IEH Institute of Environment and Health

Cranfield UNIVERSITY

Climate change – health impacts due to changes in the indoor environment; Research needs

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February 2011

Department of Health Policy Research Programme project (080/0006)

The Institute of Environment and Health (IEH) was established at Cranfield University in November 2005. The research and consultancy activities of the Institute are principally funded through specific grants, contracts and awards from UK Government Departments and Agencies.

The views expressed here do not necessarily represent those of any Government Department or Agency.

This document has been prepared as an unpublished report by the Institute of Environment and Health for the Department of Health.

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ISBN: 978-1-899110-49-0

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Summary

People in industrialised countries spend approximately 80% of their time indoors and the young and the elderly and people in poor health are likely to spend considerably more time indoors, particularly at home. Therefore all aspects of health that are related to environmental conditions can be impacted by the quality of the indoor environment. The indoor environment should provide shelter from the extremes of the outdoors and maintain a comfortable indoor climate, particularly thermal comfort, and provide appropriate protection against other environmental factors including pollutants, infectious agents and noise. Expected future changes in climate resulting from the impact of man on the atmosphere leading to global warming will impact the effectiveness of buildings to provide appropriate shelter and associated environmental conditions.

One of a range of UK government actions to mitigate effects of climate change is to reduce carbon emissions to the atmosphere from the built environment. This has resulted in an on-going process of change in the way we construct and heat new buildings as well as renovation of existing buildings to improve their energy efficiency. Broadly these changes result in more air tight and highly insulated structures. These changes can impact the quality of the indoor environment and there are concerns that some of these changes could have adverse consequences for occupant health.

This report summarises the expected changes in climate in the UK and the changes to the built environment that are occurring through mitigation and adaptation actions. It reviews available research on changes to the indoor environment with a focus on likely changes to indoor air quality and thermal comfort in homes. It concludes with recommendations for further research to investigate the quality of the indoor environment in existing homes and highly energy efficient homes, to better understand the relationship between the indoor environment and health as well as to identify whether further guidance is required on the design, construction and maintenance of new homes and renovation of existing buildings to ensure that the health of occupants is not adversely affected. These recommendations are contained within four main topics;

1) Improved understanding of indoor air quality with respect to levels of key pollutants and environmental conditions in UK homes and the factors that determine those levels / conditions and people's exposure.

2) Studies specific to energy efficient homes to address performance of new and recently renovated homes to inform requirements for future new homes and renovation programmes.

3) Development of common protocols for measuring indoor pollutants, occupant exposure to pollutants, building airtightness, ventilation rate and occupant and household activities.

4) Relationships between indoor environment quality and health, in particular studies involving vulnerable groups.

Introduction

The indoor environment is a significant determinant of population health. People in industrialised countries spend approximately 80% of their time indoors. The young and the elderly and people in poor health are likely to spend considerably more time at home, perhaps 100% on many days. Therefore all aspects of health that are related to environmental conditions can be impacted by the quality of the indoor environment. These are wide ranging and include safety in terms of prevention of accidents, the opportunity for exercise perhaps encouraged by safe access to an outside area, and well being arising from impact of the environment on mental health. A key function of the built environment is to provide shelter from the extremes of the outdoors and maintain a comfortable indoor climate; particularly thermal comfort. In so doing the building needs to provide appropriate protection against other environmental factors including pollutants, infectious agents and noise. Hence good building design supported by regulations and guidance established over many years seeks to optimise these features but this must be balanced against costs of provision.

A World Health Organisation (WHO) expert meeting has recommended that international guidance should be developed on 'healthy housing' to help prevent a wide range of diseases and unintentional injuries that can be addressed through better housing (WHO 2010). Key housing related health risks include respiratory and cardiovascular disease from indoor pollution, illness and death from temperature extremes, communicable disease spread because of poor living conditions and risks of home injuries. Inadequate ventilation is associated with higher risk to health and poor housing quality and design can exacerbate health impacts of exposure to temperature extremes that are occurring more frequently due to climate change. One recommendation is that home occupants need to know how to use their homes in a healthier manner, particularly when homes are made more weathertight to save energy.

Building Regulations set requirements to ensure the safety and performance of new (and refurbished) buildings and are reviewed periodically to take advantage of new knowledge and technology and to adapt to changing environments and people's requirements. A major driver for change both in the 1970s and more recently has been the need for increased energy efficiency and during this century the objective of reducing carbon emissions to mitigate the effects of climate change has been paramount. Indeed 'designing buildings' is identified as one of the priority areas for action by a government advisory group on the preparedness of the UK for climate change (ASC, 2010).

Almost half of the UK's carbon emissions come from the use of buildings (27% from homes and a further 17% from non-domestic buildings) and therefore increasing the energy efficiency of buildings and reducing the carbon emissions is an important part of government strategy to minimise the future impact of climate change (CLG, 2008b). It should be noted that government and environmental pressure groups have undertaken campaigns to persuade people to use less energy at home since the 1970s (Congreve, 2010). However domestic energy use has increased by 36% from 1971 to 2001, in part because of a rise in the number of households. Average energy use increased 5% over the period despite gains in energy efficiency because these gains were offset by wider use of electrical appliances and central heating. Carbon emissions from the UKs stock of 1.8 million non-domestic buildings have remained roughly constant over the past two decades and extensive energy efficiency measures are proposed for this sector as part of actions to meet the government's ambition for all buildings to have close to zero emissions by 2050 (Carbon Trust, 2009).

This report considers the current and likely future changes to the indoor environment of UK buildings driven by our response to concerns about climate change and how these could impact the health and well being of occupants. The focus is on dwellings, as that is the environment in which we spend most time, and those changes that affect air quality and temperature. The purpose is to identify gaps in knowledge and research needs***. A reader not requiring background information on climate change, changes to buildings design, and a summary of current knowledge on the quality of indoor environments and health effects, should focus on the last two sections (pages 28- 35) that address research needs.***

As a base document this report uses a study published in 2009 that reviewed published literature on indoor air quality in energy efficient homes (Crump *et al*., 2009). It additionally reviews recent publications and changes to relevant regulations impacting the indoor environment. The report does not address issues of acoustics and daylight in detail, but it should be recognised that these can also influence health and well being and optimal requirements may conflict with provision of other conditions (e.g. ventilation through opening windows may not be desirable if high levels of external noise and ventilation fans may be a source of noise). It concludes with recommendations for research to inform development of policy on protecting public health by influencing the physical properties of the indoor environment and the manner by which occupants use and interact with their indoor environment.

Climate change

The scale of the future change in climate arising from anthropogenic impact will depend upon emissions of greenhouse gases and therefore the success of governments worldwide to control these emissions. Predictions of future changes in climate are inherently uncertain because of the incomplete understanding of the complex processes determining climate and because the future emission of greenhouse gases is not known. However there is strong evidence for climate change occurring in recent decades and modelling by a wide range of groups and international peer review of their work has achieved a broad consensus about the likely future changes in climate. There is extensive literature available, most notably from the Intergovernmental Panel on Climate Change (IPCC) and the findings of their fourth assessment was published in 2007 (IPPC, 2007).

Clearly climate change will not be uniform on a global scale and it is necessary to understand the impact on a regional basis to assess the possible direct impact on human health through changes in weather etc. There will also probably be indirect impacts through changes in availability of food resources and other changes in world trade that may affect the quality of diets and availability of other resources such as fuel which could impact population health.

With regard to the UK, the possible ‘local’ effect on climate is being assessed by the UK government within the ‘Adapting to climate change programme’ and climate projections for the UK have been published together with more detailed information on the UK climate projections website (Defra 2009). Their report gives a summary of observed trends in climate over recent decades and predicted changes in climate for three scenarios with different future trends in greenhouse gas emissions.

Current observed trends in UK climate include the following features (Defra, 2009);

- Temperature in Central England risen by 1ºC since the 1970s, with 2006 being the warmest in the 348 year of records available,
- Over the past 250 years there has been a slight trend of increased rainfall in winter and decreased rainfall in summer,
- All UK regions have an increase in the amount of winter rain that falls in heavy downpours,
- Sea levels around the UK have risen by about 1mm/year over the 20th century.

Projected changes in climate across the UK for the ‘medium’ emissions scenario relative to the 1961-1990 climate are;

- All areas will get warmer, more so in summer than in winter (average regional summer temperature rise of 3 to 4ºC in the 2080s),
- Summer precipitation will tend to decrease across the UK (regional average decline of between -17 and -23% in 2080s),
- Winter precipitation tends to increase across all the UK (regional average increase of between +14% in NE to +23% in SW),
- Sea level rise and increase in storm surge.

Examples of the projections for different regions over time are shown in table 1.

Table 1. Projected changes in climate for some regions in the UK based on the medium emissions scenario (Defra, 2009).

Region	Projected change in climate	Date		
		2020s	**2040s**	**2080s**
SE England	Rise in summer temperature	1.6^{o}C	2.3 ^{o}C	3.9 ^{o}C
SW England	Decline in summer precipitation	-7%	-13%	-23%
NW England	Increase in winter precipitation	6%	10%	16%
London	Sea level rise	No data	18cm	36cm

There is therefore expected to be significant regional variation in the type and severity of climate change; for example urban areas in the south will need to plan for increased heatwaves and areas in the north may attract greater tourism (Defra, 2009).

There are two basic responses to the potential impacts of climate change (IPPC, 2007a);

- Mitigation; an anthropogenic intervention to reduce the anthropogenic forcing of the climate system; it includes strategies to reduce greenhouse gas sources and emissions and enhancing greenhouse gas sinks.
- Adaptation; adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.

Current and future changes in buildings to mitigate climate change

Existing buildings

The government encourages improvements to the energy efficiency of homes through a number of schemes such as the Warm Front initiative that addresses fuel poverty by providing financial support to householders to install measures such as improved insulation of walls and roofs and more energy efficient heating systems (DECC, 2009). It is estimated that 75% of the current housing stock will still exist in 2050 and therefore increasing the energy performance of these is an important aspect of climate change mitigation (Wright, 2008). The vast majority of the 24 million existing homes are houses and 39% predate 1944 and only 19% were built after thermal standards were raised significantly in 1980.

Roberts (2008) reviewed measures currently applied to improve the energy efficiency of existing buildings; draught proofing (draught stripping, replacing leaky windows, closing off unused chimneys), loft insulation, insulation of cavity walls, and more extensive renovation involving external insulation to side and rear walls, and internal insulation of walls and floors. In the UK, 3-4 million households meet the definition of fuel poverty (household spending more than 10% of income on energy) and it has been proposed that investment in energy efficient measures in the 550,000 fuel poor socially housed dwellings in the UK could provide significant reduction in carbon emissions and reduce fuel poverty (Jenkins, 2010).

