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The Arup Journal

Contents

To celebrate its 60th anniversary in 2006, Arup created an initiative called the Arup Cause, which included a unique partnership with the international charity WaterAid. A goal of the Arup Cause was to focus Arup's stated mission to "shape a better world" on the provision of potable water, sanitation, and hygiene education to the people most in need.

1. Mono Lake, California, shrank by half between 1941 and 1962 in supplying the water needs of Los Angeles. Since 1978, however, it has been the object of vigorous conservation efforts.

Water as a driver of change

Peter Wilkie

Ever-increasing demands on the world's limited water resources will necessitate careful management. Equitable distribution will depend on making choices at an appropriate level.

Introduction

The "drivers of change" faced by our world and the human race act on scales ranging from the global to the individual. In a previous *Arup Journal*, Simon Roberts[1] discussed the provision of energy to meet society's demands as one of these forces. His emphasis of the multi-faceted nature of the drivers and potential changes associated with energy is also evident when considering water, and its intricate relationship with systems across a range of scales.

We live on a "blue planet", the only one known to have extensive liquid water resources. All life on Earth depends on its continued availability. It is only through the presence of water that you, I, your family, our firm, our society, and our environment can survive.

Table 1. Global water distribution.

Water location	Volume (1000km^3)	% of total volume in hydrosphere	% of fresh water
Oceans	1 338 000	96.5	-
Groundwater (gravity and capillary)	24 000	1.7	
Predominantly fresh groundwater	*10 530*	*0.76*	*30.1*
Soil moisture	16.5	0.001	0.05
Glaciers and permanent snow cover:	24 064	1.74	68.7
Antarctica	*21 600*	*1.56*	*61.7*
Greenland	*2340*	*0.17*	*6.68*
Arctic islands	*83.5*	*0.006*	*0.24*
Mountainous regions	*40.6*	*0.003*	*0.12*
Ground ice (permafrost)	300	0.022	0.86
Water in lakes:	176.4	0.013	-
Fresh	*91.0*	*0.007*	*0.26*
Salt	*85.4*	*0.006*	-
Marshes and swamps	11.5	0.0008	0.03
River water	2.12	0.0002	0.006
Biological water	1.12	0.0001	0.003
Water in the atmosphere	12.9	0.001	0.04
Total volume in the hydrosphere	**1 386 000**	**100**	**-**
Total fresh water	**35 029.2**	**2.53**	**100**

The critical importance of water is shown by considering the effects of some issues evident around the world at present.

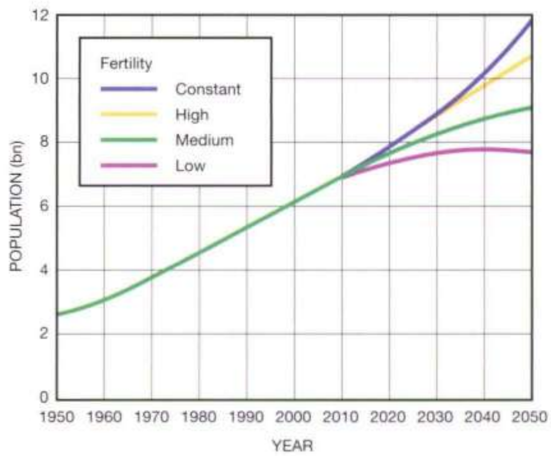
Prolonged spells of low rainfall across regions of Australia are resulting in water use restrictions to domestic, commercial, industrial, and potentially agricultural users. China's cities face critical water shortages and industrial pollution of water resources. Drought conditions across north-east Africa have devastated millions of livelihoods and impacted the economies of Kenya, Ethiopia, and Sudan. Falling groundwater levels across many agricultural regions are reducing the viability of farming. Thousands of people die each day in Asian and African villages due to restricted access to wholesome water. Increasing levels of micro-contaminants such as pesticides and prescription drugs are being monitored in rivers across Europe.

These are just a few recent water-related headlines. Water crises are evident around the world in both developed and developing countries. They appear inevitable - particularly given the uncontrollable nature of weather systems - but most water crises are not due to physical inadequacy of resource, but instead result from inappropriate choices made in managing available water qualities and quantities. Water governance is thus the driver of change that will increasingly affect society over the forthcoming decades. Whilst there is equality between the basic needs we all have for water, access is significantly dissimilar.

Global access to water

Professor Igor Shiklomanov of the State Hydrology Institute, St Petersburg, Russia, has undertaken extensive research into global water resources and water balances[2] (see Table 1). Of the total volume of the Earth's surface water, or hydrosphere, only 2.53% is fresh water, and less than 1% of hydrosphere water is readily available for human use from watercourses and groundwater. The rest is stored as glaciers and permanent snow cover.

Global water distribution is not static, there being a constant natural "flux" or transfer of water between its locations and states; the continual natural cycle of evaporation, precipitation, and transport in liquid, solid, and gaseous states provides mankind with the resource. The volumes of water listed in Table 1 form a "snapshot" of global distribution, but consideration needs to be given to the rates of transfer between the various locations. The most accessible resources are in rivers and shallow groundwater, but if these were not continually replenished they would soon be drained.



2. Historic and projected world population figures.

The rates of replenishment therefore become a critical consideration in determining the amount of water available to us and the natural environment.

Authorities including Postel[3] generally agree that globally there is some 12 500km^3 of accessible runoff each year. This figure excludes remote areas and flood flows from a total precipitation of 44 800km^3/year, and is thus the sustainable volume of water available for use. 12 500km^3/year equals 5190 litres/day of water for each of the world's 6.6bn people. To put this figure in context, each year an average of 660m^3 (1808 litres/day) is extracted for each European Union inhabitant[4]. The volume of water consumed every day by each EU resident is 567 litres[5]. This analysis seems to show sufficient water to meet the world's demand, but it is flawed.

Water's very dynamic cycle of rain, runoff, and evaporation, with enormous temporal and spatial variations as well as variable quality, completely governs its value to people and ecosystems, and climate change trends seem to be increasing evaporation rates and variability in rainfall and runoff. This being so, annual average levels of water availability, or consideration of large areas of countries or continents, have little relevance to gauging actual water scarcity and the range of associated local issues. Both factors are addressed later, and consideration must also be given to the drivers that affect future water availability.

Drivers of water availability

The total quantity of renewable water available for use on Earth will remain relatively constant. However, the pressures on it that result from choices made by individuals and groups across society will change significantly in the decades to come. The ever-changing demands imposed on water make it a driver of change.

The World Water Council's publication "World Water Vision"[6] considers three future global scenarios* based on the following drivers:

- *demographic*: population structure, population growth, urbanization, pressures for migration from developing to developed countries
- *technological:* information technology, biotechnology, water use efficiency, water pollution, new drought/pest/salt-resistant crops, sanitation, desalination
- *social:* lifestyles and cultural preferences, poverty, economic inequality
- *environmental:* committed future climate change, water-related disease, salinization, exhaustion and pollution of surface and groundwater, integrity and health of aquatic ecosystems
- *governance:* institutions, legislation, market dominance, power structure, conflicts, globalization.

These indicate that whilst availability and use are of concern, a broad range of factors affect the state of future water resources, each of which could form the basis of an in-depth analysis to determine particular local implications and effects. Whilst the results would vary greatly across the world, grouping the drivers into larger categories can allow headline trends to be identified. The two key categories that historically have had most impact on availability of water resources are population growth and development (as measured by economic growth), and they will continue to have the primary impact across most of the world.

Population growth

The current world population (December 2006) is estimated by the US Census Bureau to be 6.56bn. Although rates of growth have fallen and are expected to continue to fall, the number will continue to increase. A stabilized population may be achieved in the future (Fig 2)[7], but this will depend on future growth rates.

As the levels of water resources available to regions are generally static, a population increase will reduce the amount of water for each individual. This has evidently happened in the past, and will continue to be a significant trend in the future. Population increases have resulted in available water supplies (per person when calculated globally), decreasing by a third between 1970 and 1990.

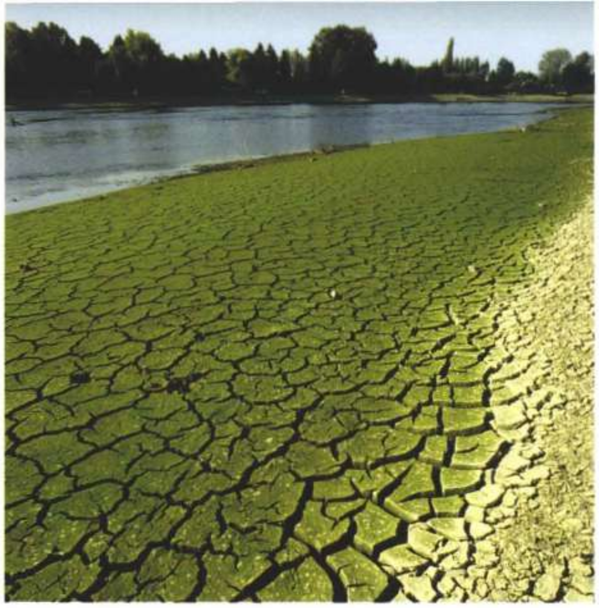
Individual countries demonstrate different population growth patterns. 96% of projected growth is in developing countries. The population of Europe is now declining, the pace of which is projected to double by 2010-2015. North America is projected to continue growing by 1% annually, predominantly due to immigration. As population increase is a driver of increased water stress, these figures are important in identifying regions where impact on water resources may change.

Development

As population growth results in increased water scarcity, this is compounded by increasing water consumption as countries develop. Industrial development and economic growth over the past 200 years have increased water consumption, and this trend shows no sign of diminishing across Asia and South America. It is also expected to become increasingly evident in Africa.

Table 2. Impacts of changing lifestyles.		Withdrawals by sector (%)		
Country income group	Annual water withdrawals per capita (m^3)	Agriculture	Industry	Domestic
Low-income	386	91	5	4
Middle-income	453	69	18	13
High-income	1167	39	47	14

*(1) basically business as usual - a continuation of current policies and extrapolation of trends; (2) private sector initiatives leading research and development, and globalization driving economic growth, with the poorest countries left behind; (3) sustainable development, with an emphasis on research and development in the poorest countries in relation to water resource availability.



3. Ignoring water conservation leads to scarcity and stress.

As well as the increased industrialization and associated pollution increase that are evident in much of the world, development within countries brings lifestyle and cultural changes. Often these involve an increase in the amount of water required to support individual lifestyles (Table 2[8]).

Greater access to water supplies for individuals and communities leads to the amount for domestic use increasing from levels that are very low - typically 15-20 litres/person/day - to much higher consumption rates of over 100 litres/person/day, depending on cost, availability, and education. The more significant impacts are from increased land irrigation and industrial usage.

Until now, industrial and agricultural development has generally been undertaken with little regard for water conservation, one consequence of which can be seen in the 75% volume reduction since 1960 of what was the world's fourth largest lake, the Aral Sea in Uzbekistan and Kazakhstan. Whilst there are exceptions like Israel, which for political reasons has implemented a rigorous water conservation programme across all sectors, development is closely tied to increased water consumption.

Harnessing water resources and making them available is often an initiating factor in a region's development. In higher income countries, technology can facilitate reductions in the amount of water needed for industrial and domestic uses, but these are usually small, and only play a role in local management practices. Globally, water use for agriculture remains inefficient due to high investment costs, low charges for the water, and historic issues relating to water rights.

Water stress

Inadequate access to water of sufficient quality and quantity to fulfil its needs makes a local population "water insecure". Many drivers, and choices made, lead to water insecurity. It may result from external drivers over which the local population has no control, or from internal drivers that affect access to water. As already noted, it may be caused by increase in pressure on a constant resource and/or a change in the amount of water available, as with the increased difficulty in pumping groundwater in many places due to historic over-pumping depleting a limited resource. To quantify and analyze the extents of water scarcity and manage the impacts, "water stress" needs to be quantified.

Calculating water stress

The most widely used measure is the Falkenmark Indicator (named after the eminent Swedish hydrologist Marin Falkenmark), which takes 1700m^3 of renewable water resources per person per year (4658 litres/capita/day) as the minimum threshold, based on estimates of water requirements in the household, agricultural, industrial, and energy sectors, and the needs of the environment.

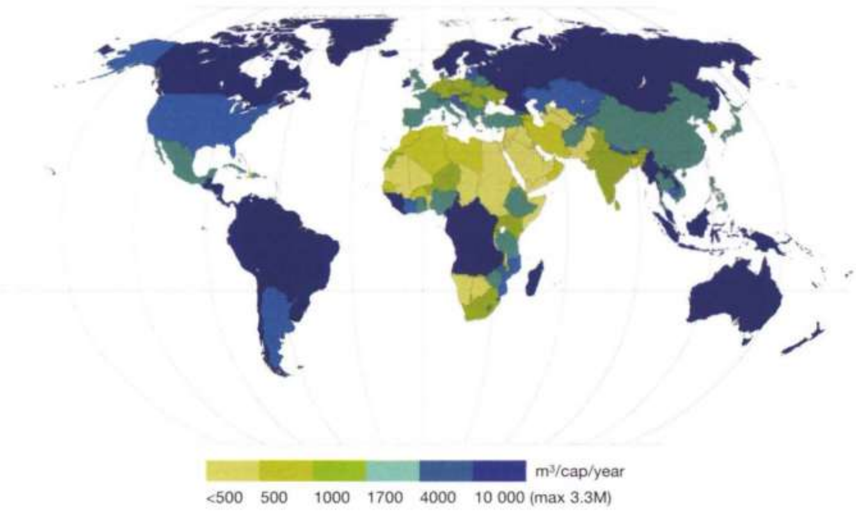
Countries whose renewable water supplies are below 1700m^3/capita/year are said to experience water stress. When the available supply falls below 1000m^3/capita/year (2740 litres/capita/day), a country experiences water scarcity, and when below 500m^3/capita/year (1370 litres/capita/day), absolute scarcity. The premise is that if there is sufficient rainfall, river inflows, and groundwater inflows from adjacent countries to provide 1700m^3/person/year, this will satisfy all the country's water needs.

This measure has major advantages, including simplicity of calculation and use, but also considerable limitations, including:

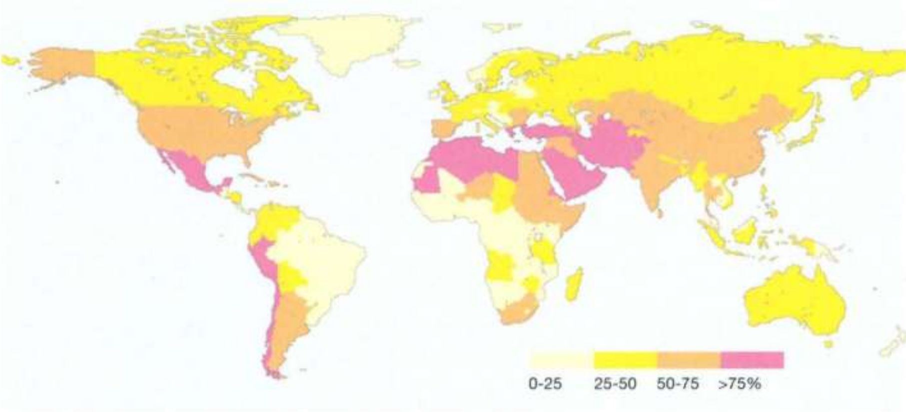
- The annual national averages hide important differences in water availability at smaller scales.
- It does not take into account the availability of infrastructure to modify water availability to users, nor political decisions that may restrict inflows.
- The simple thresholds do not reflect important variations in demand among countries due to lifestyle, climate, agricultural technologies, etc.

Scales of analysis

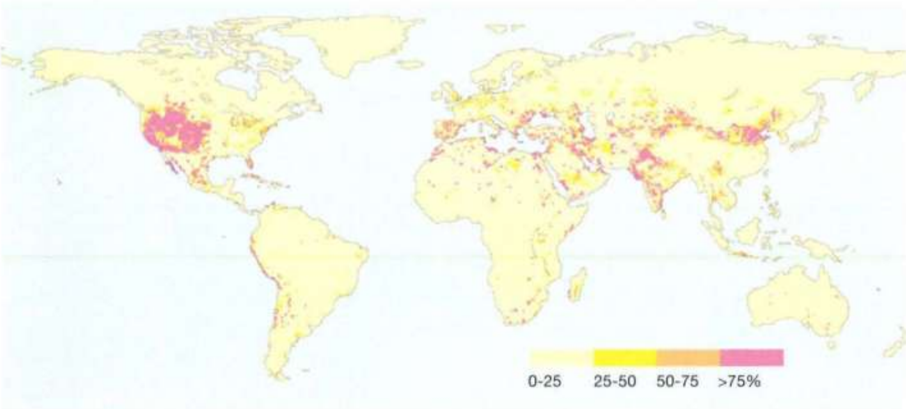
The world's available fresh water has been calculated, and areas identified that are experiencing long-term water stress and scarcity (Fig 4)[9]. A range of factors relate to the water balance, and Shiklomanov[10] has calculated that 8% of the annual renewable freshwater resources are now withdrawn each year. This is equivalent to 54% of accessible runoff now being appropriated by humans, indicating the severity of the demands we are placing on the world's limited water resources - demands that will continue to increase in many parts of the world due to population growth, increased consumption, and other drivers.



4. Renewable water resources generated within a country per person.



5. Water Stress Index calculated on a countrywide basis.



6. Water Stress Index calculated on a 0.5° x 0.5° grid basis.

Analysis of the global distribution of water resources and populations shows that more than 2bn people are affected by shortages in over 40 countries around the world, and it is predicted that by 2050 at least one in four people will be living in a country affected by chronic or recurring freshwater shortages[11].

The Water Stress Index (WSI) is a measure of the percentage of water demand that cannot be satisfied without taking measures, but applying country-wide analysis tools does not provide sufficient information to identify differences at local levels. Examining the issues on a smaller local scale reveals a much different picture in many countries, highlighting regions suffering acute stress and those that are not so highly stressed. Key examples of this can be seen in India and Spain where consideration on a national basis gives a WSI of between 50% and 75% (Fig 5)[12], but at the higher resolution of analysis there are clearly areas of very low (0-25%) and very high WSI (>75%) within the country (Fig 6)[12].

Where there is no choice

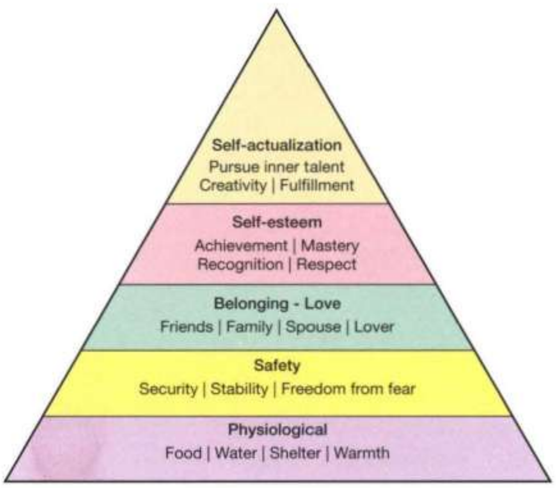
The analysis thus far has concentrated on data and facts. However, when discussing the importance of water, each number has a face, and each statistic relates to people. Where access to water is inadequate, either through physical scarcity or mismanagement, hands are forced. There is no option to forego one of the most fundamental needs we all have. There is no choice.

Maslow's "hierarchy of needs" (Fig 7)[13] is a psychological theory of motivation based on the premise that as humans meet "basic needs", they seek to satisfy successively "higher needs" in a set hierarchy: humans must prioritize base needs, and until the needs at one level are fulfilled, they will not be able to spend time or resources on the next level. As one of the foundations of Maslow's hierarchy, our physiological need for water - alongside oxygen, food, rest, protection, and reproduction - render it a compelling force. When resources becoming limiting, humans will prioritize due to necessity, and under pressure or stress higher-level needs (like self-actualization or safety) will be compromised or sacrificed to ensure the base-level needs are met.

Water is thus a powerful motivator. Through recognition of common need it can unite individuals and communities, and act as a basis of society. It is therefore surprising that only in 2002 was the human right to "sufficient, affordable, physically accessible, safe and acceptable water for personal and domestic uses" explicitly recognized in the United Nation's Covenant on Economic, Social and Cultural Rights[14]. Water plays an essential role in many of the other recognized human rights including life, food, self-determination, adequate standard of living, education, and health.

Water's motivating power can make it a catalyst for conflict and acts of self-interest. Whilst very few regions of the world have insufficient available water resources for domestic demands, it has an indirect impact on many other basic needs. 70% of global water use is in agriculture to provide food and resources, 20% in industry. Insufficient water resources to allow economic development or other regional objectives may therefore promote non co-operative responses to obtain access to more water.

Where water stress is high, and there are no options to increase the available supply, choices need to be made as to what the available water will be used for. This is discussed more in the following section on managing water, but to allow informed choices, decision-makers need to understand the drivers operating at the level where those decisions are being made. For this, education is needed.



7. Maslow's hierarchy of needs.

Education can also empower communities and organizations. Across many parts of the developing world the burden of duties associated with collecting water for domestic and agricultural use falls upon women and children.

Research shows that households in rural Africa spend 26% of their time fetching water, and generally women perform this duty[15]. They shoulder a disproportionate burden in terms of time and effort, and have no choice in the matter.

By facilitating access to improved water supplies, a vast resource of time can be freed for other more productive uses including education and economic diversification. Education allows the local conditions to be understood by the participants, and as such is fundamental to sustainable development. It allows discussion on the drivers, variables, and factors that can be changed, and on decisions about managing water resources and the demands on them.

Although water is recognized by the UN as a human right, extensive work still needs to be done across the world to ensure that people have choices - not to buy water from vendors at 10 times the price paid in developed countries; not to feed children water from polluted river beds that farm animals drink from and excrete in, etc.

Choices in water management

Sustainable use of water resources requires management of supply and demand. In both, choices must be made, and at levels appropriate to allow consideration of the locally important drivers and particular circumstances. The issue of scale is critical in effective management.

Scales of water management

The management of water resources can be considered on a range of scales:

- *Global:* Water acts as a world conveyance mechanism, with weather systems and ocean currents moving water vapour around the world and controlling precipitation levels. International trade in agricultural and industrial products shapes global water consumption patterns. Global warming may lead to changes in precipitation patterns, and in parts of the world evidence is mounting that this is already starting to occur. Changes to the temporal distribution of rainfall can make significant changes to the availability of the resource for use, with short intense rain events often leading to flooding and reducing the amount of storage possible.
- *Continental:* The world's largest rivers cross continents, with many countries drawing on their waters. Sub-surface water resources are also shared between countries, but these can be harder to quantify and manage.

8. Research shows that households in rural Africa spend 26% of their time fetching water.

- *National.* Here, water availability will shape land use and residential population patterns. Most of the world's largest cities are on their respective countries' main rivers for reasons of water supply, withdrawal for industry, waste disposal, and transport. The relative abundance of water resources across a country will affect agricultural productivity, and associated land values.
- *Provincial.* At this level, particular water uses can be identified and thus managed. There can be significant differences between adjacent provinces and counties with regard to water availability and use. Large-scale water transfer may be possible from water-rich regions to others through storage in dams, pumping, or the use of gravity pipelines and natural watercourses. Local geography will play an important role in affecting precipitation patterns.
- *Local.* Here there is a multitude of differences between water users. Reduced availability will have a particular effect and local economic productivity will be governed by access. Here we will see the impact of communities, industry and agriculture on ecosystem quality and it is at this level that it can be most effectively managed. For sustainable resource management, water resources need to be "owned" at this level. This need not be material ownership, but it is essential that the interrelationship between water resources and the actions of the local communities are understood by all, as this will lead to responsible use and management of demand.
- *Personal.* When water is considered at a personal level, its importance both physically and culturally becomes critical, as discussed previously.

Catchment

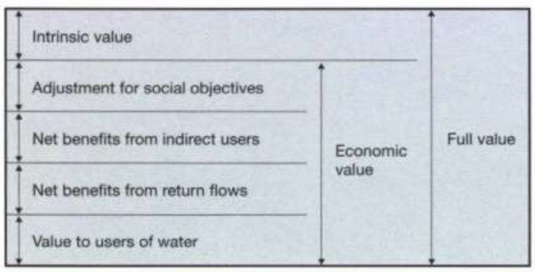
As well as these, water resources need to be considered on the basis of "catchment" (the area of land draining to a watercourse). Water catchments exist on a range of scales, and offer the most appropriate management unit to consider human intervention and management within. Water exists as a cycle, with changes in quality or quantity at any point impacting its downstream value. Water resource management needs to be undertaken in the context of the entire cycle, from where it falls on the ground to how it eventually discharges to seas and oceans or evaporates.

Considering, or attempting to manage, water resource issues in any smaller context than this will result in unsustainable solutions and eventual failure. Even when considering intrinsically local water resource issues, these need to be set in the context of the wider catchment and adjacent regions. This is the basis of integrated water resource management, widely considered the most sustainable tool for managing water.

Interactions

Local water issues are complex due to the range of interactions that exist with external drivers such as politics, governance, and the environment. One example is the use of water to irrigate crops to grow food in a particular region. Demand will be partially related to global food markets, trade tariffs, agricultural subsidies in the country, political decisions to ensure food security within countries, and production in other parts of the world.

Within countries, the volume of water available for irrigation in a particular region will depend on withdrawals in the upstream catchment, requirements downstream, and available water volumes. Consideration needs to be given to water quality, environmental damage, infrastructure availability, pricing mechanisms, demands on the water resources by industry and domestic



9. Valuation of water as used by the Expert Group Meeting in Harare in 1998.

10. It typically requires 1500 litres of water to produce 1kg of cereals such as corn or wheat.

populations, and the opportunity cost of the water used. However, it is at the local level that all the drivers listed above will have a direct effect, and analysis needs to work from the global and continental scale to the local with increasing detail and focus.

The concept of "virtual water" is an example of the implementation of choices in managing limited water resources. This term relates to water that is embodied in products, and hence "virtually" transported by the transfer of the product between regions. An example is the transfer of cereals between countries, as it typically requires 1500 litres of water to produce 1kg of cereals such as corn or wheat. Regions with scarce water resources can maximize the amount of water available for domestic and industrial uses through not using the available water for agricultural purposes. A strategy like this may have associated political considerations such as ensuring food security.

How to value water?

Many of the choices related to managing water depend on how we value it. Valuation of water is an ongoing topic of discussion in the international community, complicated by the delineation of what is included in water's value. Although water contributes to a complex system of services and resources, each of which has an economic benefit, defining its different benefits is both difficult and very specific at the local level. But to allow effective demand management and improved allocation of water between the various users competing for it, its value must be determined. Fig 9[16] presents one framework currently being developed to allow the analysis of the total value of water. Under this model, the value of water can be considered to comprise five elements:

- *Value to users of water:* These are based on the value of the industrial, agricultural, or energy production per unit of water use.
- *Net benefits from return flows:* This value is derived from the return flows such as aquifer recharge during irrigation or the downstream benefits from water diversion during hydropower generation.
- *Net benefit from indirect uses:* Indirect benefits are derived when the water diverted for one purpose is used for another such as irrigation canals for navigation or drinking water.

- *Adjustment for societal objectives:* Although hard to quantify, water supplied for irrigation and domestic use often also contributes to fulfilling societal objectives such as poverty alleviation.
- *Intrinsic value:* The full value of water includes its environmental, social, and cultural benefits, which are not accounted for by market economy instruments.

Valuing water will always be complicated by assumptions made in determining the system boundaries used in the analysis. This is particularly emphasized when considering the value gained from ecosystems, with some proponents calculating that the value from flood control, groundwater recharge, shoreline stabilization, nutrition cycling, water purification, and the preservation of biodiversity exceeds that provided by irrigation or hydropower globally. The value of water does not solely depend on its quantity but on at least four other factors – quality, location, reliability of access, and time of availability.

Making choices at an appropriate level

Choices need to be made at an appropriate level. Whilst "local" importance has been stressed above, along with the need to consider water within its natural catchment, there will be cases when the level of consideration is different.

An example of this is the River Nile, with its multiple water usage agreements and treaties from 14 different countries. A more significant issue will be groundwater, and the multi-national management of some of the world's largest aquifers under many of the arid areas of the world.

As choices need to be made at the levels best suited to the decision, these will range from global through to local, and it is at the local level that the effects of the decisions made at all other levels will become manifest. Here the balance between supply and demand becomes fundamental, as it is at this level that it affects our industry, agriculture, domestic supply, and environment.

Conclusions

I suggest that the water crisis currently faced in parts of the world is essentially a crisis of governance: a failure to govern regional water resources sustainably. Societies across the entire spectrum of economic development are facing social, economic, and political challenges in how to govern water more effectively. Put simply, in most parts of the world there are enough water resources to satisfy the personal needs of households and the requirements of industry and agriculture without excessively impacting on the natural environment. But through mismanagement, the water is not made available to those who need it. This situation is set to become increasingly critical as pressures on the world's limited freshwater resources increase.

The management of water is based on the choices that we as individuals, communities, states, and businesses make. These choices will involve the freshwater resources we develop, the technologies we employ, the methodologies used to manage our distribution and collection networks, the use we make of our "waste" water, the measures implemented to manage demand rather than simply increasing supply, the approach we take to working together to address the issues, and the value we attribute to the environment for its services to mankind.

Water for human uses is coming under increasing pressure from population growth, development, and potentially climate change. The impacts on humans and ecosystems are likely to range from adverse to very severe. Arup is in a position of knowledge, and can influence aspects of society to mitigate many of the risks associated with changes in water resources (droughts, floods etc). In providing these services we can add further value to our work.

The issues associated with water affect virtually every part of our business, in every country where the firm operates. Arup needs to identify and implement strategies to mitigate water-related risk at global, national, city and individual levels, as part of operating a sustainable consultancy business.

Peter Wilkie is an engineer in the Water Group at Arup's office in Leeds, UK. He is the lead researcher for the Drivers of Change investigation into water.

Credits

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1. The Foundation headquarters at night, showing the building's transparency.

"Stronger nonprofits, stronger communities": Kresge Foundation headquarters, Troy, Michigan

Jeffrey Huang Ashok Raiji

"Green building" principles permeate the design and construction of the headquarters of one of the USA's leading philanthropic bodies.

Introduction

Since 1924, the Kresge Foundation has supported US nonprofit organizations through capital grants, leadership building, and in-house expertise and support. With $2.9bn in assets, it helps groups that "advance the well-being of humanity" and in 2003 started the Green Building Initiative to "encourage nonprofit organizations to consider building green". The Foundation is a vanguard for bolstering the nonprofit sector, and through the regeneration of its Troy headquarters has embraced its commitment to sustainability by creating a green design showcase.

The project began in 2003 after the Foundation determined that it had outgrown its existing premises. Arup was approached directly by the architects (Valerio Dewalt Train Associates Inc, Chicago) through connections with the firm's Chicago office and reputation for sustainable and low-energy design expertise.

The expanded 26 000ft^2 (2460m^2) headquarters includes restored 19th century farm buildings integrated with a new 19 500ft^2 (1810m^2) building on a three-acre (1.2ha) site. Green considerations were fundamental to the design team's response, a prime goal being to create a low-energy building with a high-performance building envelope, use of natural light, and efficient HVAC systems.

Design challenges and approach

Key to the design was visual transparency (Fig 1). To partially mitigate the adverse energy impact of glass, insulated glazing with low emissivity coating was used, all walls and roofs were insulated above energy code requirements, and the building was partially buried below grade to take advantage of ground insulation (Fig 2). Visual connectivity to the outdoors, entrance of natural light, and heat gain/ heat loss through the façade were kept in balance.

The design philosophy also integrated the natural and the manmade: metal and glass combined with abundant wood surfaces. The mechanical system mirrors this architectural theme by coupling high-performance equipment to nature through buried ground loops to extract heating and cooling energy. System functionality thus harmonizes with the environmental consequences of building conditioning, with annual energy input and extraction in balance.

Early in the project, two schemes were envisaged for conditioning the interior space. The conventional method included a boiler and chiller system with central air-handling units and overhead VAV boxes, but for optimal energy efficiency and occupant comfort a more ambitious alternative - ground-coupled heat pumps with raised floor air delivery - was proposed.

As with any project, sustainability goals had to be balanced with total project cost, and the design team worked to be both fiscally responsible and creative. To understand the implications of various measures, the team investigated:

- the relative effectiveness of ground-coupled heat pumps
- decrease in the building's glazed percentage
- double (ventilated) façade
- super-insulated glazing
- increased building insulation
- building orientation.

Energy conservation also had a two-tier approach, involving passive heat retention and avoidance (eg high-performance building envelope, shading), and active conservation (eg high-efficiency mechanical/ electrical/plumbing systems).

Several aspects and challenges make this project unique. Two systems, the ground-coupled heat pump and the underfloor air distribution, are discussed in detail.

Heat pumps for heating and cooling

The new building is split into three zones, based on orientation and space use. Each is conditioned with its own heat pump, supplemented by perimeter fan-powered boxes (FBPs) with low-temperature hot water coils to augment cooling and heating as needed. To combat façade heat loss, these are dispersed throughout the building and grouped according to space use.

Booster fans in the FPBs induce air from the floor plenum. In winter the air is heated as it passes over activated hot water coils. In summer, the fans would normally be off, but can be energized if the space temperature increases. This allows each unit to locally treat each space as required, based on shifting occupancy and changes in other environmental heat gains (eg Sun position).

Part of the programme mandate was to retain the existing outbuildings (sheds). While they have no historical significance, they help to emphasize both the humble roots of the founder, Sebastian Spering Kresge (1867-1966), and the rural location. They were prime candidates for adaptive reuse, and two accommodate the emergency generator and one of the heat pumps. The main barn (Fig 3) was integrated with the new building to house the main mechanical and electrical rooms in its lower level and the employee lunchroom and gathering area above. The historic farmhouse was also preserved and integrated into the building, serving as the main reception with boardrooms (Fig 4).

There are two types of heat pump, one for air-side and one for water-side systems. Water-to-air heat pumps (WAHP) condition the primary air, which is distributed through the raised floor. Water-to-water heat pumps (WWHP) generate low-temperature heating hot water (130°F/54.5°C) to be distributed to the perimeter FPB reheat coils. An indirect heater is also connected to generate domestic hot water. Inclusion of this, and elimination of boilers, means no site consumption of fossil fuel or generated greenhouse gas emissions from the mechanical and plumbing system. This is quite significant as the area experiences outdoor winter design conditions of 0°F (-18°C).

All the heat pumps utilize HFC-based refrigerants (with no ozone-depleting potential), anticipating the eventual phase-out of commonly-used refrigerants to comply with the Montreal Protocol.

2. The new building is partially buried to further insulate against heat gains and losses.

3. The barn now serves as the employee lunchroom.

4. The historic farmhouse and sheds are integrated with the building and the site.

Raised floor air distribution

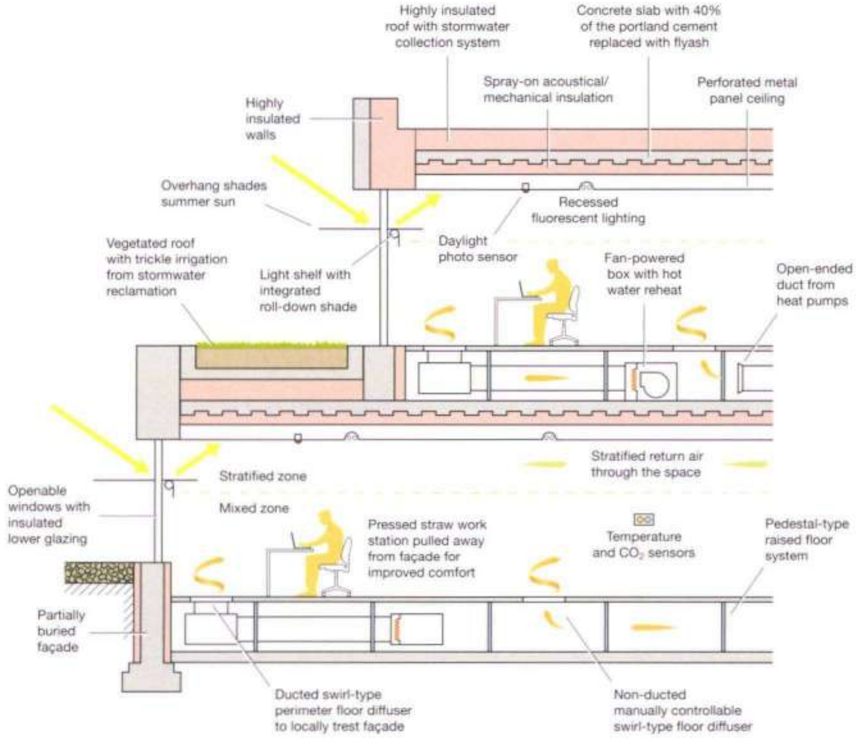
Using a pedestal-type raised floor reduces the amount of ductwork compared to overhead distribution, increases access to electrical and IT services, and improves indoor air quality and occupant comfort (Fig 5, 6). This required manually operable diffusers to be specified and installed for local thermal comfort control (Figs 7, 8).

The underfloor air is typically delivered at 62°F (17°C). Face and bypass dampers were designed into the water-to-air heat pumps to provide reheat after dehumidification of the outside air. These dampers require power only for operation, and do not increase the overall energy use by the heat pump compared to an electric reheat coil, which is often the only option for unit-mounted reheat for direct expansion (unitary) systems.

Working with discharge air temperature control, surface-mounted sensors reset the heat pump discharge temperature if condensation on the structural concrete slab is imminent due to low surface temperature. This is unlikely, however, since heat transfer between the slab and the air within the floor was mitigated firstly by spraying the underside of the upper level floor slab with an acoustically absorptive insulation that also inhibits thermal transfer, and secondly, by distributing a series of open-ended ducts from the heat pumps throughout the floor. These are never more than 50ft (15m) from the furthest floor outlet, to help maintain uniform temperature and pressure distribution throughout the floor plenum.

From the heat pumps, fans with variable speed motors distribute air. Since the occupants can manually control diffusers, and the perimeter FPBs run independently to satisfy the local space temperature, variations in the raised floor static pressure are compensated by motors that continually change speed based on the space demand.

5. Building services run through the raised floor and are easily accessible.



6. Typical building/office section.

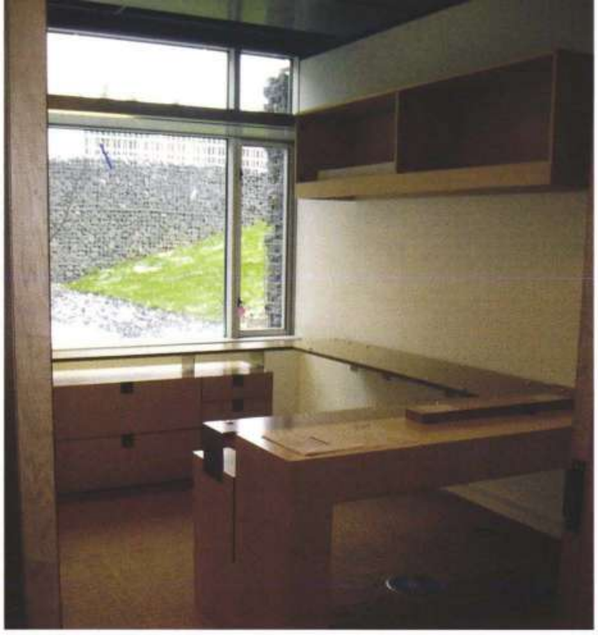
Another energy-conservation measure was demand-controlled ventilation through installing local space sensors in the large conference areas. These measure CO_2, which is a good indicator of space occupancy. The building management system monitors the indoor CO_2 concentration and compares it to that outside. If the differential is below a certain value, the outside air dampers on the heat pump close down to an appropriate level, thus reducing the outside air load required to be conditioned.

The benefits of the underfloor air distribution scheme include:

- more hours available for air-side economizer use by the heat pumps compared to an overhead distribution, due to the higher supply air temperature allowed by raised floor distribution
- lower static pressures required in the floor for air distribution, lowering fan energy usage
- less ductwork for air supply, reducing material and labour costs
- ability of the occupants to directly control their comfort
- accessibility of services within the floor to deal with expansion, change of use, and other upgrades to technology.

The ground-coupled heat pump system

By utilizing the large heat capacity of the earth, rejection and absorption of heat to and from the ground greatly increases energy efficiency of the mechanical equipment. A large condenser water loop buried in the ground rejects heat more efficiently to a stable 55°F (12.8°C) medium than to the air which is potentially at 90°F (32.2°C) during the height of summer. Conversely, the ground is relatively warm enough in the winter for energy to be extracted to heat the building. Balancing rejection and extraction of energy from the ground ensures its long-term temperature stability. Conditioning systems of this type are not used extensively in commercial buildings, mainly due to their complexity.



7. Airflow from the floor diffusers in the offices is integrated within the furniture locations and can be manually adjusted.

Concurrently with designing the interior building conditioning systems, the team mapped out the ground loop system for heat rejection and absorption for the heat pumps. Initially, since all the architectural elements were not yet finalized, crude annual energy models were created using the DOE-2 hour-by-hour energy calculation program[1]. Estimates of monthly energy demand from the program were inputted into a spreadsheet calculation simulating semi-transient two-dimensional heat transfer in the ground.

Before the bores were designed, an independent drilling company tested local soil conditions by the line source method. This gave the soil properties and the undisturbed ground temperature needed to design the borefield. The test and calculated results are based on steady-state two-dimensional heat transfer.

The spreadsheet analysis, with the DOE-2 verification, allowed the team to design 40 bores for rejecting and absorbing heat for the heat pumps throughout the year. This number was determined using the block peak load, the maximum that all the heat pumps will experience at a given hour during the day. If the sum of the peaks load was used instead to size the borefield, it would be oversized and unnecessarily costly.

At the outset of design, two essentially separate heating and cooling systems were envisaged. Heating was done primarily with hot water boilers, and cooling through the heat pumps. Calculations showed a high imbalance in annual loads, where the ground was only being used as a heat rejection medium. Without a great many bores (almost twice the number ultimately designed), the ground would begin to heat up within the first few years, continuously reducing its capacity to reject heat. Dissipation of that heat is a long process due to soil's heat capacity, and would not be able to occur on a yearly cycle.

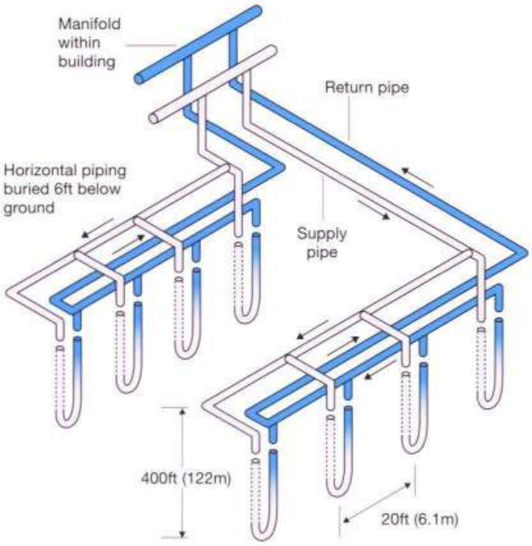
Parametric studies were done to optimize and reduce the number of bores on the site by:

- annual balancing of heating and cooling (heat extraction to heat dissipation)
- maximizing the distance between bores
- reducing or eliminating antifreeze solutions
- laying out the bores so as to reduce interference effects from adjacent bores (long, narrow arrays compared to square arrays of the same number of bores).

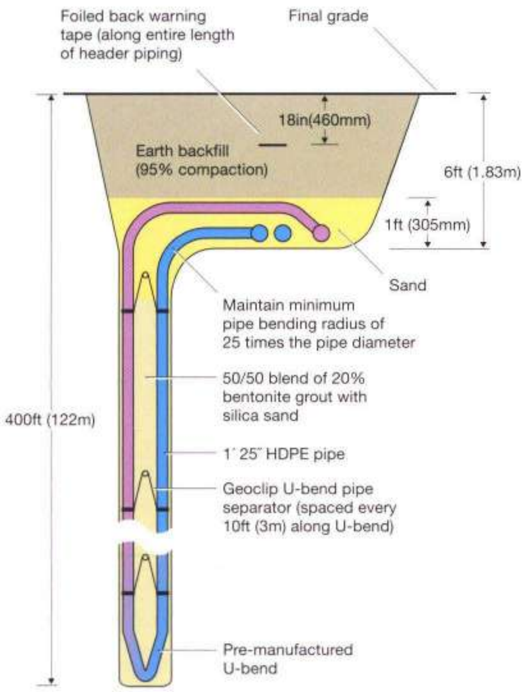
During construction the design team collaborated closely with the contractor that installed the ground coupled piping. Information sharing was easy and open; at one point, the energy model output information was sent to them for the team's calculations to be verified by the contractor's independent Professional Engineer. This was done to establish a level of comfort between designers and installers, as well as to guarantee an installation warranty. The technical audit verified that the loads matched the contractor's in-house calculations with a margin of difference within 10%, unmatched on any other of the contractor's projects.

The 40 bores are spaced 20ft (6m) apart and plunge 400ft (122m) into the earth. The number was designed conservatively, neglecting any impact that underground water movement might have on heat dissipation due to its variability.The array was laid out beneath the pervious paving of the employee parking lot, with the bore locations marked by different coloured pavers as indicators for employees, visitors, and maintenance. Putting them here meant that the energy spent on site excavation/earthwork for their installation would be combined with that for the parking lot, thus reducing the overall site impact. Careful co-ordination with the civil engineers was required, since many of the borefield details needed to be shown on their drawings, including the bore locations and the piping burial details.

8. Swirl-type floor diffusers are ducted to the FPBs for the conference rooms to mitigate heat gains and losses.



9. Bores and circuits in reverse return.



10. Cross-section of typical bore.

11. Rear view of the headquarters looking towards native plants and stormwater retention ponds.

Borefield layout

The vertical bore assembly has four major components. Earth bores 6in (150mm) in diameter were drilled, in which were inserted assemblies of exterior grade high density polyethylene piping with U-bends at the bottom, joined by heat fusion to minimize leakage. To keep the pipes separate, spring-operated clips were used to push the pipes close to the edge of the soil to improve heat transfer. A highly conductive cementitious grout was pumped within the annulus between the piping and the bore wall to further improve heat transfer and encase the piping to prevent damage from water and corrosion.

The vertical U-tubes were connected into five individual circuits manifolded together inside the main mechanical equipment room. Each circuit can be isolated by shutoff valves, which allows each system to be purged separately if sediment builds up in the circuits. The horizontal piping from the building to the vertical bores is buried 6ft (1.8m) below grade, to which is fixed underground detection tape. