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Climate Change and Architecture: Mitigation and Adaptation Strategies for a Sustainable Development

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Abstract

Buildings are responsible nowadays for more than half of the energy consumption worldwide, significantly contributing - with the CO_2 emissions they trigger - to the very causes of climate change. The knowledge gap that exists with respect to how emissions from built environments can be mitigated and, simultaneously, how buildings and their occupants can adapt to shifts in global and local climate must be filled, involving integration of established knowledge, advanced design strategies, application of innovative technologies and multidisciplinary research. Although the evidence of climate change is supported by large consensus, the amount of data and predictions currently available often results in ambiguous information for climate non-specialists. Starting from a review of the Fourth Assessment Report published by the IPCC, the paper examines the interactions between human systems and dynamic environmental forces, trying to underline the causes and consequences of the evident alteration in the climatic equilibrium of the planet and exploring how built environments can contribute to mitigate and adapt to these changing conditions.

Keywords: Climate Change, Architecture, Mitigation, Adaptation, Integrated Design

1. Introduction

The last 10 000 years have been a period of relatively stable and mild climate. Overall, this has suited mankind perfectly, creating the conditions for the development of agriculture, stable settlements, and, ultimately, the emergence of complex human societies. Obviously, there have always been slight variations in local weathers, but usually changes have taken place so slowly that animals (including humans), plants and other forms of life have had time to adapt or migrate. However, since the onset of the Industrial Revolution, the pace of these variations has been dramatically speeding up: humans have changed the chemistry of the atmosphere through the combustion of fossil fuels and living matter, bringing about the prospect of global alterations and shifts in the whole terrestrial climate system.

The threat of global warming brought about by the build-up of heat-trapping gases in the atmosphere has nowadays become common knowledge. Yet, it is just recently that we have started to realise that the actions we have undertaken since the Industrial Revolution (and probably before) may have changed, possibly in a non-reversible fashion, the relationship between human development and the natural environmental system, altering most of the basic conditions that had allowed life to thrive on Earth. In this context, buildings - with their energy consumptions and CO_2 emissions - have played a leading role.

In order to respond to these threats and meet the needs imposed by a sustainable development, a new approach to building design and construction is mandatory, one which simultaneously addresses the complex requirements of the environment with its finite resources and the needs of contemporary societies and economies. New concepts of integrated design featuring sustainable methods of generation and use of energy have to be developed, bringing together the mandates of environmental responsibility (strategies of *mitigation* of human impacts) with the notion of climate responsiveness (strategies of *adaptation* to climate change).

In pursuit of solutions, an important lesson can be derived by looking at adaptive natural systems. In Nature, almost all living organisms develop, through evolution, responsive mechanisms to endure changing conditions without depleting their resources and altering the equilibrium of their ecosystem. Considering the global climate alterations we are now facing and the speed and momentum of these shifts, an ‘adaptive’ attitude in the way built environments are conceived and inhabited can provide the conceptual basis for the building design of the future. If humans are going to prosper, they will have to re-learn how to imitate Nature’s highly effective adaptive metabolic systems, integrating ancient knowledge with current and forthcoming technology for the most ‘sustainable’ design yet seen.

2. The Science of Climate Change

2.1 The Greenhouse Effect

According to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), ‘climate’ can be defined as ‘average weather’ and is usually described in terms of the “mean and variability of temperature, precipitation and wind over a period of time, ranging from months to millions of years” (IPCC, 2007a).

The climate of the Earth is powered by the Sun, which radiates energy over a wide range of wavelengths, and predominantly in the visible part (around 54% of its emissions) of the electromagnetic spectrum. The amount of energy reaching the higher strata of the Earth’s atmosphere each second on a surface area of $1m^2$ facing the Sun during daytime is about 1370 Watts (W). Since the Earth is nearly spherical, a greater amount of solar radiation arrives for a given surface area in the tropics than at higher latitudes, where sunlight strikes with a constantly decreasing angle. Energy is then transported from tropical regions to northern or southern latitudes via atmospheric and ocean circulation.

Part of the energy that reaches the Earth is reflected directly back into space by the atmosphere, while the remaining fraction is captured by land, biota, oceans, ice caps and, to a lesser extent, by gases. The total quantity of energy absorbed per second by the terrestrial system - averaged over the entire planet - amounts approximately to $240 W/m^2$. To balance this absorbed solar radiation, the Earth must re-radiate back in space the same amount of energy. Considering that the Earth is much colder than the Sun, it emits radiative energy at much longer wavelengths, i.e. in the infrared part of the spectrum (‘thermal’ radiation). Once emitted, some of this infrared radiation is absorbed by gases in the cooler upper atmosphere (CO_2, water vapour and other naturally-occurring trace gases that, altogether, make up less than 0,1% of the atmosphere) and is radiated back to the surface; this is what is called the ‘greenhouse effect’. The warming effect of greenhouse gases (GHGs) is thus a natural process, which, incidentally, is conducive to life on our planet. Without this warming, the average temperature at the Earth’s surface would be about 30°C colder than the average +14°C currently enjoyed, and below the freezing point of water, making life as we know it simply not possible.

Nevertheless, human activities of the last two centuries - primarily the burning of fossil fuels and the clearing of forests - have greatly intensified this natural greenhouse effect, initiating a chain of events which, as we are now starting to realise, can lead to drastic climate change.

2.2 The Earth’s climate system

The system governing the climate on Earth consists of many sub-systems linked together in a non-linear fashion. The many interlinkages amongst them make it difficult to predict the overall behaviour of the global climate in response to a variation in a single sub-system like, for example, the atmosphere. The state of the atmosphere (temperature, humidity, cloud density, pressure distribution, etc.), in fact, is interactively influenced in its turn by other sub-systems such as the oceans, the cryosphere (snow and ice), the biosphere (animals and plants) and the lithosphere (e.g. volcanoes).

Considering the intricate interactions between the various sub-systems, to induce a significant alteration in the global climate, one (or more) of the following causes (often referred to as ‘climate forcing’) has to occur (Alfsen et al., 2000):

1) Alteration of the Earth’s orbit and movements;

2) Variation in the intensity of solar radiation (the so-called ‘solar constant’);

3) Shift in the geological equilibrium of the planet (such as shape or position of the continents);

4) Variation in the equilibrium of oceanic currents (e.g. Gulf Stream, El Niño-La Niña cycles, etc.);

5) Modification of the Earth’s albedo (i.e. the reflectivity of the planet’s surface and atmosphere);

6) Changes in the composition of the atmosphere due to human activity.

These driving forces operate on different time scales ranging from very long geological eras up to a more ‘human’ temporal dimension. In addition, there are many complex feedback mechanisms in the climate system that can either amplify (‘positive feedback’) or diminish (‘negative feedback’) the effects of an alteration in one of the sub-systems, generating internal reactions whose effects are difficult to predict due to the complex ramifications amongst the various factors involved. For example, evidence from ice cores (which currently represent the source of most of the information we have available on past climate alterations) testify that our planet has in several occasions during its paleoclimatic history abruptly shifted between climate extremes due to positive feedback loops (Smith, 2005).

Earth’s climate has varied with time, both locally and globally, ever since the planet formed some 4,5 billion years ago. Best known are the Ice Age of 20 000 years ago (glacial maxima), the little Ice Age that hit Europe in the early Middle Age, the following medieval warm period and the cooling of the 17th, 18th, and 19th centuries. In all of these variations, carbon dioxide (CO_2) concentration is believed to have constantly played an important role (IPCC, 2007a).

Carbon is a key element for life on Earth forming the basis of all the plants, animals and micro-organisms. Its concentration in the atmosphere, over geological time scales, has helped stabilising the climate on Earth through the 'carbon cycle', a combination of biological, chemical, and physical processes where the atmospheric CO_2 is absorbed by 'sinks' - biota (plants and animals), rocks and ocean water - for then being released back in the ecosystem with the death and decomposition of living organisms, with the weathering of rocks and/or with volcanic eruptions.