While not considered in detail in this review, it should be noted that energy efficiency programmes are being implemented in other countries. For example in the US, where housing consumes more than one-fifth of energy used, the Congress appropriated $16 billion for energy efficiency and renewable energy projects in 2009 with an emphasis on home energy retrofits (Kuholski et al., 2010).

With regard to new dwellings, the major influence of government in England, Wales and N Ireland on requirements for building design to respond to the needs to mitigate and adapt in response to climate change is through the Code for Sustainable Homes (CSH) and the building regulations. In addition the building regulations are applicable to extensions and major refurbishment of buildings. The CSH does not apply in Scotland.

New Buildings

The Code for Sustainable homes

The CSH measures the sustainability of a new home against nine categories of sustainable design, rating the 'whole home' as a complete package. The Code uses a 1 to 6 star rating system to communicate the overall sustainability performance of a new home. The Code aims to provide valuable information to home buyers, and to offer builders a tool with which to differentiate themselves in sustainability terms. There are two main documents describing the Code; one sets out the assessment process and the performance standards required (CLG 2008) and the second provides information on the detailed evidence required to meet the standards and sets out the assessment methodologies (CLG 2010). When introduced Code level 1 was above the then current regulatory standards and higher code levels are increasingly stringent - with Code 4 representing exemplary performance and Code 6 an aspirational level based on ‘zero carbon’ emissions and high performance across all environmental categories. The Code is a voluntary standard but it is also used as a condition of funding for the Homes and Communities Agency National Affordable Housing Programme, on other government projects and land, and by local authorities when they want to set sustainability-based planning conditions on housing developments in their area (CLG 2009).

There are nine categories of environmental impact assessed in the Code but none of these categories directly address indoor air quality (CLG 2010). Under category 1 the sub-category ‘Ene 2’ (Building fabric) involves calculation of a heat loss parameter that includes the airtightness of the structure, thereby influencing the amount of air infiltration. ‘Ene 4’ concerns adequate secure space for drying of clothes and standards for ventilation of any such internal space and is aimed at reducing risk of high humidity and condensation associated with that activity. Under category 7 credits are provided for good daylighting, sound insulation and provision of outdoor space. While the first two of these issues may benefit the quality of the indoor environment they do not impact upon indoor air quality. Category 8 concerns provision of guidance to understand and operate the home efficiently and through correct operation of ventilation and heating systems this should in practice benefit indoor air quality, although such benefits are difficult to quantify.

Building Regulations and ‘zero carbon’

Expected changes to the Building Regulations in 2010, 2013 and 2016 for dwellings were outlined in a forward look paper (CLG 2007) and these equate to the energy performance standards in the Code for levels 3, 4 and 6 respectively. A number of illustrative designs are described to meet the proposed new requirements that include more airtight building envelopes and options for MVHR and natural ventilation. In the section on implications, it states that advanced standards of airtightness will make a significant contribution to the 2010 and 2013 standards, particularly when coupled with high performance mechanical ventilation systems. It notes that Part F (Ventilation) of the building regulations will need to be kept under review in parallel with developments in Part L (Conservation of fuel and power) to ensure that carbon dioxide (CO_2) reductions are not achieved at the price of unsatisfactory indoor air quality.

A document on assessing the impact of the proposed policy of zero carbon homes was published by CLG in December 2008 (CLG 2008a). There is recognition in the section on environmental impact of possible consequences for air quality (section 130). This paragraph refers to possible benefits such as fewer problems with pollen and other airborne allergens in the home. It also states that negative effects are also possible, but refers to planned revision of Part F of the Building Regulations which will look specifically at ventilation system requirements and indoor air quality issues to ensure that health standards are not undermined.

A 2009 consultation document set out proposed changes to the CSH in 2010 to align it with changes to Part L of the Building Regulations and the proposed approach to adopting the 2016 definition of zero carbon. The most significant changes are within the energy section of the Code. The document refers to the December 2008 consultation (CLG 2008b) on the definition of zero carbon homes and the many responses that argued that the proposed standards were too demanding for the temperate climate in England and inappropriate as a minimum regulatory standard applicable to all dwellings. Recognising those concerns, the July statement expressed the Government’s ambition in terms of the “highest practical energy efficiency level realisable in all dwelling types.” Implicit within this phrase are six criteria including one about the indoor environmental quality:

desirable and healthy homes; ‘It would not be acceptable to require a standard which presents known and insurmountable risks to the comfort and health of occupants, e.g. because of poor indoor air quality and/or overheating.’

The document refers to advice from a specialist task group co-ordinated by the Zero Carbon Hub to “examine the energy efficiency metrics and standards which will realise our ambition of the highest practical energy efficiency level realisable in all dwelling types.” Among the recommendations are the need for further research on a number of issues including;

- achieving good air quality in low air permeability homes with different ventilation systems,
- overheating risk and mitigation.

The 2010 edition of Approved Document F, Ventilation, came into force on 1 October 2010 (HM 2010). The main changes since the 2006 edition to the legal requirements were;

- All fixed MV systems are to be commissioned and a notice provided to the Building Control Body,
- For MV systems installed in new dwellings air flow rates shall be measured on site and notice given to the Building Control Body,
- The owner shall be given sufficient information about the ventilation system and its maintenance requirements so that the system can be operated to provide adequate flow.

Regarding the technical guidance, the main changes include increasing the ventilation provision for dwellings with high design airtightness (≥ 5 $m^3/(h.m^2)$ at 50Pa) and reference to a new guide on installing, inspecting, testing and commissioning ventilation systems in dwellings. The 2006 and 2010 editions of Part L give a limit value for the required measured air permeability of 10 $m^3/(h.m^2)$ at 50Pa. There were also amendments to Part J (ADJ) concerning combustion appliances and fuel storage systems that came into effect in October 2010. These include an increase in the permanent ventilation openings for open flued appliances in very airtight homes (design air permeability ≤ 5 $m^3/(h.m^2)$) to counteract the decrease in adventitious ventilation relative to older houses. Also guidance is provided on a new requirement concerning provision of carbon monoxide (CO) alarms in the room where solid fuel appliances are installed. The alarms can be battery operated or have a fixed wiring supply and should incorporate an alarm to alert users when the working life of the alarm is due to pass.

Quality of the indoor environment in energy efficient homes

Crump *et al*., (2009) summarise sources and types of indoor air pollution that include chemical, physical and biological contaminants. The main sources of pollutants are outdoor air, combustion of fuel, tobacco smoke, building, furnishing and consumer products, office equipment, ventilation systems, people, pets, and soil gas intrusion. The main pollutants are particulates (PM_{10}, $PM_{2.5}$, ultrafines and fibres), CO, excess moisture, nitrogen oxides, sulphur dioxide, volatile organic compounds (very volatile, volatile and semi-volatile), formaldehyde, radon, ozone, ammonia and biological particulates (allergens, bacteria, fungi). The report also summarised studies of relationships between indoor air quality and health. Since 2009 other significant studies and reports include new guidance from the World Health Organisation (WHO, 2009; WHO, 2010a), and an update on risks from radon (HPA, 2010). As well as air pollutants other factors such as temperature and dampness impact the quality of the indoor environment with consequences for occupant health.

This section summarises studies that have investigated relationships between building characteristics and aspects of the indoor environment that may impact occupant health in energy efficient homes.

Indoor Air pollutants

UK studies of indoor air pollution and building characteristics

IAQ Survey of England

The only large scale study of indoor pollutants in UK homes was carried out in 1997-1999 and this measured concentrations of CO, nitrogen dioxide, formaldehyde and volatile organic compounds (VOCs) in over 800 homes selected as representative of homes in England (Coward *et al*., 2001; Coward *et al*., 2002). As part of this study relationships between pollutant levels and household activities were explored and among the statistically significant findings were that concentrations of formaldehyde and VOCs were highest in newer homes. It is not known whether these concentrations were higher because of stronger sources of these compounds in newer homes or whether lower ventilation rates occurred resulting in less efficient removal of the compounds in the indoor air, or a combination of both of these factors.

The study provided some information about occupant behaviour and the sources of pollutants such as number of householders with an occupant who smokes indoors, occurrence of painting and decorating activity, homes with an integral garage that contain a car, homes where a gas oven is used for secondary heating and those using unflued heating appliances, and the proportion of homes with an extraction fan. It also showed that having a facility such as an extract fan did not necessarily mean that it was used.

Studies of newly built homes

The most informative studies for how IAQ may be impacted by changes in building design have been two quite small studies of new homes built to requirements of the 1995 and 2006 versions of the building regulations. These measured a number of indoor pollutants and also the airtightness of the building fabric as well as the rate of ventilation in the home during the study period.

The study of 37 homes in England built since 1995 was undertaken in 2002 and all homes in the study had central heating with radiators and were double glazed with trickle ventilators in the window units to provide background ventilation (Dimitroulopoulou *et al*., 2005). The 1995 revision of Part F (ADF) involved increased provision for background ventilation based on reports of excessive condensation in new dwellings being built at that time.

Measurements of airtightness of the homes with windows and doors closed, expressed as air changes per hour at 50 Pa, were undertaken using a fan pressurisation technique prior to the monitoring of indoor pollutants. VOCs, NO_2, CO and formaldehyde were measured using diffusive samplers with an exposure period of three days to two weeks, depending on the pollutant. PM_{10} was measured using a pumped gravimetric method with a sampling period of 24 hours. Information was collected about the characteristics of the properties and the activities of occupants using questionnaires. Concurrent with the pollution measurements, a perfluorocarbon tracer method was used to determine the mean rate of air exchange of the indoor air with outside air for the two week period. The results from the indoor air quality (IAQ) measurements were statistically analysed, based on data from questionnaires, including house characteristics and occupant activity diaries. Five of the 37 homes were the subject of more detailed investigations during the following winter and summer.

The mean airtightness of the properties was comparable to the mean values for the general building stock. 70% of the study homes were less airtight than the permeability of 10 $m^3/h.m^{-2}$ recommended in building regulations (Part L (ADL)) in the 1995 edition. In winter, 68% of homes had a whole house ventilation rate below the minimum design value of 0.5 ach (air changes per hour), which according to BRE research is necessary to avoid condensation. In summer, 30% of homes had a whole house ventilation rate below 0.5 ach. Flats seemed to be less ventilated than other types of homes, both in winter and summer. Most occupants were unaware of trickle vent usage and they were fully open in only 4 homes and were fully closed in 13 of the homes. Those homes with trickle vents fully closed had the lowest ventilation rates in winter.

