The Creation of Wind Speed and Direction Data for the Use in Probabilistic Future Weather Files

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Abstract

Pseudo weather data with a high temporal resolution are of use in many fields including the modelling of agricultural systems, the placement of wind turbines and building thermal simulations. With the publication of the 2009 UK Climate Projections (UKCP09) such data can be created for future years and for various predictions of climate change. Unfortunately such—UKCP09—data does not include information about wind speed or direction due to a lack of robustness. Here we demonstrate a methodology for generating such wind data on an hourly time grid from a consideration of the potential evapotranspiration (PET) reported by the UKCP09 weather generator and information related to the correlation between observed wind speed, direction and time of year. We find our pseudo wind data is consistent with the historic observed wind. Furthermore, when used within a dynamic thermal simulation of a building, the use of such pseudo wind data

generates a consistent internal environmental in terms of ventilation rates, temperatures and energy use that is indistinguishable from simulations completed using historic observed weather for both single sided and cross ventilated buildings.

Practical Implications

The methodology presented in this paper will allow academics and buildings engineers to create realistic hourly wind speed and direction data for inclusion with the future climate data of UKCP09. This will allow the creation of consistent future weather years for use in areas such as building thermal simulation.

Introduction

Predictions of the world's climate point to an increasingly warmer world, with greater warming across land and away from the equator[1]. Predictions contained in the Intergovernmental Panel on Climate Change’s (IPCC's) fourth assessment report indicate projected mid-latitude mean temperature rises over land of ~4 °C (under the A1FI scenario)[1] and recent research[2] shows that current emission trends imply that the actual temperature increase could be far higher than the A1FI scenario suggests. This implies that several highly populated regions not used to high temperatures could be exposed to a very different summertime experience. As the events in Paris in 2003 showed, temperature rises and reductions in the range of the diurnal cycle within the built environment can have life-threatening consequences and require a substantial response from emergency services[3]. Based on the historical climate, temperatures such as those seen in Europe in 2003 have been estimated to be 1-in-1000 year events. However, modeling by the Hadley Centre shows that, projected anthropogenic climate change could make temperatures like a 2003-type summer about average by 2040[4]. This will clearly have a great impact on the energy consumption of air conditioned spaces and the thermal comfort of non-conditioned ones. It is likely that one of the strategies that will be deployed to prevent overheating is an increase in ventilation rate. For many buildings, the amount of airflow through them depends on the wind speed, and to a lesser extent the wind direction. There is therefore the need to model buildings with weather files that not only represent future temperatures but also include wind speed and direction.

The Creation of Future Weather Files

Given statements of future climate by the IPCC and others[5] a time series of typical future weather can be assembled in one of several ways, for instance by using recorded historical data for locations whose current climate matches that predicted for the location in question. This has the downside that certain weather variables, such as solar angle and hours of daylight, will be incorrect. Other methods include interpolating (in space and time) the time series produced by a global circulation model, or to run a high resolution (in space and time) regional climate model embedded within a global circulation model. All these methods have advantages and disadvantages, which are discussed in more detail by Belcher *et al.*[6]

Belcher *et al.*[6] developed a methodology for transforming historic weather files into future weather years (time series) representative of different climate change scenarios by the use of a set of simple mathematical transformations. The simplicity of this method has made it attractive to building scientists. In this method hourly weather data for the current climate is adjusted with the monthly information provided by climate scenarios derived from a regional climate model (in the case of the UK, the output from UKCIP02[7]). This methodology is commonly termed 'morphing'.

The morphing process has the advantage that it starts from observed weather from the location in question, the variables output are likely to therefore be self-consistent and it is relatively simple to undertake given the resources available to building scientists. However, it doesn't allow for fundamental changes in the weather, with for example, weather systems following alternative trajectories across the landscape than they historically have but this is an area of the climate science where there is considerable uncertainty. Another approach, and the one used as part of the latest set of climate change projections for the UK UKCP09[8], uses the projected future time series (i.e. the UKCP09 weather generator that is capable of producing hourly time series (i.e. the UKCP09 weather generator works at the daily time step, but these outputs can be disaggregated to produce hourly outputs). The weather generator can produce a large number of time series of plausible hourly weather variables for a location, it is calibrated based on historical observations and perturbed using the change factors from UKCP09. Statically representative, or extreme, periods of weather can then be selected by using an appropriate statistical method.

UKCP09 uses data from a range of climatic models to build up a probabilistic set of projections[9]. The UKCP09 weather generator allows the creation of many future weather files indicative of a future 30-year period under a particular emissions scenario. The different emissions scenarios represent a set of comprehensive global narratives that define local, regional and global socio-economic driving forces of change[10]. Each weather file will have different weather patterns and a different climate chosen from the probability density function of different climatic futures. This probabilistic approach rather than a deterministic one allows for a risk-based analysis by performing simulations using many equi-probable future weather files. Many uses of future weather files where a risk-based analysis would be useful such as the thermal simulation of building designs and wind turbine placement require information about the wind field. However, no representation of future wind is included in the UKCP09 weather generator. This is because there is considerable variation in the changes projected by the many climate models considered in the process of creating the projections with little consistent evidence of a systematic change in wind speed.

Wind speed is considered within the mathematics of the UKCP09 Weather Generator where it is used in the creation of the potential evapotranspiration (PET), but it is not an output. This is unfortunate because, for building scientists and engineers operating under various national building regulations and codes there is the need to model naturally ventilated buildings with a wind field that is consistent with the other weather variables that the building is subjected. This consistency is important because peak external temperatures in the summer, for example, are correlated with low wind speeds and therefore with an inability to cool buildings via increased ventilation.

In this paper we demonstrate a methodology for obtaining such wind data on an hourly time scale using the PET variable reported by the UKCP09 weather generator and incorporating the correlation between historically observed wind speed, direction and time of year taken from the period 1961-1990[5] corresponding to a location closest to the UKCP09 5km grid reference point). (PET is the daily estimate of evapotranspiration (sum of evaporation and plant transpiration) from a hypothetical reference crop to the atmosphere.)

The creation of mean daily wind speed from PET

Based on the probabilistic projections developed in UKCP09[10] a stochastically based weather generator has been produced by Newcastle University and the University of East Anglia and its partners to provide high resolution time series of plausible weather data on a 5 × 5 km grid for future 30-year time periods. The weather generator firstly produces a stochastic representation of rainfall from which weather variables of mean daily temperature, diurnal temperature range, vapour pressure and sunshine duration are generated maintaining the historically observed relationships between the variables. From these variables the direct and diffuse solar radiation, relative humidity and PET are calculated. Using temporal disaggregation, based on observations, the daily values are transformed into an hourly time series while maintaining the daily statistics.