A high concentration of carbon dioxide in the atmosphere leads to a warm and humid climate (warmer air can retain more humidity) that in turn, due to increased precipitation, leads to more rock erosion and consequently to a stronger sink for atmospheric CO_2 (as silicate binds to carbon in the atmosphere and is 'absorbed' by diffusion in the oceans). Conversely, low carbon dioxide concentrations induce a colder climate resulting in possible glaciations, with an ice cover that protects rocks from erosion and thus reduce CO_2 sinking. These cyclical feedbacks tend to stabilise the global climate system (temperatures and carbon concentration) in the long run (Alfsen et al., 2000).

Under natural circumstances, the release of CO_2 is offset by carbon sinks, and the climate system would be in a dynamic equilibrium with the energy received from the Sun if it were not for external forcings which could alter this balance, as it has happened several times in the paleoclimatic record of our planet.

2.2.1 Alteration of the Earth's orbit and movements

One of the causes of past climate fluctuations has been due to variations in Earth's orbit eccentricity, axial tilt (or obliquity) and precession, occurring over thousands of year-cycles. These orbital changes (induced by gravitational pull from neighbouring planets) are generally referred to as 'Milankovitch cycles', which change the amount of solar radiation received at each latitude in every season, although they can hardly affect the global annual mean (Figure 1). The Milankovitch cycles have been linked to the start and end of Ice Ages, although there are still several scientific uncertainties about how this alterations can actually be triggered (the amount of summer sunshine received in the northern hemisphere seems to play a crucial role in this process). It has been calculated that the Earth's current orbital configuration is similar to that of the warm interglacial period of 400 000 years ago, probably signifying that we may be in the early stage of an interglacial episode. Yet, the next large reduction in northern summer insolation is not expected before 30 000 years (IPCC, 2007a).

2.2.2 Variation in the intensity of solar radiation

Another likely cause of climate change in the past has been linked to variations in the energy output of the Sun, on both short and long time scales. On a short time scale, the solar output is known to vary over the 11-year solar 'sunspot cycle'. Although the total intensity of the solar radiation does not vary much during this period (by close to 0,1%), alterations in the mean temperature over land in the northern hemisphere have been correlated to this phenomenon. On a longer time scale, as a consequence of the Sun's evolution as a star, the solar radiation has increased its intensity by approximately 30% since the creation of the solar system (and thus the Earth), 4,5 billion years ago. Yet, although the solar radiation was considerably less intense at that early stage, the primordial terrestrial atmosphere contained probably much more CO_2 (and possibly methane, CH_4), and thus the 'natural' greenhouse effect contributed to keep the planet warm.

2.2.3 Shift in the geological equilibrium of the planet

Movements of tectonic plates contribute to the stirring effect of the atmosphere in concert with the rotary motion of the Earth and also cause fluctuations in atmospheric pressure. Data that go beyond the reach of ice cores seem to confirm that much warmer times than present have occurred in the Earth's paleoclimatic history due to shifts in the geological equilibrium of the planet, the formation of volcanoes and a consequently higher CO_2 concentration in the atmosphere. Dramatic changes in carbon concentration have also been linked to subduction phenomena (when one tectonic plate slides under another). In this process, vast quantities of CO_2 and debris are suddenly released, leading in the short term to a cooling of the climate (dust cutting out solar radiation), and to a warming effect in the long run, since CO_2 has a longer life in the atmosphere than dust and debris.

2.2.4 Variations in the equilibrium of oceanic currents

Due to a warming of the climate system induced by other external factors, surges of water coming from melting ice and increased rain can flow in the oceans affecting deep ocean currents; the Gulf Stream is a clear example. In this case, salty and warm surface water migrates from tropical seas to the North Atlantic heating up the north-western shores of Europe (contributing up to the 25% of the heat budget of these areas). In its movement, the current gradually becomes colder and saltier until it reaches Greenland, where due to its density it sinks to the ocean floor and, consequently, pulls more warm water from the tropics keeping active the current's 'conveyor belt'. If rain and melted land-based ice led to more freshwater runoff to the ocean, they could lower the salinity (and thus the density) of surface water undermining its ability to descend to the ocean floor. The stopping of oceanic currents would however be a reversible process (negative feedback), since colder conditions would decrease the melting of ice - and thus the plunging of fresh water in the ocean - up to a point where a new balance would be found.

2.2.5 Modification of the Earth's albedo

The extent of ice cover is another example of forcing that could be responsible for climate change. Ice has a much greater reflectivity (albedo) than water and land masses, and thus it causes solar radiation to be reflected back to space rather than be absorbed by the surface and warm the climate system. A reduction in ice cover due a climate forcing could eventually lead to even warmer conditions (positive feedback) until a further forcing would intervene to shift the equilibrium of the system. Other factors affecting the Earth's albedo can be represented by changes in cloud distribution, the presence of small particles called aerosols in the atmosphere, or alterations in the land's cover.

2.2.6 Changes in the composition of the atmosphere due to human activity

Finally, the last and possibly most dangerous cause of climate change can be linked to variations in the atmospheric concentration of greenhouse gases due to human activity. Carbon has been slowly locked in the Earth's system over million of years; yet, since the Industrial Revolution, humans have been releasing CO_2 in the atmosphere at a rate unprecedented. In addition, agriculture and industrial activities have resulted in the constantly increasing emission of other greenhouse gases such as methane (CH_4), nitrous dioxide (N_2O) and halocarbons (hydrofluorocarbons, HFCs, perfluorocarbons, PCFs and sulphur hexafluoride, SF6), which are significantly affecting the climate by altering the Earth's energy budget.

Although some scientists believe that the human influence on the climate system could be dated back at a far earlier time than the beginning of the Industrial Revolution (Note 1), the concern of our time is about climate changes comparable in magnitude to the global average difference between a glacial and an inter-glacial period (roughly 5°C), but projected to occur in a matter of decades rather than thousands of years.

Throughout their evolution as a species, humans have always been subdued to the vagaries of climate, responding to drastic climate alterations with their wits, their adaptation capacities or eventually migrating to milder zones. Yet, today our number has grown to a point where there is no room for large-scale migrations should a major climate shift make this necessary (Flannery, 2005). The challenge humans have to face today is thus to put in place *mitigation* actions necessary to prevent the planet crossing the threshold into a process of irreversible global warming that could have disastrous impacts on many aspects of life, and also to develop strategies to make their settlements and activities *adapt* to forthcoming new climate conditions which, according to the evidence available, seem now unavoidable.

2.3 Evidence of Climate Change and Projected Impacts

Climate change has been widely accepted as a reality of our times. According to the IPCC's Fourth Assessment Report (AR4), in the last two centuries atmospheric concentration of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have dramatically increased, at different rates, as a result of human activities, and now far exceed pre-industrial values (IPCC, 2007a). The global increases in carbon dioxide concentration are due primarily to fossil fuels and land use change (burning of forest, etc.), while those of methane and nitrous oxide are primarily due to agriculture.

Carbon dioxide's global atmospheric concentration has increased from a pre-industrial level of 280 ppm (parts per million) to a value of 379 ppm in 2005 (IPCC, 2007a). As per the evidence of ice cores, this concentration is unprecedented in at least the last 650 000 years. During this time, carbon dioxide varied between 180 ppm (during glacial times) and 300 ppm (warm interglacials). Values higher than today have occurred only millions of years ago due to massive forcing acting at a global scale, such as the immense and 'sudden' (from a geological perspective) release of methane-clathrates of 55 million years ago which drove CO_2 concentrations up to 2000 ppm (marking the onset of an era, the Eocene period). According to most observations and climate models available today, current concentrations cannot be justified by natural causes alone without considering human influence.

The annual average concentration growth rate of CO_2 was larger during the last decade (1, 9 ppm) than it has been since 1960, when continuous direct atmospheric measurements begun (1, 4 ppm per year, although with year-to-year variability). Specifically, carbon dioxide annual emissions have increased from an average of 23, 5 $GtCO_2$ (Gigatonnes of CO_2) per year in the 1990s to approximately 26,4 $GtCO_2$ per year in 2004-05 (IPCC, 2007a). The global atmospheric concentration of methane has increased from a pre-industrial value of about 715 ppb (parts per billion) to 1732 ppb in the early '90s and to 1774 ppb in 2005. This value largely exceeds the natural variability of the last 650 000 years, which ranges from 320 to 790 ppb; yet, growth rates have declined since the early 1990s, with total emissions being nearly constant. Finally, the global atmospheric concentration of nitrous oxide has increased at a constant growth rate since 1980 from a pre-industrial value of about 270 ppb to 319 ppb in 2005, primarily due to emissions resulting from farming activities (IPCC, 2007a).