Some relationships between the amount of ventilation and the concentration of some pollutants were found as well as correlation between particular sources and pollution, such as the presence of a gas cooker and the concentration of NO_2. Homes with lower ventilation rate had significantly higher concentrations of TVOC and acetaldehyde. Highest mean TVOC concentrations occurred in the newest homes. Comparison with air quality guidelines found concentrations within guidelines except for: TVOC; 3 homes in winter and nine in summer exceeded 300 $\mu g\ m^{-3}$, NO_2; six homes exceeded the annual mean guideline value for the winter monitoring period. In the 5 homes where more detailed measurements were undertaken the CO 1h and 8h guideline was exceeded in the kitchen of one home in winter, the NO_2 1h guideline in 3 homes, the TVOC 8 h guideline in 3 homes.

On a scale of 1 to 5 (very dissatisfied to very satisfied) occupants were asked to score how satisfied they were with the air quality in their home. A majority scored 4 or 5 and only one scored 2. They were also asked to score any problem with condensation; one property reported a severe problem and the majority reported no problems.

McKay *et al*., (2010) undertook a study to investigate whether the guidance in the 2006 edition of Approved Document (ADF) is effective at providing adequate ventilation and good IAQ.

Measurements were undertaken of airtightness, whole house air exchange rates, mechanical extract flow rates, relative humidity (RH) and some indoor pollutants in 22 occupied homes built to Parts L and F 2006 standards. The homes were located in southern England, included a mixture of types (terraced, semi-detached and detached houses, flats) and all had background ventilators with intermittent extract fans. Measurements took place over one week in each house during the period mid-March to May 2009. The pollutants measured were TVOCs, formaldehyde and nitrogen dioxide. Occupants were encouraged to make full use of the ventilation provision during the week of sampling and therefore trickle vents were fully open and extract fans in the kitchen and toilet/bathroom were applied at their highest setting during cooking and bathing. Occupants were requested not to open windows.

The study found that the ventilation provision did not meet requirements in ADF 2006 in a number of homes; the area of trickle ventilators was less than that required in three quarters of the homes, half did not have the required gap under doors, and less than half of the extract fans achieved recommended air flows. All flats and 40% of the other dwellings did not achieve the recommended background ventilation rate of 0.5 ach. It was projected that RH would exceed recommended guidelines in 4 homes. Nitrogen dioxide levels in the kitchen exceeded performance guidelines in 4 homes and over half of the homes had TVOC levels exceeding the AD (F) guideline. The authors note that occupants probably do not normally use their ventilation provision to full capacity and therefore pollutant levels may be higher during normal use. Key recommendations were;

- the ventilation system should be installed correctly,
- most airtight homes (permeability of less than $4m^3/h.m^2$) may require increased background ventilation to control pollutants (TVOC in particular),
- a larger study is necessary to further investigate the performance of new dwellings,
- consideration should be given to reducing sources of VOCs through product controls.

Studies outside the UK

Crump et al., (2009) also reviewed major studies of indoor air quality and ventilation in homes outside of the UK and noted that these were generally quite limited either in scope of the range of pollutants or numbers of homes and there was a general lack of ventilation measurements. Also it was commented that differences in climate, construction practice and social and economic circumstances mean that direct transfer of knowledge to the UK is problematic.

Logue *et al*., (2010) compiled summary data from 88 studies in the US and some other industrial countries that reported measurements of chemical pollutants in residences. They note that as outdoor air pollutant concentrations decrease and residential air exchange rates are lowered with improved air tightness, the contribution of indoor pollutant sources to overall exposure is expected to become increasingly more significant. They conducted a hazard analysis of available data to identify chronic and acute chemical contaminants of concern in US residences. They identified data on 321 chemical contaminants; 40% did not have available toxicity data. 31 chemical hazards were identified and 9 were identified as priority chemical pollutants in US homes (acetaldehyde, acrolein, benzene, 1,3-butadiene, 1,4-dichlorobenzene, formaldehyde, naphthalene, NO_2 and $PM_{2.5}$ particulates).

Offerman (2009) investigated IAQ and ventilation in 108 single family detached homes built between 2002 and 2004, including a sub-set of 26 homes with mechanical ventilation. Measurements were undertaken in 2007-2008 and included VOCs, formaldehyde, $PM_{2.5}$, NO_2, CO, CO_2, temperature and humidity over a 24 hour period. Tracer gas was used to determine outdoor ventilation rates and in addition the airtightness of the structure, performance of fans and ducting and information about occupant behaviour was recorded. They found that a substantial percentage of occupants never opened their windows, especially in winter. The median 24 hour outdoor air exchange rate was 0.26 ach (range 0.09 to 0.35) and 67% of homes had outdoor air exchange rates below the California Building Code requirement of 0.35 ach. They conclude that in new homes with low outdoor air exchange rates, indoor concentrations of air contaminants with indoor sources, such as formaldehyde and some VOCs, can become substantially elevated and exceed recommended US exposure guidelines. The ducted mechanical ventilation systems generally did not perform well because of low flow rates (64% didn't meet ASHRAE standards) and the short time they were used by occupants. Heat recovery systems performed better and their performance met industry standards.

Other factors; thermal comfort, mould, mites

The WHO undertook a major review of the scientific evidence on health problems associated with building moisture and biological agents (WHO, 2009). The most important health effects identified are increased prevalence of respiratory symptoms, allergies and asthma as well as perturbation of the immunological system. The report notes that several global trends contribute to the conditions associated with increased exposure to dampness and mould including energy conservation measures that are not properly implemented (tightened building envelopes, ventilation deficits, improper insulation) and climate change (increasing frequency of extreme weather conditions, shifting of climate zones). They conclude that relations between dampness, microbial exposure and health effects cannot be currently quantified precisely and therefore no quantitative health based guideline value for acceptable levels of contamination by micro-organisms can be established. The recommendation is therefore that dampness and mould related problems be prevented. It is noted that dampness is associated with increased growth of micro-organisms including fungi, actinomycetes and other bacteria. It may result in greater numbers of spores, cell fragments, allergens, mycotoxins, endotoxins, β-glucans, and VOCs in indoor air. Also microbial interactions and moisture can produce chemical emissions from building materials and this may play a role in health effects. Also dampness can be associated with poor ventilation which can be associated with poor IAQ. Therefore understanding the causative links between dampness and health effects is complex.

Ridley *et al.*, (2006) investigated links between ventilation and asthma / house dust mites and considered the likelihood of serious problems of mould growth in housing with multiple occupancy and low air-leakage rates. The study involved literature review, expert workshop and theoretical modelling. The authors concluded that the literature reviewed shows general consensus that a link exists between ventilation rates in dwellings and respiratory hazards such as house dust mites and these hazards are linked to respiratory problems. They identify a need for large-scale measurement studies in which all relevant studies are considered and suggest such studies would preferably be prospective. The modelling study suggested that an average ventilation of 0.5 ach or greater is needed to avoid mould growth and 0.8 ach or greater to avoid house dust mite populations increasing annually. They discuss data of relevance to understanding links between ventilation and health in a number of databases including the English House Condition Survey (EHCS), the Warm Front database and air house leakage data. For example a greater percentage of people living in dwellings built after 1980 have asthma based on the 1996 EHCS data, mould growth is related to the number of occupants based on the EHCS 2001 data and the Warm front data suggests a wide variation in occupant behaviour and moisture production rates. They identify a need for investigations of how occupants change ventilation and moisture production as a function of external temperature and into the possible role of moisture buffering of surface finishes.

Crump et al., (2009) reviewed studies concerning occupant perception and satisfaction with the indoor environment in energy efficient homes which impacts health and well being. Particular concern about the potential for overheating in homes was highlighted but there was a dearth of monitoring data in UK energy efficient homes.

Steemers and Manchanda (2010) investigated occupant satisfaction in 12 office buildings in the UK and India. They find that increased energy use in buildings is associated with reduced occupant control and that reported health conditions of occupants correlated with levels of satisfaction. Energy use was inversely correlated with well being and therefore more energy use did not improve well being. They conclude that occupants both affect the energy performance of buildings and are also affected by the environmental conditions created, and that low energy design can achieve some of the highest levels of occupant satisfaction. They believe the challenge is to design buildings that are responsive to users in terms of creating an environment that is perceived as more comfortable.

Hong *et al*., (2010) undertook a study of winter thermal comfort of 2,500 low-income dwellings in England during 2001 to 2003 to investigate the effect of energy efficient refurbishment of homes carried out under the Warm Front scheme. The mean indoor temperature increased from 17.1ºC to 19 ºC leading to an increase in the number of households feeling thermally comfortable or warmer (from 36% to 79%). There were no measurements of indoor air quality. In the context of renovating homes to be more airtight, Roberts (2008) discusses the relationship between air quality and air humidity, commenting that when old draughty windows are replaced by new types the moisture content of the interior air increases. This becomes critical once surface temperatures drop so low, such as around thermal bridges, that the relative humidity rises locally to 80% or more producing condensation and associated dampness.

Fisk et al., (2009) combined and analysed data from studies of the prevalence of symptoms of sick building syndrome (SBS) in office workers. They found that on average providing more outdoor air reduces the prevalence of symptoms (e.g. ventilation increase from 10 to 25l/s/person is associated with a decrease of about 29% in prevalence of symptoms), but given the costs of energy and risks of climate change it is important to balance the benefits and risks of increased ventilation.

On going studies

This project has not involved a structured investigation of on–going studies but the author is aware of several relevant studies. NHBC (and BRE) are part of a consortium investigating the performance of a small development of homes built to meet Code 6 requirements situated in Slough (BRE 2010). This includes assessment of the performance of mechanical ventilation systems and includes some monitoring of indoor air quality (temperature, humidity, VOCs).

The Energy Technologies Institute initiated a two year project in August 2010 to investigate ways to refurbish the existing housing stock to improve energy efficiency (ETI, 2010). The background is the challenge to treat 26 million homes for improved energy efficiency by 2050, and the need to improve the quality and effectiveness of refurbishment and reduce costs and minimise the impact of the interventions on residents (ETI 2010). The EU project INSULAtE (Improving energy efficiency of housing stock: impacts on indoor environmental quality and public health in Europe) funded under the LIFE programme began in 2010 (EU, 2010). It aims to develop protocols for measurement of indoor air quality parameters (thermal conditions, particulate, VOC and radon concentrations, mineral fibres and microbial concentrations in settled dust), and also for determination of ventilation and occupant behaviours. These will be applied to the study of multi-family buildings in 2-3 countries before and after renovation to improve energy efficiency. The project also aims to investigate several possible health outcomes such as cardio-respiratory health. A further project called Healthvent under the EU's Executive Agency for Health and Consumers started in 2010 with the aim of providing health based ventilation guidelines for non- industrial buildings in Europe (EU 2010a). The aim is to reconcile health and energy impacts and take account of the need for more energy efficient buildings.

Two on-going studies at IEH, Cranfield University concern an investigation of combustion products in energy efficient homes and a study of chemical emissions from building materials and consumer products. These are summarised in Appendix A.

