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Review article

Impact of climate change on the domestic indoor environment and associated health risks in the UK

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ABSTRACT

There is growing evidence that projected climate change has the potential to significantly affect public health. In the UK, much of this impact is likely to arise by amplifying existing risks related to heat exposure, flooding, and chemical and biological contamination in buildings. Identifying the health effects of climate change on the indoor environment, and risks and opportunities related to climate change adaptation and mitigation, can help protect public health.

We explored a range of health risks in the domestic indoor environment related to climate change, as well as the potential health benefits and unintended harmful effects of climate change mitigation and adaptation policies in the UK housing sector. We reviewed relevant scientific literature, focusing on housing-related health effects in the UK likely to arise through either direct or indirect mechanisms of climate change or mitigation and adaptation measures in the built environment. We considered the following categories of effect: (i) indoor temperatures, (ii) indoor air quality, (iii) indoor allergens and infections, and (iv) flood damage and water contamination.

Climate change may exacerbate health risks and inequalities across these categories and in a variety of ways, if adequate adaptation measures are not taken. Certain changes to the indoor environment can affect indoor air quality or promote the growth and propagation of pathogenic organisms. Measures aimed at reducing greenhouse gas emissions have the potential for ancillary public health benefits including reductions in health burdens related heat and cold, indoor exposure to air pollution derived from outdoor sources, and mould growth. However, increasing airtightness of dwellings in pursuit of energy efficiency could also have negative effects by increasing concentrations of pollutants (such as $PM_{2.5}$, CO and radon) derived from indoor or ground sources, and biological contamination. These effects can largely be ameliorated by mechanical ventilation with heat recovery (MVHR) and air filtration, where such solution is feasible and when the system is properly installed, operated and maintained. Groups at high risk of these adverse health effects include the elderly (especially those living on their own), individuals with pre-existing illnesses, people living in overcrowded accommodation, and the socioeconomically deprived.

A better understanding of how current and emerging building infrastructure design, construction, and materials may affect health in the context of climate change and mitigation and adaptation measures is needed in the UK and other high income countries. Long-term, energy efficient building design interventions, ensuring adequate ventilation, need to be promoted.

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Contents

1. Introduction

Growing scientific evidence indicates that climate change is likely to cause a range of direct and indirect effects on dwellings (Crump, 2011; IOM, 2011). People in developed countries typically spend over 90% of their time indoors (Harrison et al., 2002; Vardoulakis, 2009; Lai et al., 2004). In the UK, a study of activity patterns in Oxford found participants were spending an average of 95.6% of their time indoors, with 66% of their time spent in their homes (Schweizer et al., 2007). Furthermore, vulnerable individuals in Europe (the elderly, young children, and people with compromised health) may spend an even larger proportion (up to 100% of their time) at home (Glorieux et al., 2002; Torfs et al., 2008). It is therefore important to consider the degree to which climate change impacts on the indoor environments affect the physical and mental health and wellbeing of dwelling occupants.

Buildings account for a large proportion of energy consumption and greenhouse gas (GHG) emissions in high income countries. In the UK, residential buildings were responsible for around 25% of total GHG end-user emissions in 2012 (DECC, 2014). The UK Government is committed to an 80% reduction (from the 1990 baseline) in GHG emissions by 2050 (DCLG, 2010). Therefore, policies to mitigate and adapt to climate change in the domestic sector can play a key role in attaining this goal (Bone et al., 2010).

Although building structures are primarily intended to provide shelter and enhance wellbeing, they are also associated with a range of health hazards, such as those attributable to indoor air pollution, extreme temperatures, pests and infestations, noise, airborne infectious diseases, water or mould contamination, domestic injuries and poisoning, and mental health effects (Haines et al., 2007; Mcmichael, 2011; WHO, 2011). The form of the built environment (e.g. urban density) may also have influence on factors relating to "life-style" diseases, such as cardiovascular illness. Health inequalities can also be aggravated or mitigated by housing conditions (BMA, 2003; House of Commons, 2009; Shrubsole et al., 2015).

A number of papers have recently reviewed how climate change and mitigation and adaptation measures may affect the indoor environment, including building overheating, indoor air quality and biological contamination, mainly focusing on high-income countries (IOM, 2011; Spengler, 2012; Nazaroff, 2013). In the UK context, there has been substantial research mainly on the impact of climate change on building overheating, as well as on the relevant adaptation and mitigation measures (e.g. CIBSE, 2005; Hacker et al., 2005; Capon and Oakley, 2012; DCLG, 2012a; De Wilde and Coley, 2012; NHBC Foundation, 2012). Studies have also focused on the impacts of climate change mitigation and adaptation on indoor air quality (Shrubsole et al., 2012), and highlighted research needs in this area (Crump, 2011). There is a particular need for an improved understanding of the performance of highly energy efficient homes under climate change scenarios, the quality of their ventilation systems, and the impact on health and wellbeing of their occupants (Dimitroulopoulou, 2012; Wargocki et al., 2002; Crump et al., 2009).

In this paper we provide an overview of the interaction of climate change, the domestic indoor environment and health in the UK, focusing on (i) building overheating and thermal comfort, (ii) indoor air quality, (iii) indoor allergens and infections, and (iv) flood damage and water contamination. The discussion includes unintended harmful effects of climate change mitigation and adaptation policies, as well as opportunities for health protection and health promotion.

2. Overheating of buildings and thermal comfort

Temperatures on the Earth's surface have risen for each of the last three decades and are now higher than in any previous decade since 1850 (IPCC, 2013). In the UK, temperatures have increased since pre-industrial times, and at a rate of around 0.25 °C per decade since the 1960s (Vardoulakis and Heaviside, 2012). Central estimates of climate projections for the UK (UKCP09; Murphy et al., 2010) indicate increases in the summertime mean daily maximum temperatures up to 5.4 °C in southern England, and up to 2.8 °C in northern Britain by 2080, under a medium GHG emissions scenario. Heatwaves are also likely to become more frequent and intense in future decades (Jones et al., 2008).

The association between elevated outdoor temperatures and mortality has been extensively reported (e.g. Hajat et al., 2014; Armstrong et al., 2011; Vardoulakis et al., 2014). The elderly, people with pre-existing medical conditions (e.g. mental disorders, neurological or cardiovascular disease) and those who are overweight or have reduced mobility, are likely to be more vulnerable during prolonged hot periods and heatwaves (Haines et al., 2007; Hajat et al., 2007).

The European heatwave of August 2003, considered to be the most intense since 1500 (Luterbacher et al., 2004), has been estimated to have caused up to 70,000 additional deaths in Europe (Robine et al., 2008). In the UK, there were over 2000 excess deaths (a 17% excess for the heatwave period), with the highest impact in southern England, especially London, and on the elderly (Johnson et al., 2005). Of these, 400–800 have been attributed to poor outdoor air quality over the same period (Stedman, 2004). As a result of climate change, heatwaves are likely to be experienced more frequently in future in Europe, with suggestions that heatwaves as severe as that of 2003 will be experienced every other year by the 2040s under un-mitigated emissions scenarios (Stott et al., 2004).

Although epidemiological studies show that high temperatures result in excess deaths, such evidence is based on the link between outdoor temperatures and health effects. There is much less evidence on the mortality relationship with indoor temperatures which can vary widely from dwelling to dwelling for any given outdoor temperature (Vadodaria et al., 2014). Consequently, it has not been possible to define how indoor temperatures relate to an overheating threshold for health risk, given the very limited and indirect epidemiological evidence (DCLG, 2012a; Anderson et al., 2013). However, these factors that may modify heat risks associated with the indoor environment can be grouped into the following categories: (i) location, (ii) building characteristics, and (iii) occupant behaviour. They are briefly discussed below for the UK.