2.3.1 Radiative Forcing

The influence that a factor (such as the concentration increase of a greenhouse gas) can have on climate change is often defined in terms of its *radiative forcing*, which represents a measure of how the energy balance of the Earth-atmosphere system is influenced by that factor. Radiative forcing is expressed in units of Watts per square meter (Wm^{-2}).

The combined radiative forcing due to raises in CO_2, CH_4 and N_2O concentrations between 1750 and 2005 is calculated in +2,30 Wm^{-2}, and its rate of increase during the industrial era is unprecedented in the last 10 000 years (positive forcing causes a warming of the climate system). Other significant anthropogenic contributions to positive radiative forcing come from emissions of ozone-forming chemicals such as carbon monoxide and hydrocarbons (+0,35 Wm^{-2}), changes in halocarbons (+0,34 Wm^{-2}) and land cover (+0,1 Wm^{-2}). Conversely, human modification of the reflective properties of ice and snow cover has resulted in a small negative forcing (-0,2 Wm^{-2}), whilst emissions of aerosols (such as sulphate, organic carbon, black carbon, nitrate and dust) have overall produced a negative radiative forcing (i.e. a cooling effect) of -0,5 Wm^{-2} and an indirect cloud albedo negative forcing of -0,7 Wm^{-2}. Changes in solar irradiance since 1750 have caused just a small positive forcing, estimated in approximately +0,12 Wm^{-2} (Figure 2) (IPCC, 2007a).

As a whole, the radiative forcing from human activities is much more important for current and future climate change than the estimated forcing caused by shifts in natural processes (such as solar irradiance). Basing on the evidence of these data, Working Group I (Physical Science Basis) of the IPCC states, in its contribution to AR4, that “warming of the climate system is unequivocal, as is now evident from observations of increases in global air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level” (IPCC, 2007a).

An increasing rate of warming has taken place over the last 25 years, and 11 out of the last 12 years rank amongst the twelve warmest in the instrumental record of global surface temperature (averaging near-surface air temperature over land and sea surface temperature) since 1850. The last 100-year linear trend records an increase of approximately +0.74°C, while the linear trend over the last 50 years (+0,13°C per decade) is nearly twice that for the last 100 years. A warming of the climate system is evident in many different measurements (Figure 3). The total temperature increase from 1850 has been estimated in +0,76°C, with the warmest years of the series being 1998 and 2005 (IPCC, 2007a).

The average atmospheric water vapour content (vapour is another powerful greenhouse factor) has increased since the ‘80s over land and oceans as well as in the upper atmosphere. Mountain glaciers and snow cover have significantly declined on average in both hemispheres, contributing to sea level rise. Also the average temperature of the global oceans has increased to depths of at least 3000m, due to the fact that the oceans have been absorbing more than 80% of the heat added to the climate system. Such warming causes seawater to expand, and thermal expansion has been so far the principal contributor of sea level rise. Actually, global sea level has risen at an average of 1,8mm per year between 1961 and 2003, with a faster rate measured in the last decade (about 3,1mm per year). The total 20th-century rise is estimated to be +0,17m (IPCC, 2007a).

2.3.2 Current and Future Scenarios

In order to understand the effects of changes of such magnitude, scientists have been looking at the paleoclimatic record of climatically sensitive indicators to analyse past climate changes and refer them to potential future scenarios. These scenarios have been compared to actual observed values in order to strengthen the confidence in projections.

For the next two decades, a warming of at least +0,2°C has been projected for a range of six emission scenarios developed by IPCC (Special Report on Emission Scenarios, SRES). Continued greenhouse gas emissions at or above current rates (‘business as usual’ values) would cause further warming and induce significant changes in the 21st century’s global climate system (IPCC, 2007a). For example, the best estimate for the lower scenario produced by IPCC (B1) predicts an increase of +1,8°C at the end of this century (with a likely range comprised between +1,1°C and +2,9°C), while the best estimate for the higher emission scenario (A1F1) foresees a +4,0°C increase, with a possible range getting up to +6,4°C temperature rise. The IPCC scenarios also predict the sea level to rise at the end of the 21st century by a range between 0,18m and 0,59m. It must be pointed out here that although an increase of 4°C may not sound very much this value is actually referred to a raise in global *average* temperature - i.e. an average taken over the whole world - which roughly corresponds to the difference in temperature between the middle of an ice age and the warm periods in between glacial episodes (estimated to diverge by 5-6°C in global average). This change is moreover expected to happen not over many thousands of years, as between glacial periods, but in a matter of less than a century.

Other than creating dramatic alterations locally and globally, this sensitive warming would entail further consequences on the equilibrium of the entire climate system. Warming tends to reduce land and ocean uptake of atmospheric CO_2 thus increasing the fraction of carbon emissions that remains in the atmosphere. These increasing carbon concentrations would lead to acidification of the oceans, with further reduction of CO_2 ocean uptake (a typical positive feedback) and a consequent additional warming of the climate system. According to current data, this is already happening.

As per the contribution of the IPCC Working Group II (Impacts, Adaptation and Vulnerability) to AR4: “evidence from all continents and most oceans shows that many natural systems are being affected by climate changes, particularly by temperature increases” (IPCC, 2007b). A global synthesis of data reveals that anthropogenic warming has already had a discernible influence on many physical and biological systems. Vulnerability of terrestrial and marine biosystems, for example, is revealed in phenomena such as earlier spring events, shifts in ranges of plant and animal species, longer growing seasons, and so forth. Warming is expected to be greater over land and at higher northern latitudes, and least over the Southern Ocean and parts of the North Atlantic. A warmer world is a wetter world because there is more evaporation and also more energy in the atmospheric circulation (due to the release of latent heat from water vapour).

Hot extremes, heat waves, tropical cyclones and heavy precipitations will become more frequent and intense especially at higher latitudes, whilst subtropical land regions will become even drier. Paradoxically, more floods and more droughts are expected to be recorded in the next few decades. Water security problems will intensify in many areas already subjected to droughts, fires and lack of rainfall. At the same time, the number of people at risk of flooding due to coastal erosion and sea-level rise will increase, mainly in densely-populated and low-lying areas which have relatively low adaptive capacity (IPCC 2007b).

Climate change is also expected to negatively impact on the future of most developing countries as it will increase the pressure on availability and distribution of resources associated with rapid urbanisation, industrialisation and economic growth (Smith, 2007).

2.4 International Agreements

In cognisance of the dramatic consequences that climate change would have on many, if not all, natural and biological systems, *mitigation* and *adaptation* measures are needed to address, respectively, long-term and short-term impacts. The variety of strategies available today is indeed very broad, ranging from technical, to educational, administrative and political measures, although the number of barriers, limits and costs to their effective implementation is still to be totally estimated and understood.

Greenhouse gases emissions have grown since pre-industrial times with an increase of 70% between 1970 and 2004, the largest growth coming from the energy supply sector (+145%) (IPCC, 2007c).

Amongst the measures to curb these massive impacts at a global scale, the Protocol signed in Kyoto on 11 December 1997 - and fully come into force in February 2005 - committed industrialised nations to make legally binding restrictions in emissions of the six main greenhouse gases: CO_2, CH_4, N_2O, HFCs, PFCs and SF_6. The called-for reductions varied from country to country, but overall would cut global greenhouse gases emissions by an average of about 5,2% below 1990 levels by the period 2008-12. Developing nations such as Mexico, Brazil, and the Asian ‘giants’ India and China, were however not included in the limitations established by the Protocol.

Since each of the greenhouse gases has a different effect on the climate and remains for a different time in the atmosphere before being removed by natural processes, the Protocol combined them into a ‘basket’ and defined targets for cuts in individual gases translating these into ‘CO_2 equivalents’, which can be added to produce one single figure ($GtCO_2$-eq). To produce these carbon-equivalent amounts, each non-CO_2 gas has been multiplied by its global warming potential factor (GWP), which reflects its impact relative to carbon dioxide (e.g. methane fosters a much stronger warming than CO_2).