The NHBC have investigated whether the airtightness of homes changes significantly after construction (NHBC, 2011). Some previous studies in Sweden and UK have indicated an increase in the permeability of structures during a 12 month period after construction. This could have consequences for the energy efficiency of the homes and also the possibility of higher ventilation rates being achieved than predicted at the design stage. The NHBC study involved re-testing of airtightness of 23 homes after 12 to 36 months; a range of home types were tested and all were more airtight than $4m^3/(h.m^2)$ immediately after construction. It was found that two thirds of the homes became leakier and one third were more airtight than when first tested. In 10 of the 23 homes all trickle vents were closed. Minor mould growth was present in three homes. There were no air quality measurements undertaken. It is recommended that further research involving a larger sample of dwelling types, constructions and heating and ventilation types is needed to confirm the results of the study.

Within the Adaptation and Resilience to Changing Climate (ARCC) Co-ordination Network are a number of EPSRC funded projects focussing on the potential effects of climate change on buildings (www.ukcip-arcc.org.uk). Several projects concern prediction of future external temperatures in urban areas and the effect on internal temperatures and the possible impact of design on mitigation and adaptation. One project (DE^2RHECC) concerns design of hospital microenvironments and this addresses implications for effective airborne pathogen control as well as temperature.

Health effects of climate change

Direct effects of climate change

The changing climate will pose an increased risk to health and safety through higher temperatures, rising sea levels and a greater frequency of extreme events such as heatwaves, flooding and drought (Defra 2009). Previous experience and observed trends provides an insight into future impacts. In 2003 there were around 2,000 premature deaths in the UK due to the maximum temperatures occurring during heatwave. Average summer temperatures were 2ºC above the 1961-90 average. Such heatwaves are expected to become more common in future decades as summers as warm as 2003 are projected to be normal by the 2040s.

The Department of Health assessed possible health effects arising from climate change in a report in 2002 that was partially updated to take account of revised projections and other data in 2008 (DH 2002; DH 2008). The reviews do not directly address the health impacts of changes to the indoor environment that may arise from climate change but it is considered through the assessment of the impact on health of changes in ambient temperatures and levels of outdoor pollutants where a major part of the exposure would be expected to occur indoors.

The disproportionate affect of climate change on the health of vulnerable populations is highlighted by Sheffield and Landrigan (2010) who discuss threats to children's health and strategies for prevention. They identify six climate sensitive factors that result in increased environmental exposures or stresses relative to adults;

- Difference in physiology mean they are less effective at adapting to heat,
- Exposures (e.g. to toxins, infection, under nutrition) during periods of rapid development *in utero* and early childhood can cause devastating damage,
- Exposures are higher per body weight (breathe, drink and eat more per unit of body weight),
- Different diet and behaviours (consume more fruit and vegetables, spend more time outdoors),
- More future years of life (disease latency period, expected increase in environmental hazards in their lifetime),
- Their dependence on caregivers who may be impacted by climate change.

The authors refer to a WHO study that estimates that over 88% of the existing burden of disease due to climate change occurs in children under 5 years of age in both developed and developing countries.

Heat stress

DH (2008) notes that summers in the UK have become warmer, but no change in heat-related deaths occurred during the period 1971–2003. This suggests that the UK population is capable of adapting to warmer conditions. The increasing tolerance to heat probably resulted as much from lifestyle changes, such as greater readiness to wear informal clothing and less need for physical exertion, as from physiological adaptation to heat stress, which is relatively short term. It is predicted that there is a 1 in 40 chance that by 2012 South-East England will have experienced a severe heatwave that will cause perhaps 3,000 immediate heat-related deaths. In terms of conventional thinking about risks to health a risk of 1 in 40 is high. Winter deaths are expected to decline as the climate warms.

Understanding the effect of heatwave on health is an active topic of research. D'Ippoliti *et al.*, (2010) reviewed the effects of heat waves on mortality in European cities, including London. Heat waves of longer duration had a higher impact, and duration seemed to be a more important factor than intensity. The impact on daily mortality increased with age and females were more susceptible than males even after stratifying by age groups. This could relate to social conditions of elderly women living alone and physiological differences. Generally there was a greater effect on respiratory than cardiovascular mortality. Population characteristics like social isolation and income level have been shown to affect the susceptibility of urban populations. The authors conclude that predictions for climate change will lead to heat waves in cities not previously exposed to extreme temperatures and that prevention programs should specifically target the elderly, especially women, and those suffering from chronic respiratory disorders.

Hertel et al., (2009) is an example of a study investigating the mechanisms causing higher mortality. Their time series epidemiological study of mortality in Essen, Germany considered whether periods of sustained heat without nightly cooling influenced mortality. Mortality over time showed different patterns for cardiovascular and respiratory mortality. Periods with sustained heat especially affected respiratory mortality, whereas no distinct influence was found for cardiovascular and neoplastic mortality.

An overview of the potential of increased population heat exposure and other environmental changes to global climate change may affect the incidence and impact of non-communicable diseases is given by Kjellstrom et al., (2010). They identify the risks of cardiovascular, renal and respiratory diseases as being particularly adversely affected by climate change.

One aspect of local variation in the impact of climate change is addressed by Kershaw *et al.*, (2010) who considered the urban heat island effect in climate projections. Cities generally are warmer than their surroundings; buildings store heat gained during the day, from solar radiation and human related activity, and this heat is released during the night resulting in higher night-time temperatures. Also the geometry of urban areas can limit heat loss by radiation and convection and drainage can limit the amount of evaporative cooling. Currently UK climate projections do not include the effect of urban areas on climate. The urban heat island effect was calculated for the years 2002-2006 and found to be between 1.6ºC and 1.9ºC for central London in winter. It is suggested that the magnitude of the urban heat island will not change with climate change and that simple addition to daily regional temperatures should be sufficient to account for the effect.

Smith and Levermore (2010) in a review of the potential of urban spaces and building design for climate change mitigation and adaptation, identify the urban heat island effect as the main heat related hazard. The urban heat island is responsible for temperatures differences of up to 7ºC between cities and the surrounding countryside. Altering the urban microclimate, for example by urban greening, use of exemplary building façade, glazing and ventilation design, as well as change in people's behaviour could reduce vulnerability of city dwellers to thermal discomfort.

Flooding

Currently, floods are an important problem in the UK. Floods are associated with few direct deaths, but the full effect on health, in terms of indirect mortality and morbidity due to infectious disease, mental health, and injuries, is not known. Current evidence indicates that certain types of floods, such as spring floods due to snow melt, are likely to become less frequent under climate change, while others, such as those directly linked to sustained autumn and winter precipitation, are likely to become more frequent. Risks will evolve differently in different regions and river catchments. There is good evidence to expect an increase in the frequency of heavy precipitation, with the greatest increases in frequency occurring for short-duration, high-intensity events. Hence an increased risk of flooding may accompany no change, or even a decrease in mean rainfall or in the duration of wet spells. Floods in June/July 2007 caused flooding of 49,000 homes.

Ambient air pollution

It is forecast that the air pollution climate of the UK will continue to change (DH 2008). Though concentrations of a number of important pollutants are likely to decline over the next half-century, the concentration of ozone is likely to increase. This will increase attributable deaths and hospital admissions. The increases are likely to be significant: with the least constraining assumptions (no threshold of effect assumed) up to about 1,500 extra deaths and hospital admissions per annum might be expected.

Doherty et al., (2009) discuss the elevated levels of ozone occurring during heatwaves and the impact on mortality. They describe development of a climate-chemistry model to simulate surface temperature and ozone concentrations for a range of future UK pollutant emission scenarios. This is combined with epidemiological evidence on ozone-heat mortality relationships to also predict health burdens.

The European Respiratory Society published a position statement on the implications of climate change for the incidence and management of respiratory disease noting that climate change will affect individuals with pre-existing disease but the extent of the effect remains unclear (Ayres et al., 2009). They review key climatic factors that could potentially influence respiratory disease; extreme temperature events (hot and cold), changes in air pollution, flooding, damp housing, thunderstorms, changes in allergen disposition and consequent allergies, forest fires and dust storms. With regard to air pollution they outline the possible adverse effects of increased ozone concentrations and the uncertainty over future particle concentrations that may reduce because of greater pollution control, but also may increase from greater trans-global transport of particles from forest fires and dust storms. Also discussed is some evidence for a synergistic effect between effects of ozone, particles and temperature and the evidence that ozone potentiates the effects of allergen exposure.

Cecchi *et al*., (2010) consider likely changes in the aerobiology arising from climate change and the possible effect on prevalence of allergic asthma. They propose a number of projections;

- An early start in the year for pollen release is likely to occur with associated earlier appearance of symptoms of allergic disease,
- A longer exposure during the sensitisation phase may lead to greater likelihood of the development of allergy,
- Exposure to higher allergen load may lead to more severe atopic and respiratory symptoms and new sensitisations.

Possible adverse and beneficial impacts of changes to the indoor environment

Overviews of impact

Several publications have sought to give overviews of a range of factors that may change in indoor environments that could have consequences for public health. Crump et al., (2009) discussed possible consequences for the indoor environment of changes in design of buildings to achieve more energy efficient homes. Key factors and associated issues identified were;

- *Increased airtightness*: Assuming that reduced infiltration is appropriately offset by increased ventilation provision, the changes will impact the route of entry of air and associated interaction with surfaces and ability for control by occupant; this could change pollutant type and concentration and water balance of structure and could result in more effective ventilation or under ventilation. Overall the outcome might be beneficial or adverse.

- *Increased winter internal temperature*; there are direct benefits for vulnerable persons in fuel poverty and indirect benefits if a consequence is that more financial resources are applied to improving diet and quality of life, as well as reduced use of unflued appliances for heating. Other associated issues are a possible reduction in condensation and dampness/ mould, changes in house dust mite prevalence, and the potential increase in release of chemicals from materials into indoor air. Overall the effects may be beneficial or adverse.

- *Summer internal temperature*; appropriate designs may protect occupants against heat-waves; the outcome is therefore potentially beneficial relative to existing property, but inappropriate design could be neutral or even adverse.

- *Mechanical ventilation*; possible advantage over systems with natural ventilation of more effective removal of pollutants by ventilation and also offers the potential to remove pollutants from incoming air. But identified issues of installed systems not meeting the design specification, poor design preventing cleaning of ductwork and lack of maintenance and occupant interference with intended operation are of concern because of possible under ventilation and additional sources of pollutants. Overall the outcome can be beneficial or adverse.

- *Heat recovery aspect*; Emphasis on energy recovery can result in increased risk of indoor pollutants, for example using re-circulating cooker hoods rather than extraction to the outside.

- *Materials for construction*; Greater use of materials for insulation and more recycled products results in the possibility of increased release of chemicals into the indoor environment. This could have an adverse effect unless materials are developed and shown by appropriate testing to be low emitting.

