WHATCH’EM: The Water Height and Temperature in Container Habitats Energy Model

Version 2.1

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1. Introduction

The mosquitoes *Aedes aegypti* and *Aedes albopictus*, the primary vectors of dengue, yellow fever, and chikungunya viruses, exploit a wide range of artificial containers as sites for oviposition and development of the immature stages (Gratz 1999, 2004; Gubler 2004; Focks and Alexander 2006). These containers can range in size from small trash items (e.g., bottles and cans) to medium-sized buckets and tires to large water storage containers such as barrels/drums, tanks and cisterns (Morrison et al. 2004; Tun-Lin et al. 2009; Bartlett-Healy et al. 2012). *Ae. aegypti* larval and pupal development are strongly dependent upon availability of water and container water temperature (Bar-Zeev 1958; Rueda et al. 1990; Tun-Lin et al. 2000; Kamimura et al. 2002; Mohammed and Chadee 2011; Padmanabha et al. 2011, 2012; Richardson et al. 2011; Farjana et al. 2012). Weather-driven dynamic life-table simulation models for *Ae. aegypti* populations - such as CIMSiM (Container Inhabiting Mosquito Simulation Model) and Skeeter Buster (Focks et al. 1993a, b; Cheng et al. 1998; Magori et al. 2009; Ellis et al. 2011) – simulate the evolution of mosquito cohorts primarily through a series of empirical relationships. A simplistic regression-based empirical relationship is used in these models to estimate container water temperature and water height.

Recent work has shown that physics-based approaches toward modeling container water properties are promising for resolving the complexities of container water dynamics (Kearney et al. 2009). Here we present WHATCH'EM - The Water Height And Temperature in Container Habitats Energy Model – which calculates the temperature and water level of a specified container, based on the energy balance of the water volume. The energy balance method is used to determine surface temperature in numerical weather prediction, and a similar process is used here, adjusted for container geometries and thermodynamic characteristics. The program only requires a limited amount of meteorological data (temperature, relative humidity, and rainfall) to produce water temperature and height estimates. The program takes into account variable factors such as cloudiness, shading, container size and thermal characteristics, and any manual container filling that may occur. WHATCH'EM simulates the highly non-linear manner in which atmospheric conditions and container characteristics determine water temperature and height, leading to results that are not always intuitive and likely not simulated by simpler empirical models. WHATCH'EM has the capacity to be utilized for other mosquitoes and other container-inhabiting arthropods.

2. Model Prerequisites

In this section we describe input data and parameters to the program, and associated processing in preparation for energy balance calculations.

a. Meteorological Variables

There are three required meteorological variables, and two optional variables to the program. Input data is read at hourly intervals. Required variables are: air temperature (°C), relative humidity (%) and rainfall accumulation (mm). Optional variables include: cloud fraction (low, middle, and high) and soil temperature (°C). An input file for each location is required, in columnar format as shown:

YYYY	MM	DD	HH	DOY	T	RH	PRECIP	LC	MC	HC	TSOIL
2011	05	01	00	121	28.87	76.27	0.00	0.0000	0.0000	0.0000	32.52
2011	05	01	01	121	28.67	76.20	0.00	0.0000	0.0000	0.0000	31.76

2011 05 01 02 121	28.72	74.56	0.00	0.0000	0.0000	0.0000	31.01
2011 05 01 03 121	28.87	73.84	0.00	0.0000	0.0000	0.0000	30.26
2011 05 01 04 121	28.34	75.31	0.00	0.0000	0.0000	0.0000	29.64
2011 05 01 05 121	27.95	82.51	0.00	0.0000	0.0000	0.0000	29.02

…

where YYYY is year, MM is month, DD is day, HH is hour (24-hour format), DOY is day of year, T is temperature, RH is relative humidity, PRECIP is rainfall accumulation, LC is low-cloud fraction, MC is middle-cloud fraction, HC is high-cloud fraction, and TSOIL is soil temperature. By default, the soil temperature is taken to be at 50 mm depth.

b. Container Parameters

Several container specifications are necessary for energy balance applications. The container dimensions (each radius/length, in m), height (m), shape, thickness (m), reflectivity (based on container color), and thermal conductivity (W m^{-1} K^{-1}) are all required. Currently allowable shapes include "ROUND" (circular), "RECT" (rectangular), and "TIRE" (an automobile tire), of which surface areas are calculated based on the provided dimensions.

c. Location Parameters

Necessary location parameters include a city name, a station name, latitude (decimal degrees), longitude (decimal degrees), and elevation (m). Note that elevation is not currently used in any calculations, but would be needed for future refinements to solar radiation calculations.

d. Environment Parameters

A shade fraction (0-1) needs to be specified, based on the degree of overhead cover above the container. If cloud fraction data is not provided, then cloud fractions need to be specified for low, middle, and high levels, both daytime and nighttime (six parameters total). For container water, an initial temperature and initial level (based on percentage filled), along with a manual fill flag (T/F) and time increment (in days) of manual filling are all required. If soil temperature data is not provided, then an initial ground temperature must be specified. A time step of model iterations must be provided.

3. Preliminary Calculations

a. Container Areas

The surface area of water on top of the container is calculated as:

$$A_t = \begin{cases} \pi r_t^2 \cdots \text{ for round container} \\ l_t w_t \cdots \text{ for rectangular container} \\ 2\pi\left(r_{t1}^2 - r_{t2}^2\right) \cdots \text{ for tire} \end{cases} \quad (1)$$

where r_t is the radius of the top opening of the container, l_t is top of the container length, w_t is top of the container width, r_{t1} is the full radius of the top of the tire, and r_{t2} is the inside "donut hole" radius of the top of the tire. Similarly, the surface area of the bottom of the container is calculated as:

$$A_b = \begin{cases} \pi r_b^{\ 2} \cdots \text{for round container} \\ l_b w_b \cdots \text{for rectangular container} \\ 2\pi\left(r_{b1}^{\ 2} - r_{b2}^{\ 2}\right) \cdots \text{for tire} \end{cases} \quad (2)$$

which is the same as A_t except the dimensions of the container body are used (indicated by subscript b). The surface area of the container side walls are calculated as:

$$A_s = \begin{cases} 2\pi r_b h_w \cdots \text{for round container} \\ 2h_w\left(l_b + w_b\right) \cdots \text{for rectangular container} \\ 2\pi h_w r_{b1} \cdots \text{for tire} \end{cases} \quad (3)$$

where h_w is water height. An estimate of the surface area of the solar beam striking the side walls of the container is given by:

$$A_e = \begin{cases} 2 r_b h_w \cdots \text{for round container} \\ h_w\left(l_b + w_b\right) \cdots \text{for rectangular container} \\ 2 h_w r_{b1} \cdots \text{for tire} \end{cases} \quad (4)$$

Related calculations are done for the volume of the container material itself, by subtracting out the volume of water from the total volume of the container and water. The volumes are given by:

$$V_c = \begin{cases} \pi ht\left(2r_b + t\right) + \pi t r_b^{\ 2} \cdots \text{for round container} \\ ht\left(l_b + w_b + t\right) + l_b w_b t \cdots \text{for rectangular container} \\ 2\pi ht\left(2r_{b1} + t\right) \cdots \text{for tire} \end{cases} \quad (5)$$

b. Solar Zenith Angle

The solar zenith angle is the difference in angle of the sun from overhead. It is calculated from e.g., Monteith and Unsworth (2008) (p. 54) as:

$$z = \cos^{-1}\left(\sin\left(dec\right)\sin\left(\phi\right) + \cos\left(dec\right)\cos\left(\phi\right)\cos\left(hr\right)\right) \quad (6)$$

where *dec* is the declination angle (Cooper 1969):

$$dec = -0.4093\cos\left(\frac{2\pi\left(doy + 10\right)}{365}\right) \quad (7),$$