The calculation of PET is based on the Food and Agriculture Organisation's modified Penman method as outlined by Ekström[11]. The PET is defined as the potential evapotranspiration from a clipped grass surface 0.12 m in height and is given by the equation,

eqn. 1
$$\mathrm{PET} = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T + 273.16} U_2\left(e_a - e_d\right)}{\Delta + \gamma\left(1 + 0.34 U_2\right)},$$

where R_n is the net radiation at the crop surface, G is the soil heat flux, T mean temperature, e_d is the actual vapour pressure, e_a is the saturation vapour pressure at the air temperature (T), Δ is the slope of the saturation vapour pressure curve with temperature, γ is the psychrometric constant and U_2 is the mean daily wind speed at 2 m. The constants 900 and 0.408 represent the coefficient of the crop and wind coefficient for the reference crop respectively, in this case clipped grass. Each of the weather variables are taken at a reference height of 2 m. The temperature and actual vapour pressure are direct outputs from the UKCP09 weather generator while net radiation, soil heat flux, slope of saturation vapour pressure and vapour pressure deficit ($e_a - e_d$) can be calculated. Due to the non-linearity of the relationship between saturation vapour pressure and temperature, the mean daily saturation pressure is calculated as the mean of the saturation pressure at the daily minimum and maximum temperature. Rearranging equation 1, an expression for the mean daily wind speed consistent with the other variables can be calculated given by the equation,

eqn. 2
$$U_2 = \frac{0.408\Delta(R_n - G) + \mathrm{PET}(\Delta + \gamma)}{\gamma \frac{900}{T + 273.16}(e_a - e_d)\Delta + 0.34\gamma\,\mathrm{PET}} .$$

To demonstrate the validity of this method, weather files with a known wind field can be used to generate the PET. This value of PET can then be used to reconstruct wind speed and compared to the known value. This is not as tautological as it might sound because, within the UKCP09 weather generator the PET is truncated at 0 (PET can not be negative) and is calculated with an accuracy of only two decimal places.

There are two causes of error within the procedure. Firstly when the PET is calculated to be below 0 mm day^{-1}, it is truncated at 0 mm day^{-1}. This mainly occurs when the relative humidity is at 100 % and mainly in the winter. The calculated wind speed in this case represents the wind speed, which is required to give a PET of exactly 0 mm day^{-1} regardless of the true value. If the calculated wind speed is calculated to be below that found historically the data point is kept to not prejudice against the case of a given wind speed producing low or zero PET, else, it is recorded as missing. Secondly, when the differential of PET with respect to wind speed is high, the calculation is not precise. This is because two decimal places, as reported by the UKCP09 weather generator, are not sufficient to give an accurate wind speed since very small changes in PET create very large changes in the calculated wind speed if the differential is large. In this case the wind speed is recorded as missing regardless of the calculated value. In each of the two cases accuracy can be improved by linearly interpolating the missing wind speed from the previous data point to the next.

Figure 1 shows the calculation of mean daily wind speed against the observed wind speed for three Chartered Institute of Buildings Services Engineers' (CIBSE)[12] Test Reference Years (Plymouth, London and Heathrow) created from observed hourly data with 1095 days in total. The data shows a clear linear trend with very few outliers. In total 94% of the data is within 5 % of the observed mean daily wind speed and 97% of the data is within 10 % while linear regression to the data using a least squares fit for each location gives a gradient very close to 1 (1.001 for Plymouth, 1.002 for Heathrow and 0.991 for Manchester) and R^2 values greater than 0.99 demonstrating the goodness of fit. In total only two data points required interpolation and the majority of the scatter is due to PET being output with only two decimal places.

Temporal downscaling of the wind speed

The hourly time series output by the weather generator, although consistent with the daily weather, does not include hourly PET and hence the mean daily wind speeds calculated using PET need to be temporally downscaled to generate an hourly time series.

There are several methods that could be used to generate an hourly wind signal. It is possible to generate a wind speed time series by rolling a dice to determine a probabilistic wind speed dependent on the generated hourly variables and observed weather i.e. a wind field probabilistically consistent with the other weather variables. Unfortunately this method would require knowledge of a relationship between how the future storm tracks relate to the future weather. There is no current consensus[9] for how the UK the wind speed is likely to change in the future with considerable variation in the changes projected and little consistent evidence of a systematic change in the wind speed for the UK where the effects of climate change on wind speed will be masked by the wide range of natural variability in the wind field. In fact it is found that there is little correlation between the historically observed mean daily wind speed and the mean average temperature in the UK, as shown in figure 2. For example, in the winter, low wind speeds can be observed at low temperatures caused by an anticyclone bringing prolonged clear skies combined with longer nights cooling the land. Alternatively cyclonic weather patterns can cause strong northerly winds to carry cold air masses from the Artic. However, there are clear differences in the shape of the distribution for the each of the different seasons. In the summer (June, July and August) there are fewer occurrences of strong winds (greater than 10 ms^{-1}) at high temperatures (greater than 19 °C) where as in the winter (December, January and February) there are fewer occurrences of strong winds at low temperatures (below 0 °C) although both situations will be caused by high pressure systems. Similarly no trend is found between wind speed and temperature in the seasons Autumn and Spring (not displayed).

An alternative method for downscaling wind speeds and the one used in this paper is to use an observed hourly wind signal to produce a realistic wind pattern corresponding to the generated mean daily wind speed. For this method, observations of wind speed from the base period (1961 to 1990)[13] corresponding to a location closest to the UKCP09 5km grid reference point, are grouped by mean daily wind speed and season. These observations are compared to the mean daily wind speed calculated by the PET calculation given in eqn. 2. Assuming that daily to hourly relationships would not change in the future, the set of 24 (hourly) observations of wind speed which has a mean closest to the daily wind speed derived from PET values, is then assumed to best represent the hourly wind speed at that location for that day. This is represented as the set for which a_j is smallest given by

eqn 3. $$\left[\left(\sum_{i=1}^{24} W_{Obs}^{ij}\right) - W_{PET}\right]^2 = a_j,$$

where $W^{ij}{}_{Obs}$ is the observed wind speed on day j and hour i and W_{PET} is the calculated daily mean wind speed. In the case of more than one observed set generating the same value of a, and therefore being an equally good fit, the 24-hour series is selected randomly from the set of equally good observations. In the case of missing data points in the observed historic time series, only days with more than eight readings are used with all missing data linearly interpolated to create a full 24 hour sequence.

The creation of wind direction

Dynamic thermal models of buildings such as the Integrated Environment Solutions Virtual Environment[14] require the wind direction as well as the wind speed. Unfortunately, the UKCP09 weather generator also does not provide any information about wind direction. Without knowledge of the pressure systems, which are dominating the generated weather on a spatial and temporal basis, the wind direction is impossible to calculate from first principles. Instead our approach is to insert a probabilistic wind direction, based on historical observations from the period 1961-1990, which corresponds to the hourly weather signal, specifically, the season and the hourly wind speed. The North Atlantic Ocean Circulation (Gulf Stream) is likely to weaken in the future under increasing greenhouse gas emissions but has not been modelled to produce a complete or abrupt shutdown[9]. The weather in the UK is likely to be dominated by similar pressure systems in the future so we assume that inter-variable relationships from current observations can be considered a valid representation of the future weather patterns.

The wind direction is inferred by using observations to determine a probabilistic distribution relating wind direction, wind speed and season. Every six hours the wind direction is randomly generated from the hourly wind speed and season constrained by the observed distribution. All other hours are then linearly interpolated to create an hourly signal. The value of six hours has been chosen as a compromise to allow the wind direction to change frequently but also to prevent large inter-hour changes and is based on a spectral analysis of observed wind data. The complete temporal downscaling wind speed and direction method is illustrated in the flow diagram shown in figure 3.

Statistical comparison of pseudo wind and observed wind

In order to test the validity of our method for creating pseudo wind fields we need to compare it to historical observations. To do this, 15 versions of the

Plymouth Test Reference Year (TRY), which is based on observed data[15] were created. Each version contained a pseudo wind field calculated using the methodology outlined in this paper. These pseudo test reference years were then compared to the original TRY.

Due to a lack of observations (approximately 2700 per season) the observed wind speed time series is selected randomly from observed mean daily wind speeds that are within 10% of the calculated wind speed. This method allows for the error in the calculation procedure, as discussed above. The majority of the results are found to be within this 10% margin as demonstrated in figure 1. This method also ensures that the same wind speed is less likely to be selected for the same calculated mean daily wind speed twice, although, for higher wind speeds there are fewer observations available as shown by figure 2 being the only limited factor. Since the method is based on a random selection from possible observed hourly wind speed and wind direction, it increases the likelihood of a different wind field being produced each time the method is used.

Figure 4 shows that in each case the created wind speed contains most of the features of the original TRY. The corresponding statistics are displayed in Table 1. For each of the 15-pseudo weather files the mean annual pseudo wind speed is found to correlate well with the original weather file within an error margin of less than 2%, however, it is found that the annual pseudo wind speed is generally underestimated. This is because of the selection procedure. For larger wind speeds, there are more observations 10% below the calculated mean speed than above, giving a bias towards a lower value.

Although over the whole year this effect is small. This error could be reduced if a lower tolerance is used (e.g. 5%) or more observations were available. It is also found that the standard deviation of the created wind speed is within 3% of that of the original file. Since a complete 24-hour set of historic wind observations is used to replace the daily mean, the distribution should be very close to that of the original file and in fact both the f and T statistics show that the differences in the distributions are not statistically significant. Table 1 shows that there is a large difference on an hourly time scale with a mean difference of the order of 2 ms^{-1}. On a daily scale however, the mean difference is under 0.4 ms^{-1} and on a monthly scale the mean difference is only 0.12 ms^{-1}. This is as expected as the wind speed in the TRY are only a single statement of the possibilities of the wind speed in a particular hour. Over a longer time scale (daily or monthly) these differences are negligible.

The distribution of wind direction for both the original TRY and all artificial TRYs is shown in Figure 5. Although there are some minor differences, the artificial wind direction matches the test reference year wind direction well– replicating the prevailing wind as well the peak around 90°. The differences are because the TRY is an observed snap shot of the natural variability in the wind climate whereas the artificial wind direction is a statistical representation of the whole observational base climate. Also, for simplicity our method assumes one hour is not dependent on the previous so the interpolation does not follow the same statistical trend. However, the differences are not statistically significant and both distributions can be considered as sampled from the whole base period. Also, for the purpose of building simulation in the UK, the distribution of wind direction has relatively little effect on the energy use or over heating risk since the overall proportion of winds coming from any one direction is small. For example the wind speed of the test reference year has a 35 % chance of occurring from a south westerly direction (between South and West) as shown by figure 5 implying that the wind direction is more likely to not come from the prevailing wind.

We can see that the 15 complete artificial wind fields match well with the wind field of the TRY. Figure 4 shows that, as expected, although the calculated wind speed is different at any given time to the TRY, all 15 calculated wind speeds follow the general trends of the TRY and Figure 5 shows that the 15 artificial wind directions create a wind rosette comparable to the original TRY. The Test Reference Year is merely a snapshot of the possible wind direction distribution where as the 15 artificial wind direction contains information from the whole 1961-1990 period a hence we would not expect the match to be better than that demonstrated.

Comparison of pseudo wind and observed wind within a thermal model

Although our method has been validated against observations with the distributions of wind speed and wind direction matching well with the modelled values, the instantaneous values can vary dramatically. To provide a further test of our wind downscaling method, the 15 weather files used above were compiled into a format read by common building simulation software. Simulations of a set of buildings using the 15 files and TRY were then compared to check if the calculated wind field produces results consistent with the TRY for modelled internal airflows using an industry standard dynamic thermal modelling program (IES). The purpose of this is to examine if the instantaneous differences in wind speed and direction have adverse affects on the results produced by a building thermal simulation. In the UK the majority of buildings are naturally ventilated with either single sided or cross ventilation. Hence, wind speed and to a lesser extent direction can have a profound effect on the internal temperatures and human comfort levels within buildings. All the models include dynamic opening of windows based upon internal temperatures and occupancy. Airflow through window openings is calculated using a zonal airflow model to calculate bulk air movement in and through the building (Macroflo), driven by wind and buoyancy induced pressures across the building. For cross-ventilated building designs the airflow through window openings is highly dependant upon the calculated wind pressure differential across the building, this requires knowledge of both wind speed and direction. For single sided ventilation designs airflow through an opening is governed by turbulence, and is dependent on the temperature gradient across the opening and wind speed. For single sided ventilation the wind direction has little effect. Dynamic thermal simulations were carried out for two houses, an office block, a set of apartments and a secondary school. Details of these constructions can be found in the appendix.

Table 2 shows the averaged maximum and averaged mean values of the simulated airflow (ls^{-1}) for the 15 artificial wind fields in the different thermal models, the values for the TRY are also shown for comparison. While the percentage difference in the maximum airflow is up 25%, the mean differences are seen to be very small (< 6%). To explore this effect further the variation in the mean and maximum airflow for all the rooms within the secondary school for the 15 artificial wind fields and the TRY are shown in Figure 6. The maximum airflow varies from -12.5% to +15.2% but this is a measure of the maximum instantaneous airflow and it demonstrates the natural variability. Alternatively the mean airflow varies from -2.5% to +1.3% demonstrating that the average airflow is consistent. The instantaneous differences are simply due to differences on an hourly scale. However, by comparing the mean airflow over an entire year these instantaneous differences average out to give a near identical internal environment.

Figure 7 shows airflow within an open plan office space (10 m × 7.5 m) within an office block. Internal gains within the space are provided by the 10 occupants, computers (15 W/m^2) and lighting (12 W/m^2) the ventilation is of a single sided design through large window openings along the long axis of the office. Similarly Figure 8 shows airflow through a cross-ventilated classroom (8.4 m × 6.4 m) within the secondary school for the 15 artificial wind fields and the TRY. During occupied hours the windows are opened to control CO_2 levels within the teaching spaces and internal gains are provided by the 30 occupants and lighting (12 W/m^2). During the winter, heating maintains the internal temperature at 18°C. Figures 7 and 8 show that the artificial wind speed and direction produce airflows within the building spaces consistent with the TRY for both single-sided and cross-ventilated spaces. In both cases the internal air temperatures show good correlation, indicating that the artificial wind fields are suitable for use with building thermal simulation software. It is also found that all 15 wind fields produce a total heating energy consumption within 2.8% for the school and 2.6% for the office compared with the TRY over the entire year demonstrating the procedures usefulness when considering overheating risk and energy use predictions for future weather simulations. Similarly for house 1 the heating energy is within 6% of the TRY and both for house 2 and the apartments the heating energy is within 1% of the TRY. Although house 2 has the largest maximum difference compared to the TRY, the mean across the whole set of 15 files is within 0.76% showing the majority of the created weather files have similar heating requirements to that of the TRY.

In each case the variability of the created wind field is much smaller than the natural variability as shown by Figure 9. Here calculated airflows are for the open plan office used for figure 7, however the TRY is compared to the other 19 years of ‘real’ observed weather, which are used to compile the TRY (the list of years used can be found in table 4). Figures 7 and 9 show the same week of data and the airflow generated by the TRY is shown in red in both figures and the scale is the same. The natural variation of the internal airflow (and hence wind speed) generated by the 19 historical data sets is far greater than the variation of the 15 artificial data sets.

The TRY used was for Plymouth and is based on historical observations from the period 1983-2004. Some years such as 1991 contain missing data. Although, the available months were used to compile the TRY, the incompleteness means that these years have not been included in this table. Comparison of the statistics displayed in tables 3 and 4 again demonstrate that the natural variability between the 19 different observed wind fields and the resultant internal airflows for different years is much greater than that of the 15 calculated artificial wind fields within a TRY file and the resultant internal airflows with respect to the TRY. Table 4 shows that the difference in mean hourly airflow for the office is up to 11% compared to that of the TRY while for the difference for the 15 pseudo weather files is much smaller at 1%. The difference between the TRY and the base observed weather is generally a factor of 2 larger than the set of pseudo weather files. It is found that the difference between the TRY and other weather files airflow gets smaller as the timescale is increased from daily to weekly and then to yearly but the magnitude of the difference for the observed base set is generally much greater on all time scales. While the hourly means and standard deviations of the internal airflows caused by variation in the external wind field is comparable for the 15 artificial data sets and the 19 observed data sets, the variation is much smaller for the 15 artificial data sets if the maximum variation is considered on an hourly, daily or monthly scale.

Conclusions

In this paper we have shown that an artificial wind field on an hourly grid can be created from knowledge of the potential evapotranspiration and the use of historical observations of wind speed and direction. We have shown that this generated wind field is consistent with observations both statistically and when run through an industry standard dynamic building thermal simulation program. It is found that although the hourly variation is high, the natural variability of the wind is much greater than that of the wind field generated by our method when considered on a daily, monthly and yearly time scale. The methodology outlined in this paper allows a realistic hourly wind field to be created from the data output by the UKCP09 weather generator allowing this powerful tool to used for the creation of building simulation weather files.

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Appendix

Details of building designs used for thermal modeling:

House 1 Light weight timber frame design, Floor areas = 135.29 m^2, Ext wall area = 178.56 m^2, glazed area = 11.98 m^2.

Ground floor:- soil (0.75m), brickwork (outer leaf), cast concrete (0.1m), EPS slab (0.0635m), chipboard (0.025m), carpet (0.01m). U-Value = 0.2499 W/m^2K, SBEM thermal capacity 45.86 kJ/m^2K.

Ceiling/floor:- carpet (0.01m), chipboard (0.025m), cavity (0.25m), plasterboard (0.013m). U-Value = 1.2585 W/m2K, SBEM thermal capacity 10.37 kJ/m2K.

Internal walls:- plasterboard (0.013m), cavity (0.1m), plasterboard (0.013m). U-Value = 1.6598 W/m^{2}K, SBEM thermal capacity 10.37 kJ/m^{2}K.

External walls:- timber board (0.025m), cavity (0.09m), plywood (0.01m), mineral wool (0.075m), cavity (0.06m), plasterboard (0.013m). U-Value = 0.3364 W/m^{2}K, SBEM thermal capacity 10.37 kJ/m^{2}K.

Flat Roof:- U-Value = 0.2497 W/m^{2}K, SBEM thermal capacity 3.80 kJ/m^{2}K.

Glazing:- 4mm glass, 12mm cavity (argon), 4mm glass, U-Value (including frame) = 1.6453 W/m^{2}K

House 2 Heavy weight design, Floor areas = 135.29 m^2, Ext wall area = 178.56 m^2, glazed area = 11.98 m^2.

Ground floor:- soil (0.75m), stone chippings (0.15m), EPS slab (0.075m), cast concrete (0.15m), screed (0.01m), carpet (0.01m). U-Value = 0.2383 W/m^{2}K, SBEM thermal capacity 155.20 kJ/m^{2}K.

Ceiling/floor:- carpet (0.01m), cast concrete (0.1m). U-Value = 2.2826 W/m^{2}K, SBEM thermal capacity 97.02 kJ/m^{2}K.

Internal walls:- plaster (0.013m), concrete block (0.1m), plaster (0.013m). U-Value = 1.9306 W/m^{2}K, SBEM thermal capacity 83.06 kJ/m^{2}K.

External walls:- brickwork (0.1m), EPS slab (0.0625m), concrete block (dense) (0.1m), plaster (0.015m). U-Value = 0.3465 W/m^{2}K, SBEM thermal capacity 210.57 kJ/m^{2}K.

Flat Roof:- U-Value = 0.2497 W/m^{2}K, SBEM thermal capacity 3.80 kJ/m^{2}K.

Glazing:- 4mm glass, 12mm cavity (argon), 4mm glass, U-Value (including frame) = 1.6453 W/m^{2}K

Office Heavy weight design, Floor areas = 957.00 m^2, Ext wall area = 702.00 m^2, glazed area = 66.00 m^2.

Ground floor:- soil (0.75m), stone chippings (0.15m), EPS slab (0.075m), cast concrete (0.15m), screed (0.01m), carpet (0.01m). U-Value = 0.2383 W/m^{2}K, SBEM thermal capacity 155.20 kJ/m^{2}K.

Ceiling/floor:- carpet (0.01m), screed (0.05m), cast concrete (0.1m), cavity (0.25m), ceiling tile (0.01m). U-Value = 1.0687 W/m^{2}K, SBEM thermal capacity 3.80 kJ/m^{2}K.

Internal walls:- plaster (0.013m), concrete block (0.1m), plaster (0.013m). U-Value = 1.9306 W/m^{2}K, SBEM thermal capacity 83.06 kJ/m^{2}K.

External walls:- Vermiculite Insulating block (0.0585m), EPS slab (0.117m), concrete block (dense) (0.1m), plaster (0.015m). U-Value = 0.1937 W/m^{2}K, SBEM thermal capacity 210.57 kJ/m^{2}K.

Flat Roof:- U-Value = 0.2497 W/m^{2}K, SBEM thermal capacity 3.80 kJ/m^{2}K.

Glazing:- 4mm glass, 12mm cavity (argon), 4mm glass, 12mm cavity (argon), 4mm glass U-Value (including frame) = 1.2938 W/m^{2}K

Apartments (9 studio apartments and adjoining corridor), Floor areas = 1170.00 m^2, Ext wall area = 619.20 m^2, glazed area = 54.00m^2.

Ground floor:- soil (0.75m), stone chippings (0.15m), EPS slab (0.075m), cast concrete (0.15m), screed (0.01m), carpet (0.01m). U-Value = 0.2383 W/m^2K, SBEM thermal capacity 155.20 kJ/m^2K.

Ceiling/floor:- carpet (0.01m), cast concrete (0.1m). U-Value = 2.2826 W/m^2K, SBEM thermal capacity 97.02 kJ/m^2K.

Internal walls:- plaster (0.013m), concrete block (0.1m), plaster (0.013m). U-Value = 1.9306 W/m^2K, SBEM thermal capacity 83.06 kJ/m^2K.

External walls:- brickwork (0.1m), EPS slab (0.0625m), concrete block (dense) (0.1m), plaster (0.015m). U-Value = 0.3465 W/m^2K, SBEM thermal capacity 210.57 kJ/m^2K.

Flat Roof:- U-Value = 0.2497 W/m^2K, SBEM thermal capacity 3.80 kJ/m^2K.

Glazing:- 6mm glass, 12mm cavity, 6mm glass, U-Value (including frame) = 2.0713 W/m^2K

School, Floor areas = 11236.94 m^2, Ext wall area = 7648.02 m^2, glazed area = 846.67 m^2.

Ground floor:- soil (0.75m), stone chippings (0.15m), cast concrete (0.1m), EPS slab (0.09m), screed (0.05m), carpet (0.005m). U-Value = 0.2027 W/m^2K, SBEM thermal capacity 52.40 kJ/m^2K.

Ceiling/floor:- carpet (0.01m), cast concrete (0.1m), cavity (0.3m), acoustic tiles (0.02m). U-Value = 1.1592 W/m^2K, SBEM thermal capacity 20.56 kJ/m^2K.

Internal walls:- plaster (0.013m), brickwork (0.105m), plaster (0.013m). U-Value = 1.6896 W/m^2K, SBEM thermal capacity 79.20 kJ/m^2K.

External walls:- concrete block (0.1m), cavity (0.05m), paperboard (0.015m), glass fibre quilt (0.15m), chipboard (0.012m), plasterboard (0.013m), plastering (0.003m). U-Value = 0.2207 W/m^2K, SBEM thermal capacity 32.68 kJ/m^2K.

Flat Roof:- Aluminium (0.007m), glass fibre quilt (0.15m), steel (0.007m), cavity (0.3m), acoustic tiles (0.02m). U-Value = 0.2274 W/m^2K, SBEM thermal capacity 20.56 kJ/m^2K.

Glazing:- 6mm glass, 16mm cavity, 6mm glass, U-Value (including frame) = 19773 W/m^2K

References

1. Fourth Assessment Report. Intergovernmental panel on climate change. Avaiable from: http://www.ipcc.ch/.

2. Anderson K, Bows A. Reframing the climate challenge in light of Post-2000 emissions trends. Philosphical Transactions of the Royal Society A 2008; 366: 3863–82.

3. Vandentorren S, *et al*. Mortality in 13 French cities during the August 2003 heat wave. American Journal of Public Health 2004; 94: 1518–20.

4. Stott PA, Stone DA, Allen. MR. Human contribution to the European Heatwave of 2003. Nature 2004; 432: 610–4.

5. Murphy J. Predictions of climate change over Europe Using statistical and dynamical downscaling techniques. International Journal of Climatology 2000; 20: 489–501.

6. Belcher SE, Hacker JN, Powell DS. Constructing design weather data for future climates. Building Services Engineering Research and Technology. 2005; 26: 49–61.

7. UKCIP02. Climate change scenarios for the United Kingdom. Available from:. UKCIP http://www.ukcip.org.uk/index.php?option1⁄4com_content&task1⁄4view&id1⁄4161&Itemid1⁄4291; 2002.

8. UK Climate Projections 2009, http://ukclimateprojections.defra.gov.uk/ Scientific reports available from: http://ukclimateprojections.defra.gov.uk/content/view/1370/686/

9. Murphy JM, Sexton DMH, Jenkins GJ, Booth B, Brown CC, Clark RT, Collins M, Harris GR, Kendon EJ, Betts, RA, Brown SJ, Humphrey KA, McCarthy MP, McDonald RE, Stephens A, Wallace C, Warren R, Wilby R,

Wood RA. UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter. 2009.
Available from:
http://ukclimateprojections.defra.gov.uk/content/view/1370/686/

10. Jones, PD, Kilsby CG, Harpham C, Glenis V, Burton A. UK Climate Projections science report: Projections of future daily climate for the UK from the Weather Generator. University of Newcastle, UK. 2009.
Available from:
http://ukclimateprojections.defra.gov.uk/content/view/1370/686/

11. Ekström M, Jones PD, Fowler, HJ, Lenderink G, Buishand TA and Conway D, Regional climate model data used within the SWURVE project 1: projected changes in seasonal patterns and estimation of PET, Hydrol. Earth. Syst. Sci., 2007; 11: 1069–1083.

12. Chartered Institute of Buildings Services Engineers, http://www.cibse.org/

13. UK Meteorological Office. MIDAS Land Surface Stations data (1853-current), [Internet]. British Atmospheric Data Centre, 2006, 2010. Available from http://badc.nerc.ac.uk/data/ukmo-midas

14. Integrated environmental solutions, http://www.iesve.com/content/.

15. Levermore GJ, and Parkinson JB. Analyses and algorithms for new Test Reference Years and Design Summer Years for the UK. Building Serv. Eng. Res. Technol., 2006; 27: 311-325.

File number	Mean Hourly wind speed (ms^{-1})	Hourly Standard deviation (ms^{-1})	Mean absolute hourly difference to TRY (ms^{-1})	Mean absolute daily difference to TRY (ms^{-1})	Mean absolute monthly difference to TRY (ms^{-1})
TRY	5.38	3.36	-	-	-
1	5.30	3.34	1.97	0.35	0.11
2	5.33	3.33	1.95	0.35	0.07
3	5.38	3.37	1.99	0.33	0.07
4	5.28	3.22	1.95	0.36	0.11
5	5.33	3.27	1.95	0.35	0.08
6	5.30	3.31	1.97	0.34	0.08
7	5.31	3.35	2.00	0.36	0.11
8	5.31	3.30	1.92	0.33	0.10
9	5.33	3.33	1.94	0.34	0.09
10	5.28	3.32	1.96	0.37	0.11
11	5.35	3.33	1.93	0.36	0.08
12	5.30	3.29	1.98	0.33	0.10
13	5.29	3.23	1.93	0.35	0.10
14	5.30	3.31	1.94	0.36	0.10
15	5.38	3.36	1.94	0.34	0.12

Table 1 Wind speed statistics for the 15 files and test reference year.

(Absolute values used so magnitude of difference is shown)

	House 1	House 2	Office	Apartment	School
Artificial max	5844.6	4387.7	16587.9	4772.7	45994.2
TRY max	5630.5	5236.6	18076.5	6513.1	45921.0
Artificial mean	551.0	233.1	2039.9	62.4	2603.2
TRY mean	552.1	238.9	2053.3	66.0	2582.7

Table 2 Simulated airflow magnitudes (ls^{-1}) for the TRY and the average of the 15 artificial wind fields for the 5 different buildings (details of which are provided in the appendix) over the entire year.

File number	Mean Hourly airflow (ls^{-1})	Hourly airflow Standard deviation (ls^{-1})	Largest mean daily airflow difference to TRY (ls^{-1})	Largest mean monthly airflow difference to TRY (ls^{-1})	Yearly mean difference in airflow compared to the TRY (ls^{-1})
TRY	177.4	264.1	-	-	-
1	177.1	266.3	-203	-20	-0.3
2	177.1	266.3	-203	-20	-0.4
3	175.1	263.5	-203	-12	-2.3
4	173.8	257.5	-210	15	-3.6
5	175.3	260.8	-201	-16	-2.1
6	178.8	270.2	249	26	1.4
7	176.0	261.0	206	13	-1.4
8	175.1	262.3	144	-11	-2.3
9	177.9	268.0	187	9	0.5
10	175.2	262.8	-138	-13	-2.2
11	176.2	263.9	-167	-15	-1.2
12	176.9	263.4	179	-15	-0.5
13	176.6	263.1	-169	-11	-0.8
14	175.3	260.9	159	-11	-2.1
15	179.5	269.1	177	17	2.1

Table 3 Internal airflow statistics for the 15 files and TRY within the office.

Weather File	Mean Hourly airflow (ls^{-1})	Hourly airflow Standard deviation (ls^{-1})	Largest mean daily airflow difference to TRY (ls^{-1})	Largest mean monthly airflow difference to TRY (ls^{-1})	Yearly mean difference in airflow compared to the TRY (ls^{-1})
TRY	177.4	264.1	-	-	-
1983	170.8	257.4	380	42	-6.6
1984	172.3	259.9	-430	-41	-5.1
1985	177.5	272.5	-414	85	0.1
1986	179.3	284.0	-440	-103	1.9
1987	158.5	251.6	588	-73	-18.9
1988	186.5	279.1	524	85	9.1
1989	191.1	282.5	452	74	13.7
1990	187.5	274.1	-384	137	10.1
1992	165.2	254.7	-433	-87	-12.2
1993	167.0	254.7	-466	49	-10.5
1994	187.0	285.2	444	57	9.6
1995	177.2	269.1	-471	75	-0.2
1996	158.4	249.0	-465	-57	-19.0
1998	193.0	290.0	468	57	15.6
2000	188.8	279.0	382	65	11.4
2001	175.5	259.5	544	36	-1.9
2002	189.7	289.0	-318	151	12.3
2003	171.9	244.4	-318	-34	-5.5
2004	175.5	261.0	400	-36	-1.9

Table 4 Internal airflow statistics for the TRY and other observed weather years used to compile the TRY within the office.

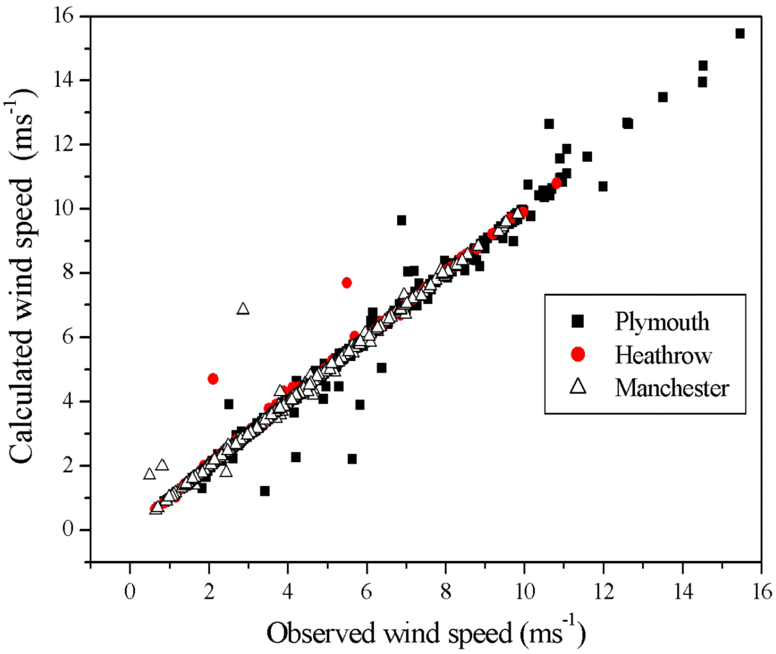


Figure 1 Observed mean daily wind speed for three locations against calculated mean daily wind speed reconstructed from PET. The correlation of the data is high with $R^2 > 0.99$ for all three data sets.

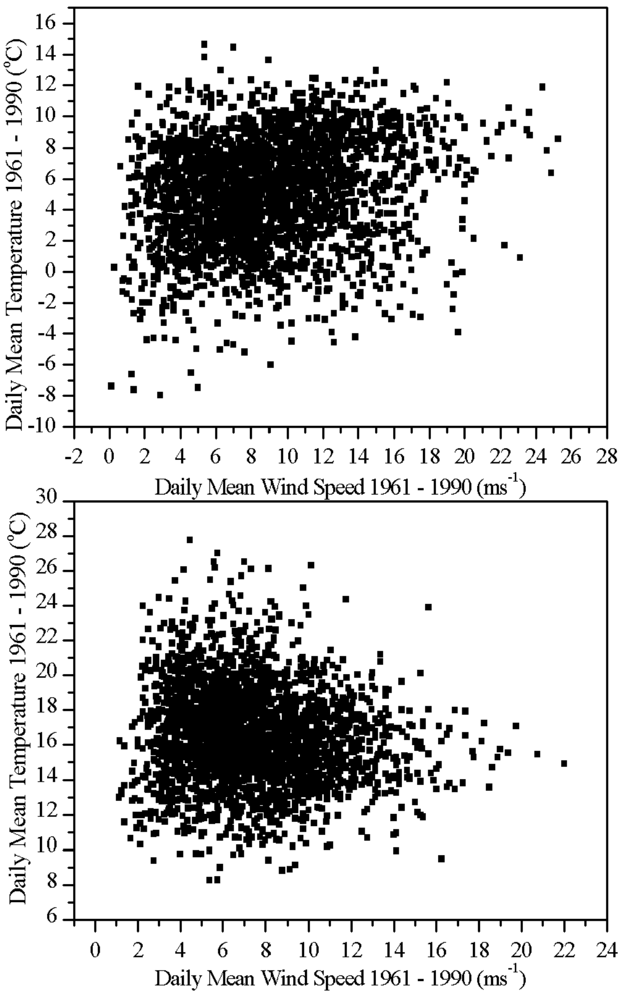


Figure 2 Graphs showing the seasonal correlation between observed mean daily wind speed and mean daily temperatures for the 1961-1990 period at Heathrow. Only two seasons are shown for clarity, winter (top) and summer (bottom).

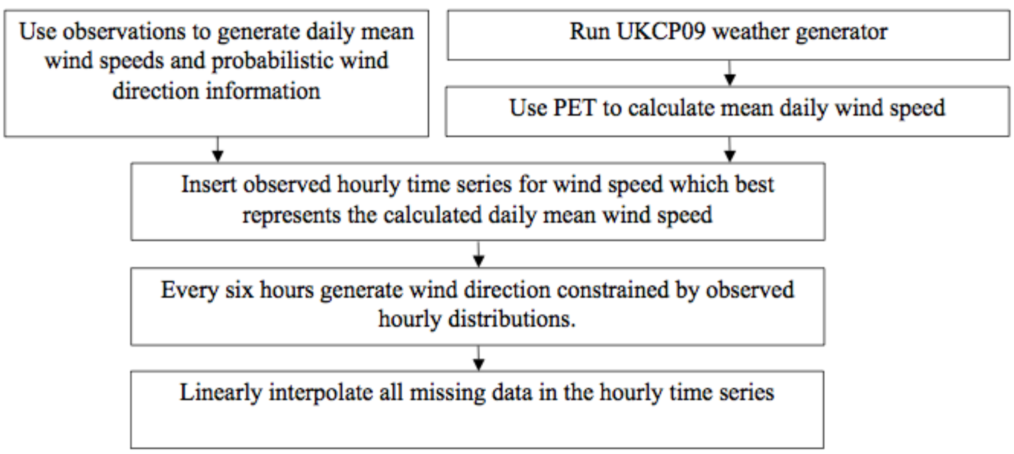


Figure 3 Flow diagram showing the method for creating hourly wind direction and wind speed from the UKCP09 weather generator.

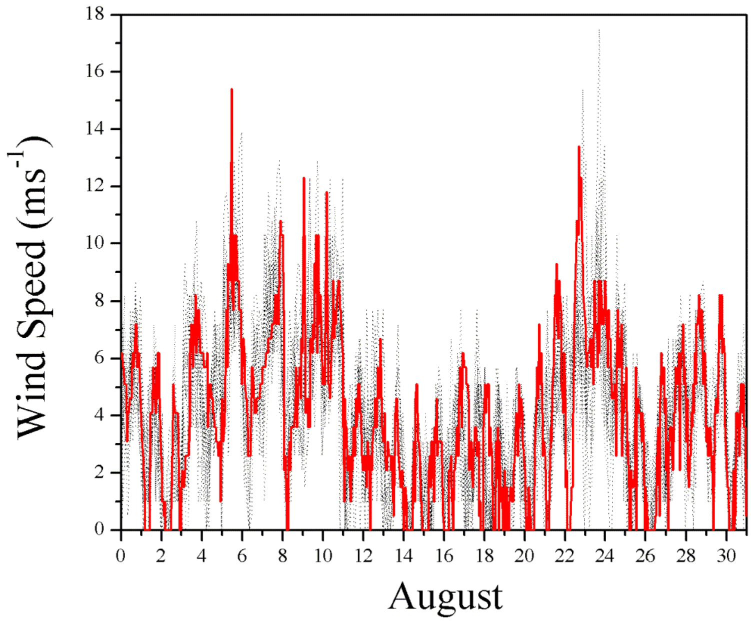
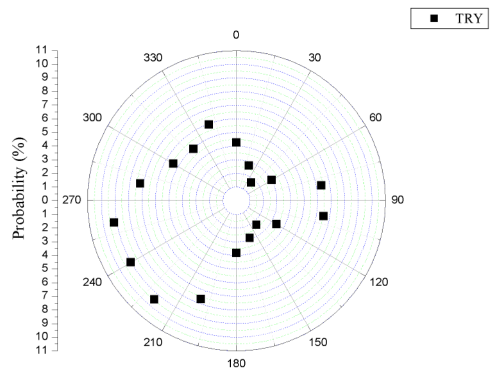


Figure 4 Plot of 15 possible wind time series (black dash) and the observed wind time series from the TRY (solid red line) for the month of August.



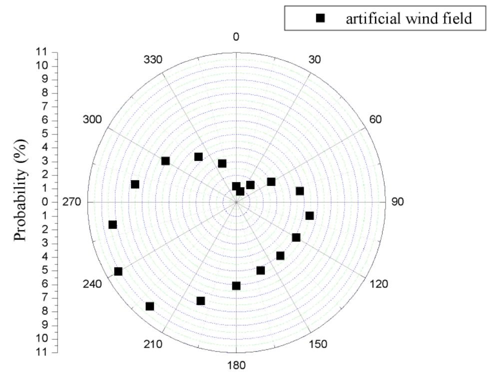


Figure 5 Polar plots of wind direction against probability for the TRY (top) and the 15 generated wind fields (bottom). Points are shown in 20° increments for clarity.

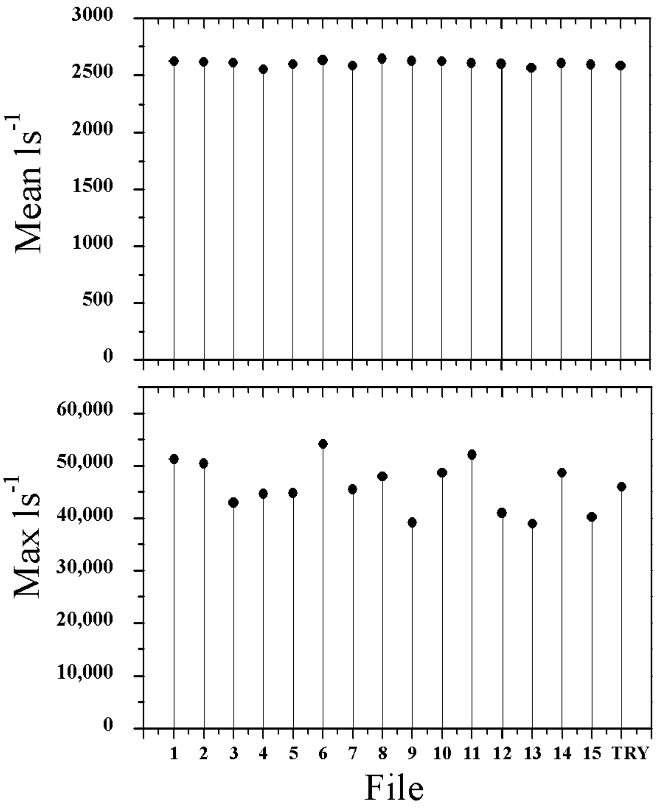


Figure 6 Plot of the variation of mean and maximum airflow within the secondary school for the 15 artificial wind fields with respect to the TRY.

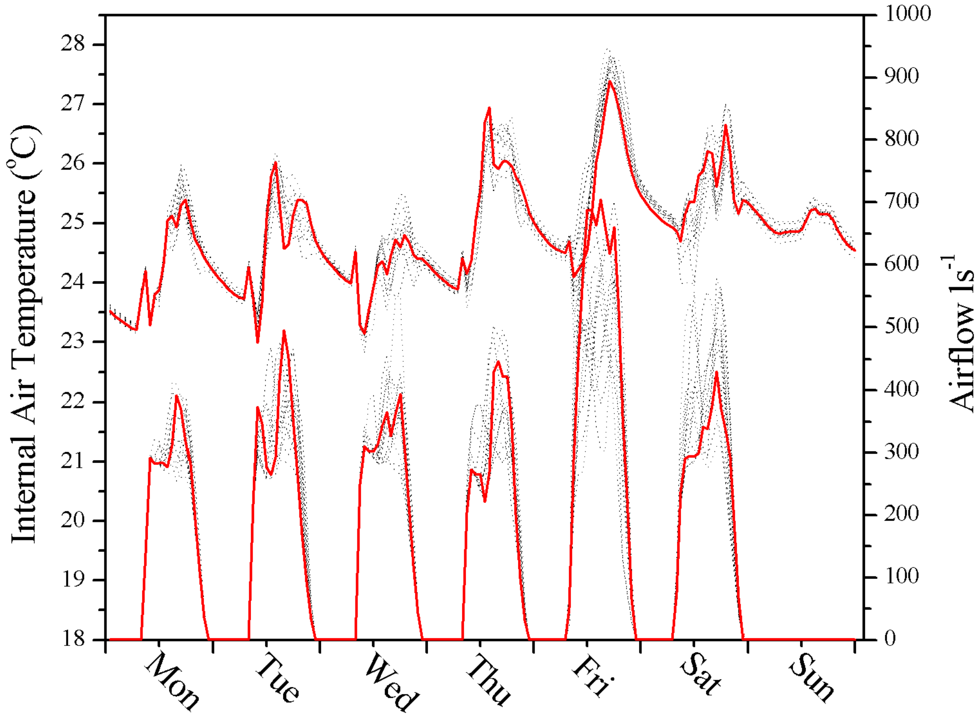


Figure 7 Plot of air temperatures (top) and airflow magnitude (bottom) for a typical week in summer for the TRY (red) and the 15 calculated wind fields (black dash) for a large open plan office. Note the windows are only open during occupied hours when the internal air temperature is > 24°C.

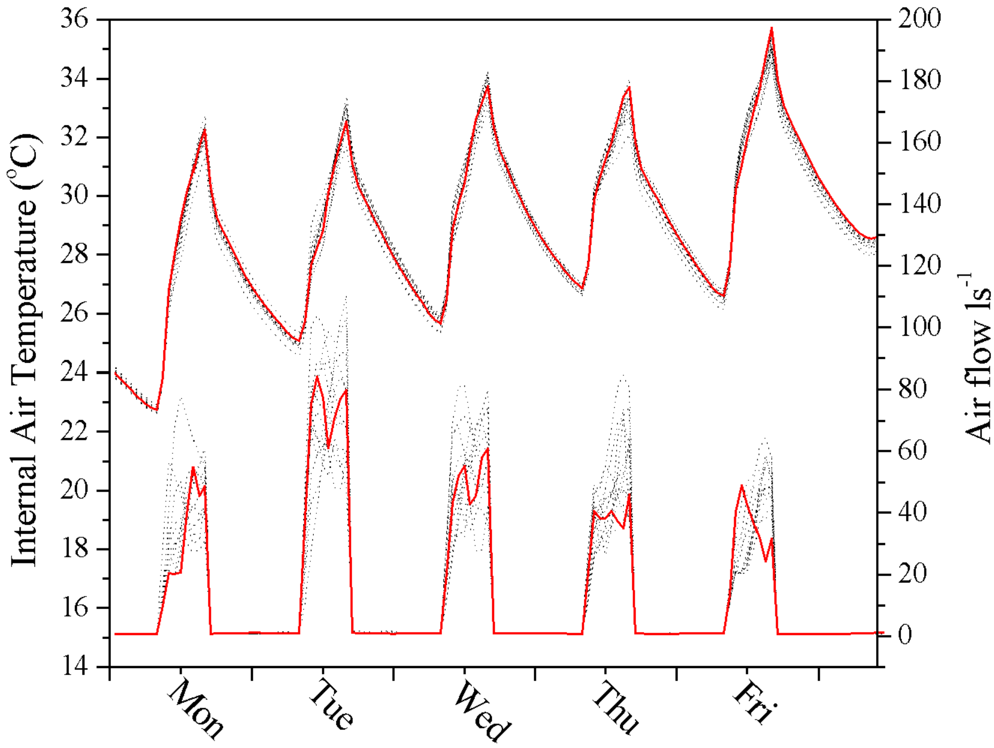


Figure 8 Plot of air temperatures (top) and airflow magnitude (bottom) for a typical school week in summer for the TRY (red) and the 15 calculated wind fields (black dash) for a cross-ventilated classroom within the secondary school. Note the windows are only open during occupied hours.

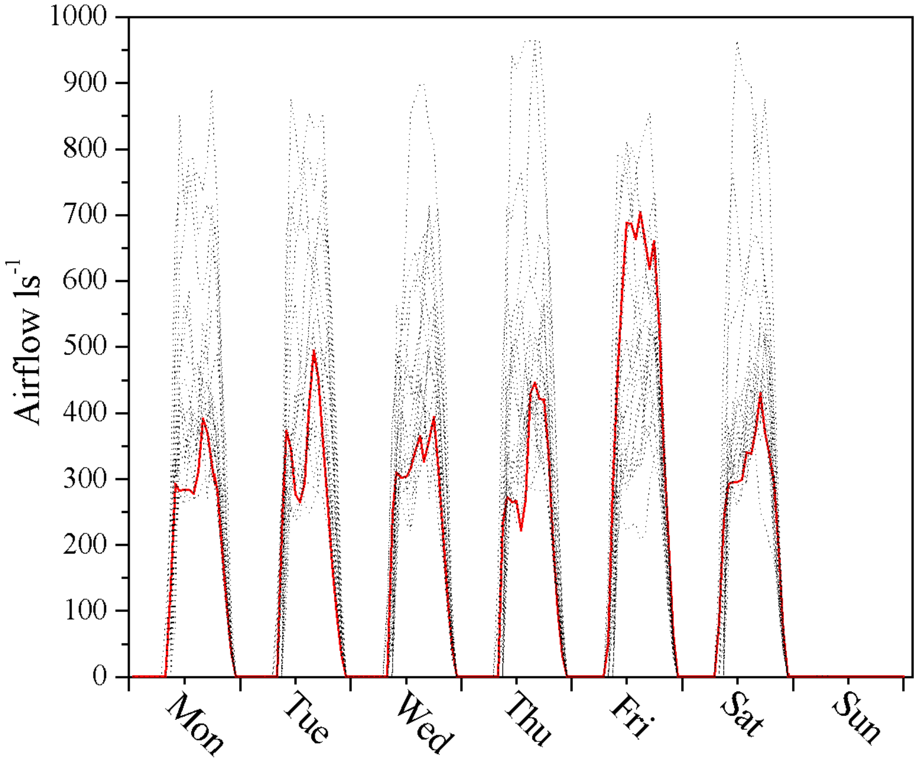


Figure 9 Plot of airflow magnitude for a typical week in summer for the TRY (red) and the 19 other observed weather years used to compile the TRY (black dash). The construction details and week considered are the same as displayed in figure 7, a list of the years used can be found in table 4.