UNIVERSITY OF CAMBRIDGE

Predicting the diversity of internal dwelling temperatures from the English residential sector

Scott Kelly, Michelle Shipworth, David Shipworth, Michael Gentry, Andrew Wright, Michael Pollitt, Doug Crawford-Brown, Kevin Lomas

Scott Kelly: sjk64@cam.ac.uk

The Cambridge Centre for Climate Change Mitigation Research (4CMR)

Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Agenda

- Background
- Contribution
- Statistical model
- Data sources
- Model development
- Results
- Model diagnostics
- Conclusions

Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Background

TOTAL UK ENERGY CONSUMPTION

Consumed within buildings

HM Government (2006)

20% Hot water

20% Lights + Appliances

60% Home heating

90% Of all UK dwellings now have central heating systems.

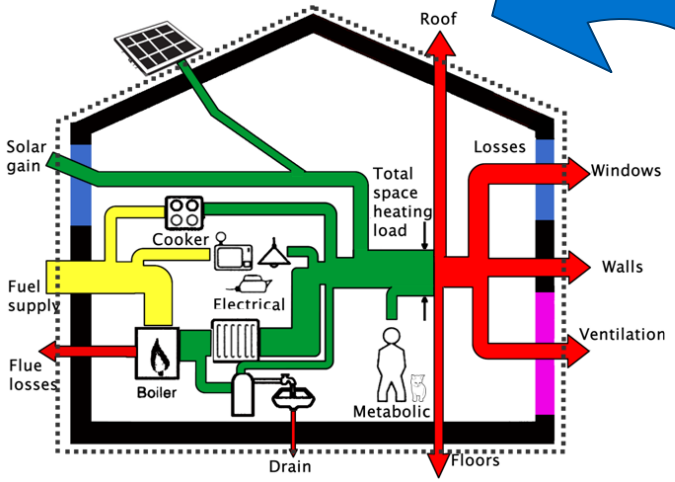
Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Putting internal temperature at the heart



Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Reconciling domestic energy predictions

Engineering models are dominated by bottom-up building physics models .

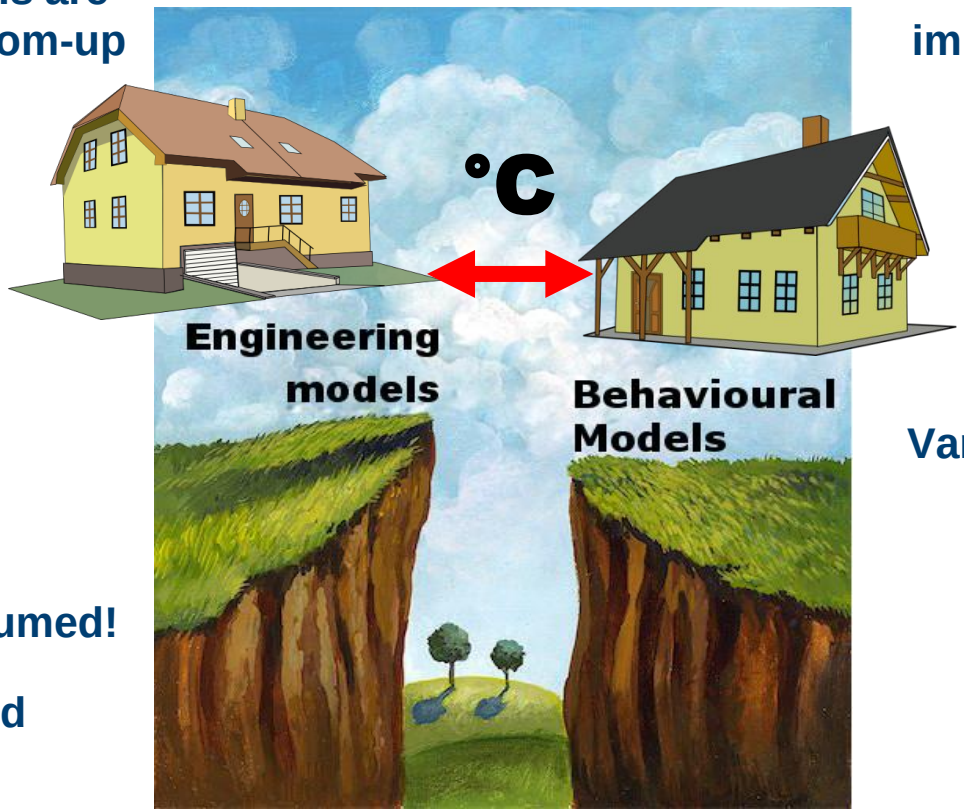
Wright (2009)
Swan (2009)
Audenart (2011)
BRE (2001)
Utley (2007)...

Building envelope

Heating systems

Temperatures assumed!

Behaviours ignored



Behaviour is *at least* as important as other factors for explaining dwelling energy consumption.

Lutzenhiser (1992)
Royal Commission (2007)
Crosbie and Baker (2010)
Lomas (2010)
Wall and Crosbie (2009)...

Variance due to behaviour:

51% Heat

37% Electricity

11% Water

Gill and Tierney (2010)

Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Predicting dwelling temperatures is important!

- All factors being equal energy demand is most affected by internal temperature demand. **Firth (2009), Cheng (2011)**
- Top-down models calibrate global internal temperatures across B-Stock
- Bottom-up models assume constant temperature OR base temperature on assumptions about the physical properties of the dwelling.
- Improved energy demand predictions are going to become increasingly important as smart grid technologies are implemented.

UNIVERSITY OF CAMBRIDGE

Why new methods are required (panel methods)

- Dwellings are heterogeneous
- Temperature profiles are dynamic
- Space and time are both important in modelling
- Lots of information generates large datasets

Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Contribution

- First time a panel model used to predict internal temperatures
- **Bridge** between physical and behavioural prediction models
- Offers improved estimates of energy demand predictions
- Allows statistical inferences to be made about competing factors.
- A new tool that will benefit existing building stock models

Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Why use panel methods

Panel methods (cross-section and time-series)

- higher *dof* thus are generally more efficient
- Capture variation over time and over cross-sections
- Information on time-ordering of events (i.e. weather effects)
- Control of individual unobserved heterogeneity
- Allow for contemporaneous correlation across sample

Standard conditions still apply – but can be over come with several methods:

i) $E(\varepsilon_i \mid x_i) = 0$ (exogeneity of regressors)

ii) $E\left(\varepsilon_i^2 \mid x_i\right) = \sigma^2$ (conditional homoskedasticity)

iii) $E\left(\varepsilon_i \varepsilon_j \mid x_i x_j\right) = 0,\ i \neq j$ (conditionally uncorrelated correlations)

UNIVERSITY OF CAMBRIDGE

Statistical model

Choosing the correct model depends on several factors:

- The size of the N (cross-sections) and the size of X (time-periods)
- Type of variables included (are regressors time invariant?)
- Do regressors co-vary over-time and over cross section?

REJECTED MODELS

- **Ordinary Least Squares (OLS)**
- **Pooled regression (PR)**
- **Fixed Effects (FE)**
- **Least Square Dummy Var (LSDV)**

ACCEPTED MODELS

- **Random Effects (RE)**
- **General Least Squares (GLS)**
- **Panel Corrected SE (PCSE)**
- **Driscol and Kraay (XTSCC)**

UNIVERSITY OF CAMBRIDGE

Description of data source

- CARB-HES is most comprehensive UK home energy survey (UCL)
  McMichael (2011)
- Data collected between July 2007 – February 2008
- Contains behavioural, socio-demographic and physical variables.
- Two temperatures (living and bedroom) @ 45 minute intervals
- External daily mean temperatures taken for 9 Gov office regions

Variable name	CAB-HES Survey (%)	EHCS 2007 (%)[1]
Tenure type		
Owner occupied	303 (71%)	7710 (71%)
Privately rented	46 (11%)	2,161 (12%)
Local Authority	39 (9%)	3,501 (9%)
Housing Association	38 (9%)	2,232 (8%)
Dwelling type		
Terraced	97 (23%)	4,775 (28%)
Semi-detached	125 (29%)	4,183 (28%)
Bungalow or detached	123 (29%)	3,661 (27%)
Flats	82 (19%)	3,598 (17%)
Dwelling Age		
Pre 1919	62 (15%)	3014 (21%)
1919 – 1944	79 (18%)	2,755 (17%)
1945 – 1964	98 (23%)	3,868 (20%)
1965 – 1980	96 (22%)	3,855 (22%)
Post 1980	90 (21%)	2,725 (20%)
Total number of households in survey	427	15,604