ϕ is latitude in degrees, and *hr* is the hour angle:

$$hr = \left| \frac{\pi\left(12 - tod\right)}{12} \right| \quad (8)$$

where *tod* is the time of day.

c. Optical Thickness

The atmospheric optical thickness represents an extinction coefficient of solar radiation, due to attenuation from scattering and absorption by both molecules and aerosols. Optical thickness is parameterized from Burridge and Gadd (1974) as:

$$\tau = -\ln\left[\left(0.6 + 0.2\cos\left(z\right)\right)\left(1 - 0.4c_h\right)\left(1 - 0.7c_m\right)\left(1 - 0.4c_l\right)\right] \quad (9)$$

where z is solar zenith angle and c_h, c_m, and c_l are cloud fractions at high, middle, and low levels, respectively.

d. Saturation Vapor Pressure

The saturation vapor pressure is the partial pressure of water vapor when the air is saturated. It is calculated from e.g., Monteith and Unsworth (2008) (p. 13) using:

$$e_s = 0.611e^{\left(\frac{\lambda}{R_v}\frac{1}{273} - \frac{1}{T_a}\right)} \quad (10)$$

where λ is the latent heat of vaporization, R_v is the gas constant for water vapor, and T_a is air temperature.

e. Vapor Pressure

Vapor pressure is the partial pressure of water vapor in a given mass of air. It is calculated using:

$$e = e_s\left(\frac{RH}{100}\right) \quad (11)$$

where e_s is saturation vapor pressure and *RH* is relative humidity (%).

f. Ground Temperature (if necessary)

If ground temperature data is not provided, it is calculated based on near-surface air temperature. For the first 24 hours of simulation, the estimated ground temperature is simply the running average of air temperature. Once 24 hours of air temperature data is available, ground temperature is estimated using a sinusoidal diurnal wave of air temperature, offset in time and dampened in amplitude. First, the damping depth of the thermal wave is defined from Arya (2001) (p. 53) as

$$d = \sqrt{\frac{P\alpha_g}{\pi}} \quad (12)$$

where P is the period of the thermal wave (one day) and α_g is the thermal diffusivity of the soil. The ground temperature is then calculated from Arya (2001) (p. 53):

$$T_g = \overline{T_g} + A_s e^{\left(-z/d\right)} \sin\left[\left(\frac{2\pi}{P}\right)(t - t_m) - \frac{z}{d}\right] \quad (13)$$

where $\overline{T_g}$ is the daily average ground temperature (over the past 24 hours), A_s is the amplitude of the thermal wave, z is the depth of the ground temperature observation, d is the damping depth defined above, t is the time of the day (in seconds), and t_m is the time of the day when the ground temperature is equal to the daily average ground temperature (defined here to be constant at 11 AM local time).

g. Clouds

If cloud fraction data is not provided, then the specified low, middle, and high cloud fractions for day and night are used. Day is defined as 1 PM – 4 PM local time, night is defined as 9 PM – 8 AM local time, and any other time of day uses the average of the day and night values. For either observed or specified cloud fractions, the total cloud fraction is defined as half of the sum of the low, middle, and high cloud fractions, not to exceed 1.0.

4. Energy Balance Calculations

Once the necessary input data and parameters are provided, estimates of the energy balance for both water and container are calculated. The energy balance for water is calculated based on the following equation:

$$Q_{S_W} = Q_{SW\downarrow} + Q_{LW\downarrow} - Q_{LW\uparrow} - Q_{H\uparrow} - Q_{L\uparrow} - Q_{C\downarrow} - Q_{C\rightarrow} \quad (14),$$

where Q_{SW} is heat storage in water (representing the change of temperature of the water), $Q_{SW\downarrow}$ is downward shortwave radiation, $Q_{LW\downarrow}$ is downward longwave radiation, $Q_{LW\uparrow}$ is upwards longwave radiation, $Q_{H\uparrow}$ is upwards/downwards sensible heat transfer, $Q_{L\uparrow}$ is latent heat transfer, $Q_{C\downarrow}$ is conduction between the container bottom and water, and $Q_{C\rightarrow}$ is conduction between the container side walls and water.

The energy balance for the container is

$$Q_{S_C} = Q_{SW\rightarrow} + Q_{LW\rightarrow} - Q_{LW\leftarrow} - Q_{H\leftarrow} - Q_{G\downarrow} + Q_{C\downarrow} + Q_{C\rightarrow} \quad (15),$$

where Q_{SC} is heat storage in the container, $Q_{SW\rightarrow}$ is sideways inbound shortwave radiation, $Q_{LW\rightarrow}$ is sideways inbound longwave radiation, $Q_{LW\leftarrow}$ is sideways outbound longwave radiation, $Q_{H\leftarrow}$ is sideways sensible heat transfer, $Q_{G\downarrow}$ is conduction between the ground and the container bottom, $Q_{C\downarrow}$ is conduction between the container bottom and the water, and $Q_{C\rightarrow}$ is conduction between the container side walls and water All terms are in units of power (Watts), and the sign convention is that all radiation terms are positive *into* the container and all other terms are positive *out of* the container. Figure 1 shows a schematic of the energy balance described by (14) and (15). Details regarding the calculation of each term of (14) and (15) will now be discussed in turn.

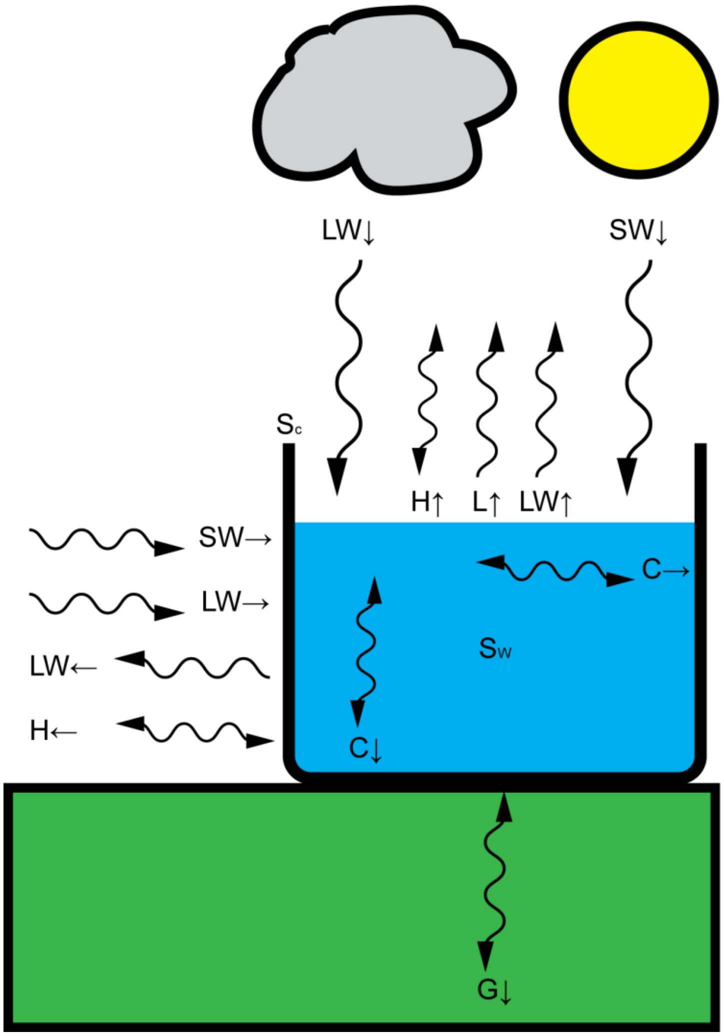

Figure 1. Schematic showing terms of energy balance model introduced in equations (14) and (15). Terms are described in the text.