After the official ratification of the Kyoto Protocol, a series of initiatives and regulations on climate change, energy security and sustainable development have started to be put in place in a number of countries worldwide. Yet, regardless of these efforts, the IPCC predicts that global greenhouse gases concentrations will still continue to grow over the next decades, with an increase by a range of 9,7 to 36,7 $GtCO_2$-eq until 2030 (IPCC non-mitigation scenario). These rises in concentrations will mainly come from developing economies where the most quickly rising per capita emissions are being recorded (although total figures are still substantially lower than most developed nations) (IPCC, 2007a).

The question mark now is to define the threshold of dangerous climate change and the concentration level of greenhouse gases (especially carbon dioxide) which would prevent ‘dangerous anthropogenic interference with the climate system’ (definition introduced by the United Nation Framework Convention on Climate Change); “such level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable way” (United Nations, 1992).

Currently, IPCC refers to stabilisation targets for CO_2 between 445 and 710 ppm by 2030 (IPCC 2007c), with a general agreement at 550 ppm, double the pre-industrial level. However, it is relevant to say that, considering the projected growth in emissions from developing countries, the limited targets of Kyoto are little more than irrelevant towards this target, since cuts of around 70% by the next decades would be needed to keep the atmospheric greenhouse gases concentration at double the pre-industrial levels. Yet, meeting this objective would still represent a serious challenge for human economies!

Considering that when CO_2 is emitted a known proportion of it is absorbed by carbon sinks (a little less than 50% over a century) while another part remains in the atmosphere, Flannery (2005) suggests that it is possible to calculate, in very rough figures, a hypothetical carbon budget to be met by mankind in the years to come. Before the Industrial Revolution, CO_2 concentration in the atmosphere was around 280 ppm, which corresponds to around 585 $GtCO_2$; currently, the figures are around 379 ppm or 790 $GtCO_2$ (2005 data). If international agreements were to decide for a stabilisation level at double the pre-industrial times, it means that human CO_2 emissions will have to be limited to around 600 $GtCO_2$ in the next 100 years. In fact, nearly half of this carbon would remain in the atmosphere (the other part being absorbed by carbon sinks), thus raising CO_2 levels up to about 1100 $GtCO_2$, (or 550 ppm, double the pre-industrial level) by the end of the 21st century. However, this could be a really tough target for humanity, since it would imply a rate of global emissions limited to 6 $GtCO_2$ per year over the next decades. If this figure is compared with the average 13,3 $GtCO_2$ which have been emitted each year during the ‘90s and is also combined with the expected rise in population and the economical and industrial growth of developing countries, the challenge to be met reveals to be quite extraordinary (Flannery, 2005).

Nonetheless, even if targets would be established and agreed at an international level and actions to reduce ‘business as usual’ rates of emissions were immediately put in place, climate models suggest that with concentrations of greenhouse gases and aerosols constant at year 2000 levels, still a warming of about +0,1°C per decade would have to be expected in the next fifty years due to the ‘momentum’ of the climate system, the slow response of the oceans and the time needed to remove greenhouse gases from the atmosphere (IPCC, 2007a). For this reason, it is imperative that long-term *mitigation* measures are coupled with short-term *adaptive* strategies in order to diminish the risks and projected consequences associated with climate change, as most impacts will increase in magnitude in the near future.

All things considered, there is an urgent demand to fill the gap in knowledge concerned with how, methodologically, *mitigation* and *adaptation* strategies and technologies can be applied and integrated with current development standards and needs in order to keep pace with climate change. A specific reference is made here to the adoption of sustainable measures within the building sector, one of the greatest contributors to climate change. In the attempt to fill this gap, a breakthrough could paradoxically be represented by looking back at the very roots of the natural system humans are part of.

3. Mitigation and Adaptation Strategies in the Built Environment

3.1 Technology at the cutting edge

We live challenging times.

Following exhaustive evidence, it is possible to make reasonably confident predictions on the repercussions that climate change will have on most aspects of life on Earth, and consider their consequences on the future of human activities.

The contribution of Working Group III (Mitigation of Climate Change) to the Fourth Assessment Report of the IPCC indicates some actions to be taken into account - in the short and medium term (before 2030), as in the long term (after 2030) - so as to curb human impacts and mitigate harmful consequences for the environment as a whole. These actions include primary measures to be applied within the energy and building sectors, but also on transports, industry, agriculture, forestry and waste management. By implementing these strategies, “energy efficiency options could sensibly reduce CO_2 emissions with net economic and environmental benefits, improving comfort, social welfare and enhancing energy security” (IPCC, 2007c).

Buildings will constitute a primary challenge in the ‘battle’ to mitigate the causes and effects of climate change, in that, primarily, we tend to spend a very large share of our time in them (often accountable to more than 90% of our day), whilst they also house the biggest part of our social, business, cultural and private activities. In addition, human settlements have undoubtedly been proven to be one of the very contributors to the current climate crisis (Steemers, 2003).

Between 1970 and 1990, direct emissions (i.e. not including those due to the electricity consumed) from buildings have increased by 26%. Considering also the electricity required for the functioning of mechanical systems and services (such as heating and cooling), the total increase of direct and indirect emissions from the construction sector is much higher (75%) than direct emissions alone (IPCC, 2007c). Buildings consume enormous amounts of energy during their entire life-cycle (from construction, through operation, to dismantle) depleting non renewable resources and releasing greenhouse gases in the atmosphere. Their energy budget is accounted nowadays for more than half of worldwide consumptions (mostly coming from the burning of oil, coal and natural gas), significantly contributing - with the massive CO_2 emissions they trigger - to the very causes of climate change. The development of design strategies for buildings to reduce their dependency on fossil fuels, curb their energy demands, exploit clean power sources and minimise their wastes becomes thus mandatory (also in cognisance of the uncertain future costs and actual availability of hydrocarbon-based forms of energy).

The measures suggested by the IPCC define a clear path that developed economies, together with emerging countries, should take on the road to reducing the pressure of human ‘habitats’ on the environment and avoid dramatic consequences. In this context, advances in technology can clearly play a major role by making viable practical ways to use cleaner and renewable forms of energy without increasing the Earth’s carbon budget and enhancing the quality of building design from an environmental point of view (Smith, 2005 and 2007).

Looking at recent advances in knowledge, it is possible to identify a range of ‘sustainable’ low-energy technologies that, in the near future, could contribute to curb the stress that mankind is imposing on the climate system (Table 1). However, in order to successfully reduce humans’ climate forcing, innovation in the production and management of energy in built environments will have to be coupled with more responsive (and responsible) design strategies for both new and existing buildings.

To effectively mitigate long-term impacts and adapt in the short-term to inevitable climate alterations, the challenge is thus to identify and effectively put in place the *design methodologies* by which sustainable technologies can be integrated with current building models in order to guarantee the continuous social and economic growth of human developments, whilst limiting emissions and effectively responding to the consequences of climate alterations which are expected in the next few decades. As a matter of fact, it is the overall design of the building - its structure, envelope, interiors, services - rather than the mere application of advanced technology *per se* that governs the delicate balance amongst the factors determining the conditions inside (and outside) built spaces.

Hence, it is through strategic integrated design and the thorough implementation of knowledge - both existing and forthcoming - that buildings should succeed in integrating their functions and requirements with dynamic environmental forces, guaranteeing comfort for their users with an efficient use of energy and without harmful wastes and emissions.

3.2 Integrated Building Design

As per the conclusions of the IPCC Fourth Assessment Report, amongst the key sectorial mitigation technologies and practices which are suggested to be applied within the design of built environments before 2030, an essential role is to be played by "integrated design" of buildings, which should be exploiting advances in technology and implement both passive and active techniques in order to provide comfort for their users and reduce their energy requirements (IPCC, 2007c).

Nevertheless, in the attempt to provide simple and straightforward guidelines for the integrated and sustainable design of buildings able to mitigate their pressure on the environment, there is the obvious risk of giving recommendations which are either too specific to a particular circumstance, either too vague. Thermal performances, ventilation, light distribution, visual comfort, etc. are all variables that need to be carefully balanced according to specific requests, distinct environmental contexts, climate scenarios, and contingent technical choices. In addition, architecture is expected not only to serve the simple task of a filter against the elements, but also to provide the service functions that its users are accustomed to (Hawken et al., 1999). This raises the practical question of how to make building design progress in order to satisfy contemporary needs and, simultaneously, reduce energy consumptions and consequent environmental impacts.