- *Ground contaminants*; Changes in internal pressures and temperatures could affect the routes of entry of soil gases, including radon. This will also depend on the floor structure.

Bone *et al*., (2010) discuss the possible impacts of energy efficiency measures on public health. They note that relationships between housing and health are complex and difficult to measure. They consider that the available evidence suggests that energy efficiency measures are largely positive but note concerns about the possible impact of increased air tightness on occupant health in the absence of adequate ventilation. They note the following issues;

- Increase in levels of indoor pollutants such as CO, environmental tobacco smoke (ETS), nitrogen dioxide (NO_2), formaldehyde, VOCs and radon if reduced ventilation.
- While filtration of supply air in mechanical ventilation (MV) systems offers possible advantages for reducing concentrations of particulates in incoming air, there is concern that occupants may not use the system for at least some of the time.
- Relative humidity (RH) could increase if ventilation is reduced and this could promote mould growth and proliferation of dust mites with consequent health effects.
- The impact on incidence of CO poisoning is hard to predict – lower ventilation could increase risk but less reliance on fuel combustion in the home could reduce risks.
- The relation between radon levels in the home and energy saving measures is complex e.g. installation of double glazing and draught proofing has been associated with higher radon levels because of reduced ventilation as a result of increased airtightness.
- With regard to risks of summer overheating, while insulation may reduce internal heating through walls and roofs, if this does occurs through for example solar gain via windows, the insulation may prevent heat escaping to the outdoors. There is a particular concern about the adequacy of ventilation provision to achieve effective night cooling.
- Warmer summers may be associated with higher outdoor levels of irritating gases such as ozone which will impact the indoor environment, including by reaction with internal materials to produce secondary pollutants in the indoor air.
- Higher temperatures and humidities could result in higher off gassing of chemicals form materials into the indoor environment.

Ayres et al., (2009) in their position statement on respiratory disease and climate change draw attention to the adverse effects of emissions from biomass fuels largely in the context of their use in developing countries. They refer to possible adaptive behaviour such as minimising time spent outdoors to avoid heat that could affect human exposure. Also identified is the possible increased use of air conditioning for cooling buildings with a consequent increase in energy use and potential for higher levels of ambient pollution. The relationship between respiratory health and dampness is discussed, noting a USA study that attributes approximately a fifth of all cases of asthma to exposure to damp and mould. Changes in indoor conditions could permit house dust mites to become established in regions where cold winters and heating have previously limited colonisation. They note that there is some evidence for better insulated homes having improved temperature with occupants having improved markers of health and some evidence for use of environmental control being able to reduce dust mite populations.

Mudari (2010) reviewed the impact of climate change on the indoor environment and discussed possible health effects in the USA as well as the predicted economic impact. Table 2 from the report summarises identified effects and predicted health impacts. With regard to indoor environmental quality the key issues identified relate to temperature, ventilation, indoor chemistry, moisture, vulnerability to diseases, pests and pesticides. In their conclusions they expect a rise in indoor temperatures only partly mitigated by climate change with some health impact, including perceptions of poorer IAQ, increased SBS symptoms and some increase in respiratory symptoms. Temperature extremes may result in electricity demand (for cooling) exceeding capacity and this will exacerbate health effects. The expected decrease in the amount of ventilation is expected to have a profound effect on all categories of health impacts associated with exposure to indoor pollution. The author notes that outdoor ventilation reduction in the 1970s was associated with complaints of building sickness and a recognition that indoor pollution can be a major public health threat. He suggests that increased control of sources of indoor pollution combined with filtration and air cleaning technologies could allow some reduction in ventilation without affecting IAQ. Also reduced ventilation in buildings could increase the potential for disease transmission.

Ozone is described as a rapidly emerging pollutant and an important indoor air concern. The increase in concentrations is considered as being potentially one of the most important environmental impacts on public health due to climate change. Air cleaning systems could remove ozone from ventilation air, and indoor air and manufacturers of products used indoors (particularly fragranced products and cleansers) could be encouraged to reduce the use of those VOCs that readily react with ozone. Extreme weather events causing increased dampness in homes are expected to cause substantial increases in allergy, asthma and respiratory symptoms. Guidance on mitigating dampness would be useful and temporary housing should not contain formaldehyde laden materials.

Table 2. Effects of climate change on IAQ (Mudari, 2010).

Climatological Effect and Adaptations	Indoor Environmental Effect		
	Effect on indoor climate and indoor pollution	**Effect on health, comfort & productivity**	**Value (cost) of health, comfort, & productivity change***
Outdoor Temperature Mean rise in outdoor temperature rise	Indoor temperature rises.	Sick Building Syndrome (SBS) increases from temperature rise.	Percentage increase in SBS (1)
	Increased use of air conditioning Potential for increased off-gassing of VOCs.	Potential increase in respiratory symptoms	Percentage increase in SBS (1)
Increased frequency and intensity of heat waves	Inability of air conditioning to condition indoor air Extreme heat stress	Multiple effects	Percentage increase in respiratory symptoms (2) Percentage increase in premature death (2)
Outdoor Pollution Increased outdoor pollution (especially particulates and ozone)	Increased particulates and ozone come indoors Increased ozone reaction byproducts (indoor chemistry)	Increased respiratory ailments Increased SBS and respiratory symptoms	Percentage increase in respiratory symptoms (3). Percentage increase in SBS (1)

Climatological Effect and Adaptations	**Indoor Environmental Effect**		
	Effect on indoor climate and indoor pollution	**Effect on health, comfort & productivity**	**Value (cost) of health, comfort, & productivity change***
Moisture and Water Events Increased mean outdoor humidity	Increased indoor relative humidity, condensation, and mold growth	Asthma, allergies, and respiratory symptoms	Percentage increase in allergies, asthma, and respiratory symptoms (3)
Increased frequency and intensity of extreme precipitation episodes, with flooding in inland areas Higher intensity of storm surges and sea level rise in coastal areas, with increased flooding in East and Gulf Coast Regions	Increased wet, damp conditions, building damage, and mold	Asthma, allergies, and respiratory symptoms.	Percentage increase in allergies, asthma, and respiratory symptoms (3)
Increased harborage of rodents	Increased rodent infestation indoors due to rodent migration from outdoors to indoors and possible cockroach infestation due to dampness	Allergies, asthma, and respiratory symptoms.	Percentage increase in allergies, asthma, and respiratory symptoms (3)
	Increased use and exposure to pesticides		Percentage increase in SBS (1)
Temporary housing provided in flooded areas	Increased formaldehyde and VOC exposures	SBS from pesticides, formaldehyde, and VOC	

Climatological Effect and Adaptations	Indoor Environmental Effect		
	Effect on indoor climate and indoor pollution	**Effect on health, comfort & productivity**	**Value (cost) of health, comfort, & productivity change***
Outdoor Air Ventilation Pressure to reduce energy use to lower GHG; because of the cost of increased air conditioning results in reduced outdoor air ventilation	All existing indoor pollutants rise in inverse proportion to reduced ventilation	Increases in all existing indoor air health, comfort, and productivity effects	Percentage increases in all categories except heat waves (5)
Ecological Shifts and UV Radiation Changes in population and geographical distribution of disease pathogens, vectors, and hosts	Increases in disease outbreaks	Disease transmission in indoor environments	Percentage increase in communicable diseases (4)

GHG = greenhouse gas

A number of other studies focussed on the effects of individual factors or actions and these are summarised below.

Overheating

Peacock *et al*., (2010) have modelled risks of overheating in UK domestic buildings; a problem is most likely to occur in the south of England and for lightweight constructions. Even with window opening the average internal temperature is predicted as being over 28ºC for 12% of the year and there could be a cooling problem at night in bedrooms for a third of the year. A similar study for schools identifies that for many cases there is a risk of overheating problems (Jenkins *et al*., 2009). Coley and Kershaw (2010) have modeled the relationship between increases in external temperature due to climate change and increases in internal temperature. They found the relationship to be linear and consider that derived coefficients can be used to judge the resilience of particular structures to climate change.

A government expert committee reviewed the UK's preparations to adapt to climate change and noted the importance of designing and renovating properties so that they are suited to current and future temperatures (ACS, 2010). They note that buildings are already vulnerable to overheating and that this is likely to get worse as temperatures increase. While building regulations require consideration of heat and solar gain as part of energy efficiency the committee commented that they do not directly address the impact of overheated buildings on the health and comfort of occupants.

The impact of changing climate will depend significantly on how individuals, government and voluntary services plan for and adapt to the changes in climate. For example appropriate planning and actions can reduce the risks of health effects during heatwaves and actions such as flood defences and water catchment management can reduce the risk of floods (Defra, 2009).

DH (2008) gives examples of how reducing risks to health can be achieved through adaption of behaviour. Appropriate advice includes having an electric fan available and ensuring that windows can be opened. Shading of windows from direct sunshine, for example by outside shutters, will prevent greenhouse heating. If shading is impractical, the use of thick curtains can reduce heating of the indoor environment. Windows should be opened in the early morning, and shut if the outdoor temperature rises above indoor temperature. If the indoor temperature rises enough to cause heat discomfort, a fan will need to be started. Water can be sprinkled on the face, arms and clothing if necessary to reinforce evaporative cooling by sweat, particularly in people taking medical drugs that suppress sweating. If indoor humidity rises enough to prevent evaporation and cause heat discomfort, windows will need to be opened again to provide air unsaturated with water vapour.

Aeroallergens and other pollutants

Beggs (2010) reviewed research on adaptation of climate change on aeroallergens and allergic respiratory disease. The potential of climate change to have a significant impact on the level and type of exposure to aeroallergens such as pollen and mould spores and therefore related diseases such as asthma and allergic rhinitis is discussed. With regard to the built environment the following are identified;

- Governments could consider which plant species are used in populated areas, and in particular to avoid aeroallergen from mitigation tree planting and urban reforestation. The aeroallergen potential of all species involved in proposed land use planning for reducing greenhouse gas emissions such as new green spaces, green roofs and use of trees with high growth rate for additional green cover should be considered. Better management could produce a long term reduction in the ambient pollen allergen concentration and thereby reduce allergic respiratory disease. The benefits of green spaces and associated planting to provide shade as well as opportunity for exercise for people are recognised. Physical activity can combat obesity which is linked to risk of type II diabetes and these are risk factors for onset or exacerbation of childhood and adult onset asthma (and allergic airways disease).
- Settlement planning should avoid housing in flood prone areas because of concerns about indoor moisture levels and moulds and associated respiratory diseases.
- Building design and heating, ventilating and air conditioning can be used to control both indoor allergen production and the exchange of allergens between indoor and outdoor environments. There is potential to reduce amounts of pollen entering indoor spaces and to control indoor aeroallergen sources (indoor mould, house dust mites, allergens from cockroaches, rodents and other pests), although impacts of climate change on indoor aeroallergens has received far less attention than those on outdoor allergens.