a. Downward Shortwave Radiation ($Q_{SW\downarrow}$)

$Q_{SW\downarrow}$ is the downward solar radiation absorbed by the water through the top opening of the container. The shortwave radiation absorbed into the water is that not reflected or blocked by shade. $Q_{SW\downarrow}$ is calculated using

$$Q_{SW\downarrow} = S_t A_t (1 - a_w)(1 - \beta) \quad (16)$$

where S_t is the total downward shortwave radiative flux:

$$S_t = S_* d_f T_k^{a_m} \cos(z) \quad (17)$$

where S_* is the solar constant, d_f is the distance factor (Beckman and Duffie 2006):

$$d_f = \left[1 + 0.01673 \cos\left(\frac{2\pi(doy - 1)}{365}\right)\right]^2 \quad (18)$$

where *doy* is the day of the year, T_k is the atmospheric transmissivity:

$$T_k = e^{-\tau} \quad (19)$$

where τ is the optical thickness, a_m is the airmass number (Kasten and Young 1989):

$$a_m = \left[\frac{1}{\left|\cos(z)\right| + 0.50572(96.07995 - z_d)^{-1.6364}}\right] \quad (20),$$

z is the solar zenith angle (z_d is the zenith angle in degrees), A_t is container top area, a_w is the reflectivity coefficient of water, which varies based on zenith angle (e.g., Cogley 1979):

$$a_w = 0.5\left[\frac{\sin^2(z - r)}{\sin^2(z + r)} + \frac{\tan^2(z - r)}{\tan^2(z + r)}\right] \quad (21),$$

where r is the angle of refraction:

$$r = \sin^{-1}\left(\frac{\sin(z)}{N}\right) \quad (22),$$

where N is the index of refraction, and β is the shade fraction.

b. Sideways Inbound Shortwave Radiation ($Q_{SW\rightarrow}$)

$Q_{SW\rightarrow}$ is the solar radiation absorbed by the container side walls. It is composed of two components – solar radiation directly striking the container side walls, and diffuse solar radiation, not reflected by the container. $Q_{SW\rightarrow}$ is calculated using

$$Q_{SW\rightarrow} = (1 - a_c)(Q_b + Q_d) \quad (23)$$

where a_c is the reflectivity coefficient of the container, Q_b is the direct component:

$$Q_b = A_e S_b \tan(z)(1 - \beta) \quad (24)$$

where A_e is the surface area of the direct beam on the side walls, S_b is the direct shortwave flux, calculated from the difference between total shortwave flux (calculated for $Q_{SW\downarrow}$) and diffuse shortwave flux:

$$S_b = S_t - S_d \quad (25),$$

z is the solar zenith angle, and β is the shade fraction. The diffuse shortwave flux is a combination of solar radiation reflected from the ground onto the container side walls and atmospheric scattering, modified by shade:

$$Q_d = A_s \left(0.5 S_d \left(1-\beta/2\right) + 0.5 a_g S_t \left(1-\beta\right)\right) \quad (26)$$

where A_s is the surface area of the side walls, S_d is the scattered solar flux, parameterized from Monteith and Unsworth (2008) (p. 64) as:

$$S_d = S_t \left(0.68\tau + 0.1\right) \quad (27),$$

where τ is the optical thickness, and a_g is the reflectivity coefficient of the ground surface.

c. Downward Longwave Radiation ($Q_{LW\downarrow}$)

$Q_{LW\downarrow}$ is longwave radiation absorbed by water through the top opening of the container, emitted by the atmosphere and shading surface. The emitted longwave radiation is dependent on the temperature (through the Stefan-Boltzmann law) and properties of the emitting body. $Q_{LW\downarrow}$ is calculated using:

$$Q_{LW\downarrow} = A_t \left[\left(1-\beta\right)\varepsilon_a \sigma T_a^{\ 4} + \beta \varepsilon_s \sigma T_s^{\ 4}\right] \quad (28),$$

where A_t is the container top area, ε_a is emissivity of the atmosphere, parameterized from Prata (1996) and Crawford and Duchon (1999):

$$\varepsilon_a = clf + \left(1-clf\right)\left(1-\left(1+c\right)\exp^{-\sqrt{1.2+3c}}\right) \quad (29),$$

where c is

$$c = \left(46.5\left(\frac{e}{T_a}\right)\right) \quad (30),$$

clf is the ratio of the calculated and clear-sky incident solar radiation subtracted from 1, e is vapor pressure (in hPa), T_a is air temperature, σ is the Stefan-Boltzmann constant, β is shade fraction, ε_s is emissivity of the shading surface, and T_s is the temperature of the shading surface (assumed equal to the air temperature).

d. Upward Longwave Radiation ($Q_{LW\uparrow}$)

$Q_{LW\uparrow}$ is the longwave radiation emitted by water in the container into the atmosphere above. It depends on the temperature and emitting properties of water. $Q_{LW\uparrow}$ is calculated using:

$$Q_{LW\uparrow} = A_t \varepsilon_w \sigma T_w^{\,4} \quad (31)$$

where A_t is the top container area, ε_w is emissivity of water, σ is the Stefan-Boltzmann constant, and T_w is water temperature.

e. Sideways Inbound Longwave Radiation ($Q_{LW\rightarrow}$)

$Q_{LW\rightarrow}$ is longwave radiation emitted by the atmosphere and ground, and half of each is assumed absorbed by the container side walls. It is calculated using:

$$Q_{LW\rightarrow} = A_s \left(0.5\varepsilon_g \sigma T_g^{\,4} + 0.5\varepsilon_a \sigma T_a^{\,4}\right) \quad (32)$$

where A_s is surface area of the container side walls, ε_g is emissivity of the ground surface, σ is the Stefan-Boltzmann constant, T_g is the ground (soil) temperature, ε_a is emissivity of the atmosphere, and T_a is air temperature.

f. Sideways Outbound Longwave Radiation ($Q_{LW\leftarrow}$)

$Q_{LW\leftarrow}$ is longwave radiation emitted by the container side walls to the surrounding air. It is calculated using:

$$Q_{LW\leftarrow} = A_s \varepsilon_c \sigma T_c^{\,4} \quad (33)$$

where A_s is surface area of the container side walls, ε_c is emissivity of the container, σ is the Stefan-Boltzmann constant, and T_c is the temperature of the container (assumed equal to the water temperature).

g. Vertical Sensible Heat Transfer ($Q_{H\uparrow}$)

