Paper No 341: Potential for the implementation of evaporative cooling in a subhumid warm climate through the use of the *humidex index.*

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Abstract
In this paper we analyzed the application of direct evaporative cooling (dEC) in a subhumid warm climate (*Aw,* a savanna, Köeppen classification.) Three localities with different altitudes – 0.0, 500 and 1,000 mosl – in the state of Colima, Mexico, were studied. Despite the fact that bioclimatic theory does not recommend applying dEC to such climate, the results suggest that its application can significantly increase comfort hours.
The humidex index, widely used by the Canadian meteorological service, is the thermal sensation that is perceived by a human being through the combined effect of relative heat and humidity. This index was used to provide a clear estimator of increase in comfort hours. dEC implies an increase in relative humidity, and thus, when analyzed through any other index, it was seen it brings about an important decrease in temperature; however, it also causes an increase in hygric discomfort hours. However, the utility of the humidex index lies in the fact that by integrating both variables into one single data, it can be determined whether dEC does indeed increase comfort.
Firstly, the mean times which were a result of evaporative cooling with different humidification efficacies were calculated. Then the humidex index for these new heat and humidity conditions was also calculated, and the sensations of *no discomfort* (or comfort,) *some discomfort, great discomfort* and *dangerous* were registered.
At 0.0 mosl, comfort hours can be increased by 190%; at 500 mosl, by 220%, and at 1,000 mosl, by 150%. It is concluded that evaporative cooling is a technique with high potential for use in subhumid warm climates, and one which does not affect hygric comfort.

Keywords:

1. Introduction

The state of Colima, Mexico, is located on the Pacific coast at a latitude of 19º 23’ N. Manzanillo (0.0 mosl,) Colima city, (500 mosl) and Cuauhtémoc (1,000 mosl) are three of its municipalities.
These localities have a subhumid warm climate (*Aw*, Köeppen classification) *[4]* also called savanna, with an average temperature of 18ºC all year. Subhumid warm climates are classified as such based on seasonal rainfall distribution and on their extended dry season during winter. Precipitation during the wet season is usually less than 1,000 millimeters, and takes place only during summer.
It is reported elsewhere that despite variations in humidity, it is possible to increase comfort hours without sacrifice of hygric comfort during the dry season.
This paper is the result of a theoretical study that evaluates the conditions of an open environment without considering the influence of a building’s thermal mass.
Currently, the availability of water for cooling systems is becoming a problem especially in arid areas; because, cooling water must compete with water for human consumption. In this work we propose the use of evaporative cooling as a green alternative to water consuming systems, specially in arid territories.

1.1 Evaporative cooling

Evaporation is an adiabatic process where a substance goes from liquid to gas state. In the case of evaporative cooling, water takes 540 *cal* (latent heat of vaporization) from air, cooling it and adding humidity to it without the spend of energy outside the system itself.
The method has yielded good results in Arabic and Moor architecture, as well as in the cultures that settled in arid lands and by using fountains, patios, water mirrors and water cooling towers.
From a physics-climatic point of view, evaporative cooling is more effective in arid climates. This is due to that there is low concentration of water vapor in the atmosphere, and thus, the air can retain more of it. The presence or absence of humidity determines the difference between dry bulb temperature (DBT) and wet bulb temperature (WBT.) This difference is called depression of WBT (dWBT) *[11]* which is basically the lowest temperature at which it is theoretically possible to cool an air sample through evaporative cooling.
Givoni *[12]* states that dEC may be used only when WBT does not exceed 22ºC. Following the research carried out by Givoni, it was found that

in an *Aw* climate there is a time of year in which WBT does not exceed 22ºC. This contradicts with the generalized belief in bioclimatic architecture theory that says dEC should not be used in *Aw* climates. Our research shows there is a time of the year which is dry and long enough for the successful implementation of dEC.

Ghiabaklou *[8]* evaluated comfort conditions through the use of EC in moderate humidity conditions, and states that it is possible to implement it, as per parameters in Fanger's predicted mean vote. Comfort is a very important parameter. The objective of this investigation was not only thermal confort, but also to find a balance between thermal and hygric comfort. This is so because dEC lowers DBT, but also causes RH to increase, cancelling the desired comfort; 80% of RH is taken as the uppermost parameter for hygric comfort. Thus, in this paper, by *comfort* we mean the value that is within the range of relative comfortable temperature and humidity.

Belarbi *[2]* and Pearlmutter *[17]* have successfully evaluated dEC's high potential for cooling as well as its low energy consumption. This reference is relevant to our paper because it is a direct evidence that the strategy is effective and allows low energy consumption, thus, a feasible proposal as an acclimatization alternative.

1.2 The humidex index

The humidex index is one of the most used discomfort indexes to evaluate how current temperature and relative humidity can affect the discomfort sensation. It is defined as follows *[15,16,20]:*

$$Humidex = DBT + h \quad \textit{(ec 1)}$$

$$h = \frac{5}{9}(e - 10) \quad \textit{(ec 2)}$$

$$\boldsymbol{e} = \frac{RH}{100} * e_s \quad \textit{(ec 3)}$$

DBT is dry bulb air temperature (in °C), *e* is the water vapour pressure of the air (hPa,) RH is relative humidity.

If the value of the vapour pressure is not available, it can be estimated through a function that combines relative humidity and dry bulb temperature, as follows:

$$\boldsymbol{e_s} = 6.112\, X 10^{7.5 * \frac{DBT}{237.7+DBT} * \frac{RH}{100}} \quad \textit{(ec 4)}$$

The humidex index is based on the perceived temperature. The index takes into account the combined effect of heat and humidity.A high humidity level in the environment may obstruct the process of sweat evaporation of the human skin.

Table 1 shows the comfort values of the humidex index adequate for the localities under study, based on Gómez *[13].*

Table 1: Humidex comfort levels with the appropriate temperature range for the localities under study (Gómez, 2006)

No discomfort	*24.0 - 30.5 °C*
Some discomfort	*30.6 - 36.0 °C*
Great discomfort	*36.1 - 40.0 °C*
Dangerous	*40.1 - 45.0 °C*

2. Materials and methods

Climatological norms were used to analyze climate data in the three localities. From monthly average data, monthly hourly means were drawn for DBT, RH and WBT *[5,6,21,22,23].*

The *reference timetable* comprises the 13 hours between 08:00 hrs and 20:00 hrs. We chose this reference timetable due to we were interested in evaluating EC's potential for use just during the daylight, at nights humidity rises and implementing this may be counterproductive.

The reference timetable is made up of 4,745 hours, which were calculated as follows: 13 hours (08:00 hrs to 20:00 hrs) x 365 days a year.

2.1 Climatic characterization of studied localities

Figure 1 shows dry bulb and wet bulb temperatures, as well as relative humidity, for the locality that is at sea level.

In regards to relative humidity during the dry season, the highest is 90%, and the lowest, 50%, which allows for a 40% oscillation.

In the wet season, the highest reaches 95%, and the lowest, 65%, allowing for a 30% oscillation.

The highest dry bulb temperature in the dry season is 30ºC, the lowest is 20ºC, and oscillation is 10ºC. In the wet season the highest is 32ºC and the lowest is 23ºC.

Wet bulb temperature in the dry season is 23ºC, and has 7ºC of difference with DBT. If dEC system is used, with a 0.7 humidification efficacy, maximum DBT can be reduced by 4.9ºC. In the wet season, maximum DBT can only be reduced by 4.2ºC.

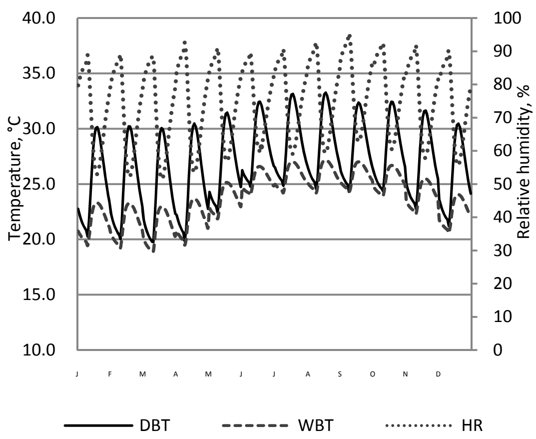

Fig 1. Mean monthly hours of dry bulb temperature, wet bulb temperature and relative humidity, for a 0.0 mosl locality

Figure 2 shows dry and wet bulb temperatures, as well as relative humidity, for the locality found at 500 mosl.

The highest relative humidity during the dry season is 80%, and the lowest is 35%, which allows for a 45% oscillation. In the humid season, the highest is 95%, the lowest 60%, and oscillation is 45%. In contrast, in the humid seasonfor the hygric comfort threshold is overcome

Maximum dry bulb temperature in the dry season is 35ºC, minimum is 18ºC, and there is a 17ºC oscillation. Overheating is identified, which together with a low relative humidity, suggests the implementation of EC. In the humid season, the highest temperature is 32ºC and the lowest is 22ºC.

Wet bulb temperature in the dry season is 20ºC, and has a 15ºC difference with DBT. If dEC system is used, with a 0.7 humidification efficacy, maximum DBT can be reduced by 10.5ºC. In the wet season, maximum DBT can only be reduced by 4.9ºC.

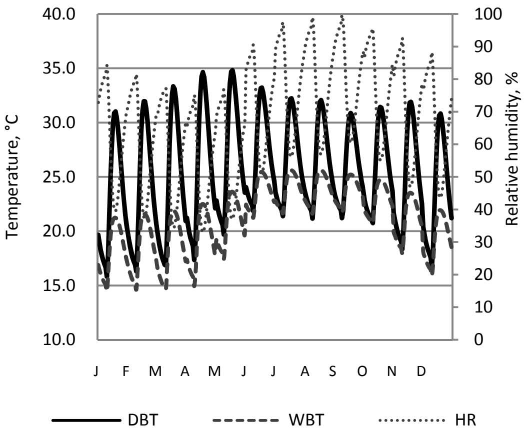

Fig 2. Mean monthly hours of dry bulb temperature, wet bulb temperature and relative humidity, for a 500 mosl locality

Figure 3 shows dry bulb and wet bulb temperatures as well as relative humidity for the locality found at 1,000 mosl.

The highest relative humidity during the dry season is 80%, and the lowest is 45%, which allows for a 35% oscillation. In the humid season, the highest is 95% and the lowest 55%, and oscillation is 40%.

Maximum dry bulb temperature in the dry season is 30ºC, minimum is 15ºC, and there is a 15ºC oscillation. In the humid season, the highest is 29ºC and the lowest is 20ºC.

Wet bulb temperature in the dry season is 20ºC, and has 10ºC difference with DBT. If dEC system is used, with a 0.7 humidification efficacy, maximum DBT can be reduced by 7ºC. In the wet season, maximum DBT can only be reduced by 4.2ºC.

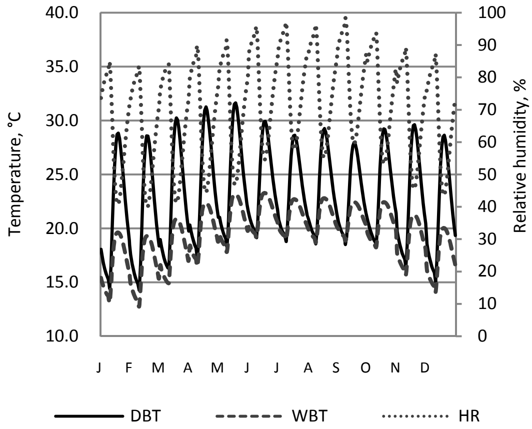

Fig 3. Mean monthly hours of dry bulb temperature, wet bulb temperature and relative humidity, for a 1,000 mosl locality

2.2 The humidex index in studied localities

The locality found at 0.0 mosl is the most humid and warm of the three. It is localizated on the coast, where most of the humidity comes from. *Table 2. S*hows the number of hours per humidex value. This figure is based on the reference timetable (see materials and methods.)

The diagnosis that can be drawn through the humidex index shows that only 11% of the studied hours fall under *no discomfort,* while the rest of them (98%) fall somewhere in the *discomfort* category, ranging from *some* to *dangerous*.

Table 2: Comfort levels associated with different humidex values and studied hours under normal conditions without use of direct evaporative cooling.

Health Impact	Humidex range	Hours	%
No discomfort	24.0-30.5	517	*11*
Some discomfort	30.6-36.0	710	*15*
Great discomfort	36.1-40.0	1653	*35*
Dangerous	40.1-45.0	1866	*39*
Total studied hours		4745	*100*

The locality found at 500 mosl is warm but less humid. It is located in a valley, and between the ocean and the valley there is a mountain range which controls the humidity coming from the ocean.

Table 3. Shows that 22% of hours are found in the *no discomfort* range, while the remaining (88%) are located within some of the *discomfort* categories.

Table 3: Comfort levels associated with different humidex values and studied hours under normal conditions without use of evaporative cooling.

Health Impact	Humidex range	Hours	%
No discomfort	24.0-30.5	1,065	*22*
Some discomfort	30.6-36.0	1,186	*25*
Great discomfort	36.1-40.0	1,734	*37*
Dangerous	40.1-45.0	760	*16*
Total studied hours		4745	*100*

The locality found at 1,000 mosl is the least humid and warm of the three. It is located at the skirts of a volcano, and thus, its climate is less warm and humid. However, it is classified as an *Aw* climate.
Table 4. Shows that 58% of hours are found in the *no discomfort* range, while the remaining (42%) are located within some of the *discomfort* categories.

Table 4: Comfort levels associated with different humidex values and hours under normal conditions without use of evaporative cooling.

Health Impact	***Humidex* range**	**Hours**	**%**
No discomfort	24.0-30.5	2,737	*58*
Some discomfort	30.6-36.0	1,389	*29*
Great discomfort	36.1-40.0	507	*11*
Dangerous	40.1-45.0	112	*2*
Total studied hours		4745	*100*

3. Results

In this section we shall discuss the increase in comfort hours as well as the decrease in discomfort that were obtained as a result of dEC implementation.

3.1 Potential for implementation in a locality at sea level

When comparing *Table 5* with *Table 2,* an increase from 11% to 21% in *no discomfort* hours was observed. There was a proportional increase of , *no discomf*ort hours by 190%.
Values for *some discomfort* showed a slight increase; however, values for *great discomfort* and *dangerous* decreased compared to their original values. This results suggest that EC does not only increase comfort sensations, but also decreases extreme discomfort conditions. In this locality the increase in comfort was small, as compared to the other localities.

Table 5: Comfort levels associated with different humidex values and studied hours under normal conditions without use of evaporative cooling.

Health Impact	**Humidex range**	**Hours**	**%**
No discomfort	24.0-30.5	973	*21*
Some discomfort	30.6-36.0	1257	*26*
Great discomfort	36.1-40.0	1014	*21*
Dangerous	40.1-45.0	1501	*32*
Total studied hours		4745	*100*

3.2 Potential for implementation in a locality at 500 mosl

When comparing *Table 6* with *Table 3*, the increase from 22% to 48% there was a significant increase of 220%.
In regard to the *some discomfort, great discomfort* and *dangerous* values, they were reduced compared with to their initial state. In this case, EC do not only increased comfort, but it also reduced extreme discomfort sensations. EC had a higher impact in the locality found at 0.0 mosl, in terms of a higher number of comfort hours.

Table 6: Comfort levels associated with different humidex values and studied hours. Evaporative cooling in use.

Health Impact	**Humidex range**	**Hours**	**%**
No discomfort	24.0-30.5	2,281	*48*
Some discomfort	30.6-36.0	852	*18*
Great discomfort	36.1-40.0	1095	*23*
Dangerous	40.1-45.0	517	*11*
Total studied hours		4,745	*100*

3.3 Potential for implementation in a locality at 1,000 mosl

When comparing *Table 7* with *Table 4,* an increase from 58% to 88% in *no discomfort* hours was observed. The increase was significant but not as much as in the locality at 500 mosl, in this case the increment of *no discomfort* hours was only 150%

In regard to the *some discomfort, great discomfort* and *dangerous* values*,* they practically disappear compared to their initial state. In this case, it was confirmed that besides increasing comfort, EC cancels extreme discomfort sensations. Compared to the localities found at 0.0 and 500 mosl, in this locality EC can work as the only acclimatization system, given the fact that its hygrothermal conditions allow for the use of EC.

Table 7: Comfort levels associated with different humidex values and studied hours. Evaporative cooling in use.

Health Impact	**Humidex range**	**Hours**	**%**
No discomfort	24.0-30.5	4,197	*88*
Some discomfort	30.6-36.0	507	*11*
Great discomfort	36.1-40.0	20	*0.5*
Dangerous	40.1-45.0	20	*0.5*
Total studied hours		4,745	*100*

4. Discussion

The use of evaporative cooling in a warm subhumid climate is potentially useful. These data show that EC increase comfort hours by over 100%. On the other hand, the humidex index provides an overview about the decrease in extreme discomfort sensations when evaporative cooling is implemented.
It is important to mention that, although evaporative cooling has a greater efficacy in arid climates, where the water is scarce, and thus, its consumption for EC systems and human use are

forced to compete. Therefore, it is important to evaluate whether EC does indeed reduce costs, and if so, this would point in the direction of implementing a passive or low energy consumption acclimatization system that is selective for each season and for each particular locality.

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6. References

1. Beccali, M., Cellura, M., Lo Brano, V., & Marvuglia, A. (2007). Short-term prediction of household electricity consumption: Assessing weather sensitivity in a Mediterranean area. *Renewable & sustainable energy reviews* , Article in press.

2. Belarbi, R. (2006). Modeling of water spray evaporation: Application to passive cooling of buildings. *Solar energy* , 1540-1552.

3. Conti, S. (2006). General and specific mortality among the elderly during the 200 the 2003 heat wave in Genoa. *Environmental research , 103*, 267-274.

4. E, G. (1990). Climas. In *Atlas Nacional de Mexico, Vol II.* México: Instituto de geografía, UNAM.

5. Elías, P. (2007). *Potencial de uso del enfriamiento evaporativo en tres localidades calido subhúmedas del estado de Colima.* Tesis de doctorado., Universidad de Colima.

6. Elías-López, P. (2005). Panorama y perspectiva de la aplicación del enfriamiento evaporativo en clima cálido subhúmedo. *Revista ASINEA , XIII* (27), 138-145.

7. Faires, V., & Clifford, M. (1997). *Thermodinamics.* (J. Escobar, Trad.) Mexico: Limusa.

8. Ghiabaklou, Z. (2003). Thermal comfort prediction for a new passive cooling system. *Building and environment , 38*, 883-891.

9. Givoni, B. (1998). *Climate considerations in building and urban design.* New York: Van Nostran Reinhold.

10. Givoni, B. (1976). *Man, climate and architecture* (2nd ed.). New York: Van Nostrand Reinhold.

11. Givoni, B. (1994). *Passive and low energy cooling of buildings.* New York: Wiley.

12. Givoni, B. (1997). Performance of the "shower" cooling tower in different climates. *Renewable energy , 10*, 173-178.

13. Gomez, G., Gómez A., A., & Elías, P. (2006). Adaptación del índice humidex para el clima de la ciudad de Colima, México. In M. Rodriquez Viqueira, *Estudios de arquitectura bioclimática* (Anuario 2006 ed., Vol. VIII, pp. 79-92). México: UAM-A-Limusa.

14. Jáuregui, E., & Soto, C. (1967). Wet bulb temperature and discomfort index areal distribution in Mexico. *Biometeor , II* (1), 21-28.

15. Masterton, J. R. (1979). A method of quantifying human discomfort due to excesive heat and humidity. *Environment Canada* , 1-79.

16. *Meteorological Service of Canada, 2006*. (s.f.). Recuperado el June de 2006, de http://msc-smc.ec.ca/cd/brochures/humidity_e.cfm#2

17. Pearlmutter, D. (2007). A multi-stage down-draft evaporative cool tower for semi-enclosed spaces: Experiments with a water spraying system. *Solar energy* , Article in press.

18. Rainham, D., & Smoyer-Tomic, K. (2003). The role of air pollution in the relationship between a heat stress index and human mortality in Toronto. *Environmental research , 93*, 9-19.

19. Servicio Meteorológico Nacional. (2000). *Normales climatológicas 1971-2000.* Servicio meteorológico nacional.

20. Smoyer-Tomic, K., & Rainham, D. (2001). Beating the heat: Development and evaluation of a Canadian hot weather health-response plan. *Environmental health perspectives , 109* (12), 1241-1248.

21. Tejeda-Martínez, A. (1991). An exponential model of the curve of mean monthly hourly air temperature. *Atmósfera* (4), 139-144.

22. Tejeda-Martínez, A., & García-Cueto, O. (2002). A comparative simple method for human bioclimatic conditions applied to seasonally hot/warm cities of Mexico. *Atmósfera* (15), 55-66.

23. Tejeda-Martínez, A., Maruri, J., & Martínez, A. (1991). Three statistical model for simulation of the mean monthly wet bulb air temperature in Mexico. *Atmósfera* (4), 279-282.