1. Weighted sample taken from the English House Condition Survey 2007-08 (Communities and Local Government 2009)

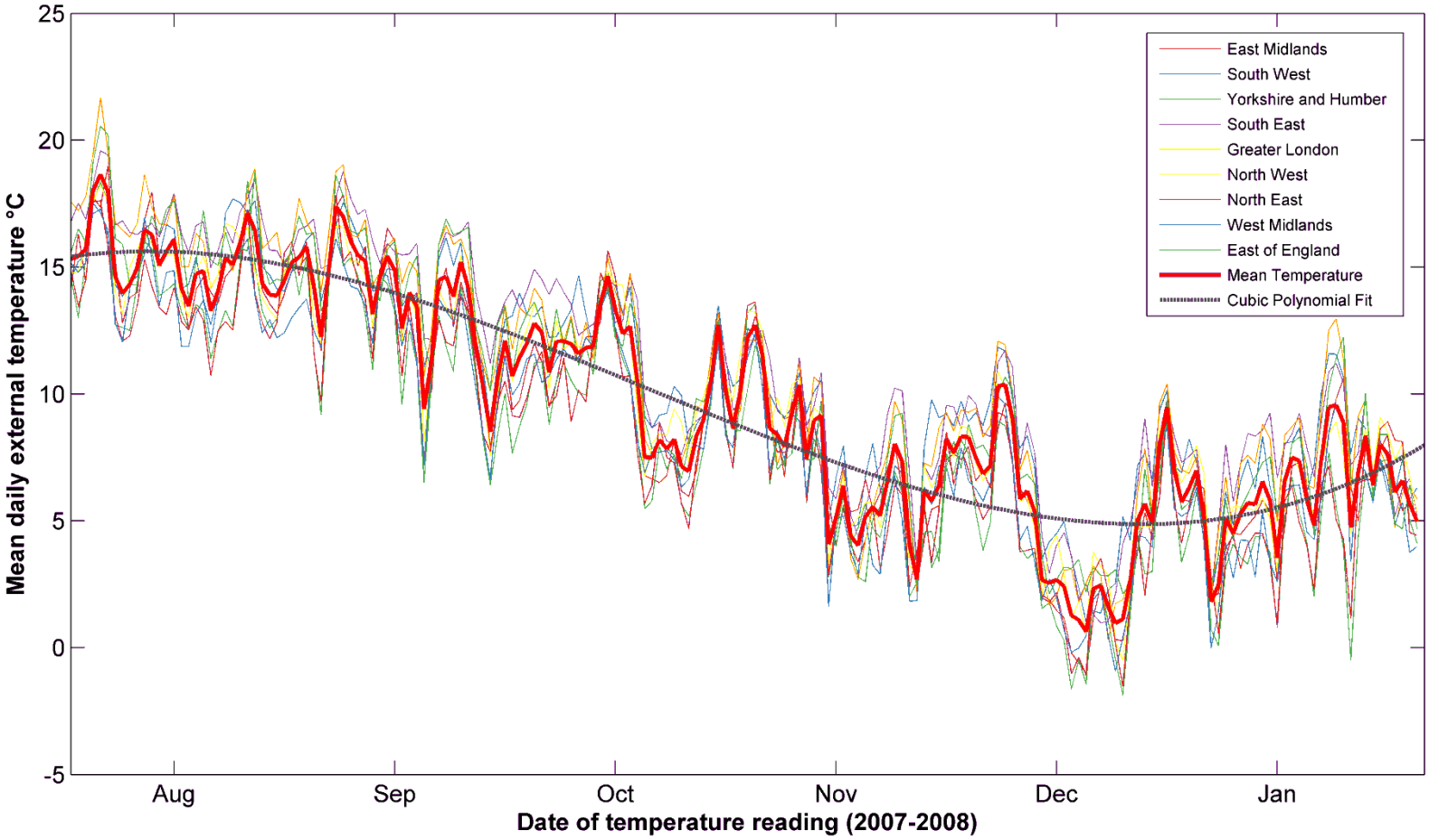
Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

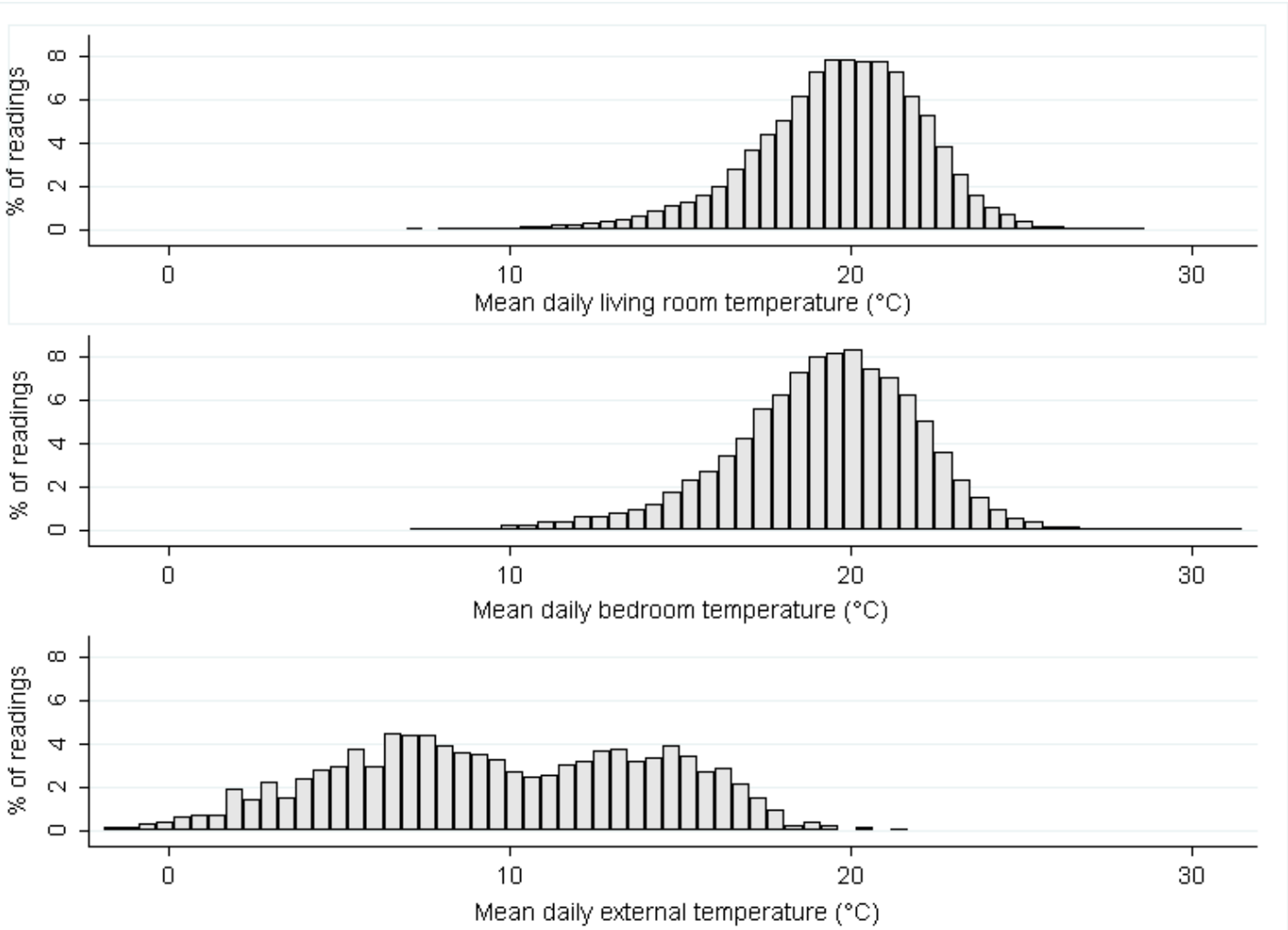
External temperatures



Data Source: British Atmospheric Data Archive (2007-2009)