To meet these demands, a new *integrated design process* has to be developed that could potentially lead towards an innovative and progressive architecture, one that could easily and sustainably respond to current, as well as predicted, climate conditions and contextual situations. Yet, this pioneering new design process, in its most basic concept, can be paradoxically related to the very known, albeit nowadays scarcely exploited, rules of the natural world we are all part of (Luther and Altomonte, 2007).

3.2.1 Inspirations from Nature

Biomimicry (from *bios*, life, and *mimesis*, to imitate) is a new science that studies Nature's best ideas and then uses the inspiration derived from natural designs and processes to solve human problems (Benyus, 1997). The "conscious emulation of life's genius" represents - in a society that has for so many centuries been convinced of its capacity of dominating or sometimes even 'improving' Nature - a radically novel approach, a revolutionary era based on what we can *learn* from Nature rather than, as we have been doing since the Industrial Revolution, merely *extracting* from it. According to Benyus (1997), looking at the ecology of our planet we may realise that there is more to discover than to invent. Life, imaginative by its own nature, has probably already solved most of the problems we are facing today. The challenge for us is to understand these strategies and replicate them in our own activities.

Responsive organisms have inhabited Earth well before humans, developing and perfecting their techniques of survival. Throughout a long path of trial and error - about 3,8 billion years since the first bacteria - species have responded to their environments and evolved to secure themselves nourishment and shelter, and all without burning fossil fuels or producing wastes that, in the long term, could have harmed the global ecosystem (Benyus, 1997). Contrary to most of human technological endeavours, all natural systems and structures have always been operating uniquely on the direct (and indirect) energy received from the Sun, which has interacted with the geochemistry of the Earth's to sustain every regenerative biological system (McDonough and Braungart 2003). Photosynthesis, which literally means 'putting together with light', is the process by which green plants transform sunlight, CO_2 and water into oxygen and nutritive sugars, rich in energetic content. Thanks to sunlight, life sustains itself, supplying all its energy needs without burning fossil fuels.

Maximum economy, minimum waste and thorough integration and coordination of functions have been the strategies that Nature has exploited through millenary evolution (Forbes, 2005). Building on this 'biomimetic' metaphor - where the flexible cooperation of several constituents contributes to the metabolism and well-being of living creatures - the proposal here is to develop a design method based on the integration of specialised and interconnected competences.

In order to do so, not only the use of cutting-edge technologies and tools has to be carefully weighed and optimised, but more integrated design strategies have to be accordingly implemented basing on climate, environment, orientation, functions and users needs. Not too long ago we were still basing our designs on a strict relationship with the natural environment, designing buildings that could be compared to living organisms in their ability to respond to climate and topography and regulate internal comfort without utilising non-renewable forms of energy. Looking at vernacular forms of architecture all around the world, we realise how those building design practices, together with the behaviour of their occupants, were uniquely based on climate and contextual characteristics.

As hundreds of thousands of years ago our ancestors moved from temperate Africa to northern regions, not only they had to wear warmer clothes but they also had to develop techniques to protect them from the threats of colder climates. To allow their metabolic mechanism to remain unaffected, humans had to evolve in both their physical features as in their techniques for creating protecting structures. This process resulted in the production of an extraordinary diversity of dwellings, built of local materials and shaped to suit local climates, landscapes and societies; exempla of supreme responsiveness that we should now try to imitate. The *Igloos* of the Inuit, the *Tepee* of the Indians and several other ‘primitive’ construction forms testify how climate can dictate the forms of architecture, dampening harsh extremes by uniquely using materials and techniques available locally. Neither building type had a negative impact on the environment, whilst identifying the culture of the people that built them (Roaf, 2005).

The challenge we are facing today therefore consists in moving from a design approach that exploits technological development for its own sake to one that has environmental and human objectives.

A new design paradigm must be implemented so as to conceive buildings able to ensure comfort and health for their inhabitants without impacting negatively on the environment. This paradigm should be developed disregarding established discipline boundaries and transferring knowledge between seemingly distant scientific fields, which include architecture, physics, engineering, climatology, physiology, psychology and biosciences.

3.2.2 Sustainable Design Framework

Basing on this awareness, a theoretical design ‘framework’ can be defined founded upon a number of strategies and criteria that should be systematically evaluated and developed within the building design process for mitigating the impacts of built structures on the environment. Previous work by the author (Altomonte and Luther, 2006) proposed a new integrated building design process which is methodologically structured upon the measured and iterative analysis of the following interconnected building categories and principles:

1) *Site & Climate Analysis*; comprising the analysis of site, exposure, climate, orientation, topographical factors, local constraints and the availability of natural resources and ecologically sustainable forms of energy considered in relation to the duration and intensity of their use (*genius loci*, Olgyay, 1963).

2) *Flexible & Adaptive Structural Systems*; investigating the characteristics of the structure, its permanence or temporariness, its integration with other building components such as interior, envelope or mechanical systems, the fixing to the footings or founding materials and the desired aesthetic effect.

3) *Renewable & Environmental Building Materials*; concerning the efficiency of a material or a product, size available, standardization, structural adequacy, complexity, appropriateness, cost, labour involved, plantation origin, method of growth (especially for natural materials), embodied energy (i.e. total energy required to create, harvest, transport, use, maintain and dispose a product), recycled and reused content (deconstruction, adaptability), toxicity level (wastes, pollution), etc.

4) *Modular Building Systems*; exploring the construction and assembling methods of building components in order for the various single elements to be eventually isolated and or substituted without adverse complication to the whole, thus allowing for shorter times of construction, reduced energy consumption and wastes, maintenance and/or replacements, flexibility and interchangeability.

5) *Building Envelope Systems*; investigating the role and the design of components, devices and systems acting as an interface, a dynamic filter between internal and external environments in order to control the energy flows that, directly or indirectly, enter (or leave) an enclosed volume, including consideration of orientation, seasonal variations, surrounding environment, function of the building, user requirements and façade typology.

6) *Renewable & Non-conventional Energy Systems*; integrating in built structures sources of energy that can be exploited without reducing or exhausting their point of origin and which could be collected directly on site or in centralized areas with little or no ecological impact.

7) *Innovative Heating, Ventilation & Air Conditioning Systems*; developing strategies to provide acceptable interior conditions for the occupants in terms of thermo-hygrometric and air quality comfort, exploiting mechanically-regulated, hybrid, or, preferably, totally passive techniques.

8) *Water Collection & Storage Systems*; analysing the methods, system and strategies to collect, store, distribute, use,

recycle and re-use water, a vital element for life and a fundamental resource in all inhabited buildings.

The proposed building categories and principles identify only partially the infinite opportunities offered by design and technical decisions to improve the sustainability of built environments. Indeed, within the proposed integrated design process each system contributes and interacts with the others rather than behaving as an individual entity, therefore enhancing energy efficiency and mitigating impacts on the environment whilst optimizing the use of the accessible resources and contributing to the well-being of the building occupants.

The objective of this sustainable design framework is thus not to define a sequential recipe to be applied identically in every contextual situation, but rather to set up a holistic and iterative methodology where the potential implications of each building category and principle - and therefore, of each building component - is carefully considered in relation to the whole and measured against climate, site and a range of other factors, which have to include, obviously, also social, economic and cultural values.

3.3 Structural and Behavioural Adaptation

The thorough application of advanced technologies within an integrated design framework could prove to be effective in reducing consumptions and emissions particularly within the building sector. However, considering the momentum of climate change already built up, long-term *mitigation* actions will necessarily need to be coupled with short-term *adaptive* strategies that could warranty the continuous sustainable development of human civilisations.

In the last decade, the United Framework Convention on Climate Change (UNFCCC) has been supporting, promoting, and directly funding a number of initiatives to identify the priority actions required for responding to urgent needs with regard to adaptation to climate change. These initiatives have concentrated especially on least developed countries which are more vulnerable to climate alterations and less able to adapt to their consequences. Amongst these, the *Special Climate Change Fund* (SCFF), established in 2001 to finance projects relating to adaptation to climate alterations, the *Least Developed Countries Fund* (LDCF), created to support the preparation and implementation of *National Adaptation Programmes of Action* (NAPAs) in more vulnerable economies, the *Adaptation Fund*, introduced to finance concrete adaptation projects in developing countries that are parties to the Kyoto Protocol.