$Q_{H\uparrow}$ is the sensible heat transfer (primarily through turbulent convection) between the water in the container and the air above. We assume that in the sheltered areas where most containers are found, wind speeds are low, and free convection dominates. It is calculated from Monteith and Unsworth (2008) (p. 161):

$$Q_{H\uparrow} = \frac{A_t C_a \left(T_w - T_a\right)}{r_H} \quad (34)$$

where A_t is the container top area, C_a is the heat capacity of air, T_w is water temperature, T_a is air temperature, and r_H is heat transfer resistance from Monteith and Unsworth (2008) (p. 161):

$$r_H = \frac{d}{Nu\,\alpha_a} \quad (35)$$

where d is characteristic of the dimension of the body, taken here as the diameter of the container, Nu is the Nusselt Number, which represents convective heat loss based on wind speed and the shape of the container (Monteith and Unsworth 2008, p. 163):

$$Nu = B_1 Gr^{A_1} \quad (36),$$

where A_1 and B_1 are geometric constants (Table A.5 in Monteith and Unsworth 2008) and Gr is the Grashof Number, which is the ratio of a buoyancy force times an inertial force, divided by a viscous force (similar in function to the Reynolds number in forced convection, which determines the transition between laminar and turbulent boundary layers) (Monteith and Unsworth 2008, p. 163):

$$Gr = 158 d^3 \left| T_w - T_a \right| \quad (37),$$

when appropriate values for the thermal expansion and kinematic viscosity of air are considered, and α_a is the thermal diffusivity of air.

h. Horizontal Sensible Heat Transfer ($Q_{H\leftarrow}$)

$Q_{H\leftarrow}$ is the sensible heat transfer (primarily through turbulent convection) between the container and surrounding air. It is calculated using:

$$Q_{H\leftarrow} = \frac{A_s C_a \left(T_c - T_a \right)}{r_H} \quad (38)$$

where A_s is the surface area of the container side walls, C_a is heat capacity of air, T_c is container temperature (assumed equal to water temperature), T_a is air temperature, and r_H is heat resistance, calculated identically to that used for $Q_{H\uparrow}$, except that constants A_2 and B_2 are used in calculation of the Nusselt Number.

i. Vertical Latent Heat Transfer ($Q_{L\uparrow}$)

$Q_{L\uparrow}$ is the latent heat transfer, associated with phase changes of water. Specifically for this application, it is the heat supplied to vaporization of water in the container to the air above, and represents a heat sink for the water in the container. It is calculated using:

$$Q_{L\uparrow} = \frac{A_t C_a \left(e_s - e \right)}{\gamma r_W} \quad (39)$$

where A_t is the container top area, C_a is the heat capacity of air, e_s is saturation vapor pressure, e is vapor pressure, γ is the Psychrometer constant, and r_W is the water vapor transfer resistance, which is assumed equal to r_H calculated for $Q_{H\uparrow}$ (Arya 2001, p. 247).

j. Ground Heat Transfer ($Q_{G\downarrow}$)

$Q_{G\downarrow}$ is heat conduction between the bottom of the water container and the underlying soil. This term depends primarily on calculation of the temperature gradient between the soil and container. The distance of the temperature difference between water and ground is taken as the depth of the ground temperature observation (default is 50 mm), and half of the thickness of the container. $Q_{G\downarrow}$ is calculated based on Arya (2001) (p. 49):

$$Q_{G\downarrow} = \frac{A_b\left(T_c - T_g\right)}{\sum\left(\frac{\Delta z}{k}\right)} \quad (40)$$

where A_b is the area of the bottom surface of the container, T_g is the ground temperature, T_c is container temperature, Δz is depth, and k is thermal conductivity, with the ratio of the last two terms summed for the ground layer and half of the thickness of the container.

k. Conduction – Bottom of Container ($Q_{c\downarrow}$)

$Q_{c\downarrow}$ is the heat conduction between the bottom of the container and the water. The distance of the temperature difference between container and water is taken as half of the container depth and half of the water depth. $Q_{c\downarrow}$ is calculated as

$$Q_{C\downarrow} = \frac{A_b\left(T_w - T_c\right)}{\sum\left(\frac{\Delta z}{k}\right)} \quad (41),$$

where A_b is the area of the bottom surface of the container, T_w is the water temperature, T_c is container temperature, Δz is depth, and k is thermal conductivity, with the ratio of the last two terms summed for half of the thickness of the container and half of the depth of the water.

l. Conduction – Side Walls of Container ($Q_{c\rightarrow}$)

$Q_{c\rightarrow}$ is the heat conduction between the sides of the container and the water. The distance of the temperature difference between container and water is taken as half of the container thickness and the radius of the container. $Q_{c\rightarrow}$ is calculated as

$$Q_{C\rightarrow} = \frac{A_s\left(T_w - T_c\right)}{\sum\left(\frac{\Delta z}{k}\right)} \quad (42),$$

where A_s is the area of the side walls of the container, T_w is the water temperature, T_c is container temperature, Δz is depth, and k is thermal conductivity, with the ratio of the last two terms summed for half of the thickness of the container and the radius of the water.

5. Water Height and Temperature Calculations

Once the heat storage term Q_s has been calculated using the water and container energy balance equations (14) and (15), the water height in the container and the water temperature are both updated. First, the accumulated evaporation of water from the container is calculated from the latent heat transfer $Q_{L\uparrow}$ using the equation (Monteith and Unsworth 2008, p. 255):

$$E = \frac{Q_{L\uparrow}\Delta t}{A_t \lambda \rho_w} \quad (43)$$

where Δt is the time period of the accumulated evaporation (default is hourly), A_t is the top container area, λ is the latent heat of vaporization, and ρ_w is the density of water. The water height change is then calculated based on the difference between the evaporation and precipitation over the time period Δt:

$$\Delta h_w = P(1-\beta)\left({}^{A_t}\!/\!_{A_b} \right) + MF - E \quad (44)$$

where Δh_w is the water height change, P is precipitation accumulated over the time period Δt, β is the shade fraction (precipitation received in the container is dependent on the shade fraction), A_t is container top area, A_b is container bottom area, and MF is any manual fill. Currently, the minimum water height allowed in the program, for numerical stability reasons, is 15 mm. Below this, water temperature and all energy balance terms are set to a missing value, and a constant evaporation rate is set (default is 0.02 mm/hour). If, through precipitation or manual filling, water height returns above 15 mm, then calculations are restarted with water temperature set to the initial water temperature specified at the beginning of the program.

With updated water height, the change to the temperature of the water in the container is calculated as:

$$\frac{\Delta T_w}{\Delta t} = \frac{Q_{sw}\Delta t}{A_t h_w C_w} \quad (45)$$

where ΔT_w is the temperature change, Δt is the model time step, Q_{sw} is the heat storage term, A_t is the container top area, h_w is the updated water height, and C_w is the heat capacity of water. The container temperature is calculated using:

$$\frac{\Delta T_c}{\Delta t} = \frac{Q_{sc} \cdot \Delta t}{V_c C_c} \quad (46)$$

where ΔT_c is the temperature change, Δt is the model time step, Q_{sc} is the heat storage term, V_c is the volume of the container, and C_c is the heat capacity of the container material.