UNIVERSITY OF CAMBRIDGE

Data analysis



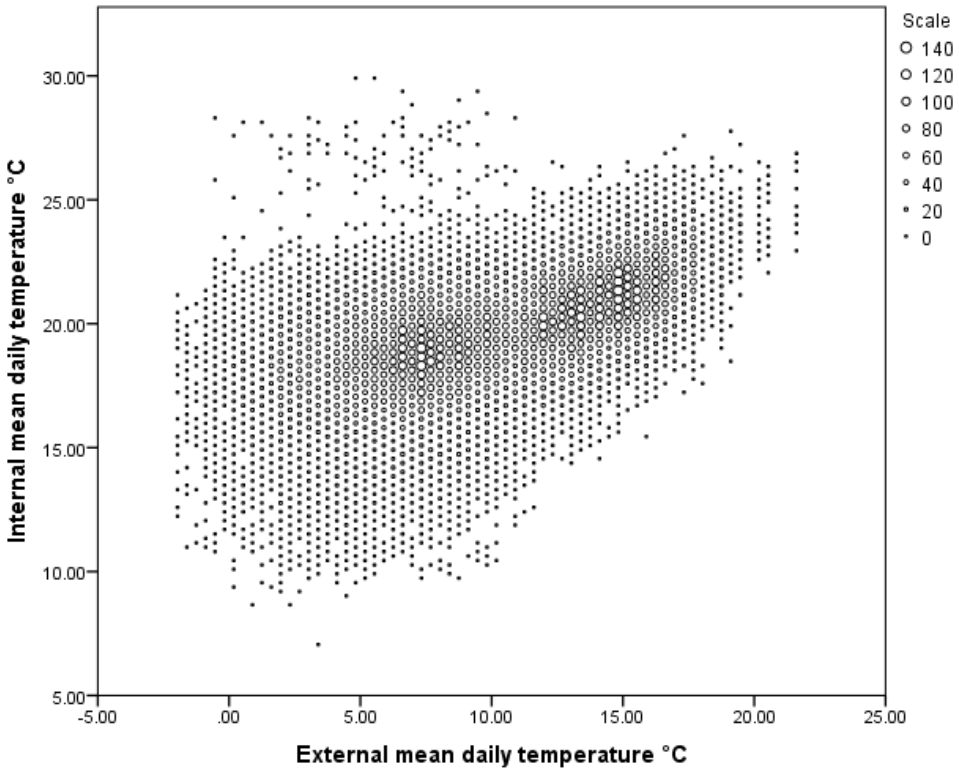
Tyndall°Centre for Climate Change Research

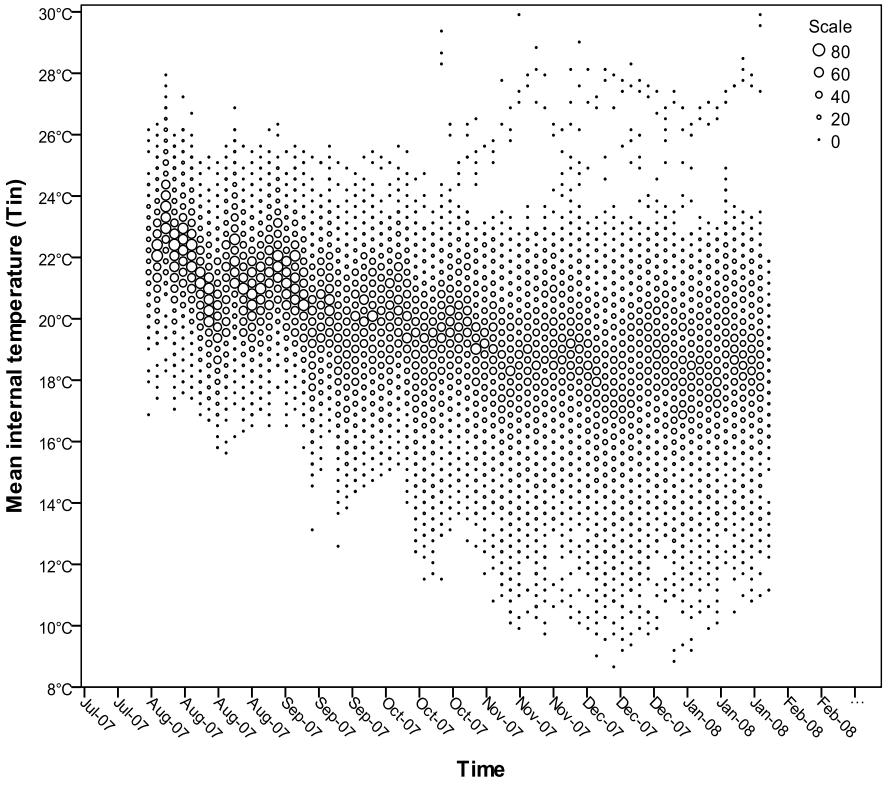
UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Plotting temperature





Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Model development

Model:

$$Tin_{it} = \alpha + \mathbf{\Gamma}_{it}\boldsymbol{\beta}_1 + \mathbf{\Psi}_{it}\boldsymbol{\beta}_2 + \mathbf{\Theta}_{it}\boldsymbol{\beta}_3 + (\nu_i + \varepsilon_{it}); \qquad i = 1, ..., N \quad t = 1, ..., X$$

$\mathbf{\Gamma}_{it}$	**Matrix of intransmutable variables (location, external temperature)**
$\mathbf{\Psi}_{it}$	**Matrix of behavioural and socio-demographic variables (heating patterns, age etc)**
$\mathbf{\Theta}_{it}$	**Matrix of building physical characteristics (insulation, double glazing etc)**
ν_i	**Between entity error term**
ε_{it}	**Idiosyncratic error term**
$\boldsymbol{\beta}_1$	**Corresponding array of parameter coefficients**

Unbalanced panel: 42,723 data-points (266 dwellings and 184 time periods)

UNIVERSITY OF CAMBRIDGE

Description of variables

Room thermostat is a dichotomous variable that indicates if a room thermostat is present in the dwelling.

Thermostat setting is the respondent's declared thermostat setting for the dwelling in degrees Celsius and has been grouped into four categories (*Table 3*).

Thermostatic Radiator Valve (TRV) is a dichotomous variable indicating if the only type of temperature control is with thermostatic radiator valves.

Central heating hours reported is a continuous scale variable indicating the average number of central heating hours reported per day over the week including weekends.

Regular heating pattern is a dichotomous variable indicating if the home is heated to regular heating patterns during the winter.

Automatic timer is a dichotomous variable indicating that the home uses an automatic timer to control heating.

Household size is the number of occupants living in the dwelling at the time of the survey;

Household income is the gross take-home income for the whole household and has been categorised into seven income bands;

Child<5 is a dichotomous variable indicating if any infants under the age of five are present in the dwelling;

Children<18 is a discrete scale variable indicating the number of children under the age of 18 living in the dwelling;

UNIVERSITY OF CAMBRIDGE

Description of variables

Age<59 is a dichotomous variable indicating if the oldest person living in the dwelling is under 64 years of age. For this analysis, this will also be the comparison category that other ages are compared against;

Age59-64 is a dichotomous variable that represents if the oldest person living in the dwelling is aged between 59 and 64;

Age64-74 is a dichotomous variable that represents if the oldest person living in the dwelling is aged between 64 and 74;

Age>74 is a dichotomous variable that represents if the oldest person in the dwelling is over 74;

Owner occupier is a dichotomous variable and indicates the dwelling is owned by the occupants;

Privately Rented is a dichotomous variable and indicates the dwelling is privately rented by the occupants;

Council tenant is a dichotomous variable and indicates if the dwelling is leased from the council;

Housing Association is a dichotomous variable and indicates if the occupants rent the property from a housing association or registered social landlord (RSL);

Weekend heat same as weekday is a dichotomous variable and indicates a positive response to the question: “Do you heat your home the same on the weekend as during the week?”;

Weekend temperature *reading* is a dichotomous variable indicating if the temperature reading was recorded during the weekend;

UNIVERSITY OF CAMBRIDGE

Description of variables

Detached House is a dichotomous variable and indicates the dwelling is detached;

Semi-Detached is a dichotomous variable indicating a semi-detached dwelling;

Terraced house is a dichotomous variable indicating a terraced house;

Not a house is a dichotomous variable used to represent flats and apartments or any other building not considered as a stand-alone house.