Carslaw et al., (2009) summarised evidence for the occurrence of indoor chemistry and particularly the ozone initiated reactions with organic compounds that may produce chemicals and particulates with potential adverse effects. Increased concentrations of ozone outdoors could lead to an increase in such reactions indoors.

Impact of improvement to older properties

Poor quality housing is associated with adverse health impacts and therefore renovation to increase energy efficiency can have potential health benefits. Howden- Chapman *et al*., (2007) summarised evidence for links between inadequate heating, damp, cold and mouldy homes and poor health. They note that;

- Badly constructed and older houses are difficult and expensive to heat,
- Inadequate warmth in homes has health consequences, particularly in winter,
- Money spent on energy cannot be spent on other necessities such as food,
- Older people, babies and sick people have less robust thermoregulatory systems and are likely to spend more time indoors and are therefore under more physiological stress in colder homes,
- Cold houses are more likely to be damp leading to mould growth and associated respiratory symptoms.

The health impact of improved energy efficiency measures undertaken under the Warm Front scheme in England and Wales has been evaluated and the studies conclude that the measures are having a positive impact on improving mental health, alleviating respiratory problems in children and reducing deaths of older people (Green and Gilbertson, 2008). Energy efficiency and indoor temperatures increased and higher indoor temperatures produced lower humidity and less dampness. The report refers to a conundrum with regard to whether warm homes provide better health; dust mites thrive in warm humid conditions and mould grows in cold damp conditions and both are linked to respiratory problems – the challenge is to create an indoor environment that discourages both mould and mites. The impact of the scheme on climate change mitigation is less beneficial as overall fuel consumption increased. This is in contrast to the expected benefits of reduced CO_2 release to the atmosphere resulting from energy efficiency measures (DH, 2009).

To assess the impact of installation of improved insulation in New Zealand Howard-Chapman *et al*., (2007) undertook a study involving 1350 homes in New Zealand. One group of homes was subjected to intervention to improve the insulation of the ceiling and floors and undertake draught proofing of windows and doors. Measurements of house temperature and some other environmental characteristics were undertaken and self reporting of occupant experience was used as well as independent measures of use of health services. It was concluded that the insulation of homes resulted in significantly warmer and drier indoor environments and improved self rated health, self reported wheezing, days off school and work, and visits to general practitioners and a trend for fewer hospital admissions for respiratory conditions.

While not specifically addressing renovations for improved energy efficiency Herbrath and Matysik (2010) investigated the elevation in VOC levels that occurs as a result of renovation activities such as painting of walls, carpeting and new furnishings in homes and offices in Germany. They found that an average time of 2 to 8 weeks was required before VOC concentrations declined to a guideline concentration and a minimum wait of 6 weeks is proposed to ensure levels of air pollution return to 'normal' levels. They propose that an appropriate waiting time should be adopted for public buildings and institutions (especially nurseries and playschools) and this should also be considered for implementation in homes.

Wilkinson *et al*., (2009) modelled the effect on public health of strategies to improve energy efficiency in UK housing and concluded that if implemented correctly they could have appreciable benefits for health mainly through improved indoor air quality and control of winter indoor temperatures. The modelling considered combustion sources and ventilation characteristics in five scenarios; building fabric improvement, ventilation systems improvement, home fuel switching to electricity, occupant behaviour and combined scenario. The greatest gain in health from the 4 individual scenarios was from fuel switching and this was mainly because of reduced exposure to particles. Some of the apparent benefit through improvement to the fabric and ventilation relates to ventilation system changes and air filtering (of particulates) in mechanical ventilation systems. The authors comment that these benefits could be substantially reduced if systems are not well fitted, operated and maintained.

Kuholski et al., (2010) comment that many conventional energy upgrades of homes can harm occupants health, for example tightening of a home to reduce outside air exchange can degrade IAQ and increase risk factors associated with asthma, allergies and respiratory ailments. Also there is the potential to trap gases like radon and efforts to install insulation can disturb lead-based paint thereby creating a hazard. They also refer to studies that properly integrated energy and health programs have health benefits, including a US study of renovated homes which found risks of fires were reduced and residents had less respiratory illness.

Recommendations for research to understand relationship between changes to the indoor environment and health

Crump *et al*., 2009 identified the following broad areas of research needs concerning the indoor environment in energy efficient homes;

i) Addressing the performance of products and designs for high energy efficiency homes and provision of guidance for installers and users.
   - Noise; it is a key driver to occupants for reducing fan speeds of mechanical ventilation systems and therefore it is critical that installed noise is at an acceptable level; minimum standards need to be determined and introduced.
   - Dust and dirt (cleaning of fan units and ductwork); there is a need to evaluate the build up of dust and dirt within fan units in UK dwellings and develop guidance on good practice maintenance.
   - Purge ventilation; need to consider provision of purge ventilation in homes with MVHR, in particular in urban homes where it may not be possible to achieve by opening windows and therefore it may not be possible to maintain thermal comfort in summer.
   - Filtration; the level of filtration of inlet air for MVHR (mechanical ventilation and heat recovery) systems needs further investigation, particularly for urban dwellings along with issues of maintenance.
   - Demand controlled ventilation; there is a need to ensure that minimum settings available on MVHR systems intended for application in empty rooms (that are in some cases below AD F ventilation recommendations) are not a risk to health. Guidance is required on acceptable minima.
   - Emissions of chemicals from materials; there is a need to assess whether product standards are adequate to achieve good IAQ in Code 4 to 6 homes and whether further controls are required.

ii) Post commissioning and post occupancy evaluation of performance of buildings meeting Code Level 4 to 6 requirements. The following parameters should be determined and assessed;

   - The performance of any MV equipment at installation and over 12 months of use (and preferably longer),

   - The rate of air exchange under a range of occupancy behaviours and different seasons,

   - Temperature and humidity,

   - Internally generated pollutants (VOCs, formaldehyde, NO_2 and CO in homes with combustion appliances, particles, CO_2),

- Other outdoor and indoor generated pollutants (ozone, polyaromatic hydrocarbons, Semi-volatile VOCs in dust,
- Additional parameters that may become significant as homes become aged (mites and mite allergen, other allergens, fungi and bacteria),
- Further parameters where ground contamination may be elevated (radon, methane)
- Noise of the MVHR system, especially where occupants lower airflow rates),
- Occupants understanding and interaction of ventilation systems, including maintenance,
- Occupant's satisfaction with the indoor environment including perception of IAQ and possible SBS symptoms.

It was noted that investigations of building performance could involve studies of only Code 4 -6 homes and results compared against available guidelines although a larger study making comparison with a control group of other homes may be more powerful. Also the studies should not be limited to the first year after occupancy but longer term studies are required to take account of possible inadequate maintenance and long term performance of systems, as well as occupant misuse and interference.

With regard to radon, the Health Protection Agency (HPA) recommend a new target level for the annual mean concentration of radon in homes that should not be exceeded to protect human health (HPA, 2010). This level of 100 Bqm^{-3} should provide an objective for remedial action in existing homes and preventive action in new homes. They advise that Building Regulations and supporting documents are amended to require all new buildings to incorporate basic radon protection measures. One factor affecting the radon concentration is the amount of internal ventilation. It is recommended that more research is undertaken on the effectiveness of radon prevention measures in new buildings.

Based on the findings of the IAQ and ventilation study of 108 homes in California, Offerman (2009) recommended a number of actions and areas for further research including;

i. Consideration should be given to installing MV systems in new residences to provide a dependable and continuous supply of outdoor air for the purpose of controlling indoor air pollutants. This is because the homes are relatively airtight and many people do not use their windows for ventilation which results in low air exchange rates and elevated concentrations of contaminants with indoor sources.

ii. Consideration should be given to regulating the emissions of air contaminants from building materials (noting that the Californian Resources Board are implementing controls on emissions of formaldehyde from composite wood products).

iii. Because of the high frequency that recommended guidelines for exposure to formaldehyde are exceeded and because formaldehyde is a known human carcinogen, consideration should be given to undertaking focused studies on quantifying emission rates from all potential indoor sources and developing regulations to reduce indoor formaldehyde concentrations.

iv. Additional studies of IAQ and ventilation should be conducted to examine the significance of nighttime cooling by natural or mechanical means.

v. Further studies in homes with MV systems should be conducted to confirm the findings; both installation and field performance should be evaluated.

vi. Home builders should be educated about the importance of conveying to homeowners the need for ventilation and how systems operate and the need for designing systems that are easy to maintain. In addition consideration should be given to creating an easy to read fact sheet for the public about residential ventilation systems and the importance of their operation and maintenance for IAQ.

vii. Research should be conducted to investigate residential exposures to ozone-initiated reaction products in indoor air.

In preparation for a policy review meeting organised by the Belgian EU presidency a background document on sources and effects of indoor pollutants was prepared (Bluyssen 2010) and this included identification of research needs including;

1. Assessment of the health effects of short- and long-term exposure in indoor environments, especially in homes and schools. Epidemiological studies should be performed on the relationship between health and measured indoor levels, taking into account exposure time and exposure variability and also vulnerable groups. Studies are needed on the effects of products which emit indoor air pollutants that can react in indoor air (e.g. terpenes), on the possible effects of fine and ultrafine particles, and of man-made nano-particles in indoor air. Clinical studies (including biochemical markers of effect) are needed to clarify the effects due to the exposure to microbiological agents. Research is needed on the effects due to combined exposure to indoor air pollutants and on the objective methods for their evaluation, including development of validated modelling tools.

2. Assessment of exposure patterns (short and long term in different environments) to indoor air pollutants, and identification of the most relevant exposure indicators.

3. Definition of indoor exposure guidelines, in particular for dwellings and schools.

4. Characterization of pollution sources in buildings and technologies to control the sources and their effects on health and wellbeing. Source apportionment of the pollutants in indoor environment. Assessment of the emissions of chemicals from consumer products. Harmonization of all monitoring and assessment methods and labelling systems.

5. Research on ventilation rates and energy use in different types of existing buildings and effects on indoor air quality and climate, health and wellbeing. Research is needed to establish the relationship between improved controls of indoor sources, ventilation rates and air cleaning to develop systems that can be effectively controlled based on outdoor and indoor air quality. The relationship between materials emissions and ventilation requirements should be evaluated simultaneously when developing the criteria for low emitting materials. The relationship of the ventilation systems and rates with the dispersion of pathogenic microbes within the building should be evaluated.

6. The research on the dynamics of the air with the surfaces indoors is a key element towards the fine tuning of the ventilation needs. Currently, with all computing models capacities, the limiting factor resides clearly on the quantification of the role of the adsorption/desorption phenomena for the different chemical substance/surface material interactions.