6. Program Operation and Output

WHATCH'EM is designed for a UNIX-type computing environment. It requires a FORTRAN 90 compiler to compile the main program code. There is a driver program written in Perl that requires two modules: Statistics::Descriptive and POSIX. Optionally, the NCAR Command Language (NCL) is required for plotting routines. When the WHATCH'EM archive is unpacked, the main code is in the "src" directory. "container_main.f90" is the main FORTRAN 90 program, with all subroutines and constant declarations in the module file “container_mod.f90”. The commands in “compile_container” can be modified for the user’s necessary/preferred FORTRAN compile commands, and then “compile_container” can be executed to generate the “container.exe” executable, which is linked into the base directory.

“run_container.pl” is the Perl-based driver program. All user modifications are specified in the top section of the file. Here, specifications for the locations, containers, shading, clouds (if not provided), initial conditions, and program operation (whether cloud cover and/or soil temperature data is provided, and manual container fill) can be set. This program is then executed to run WHATCH’EM, calling the FORTRAN executable for the series of experiments specified. There is also an option in run_container.pl to run a series of plotting routines using NCL.

When “run_container.pl” is run, the primary program output is written to the “output” directory, with directories created for each specified site name. The file names are structured by “<TYPE>_<CITY>-<SUBLOC>_<CONTAINER>_<COLOR>_<SHADING>.txt”, where TYPE is described below, CITY is the primary location, SUBLOC is a specified location name within a given city, CONTAINER is container type, COLOR is container color, and SHADING is shading description. If cloud cover is specified, then cloud amount description is appended to the file name after SHADING. There are three types of files created:

- “container_output”: The energy balance terms, water height, and water temperature are calculated for the entire time period of interest at the time interval specified. After a seven line header that includes a listing of location, container, and physical parameters, the following variables are output: year, month, day, hour, downward shortwave (SWDOWN), sideways shortwave (SWSIDE), downward longwave (LWDOWN), upward longwave (LWUP), sideways inbound longwave (LWIN), sideways outbound longwave (LWOUT), vertical sensible heat (SHUP), horizontal sensible heat (SHOUT), latent heat (LHUP), bottom conduction (container-water) (GHW), ground heat (into container) (GHC), side conduction (container-water) (COND), energy balances for water and container (BAL_W and BAL_C), evaporation (EVAP), water height (WH), ground temperature (TG), air temperature (TA), container temperature (TCON), and water temperature (TW).
- “energybal_avg”: The energy balance terms specified above are averaged throughout the time period to provide diurnal averages.
- “stats”: Basic statistics are calculated for average daily water and container temperatures (mean, maximum, and minimum), number of days with water level greater than 15 mm, and a frequency distribution of days of water temperature within 2°C temperature ranges.

Additional output is written to the “stats” directory, where the output from the “stats” files mentioned above are compiled for all experiments into two files, “stats_temperature.txt” and “stats_waterheight.txt”.

There are 14 types of plots created when the optional plotting routines are run, identified by the directory within the “plots” directory and the NCL script called. Examples of each of these plots are shown below for a simulation in Mexico of boreal summer 2011.

- “avg_temperature” (run with plot_t_avg.ncl): Average diurnal cycle for water, container, air, and ground temperatures. Files naming structure is “<CITY>-<SUBLOC>-<CONTAINER>-<COLOR>-<SHADING>.ps” (cloud description appended if necessary). Example shown in Fig. 2.

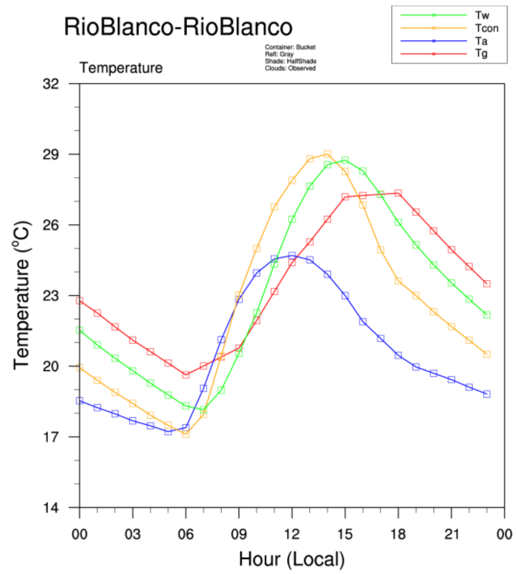

Figure 2. Diurnal cycle of average temperature. Tw is water temperature, Tcon is container temperature, Ta is air temperature, and Tg is ground temperature.

- “bar_dtr” (run with plot_bar_dtr.ncl): Average diurnal temperature range (DTR) for all containers and locations. File naming structure is “DTR-<COLOR>-<SHADING>.ps” (cloud description appended if necessary). Example shown in Fig. 3.

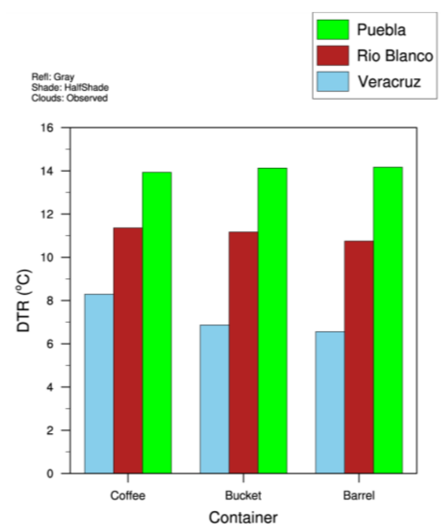

Figure 3. Average diurnal temperature range (DTR) by container and city.

- “bar_temperature” (run with plot_bar_t.ncl): Average temperature for all containers and locations, for water (W) and container (C), for mean, maximum, and minimum. File naming structure is “<C|W><MEAN|MAX|MIN>-<COLOR>-<SHADING>.ps” (cloud description appended if necessary). Example shown in Fig. 4.

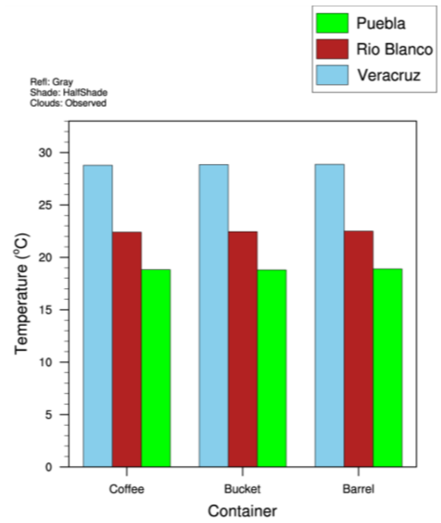

Figure 4. Average daily temperature by container and city.

- “bar_waterheight” (run with plot_bar_wh.ncl): Number of days with water height above 15 mm for all containers and locations. File naming structure is “wh-<COLOR>-<SHADING>.ps” (cloud description appended if necessary). Example shown in Fig. 5.

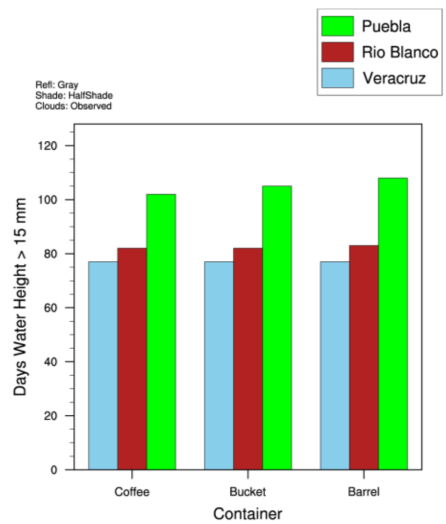

Figure 5. Days with water height greater than 15 mm by container and city.