Gas Central heating is a dichotomous variable used to represent if the dwelling has gas central heating;

Non central heating is a dichotomous variable used to represent dwellings with non-central heating systems (i.e. wood stove, electric fan heaters etc);

Electricity is main fuel is a dichotomous variable that represents if electricity is the main type of heating fuel;

Additional gas heating in living *room* is a dichotomous variable used to represent the presence of gas heating in the living room in addition to central heating.

Additional electricity heating in living *room* is a dichotomous variable used to represent the presence of electric heating in the living room in addition to central heating.

Additional other heating in living room is a dichotomous variable used to represent if the presence of additional other forms of heating in the living room.

UNIVERSITY OF CAMBRIDGE

Description of variables

Year of construction is an ordered categorical variable specifying the year the building was constructed.

Roof insulation thickness is an ordered categorical variable representing the thickness of the roof insulation.

Extent of double glazing is an ordered categorical variable indicating the proportion of double glazing in the dwelling.

Wall U-Value is an ordered categorical variable and represents the average U-Value of external walls.

Geographic region is a dichotomous control variable indicating the geographic location of the dwelling

External Temperature is a scale variable of the mean daily external temperature for the region.

External Temperature^2 is the square of External temperature

UNIVERSITY OF CAMBRIDGE

Model tests

- Missing values were shown not to be a problem (MCAR) < 5%
- Mean substitution was used to replace the missing values.
- Test for OLS in favour of RE was rejected using Breusch-Pagan Lagrange Multiplier (LM) test
- Serial correlation was rejected using Druckers test.
- Non-stationarity was rejected using Fisher-type test and Levin-Lin-Chu test
- A modified Wald statistic suggested heteroskedasticity of model residuals was present. Confirmed again with Likelihood ratio test.

UNIVERSITY OF CAMBRIDGE

Results

Number Obs: **42,723**
Groups: **233**
Time periods: **184**

	Models				
	1	**2**	**3**	**4**	**5**
Model Assumptions					
Type of estimator	GLS	GLS	PCSE/OLS	PCSE/OLS	XTSCC
Heteroskedastic errors	yes	yes	yes	yes	yes
Contemporaneous correlation	no	no	yes	no	yes
Serial correlation	no	yes	yes	no	yes
Model Variables					
Text	0.034 (5.41)***	0.09 (21.52)***	0.052 (2.26)*	0.107 (6.34)***	0.052 (2.23)*
Text^2	0.013 (40.51)***	0.005 (23.64)***	0.012 (10.75)***	0.005 (5.67)***	0.012 (7.97)***
(A)	- -	- -	- -	- -	- -
(A) North East	-1.303 (-30.20)***	-1.525 (-11.18)***	-1.392 (-25.06)***	-1.43 (-8.48)***	-1.392 (-11.34)***
(A)	-0.637 (-15.31)***	-0.989 (-7.53)***	-0.629 (-9.38)***	-0.966 (-6.09)***	-0.629 (-4.50)***
(A)	-0.916 (-24.38)***	-1.072 (-9.12)***	-1.031 (-20.57)***	-0.945 (-5.88)***	-1.031 (-11.98)***
(A)	-0.501 (-11.62)***	-0.847 (-6.37)***	-0.458 (-10.53)***	-0.779 (-4.93)***	-0.458 (-6.09)***
(A)	-0.597 (-15.76)***	-0.927 (-7.74)***	-0.828 (-13.17)***	-0.926 (-6.05)***	-0.828 (-6.69)***
(A) South West	-0.569 (-15.99)***	-0.757 (-6.68)***	-0.765 (-16.40)***	-0.729 (-5.35)***	-0.765 (-8.74)***
(A) East of	-0.730 (-19.09)***	-0.852 (-6.92)***	-0.667 (-18.52)***	-0.681 (-4.50)***	-0.667 (-10.70)***
(A) South East	-1.332 (-34.18)***	-1.352 (-10.47)***	-1.464 (-35.00)***	-1.361 (-9.82)***	-1.464 (-18.44)***
T_Stat	-0.277 (-12.83)***	-0.338 (-5.20)***	-0.236 (-15.05)***	-0.319 (-4.42)***	-0.236 (-8.73)***
T_Settingesp	-0.078 (-7.38)***	-0.095 (-2.81)**	0.035 (4.18)***	-0.077 (-2.33)*	0.035 (2.02)*
TV	-0.091 (-3.62)***	-0.077 (-0.96)	-0.169 (-7.76)***	-0.225 (-2.39)*	-0.169 (-4.40)***
CH_Hours	0.055 (34.70)***	0.055 (10.87)***	0.069 (25.96)***	0.055 (9.38)***	0.069 (11.79)***
eg_Pat	0.882 (19.90)***	0.602 (3.76)***	1.189 (23.72)***	0.683 (4.19)***	1.189 (11.14)***
Auto_Timer	-0.079 (-4.53)***	-0.097 (-1.76)	-0.031 (-2.53)*	-0.069 (-1.34)	-0.031 (-1.27)
HH_Size	0.200 (16.72)***	0.213 (5.21)***	0.25 (20.07)***	0.217 (5.65)***	0.25 (9.19)***
HH_Income	0.125 (18.44)***	0.126 (5.58)***	0.084 (8.73)***	0.118 (5.06)***	0.084 (4.05)***
Child<5	0.752 (23.17)***	0.829 (8.84)***	0.495 (19.67)***	0.765 (7.76)***	0.495 (10.32)***
Children<18	0.157 (9.55)***	0.051 (-0.95)	0.219 (26.48)***	0.029 (-0.59)	0.219 (9.12)***

Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

χ^2

UNIVERSITY OF CAMBRIDGE

Results

(B) Age<60	- -	- -	- -	- -	- -
(B) Age60-64	0.148 (6.47)***	0.066 (-0.85)	0.051 (2.19)*	-0.033 (-0.45)	0.051 (-1.04)
(B) Age64-74	0.486 (20.49)***	0.406 (5.31)***	0.37 (14.65)***	0.409 (4.49)***	0.37 (7.45)***
(B) Age>74	0.660 (23.18)***	0.775 (7.62)***	0.585 (22.03)***	0.829 (7.27)***	0.585 (11.12)***
(C) Owner	- -	- -	- -	- -	- -
(C) enter	0.757 (21.16)***	0.811 (7.09)***	0.94 (32.59)***	0.895 (7.73)***	0.94 (14.75)***
(C) Council	1.263 (41.03)***	1.288 (13.40)***	1.374 (35.27)***	1.303 (14.18)***	1.374 (17.90)***
(C) H_Assoc	0.667 (15.87)***	0.873 (6.09)***	0.448 (15.10)***	0.867 (6.90)***	0.448 (8.27)***
WE_Same	-0.572 (-22.78)***	-0.515 (-6.24)***	-0.438 (-26.95)***	-0.56 (-6.79)***	-0.438 (-12.85)***
WE_Temp	0.049 (3.20)**	0.083 (13.64)***	-0.038 (-0.59)	0.088 (2.82)**	0.038 (-0.68)
(D) Detached	- -	- -	- -	- -	- -
(D) SemiDet	0.740 (34.13)***	0.623 (8.93)***	0.694 (29.90)***	0.683 (8.98)***	0.694 (13.38)***
(D) Terraced	0.664 (27.67)***	0.671 (8.54)***	0.607 (33.31)***	0.69 (9.61)***	0.607 (17.36)***
(D) NotHouse	0.621 (18.44)***	0.428 (4.07)***	0.541 (21.42)***	0.327 (3.28)**	0.541 (11.93)***
Gas_CH	-0.691 (-19.57)***	-0.566 (-5.03)***	-0.564 (-24.93)***	-0.57 (-4.71)***	-0.564 (-11.88)***
Non_CH	0.179 (6.58)***	0.071 (-0.78)	0.058 (4.60)***	-0.054 (-0.63)	0.058 (2.33)*
Elec_Main	0.140 -1.95	-0.103 (-0.42)	1.008 (13.20)***	-0.07 (-0.29)	1.008 (6.46)***
Gas_OH	-0.094 (-3.45)***	0.007 (-0.07)	-0.071 (-4.77)***	-0.007 (-0.08)	-0.071 (-2.17)*
Elec_OH	0.081 (2.60)**	0.245 (2.51)*	-0.195 (-8.14)***	0.285 (3.09)**	-0.195 (-4.32)***
Other_OH	-1.091 (-32.00)***	-0.951 (-8.36)***	-1.016 (-32.29)***	-0.88 (-7.55)***	-1.016 (-17.69)***
Build_Age	0.054 (12.59)***	0.058 (4.16)***	0.042 (8.07)***	0.039 (2.59)**	0.042 (4.12)***
oof_Ins	0.081 (18.85)***	0.07 (5.10)***	0.125 (32.72)***	0.07 (4.88)***	0.125 (15.06)***
Dbl_Glz	0.190 (27.31)***	0.206 (9.17)***	0.188 (25.44)***	0.225 (10.39)***	0.188 (12.44)***
Wall_U	0.072 (8.48)***	0.067 (2.88)**	0.076 (9.18)***	0.086 (3.69)***	0.076 (4.54)***
Alpha (constant)	15.080 (170.88)***	15.819 (58.35)***	14.224 (79.91)***	15.599 (44.58)***	14.224 (46.27)***