7. Research is needed on the susceptibility for the potential growth of fungi on construction products. Several factors influence the risk of microbial growth some of which are related to the indoor environment (air velocity, relative humidity and temperature near surfaces) and, others to product characteristics (nature of the surface and structure of the material). Studies on this contribution will be important.

8. Research and new technology to clean the indoor air and the outdoor air used for ventilation. Development of low energy technologies for ventilation for better air quality, e.g. via improvement of air distribution efficiency, and air quality based intelligent control of ventilation and air cleaning,

9. Research is needed to develop and test urban planning tools to model – from short term to life cycle - the population exposures, energy requirements and pollution loads of alternative plans – from an individual building to entire urban areas.

10. There is a need to promote the development of robust tools for sustainable buildings where low energy demand, energy efficiency, life cycle analysis, environmental assessment and proper performance goals (comfort, good indoor air quality) and management are assured from the design phase to the commissioning period. That will require:

- Comprehensive criteria and tools to assess the holistic performance of buildings,

- Integrated tools assessing the compromise between good IAQ and low energy use and soft control and management strategies.

With regard to indoor chemistry and consequences for health, Carslaw et al., (2009) suggest several areas for further research including the need for large multidisciplinary indoor field campaigns in typical indoor environments measuring a wide range of health relevant chemical and physical properties with an emphasis on biologically reactive material and others not previously considered, such as surfactants and pesticides. There is a requirement to measure labile species and radicals indoors, perhaps with new techniques and to determine the chemical composition of particles.

A UK government report (HM, 2010a) on how the construction industry can achieve low carbon construction made a number of recommendations for actions including the need to form a collective view on strategic research and development priorities, suggesting for example for public sector funders to create and own a 'Strategic retrofit research agenda'. Two recommendations are directly relevant to the indoor environment;

- Recommendation 8.2; That, to avoid the risk of a new generation of sick buildings, the promotion of the health and well being of occupiers should be placed on an equal footing with the current emphasis on carbon reduction.

- Recommendation 8.3; The industry should agree and implement Indoor Air Quality standards to include Indoor Air Quality plans, and enforceable targets for a maximum allowable concentration of toxic contaminants and emissions in interior environments for buildings with sealed envelopes.

Recommended priorities for research

With regard to the core issues in this report about understanding how changes to the indoor environment arising from the changes to the built environment now occurring to mitigate climate change, equal priority should be given to both new homes and renovated homes. Changes to both are central to achieving government carbon targets for 2050 and beyond and policies towards achieving these targets are currently having a significant impact in both sectors.

There is currently a dearth of data characterising the performance of homes, even against guidelines for rates of ventilation and air quality parameters set out in design guidance such as the building regulations. The studies need to include a range of housing types and people in different economic and social groups.

Concerning better understanding of the quality of the indoor environment in homes and its impact on health there are four broad areas of research identified;

1) ***Improved understanding of indoor air quality with respect to levels of key pollutants and environmental conditions in UK homes and the factors that determine those levels / conditions and people's exposure.***

There is a need to improve our knowledge about conditions in UK homes with respect to indoor contaminants and ventilation performance of homes. The most comprehensive information available from the IAQ survey of England was completed over a decade ago. This examined some specific pollutants in a nationally representative sample of homes. Since the IAQ Survey was undertaken there have been many changes in social, technological and economic factors that influence the levels of indoor pollutants e.g. use of consumer products, increased use of home electronic goods, more home working, increased home insulation and airtightness, increased traffic, changes in smoking habits, and greater care of the elderly and health compromised people in their homes. Subsequent studies such as those concerning new and renovated homes outlined in this report and others focussed on understanding exposure (e.g. Harrison et al., 2009) have been relatively small in scale and limited to few pollutants. Therefore the need is for a comprehensive study to understand the environmental conditions and stressors in UK homes and the interaction with house characteristics (including ventilation provision) and occupant activity.

There is also a need to consider the emerging as well as more 'classical' indoor pollutants. These include substances such as nanoparticles, semi-volatile compounds and products of indoor chemistry. Related to this is the possible impact of how the changes in materials used in buildings such as recycled materials, new insulants and other manufactured materials can impact the exposure of the population to potential pollutants.

Further there is need to assess the scope for improved indoor pollution source control as this offers the potential for some modest reduction in ventilation rates (with associated energy savings) without compromising indoor air quality with respect to a range of pollutants. One approach is to develop a system of labeling low emitting indoor products as currently undertaken in some countries such as Germany and France and also indoor air quality management plans that may incorporate use of low emitting products as well as the appropriate use and maintenance of ventilation provision.

2) S***tudies specific to energy efficient homes to address performance of new and recently renovated homes to inform requirements for future new homes and renovation programmes***.

Studies are required that are not only focused on the energy performance of the building but also the air quality parameters, and other indoor environment characteristics that can affect the health and well being of occupants. These could include case control studies and with respect to renovation could be intervention studies. It is important to take account of how occupants interact with technologies that have not previously been commonly used in UK homes e.g. MVHR and consider long term performance. The previous section of this report details parameters for investigation. The very limited studies of newly built UK homes have demonstrated that they tend to be under ventilated with respect to design objectives. They also show that levels of VOCs are often above target values and combustion gas concentrations are elevated by gas cooking. There is little information about other factors such as mould, allergens, ozone and particulates.

3) ***Development of common protocols for measuring indoor pollutants, occupant exposure to pollutants, building airtightness, ventilation rate and occupant and household activities***.

While to some extent common protocols exist, for example in international and British standards for some specific air pollutants, there is no accepted ‘manual’ for investigation of the indoor environment. Such a common approach that is developed from current best practice would allow more informative comparison of data from different studies (in the UK and elsewhere) and the findings are more likely to be more widely applied. It would also inform compliance checking against indoor air quality guidelines and ventilation parameters to assess building performance with regard to health and well being.

4) Relationships between indoor environment quality and health, in particular studies involving vulnerable groups.

Children, the elderly and those with respiratory and allergic disease are susceptible to health effects of ambient air pollution and therefore are critical groups for the study of links between symptoms, indoor air pollution and ventilation. These studies should incorporate measures of exposure (including biomonitoring) as well as modelling and would probably be most powerful as cohort studies. Given the ageing population and the increase in care at home of the elderly and those suffering ill health, it is of growing importance to ensure provision of an optimal indoor environment for these population groups.

The prime objective of the four proposed research areas is to assess whether current and future guidance on design, construction and maintenance of new and renovated homes is adequate to deliver improved health and well being of occupants as well as energy savings. The research would also inform development of improved guidance and complement modeling studies focused on effects of climate change on temperature.

As with all the research areas outlined above, there will be a difficult balance between numbers of homes, number of pollutants and indoor conditions that are included in studies given limited resources. However considerable work in recent years including by international groups such as the WHO, and within European Collaborative Actions (e.g. Urban and Indoor Air and Human Exposure) provides a considerable knowledge base to inform such decisions. There is a growing recognition of the need for the importance of the indoor environment for determining people’s exposure to a wide range of environmental stressors and the role of the quality of housing for population health. Therefore there is a strong need for the substantial changes now underway to our indoor environment as a result of measures to improve energy efficiency to be thoroughly evaluated to ensure that people’s health is not unwittingly compromised and that potential benefits for health of these changes are realised.

References

ASC (2010). How well prepared is the UK for climate change. First report of the Adaptation Sub-committee, 16 September 2010.

Ayres J., Forsberg B., Annesi-Maesano I., Dey R., Ebi K., Helms P., Medina-Ramon M., Windt M., and Forastiere F. (2009). Climate change and respiratory disease: European Respiratory Society position statement. Eur Respir J, 34: 295-302.

Beggs (2010). Adaptation to impacts of climate change on aeroallergens and allergic respiratory diseases. Int J Environ Res. Public Health, 7, 3006-3021.

Bluyssen P. (2010). Background document; Indoor sources and health effects: background information and ways to go June 2010. Proceedings ofProduct Policy and Indoor Air Quality September 23 & 24, 2010, Brussels. http://www.health.belgium.be/eportal/Aboutus/eutrio/environment/Indoor/index.htm?fodnlang=en

Bones A, Murray V, Myers I, Dengel A and Crump D (2010). Will drivers for home energy-efficiency harm occupant health? Perspectives in Public Health, May 2010.

BRE (2010). Low carbon homes put to the test. Constructing the Future 46. BRE Watford, Winter 2010.

Carbon Trust (2009). Building the future, today – transforming the economic and carbon performance of the buildings we work in.Carbo Trust report CTC 766, 2009.

Carslaw N., Langer S. And Wolkoff P. (2009). New directions; where is the link between reactive indoor air chemistry and health effects? Atmospheric environment 43, 3808-3809.

Cecchi L., D'Amato G., Ayres J., Galan C., Forastiere F., Forsberg B., Gerritsen J., Nunes C., Behrendt H., Akdis C., Dahl R., and Annesi-Maesano I. (2010). Projections of the effects of climate change on allergic asthma: the contribution of aerobiology. Allergy, 65, 1073-1081.

CLG (2007). Building Regulations – energy efficiency requirements for new dwellings; a forward look at what standards may be in 2010 and 2013. Communities and Local Government, London UK.

CLG (2008). The code for sustainable homes – setting the standard in sustainability for new homes. February 2008,Communities and Local Government, London UK.

CLG (2008a). Definition of zero carbon homes; impact assessment. Communities and Local Government Publications, West Yorks.

CLG (2008b). Definition of zero carbon homes and non-domestic buildings. Consultation. Communities and Local Government Publications, West Yorks.

CLG (2009). Sustainable New Homes – The Road to Zero Carbon. Consultation on the Code for Sustainable Homes and the Energy Efficiency standard for Zero Carbon Homes. Communities and Local Government, London UK., prosperity

CLG (2010). Code for sustainable homes; Technical guide, November 2010. Communities and Local Government, London UK.

Coley D. and Kershaw T. (2010). Changes in internal temperature within the built environment as a response to climate change. Building and environment, 45, 89-93.

Congreve A. (2010).Housing, sustainability and behaviour change. Environmental Scientist, August, p. 16-19, 2010.

Coward SKD, Brown V M, Crump D R, Raw GJ and Llewellyn JW Indoor air quality in homes in England. Volatile Organic compounds. BRE Report BR 446, CRC Ltd., London, 2002. ISBN 1 86081 566 9.

Coward S, Llewellyn J, Raw G, Brown V, Crump D and Ross D. Indoor air quality in homes in England. BRE report BR 433, CRC Ltd, London, 2001. ISBN 1 86081 5308.

Crump D, Dengel A and Swainson M. (2009). Indoor air quality in highly energy efficient homes – a review. NHBC Foundation report NF18, IHS BRE Press, July 2009.