- “clouds_precip” (run with plot_clouds_precip.ncl): Daily cloud cover and precipitation for each site. File naming structure is “clouds-precip-<CITY>-<SUBLOC>.ps” (cloud description appended if necessary). Example shown in Fig. 6.

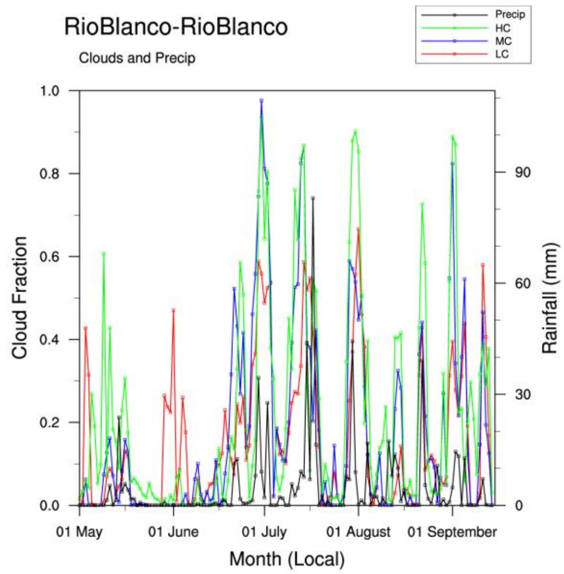

Figure 6. Cloud fraction(HC, MC, and LC refer to high, middle, and low cloud, respectively) and rainfall time series from input data.

- “comparison_cities” (run with plot_comparison_city.ncl): Water temperature and height for each site. For temperature. dashed lines represent minimum and maximum daily values. File naming structure is “<temperature|waterheight>-<CONTAINER>-<COLOR>-<SHADING>.ps” (cloud description appended if necessary). Example shown in Fig. 7.

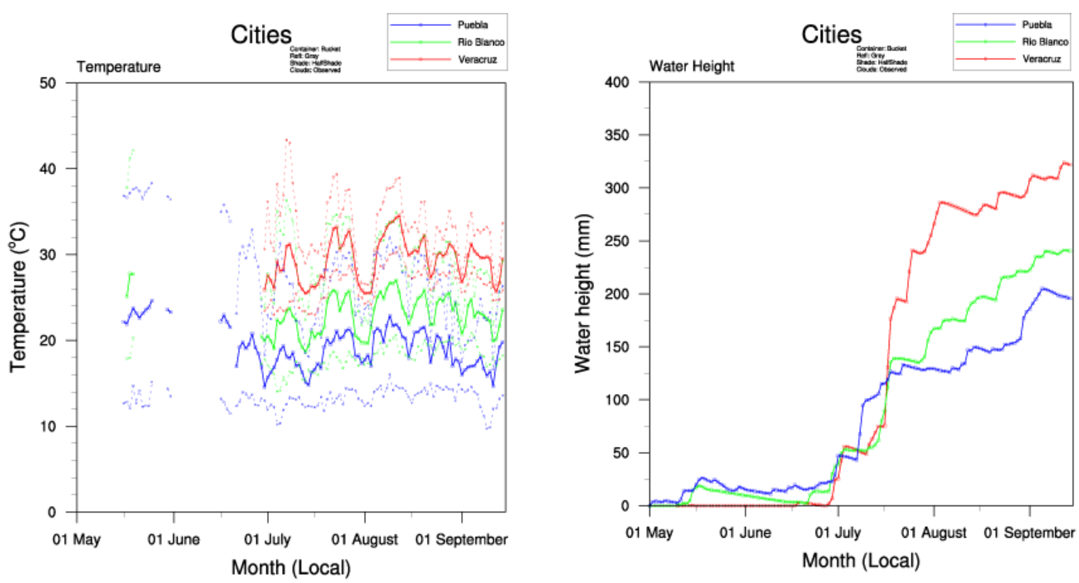

Figure 7. Temperature and water height time series by city. Dashed lines in temperature plot represent daily maximum and minimum values.

- “comparison_clouds” (run with plot_comparison_cloud.ncl): Water temperature and height for different cloud experiments. Only run if cloud amounts specified. File naming structure is “<temperature|waterheight>-<CITY>-<SUBLOC>-<CONTAINER>-<COLOR>-<SHADING>-clouds.ps”. Example shown in Fig. 8.

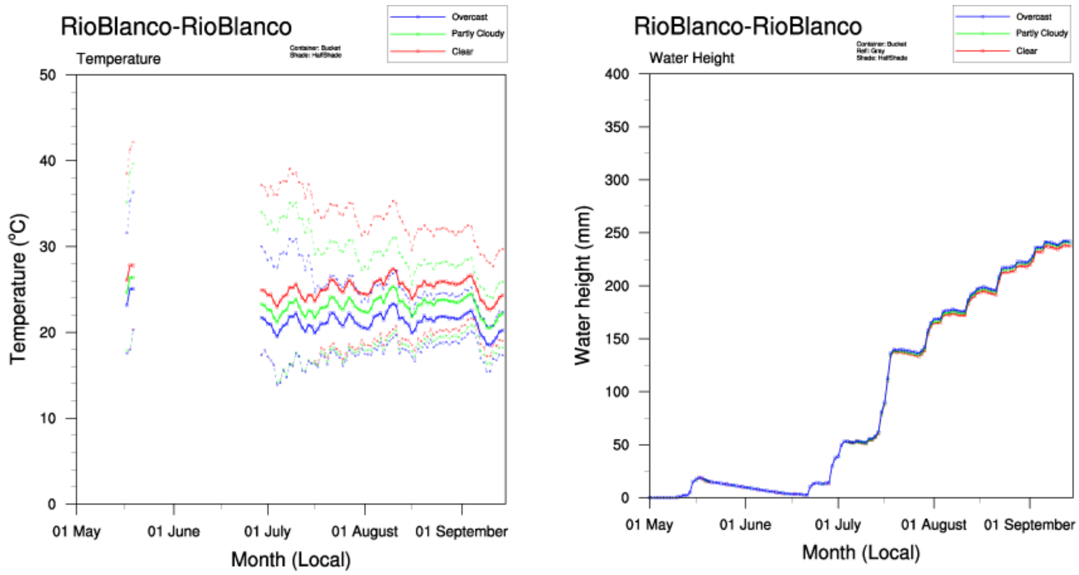

Figure 8. Temperature and water height time series by cloud specification. Dashed lines in temperature plot represent daily maximum and minimum values.

- “comparison_containers” (run with plot_comparison_container.ncl): Water temperature and height for each type of container. For temperature, dashed lines represent minimum and maximum daily values. File naming structure is “<temperature|waterheight>-<CITY>-<SUBLOC>-<COLOR>-<SHADING>-containers.ps” (cloud description appended if necessary). Example shown in Fig. 9.