Summary Statistics

	51,201***	14,292***	50,398***	3,250***	-
Log Likelihood	-77,840	-	-	-	-
MSE	1.87	1.95	1.84	1.93	1.84
R^2	-	-	0.45	0.88	0.45

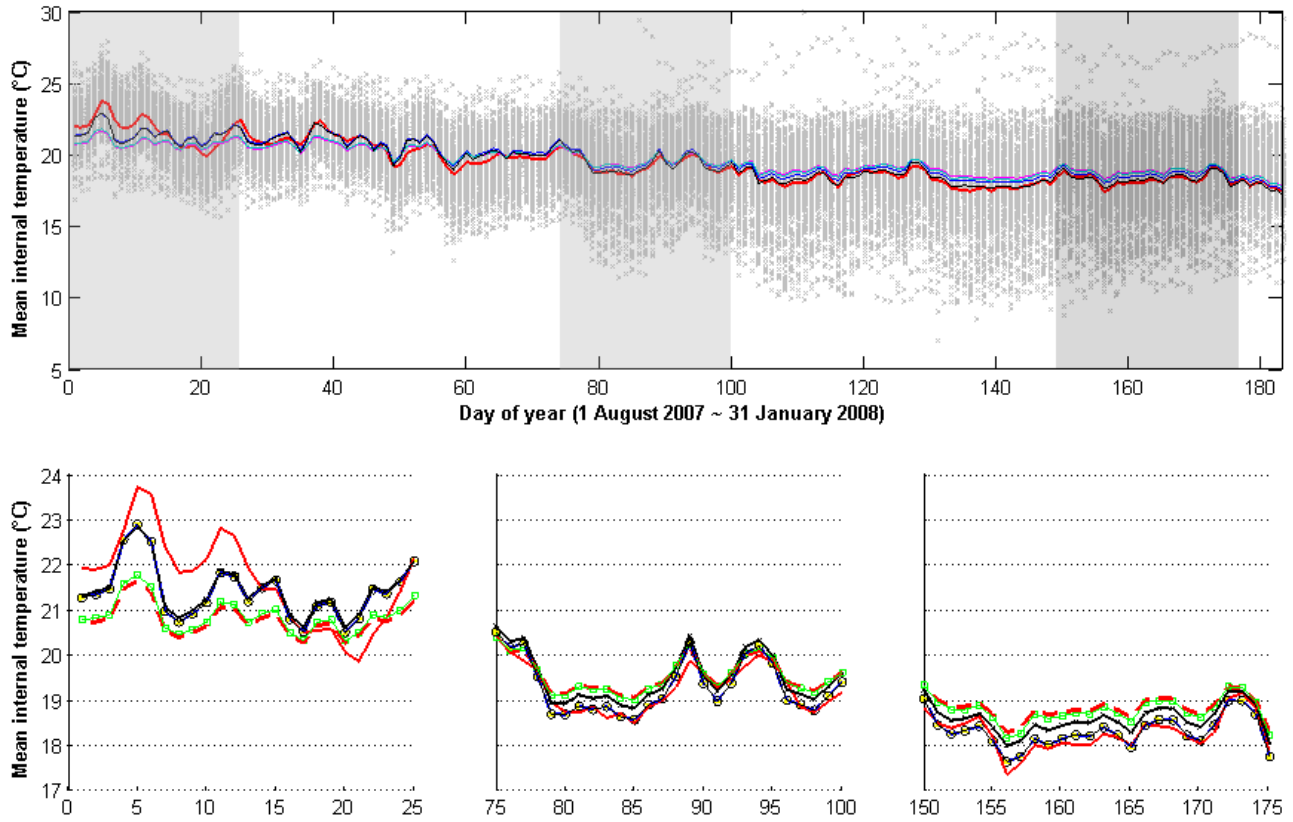
Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Comparison of different models



Tyndall Centre for Climate Change Research

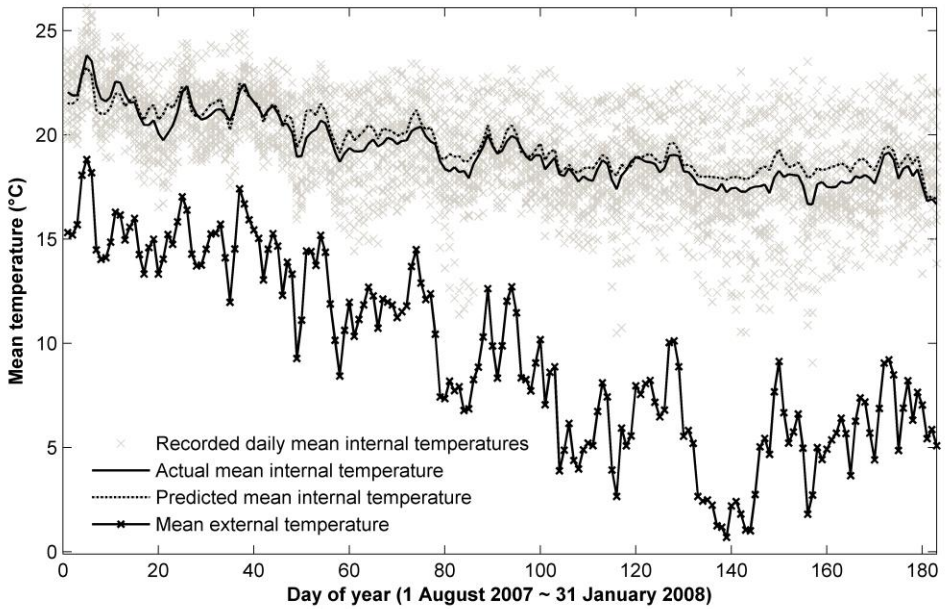
UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Model diagnostics / validation

- Residual plots used to test against standard regression assumptions
- Multicolinarity between model variables tested using VIF's = 2.71
- 10% of data with held during model estimation for post estimation (n=27)