These initiatives lay down an agenda for the path that should be taken globally. Adapting to predicted drastic climate shifts will require efforts and changes in every sector of human development and at every level, from the personal sphere up to the setting up of international agreements. Adaptation responses will necessarily include changes in policies (e.g. risk management), technologies (e.g. protecting measures, advanced weather forecasts, flexible building techniques, etc.), infrastructures (e.g. design specifications and safety requirements of transport networks), and management (e.g. energy use, distribution of resources, water consumption, etc.).

As far as buildings are concerned, older built structures may present characteristics that make them more resilient to global warming (e.g. high thermal mass, tall windows and ceilings, etc.), although they will be likely to perform poorly by modern standards and requirements. However, in the context of climate change scenarios typically spanning for a time scale that goes beyond a century, the true challenge will be represented by the development of adaptive strategies for the design of *new* constructions, and this will assume a vast relevance especially in developing countries, where massive barriers - technological, financial, and institutional/political - are yet to be fully overcome (Steemers, 2003).

In order to meet this further challenge, the natural system could again offer us the inspiration needed to implement adaptive building techniques and apply them to human built structures so as to accommodate changing conditions such as modified distribution of cloud density and cover, extremes in temperatures, humidity variations, pressure distributions, alterations in rainfall, changes in wind patterns and intensities, soils stability, etc. As a matter of fact, the implementation in buildings of an ‘adaptive talent’ simply extends ideas and principles consistent with the propositions of Charles Darwin, who held that the capacity to survive depends on the ability to adapt to a changing environment. Looking at natural systems, we may realise that all living organisms develop adaptive mechanisms to help them to endure and prosper against shifting climatic conditions or contextual alterations. Some of their adaptive responses are deemed *structural*, i.e. physical features of an organism like the bill on a bird or the fur on a bear; other adaptations could be said to be *behavioural,* with the term meaning the things organisms do to survive. Species that can adapt to changes in the environment flourish and thrive; species that can not may soon die out (Wigginton and Harris, 2002).

3.3.1 Structural Adaptation Strategies

Buildings are often assimilated to complex systemic organisms where all the *structural components* (including load-bearing elements, envelopes, services and internal partitions, such as floors and walls) are part of a whole, interconnected, architectural design. The implementation of structural adaptation in buildings can thus be intended as the application of flexible and adaptive design methodologies whereas the responsiveness to variation in climatic conditions can be tolerated and distributed due to an interlinked cooperation amongst various building constituents.

As far as supporting systems are concerned, there is nowadays an increasing interest in the subject of structurally adaptive construction techniques, although these are often primarily driven by market forces and letting potential of the building rather than by a 'sustainable' response to climate change. A flexible design may endow the construction primarily with some degree of elasticity concerning the arrangement, functionality and subdivision of internal spaces, thus making the built organism more resilient to variations in environmental factors (and consequent requirements) with a minimum demand for energy. Within the previously proposed sustainable design framework, these concerns could be certainly addressed with the implementation of *flexible and adaptive structural systems* and the adoption of a *modular building design*, strategies which could give a significant contribution to increase the resilience of the building towards climate alterations and changes in functions and occupants needs.

As reported by Steemers (2003), an additional interesting avenue of research in this field is focused on the 'diversified lifetime' of building components, a design methodology which proposes that built structures are basically composed by distinct parts, each with a different design life. Fernandez (2002) describes the number of technologies needed for a flexible structural design by saying: "design for disassembly, separation technologies, materials reclamation and recycling, loose-fit detailing, lightly-treading foundations and other techniques, will contribute to a suite of technologies necessary for building to change over time". Although not explicitly formulated to provide specific answers to adapt to climate change, the concept of 'diversified lifetime' presents an interesting approach towards the design and construction of buildings which could structurally respond to a variation in external climate conditions and adjust to a set of new requirements by their users.

Also in terms of the design of *building envelopes*, and their integration with *building services*, an adaptive design methodology (e.g. façade type, system integration, etc.), carefully weighed with the implementation of cutting-edge technologies, can result in significant steps forward in the challenge of adaptation to changing climate conditions, other than 'simply' contributing to reduce energy needs and CO_2 emissions and maximizing the well-being of building occupants (Altomonte, 2007). In this context, the adaptive capacity of the building envelope can be supported by a number of devices and components which, as previously illustrated, are currently being developed in order, for example, to:

1) Shield internal spaces from changes in solar radiation and minimise thermal losses (solar control / low-emissivity coatings, multiple glazed units with gas fillings, fixed or movable external shading devices, vacuum glazing, transparent insulating materials, aerogels, etc.);

2) Maximise daylight transmission and distribution, whilst reducing glare and contrast (manually- or automatically-controlled blind systems, reflective lamellae, prismatic screens, holographic optical elements, light shelves, laser cut panels, anidolic ceilings, etc.);

3) Exploit extremes of environmental factors to generate energy (e.g. semi-transparent PV cells, building integrated wind turbines, heat recovery systems, etc.);

4) Normalise peaks in temperature and moderate day-night and seasonal thermal variations (e.g. exposed thermal mass, vaulted ceilings, phase change materials, vacuum insulated panels, etc.);

5) Tolerate changes in structural loads (e.g. advanced structural adhesives, flexible bonds, thermal expansion joints, thermal ageing resistance, structural glazing tapes, etc.);

6) Adaptively change the optical properties of the façade according to internal and external stimuli (chromogenic glass), both passively (e.g. photochromic, thermochromic and thermotropic glass) and/or actively (e.g. electrochromic glazing, gasochromic devices, Liquid Crystal Displays, Suspended Particles Devices, etc.);

7) Automatically control artificial lighting levels and HVAC (Heating, Ventilation & Air Conditioning) systems according to continuously-monitored physical parameters (Building Management Systems and IT sensors) and user needs (e.g. adaptive biomimetic control systems) (Guillermin and Morel, 2002).

Further to this, innovative façade typologies are being investigated to achieve pressure balance in the building envelope and successfully accommodate condensation, weathering and increased wind forces, whilst advanced control strategies are being researched and tested to regulate the rates of air exchanges between internal and external environments, especially in terms of ventilation and heat transfers. These systems and control strategies fall, in general, under three categories:

(1) *Passive systems*: single or multiple skin façades where air (and heat) exchanges between inside and outside are passively dictated by natural ventilation principles or by convective movements due to buoyancy and direct or indirect solar gains (e.g. single skin façades, cavity systems, naturally-ventilated double skin façades, etc.);

(2) *Active systems*: automated strategies dictate the rate of air movement and ventilation, often in synchronisation with internal HVAC building services schedules (e.g. active walls, mechanically-ventilated double skin façades, pressure equalisation systems, etc.);

(3) *Interactive systems*: the strategies that regulate air movements and heat distribution exploit essentially passive

principles, although these can be overridden by active controls that, in case of extreme climate conditions, operate in integration with mechanical building services (e.g. interactive walls, façades with built-in fans, extractors, heat exchangers, etc.).

3.3.2 Behavioural Adaptation Strategies

Other than just developing methodologies to structurally adapt the design of buildings to expected climate alterations, another important adaptive contribution that the designer should take into account to successfully respond to changing conditions can be represented by the occupants' responsibility, which can strongly help to create resilient built environments that are both comfortable and sustainable.

As a matter of fact, it is interesting to point out that, amongst the actions proposed by the Working Group III of the IPCC to mitigate human impacts and adapt to climate change, particular relevance is actually given to "changes in lifestyle and behaviour patterns" (IPCC, 2007c). In this context, a specific role has to be assumed by education and training programmes which can help to overcome non-technological barriers to the acceptance and application of adaptive strategies and measures - in the household as on the workplace - contributing to changes in culture, habits, choices (e.g. appliances) and application of technologies which could result in considerable increase in responsive capacities of buildings (and their occupants) and, ultimately, also in sensitive reductions in CO_2 emissions.

