δx

Rise in temperature of plane n = Δt(Temp[n-1]-2Temp[n]+Temp[n+1])k/({Δx^2}dC)

Fig. 4. Basic Soil Conduction Model.

The model also takes account of the following:

1.Soil Properties.

The soil beneath the floor of the LCME is divided into 10 layers, and each layer may be assigned its own thickness, conductivity, density and thermal capacity. The surface of the soil is assigned reflectivity and absorbtivity in the shortwave and longwave. It is also assigned a longwave emissivity.

2.Canopy Properties.

The roof canopy is assumed to have no thermal capacity. It does have both long- and shortwave reflectivity, absorbtivity, transmissivity and longwave emissivity.

3.Solar and other Weather Input (5,9).

The solar intensity on a horizontal surface can be specified at hourly intervals throughout the day. Dry bulb air temperature and relative humidity are assumed to vary sinusoidally. The program user supplies the lowest and highest daily values and the time at which the lowest value occurs.

4.Heat Sources and Sinks.

a.Infiltration of outside air.

b.Artificial sources of power at floor and canopy levels.

c.Absorbtion of specified fractions of long- and shortwave radiation inside the enclosure by plants.

5.Sequence of Calculations.

The program performs its calculations at regular time steps throughout the day and night, typically hourly or half hourly. Before it can begin these calculations it must 'initialise' the soil, that is to say it must establish realistic temperatures in each of the soil layers. This it does based upon the user's guessed range of soil surface temperature variations. At any depth the temperature range is calculated from (7):

$$\Delta T_z = \Delta T_0\, e^{-z\sqrt{(\pi/KP)}}$$

where ΔT_z is the surface wave amplitude, ΔT_0 is the wave amplitude at depth z, K is the thermal diffusivity of the soil and P is the wave period in seconds (86400 in the case of diurnal cycles). The time lag is calculated from:

$$t = (z/2)\sqrt{(\pi/KP)}$$

where t is the time lag. The canopy temperature is initialised by searching for a temperature at which radiative and convective fluxes are in equilibrium. Initialisation and analysis begin at a time chosen by the user. Checks have shown that the predictions of the model are not sensitive to the choice of time.

Once conditions have been initialised, it is possible to proceed with the main analysis. The sequence of events is shown in figure 5. At each time step the results of the calculations are plotted graphically on the screen of the computer and are also printed in tabular form. The graphical output of a typical run is shown in figure 6.

The temperature of the surface of the ground represents the conditions at the floor of the enclosure, which are always cooler than the outside air. During the daytime the canopy heats up to much higher than the air in order to find equilibrium between its solar gains and its longwave and convective losses. At night the opposite occurs and the canopy reaches equilibrium at temperatures between the ground and the air, with longwave radiative losses balancing small convective gains. The small steps in the sky temperature are a feature of the model used, which changes slightly at dawn and dusk.

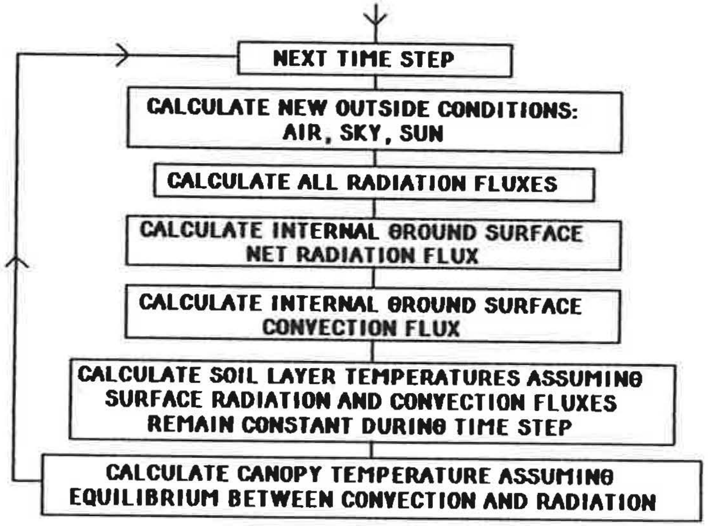


Fig. 5. Analysis Sequence.

Table 1 lists all the parameters used in the run presented in figure 6.

Analysis Begins at 6am. No infiltration or artificial power input.

Radiative Properties (%).

	Absorbed	Reflected	Transmitted	Emitted
Canopy Short	25	25	50	0
Canopy Long	15	75	10	15
Soil Long	85	15	0	85
Soil Short	65	35	0	0

Soil Conductive Properties

Thickness m	Conductivity W/m/K	Capacity J/m3/K	Density kg/m3
0.05	0.3	1280000	1600

Outside Air

Lowest Temp	Highest Temp	Lowest RH	Highest RH
21°C at 5am	37°C	13%	36% at 2pm

Solar Input.

Time	5am	6am	7am	8am	9am	10am	11am	12
	7pm	6pm	5pm	4pm	3pm	2pm	1pm	
W/m2	0	150	300	500	700	800	850	900

Table 1 Basic Parameters

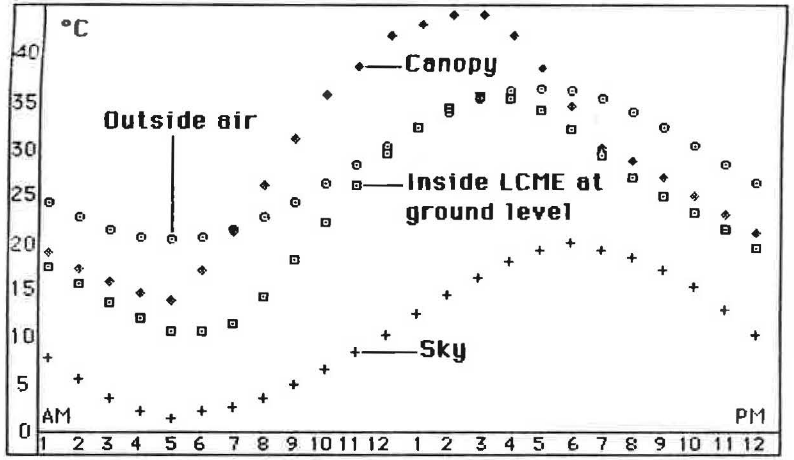


Fig. 6. Typical Daily Cycle Of LCME

The results presented in figure 6 are for just one of 45 combinations of canopy radiative properties that have been examined. The range of radiative properties are given in tables 2 and 3.

	Absorbed	Reflected	Transmitted	Emitted
A)	0	0	100	0
B)	0	25	75	0
C)	0	50	50	0
D)	0	75	25	0
E)	0	100	0	0
F)	25	0	75	0
G)	25	25	50	0
H)	25	50	25	25
I)	25	75	0	25
J)	50	0	50	50
K)	50	25	25	50
L)	50	50	0	50
M)	75	0	25	75
N)	100	0	0	100

Table 2 Canopy Longwave Properties (%)

	Absorbed	Reflected	Transmitted	Emitted
1)	10	70	20	0
2)	15	75	10	0
3)	20	75	5	0

Table 3 Canopy Shortwave Properties (%)

Table 4 summarises the results of these runs. The conclusions that can be made from these results are, perhaps, not surprising and therefore encouraging. It is clear that significant reductions in temperature are possible by passive means alone. There are at least three basic conclusions to be drawn from these analyses. The first is that the longwave absorbtivity of the LCME's canopy should be as low as possible. The second is that its longwave reflectivity should be as low as possible. The third is that absorbtivity is more crucial than reflectivity. These can be summarised by saying that longwave transmissivity should be as high as possible.

Shortwave: Longwave	1	2	3
A)	37.3°C	27.3	22.4
B)	40.9	28.6	22.4
C)	43.8	29.0	21.0
D)	47.5	27.2	13.4
E)	48.3	*	*
F)	42.8	32.9+	28.6
G)	47.4	35.9	30.6
H)	52.9	38.8	32.1
I)	58.3	40.3	31.0
J)	46.0	37.2	33.2
K)	51.7	41.5	36.4
L)	58.2	45.9	40.9
M)	48.7	40.3	36.5
N)	56.2	45.6	41.7
O)	51.5	43.0	39.8

* Did not converge to a solution after 48 hrs   + Illustrated in Figure 6

Table 4 Summary of Maximum Internal Ground Level Temperatures For Different Combinations of Canopy Short- and Longwave Properties.

Extensive runs have been carried out to make sure that the results being obtained are not sensitive to any of the assumptions made or particular values of parameters chosen. These are summarised in Table 5. The parameter that has the most marked effect on peak internal temperature is the assumed absorbtion of longwave radiation within the LCME by, for example, vegetation. Leaves are very good absorbers of longwave radiation (95% is a typical figure). However the behaviour of a plant stand is different from the behaviour of its individual leaves (7). A more realistic model of plant behaviour would have daytime shortwave and longwave absorbtion by the stand partly offset by convection and longwave emission; at night it is quite likely that convection would partly compensate net longwave heat loss by the leaves. The next stage in the development of this program is to construct a simple model of plant stand behaviour.

Apart from the absorbtion of longwave radiation by plants, the parameter that has the most marked effect on the model's predictions is the thickness of the soil layers. This is not surprising because it can easily be shown that with a dry sandy soil (the kind of soil whose properties have been assumed) daily temperature fluctuations penetrate to a depth of less than 0.5m. Even annual fluctuations reach only about 5m. It is therefore important to have thin enough upper layers in the soil so that the model can perform appropriately.

Parameter	Maximum Internal Temperature
Basic regime (Table 1)	35.9°C
Begin analysis at 6pm	36.2
10% absorbtion of internal longwave radiation	24.1
10% absorbtion of internal shortwave radiation	34.3
10W/m2 power supplied to the canopy	36.6
10W/m2 power supplied to the ground	36.2
500m3/hr infiltration of outside air	36.2
Peak solar input increased to 900..1000..900W/m2	36.7
Soil conductivity doubled	35.7
Soil thermal capacity doubled	31.9
Soil longwave absorbtivity/emissivity increased to 90%	36.2
Soil shortwave reflectivity increased to 45%	34.8
All soil layer thicknesses doubled to 0.1m	32.4
Soil lower 5 layers only doubled to 0.1m	36.2
Ground convection increased by 25%	36.3
Canopy convection increased by 25%	35.7
Outside air highest temperature increased to 40°C	38.5
Minimum RH reduced to 5%	33.0
Minimum outside air temperature increased to 23°C and Maximum RH increased to 47% (July/August weather)	37.0

Table 5. Summary of Sensitivity Runs.

Briefly, the conclusion of this paper is that it is possible to design and construct LCMEs that maintain within themselves climates that are significantly cooler than outside. These LCMEs function by passive means alone: that is to say, they need no airconditioning or other power-consuming devices. Their potential uses are extensive: agriculture and horticulture are obvious choices. Computer studies have shown that a louvred roof canopy that provides the necessary thermal control still admits sufficient daylight for vigourous plant growth. Other uses include shopping centres, office parks and manufacturing facilities. In all these cases, the LCME would provide a volume of space in which other more conventional buildings would be constructed. These conventional buildings would then require far less insulation and airconditioning than they would if they were outside the LCME.

References.

(1) Alamdari, F. and Hammond, G.P., Improved data correlations for buoyancy-driven convection in rooms. Building Services Engineering Research & Technology, Volume 4, No. 3, pp106-112, 1983.
(2) Berdahl, P. and Fromberg, R., The thermal radiance of clear skies. Solar Energy, Volume 29, No. 4, pp299-314, 1982.
(3) Fuller, R.B. and Marks, R., The dymaxion world of Buckminster Fuller,Anchor Books, New York, 1973.
(4) Ingersoll, L.R. et al., Heat Conduction, The Univ. of Wisconsin Press, 1954.
(5) Koenigsberger, O.H. et al., Manual of Tropical Housing and Building, Longman, 1980.
(6) Laing, N., The use of solar and sky radiation for air conditioning of pneumatic structures. 1st International Colloquium on Pneumatic Structures, IASS, Stuttgart, 1967.
(7) Oke, T.R., Boundary Layer Climates, Methuen, London, 1978.
(8) Wendt, R.L. et al., Large Climate-Moderating Envelopes for Enclosed Structures, Oak Ridge National Laboratory, Tennessee, 1981.
(9) Western SUN, Arizona Solar and Weather Information, Oregon, 1980.