2.1. Location

Southern England is likely to face the largest risk of indoor overheating in the UK, since outdoor temperatures are among the highest for the UK (DCLG, 2012a, 2012b). It is estimated that naturally ventilated, super-insulated dwellings in London may not meet comfort targets in 2010–2040 without mechanical cooling in hot weather (Peacock et al., 2010).

Around 80% of dwellings in England and Scotland, 65% in Wales and 60% in Northern Ireland are located in urban areas (Capon and Oakley, 2012). To varying degrees, these dwellings may be affected by the urban heat island effect (UHI), which leads to increased ambient temperatures in urban centres compared with the surrounding countryside. The UHI effect is typically higher at night than during the day, and the temperature increment at the centre of a large city can be as large as 5–10 °C compared with surrounding countryside (Knight, 2010; Tomlinson et al., 2012). During the heatwave of August 2003, the urban heat island intensity in London reached a maximum value of 9 °C (Mayor of London, 2006), and was up to around 7 °C in Birmingham (Heaviside et al., 2015). The UHI effect may be considered as beneficial in winter, since it reduces the cold weather impacts and heating demand (Mavrogianni et al., 2009). However, in summer, and especially during heatwaves, the UHI effect may exacerbate building overheating and related health impacts (Davies et al., 2008), since it prevents buildings from cooling down, particularly at night (Watkins et al., 2007).

Monitoring of summertime temperatures in a nationally-representative sample of English dwellings showed that, on average, flats were generally the warmest and detached houses the coolest (Beizaee et al., 2013; Lomas and Kane, 2013). However, overheating propensity is determined by a multitude of factors, including the floor level, orientation and shading of the dwelling (Porritt et al., 2011). Small top-floor flats appear to be considerably more vulnerable due to the heating of the roof from which there is often poor thermal insulation (Orme and Palmer, 2003; Orme et al., 2003; CIBSE, 2005). Living in a top floor flat or right under the roof (e.g. loft conversions) generally increases exposure to high temperatures and related health risks (Vandentorren et al., 2006). On the other hand, ground floor living areas may be relatively cool (Capon and Hacker, 2009).

In the UK, high indoor temperatures appear to be more of an issue in bedrooms than in living rooms (Firth et al., 2007, Firth and Wright, 2008; Mavrogianni et al., 2010; Beizaee et al., 2013), and often exceed the Chartered Institution of Building Services Engineers (CIBSE) static overheating guideline of 26 °C for bedrooms and 28 °C for other living areas. Data from national monitoring campaigns show that bedroom temperatures are generally lower during the night and early morning and gradually increase during daytime, reaching their peak in the evening (Firth and Wright, 2008; Beizaee et al., 2013).

2.2. Building characteristics

Although location determines variation in indoor temperatures, the built form and permeability of the building envelope, and ventilation strategy, can be even more powerful determinants of dwelling-to-dwelling variation in indoor temperatures (Mavrogianni et al., 2012; Oikonomou et al., 2012). Traditionally, UK dwellings have high levels of air permeability, which is a measure of airtightness of the building fabric, often exceeding building regulations (ADL1A, 2010). Improving airtightness in dwellings entails reducing air leakage through the uncontrolled flow of air through gaps and cracks in the building fabric. This prevents heat loss, which in winter reduces energy use and associated carbon dioxide emissions, and can improve thermal comfort and reduce cold-related impacts on occupants' health (EST, 2005; EST, 2007). However, by improving airtightness, especially in Passivhaus (i.e. houses with high standards of energy efficiency) and super insulted dwellings, the risk of overheating may increase during hot weather periods unless other means of ventilation and active cooling systems are available (Sharples and Lee, 2009; McLeod et al., 2013). The recommended values of air permeability range from 10 $m^3/h/m^2$ for conventional houses (ADL1A, 2010) to less than 1 $m^3/h/m^2$ for "low carbon" homes (PassivHaus Standard, IPHA, 2014; ATTMA, 2010).

The building characteristics which increase overheating risk can be different across different UK climate regions, meaning that it is not always appropriate to generalise the results of a local study across the entire country (Taylor et al., 2014b). However, newly constructed houses with high levels of insulation generally have the potential to be at higher risk of overheating than older, less well insulated houses (Pathan et al., 2008; DCLG, 2012a). An analysis of houses built before 1994 in the UK showed that some of the factors affecting airtightness are the year of construction, type of wall and floor, season of the year, and the extent of drying out of the timber structure during the first year of occupancy (Stephen, 1998). The stock of old dwellings in the UK has a very broad range of air permeability values, with homes built since about 1980 being more airtight on average than those built over the period 1930–1980 (Etheridge et al., 1987; Stephen, 1998; Dimitroulopoulou et al., 2005; Pan, 2010). Dwellings built with precast concrete panels are significantly more airtight than those built with timber frame, whilst the masonry and reinforced concrete frame dwellings are the leakiest (Pan, 2010).

Heavy construction materials, such as concrete and stone, generally increase the thermal mass of a building, meaning that internal air temperature responds slowly to external variations. Depending upon the location of any insulation, thermal mass may help reduce the risk of extreme temperatures, but may also trap unwanted internal thermal gains and potentially increase overheating risk in some climates (Peacock et al., 2010; Hacker et al., 2005). Thermal mass can reduce the peak indoor temperature during the day, but also keep the building warmer during the night, therefore effective temperature control is required through night-time ventilation in buildings constructed with these materials.

2.3. Occupant behaviour

Dwelling occupants can usually appreciably alter indoor temperatures during periods of heat by adjusting ventilation (e.g. opening windows) and shading, using cooling systems (where available), and influence their own thermoregulation by adjusting clothing, location within the home, and using fans and other measures (Fuller and Bulkeley, 2013; Mavrogianni et al., 2014). The choice of when to open windows is typically made spontaneously as a direct response to experienced temperatures rather than as a deliberate strategy to optimise cooling.

Occupant behaviour also depends on socio-economic status, occupant age, personal knowledge and preferences (Wei et al., 2014). Older people, socioeconomically deprived populations, isolated individuals, as well as the very young and people with pre-existing medical conditions have all been reported to be at higher risk of heat-related mortality/morbidity. This risk may in part reflect underlying medical conditions and physiological vulnerability, but in some cases also less access to control measures (e.g. air conditioning), or poorer knowledge or ability to control exposure to heat (PHE, 2013).

2.4. Climate change mitigation and adaptation to building overheating

Improved building design and refurbishment are important measures to help adapt to higher temperatures under climate change (DCLG, 2012b). However, the rate of replacement of the UK housing stock is low (about 1% a year (Roberts, 2008a)), and it has been estimated that around 70% of the current stock will still be available in 2050 (SDC, 2006). Therefore, planned adaptation of existing homes through retrofit measures (e.g. ventilation and cooling systems) is crucial.

Air conditioning can reduce thermal discomfort and health risks of overheating dwellings, but it entails considerable energy consumption (with implications of cost, especially for low income households, and additional carbon dioxide emissions), it may contribute to the urban heat island effect and it is dependent on an uninterrupted power supply during periods of hot weather when demand may overload the electricity supply infrastructure, increasing the risk of power failure (Kovats and Hajat, 2008; Ostro et al., 2010). It is therefore recommended to use passive control measures to minimise the need for air conditioning.

