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**Global and local bioclimatic predilections for rebalancing the heating and cooling of buildings**

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**APPENDIX A Supplementary Information**

Greenhouse gas emissions are attributed to buildings includes rising demand for cooling[5]. The built environment’s relative sectoral share of the greenhouse gas pollution may have paused, but there is cause for concern that it will rebound unless action is taken to avoid unnecessary lock-in of air-conditioning[6]. So international development policy-makers hope that innovative building designs will deliver a several-fold decrease of energy-intensity while improving indoor conditions[22]. Architectural solutions may provide relief from heat but not from humidity. Passive designs are most effective providing shelter from rain, wind, and cold. Shelter provided with active mechanical building services may be necessary when wet bulb globe temperature is unacceptably high. To estimate which HVAC package is locally appropriate, refer to nearby comparable meteorological stations detailed in the file “RESULTSout\_1987-2020.csv” (n=16,582 records) that can be downloaded at doi.org/10.5518/967– but beware of microclimatic variability in urban heat islands.

**S.1 Maximum WBGT under shade**

Many developers have a predilection to prescribe air-conditioning of all buildings without assessing the local risk of extreme heat and humidity. Before committing to investment in building services, architects and planners should employ bioclimatic analysis to determine if such capital and operating expense could be avoided with sufficient passive design features. Ambient heat and humidity are quantified by the coincidence of pressure, temperature, and dew point observations from the global network of barometers, thermometers, and chilled mirror hygrometers operated by members of the World Meteorological Organization (WMO). The present work assumes the threshold of sufficiency for passive and low energy cooling according to occupation health managers’ wet bulb global temperature in shade (WBGTs). This measure of human physiological stress is weighted 70% by wet-bulb and 30% by dry-bulb in shade, to assess safe limits of physical exertion under trees. WBGT is also assessable for exposure to radiation, but the present analysis applied the threshold under effective shade since mean radiant temperature closely approaches the ambient air temperature records of weather forecasting. Therefore, maximum afternoon WBGTs have been assessed to guide developers whether to embark on design of ventilation, evaporative cooling, or air-conditioning systems in any particular project site where meteorological observations have been shared with NOAA’s global surface observations of the day (GSOD) – an open-access repository of WMO data.

Temperature and pressure are two of the three crucial determinants of the thermodynamic state of moist air, complemented by any one of many measures of humidity [33]. Assuming barometric pressure is a quasi-constant parameter (typically estimated as mean pressure at sea level) facilitates bioclimatic analysis of the coincident combinations of heat and humidity [47]. Psychrometric plotting temperature observations with a dry thermometer (dry bulb) measured across the horizontal axis, while each coincident humidity ratio of the mixture of air and water vapor (g H2O/kg air) is measured up the vertical axis. Lines of equal dew point temperature are parallel with humidity ratio, both being independent of temperature. The total sensible and latent heat of moist air is represented by plotting lines of equal enthalpy – which are dependent on dry bulb temperature as well as humidity ratio. Enthalpy lines are almost parallel with lines of wet-bulb temperature – the temperature that is approached by evaporation of a wick wrapped around the bulb of a thermometer, information useful in the design and operation of systems that mitigate heat and humidity indoors and to assess outdoor thermal stress. Without manual use of a sling-psychrometer, determination of the wet-bulb coincident with dry-bulb requires an iterative computational solution [33]. Dew point temperature (as well as absolute humidity content of air) are relatively constant during daylight hours [48-52]. Thence anyone may assess heat stress of the combination of heat and humidity in a well shaded ventilated shelter, by estimating WBGTs at the time of daily maximum dry-bulb temperature on the basis that the mean daily dew point temperature holds into the afternoon.

Presuming that mortalities have been related to vulnerable populations without sufficient shelter, the present analysis indicates geographic regions where access to air-conditioning may be necessary. Passive measures that serve well in winter can cause overheating in summer and are ineffective with respect to humidity, so necessity for active air-conditioning has emerged in places and may increase with urbanization and climate change.

The present article was initially conceived in response to others’ finding of a threshold for 20 days exceedance in worst case years being deadly [2]. They compared published cases studies of fatal heat waves (1980 – 2014) with NCEP/DOE AMIP-II 2.5° gridded reanalysis that they then interpolated down to 1.5° to align within 167 km of case studies. I recognized that their finding of a “deadly curve” was very similar in form to the wet bulb globe temperature in shade, although they employed the mean daily coincidence of heat and relative humidity to generate bioclimatic maps of risk. Their “risky curve”[2] is in congruence with 20.1°C WBGTs and that red dash-dot 26.5°C WBGTs is in congruence with the “deadly curve”[2] plots of heat and humidity(Main text Fig.1b). Their red colored horizonal arrow extends about 7 degrees on the deadly side of their threshold, and this coincidentally is where I overplotted with black dot-dash line 32.2°C WBGTs – also known as “black-flag” extremely dangerous heat and humidity. Diurnal temperature range of 14K, or seven degrees between the daily mean and the daily maximum is not atypical.

So I have approximated their deadly threshold [2], by searching for locations where the black-flag conditions (daily maximum ≥ 32.2°C WBGTs) have been experienced 20 days per year in a hot year. My preliminary analysis of GSOD stations was during the 15-30 years regression of daily observations ending 2016 plus standard estimate of interannual variability, resulted in the global map in the left panel of Supplementary Information Fig.S1 – indicating a similar pattern of stressful heat and humidity to Mora, et al.[2] for documented heat wave events. They noted that lethality of climatic conditions could be mediated by various measures such as vegetation and passive measures, so the present article seeks to identify the sufficiency of low-energy systems before resorting to air conditioning.

Fig.1b and Fig.S1b herein provide global relative humidity versus temperature RH/T comparison of WGBTs threshold flags compared with daily deadly and risky curves from Figure 1 of Mora, et al. [2]. Left frame presents my calculation of “worst years’ daily afternoon max yellow-flag”, days per annum that maximum daily conditions exceeded threshold (WBGTs>29.4°C) plus one standard estimate of interannual variability during 15-30 years of daily observations until 2016. Resulting yellow areas are where such conditions could be expected more than 20 days per year in hot years (Fig.S1a) is very similar to Figure 1a of Mora, et al. [2], who incidentally specified 20 d/y annual exposure is associated with deadly heat and humidity. Figure 1b of Mora, et al. [2] was then overplotted (Fig.S1b). Black-flag (WBGTs≥32.2°C) afternoon maximum conditions plot black dash-dot-dot curve, which is 7 ° to the right of “Deadly” curve based on daily mean. I Maximum afternoon black-flag threshold is comparable to their “deadly curve” as seven degrees is not untypical of diurnal excursions from mean conditions. Also note Fig.S1b daily mean conditions’ red dash-dot 26.5°C WBGT (0.9°C above white-flag) fits much of their deadly curve (red). Logistic fits of Risky and Deadly curves [2] assume sea level pressure for plotting white-, green-, yellow-, red- and black-flag threshold by RH/T (Supplementary Information Table S1).

**** **Supplementary *Fig.S1***  **Geographical distribution of risky heat and humidity and their climatic conditions** ***a)*** Worst years’ daily afternoon max yellow-flag conditions during 15-30 years of daily observations ending 2016. Calculated mean days per annum plus standard estimate of interannual variability of daily afternoon maximum WBGT under shade >29.4°C.  ***b)*** Mean daily WBGT under shade plotted blue dash-dash 20.1°C, red dash-dot 26.5°C, and black dash-dot-dot 32.2°C overlayed on the right panel of Mora et al. Figure 1.

**Supplementary Table S1**: **Logistic curve fits of various thresholds of temperature and relative humidity (RH), comparing Mora, et al. (2017) [2] “risky” and “deadly” with shade Wet Bulb Globe Temperature (WBGTs) flag colors.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Curves @ sea level pressure | inflection | Max (@ 0 RH) | Min (@ ∞ RH) | coeffHill |
| Black WBGTshade (90°F) | 73.3 % RH | 58.0°C | 12.5°C | 0.8111 |
| Red WBGTshade (88°F) | 76.0 % RH | 55.8°C | 11.6°C | 0.8189 |
| Yellow WBGTshade (85°F) | 78.1 % RH | 52.7°C | 10.8°C | 0.8344 |
| Green WBGTshade (82°F) | 84.1 % RH | 49.5°C |  9.2°C | 0.8410 |
| White WBGTshade (78°F) | 87.8 % RH | 45.4°C |  8.1°C | 0.8672 |
| Deadly (Mora, et al. 2017) | 40.0 % RH | 50.6°C | 17.9°C | 1.1788 |
| Risky (Mora, et al. 2017) | 26.0 % RH | 38.9°C | 16.6°C | 1.3494 |
| Temperature = Min + (Max - Min)/(1+(RH/inflection)^coeffHill) |  |

So, the main article employs the daily afternoon maximum WBGT under shade (WBGTs). WBGTs flag threshold exceedances were calculated in the present research on the basis of daily maximum conditions (Fig.1a) on the same days as daily mean HVAC preferences (Fig.3c). Both of these psychrometric charts have been marked with two closely parallel black lines to denote white-flag threshold (29.4°C WBGTs). Psychrometric charts use Damascus’ airport for an example, where white-flag threshold was never exceeded on the mean daily HVAC chart (Fig.3c) but occasionally crossed on WBGTsmax chart (Fig.1a). Compare with others’[2] heat-stress chart of daily mean relative humidity(RH) versus temperature chart where white-flag threshold is also marked by two closely parallel black lines. Damascus’ airport HVAC chart (Fig.3c) and the global heat-stress chart (Fig.1b) each have data-clusters obliquely intersected by the threshold. Plotted on daily mean RH vs temperature heat risk(Fig.1b), white-flag threshold is closely aligning with others’[2] deadly curve, with only nine heatwave events[2] reported between their deadly curve and the white-flag curve. In the example of maximum daily conditions circa Damascus’ airport(Fig.1a) grey indicates comfortable, green uncomfortable, yellow stressful, and red the few rare dangerous afternoons in the most recent 34 year sample.

Yet the white-flag threshold clears every datapoint of mean daily HVAC preference (Fig.3c), observed mid-morning, after dawn’s minimum while rising towards each afternoon’s maximum. The use of daily mean conditions for assessment of HVAC preferences is premised upon buildings having sufficient thermal inertia. Passive buildings’ indoor conditions may “float” in response to outdoor conditions approaching yellow-flag threshold WBGTs ≥29.4°C, but cold drinks or summer holidays could avoid resorting to installation of whole-house air-conditioning. Specific humidity (Fig.3c and Fig.1a) ordinate is constant throughout the day[52], so Damascus’ airport’s diurnal temperature range of 14°C translates the white-flag threshold 7°C to the right to approximately overlay the yellow-flag curve (Fig.1b). This station experienced only 10 days with aspirated shade WBGTsmax ⩾29.4 °C during 34 years, illustrating a situation where ventilation and evaporative cooling would have sufficed if water were available. Air-conditioning might not be necessary since the daily maximum threshold criteria is at least ten days of yellow flag or worse stress per annum (⩾10 YsD). The air-conditioning installed circa Damascus’ airport was possibly due to the predilection of the airport developers.

**S.2 Sufficient HVAC**

This paper uses the Syrian capital Damascus’ airport as an example location that calls for a wide range of occasional heating and cooling desires (Fig 2c) to illustrate a situation where air-conditioning is not justified if buildings were designed to employ other measures. HVAC strategies have been guided by bioclimatic design principles [53] on the basis that buildings have sufficient thermal capacity to mitigate diurnal temperature range so that daily mean values are used, as arbitrarily illustrated at Damascus (Fig.3c and Supplementary Table S3).

Illustrating the fit-for-purpose HVAC system suggestion scheme [53], the case of Damascus found an average of less than 6 d/y that air-conditioning might have been desirable and less than 10 d/y when an air-source heat pump would have been challenged by evaporator frosting [42, 53]. Interestingly frosting-days have decreased, showing air-souce heat pumps have recently become more suitable at this location. As each meteorological station was assigned the most appropriate of either all-passive cooling during summer and solar gain through windows during winter (Pc/Ps) or one of sixteen HVAC combinations – air-source heat pump heating for winter with evaporative cooling for summer (Hp/Ev) is suggested for Damascus’s neighborhood. About 2% of the global population sample resides within such Hp/Ev localities.

The present analysis (Supplementary Information and [53]) for suggested HVAC strategies are location-specific(Fig.3a, Fig2b and [26]). Interpretation in regions without ground-truth might be interpolated from established stations within the same bioclimatic zone [40]. A reader with a specific locale in mind should ask what other HVAC typology would suffice if air-conditioning is not necessary. Ideally nearby stations among the on-line files[26] or mapped (main article Fig.3) provide a starting point for new developments as well as retrofit projects. As the present publication format does not provide for dynamic graphical zooming, two-dimensional histograms of climate zones and HVAC suggestions are presented in Supplementary Information Fig.S2 – which illustrates that there may be several HVAC package typologies within any particular Köppen-Geiger climate zone. Local regulations and conventions might not concur, so the forgoing is only offered for briefing the concept-design of near-zero energy building projects.

Each of the 34 years (1987-2020) analyzed could include up to 365 or 366 GSOD records [30] of daily minimum, mean, and maximum temperature as well as daily dewpoint temperature and barometric pressure – which were assumed to be quasi-constant each day. If pressure was not provided then the station altitude was used to estimate pressure, as necessary to establish wet-bulb temperature, specific-humidity, and enthalpy using established psychrometric formulae[33].

**** **Supplementary Fig.S2: 2D histograms of HVAC preferences and climate zones a)** frequency of combination of winter heating modes (Hu, Hp, Gs) and summer cooling modes (Vt, Ev, Ac). **b)** Frequency of coincidence of HVAC heating/cooling combination types and climate zones.

**S.3 Trends and means**

The present article has assumed that a long-term average based on daily mean conditions exceeding defined thresholds is deemed acceptable up to 10 days per annum (10 days p.a.). Otherwise it is appropriate to consider the succeding stage of heating, ventilation, and air-conditioning (HVAC). For example 10 days p.a. ice-up of air-source heatpump evaporators would be tolerated – but if icing persists additional days per annum then combustion heating or ground-source heat pumps would be prefereable. Direct expansion vapour compression (DX) air-conditioning is only suggested if there are more than 10 days p.a. calling for dehumidification rather than ventilation or evaporative cooling. DXD denotes the number of days per annum (days p.a.) air-conditioning as detailed in the following section on HVAC strategies.

Days of threshold exceedance in a extreme years could be estimated by adding the interannual standard deviation[26] to the long-term mean. Inter-decadal trending is not suggested as that would exceed the life of typical HVAC packages and it is not certain that linear regression trends would continue after the last observation. An alternative benchmark is to add the standard estimate of error of the interannual variability to the regression trend estimate at the latest – this could be an indication of the current climate in a non-stationary time series. On-line CSV files [26] include such rates and statistics for HDD, CDD, ChD, DXD, WsD, and YsD.

Matlab’s two-sided Durbin-Watson test (DW) was applied and recorded as mentioned in the main text sub section 2.3. DW was used to assess if there was any autocorrelation among the residuals of the linear models of heating or cooling degree days. Supplementary Fig.S3 illustrates that there more deviation of Durbin-Watson (D-W) statistics above and below the ideal value of 2 in cases with less than 14 years of observations of heating and cooling degree days. The spread between the 1st and 3rd quartiles indicates the central half of the population, and the first quartile deviates further from the centre after one decade (10 y) so it was judged that less auto-correlation would bias trend analyis by adopting a threshold of at least 14 years.

**** **Supplementary Fig.S3: Durbin-Watson statistics of HDD & CDD linear regression if p≥0.05**

Green marks scatterplot D-W statistics as ordinate versus number of annals as abscissa.  Continuous orange and blue lines denote 3rd and 1st quartiles, while median is dashed black line.

**S.4 Adiabatic cooling formulae for shedding compressor load (example demand response)**

All building services can be delivered with lower capital and operating costs by first applying practical passive means to reduce heating and cooling loads. Better building services equipment, down-sized to operate in nearly-passive architecture, has a better chance of being drivable with rooftop PV panels or other renewable energy generation.

The present study takes a further step in closing the gap between supply and demand by presenting formulae to estimate the potential of adiabatic evaporative cooling of air-conditioning system condensing units. I have avoided detailed prejudice of individual building services systems, by assuming the cooling duty is relative to the enthalpy-difference of outdoor air above a reference wet-bulb temperature Thumid of 19.4°C (67°F) above which direct evaporative cooling systems are not able to provide comfortable relief [54]. Assuming 0.6K approach to wet-bulb, this allows for seven Kelvin rise (20°C to 27°C) to provide comfort.

Based on exergetic efficiency of vapour-compression cooling[55] at conventional range and approach temperatures [56] and using formulae derivations herein, a global analysis of potential for adiabatic demand reduction worldwide is tabulated in on-line materials[26], with an example of Damascus’ airport psychrometric chart Fig.2c and Supplementary Table S2.

The efficiency gain of adiabatic evaporative cooling condensers is derived from the Carnot coefficient of performance for cooling COPC based on the cold heat flow at the evaporator Qc and the heat rejection at the condenser Qh in equation S1, as equivalent to equations S2, S3 and S4 with the low temperature TL, high temperature TH, evaporator apparatus dew point TADP, ambient air dry-bulb temperature Tdb, and ambient air wet-bulb Twb in absolute units (Kelvins).

 COPC = Qc/(Qh-Qc) (eqn S1)

 COPC = TL/(TH-TL) (eqn S2)

COPC,dry = TADP/(Tdb - TADP) (eqn S3)

COPC,wet = TADP/(Twb - TADP) (eqn S4)

Thereby the ratiodry/wet of COPdry:COPwet is given in equation S5, where temperature may be based on Centigrade units because of relative differences are taken in both numerator and denominator.

ratiodry/wet = (Twb - TADP)/(Tdb - TADP) (eqn S5)

Reduce compression work with refrigerant evaporator temperature TADP, daily minimum dry-bulb and wet-bulb Tdb,min and Twb,min, and their increases by time of day of interest ΔTwb and ΔTdb, then savings of vapour compression work at time of day is work shed by adiabatic evaporation of water in air entering entering the condenser, summarized by equation S6.

shedding =[1-(Twb,min+ ΔTwb - TADP)/(Tdb,min + ΔTdb-TADP)] (eqn S6)

TADP is typically 8°C for comfort air-conditioning evaporators, and the drybulb and wetbulb temperatures can be calculated by equations S7 and S8 at the daily dawn minima (Tdb,min and Twb,min), and also t their afternoon maxima (Tdb,max and Twb,max).

 Tdb,mean = Tdb,min + ½ ΔTdb = Tdb,max – ½ ΔTdb (eqn S7)

 Twb,mean = Twb,min + ½ ΔTwb = Twb,max – ½ ΔTwb (eqn S8)

**S.5 Example of WMO station 400800 Damascus 34 annals of WBGT, HVAC & degree days**

Damascus’ airport provides a place-based example of assessments that coincidentally highlights a number of issues. Damascus’ 600 m elevation inland of the Anti-Lebanon Mountains happens to be ideal for evaporative cooling since aqueducts have provided secure water for millennia. The present global analysis has not confirmed water availability – but does indicate nearby lower elevation coastal locations often deserve air-conditioning for comfort, such as the Lebanese capital Beirut.

Damascus’ airport psychrometric plot (Main Article Fig.3c) happens to have experienced conditions that represent varying degrees of desirability of all seven HVAC modes: three heating/humidifying (Gs, Hp, Hu), passive solar or coolth (Ps, Pc) , and three cooling/dehumidifying (Vt, Ev, Ac). On average, there were <2 d/y when humidification (Hu) would have been nice to have in Damascus’ airport – which could have been provided by indoor evaporation boosted by a small heat source. More importantly there averaged 104 d/y when relief from summer heat could have been achieved without air-conditioning, of which 58 d/y when fanned ventilation (Vt) would be sufficient (Main Article Fig.3c) – which can be provided by evaporative cooling equipment (Ev). Thus, Damascus’ airport exemplifies somewhere air-conditioning was occasionally desirable, but not necessarily had water been available for evaporative cooling. Also it is interesting that Damascus’ airport winter weather is suitable for air-source heat pump (Hp) installations, which are typically packed with reversible functionality to also serve as air-conditioners (Ac) in summer, and so indirect evaporative cooling by adiabatic cooling could be worthwhile [20]. Regionally (Fig.3b) there are higher altitude and also higher latitude locations where ventilation would suffice in summer, while combustion heaters or ground-source heat pumps are suggested in winter (Gs/Vt), except coastal fringes are suited to reverse-cycle heatpump/air-conditioning (Hp/Ac). Generally air-conditioning is a reasonable expectation in countries to the south of Damascus (33.5°N), with the exception of mountainous areas.

The psychrometic chart was invented 120 years ago to facilitate air-conditioning engineering [47], by plotting the absolute humidity of air as an ordinate of dry bulb temperature on the abcissa. Passive bioclimatic architectural design methods aligned with psychrometrics[57] 35 years ago to enable a common framework to compare outdoor conditions with the ability of HVAC systems to maintain thermal comfort. Psychrometric plots of daily mean HVAC preference (Main article Fig.3c) and daily maximum thermal stress measured by WBGTs flags (Methods Fig.1a) in the case of Syrian capital Damascus’ airport. The analyis was adjusted for the station 616m elevation, and the psychrometric charts summarise the 34-year average, while interannual variations are revealed in Supplementary Tables S3 and S4, and plotted as 34-year time series (Supplementary Fig.S4c and S4d). There is an obvious trend of increasing both evaporatve and DX cooling on the HVAC time series, and increasing days in both white- and green-flag WBGTs. There is also an appearent trend of decreasing trend in heating-demand. The interannual demand of heating, ventilation, and/or air-conditioning is genaerally accepted to be related to heating and cooling degree days (HDD and CDD)[58].

**** **Supplementary Fig.S4: Damascus’ airport annals of daily observations each year 1987-2020**

**a)** HDD18 and CDD24. **b)** Percentage adiabatic cooling potential to shed compressor load: year’s best instance; average of daily peaks; average of daily means; and average of daily lows.

**c)** HVAC mode preference based on daily mean.  **d)** WBGT flags as well as colder purple, navy, and blue below white-flag threshold – each class based on daily maximum shaded conditions.

**Supplementary Table S2: Heating and cooling degree days based on mean daily conditions (1987-2020) Example from Damascus International Airport, Syria, WMO 400800 3.412 °N Long: 36.516 °E, 616m elevation, 94.14 hPa. Relates to Supplementary Fig.S4a.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| YEAR | icyDD (5°C) | HDD (18.3°C) | CDD (24.0°C) | wbDD (19.4 °C) | Enthalpy-days hD (reference 58.2 J/g) |
| 1987 | 31 | 1672 | 238 | 4 | 13 |
| 1988 | 34 | 1526 | 272 | 5 | 18 |
| 1989 | 75 | 1570 | 232 |  |  |
| 1990 | 19 | 1553 | 244 |  |  |
| 1991 | 50 | 1496 | 199 | 1 | 2 |
| 1992 | 112 | 1950 | 186 | 1 | 5 |
| 1993 | 71 | 1682 | 224 | 1 | 4 |
| 1994 | 19 | 1434 | 292 | 0 | 1 |
| 1995 | 31 | 1596 | 267 |  |  |
| 1996 | 24 | 1471 | 323 | 7 | 24 |
| 1997 | 19 | 1675 | 207 | 2 | 6 |
| 1998 | 30 | 1391 | 406 | 13 | 45 |
| 1999 | 2 | 1380 | 289 | 1 | 4 |
| 2000 | 27 | 1610 | 407 | 4 | 14 |
| 2001 | 4 | 1293 | 396 | 2 | 7 |
| 2002 | 23 | 1398 | 342 | 2 | 7 |
| 2003 | 8 | 1459 | 355 | 0 | 1 |
| 2004 | 2 | 1454 | 287 |  |  |
| 2005 | 10 | 1464 | 266 | 1 | 3 |
| 2006 | 20 | 1581 | 348 | 1 | 4 |
| 2007 | 19 | 1502 | 373 | 5 | 19 |
| 2008 | 23 | 1501 | 414 | 8 | 28 |
| 2009 | 8 | 1433 | 326 | 0 | 0 |
| 2010 | 2 | 1098 | 510 | 11 | 39 |
| 2011 | 3 | 1603 | 305 | 0 | 2 |
| 2012 | 14 | 1378 | 459 | 14 | 48 |
| 2013 | 25 | 1342 | 320 | 1 | 3 |
| 2014 | 9 | 1287 | 318 | 5 | 16 |
| 2015 | 32 | 1386 | 423 | 8 | 26 |
| 2016 | 17 | 1294 | 468 | 19 | 67 |
| 2017 | 9 | 1414 | 457 | 3 | 8 |
| 2018 | 0 | 1090 | 380 | 4 | 13 |
| 2019 | 3 | 1480 | 423 | 0 | 0 |
| 2020 | 9 | 1302 | 482 | 5 | 19 |

**Supplementary Table S3:** **Preferred HVAC mode based on mean daily conditions (1987-2020) Example from Damascus International Airport, Syria, WMO 400800 3.412 °N Long: 36.516 °E, 616m elevation, Standard press 94.14 hPa. Relates to Supplementary Fig.S4c and summarizing main article Fig.3c.**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| YEAR | icy | Heat pump | humidif | comfort | ventilate | Evap cooling | DX air-conditioning |
| 1987 | 11 | 198 | 2 | 64 | 60 | 26 | 4 |
| 1988 | 16 | 168 | 0 | 66 | 52 | 31 | 8 |
| 1989 | 27 | 150 | 2 | 75 | 68 | 30 | 0 |
| 1990 | 7 | 182 | 2 | 76 | 61 | 32 | 0 |
| 1991 | 20 | 166 | 0 | 91 | 61 | 25 | 1 |
| 1992 | 45 | 161 | 1 | 80 | 53 | 23 | 3 |
| 1993 | 29 | 163 | 0 | 82 | 63 | 27 | 1 |
| 1994 | 10 | 171 | 0 | 63 | 86 | 34 | 0 |
| 1995 | 9 | 190 | 0 | 54 | 68 | 41 | 0 |
| 1996 | 8 | 187 | 0 | 62 | 60 | 39 | 10 |
| 1997 | 11 | 186 | 0 | 71 | 69 | 23 | 4 |
| 1998 | 9 | 184 | 0 | 59 | 44 | 56 | 13 |
| 1999 | 1 | 180 | 1 | 72 | 69 | 37 | 4 |
| 2000 | 10 | 184 | 1 | 63 | 44 | 55 | 9 |
| 2001 | 2 | 185 | 1 | 57 | 60 | 56 | 4 |
| 2002 | 8 | 175 | 0 | 66 | 67 | 43 | 6 |
| 2003 | 4 | 168 | 3 | 75 | 49 | 62 | 3 |
| 2004 | 2 | 176 | 2 | 84 | 61 | 41 | 0 |
| 2005 | 8 | 178 | 1 | 83 | 56 | 35 | 4 |
| 2006 | 9 | 178 | 0 | 59 | 63 | 54 | 2 |
| 2007 | 12 | 170 | 0 | 68 | 58 | 50 | 7 |
| 2008 | 11 | 165 | 9 | 60 | 49 | 65 | 7 |
| 2009 | 3 | 183 | 3 | 64 | 62 | 50 | 0 |
| 2010 | 1 | 162 | 6 | 63 | 52 | 68 | 13 |
| 2011 | 1 | 191 | 0 | 71 | 53 | 46 | 3 |
| 2012 | 7 | 153 | 1 | 78 | 47 | 60 | 17 |
| 2013 | 15 | 177 | 4 | 57 | 56 | 53 | 3 |
| 2014 | 3 | 173 | 1 | 77 | 63 | 40 | 8 |
| 2015 | 14 | 149 | 1 | 64 | 50 | 54 | 11 |
| 2016 | 9 | 150 | 3 | 76 | 39 | 56 | 21 |
| 2017 | 5 | 173 | 4 | 58 | 47 | 67 | 6 |
| 2018 | 0 | 165 | 3 | 65 | 64 | 52 | 8 |
| 2019 | 2 | 187 | 0 | 46 | 61 | 68 | 1 |
| 2020 | 4 | 176 | 1 | 58 | 48 | 71 | 6 |

**Supplementary Table S4: Enthalpy days based on mean daily conditions (1987-2020) Example from Damascus International Airport, Syria, WMO 400800 3.412 °N Long: 36.516 °E, 616m elev, Standard pressure 94.14 hPa. Relates to Supplementary Fig.S4b.**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| YEAR | Enthalpy-days hD (reference 58.2 J/g) | leastEv | minEv | averEv | maxEv | bestEv |
| 1987 | 13 | 22.03 |  | 37.43 | 46.36 | 49.85 |
| 1988 | 18 | 12.41 |  | 33.09 | 42.35 | 44.94 |
| 1989 | 0 |  |  |  |  |  |
| 1990 | 0 |  |  |  |  |  |
| 1991 | 2 | 13.65 |  | 31.49 | 42.46 | 45.47 |
| 1992 | 5 | 18.64 |  | 34.24 | 43.97 | 45.21 |
| 1993 | 4 | 18.97 |  | 30.53 | 42.98 | 45.76 |
| 1994 | 1 | 21.21 |  | 33.86 | 43.29 | 43.29 |
| 1995 | 0 |  |  |  |  |  |
| 1996 | 24 | 19.4 |  | 35.4 | 45.57 | 48.67 |
| 1997 | 6 | 19.11 |  | 35.46 | 44.94 | 46.43 |
| 1998 | 45 | 18.93 | 18.93 | 36.87 | 46.57 | 50.66 |
| 1999 | 4 | 22.3 |  | 36.74 | 45.83 | 47.6 |
| 2000 | 14 | 21.71 |  | 36.49 | 46.2 | 49.76 |
| 2001 | 7 | 23.19 |  | 37 | 47.02 | 47.67 |
| 2002 | 7 | 22.33 |  | 38.99 | 46.29 | 49.17 |
| 2003 | 1 | 24.07 |  | 38.66 | 47.46 | 48.54 |
| 2004 | 0 |  |  |  |  |  |
| 2005 | 3 | 22.29 |  | 36.48 | 45.83 | 47.5 |
| 2006 | 4 | 26.3 |  | 37.16 | 44.38 | 46.15 |
| 2007 | 19 | 22.04 | 22.94 | 35.46 | 44.57 | 48.2 |
| 2008 | 28 | 22.02 | 22.45 | 33.37 | 43.91 | 48.98 |
| 2009 | 0 |  |  |  |  |  |
| 2010 | 39 | 22.93 | 24.1 | 38.36 | 47.04 | 50.33 |
| 2011 | 2 | 21.4 |  | 36.14 | 46.25 | 49.43 |
| 2012 | 48 | 22.2 |  | 35.81 | 44.81 | 50.37 |
| 2013 | 3 | 24.19 |  | 37.23 | 45.54 | 47.87 |
| 2014 | 16 | 20.87 |  | 35.35 | 44.62 | 47.84 |
| 2015 | 26 | 14.91 |  | 36.23 | 45.67 | 51.88 |
| 2016 | 67 | 16.51 | 18.42 | 33.83 | 44.42 | 48.26 |
| 2017 | 8 | 26.92 |  | 38.84 | 47.78 | 51.99 |
| 2018 | 13 | 20.29 |  | 35.07 | 44.74 | 46.9 |
| 2019 | 0 | 23.75 |  | 34.6 | 46.09 | 47.89 |
| 2020 | 19 | 21.87 |  | 40.55 | 48.73 | 51.28 |

**Supplementary Table S5**: **WBGTsmax maximum daily conditions in shade (1987-2020) Damascus International Airport, Syria, WMO 400800 3.412 °N Long: 36.516 °E.**

**Relates to Supplementary Fig.S4d and summarizing Main Text Fig.1a.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Warning Flags ref max daily T (°C) | White | Green | Yellow | Red | Black |
| YEAR | colder | >=15.0 | >=20.0 | >=25.6 | >=27.8 | >=29.4 | >=31.1 | >=32.2 |
| 1987 | 156 | 66 | 117 | 20 | 6 | 0 | 0 | 0 |
| 1988 | 137 | 67 | 102 | 35 | 0 | 0 | 0 | 0 |
| 1989 | 120 | 79 | 128 | 25 | 0 | 0 | 0 | 0 |
| 1990 | 137 | 74 | 128 | 20 | 1 | 0 | 0 | 0 |
| 1991 | 128 | 81 | 132 | 23 | 0 | 0 | 0 | 0 |
| 1992 | 150 | 73 | 126 | 17 | 0 | 0 | 0 | 0 |
| 1993 | 136 | 71 | 135 | 23 | 0 | 0 | 0 | 0 |
| 1994 | 127 | 71 | 143 | 23 | 0 | 0 | 0 | 0 |
| 1995 | 144 | 70 | 114 | 34 | 0 | 0 | 0 | 0 |
| 1996 | 149 | 50 | 120 | 39 | 8 | 0 | 0 | 0 |
| 1997 | 152 | 46 | 147 | 18 | 1 | 0 | 0 | 0 |
| 1998 | 119 | 84 | 100 | 49 | 10 | 3 | 0 | 0 |
| 1999 | 133 | 67 | 123 | 39 | 2 | 0 | 0 | 0 |
| 2000 | 147 | 69 | 102 | 40 | 8 | 0 | 0 | 0 |
| 2001 | 117 | 90 | 122 | 30 | 6 | 0 | 0 | 0 |
| 2002 | 135 | 77 | 125 | 25 | 3 | 0 | 0 | 0 |
| 2003 | 151 | 43 | 127 | 40 | 3 | 0 | 0 | 0 |
| 2004 | 126 | 79 | 145 | 16 | 0 | 0 | 0 | 0 |
| 2005 | 148 | 64 | 120 | 33 | 0 | 0 | 0 | 0 |
| 2006 | 144 | 65 | 120 | 36 | 0 | 0 | 0 | 0 |
| 2007 | 152 | 43 | 135 | 32 | 2 | 1 | 0 | 0 |
| 2008 | 130 | 84 | 107 | 40 | 5 | 0 | 0 | 0 |
| 2009 | 140 | 77 | 124 | 24 | 0 | 0 | 0 | 0 |
| 2010 | 110 | 80 | 116 | 47 | 11 | 1 | 0 | 0 |
| 2011 | 162 | 54 | 115 | 33 | 1 | 0 | 0 | 0 |
| 2012 | 135 | 59 | 118 | 42 | 9 | 0 | 0 | 0 |
| 2013 | 125 | 85 | 107 | 46 | 2 | 0 | 0 | 0 |
| 2014 | 119 | 84 | 120 | 38 | 4 | 0 | 0 | 0 |
| 2015 | 130 | 49 | 116 | 39 | 8 | 1 | 0 | 0 |
| 2016 | 117 | 84 | 91 | 48 | 14 | 0 | 0 | 0 |
| 2017 | 128 | 82 | 86 | 55 | 9 | 0 | 0 | 0 |
| 2018 | 116 | 74 | 123 | 41 | 3 | 0 | 0 | 0 |
| 2019 | 146 | 54 | 118 | 46 | 1 | 0 | 0 | 0 |
| 2020 | 127 | 72 | 98 | 56 | 7 | 4 | 0 | 0 |

Notice in psychrometric charts (main article Fig.3c and Fig.1a) that the multitude of parallel diagonal single black lines are wet-bulbs, and that 19.4°C Thumid basis of enthalpy-days would be between the 19° and 20° lines. This is clearly the upper limit of evaporative cooling days marked in blue on panel d HVAC preferences. Forced ventilation cooling days (marked in green) straddle the area where Thumid approaches the saturation curve, indicating that if air-conditioning were installed and locked into operation without fresh air ventilation then there would be a dehumidification duty that could be estimated in terms of wet-bulb degree days with Thumid as the base, or enthalpy-days as explained.

Graphical presentations of annals (Supplementary Fig.S4a-S4d) are summarized in Supplementary Tables S2 through S5. Heating and cooling degree days are plotted (Fig.S4a) with more information in Table S1. Estimates of the percentage savings “shedded” that could be available from adiabatic cooling condensers are presented (Supplementary Fig.S4b and Supplementary Table S2). The interface between green and yellow denotes the “average mean” each year could be factored into the enthalpy-days demand in situations where air-conditioning would have been installed and locked-in. The average saving percentage at the time of daily maxima is denoted “average peak” between yellow and red, while the greatest moment each year is denoted “best shed” at the upper limit of red colour (Fig.S4b). The average of daily minima each year is denoted as “average low”, while the worst moment each year is denoted “low shed” between the lower white area and either the sliver of blue or the green area where blue is absent (Fig.S4b).

Total heating and cooling degree days are compared, year-by-year (Fig.S4a), demonstrating a predilection for an increase in demand for cooling in summer while demand for heating in winter has decreased (H~>C) over the 34 years. On-line materials[26] include linear regression analysis of trends of heating and cooling degrees, enthalpy-days, DX-air-conditioning-days, and WBGTs white- and yellow- (or worse) flag-days at all locations with at least 14 years of observations.

HVAC preferences and WBGTs flags (Fig.S4c and S4d) summarized in Tables S3 and S4 suggest trends, but these were not as consistently significant as heating and cooling degree days. An observation is that thresholds of white- and green-flag WBGTs is comparable to the call for DX cooling among daily HVAC preferences. This is understandable comparing psychrometric charts (main article Fig.3c and Fig.1a), where the same daily data are plotted, comparing daily maximum WBGTs stress flags with daily mean HVAC preference. The proportion of the swarm of data points divided by the threshold of daily maximum white-flag WBGTs is generally similar to the proportion divided by the daily mean Thumid (19.4°C wb). This confirms that DX air-conditioning is a reasonable expectation when well shaded ventilated shelters cannot avoid stressful occupational conditions.

**S.6 Global Summary of the Day (GSOD) compared with hourly data**

Daily observations of minimum and maximum temperature[30] annals are abundantly longer than hourly observations, but the latter have been improving as automatic weather stations have been deployed around the world[59], with the greatest resolution available in the last decade.

Damascus’ airport is used as a case study example (Fig.S4) to compare daily analysis across years 1987-2020. Presentation of month-by-month analysis of year 2020’s hourly WBGTs (Fig.S5a, S5c) and HVAC preferences (Fig.S5b, S5d) develop in clocks that have been iconized on maps to compare with other stations in the region (Fig.S5e, S5f).

Stacked polar histogram ***seasonal clocks*** are introduced (Fig.S5c and S5d) to map month-by-month analysis of year 2020’s hourly data from Damascus’ airport (Fig.S4c and d) in comparison with concurrent observations at nearby stations in geographically neighboring countries. Seasonal clocks are arranged clockwise with January commencing at the top. Seasonal clocks and are subject to interannual variability[60], and so only year 2020 data was presented. Mapped monthly clocks’ radial axis for WBGT (Fig.S5c) was cut-off at the inner seventh of each month, to emphasis heat stress events – notionally the worst 24 hours each week. Mapped monthly HVAC clocks of radially summaries all hours of each month (Fig.S5d).

**** **Supplementary Fig.S5: Damascus 2020 hours/month and seasonal clocks in nearby Lebanon**

**S5a)** Hourly WBGT shade stress flags hourly by month.    **S5b)** Hourly HVAC preference by month.

**S5c)** Damascus seasonal clocks year 2020 hourly analysis of HVAC.

**S5d)** Damascus seasonal clocks year 2020 hourly analysis of WBGTs.

**S5e)** Map of Lebanon and Damascus with seasonal clocks of year 2020 hourly analysis of HVAC.

**S5f)** Map of Lebanon and Damascus with seasonal clocks of year 2020 hourly analysis of WBGTs.

****** ***Supplementary Fig.S6***: Damascus’ airport July 2020 comparison ISD hourly and GSOD daily data

WMO stations provide much more data than has been registered in GSOD, but it has been a lumpy progression from manual observation mid-morning with ‘thrown back’ observation of the previous days’ minimum and maximum with a registering thermometer. Airport stations had provided 3-hourly observations, with gaps during unmanned segments of the diurnal cycle, until automatic weather instrumentation become a more prevalent source. In order to increase confidence in the continuing annals of daily observations it is possible to compare the latest with recently available hourly datasets NCDC Integrated Surface Database (ISD)[59].

Year 2020 GSOD daily and ISD hourly dry-bulb and dewpoint temperatures from Damascus’ airport meteorological station (WMO 400800) are superimposed for comparison (Fig.S6). It is clear that GSOD mean daily mean adopts observation at 9 AM, which appears to be a reasonable approximation of average diurnal patterns revealed by the ISD dataset.

**S.7 Repository** **doi.org/10.5518/967**

Detailed methodological steps of the research can be deciphered from Matlab scripts used.

On-line material [26] is provided Creative Commons 4.0 at doi.org/10.5518/967 from which maps, charts, and summary statistics can be derived also includes the following output:

RESULTSstats\_1987-2020.csv (n=16,582 records)

RESULTSrates\_1987-2020.csv (n=16,582 records)

RESULTSout\_1987-2020.csv (n=16,582 records)

Geography.csv (n=16,582 records), which contains information extracted from geographical datasets[4, 13-15] intersected with those stations locations which specified latitude and longitude coordinates.

Also available are input files:

placenames.txt

stations.txt

isd-history\_2021.csv (adaptation ftp://ftp.ncdc.noaa.gov/pub/data/noaa/isd-history.txt)

WB\_2021\_u\_.m (main Matlab script)

psych.m function[wbC H20]= psych(dbC, dpC, stPa)

H2O\_psych.m function H2O = H2O\_psych(dbC, dpC, stPa)

WBloop\_2021\_u.m function[ASHRAEcz, timeframe, HDDstats, CDDstats, ChDstats,

 WBGTstatsW, WBGTstatsY, DXstats, PC, savings, Basis]

= WBloop\_2021\_u(WMO,WBANo, startyear)

k\_stats2.m (post-processing Matlab script yielding main article Tables 2, 3 and 4)

For example, of any one station results, Syrian capital Damascus’ airport (WMO 400800), from RESULTSrates\_1987-2020.csv [26] contains five statistics relating to heating degree days:

[HdD18=1464, std\_H=166, slope\_H=-10.12, SEE\_H=134, HDD18=1297]

HdD18, the long-term average HDD18.3°C was 1463°·days pa, while slope\_H -10.12°·days pa² with an interannual standard estimate of error SEE\_H 134°·days pa. HDD18 linear regression at end of timeline is estimated as 1297°·days pa since the pVal\_H<0.05 as found in accompanying file RESULTSrates\_1987-2020.csv and so rejects the null hypothesis of a stationary climate.

[adjR2\_H=0.349, ob\_H=34, pVal\_H=0.0001, DuWa\_H=2.543, pVDWH=0.149]

Thus, the HDD at Damascus’ airport circa year 2020 can be estimated as HDD18 ± SEE\_H (1297±134°·days pa). If the p-value had been greater than 0.05 then HDD18 would have been reported as constant estimate plus standard deviation HdD18+Std\_H = 1630°·days pa. But the 34 years of observations and D-W statistics do not suggest auto-correlation, and so the reduction of winter heating demand at this locale is persistant.

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