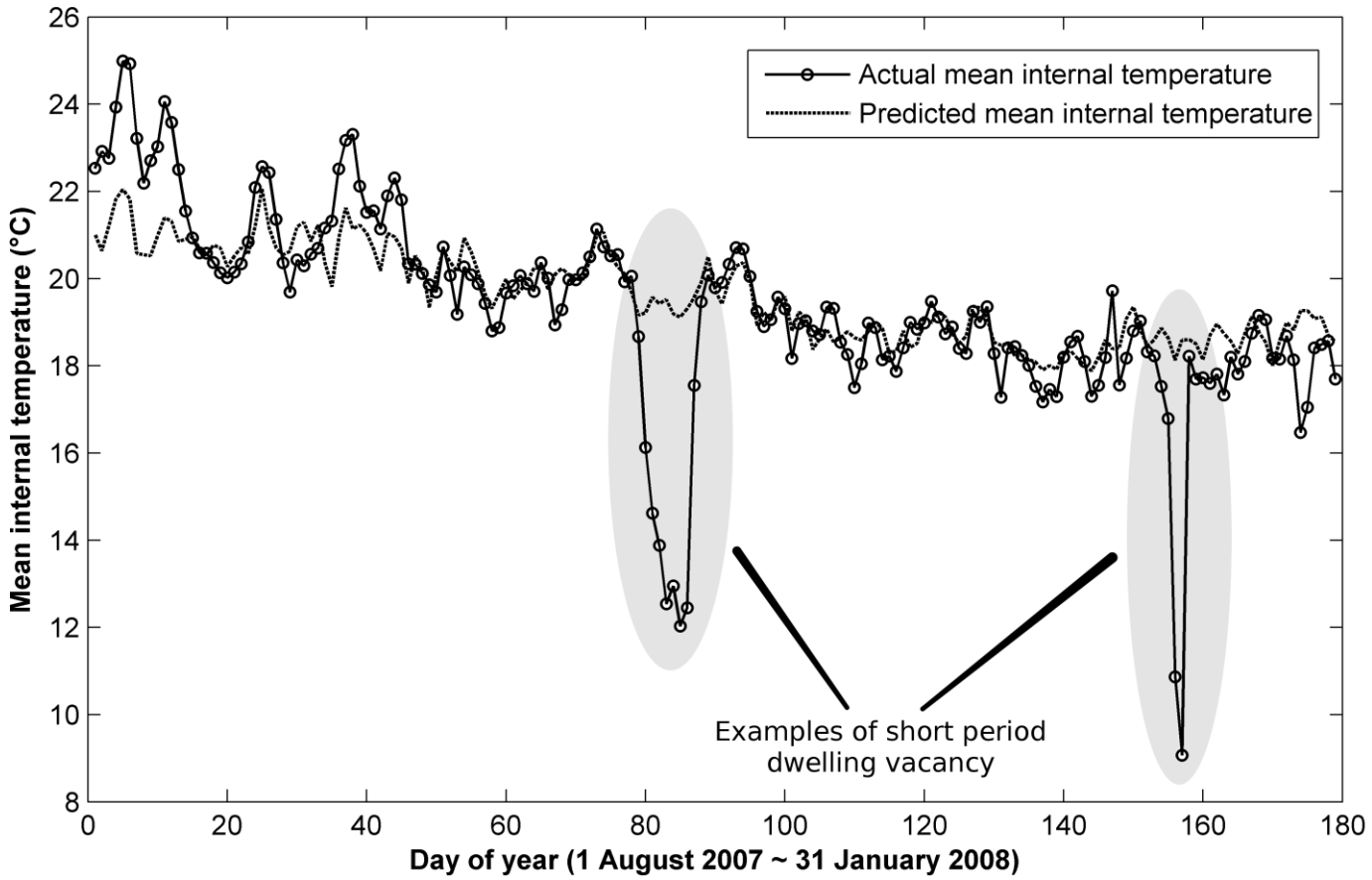
Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Results for one dwelling



Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Discussion

Intransmutable variables ~ [0 – 6.8°C]

- Geographic location: Highest (London) and Lowest (NE and SE)
- External temperature: Very important factor and non-linear effects

Heating controls ~ [0.38°C]

- -VE: Presence of thermostat reduces internal temperatures [-0.24°C]
- -VE: Thermostatic Radiator Valves reduce temperatures [-0.17°]
- +VE: Thermostat set point increases temperatures [~0.14] for <18°C to 22°C
- NE: Automatic timers have no statistically significant effect

UNIVERSITY OF CAMBRIDGE

Discussion

Human behaviour effects ~ [2.87°C]

- +VE: Heating duration: each additional hour of heating [+0.07°C]
- +VE: Regular heating pattern [+1.19°C] (routine habits are very important)
- NE: Weekend effect is not statistically significant
- -VE: Do you heat the house the same on the weekend? [-0.44°C]

Socio-demographic and occupancy effects ~ [3.7°C]

- +VE: Occupancy, each person increases temperature [+0.25°C] **Kelly (2011)**
- +VE: Household income seven discrete bands [+0.085°C] or [0.6°C]
- +VE: Children. Child <5 ~ [0.5°C]. Each Additional child [~0.22°C]
- +VE: Elderly. 60-64 [NE]. 64-74 [+0.37°C]. >74 [0.59°C].

UNIVERSITY OF CAMBRIDGE

Discussion

Tenure effects ~ [1.37°C]

- Housing association [+0.49°C] warmer than owner occupiers
- Privately rented [0.94°C] warmer than owner occupiers
- Council tenants [1.37°C] warmer than owner occupiers

Heating system effects ~ [2.0°C]

- +VE: Homes that use electricity [1.0°C] warmer (storage heaters)
- +VE: Other forms of heating [+0.06°C] (includes CH homes).
- -VE: Additional heating in main room of house: Gas [-0.07°C]; Elec [-0.2°C]
- -VE: Alternative heat sources (wood, biomass etc): [-1.0°C]

UNIVERSITY OF CAMBRIDGE

Discussion

Building efficiency effects ~ [3.38°C]

- +VE: Roof insulation (8 categories of +25mm) [0.13°C] (max: 1.0°C)
- +VE: U-Value of walls (4 categories) [0.08°C] (max 0.32°C)
- +VE: Double glazing (5 categories) [0.19°C] (max 0.94°C)

Building typology ~ [0.7°C]

- +VE: Detached coldest, flats [+0.54°C], terrace [0.61°C], semi-det [+0.7°C]
- -VE: Age of dwelling (10 categories) age category [+0.04°C]

UNIVERSITY OF CAMBRIDGE

Discussion

- First time panel regression has been used to predict internal temps
- Most model variables are shown to be statistically significant
- Internal dwelling temperatures predicted to ±0.71°C at 95% confidence
- External temperatures have a non-linear effect to second power
- Heating controls lower mean internal temperatures (except auto-timers)
- Thermostat set-point and heating duration increase temp
- Second room heaters lead to lower average internal temperatures
- Model can explain 45% of variance of internal temperatures ($R^2 = 0.45$)
- Model is useful for statistical inference and prediction

UNIVERSITY OF CAMBRIDGE

Acknowledgements

- UCL Energy institute for providing the data and financial support allowing me to carry out this research
- The co-authors for their valuable comments and feedback
- My supervisors Dr Michael Pollitt and Professor Doug Crawford-Brown for their comments
- Mathieu Durand-Daubin and two other blind reviewers for their comments and improvement of the article.
- This work has been conducted under the People Energy and Buildings: Distribution, Diversity and Dynamics project (EP/H051112/1) jointly funded by the Engineering and Physical Sciences Research Council (EPSRC) and EDF Group. The data is drawn from the CaRB Home Energy Survey conducted as part of the Carbon Reduction in Buildings project (GR/S94377/01) jointly funded by the Carbon Trust and the EPSRC. The authors would like to thank the sponsors for their support.

Tyndall Centre for Climate Change Research

UCL ENERGY INSTITUTE

4CMR Foreseeing Mitigation

UNIVERSITY OF CAMBRIDGE

Bibliography

Audenaert, A., Briffaerts, K. and Engels, L., 2011. Practical versus theoretical domestic energy consumption for space heating. *Energy Policy*. Available at: DOI:10.1016/j.enpol.2011.05.042 [Accessed August 3, 2011].

Baltagi, B., 2005. *Econometric analysis of panel data*. 3rd ed., Chichester; Hoboken NJ: J. Wiley & Sons.

Baltagi, B., 2009. *A companion to Econometric analysis of panel data, 4th edition*., Hoboken N.J.; Chichester: Wiley; John Wiley [distributor].

Beasley, T.M., 1998. Comments on the Analysis of Data with Missing Values. *Multiple Linear Regression Viewpoints*, 25(1), p.40–45.

Boardman, B., Darby, S., Hinnells, M., Jardine, C.N., Palmer, J. and Sinden, G., 2005. *40% house*. Environmental Change Institute. Technical report. Available at: http://www.eci.ox.ac.uk/research/energy/downloads/40house/40house.pdf [Accessed May 17, 2009].

BRE, 2002. *BREDEM-8: model description, 2001 update*. B. Anderson, ed., Watford: BRE.

British Standards, 1995. Moderate thermal environments: determination of the PMV and PPD indices and specification of the conditions for thermal comfort. Available at: http://www.iso.org/iso/catalogue_detail.htm?csnumber=14567 [Accessed December 8, 2011].

Cameron, A. and Trivedi, P.K., 2009. *Microeconometrics using Stata*., College Station Texas: Stata Press.

Cheng, V. and Steemers, Koen, 2011. Modelling domestic energy consumption at district scale: A tool to support national and local energy policies. *Environmental Modelling & Software*, 26(10), p.1186–1198. Available at: DOI:16/j.envsoft.2011.04.005 [Accessed August 1, 2011].

UNIVERSITY OF CAMBRIDGE

Bibliography

Communities and Local Government, 2009. *English House Condition Survey (EHCS) 2007: annual report.*, London: Communities and Local Government. Available at: http://www.communities.gov.uk/documents/statistics/pdf/1346262.pdf.

Communities and Local Government, 2008. English House Condition Survey. Available at: http://www.communities.gov.uk/housing/housingresearch/housingsurveys/englishhousecondition/.

Crosbie, T. and Baker, K., 2010. Energy-efficiency interventions in housing: learning from the inhabitants. *Building Research & Information*, 38(1), p.70. Available at: DOI:10.1080/09613210903279326 [Accessed April 29, 2010].

van Dam, S.S., Bakker, C.A. and van Hal, J.D.M., 2010. Home energy monitors: impact over the medium-term. *Building Research & Information*, 38(5), p.458–469. Available at: DOI:10.1080/09613218.2010.494832.

Darby, S., 2010. Smart metering: what potential for householder engagement? *Building Research & Information*, 38(5), p.442–457. Available at: DOI:10.1080/09613218.2010.492660.

de Dear, R. and Schiller Brager, G., 2001. The adaptive model of thermal comfort and energy conservation in the built environment. *International Journal of Biometeorology*, 45(2), p.100–108. Available at: DOI:10.1007/s004840100093 [Accessed May 22, 2009].

DECC, 2008. *The potential for behavioural and demand side management measures to save electricity, gas and carbon in domestic sector, and resulting supply side implications*. London: DECC. Technical report. Available at: http://www.defra.gov.uk/environment/climatechange/uk/energy/energyservices/documents/decc-save-energy-implications.pdf [Accessed April 14, 2009].

DEFRA, 2005. *SAP2005*. Technical report. Available at: http://projects.bre.co.uk/sap2005/pdf/SAP2005_9-83.pdf.

UNIVERSITY OF CAMBRIDGE

Bibliography

DETR, 1996. *English House Condition Survey: User Guide*. Technical report. Available at: http://www.communities.gov.uk/housing/housingresearch/housingsurveys/englishhousecondition/ [Accessed March 10, 2010].

Donner, A., 1982. The Relative Effectiveness of Procedures Commonly Used in Multiple Regression Analysis for Dealing with Missing Values. *The American Statistician*, 36(4), p.378–381. Available at: DOI:10.2307/2683092 [Accessed February 3, 2012].

Druckman, A., Chitnis, M., Sorrell, S. and Jackson, T., 2011. Missing carbon reductions? Exploring rebound and backfire effects in UK households. *Energy Policy*, 39(6), p.3572–3581. Available at: DOI:16/j.enpol.2011.03.058 [Accessed June 1, 2011].

Drukker, D., 2003. Testing for serial correlation in linear panel-data models. *Stata Journal*, 3(2), p.168–177. Available at: [Accessed November 28, 2011].

Emery, A.F. and Kippenhan, C.J., 2006. A long term study of residential home heating consumption and the effect of occupant behavior on homes in the Pacific Northwest constructed according to improved thermal standards. *Energy*, 31(5), p.677–693. Available at: DOI:16/j.energy.2005.04.006 [Accessed June 29, 2011].

Feist, W. and Schnieders, J., 2009. Energy efficiency – a key to sustainable housing. *The European Physical Journal - Special Topics*, 176(1), p.141–153. Available at: DOI:10.1140/epjst/e2009-01154-y [Accessed October 12, 2009].

Firth, S. K., Lomas, K. J. and Wright, A. J., 2010. Targeting household energy-efficiency measures using sensitivity analysis. *Building Research & Information*, 38(1), p.25. Available at: DOI:10.1080/09613210903236706 [Accessed April 29, 2010].

UNIVERSITY OF CAMBRIDGE

Bibliography

Gill, Z.M., Tierney, M.J., Pegg, I.M. and Allan, N., 2010. Low-energy dwellings: the contribution of behaviours to actual performance. *Building Research & Information*, 38(5), p.491–508. Available at: DOI:10.1080/09613218.2010.505371.

Greene, W., 2012. *Econometric analysis*. 7th ed., Boston: Prentice Hall.

Greening, L.A., Greene, D.L. and Difiglio, C., 2000. Energy efficiency and consumption -- the rebound effect -- a survey. *Energy Policy*, 28(6-7), p.389–401. Available at: DOI:10.1016/S0301-4215(00)00021-5 [Accessed March 29, 2011].

Heyman, B., Harrington, B.E., Merleau-Ponty, N., Stockton, H., Ritchie, N. and Allan, T.F., 2005. Keeping Warm and Staying Well. Does Home Energy Efficiency Mediate the Relationship between Socio-economic Status and the Risk of Poorer Health? *Housing Studies*, 20(4), p.649–664. Available at: DOI:10.1080/02673030500114656 [Accessed June 18, 2010].

Hitchcock, G., 1993. An integrated framework for energy use and behaviour in the domestic sector. *Energy and Buildings*, 20(2), p.151–157. Available at: DOI:10.1016/0378-7788(93)90006-G [Accessed May 13, 2010].

HM Government, 2006. *Climate Change - The UK Programme*. Technical report. Available at: http://www.defra.gov.uk/environment/climatechange/uk/ukccp/pdf/ukccp06-all.pdf [Accessed April 24, 2009].

Hunt, D.R.G. and Gidman, M.I., 1982. A national field survey of house temperatures. *Building and Environment*, 17(2), p.107–124. Available at: DOI:10.1016/0360-1323(82)90048-8 [Accessed December 7, 2011].

Hutchinson, E.J., Wilkinson, P., Hong, S.H. and Oreszczyn, Tadj, 2006. Can we improve the identification of cold homes for targeted home energy-efficiency improvements? *Applied Energy*, 83(11), p.1198–1209. Available at: DOI:10.1016/j.apenergy.2006.01.007 [Accessed June 18, 2010].

Janoski, T., 1994. *The comparative political economy of the welfare state*., Cambridge UK: Cambridge University Press.

UNIVERSITY OF CAMBRIDGE

Bibliography

Jenkins, D.P., Peacock, A.D., Banfill, P.F.G., Kane, D., Ingram, V. and Kilpatrick, R., 2012. Modelling carbon emissions of UK dwellings – The Tarbase Domestic Model. *Applied Energy*, 93, p.596–605. Available at: DOI:10.1016/j.apenergy.2011.11.084 [Accessed July 17, 2012].

Johnston, D., 2003. *A physically Based Energy and Carbon dioxide emission model of the UK Housing Stock*. Available at: http://www.leedsmet.ac.uk/as/cebe/assets/djthesis.pdf [Accessed May 15, 2009].

Kahneman, D., 2003. Maps of bounded rationality: Psychology for behavioural economics. *The American economic review*, 93(5), p.1449–1475.

Kelly, S., 2011a. Do homes that are more energy efficient consume less energy?: A structural equation model of the English residential sector. *Energy*, 36(9), p.5610–5620. Available at: DOI:16/j.energy.2011.07.009 [Accessed September 1, 2011].

Kelly, S., 2011b. External English temperature database documentation (2007-2008). Available at: Request: sjk64@cam.ac.uk.

Kmenta, J., 1971. *Elements of econometrics.*, New York: Macmillan.

Kremelberg, D., 2011. *Practical statistics: a quick and easy guide to IBM SPSS statistics, STATA, and other statistical software*., Los Angeles: SAGE Publications.

Kusiak, A., Li, M. and Zheng, H., 2010. Virtual models of indoor-air-quality sensors. *Applied Energy*, 87(6), p.2087–2094.

Lomas, K. J., 2010. Carbon reduction in existing buildings: a transdisciplinary approach. *Building Research & Information*, 38(1), p.1. Available at: DOI:10.1080/09613210903350937 [Accessed March 11, 2010].

Lutzenhiser, L., 1992. A cultural model of household energy consumption. *Energy*, 17(1), p.47–60. Available at: DOI:10.1016/0360-5442(92)90032-U [Accessed December 20, 2010].

UNIVERSITY OF CAMBRIDGE

Bibliography

McMichael, M., 2011. *People Energy and Buildings: Review of relevant databases*. London: UCL Energy Institute. Technical report.

Natarajan, S. and Levermore, G.J., 2007. Predicting future UK housing stock and carbon emissions. *Energy Policy*, 35(11), p.5719–5727. Available at: DOI:10.1016/j.enpol.2007.05.034 [Accessed March 20, 2009].

O'brien, R.M., 2007. A Caution Regarding Rules of Thumb for Variance Inflation Factors. *Quality & Quantity*, 41(5), p.673–690. Available at: DOI:10.1007/s11135-006-9018-6 [Accessed December 21, 2011].

Olander, F. and Thogersen, J., 1995. Understanding of consumer behaviour as a prerequisite for environmental protection. *Journal of Consumer Policy*, 18(4), p.345–385. Available at: DOI:10.1007/BF01024160 [Accessed February 4, 2012].

Olinsky, A., Chen, S. and Harlow, L., 2003. The comparative efficacy of imputation methods for missing data in structural equation modeling. *European Journal of Operational Research*, 151(1), p.53–79. Available at: DOI:10.1016/S0377-2217(02)00578-7 [Accessed June 30, 2010].

Oreszczyn, Tadj and Lowe, R., 2010. Challenges for energy and buildings research: objectives, methods and funding mechanisms. *Building Research & Information*, 38(1), p.107. Available at: DOI:10.1080/09613210903265432 [Accessed April 29, 2010].

Parks, R.W., 1967. Efficient Estimation of a System of Regression Equations when Disturbances are Both Serially and Contemporaneously Correlated. *Journal of the American Statistical Association*, 62(318), p.500–509. Available at: DOI:10.2307/2283977 [Accessed November 27, 2011].

Richardson, I., Murray Thomson and David Infield, 2008. A high-resolution domestic building occupancy model for energy demand simulations. *Energy and Buildings*, 40(8), p.1560–1566. Available at: DOI:10.1016/j.enbuild.2008.02.006 [Accessed March 29, 2012].

UNIVERSITY OF CAMBRIDGE

Bibliography

Rowntree, R.H., 1928. Measuring the Accuracy of Prediction. *The American Economic Review*, 18(3), p.477–488. Available at: [Accessed January 9, 2012].

Royal Commission, 2007. *26th Report - The Urban Environment*. Technical report. Available at: http://www.rcep.org.uk/urban/report/urban-environment.pdf [Accessed May 3, 2009].

Shipworth, M., 2011. Thermostat settings in English houses: No evidence of change between 1984 and 2007. *Building and Environment*, 46(3), p.635–642. Available at: DOI:10.1016/j.buildenv.2010.09.009 [Accessed December 16, 2010].

Shipworth, M., Firth, Steven K., Gentry, M.I., Wright, Andrew J., Shipworth, D.T. and Lomas, Kevin J., 2010. Central heating thermostat settings and timing: building demographics. *Building Research & Information*, 38(1), p.50. Available at: DOI:10.1080/09613210903263007 [Accessed June 9, 2010].

Shorrock, L.D., 2000. Identifying the individual components of United Kingdom domestic sector carbon emission changes between 1990 and 2000. *Energy Policy*, 28(3), p.193–200. Available at: DOI:10.1016/S0301-4215(00)00011-2 [Accessed December 6, 2009].

Shorrock, L.D., 2003. A detailed analysis of the historical role of energy efficiency in reducing carbon emissions from the UK housing stock. *ECEE*. Available at: http://www.bre.co.uk/filelibrary/rpts/eng_fact_file/Shorrock.pdf [Accessed May 21, 2009].

StataCorp, 2009a. *Stata longitudinal panel data: reference manual*. 11th ed., Texas, USA: Stata Corporation.

StataCorp, 2009b. *Stata Statistical Software*., Texas, USA: College Station.

StataCorp, 2011. FAQ: Testing for panel-level heteroskedasticity and autocorrelation. Available at: http://www.stata.com/support/faqs/stat/panel.html [Accessed December 19, 2011].

UNIVERSITY OF CAMBRIDGE

Bibliography

StataCorp, 2010. *Stata reference manual extract*. 11th ed., Texas, USA: Stata Press.

Stevenson, F. and Leaman, A., 2010. Evaluating housing performance in relation to human behaviour: new challenges. *Building Research & Information*, 38(5), p.437–441. Available at: DOI:10.1080/09613218.2010.497282.

Summerfield, A.J., Lowe, R.J., Bruhns, H.R., Caeiro, J.A., Steadman, J.P. and Oreszczyn, T., 2007. Milton Keynes Energy Park revisited: Changes in internal temperatures and energy usage. *Energy and Buildings*, 39(7), p.783–791. Available at: DOI:10.1016/j.enbuild.2007.02.012 [Accessed December 13, 2011].

Summerfield, A.J., Lowe, R.J. and Oreszczyn, T., 2010. Two models for benchmarking UK domestic delivered energy. *Building Research & Information*, 38(1), p.12–24. Available at: DOI:10.1080/09613210903399025 [Accessed June 15, 2011].

Summerfield, A.J., Pathan, A., Lowe, R.J. and Oreszczyn, T., 2010. Changes in energy demand from low-energy homes. *Building Research & Information*, 38(1), p.42. Available at: DOI:10.1080/09613210903262512 [Accessed June 9, 2010].

UK Meteorological Office, 2011. *Historical Central England Temperature (HadCET) Data*. Hadley Centre. Technical report. Available at: http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_CET.

Utley, J.I. and Shorrock, L.D., 2007. *Domestic Energy Fact File 2007: England Scotland, Wales and Northern Ireland*. Technical report. Available at: http://www.bre.co.uk/filelibrary/rpts/eng_fact_file/countryfactfile2007.pdf [Accessed May 26, 2009].

Wall, R. and Crosbie, T., 2009. Potential for reducing electricity demand for lighting in households: An exploratory socio-technical study. *Energy Policy*, 37(3), p.1021–1031. Available at: DOI:10.1016/j.enpol.2008.10.045 [Accessed March 19, 2010].

Wooldridge, J., 2003. *Introductory Econometrics: A Modern Approach*. 2nd ed., Australia ;;Cincinnati Ohio: South-Western College Pub.

UNIVERSITY OF CAMBRIDGE

Bibliography

Wooldridge, J., 2002. *Econometric analysis of cross section and panel data*., Cambridge Mass.: MIT Press.

Wooldridge, J.M., 2005. *Introductory Econometrics: A Modern Approach*. 3rd ed., South-Western College Pub.

Wright, A., 2008. What is the relationship between built form and energy use in dwellings? *Energy Policy*, 36(12), p.4544–4547. Available at: DOI:10.1016/j.enpol.2008.09.014 [Accessed September 12, 2009].

Yun, G.Y. and Steemers, K., 2011. Behavioural, physical and socio-economic factors in household cooling energy consumption. *Applied Energy*, 88(6), p.2191–2200. Available at: [Accessed March 7, 2011].