More generally, climate change mitigation and adaptation measures for dwellings should be considered in a joined up approach that minimises GHG emissions and reduces health risks. Table 1 summarises the climate adaptation measures that may be used in order to reduce overheating. The effectiveness of some of these measures has been ranked based on modelling and associated assumptions and shows that shading solar radiation was a highly effective way to reduce annual overheating; however, the combination of all the adaptation options was the most effective intervention (Gupta and Gregg, 2012; Porritt et al., 2012).

Occupant behaviour can also have a significant impact on overheating (DH, 2008a; Vardoulakis and Heaviside, 2012; Mavrogianni et al., 2014). Comparison of hard adaptations (structural building adaptation) against soft adaptation (behavioural change) showed that both can lead to similar reductions in temperatures and hours of overheating (Coley et al., 2012). CIBSE has published practical advice on avoiding overheating in European buildings (CIBSE, 2013).

3. Indoor air quality

Exposure to high concentrations of air pollutants indoors can cause both acute and chronic health effects. An example of acute effects is the intoxication and death due to short-term exposure to high concentrations of carbon monoxide (CO) (Raub et al., 2000; De Juniac et al., 2012), while chronic health effects include radon-related lung cancer (Darby et al., 2005), effects related to second hand tobacco smoke (e.g. chronic obstructive pulmonary disease (Jordan et al., 2011)), respiratory infections, cardiovascular disease, and a range of allergic symptoms, such as atopic dermatitis, rhinitis, conjunctivitis and hay fever (Chauhan and Johnston, 2003; Blanc et al., 2005). Certain pollutants, such as tobacco smoke and other combustion products, house dust mites and pollen may aggravate asthma symptoms (Jones, 1999; Rushton, 2004). Karakitsios et al. (2014) reviewed studies carried out during the period 1995–2010 on air pollutant concentrations in EU dwellings and associated them to potential risks and health impacts.

The indoor levels of air pollutants are affected by both external and internal factors (WHO, 2011; Sarigiannis, 2013). The external factors include: i) outdoor air pollution concentrations associated with anthropogenic and natural sources; ii) radon emitted from soil and building materials, or contained in groundwater and released indoors from the use of drinking water, and landfill gases such as methane emitted from contaminated soil, which may enter into the indoor environment through cracks and gaps in the building envelope; iii) dispersion characteristics of pollutants around the building influenced by the type, position and distance of the source of pollutants from the receptors, the size, shape, orientation and arrangement of the buildings in question, the topography of the area and meteorological conditions (Vardoulakis et al., 2003; Crump et al., 2004; Kukadia and Hall, 2004; Milner et al., 2004; Hall and Spanton, 2012).

Furthermore, indoor air quality levels are highly variable, depending on internal factors that include: (i) The physical and chemical properties of pollutants (gaseous or particulate, reactivity, deposition, size for particulates); (ii) indoor sources of pollutants, such as gas cookers, stoves, fireplaces, building and furnishing materials; (iii) building characteristics including infiltration and ventilation rates; (iv) occupant activities, such as opening of windows, cooking, tobacco smoking, and use of consumer products and extractor fans (Milner et al., 2011; Nazaroff, 2013).

In the absence of indoor sources, indoor concentrations of air pollutants such as combustion products and particulate matter are affected by the ingress of outdoor air into the indoor environment and are usually lower than outdoor concentrations due to attenuation by the building envelop (e.g. Dimitroulopoulou et al., 2001; Dimitroulopoulou et al., 2006; Taylor et al., 2014). However, in the presence of indoor sources, model simulations and experimental results show that these pollutant concentrations in homes may well exceed outdoor levels (Aizlewood and Dimitroulopoulou, 2006; Crump et al., 2005; Delgado-Saborit et al., 2009; Lai et al., 2004; WHO, 2010; Milner et al., 2011), resulting in indoor/outdoor (I/O) ratios greater than 1 (see Sections 3.1–3.2). The ventilation characteristics which determine these concentrations may be substantially influenced by adaptations to the dwelling designed to improve energy efficiency or reduce other forms of health risk (primarily temperature-related).

Outdoor air pollutant concentrations related to combustion products and other anthropogenic sources are generally projected to decrease in the future in the UK due to emission control measures (e.g. cleaner fuels and improved vehicles technologies), with the exception of ground-level ozone which is generated though atmospheric chemistry processes influenced by ambient temperature, climate-sensitive biogenic emissions and dry deposition rates (Williams, 2007; Heal et al., 2013). As a consequence, the impact of indoor sources on air quality in homes may become more prominent. Furthermore, occupant behaviour and changes in activities as a result of climate change (e.g. opening of windows in summer), may also affect indoor pollutant levels. Section 3 presents the emission sources of some key indoor pollutants and their effects on health.

3.1. Combustion products

Indoor levels of nitrogen dioxide (NO_2) and CO are influenced by indoor sources, ventilation conditions, occupancy (with larger households generally having higher pollutant levels) and location (with highest values in towns and lower levels in suburban and rural areas) (Dimitroulopoulou et al., 2005; Dimitroulopoulou et al., 2001). High outdoor concentrations in the UK typically originate from local traffic or other combustion sources. In the indoor environment, these inorganic pollutants are products of combustion produced by open fires, tobacco smoking, fossil fuel and biomass fuelled cooking and heating appliances.

In the absence of indoor sources, indoor NO_2 levels are typically lower than outdoors, as a result of indoor deposition and infiltration/ventilation conditions (e.g. Grontoft and Raychaudhuri, 2004). A

Table 1
Adaptation measures to reduce building overheating.

Adaptation measure	Impact on built environment	Study design	Reference
Management of the external microclimate			
Plant trees strategically	Reduce external temperatures and improves shading	Modelling study; UKCP09, worst-case scenario: ('extreme' climate change for the climate periods 2020s, 2050s and 2080s) Case study: Oxford Home typologies: detached, semi-detached; standard dwelling configurations (BEPAC (Allen and Pinney, 1990))	Gupta and Gregg (2012)
Construct cool paving	Reduce external temperatures		Gupta and Gregg (2012)
Create green roofs	– Reduce the roof temperature by absorbing heat into their thermal mass and due to evaporation of moisture, as long as they do not dry out; – Roof structure may need to be modified to improve stability and water tightness; – Plants need to be carefully selected to avoid risks related to aeroallergens (pollen).	Porritt et al. (2011): Four dwelling types typical of London and South East England, (19thC terraced, 1930s semi--detached, 1960s flats, modern detached) Methods: data from the English House Condition Survey (EHCS) and Energy Saving Trust's Homes Energy Efficiency Database (HEED). EnergyPlus to set air change rates based on SAP (2009). Weather data from the 2003 heatwave Porrit et al. (2012): Modelling study (EnergyPlus v6.0, DesignBuilder (v2.3.5)); Targeted dwellings in Greater London: 19th C typical end and mid solid-wall terrace houses, with four orientations, two occupancy profiles and using weather data from the 2003 heatwave	Porritt et al. (2011; 2012)
Minimising internal solar gains			
Paint external walls a light colour to increase their reflectivity	Particularly effective for dwellings with solid external walls and larger external wall areas (e.g. end-terraced house). Painted walls need to be kept clean.	See above	Porritt et al. (2011; 2012)
Install external shutters	– Improve solar shading but potentially problematic in terms of cleaning and maintenance; – Increase security; – More effective than internal blinds or curtains, as solar radiation, already passed through the windows before being absorbed by the blinds or curtains, is transmitted to the room as heat.	Roberts (2008b): Review of the effects of climate change on the built environment. For the other refs, see above.	Roberts (2008b), Porritt et al. (2011; 2012), Gupta and Gregg (2012)
Install external awnings for south and west facing windows	Benefits for rooms that tend to be heavily occupied during the daytime (e.g. living rooms)	See above	Roberts (2008b)
Install double glazing and double glazing with low-e coatings	Reduce heat gain in summer as well as heat loss in winter	See above	Roberts (2008b) Porritt et al. (2011; 2012)
Install low e-triple glazing Specialist low SHGC (or g-value) glazing	Control solar energy by reducing visible transmittance, which would affect daylight levels all year round	See above	Porritt et al. (2011; 2012)
Management of internal heat			
Increase thermal mass on floors and/or walls in combination with adequate night cooling (purge ventilation, combined with fans):	Effective but the location of thermal mass (floors and/or walls) is a highly sensitive issue: If misplaced or misused, thermal mass has the potential to increase hours of overheating and/or increase space heating energy.	Coley et al. (2012): Modelling study for school and large house in London (Islington), constructed under the assumption of UK 2006 Building Regulations (light weight) Weather data: Current climate and projections for 2050 (UKCP09). 10th, 50th and 90th percentiles used for a high emissions (A1FI) scenario. For the other refs, see above.	Coley et al. (2012), Gupta and Gregg (2012)
External wall insulation	– Keep homes cool in the summer and increase winter heating efficiency – Reduce heat loss through the building fabric at night; but must ventilate at night	See above	Roberts (2008b)
Internal wall insulation	Reduce heat loss in summer; may not be recommended for certain building types	Modelling study: EnergyPlus dynamic thermal simulations of (a) 15 dwelling archetypes (including ground-, mid- and top-floor level flats); (b) 2 insulation levels (as-built and post-retrofit) for 4 construction elements (external walls, windows, ground floor, roof/loft); (c) 4 orientations of the principal facade; and (d) 2 external environment morphologies. Two summer year weather data represent current and future climate: CIBSE 1984-2004 and UKCP09 future weather file (50th percentile of	Mavrogianni et al. (2012)

(continued on next page)

Table 1 (*continued*)

Adaptation measure	Impact on built environment	Study design	Reference
		external temp for the 2050s, medium emissions scenario).	
Internal roof insulation	Very effective for the top floor flat, less effective for houses with pitched roofs containing loft insulation	See above	Porritt et al. (2011)
Loft insulation	Little effect on overheating reduction	See above	Porritt et al. (2011)
Replace carpets with wooden floors or tiles to expose the cooling effect of the ground	Increase heat loss in summer, but colder homes in winter, particularly with tiles	See above	Roberts (2008b),
Reduce lighting and other electrical gains	Control internal heat Reduce energy consumption	See above	Coley et al. (2012)
Ventilation			
Increase natural ventilation at night	Increase heat loss in summer and provide a cooling benefit during the daytime Limitation: security issues	See above	Roberts (2008b), Porritt et al. (2011), Gupta and Gregg (2012)
Install ceiling fans in each room	Better circulation of air and reduced indoor temperatures	See above	Roberts (2008b), Porritt et al. (2011), Gupta and Gregg (2012)
Open windows	During the peak daytime hours: Effective for end-terraced house with daytime occupancy (elderly); Not effective for top floor flat with daytime occupancy. Safety/security issues as well as noise need to be considered. Open windows in the early morning if temperatures are low, and shut them if the outdoor temperature rises above indoor temperature during daytime.	See above	Porritt et al. (2011; 2012)
Open windows at a lower set point	Control the internal heat	See above	Coley et al. (2012)
Air conditioning	Provide cooling comfort but increase CO_2 emissions Increase outdoor temperatures in built up areas	See above	Gupta and Gregg (2012), Papadopoulos (2001)

comprehensive study in UK homes (Coward and Raw, 1996) reported indoor/outdoor (I/O) ratios, over a one-year period, with mean values of 0.6–0.7 in homes without gas cooking, whereas for homes with gas cooking this ratio was approximately 1.4 for kitchens and 0.9 for living rooms. Decreases in indoor NO_2 emissions are expected in the future, if new dwellings use electricity instead of gas for cooking.

Several studies have examined the health effects of exposure to outdoor NO_2 COMEAP, 2010a, and for the indoor environment, health effects are well documented (WHO, 2010). There is significant association of various respiratory symptoms (e.g. wheeze) or lung function indices with indoor NO_2 concentrations or personal exposure in epidemiological studies of asthmatic children; associations for non-asthmatic children have been reported less consistently. There is also recent evidence suggesting that children with asthma or infants who are at risk of developing asthma are more sensitive to the respiratory effects of indoor NO_2 exposure. Furthermore, although there seems to be a suggestion of stronger associations of respiratory health with indoor NO_2 in females compared with males, it is not clear whether this is due to women spending more time indoors or a biological basis (Breysse et al., 2010).

CO is a relatively unreactive gas and is not deposited on internal surfaces. It can cause accidental poisoning in occupants, with varying health effects from headache and dizziness, nausea and sickness to coma and death. High but non-lethal exposure can result in long-lasting neurological effects (Croxford et al., 2008). In the absence of indoor sources, outdoor concentration is the main parameter affecting indoor CO concentration, which is generally low in UK houses. Under these conditions, the I/O ratio is almost 1.0. With gas cooking and smoking, peak CO concentrations may be increased from background levels (typically <1 mg/m^3) and I/O ratios of 1.4 and 1.2 have been reported, respectively (Dimitroulopoulou et al., 2006). This indicates that gas cooking should not be an issue of concern, under normal ventilation conditions. However, high peaks (>100 mg/m^3) can occur with malfunctioning or inappropriately used flued and unflued domestic appliances (boilers, heaters, fires, stoves and ovens), which burn carbon containing fuels (coal, coke, gas, kerosene and wood) (COMEAP, 2004; WHO, 2010; Mccann et al., 2013). Increasing airtightness of dwellings may increase concentrations of CO to levels that could cause poisoning or lead to chronic exposure with subclinical adverse health effects.

3.2. Particulate matter

Particulate matter (PM) in houses may originate from various outdoor sources (e.g. road transport, industry and construction), indoor combustion (e.g. wood burning, cooking activities, and tobacco smoking). PM can also be of biological origin, resuspended dust particles, and secondary particles generated by indoor air chemistry (Arvanitis et al., 2010). The use of wood burning stoves may increase in permitted zones in the UK, as a result of changing affordability of fossil fuels and the trend towards renewable energy sources (Fuller et al., 2014). Whilst particulate pollution from modern stoves is much lower than was previously common with open fires, higher emissions can still occur during start-up, stoking and reloading (Gustafson et al., 2008). Reviewing the relationship between indoor and outdoor particles, Chen and Zhao (2011) found that $PM_{2.5}$ I/O ratios greater than 3.0 occur in the presence of indoor smoking and combustion sources (e.g. fireplaces). PM can be removed from indoors by deposition, filtration and ventilation (Géhin et al., 2008).

Long- and short-term exposure to ambient concentrations of fine particles with aerodynamic diameter generally less than 2.5 μm

($PM_{2.5}$) has been associated with increased cardiovascular and respiratory mortality and morbidity (COMEAP, 2010b; Arvanitis et al., 2010). PM generated from indoor combustion processes has been associated with increased respiratory illness (wheezing, cough, including asthma) and COPD (Simoni et al., 2002; Weisel, 2002; Triche et al., 2005; Orozco-Levi et al., 2006). Exposure to passive smoke has been associated with higher risk of coronary artery diseases, lung cancer, respiratory diseases and stroke (US-DHHS, 2006). There are some specific components of indoor mineral dust particles (e.g. boron, metals and soil minerals) that are classified as human carcinogenic or toxic to reproduction (IARC, 1997; IARC, 2002). Asbestos is also classified as human carcinogen (IARC, 2012) and its use is forbidden today by the building regulations. Indoor air chemistry products, especially those of ozonolysis of terpenes (limonene and a-pinene) emitted from cleaning products, include fine and ultrafine particles (UFPs), which may cause irritation of the eyes and upper airways at high ozone and terpene indoor concentrations (Clausen et al., 2001; Wilkins et al., 2003). There is also some limited evidence that the effect of simultaneous exposure to dust (i.e. total suspended particles) and ozone at relatively high concentrations is larger than the effect of these two pollutants individually in indoor environments (Mølhave et al., 2005).

3.3. Volatile organic compounds

Volatile organic compounds (VOCs) such as formaldehyde, benzene and other aromatic hydrocarbons are common indoor air pollutants emitted from building materials, furniture, paints, consumer products, tobacco smoke and other combustion sources (e.g. Bernstein et al., 2008; Dimitroulopoulou et al., 2015). At European level, there are significant differences in sources and emission strengths of indoor chemicals and risk assessments are difficult to perform due to the limited amount of indoor air quality data available or the lack of harmonised sampling protocols (Sarigiannis et al., 2011; Kotzias et al., 2005). Similarly, in the UK, there are limited indoor air quality data concerning the current situation and of relevance to energy efficient homes.

The health effects of VOCs include irritation to the eyes or nose, headaches, dizziness, nausea and allergic reactions (Jones, 1999). Some VOCs are carcinogenic, e.g. formaldehyde and benzene (Duarte-Davidson et al., 2001). There is evidence suggesting a link between VOCs emitted from consumer products and an increased risk of certain symptoms, such as wheezing, vomiting, diarrhoea and headache among infants and their mothers (Farrow et al., 2003). Frequent use of domestic consumer products in the prenatal period has been associated with persistent wheezing in young children (Sherriff et al., 2005). Venn et al. (2003) concluded that domestic VOCs are not a major determinant of risk or severity of childhood wheezing illness, though formaldehyde may increase symptom severity, and indoor damp increases both the risk and severity of childhood wheezing illness. In the context of climate change and its mitigation policies, increased airtightness in the absence of adequate mechanical ventilation may increase indoor VOC levels.

3.4. Persistent organic pollutants

Persistent Organic Pollutants (POPs) such as polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs), are ubiquitous in the indoor environment and have been associated with a wide range of negative health effects including cancer, immunosuppression, metabolic, neurobehavioural, endocrine and reproductive disorders (UNEP, 2011). Although overall levels of POPs will continue to decline globally as a result of global emission reduction initiatives such as the Stockholm Convention, there is a risk that human exposure to POPs, via inhalation of air and ingestion of surface dust in the indoor environment, may be altered directly and indirectly by climate change. For example, higher indoor temperatures will lead to greater volatile emissions of POPs, as well as VOCs, from household products and materials leading to higher indoor concentrations, although enhanced natural ventilation (e.g. opening of windows) may balance higher indoor volatile emissions during summer (Haghighat and De Bellis, 1998; Hazrati and Harrad, 2006; Lamon et al., 2009). POP concentrations are typically 1–2 orders of magnitude higher in indoor air compared to outdoor air (Bohlin et al., 2008; Harrad et al., 2010). Furthermore, indoor sources of certain POPs used as brominated flame retardants, such as PBDEs, and fabric treatment products for stain resistance, such as perfluorooctane sulfonate (PFOS), may become more significant in future climate-controlled buildings (UNEP, 2011). Increased use of thermal wall insulation in houses may increase indoor contamination with flame retardants, such as hexabromocyclodecane (HBCD) used in insulation materials.

3.5. Radon

Radon is a naturally occurring radioactive gas, emitted from rocks and soils, which can enter buildings and reach high indoor concentrations (WHO, 2009a). Radon is the largest natural source of human exposure to ionising radiation in the UK. Concentrations are distributed log-normally with geological conditions being the primary source of variation (Hunter et al., 2009). Most radon enters buildings with soil gas that is drawn in by the slightly lower air pressure indoors caused mainly by heating and ventilation. The highest radon levels in the UK have been found in southwest England but many other areas have significant numbers of homes with more than ten times the average level (Miles et al., 2007, 2011). Most radon exposure arises in the home, is broadly proportional to indoor radon concentration and is estimated to be responsible for more than 1100 lung cancer deaths in the UK per year. Half of these deaths occur among the quarter of the population who are current smokers (AGIR, 2009).

Radon has been shown to vary seasonally in the majority of buildings (Miles et al., 2012). Ventilation is the most effective mechanism of radon removal from indoor air as low ventilation rates can cause a build-up of radon gas in properties (Scivyer, 2001). Climate change adaptation and mitigation measures affecting building ventilation may therefore have an influence on radon exposure (Hunter et al., 2009; Milner et al., 2014). Building regulations require the installation of measures to prevent radon ingress in new and extended/refurbished dwellings in high radon areas. These mitigation measures can reduce high radon levels in buildings (PHE, 2014a, 2014b).

3.6. Ozone

Ozone (O_3) is an irritant gaseous pollutant whose adverse effects on health include reduced lung function, exacerbation of chronic respiratory illness, increases in respiratory hospital admissions and all-cause mortality (WHO, 2000). Exposure to ozone may also increase the risk of sensitisation to airborne allergens in predisposed individuals (D' Amato, 2002).

Infiltration from outdoors is the dominant factor affecting indoor ozone concentrations, in the absence of indoor sources (printers, photocopiers, electronic appliances). High outdoor ozone levels have been observed during heatwaves in the UK as sunny and settled weather conditions favour the build-up of ozone downwind from polluted areas (Stedman, 2004). In urban areas, outdoor ozone levels are usually higher near the top of urban canyons compared with street-level concentrations (Vardoulakis et al., 2011). Buildings offer protection from ozone, due to a combination of envelope filtration, deposition on internal surfaces and reaction with gas-phase indoor compounds (Weschler, 2004; Coleman et al., 2008; Walker and Sherman, 2013; Nazaroff, 2013).

Changes in building design, construction and operation, in part influenced by climate change responses, may alter indoor ozone levels. Ozone infiltration may be enhanced by larger increases in ground-level ozone concentrations predicted in urban areas compared to rural areas in the UK (Heal et al., 2013). Warmer summer temperatures may result in occupants opening more often their windows in naturally ventilated houses during periods of high outdoor ozone levels (Fabi et al., 2012). Increased indoor concentrations of ozone could result in higher levels of formaldehyde and UFPs through chemical reactions (Uhde and Salthammer, 2007), although ozone is removed rapidly in the indoor environment by deposition on surfaces and by gas-phase reactions (Jakobi and Fabian, 1997; Weschler, 2006). Therefore, the overall impact of potentially higher ambient concentrations, the increased airtightness in new built houses, and any changes in ozone-initiated chemical reactions on indoor ozone levels is uncertain and needs further investigation.

3.7. Climate change mitigation and adaptation measures and indoor air quality

Energy efficiency interventions in dwellings are typically associated with appreciable change in airtightness. As a result, home ventilation may be reduced, if the golden rule "build tight, ventilate right" is not followed. It is a concern that whilst enhanced thermal efficiency in dwellings may be achieved by reducing the permeability of the building envelope, this could result in the accumulation of indoor air pollutants, such as PM and environmental tobacco smoke (Gens et al., 2014), if adequate ventilation levels are not maintained.

In terms of natural ventilation, background ventilators (e.g. trickle ventilators), when open, allow a controlled amount of ventilation to take place. However, studies in the UK showed that in 75% of the dwellings the trickle vents were closed since the occupants were not aware or their use and impact (Dimitroulopoulou et al., 2005).

Changes in building regulations have led to increased use of mechanical ventilation with heat recovery (MVHR) systems. These can substantially increase ventilation rates, reducing exposure to pollutants from indoor sources, if properly installed, operated (occupants are often unaware of their control), and maintained, and from outdoor sources if air filtration is provided (Wilkinson et al., 2009; Shrubsole et al., 2012). However, removing indoor pollution sources is a more effective way to control indoor air quality than diluting pollutant concentrations by ventilation. Therefore, indoor emission sources should be controlled wherever possible (e.g. by use of low emitting materials and products). A range of adaptation measures that can be implemented to control ventilation, while maintaining acceptable levels of indoor air quality, are presented in Table 2.

Table 2
Adaptation measures to improve indoor air quality.

Adaptation measure	Impact on indoor air quality	Reference
Remove indoor sources		
–Have all appliances, flues and chimneys correctly installed and serviced by trained, reputable, registered and competent engineers –Keep rooms well ventilated while using an appliance and do not block chimneys, flues or air vents; –Fit an audible CO alarm that meets European Standard EN 50291.	Reduce indoor concentrations of combustion products (CO, NO_2)	DH (2008b)
–Use furnishing, DIY, construction, and consumer products with low VOC emissions.	Reduce VOC emissions from building materials and consumer products	EU VOC labelling schemes[a]
Ventilate right		
Optimum location of ventilation inlets away from outdoor pollution sources	Minimise the ingress of outdoor air pollutants into the indoor environment	Kukadia and Hall (2004), Zero Carbon Hub (2012)
Increased airtightness in combination with mechanical ventilation (Mechanical Ventilation with Heat Recovery systems (MVHR)),	– Prevent ingress of outdoor air pollutants; – Remove indoor air pollutants generated from indoor sources (as long as MVHR systems are properly installed, operated and maintained)	Wilkinson et al. (2009) Shrubsole et al. (2012) Taylor et al. (2013a, 2013b) Gens et al. (2014)
Air filtering in mechanical ventilation systems	Remove a fraction of allergens, particles and ozone	Weschler (2006)

[a] European ecolabel (e.g. textile-covered flooring, wooden flooring, mattresses, indoor and outdoor paints and varnishes: Europe) — http://ec.europa.eu/environment/ecolabel/.

4. Indoor allergens and infections

In indoor environments, dust mites, damp and mould, pets, pests, and insects are the major sources of allergens. Exposure to allergens produced in the indoor environment may be exacerbated by airtightening of dwellings which may reduce the rate of removal of the allergens, or of moisture produced indoors through activities such as cooking, showering and drying laundry.

Mould and bacteria are ubiquitous microbial contaminants in buildings that can grow once sufficient moisture levels are present. These microorganisms can cause health problems in building occupants through the aerosolisation of spores, cell fragments (glucans), metabolic byproducts such as Microbial Volatile Organic Compounds (MVOCs), and toxins such as mycotoxins or endotoxins (Rea et al., 2003; Fisk et al., 2007). Occupants of damp and mouldy buildings are at increased risk of allergic and hypersensitivity reactions, exposure to toxins, and infections.

Hypersensitivity is one of the primary health problems caused by the poor indoor air quality in damp homes (Mudarri and Fisk, 2007). Sensitisation to fungi (Bush and Prochnau, 2004; Pirhonen et al., 1996), bacteria (Pauwels et al., 1980), aerosolised glucans (Douwes, 2005) and metabolic by-products produced by protozoa (Edwards et al., 1976) have been observed. Common indoor moulds such as *Penicillium* spp. and *Aspergillus* spp. can cause immediate type hypersensitivity, while hypersensitivity pneumonitis can occur in buildings with Heating, Ventilation, and Air Conditioning (HVAC) systems contaminated by bacteria and mould. Finally, allergic bronchopulmonary aspergillosis and allergic fungal sinusitis may occur when fungi grow inside the airway, leading to allergic reactions. Toxicity is another mechanism in which indoor microorganisms may lead to health problems for building occupants. Filamentous fungi may produce over 300 different mycotoxins, which may have carcinogenic, immunotoxic, cytotoxic, neurotoxic, mutagenic, and teratogenic effects (Gutarowska and Piotrowska, 2007). Endotoxins have been suggested to cause rheumatic diseases (Lorenz et al., 2006) and increased risk of respiratory problems (Liu, 2008). Direct infection of building occupants due to indoor damp-related microorganisms is rarer, but can occur in severely immunocompromised individuals.

In modern, well-insulated homes, the warm and potentially humid indoor climate is ideal for dust mites to grow, increasing the risk of exposure to their allergy-causing proteins. Climate change can affect the ecosystem and population dynamics of pests and insects and lead to change in the type, pattern and exposure level of allergens and animal species in houses (IOM, 2011). Outdoors, climate change may result in an earlier appearance and longer exposure to seasonal aeroallergens (Kennedy and Smith, 2012), whose infiltration into the indoor environment will vary with ventilation rate and penetration factor. Pests and insects can also carry pathogens and affect the risk of infection indoors.

Microbial infestation leading to allergic reactions or infection may occur for reasons other than damp. *Legionella* species, *nontuberculous mycobacteria*, *Pseudomonas aeruginosa*, *Acinetobacter* spp. and *Enterobacter* spp. may grow in water reservoirs such as evaporative cooling systems and cooling towers (CDC, 2003). *Legionella* in particular can more readily amplify in these environments and mains water entering buildings in a warmer environment (Morey, 2010), and cooling systems may become more common in a warmer UK climate. The addition of features such as green walls and roofs, rainwater harvesting and greywater recycling systems in buildings can also create a new habitat for microbial growth and dispersal (EA, 2011; Schenck et al., 2010). If a pathogenic ecosystem is established, it can provide a continuous microbial source and pathway to adversely affect public health outcomes unless adequate mitigation actions are implemented. These urban water infrastructures can also become a breeding ground for disease vectors such as mosquitoes. However, a suitable climate is required to support such an ecosystem. If established, the proximity of this ecosystem to the indoor environment can pose a higher vector-borne disease transmission risk to the occupants.

The built environment can play a role in the airborne transmission of infections such as tuberculosis (TB) through poor ventilation and overcrowding. Some studies also suggest an association between indoor air pollution and respiratory infections such as TB (Sumpter and Chandramohan, 2013). There is strong evidence of an association between ventilation, airflow and the transmission of airborne infectious diseases in buildings, but insufficient data to quantify the minimum ventilation requirements in various indoor environments for preventing transmission (Li, 2007). It is possible that with a growing population in parts of the UK, space available per person may decrease in residential buildings, especially in densely populated urban areas (Williams, 2009). Furthermore, the volume of rooms is decreased, since new homes are often smaller in area and room height, reducing the dilution as well as the surface area to act as moisture sink. To compensate for this risk factor, ventilation rates in residential buildings may need to be increased to maintain the same amount of fresh air supply per person. Climate change mitigation policies focusing on energy efficiency in the built environment could have an opposite effect on ventilation rates in future buildings. Reducing ventilation rates can also increase the humidity level indoors and promote mould growth. It should be noted that temperature and relative humidity affect the survival time of bioaerosols, while sunlight is a natural disinfectant.

Finally, climate change is likely to increase dust levels in the atmosphere, particularly in the summer due to drier weather conditions, with dust particles able to carry different kinds of pathogens (Morey, 2010). The ingress of airborne dust and pollen into dwellings needs to be taken into consideration as part of climate change mitigation and adaptation policies. An increase in dust removal by air filtration and domestic cleaning could become important to lower indoor levels of dusts containing allergens.

5. Flood damage and water contamination

Flooding is predicted to become more common in the UK in the future, due to changes in climate and land use. Rising sea levels caused by melting land ice and a rise in sea surface temperatures are predicted to lead to an increase in tidal flooding, while more frequent heavy precipitation events, particularly in winter, are predicted to contribute to increased surface and fluvial flooding (UKCP09). The Climate Change Risk Assessment for the Floods and Coastal Erosion Sector estimates that one in six of all UK properties are vulnerable to some degree of flood risk (Ramsbottom et al., 2012). The continued expansion and development of urban areas may exacerbate the flood risk, due to housing development on floodplains and the reduction of green space ratio in the built environment, critical for stormwater runoff mitigation. In addition to flooding, heavy rainfall and storms can lead to an increase in health impacts and physical damage to domestic properties, including damage to the building itself or supporting infrastructure, and moisture damage due to leaks in building envelopes (Goldman et al., 2014).

The management of flood defences, surface water run-off, and flood and storm-proofing of vulnerable dwellings can help mitigate the effect of floods and storms. However, when flooded, the quality of the building structure and hygrothermal properties of the construction materials determine moisture transport into the indoor environment and building envelope (IOM, 2011). This can lead to a number of consequences, including physical damage to the building stock and short and long-term health consequences for building occupants. An increased frequency of heavy precipitation and flooding events will therefore put pressure on existing buildings and pose a health risk to their occupants (Vardoulakis and Heaviside, 2012). The health impacts of floods in the UK, as well as adaptation measures for flooding, are discussed below.

5.1. Health impacts of floods

Health impacts of floods may be considered to be directly or indirectly caused by floodwater. Direct health effects include those that are caused by the floodwater itself, including drowning, physical trauma, and electrocution, while indirect health consequences can include faecal-oral disease, vector-borne disease, acute asthma, skin rashes, outbreaks of gastroenteritis and respiratory infection, poisoning, mental health issues, and problems associated with displacement and disruption to people's lives (Jonkman and Kelman, 2005; WHO, 2006). It is thought that the risk of death following a flood is influenced by the scale, depth, duration, suddenness, and velocity of the flood (Ahern et al., 2005). The health impacts from a flood continue to occur after the immediate event, during the clean-up process, and may persist for months or years (WHO, 2002; WHO, 2006). Consequences can be severe – for example a 50% increase in all-cause mortality in the flooded population was reported in the year following the 1968 Bristol floods (Bennet, 1970).

Physical injuries following flooding can be caused by direct contact with flood waters (Schnitzler et al., 2007), while people are being evacuated from their homes and during the clean-up process (Jakubicka et al., 2010; WHO, 2006), or due to a collapse of a structurally-weakened building (Kelman, 2004). CO poisoning is also a serious health risk associated with flooding, occurring in the aftermath of the flood when generators or fuel-powered equipment are used indoors for drying or pumping out flood water (PHE, 2014b). High numbers of fatalities and near fatal events from CO poisoning have occurred in the USA in the aftermath of floods caused by hurricanes (CDC, 2005; Richardson and Eick, 2006) as a result of inappropriate use of fossil fuelled electricity generating equipment (e.g. electricity generators used during clean-up operations post flooding, pumps for water removal, electric heaters for drying out process and power tools). As flooding risk in winter may increase in the UK due to climate change, the public need to be made aware of the high risk of CO poisoning associated with inappropriate generator use.

During flooding and heavy rainfalls, sewage systems can become overwhelmed and may overflow, releasing human and opportunistic pathogens into the floodwater. Infections such as those caused by *Leptospirosis*, *Escherichia coli*, or *Salmonella* that may be caused by flooding are rare in the UK, as pathogens are thought to become diluted by flood water (NHS, 2010), however there is a lack of available data on the association between flooding and infectious diseases in Europe (WHO, 2002). The persistence of flood-borne microorganisms on building surfaces is dependent on the level of sewage contamination of the water and the drying rate of the surface (Taylor et al., 2013a, 2013b). Food and water may also become contaminated by bacteria, sewage, agricultural waste or chemicals during flooding events (CDC, 2008; PHE, 2014b), leading to infection risk. The limited understanding of the long-term health consequences of flooding is due to the lack of data on non-drowning or non-immediate deaths following a flood (Few et al., 2004; Alderman et al., 2012).

In addition to microorganisms carried by floodwater, damp indoor spaces caused by floodwater or storm leakage can result in the growth of ubiquitous mould and bacteria that might not otherwise have sufficient moisture conditions to become established. Mould species, for example, *Cladosporium*, *Aspergillus*, *Penicillium*, *Alternaria*, and *Stachybotrys* species of fungi have all been observed in flooded dwellings (Solomon et al., 2006; Dumon et al., 2009). Mould species with higher moisture requirements (e.g. *Alternaria* and *Stachybotrys*) are typically found more frequently in flooded properties, while those with lower moisture requirements (*Aspergillus* and *Penicillium*) can be found more frequently in damp but unflooded properties (Dumon et al., 2009). Bacteria, *mycobacteria*, Gram-negative bacteria (Andersson et al., 1997; Hyvärinen et al., 2002; Torvinen et al., 2006], *Streptomyces* species (Lignell, 2008), and protozoa (Yli-Pirilä, 2009) have also been found on surfaces in damp homes. Damp indoor environments have been associated with respiratory health problems (WHO, 2009b), and a number of studies have shown an association between flooded and water-damaged homes and respiratory problems (e.g. Dales et al., 1991; Ross et al., 2000).

Mental health effects are one of the most significant issues following flooding in the UK, and can often last longer and be more pronounced than physical health problems (Tapsell and Tunstall, 2000; Reacher et al., 2004; Carroll et al., 2009). A study of the aftermath of the 2007 floods found that the prevalence of all mental health symptoms examined (psychological distress, probable anxiety, probable depression and probable post-traumatic stress disorder (PTSD)) were two to five times higher among individuals who reported flood water in the home compared to individuals who did not (Paranjothy et al., 2011). People who are forced to move out of their homes because of flooding have also been observed to have a two-fold increase in mental health problems compared to those in unflooded dwellings (Pitt, 2008).

While all populations are at risk of the health impacts associated with flooding, certain groups are at higher risk of morbidity and mortality. Limited evidence indicates that the elderly are most at risk of flood mortality in the UK (Bennet, 1970; Ahern et al., 2005). There is only limited evidence regarding the impacts of flooding on health by socio-economic status. However, there is a clear socio-economic gradient in the populations most at risk of coastal flooding in England, with poorer communities at higher risk (Walker et al., 2003; Fairburn and Braubach, 2010). Conversely, for river flooding, high flood risk areas tend to include higher income households (Fielding et al., 2007). The Social Flood Vulnerability Index (SFVI) has attempted to estimate the vulnerability of the UK populations to health problems following flood events (Tapsell et al., 2002).

5.2. Climate change adaptation and mitigation measures for flooding

The ability of flooded or water-damaged dwellings to dry following a flood will dictate the length of time conditions inside remain suitable for microbial growth or survival, and therefore the amount of time occupants either live in unhealthy buildings or are displaced from their homes. The ability of typical dwellings to dry following floods depends on the ability to ventilate the property, the type of wall and floors in the buildings, and the actions taken to speed up drying (Taylor et al., 2013a). Dwellings with limited ventilation potential, such as flats with single-aspects or more airtight dwellings, will take longer to dry. Modern walls, such as glass-fibre, cellulose, and vermiculate insulated cavity walls and those with Autoclaved Aerated Concrete (AAC) may also take longer to dry due to the ability of these materials to retain water (Taylor et al., 2013a). Consequently, modern airtight flats may be most vulnerable to prolonged damp following a flood event. More extensive use of "green" construction materials in buildings may be seen as a climate change mitigation measure to reduce GHG emissions. Environmentally friendly "green" construction materials, e.g. cellulose and wood products, require less energy for manufacturing compared to traditional construction materials such as steel, aluminium and concrete (UNEP, 2009). However, organic building materials have nutrients capable of supporting microbial growth, and treatments used to protect them can degrade over time or be washed when submerged in water. Therefore, the use of "green" construction materials in the building sector needs to be carefully considered in relation to future climatic conditions.

Although the location of buildings currently vulnerable to tidal and fluvial flooding in the UK can be predicted, consideration should be given to the effect that climate change may have on the extent and potential severity of flooding in the future. Flood defence schemes are expensive, and there has been an increased focus on adaptation rather than flood prevention (Penning-Rowsell and Wilson, 2006). Buildings can be built or adapted to be more resilient to flooding by preventing the ingress of floodwater into a building ('dry' flood-proofing) or by adapting the building to minimise the potential damage of floodwater ('wet' flood-proofing). Measures for short-term dry-flood proofing involve blocking the entrance of the water. However, in deep floods (>0.9 m), preventing the water entering the building might be discouraged in order to avoid the imbalance between external and internal water levels, which can cause structural damage to the walls. 'Wet' flood-proofing measures aim to reduce the time and cost of recovering

Table 3
Adaptation measures for flooding in the built environment.

Adaptation measure	Impact on built environment	Reference
Adaptation of existing building stock		
Identify and block all potential entry points (doors, airbricks, sinks and toilets, and gaps in external walls around pipes and cables)	Avoid water entering the building (resistance measures for short-duration floods). Cannot avoid rise of groundwater which can occur through the floor.	TRCCG (2008)
Prevent water entering through the walls	Avoid structural damage to steel components and permanent damage to certain insulation types. Avoid mould growth within the walls (resistance measures for longer duration floods)	Roberts (2008a)
Fit rising hinges so doors can be removed	In deep floods, it helps prevent structural damage by allowing water entering the building, avoiding the imbalance between internal and external water levels	Roberts (2008a)
Use water-resistant paint for the lower portions of internal walls	Reduce mould growth	Roberts (2008a) RIBA (2011)
Raise electrical points above flood level with wiring drops from above	Prevent electrical blackout	Roberts (2008a) RIBA (2011)
Relocate meters and the boiler above flood level	Prevent damage on meters and boilers	Roberts (2008a) RIBA (2011)
Replace carpets with vinyl and ceramic tiles and rugs	Reduce time for drying out	Roberts (2008a) RIBA (2011)
Adaptation for new buildings		
Build the house on high ground or on stilts, in flooding areas	Prevent houses from flooding	Roberts (2008b)
Build strong wall system and a roof construction in which surface material is both glued and connected with nails, in the strongest pattern possible	Improve resistant to strong winds and natural disasters	Roberts (2008b)
Avoid cavity walls that generally take longer to dry out	Speed up drying up process	Roberts (2008b)
Raise door thresholds, service entry points and meters above predicted flood levels.	Avoid damage	Roberts (2008b)
Avoid the use of plasterboard and gypsum-based materials.	Avoid mould growth	Roberts (2008b)
Avoid large areas of glass (e.g. glass patio doors, large windows and conservatories)	Avoid damage due to hydrostatic and hydrodynamic forces	Roberts (2008b)
Choose construction materials that are expected to be damaged but are cheap and easy to replace	Reduce repair costs after flooding	Roberts (2008b)
Add additional weep holes at the bottom of cavity walls	Allow water to drain out and speed up the drying process	Roberts (2008b)
Use recessed window and door reveals	Provide protection against wind-driven rain	Roberts (2008b)

from flooding and can be undertaken during the maintenance or redecoration of the dwelling. Typical adaptation measures are presented in Table 3. Ideally, new developments should be placed away from flood-risk areas. However, when this is not possible, then homes, surrounding landscapes, and local infrastructure should be designed and built to be more resilient to flooding.

6. Conclusions and recommendations

Climate change may have several direct and indirect adverse health effects in the indoor environment related to building overheating, indoor air pollution, biological contamination, and flooding and water damage. Joined-up climate change mitigation and adaptation measures in the residential building sector involving improved building design and ventilation, passive cooling, and energy efficiency measures can result in benefits to health, if well designed and successfully implemented.

New buildings should be designed to address the health effects of climate change in the indoor environment but also to minimise the impact of the built environment on the climate by reducing fossil fuel use. New buildings should make more use of low carbon energy sources. Furthermore, they can incorporate new technologies that help reduce energy use, including the embodied energy in the materials they contain (Roberts, 2008b). For adaptation of the existing building stock to climate change, passive measures (e.g. external shading and shutters) can help maintain comfortable indoor temperatures and minimise the need for and environmental cost of air conditioning.

Ventilation is a key aspect that affects indoor air quality (chemical and microbial), moisture-related allergens (mould and dust mites) and thermal comfort in dwellings. Behavioural aspects of building occupancy and improved thermal efficiency, aiming to save energy, may compromise indoor air quality and increase indoor temperatures. Therefore the ventilation performance of highly energy efficient homes should be investigated further.

There is a need to further characterise potential health risks and benefits, such as reduced cold-related mortality, associated with current and future building infrastructure (including construction materials, indoor products, furnishings and mechanical ventilation systems) under different climate change scenarios. Practical health impact assessment methodologies, accounting for the combined direct and indirect effects (including health equity) of climate change in the indoor environment, should be developed. These may be based on adjusted epidemiological exposure-response relationships derived from outdoor data to reflect indoor environmental conditions and occupancy patterns.

Overall, climate change is likely to act as a risk modifier in the indoor environment, potentially amplifying existing health risks associated with exposure to high indoor temperatures, air pollutants, contaminated water, allergens and mould, and exacerbating health inequalities. Well-targeted and cost-effective adaptation and mitigation measures could minimise these risks and provide ancillary health benefits.

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