As previously mentioned, throughout their evolution humans have been able to respond, with their intelligence and behaviour, even to the most extreme of the climates, showing evidence of tremendous adaptive skills. Specifically, Steemers (2003) suggests that there are broadly three categories in which *behavioural adaptations* of the inhabitants can directly influence the design and the operation of buildings, adjusting their requirements to dynamic environmental conditions:

1) *Spatial*, which is referred to the capacity of designing, arranging and utilising internal spaces in accordance with the expected environmental conditions that characterise the various parts of a building. For example, in hot-arid climates, occupant spatial patterns - i.e. the relocation of activities inside the house according to the seasons and the time of the day - have guaranteed for centuries a significant improvement of occupant comfort without the use of any energy-consuming system;

2) *Personal*, i.e. the capacity of building occupants to adapt their clothing (also on the workplace), modify their activity levels, change their posture, have access to hot/cold beverages, or use verandas, external courtyards, etc. according to external weather parameters (temperature, solar radiation, winds, etc.), individual preferences and/or contextual climate-driven demands (e.g. working schedules);

3) *Control*, which is the possibility given to the building users to have at least some level of direct control over the devices that influence their immediate environment (e.g. blinds, lighting systems, etc.), so as to maximise the adaptability of the building according to external factors and occupants' requests. This is specifically important in modern commercial buildings, which are often fitted with 'intelligent' building services and automated management systems. Although the capacity of overriding (temporarily) the automatic control could (seldom, actually) partially jeopardise optimum energy performances, this strategy has been proven to be beneficial in terms of psychological well-being and users satisfaction.

Obviously, a number of other mitigation and adaptation strategies and techniques could be applied to various other sectors of human activity (e.g. transport, energy, industry, waste management, etc.) with potential impacts on both reduction of emissions and responsiveness to climate change. However, discussion of these is beyond the scope of this paper.

In summary, it is very likely that the portfolio of technologies and know-how needed to make built environments minimize their impact on the ecosystem and adapt to shifting climatic conditions is already with us, as long as integrated design and behavioural strategies are put in place for their implementation. Making the most of ancient, existing and forthcoming knowledge (also featuring hybridisations between seemingly distant disciplinary fields), the design of buildings has to progress in response to environmental and users demands, re-establishing the fundamental connection between humans and the natural system that has sustained us so far, cradling and nourishing us, making all of our (sometimes insane) actions possible. A sustainable future is possible, but there is still a long way to go.

4. Concluding Remarks

The age of 'climate crisis' is upon us. After two centuries of Industrial Revolution, we are only now realising that the world we have artificially built is strictly interconnected with the real, biological one.

The work of the IPCC, unanimously applauded and crowned by the 2007 Nobel Peace Prize, has managed to establish a global awareness to the climate problem. If the vital information contained in its Fourth Assessment Report is correctly received and endorsed by policy makers, market actors, technical practitioners (including those which operate within the built environment sector), and the general community, an array of national and international synergies could be stimulated and put in place, providing the solid foundation for a sustainable future.

At the time of writing this paper, the United Nation Climate Change Conference in Indonesia (13th Conference of Parties to the UNFCCC), involving thousands of delegates from 192 nations, laid out the Bali Action Plan, a "roadmap" for negotiations set to produce, by 2009, a global climate treaty for the period post-2012, when the first phase of the Kyoto Protocol will expire. Although the Action Plan failed to establish binding targets in terms of emission reductions, for the first time representative from both developed and developing nations recognised that "deep cuts in global emissions" are required and decided to launch a process leading to (a) a shared vision for a "long-term global goal for emission reductions"; (b) enhanced national and international action on mitigation of climate change including "measurable, reportable and verifiable nationally appropriate mitigation commitments or actions" and reduction in deforestation and forest degradation in developing countries; (c) the implementation of adaptation initiatives, particularly in poorer nations; (d) enhanced actions and cooperation on technological development, diffusion and transfer; (e) the provision of financial resources and investment "to support action on mitigation and adaptation" (UNFCCC, 2007).

In support of the results that the Bali Roadmap and the subsequent process will hopefully achieve in responding to the threats of climate change, the suggestions made here are that, other than just exploiting technological progress, we can study, learn and be inspired by adaptive natural systems to produce a more sustainable and integrated building design that could contribute to mitigate and adapt to current and predicted alterations. The questions may be: why haven't we always been working with something that was compatible with Nature? Wouldn't that have been more easy and avoided a lot of problems? Ironically, it always takes dramatic circumstances to become aware of the need to assume responsibility of our actions and adopt all the possible strategies to wisely utilise our skills, efficiently manage our resources, and achieve well-being into our 'habitats' in harmony with a dynamic natural environment.

By following a mitigation and adaptation path in the battle to keep pace with shifts in climate, we could do more than simply guaranteeing a fertile future for ourselves and for the next generations, as the well-known definition of 'sustainable development' requires. As Janine Benyus (1997) has put it: "if we succeed, evolution will not have produced this giant [human] brain in vain".

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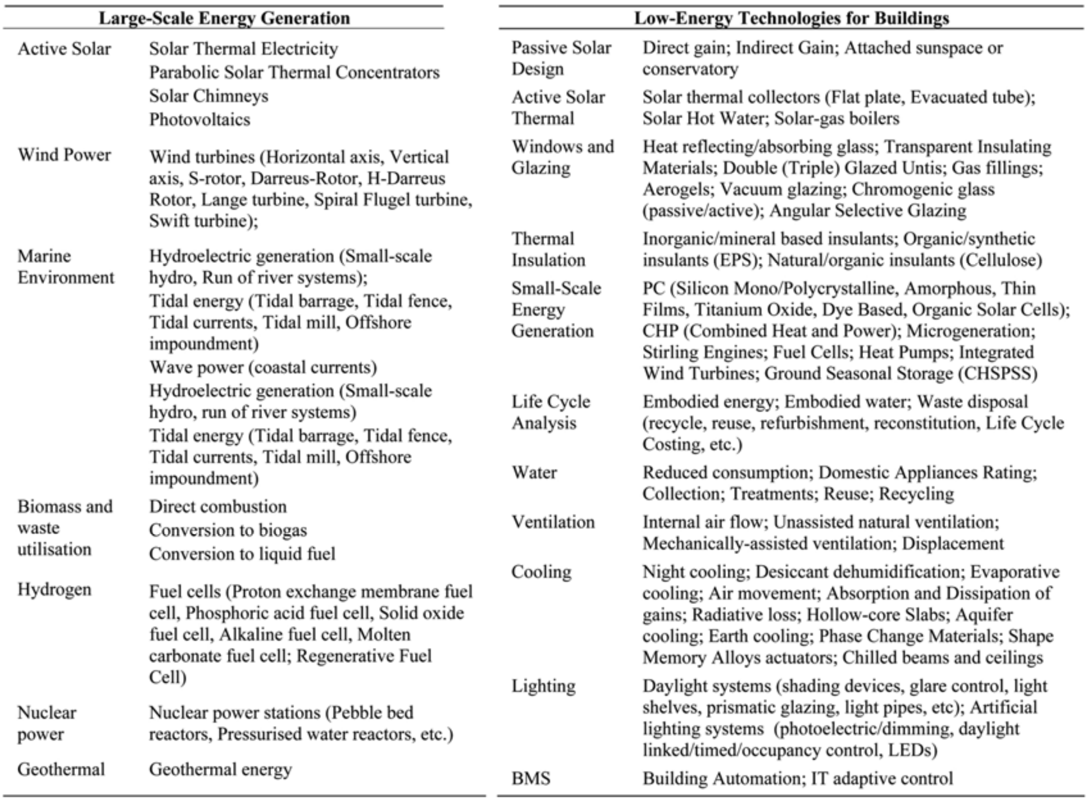
Notes

Note 1. According to Ruddiman (2003), there is a distinctive factor that could have influenced the warm and stable period of the last 10 000 years and differentiated it from the previous interglacials, all characterised by unsteady cooling followed by the sudden appearance of another Ice Age: this factor is represented by the settled presence of humans. In particular, charting the levels of methane and CO_2 bubbles in ice sheets, some anomalies may suggest that the beginning of agriculture (with their CH_4 emissions) could have strongly influenced the greenhouse gases concentration in the atmosphere well before the 18th century.

Table 1. Technologies for mitigation and adaptation



Large-Scale Energy Generation	
Active Solar	Solar Thermal Electricity Parabolic Solar Thermal Concentrators Solar Chimneys Photovoltaics
Wind Power	Wind turbines (Horizontal axis, Vertical axis, S-rotor, Darreus-Rotor, H-Darreus Rotor, Lange turbine, Spiral Flugel turbine, Swift turbine);
Marine Environment	Hydroelectric generation (Small-scale hydro, Run of river systems); Tidal energy (Tidal barrage, Tidal fence, Tidal currents, Tidal mill, Offshore impoundment) Wave power (coastal currents) Hydroelectric generation (Small-scale hydro, run of river systems) Tidal energy (Tidal barrage, Tidal fence, Tidal currents, Tidal mill, Offshore impoundment)
Biomass and waste utilisation	Direct combustion Conversion to biogas Conversion to liquid fuel
Hydrogen	Fuel cells (Proton exchange membrane fuel cell, Phosphoric acid fuel cell, Solid oxide fuel cell, Alkaline fuel cell, Molten carbonate fuel cell; Regenerative Fuel Cell)
Nuclear power	Nuclear power stations (Pebble bed reactors, Pressurised water reactors, etc.)
Geothermal	Geothermal energy

Low-Energy Technologies for Buildings	
Passive Solar Design	Direct gain; Indirect Gain; Attached sunspace or conservatory
Active Solar Thermal	Solar thermal collectors (Flat plate, Evacuated tube); Solar Hot Water; Solar-gas boilers
Windows and Glazing	Heat reflecting/absorbing glass; Transparent Insulating Materials; Double (Triple) Glazed Untis; Gas fillings; Aerogels; Vacuum glazing; Chromogenic glass (passive/active); Angular Selective Glazing
Thermal Insulation	Inorganic/mineral based insulants; Organic/synthetic insulants (EPS); Natural/organic insulants (Cellulose)
Small-Scale Energy Generation	PC (Silicon Mono/Polycrystalline, Amorphous, Thin Films, Titanium Oxide, Dye Based, Organic Solar Cells); CHP (Combined Heat and Power); Microgeneration; Stirling Engines; Fuel Cells; Heat Pumps; Integrated Wind Turbines; Ground Seasonal Storage (CHSPSS)
Life Cycle Analysis	Embodied energy; Embodied water; Waste disposal (recycle, reuse, refurbishment, reconstitution, Life Cycle Costing, etc.)
Water	Reduced consumption; Domestic Appliances Rating; Collection; Treatments; Reuse; Recycling
Ventilation	Internal air flow; Unassisted natural ventilation; Mechanically-assisted ventilation; Displacement
Cooling	Night cooling; Desiccant dehumidification; Evaporative cooling; Air movement; Absorption and Dissipation of gains; Radiative loss; Hollow-core Slabs; Aquifer cooling; Earth cooling; Phase Change Materials; Shape Memory Alloys actuators; Chilled beams and ceilings
Lighting	Daylight systems (shading devices, glare control, light shelves, prismatic glazing, light pipes, etc); Artificial lighting systems (photoelectric/dimming, daylight linked/timed/occupancy control, LEDs)
BMS	Building Automation; IT adaptive control

The Table summarises various cutting-edge sustainable techniques available for large-scale energy generation and a number of low-energy technologies to be integrated in the design of buildings

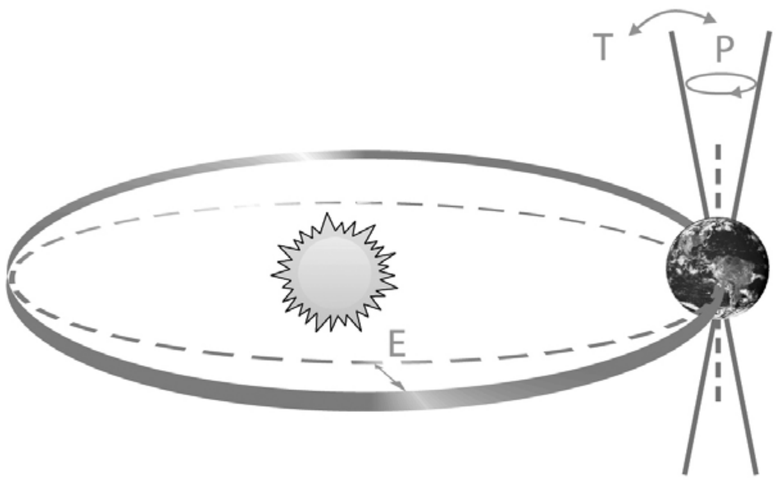


Figure 1. Schematic of the Earth's orbital changes

'T' denotes changes in the tilt of the Earth's axis (which takes 42 000 to run its course), 'E' denotes changes in the eccentricity of the orbit (whose shape changes on a 100 000-year cycle), and 'P' denotes precession, i.e. changes in the direction of the axial tilt (22 000-year cycle)

(Source: IPCC, 2007a)

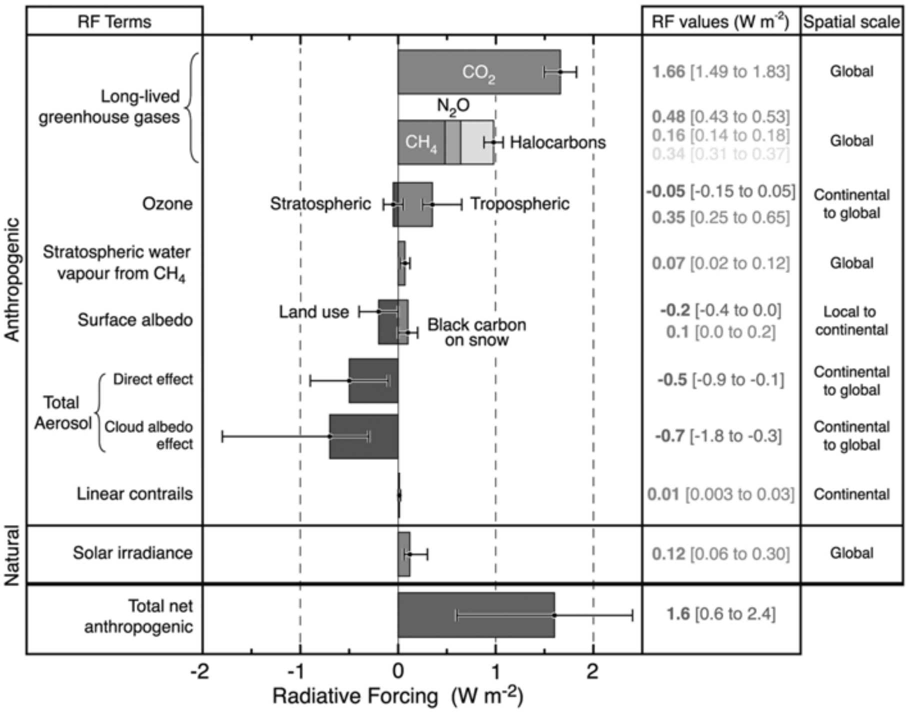


Figure 2. Summary of the main components of the radiative forcing of climate change

The Figure illustrates and provides an estimate of the radiative forcing on the natural system due to natural causes and anthropogenic activities

(Source: adapted from IPCC, 2007a)

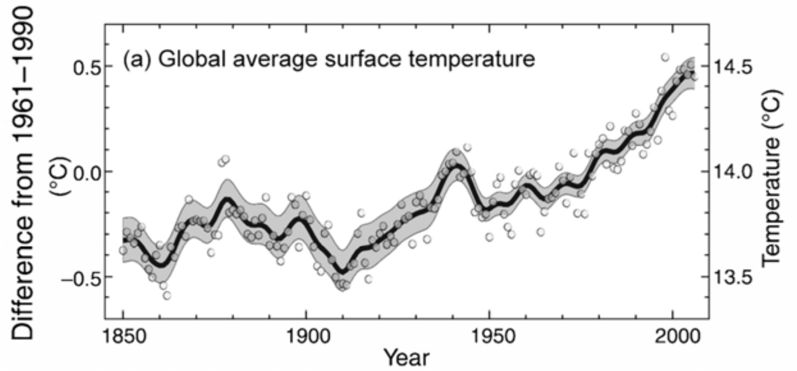


Figure 3. Variations in global average surface temperature relative to the period 1961-1990

The Figure presents the variations in global average surface temperature between 1850 and 2005 relative to corresponding averages for the period 1961-1990 (circles show yearly variability)

(Source: adapted from IPCC, 2007a)