DECC (2009). The Warm Front Scheme Annual Report 2008/09. Department of Energy and Climate Change, 2009.

Defra (2009). Adapting to climate change; UK climate projections. Department for Environment Food and Rural Affsairs, London, product code PB13274, June 2009.

DH (2002). Health effects of climate change. Department of Health, London.

DH (2008). Health effects of climate change in the UK 2008; an update on the Department of Health report 2001/02. Department of Health, London.

DH (2009). Health and winter warmth – reducing health inequalities. South East Regional Public Health Group Fact Sheet, Department of Health, December 2009.

Dimitroulopoulou S, D Crump, S K D Coward, V Brown, R Squire, H Mann, M White, B Pierce and D Ross. Ventilation, air tightness and indoor air quality in homes in England built after 1995, BRE report BR 477, BRE, Garston, 2005.

D'Ippoliti D, Michelozzi P, Marino C, deDonato F, Menne B, Katsouyanni K, Kirchmayer U, Analitis A, Medina-Ramon M, Paldy A, Atkinson R, Kovats S, Bisanti L, Schneider A, Lefranc A, Inguez C and Perucci C. (2010). The impact of heatwaves on mortality in 9 European cities: results from the EuroHEAT project. Environmental Health, 9:37.

Doherty R., Heal M., Wilkinson P., Pattenden S., Vieno M., Armstrong B., Atkinson R., Chalabi Z., Kovats S., Milojevic A., and Stevenson D. (2009). Current and future climate- and air pollution-mediated impacts on human health. Environmental health, 8 (Suppl 1) S8.

ETI (2010). £3m Buildings Retrofit project. http://www.energytechnologies.co.uk/home/news/10-08-13/ETI_Announces_%c2%a33M_Buildings_Retrofit_Project.aspx

EU (2010), Insulate – Improving energy efficiency of housing stock: impacts on indoor environmental quality and public health in Europe, LIFE 09, ENV / FI / 00573.

Fisk W., Mirer A., and Mendell M. (2009). Quantitative relationship of sick building syndrome symptoms with ventilation rates. Indoor air, 19 (2), 159-165.

http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=3725#EI

EU (2010a). Health based ventilation guidelines for Europe (HealthVent). www.healthvent.eu

Green G and Gilbertson J (2008). Warm Front Beter Health - Health impact evaluation of the Warm Front scheme. Centre for Regional, Economic and Social Research, Sheffield Hallam University, May 2008.

Harrison R., Delgado-Saborit J., Baker S., Aquilina N., Meddings C., Harrad S., Matthews I., Vardoulakis S., and Anderson R. (2009). Measurement and Modeling of Exposure to Selected Air Toxics for Health Effects Studies and Verification by Biomarkers. Research Report 143. Health Effects Institute Boston, Massachusetts.

Herbrath O. And Matysik S. (2010). Decreasing concentrations of volatile organic compounds (VOC) emitted following home renovations. Indoor air, 20: 141-146.

Hertel S., Le Tetre A., Jockel K., and Hoffmann B. (2009). Quantification of the heat wave effect on cause-specific mortality in Eseen, Germany. Eur. J Epidemiol, 24: 407-414.

Hong S., Gilbertson J., Oreszczyn T., Green G., and Ridley I. (2009. A field study of thermal comfort in low income dwellings in England before and after energy efficient refurbishment. Building and Environment, 44, 1228-1236.

HM (2010). The Building Regulations 2000, Ventilation: Approved Document F, 2010 edition. HM Government 2010.

HM (2010a). Low carbon construction; Innovation and growth team; Final report. HM Governement, Autumn 2010.

HPA (2010). Limitation of human exposure to radon – advice from the Health Protection Agency. Report RCE-15, Health Protection Agency,2010.

IPPC (2007). Climate change 2007: Synthesis report. An assessment of the intergovernmental panel on climate change.

IPPC (2007a). Glossary. In Climate Change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 2007.

Jenkins D. (2010). The value of retrofitting carbon-saving measures into fuel poor social housing. Energy policy, 38, 832-839.

Jenkins D., Peacock A., and banfill P., (2009). Will future low-carbon schools in the UK have an overheating problem Building and Environment, 44, 490-501.

Kershaw T, Sanderson M, Coley D and Eames M (2010). Estimation of the urban heat island for the UK climate change projections. Building Serv. Eng. Res. Technol. 31, 3, pp. 251-263.

Kjellstrom T., Butler A., Lucas, R., and Bonita R. (2010). Public health impact of global heating due to climate change: potential effects on chronic non-communicable diseases. Int J public health, 55: 97-103.

Kuholski K, Tohn E and Morley R (2010). Healthy energy efficient housing: using a one-touch approach to maximise public health, energy, and housing programs and policies. J Public Health Management Practice 16 (5) E Supp S68-S74.

Logue J., McKone T., Sherman M., and Singer B. (2010). Hazard assessment of chemical air contaminants measured in residences. Lawrence Berkeley National Laboratory report LBNL 3650-E, Berkeley, USA, 2010.

McKay S, Ross D, Mawditt I and Kirk S (2010). Ventilation and indoor air quality in Part F 2006 homes. Department for Communities and Local Government report BD 2702, March 2010, London.

Mudari D. (2010). Public Health Consequences and Cost of Climate Change Impacts on Indoor Environments. Indoor Environment Division, US EPA, Washington, USA, 2010.

NHBC (2011, in press). Ageing and airtightness – How dwellings air permeability changes over time. NHBC Foundation, report NF24, 2011.

Offerman F. (2009). Ventilation and indoor air quality in new homes. California Environmental Protection Agency Air Resources Board, report CEC-500-2009-085, San Francisco, November 2009.

Peacock A., Jenkins D., and Kane D. (2010). Investigating the potential of overheating in UK dwellings as a consequence of extant climate change. Energy policy, 38, 3277-3288.

Roberts S. (2008). Altering existing buildings in the UK. Energy policy, 36, 4482-4486.

Ridley I., Pretlove S., Ucci M., Mumovic D., Davies M., and Oreszczyn T. (2006). Asthma/Dust mite study – final report. Building Research Technical Report 7/2005. Office of Deputy Prime Minister, March 2006.

Sheffield P. And Landrigan P. (2010). Global climate change and children's health: threart and strategies for prevention. Environmental health perspectives, October 2010.

Smith C. and Levermore G. (2008). Designing urban spaces and buildings to improve sustainability and quality of life in a warmer world. Energy policy, 36, (12), 4558-4562.

Steemers K. And Manchanda S. (2010). Energy efficient design and occupant well being; case studies in the UK and India. Building and Environment, 45, 270-278.

Wilkinson P, Smith K, Davies M, Adair H, Armstrong B, Barrett M, Bruce N, Haines A, Hamilton I, Oreszczyn T, Ridley I, Tonne C and Chalabi Z (2009). Health and climate change 1 – Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. The Lancet, 374, 1917-1929.

WHO (2009). Dampness and Mould – WHO guidelines for indoor air quality. World Health Organisation, Copenhagen, 2009.

WHO (2010). Housing and Health – 'Healthy Housing' – experts call for international guidelines.

WHO (2010a). WHO guidelines for indoor air quality: selected pollutants. World Health Organisation Regional Office for Europe, WHO Press, 2010.

http://www.who.int/hia/housing/en/print.html

Wright A. (2008). What is the relationship between built form and energy use in dwellings. Energy Policy, 36, 4544-4547.

Appendix

Summary of two current studies of indoor air quality at Cranfield university relevant to energy efficient homes

Risks to health of carbon monoxide and other combustion gases in energy efficient homes

Researchers; Arun Sharma (postgraduate student) and Derrick Crump (supervisor)

The project aims to investigate risks to health of indoor air pollutants that may arise from use of combustion appliances such as cookers and heaters in energy efficient homes.

In a bid to cut carbon emissions substantial changes are being made to the design and construction of both new and refurbished homes and this is being driven by requirements in the Code for Sustainable Homes and the Building Regulations. These changes include increased airtightness of homes in order to lower thermal loss, greater use of mechanical ventilation with heat recovery and use of alternative 'greener' energy, including biomass fuels (e.g. wood and wood pellets). There are concerns that inadequate ventilation resulting from poor design or equipment performance, as well as improper use and maintenance by occupants could result in increased levels of indoor pollutants.

Suitable homes for the project are new or retrofit homes built or refurbished in accordance with 2006 building regulations or to a higher standard of energy efficiency. Although the project is looking at combustion products within energy efficient homes, new homes with no combustion appliances e.g. gas cookers, biomass fires, would also be useful for comparison purposes.

The project will monitor air pollutants in approximately 20 energy efficient homes during the heating season over a period of up to two weeks with various monitors placed in the kitchen and other habitable rooms. The monitors are quiet and unobtrusive and the data obtained will be used in conjunction with questionnaire and activity diaries kept over the main two day monitoring period. We are currently seeking additional homes for monitoring and would welcome assistance with their recruitment to the study.

We are grateful to the Gas Safety Trust for their support for this project.

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The Gas Safety Trust – Proud funders of this programme

The development of improved methods for the characterisation of organic chemicals emitted into indoor air by construction and consumer products

Researchers; Veronica Brown (postgraduate student) and Derrick Crump (supervisor)
A wide range of organic chemicals are released from construction and consumer products and these have the potential to adversely affect indoor air quality (IAQ) in buildings. Energy efficiency measures to combat climate change, including construction of new air-tight building structures have raised concerns about IAQ and possible health effects. There are a number of government initiatives in Europe and America that are developing regulatory and voluntary controls of product emissions. In support of these actions appropriate test methods are required to determine the wide range of chemicals of interest. These methods need to be robust and suitable to be carried out in industrial laboratories.
The project aims to optimise the use of thermal desorption/gas chromatography/mass spectrometry (TD/GC/MS) methods to determine the chemicals included in various target lists such as those formulated by governments in France and Germany, and the list to be defined as part of the on-going EU harmonisation of labelling of low emitting construction products. The project involves developing and optimising methods for the collection of chemicals on sorbents, the resolution of target chemicals by gas chromatography and their identification and quantification by mass spectrometry.
The project will undertake emissions tests of a range of products using micro-scale test chambers (in particular a Markes µ-CTE and a FLEC emission cell). Markes International's new data analysis software (TargetView) will be applied to the processing of the chromatograms to determine whether a greater number of compounds can be identified and whether the time required for processing of the data is significantly reduced. The possibility of extending the range of compounds which can be determined by use of different sorbents will be investigated. It is also planned to compare the performance of two different MS technologies, quadrupole and TOF (Time of Flight).
We would welcome opportunities to collaborate further with product manufacturers. We wish to test a range of newly manufactured products and would be glad to share results obtained from testing of any products provided.
We are grateful to Markes International for their support for this project.
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