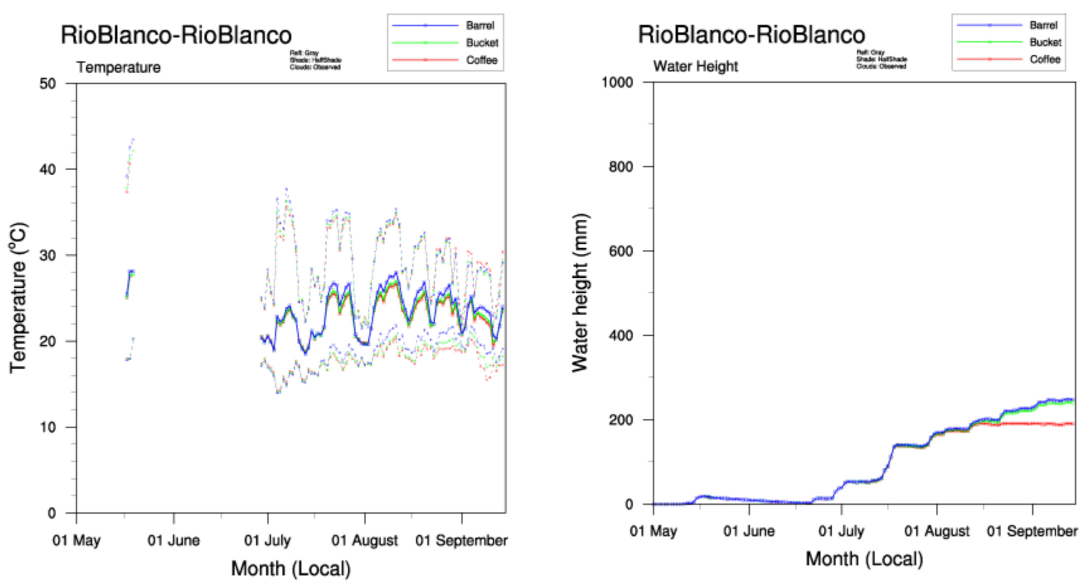

Figure 9. Temperature and water height time series by container type. Dashed lines in temperature plot represent daily maximum and minimum values.

- "comparison_refls" (run with plot_comparison_refl.ncl): Water temperature and height for each color (reflectivity). For temperature, dashed lines represent minimum and maximum daily values. File naming structure is "<temperature|waterheight>-<CITY>-<SUBLOC>-<CONTAINER>-<SHADING>-refls.ps" (cloud description appended if necessary). Example shown in Fig. 10.

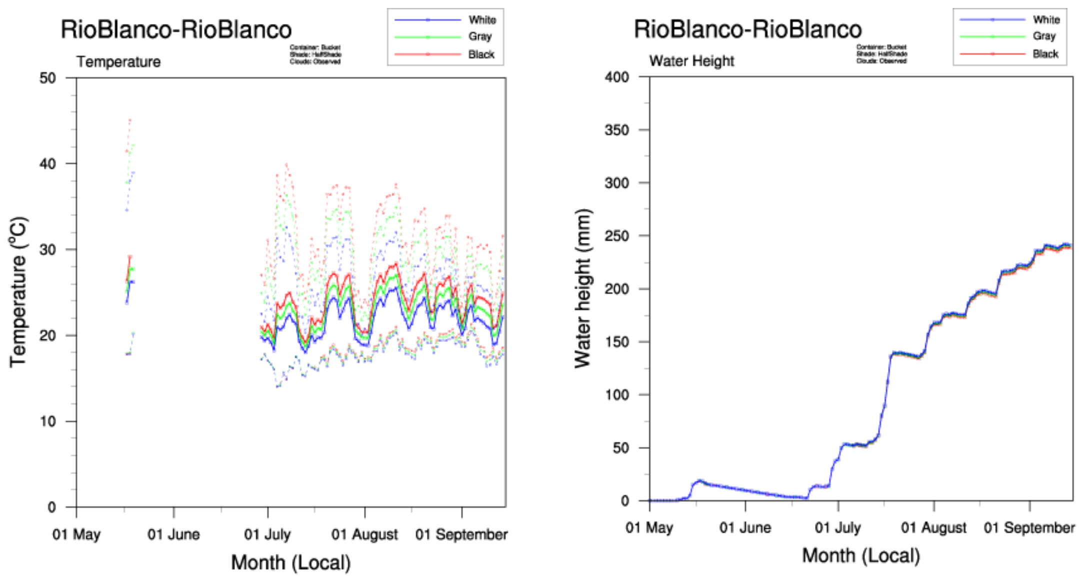

Figure 10. Temperature and water height time series by color (reflectivity). Dashed lines in temperature plot represent daily maximum and minimum values.

- "comparison_shade" (run with plot_comparison_shade.ncl): Water temperature and height for each shade cover category. For temperature, dashed lines represent minimum and maximum daily values. File naming structure is "<temperature|waterheight>-<CITY>-<SUBLOC>-<CONTAINER>-<COLOR>-shade.ps" (cloud description appended if necessary). Example shown in Fig. 11.

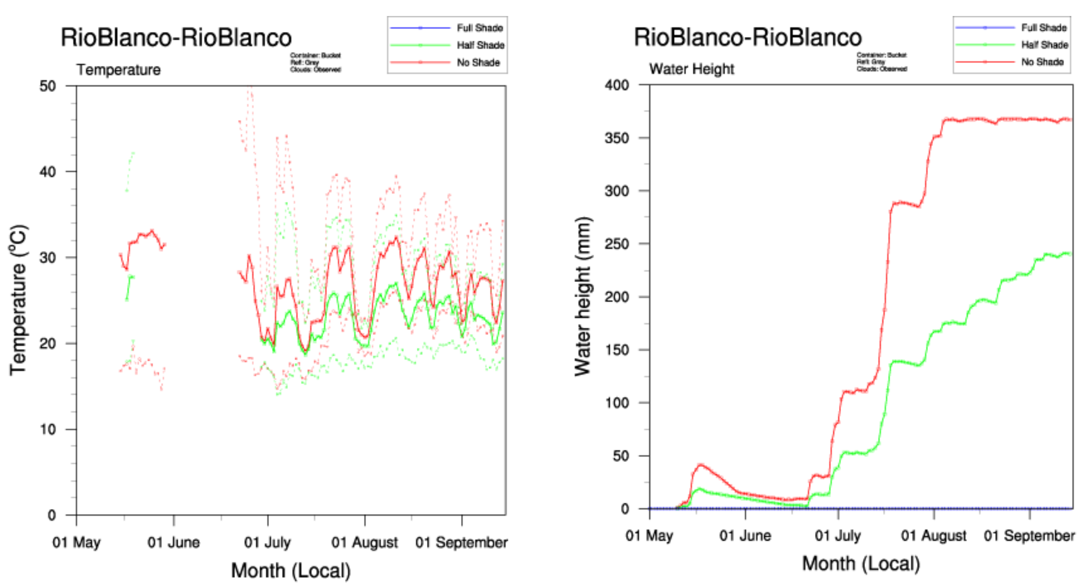

Figure 11. Temperature and water height time series by shade. Dashed lines in temperature plot represent daily maximum and minimum values.

- "energy_balance" (run with plot_energy_balance_avg_con.ncl and plot_energy_balance_avg_water.ncl): Diurnal average energy balance terms for container and water. The individual radiation terms are plotted separately. File naming structure is "<CITY>-<SUBLOC>-<CONTAINER>-<COLOR>-<SHADING>-<container_FullBal|water_FullBal|RnBal>.ps" (cloud description appended if necessary). Example shown in Fig. 12.

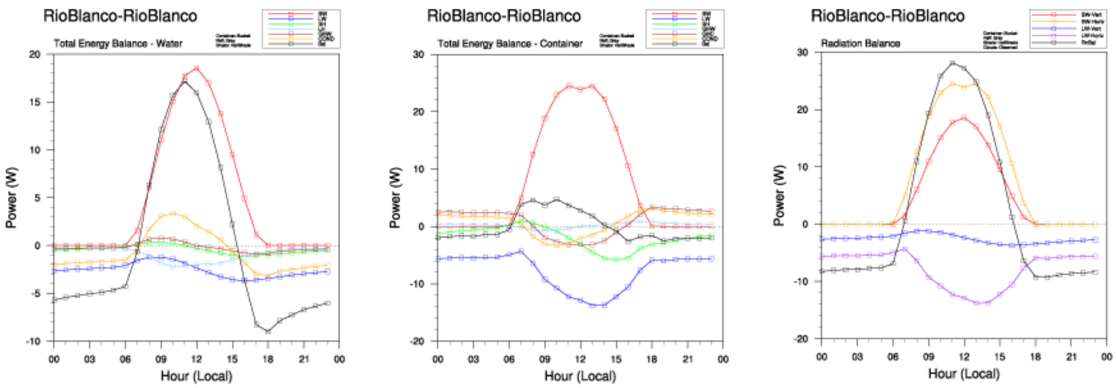

Figure 12. Diurnal cycle of average energy balance terms for water, container, and radiation terms.

- "freq_distribution" (run with plot_freq_dist_t.ncl): Histogram of average daily temperature for each site. File naming structure is "tmean-<CONTAINER>-<COLOR>-<SHADING>.ps" (cloud description appended if necessary). Example shown in Fig. 13.

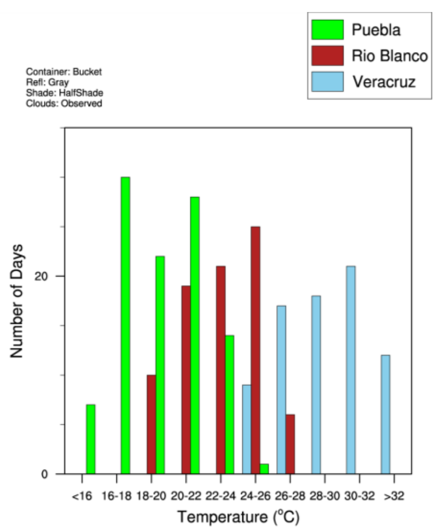

Figure 13. Histogram of average daily temperature by city.

- "temp_and_rh" (run with plot_temp_rh.ncl): Daily average air temperature and relative humidity. File naming structure is "temp-rh-<CITY>-<SUBLOC>.ps" (cloud description appended if necessary). Example shown in Fig. 14.

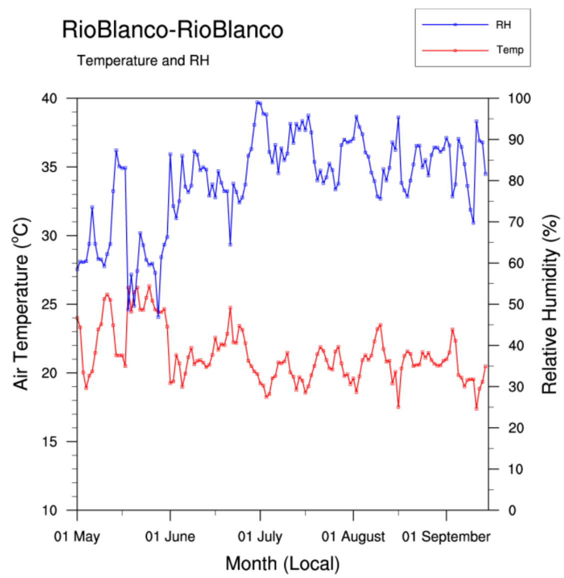

Figure 14. Air temperature and relative humidity from input data.

- "temperature" (run with plot_t.ncl): Daily average water, container, air, and ground temperature. File naming structure is "<CITY>-<SUBLOC>-<CONTAINER>-<COLOR>-<SHADING>.ps (cloud description appended if necessary). Example shown in Fig. 15.

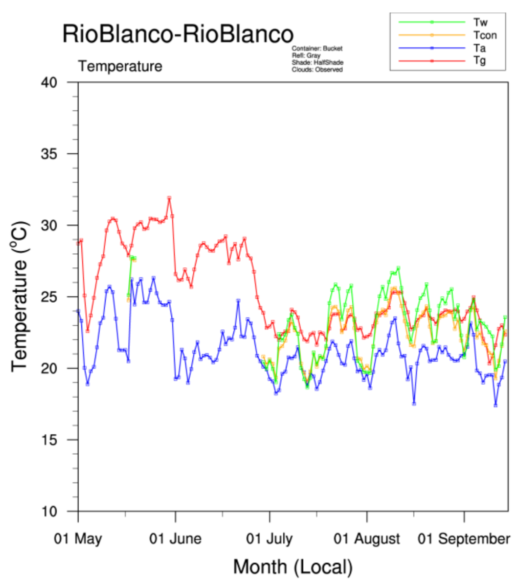

Figure 15. Temperature time series.

An important note is that if manual fill is turned off, there will be no results for "FullShade" conditions, because the containers will not have any water, and some plotting routines for these simulations will fail.

Appendix A: Table of Constants

λ: Latent heat of vaporization (at 20°C) = 2.45 x 10^{-6} (J kg^{-1})
R_v: Gas constant for water vapor = 461 J K^{-1} kg^{-1}
C_a: Heat capacity of air = 1.23 x 10^3 J K^{-1} m^{-3}
C_w: Heat capacity of water = 4.18 x 10^6 J K^{-1} m^{-3}
C_c: Heat capacity of container material = 2.20 x 10^6 J K^{-1} m^{-3}
ρ_w: Density of water = 1.0 x 10^3 kg m^{-3}
a_g: Reflectivity of ground = 0.2
σ: Stefan-Boltzmann constant = 5.67 x 10^{-8} W m^{-2} K^{-4}
N: Index of Refraction of water = 1.33
ε_g: Emissivity of ground = 0.95
ε_c: Emissivity of container = 0.95
ε_s: Emissivity of shelter = 0.90
γ: Psychrometer constant = 0.067 kPa K^{-1}

α_a: Thermal diffusivity of air = 2.06 x 10^{-5} m^2 s^{-1}
α_g: Thermal diffusivity of soil (clay, 50% saturated) = 3.40 x 10^{-7} m^2 s^{-1}
k_w: Thermal conductivity of water = 0.57 W m^{-1} K^{-1}
k_g: Thermal conductivity of soil (clay, 50% saturated) = 0.915 W m^{-1} K^{-1}
S_*: Solar constant = 1366 W m^{-2}
A_1: Nusselt Number coefficient = 0.25
B_1: Nusselt Number coefficient = 0.5
A_2: Nusselt Number coefficient = 0.25
B_2: Nusselt Number coefficient = 0.58

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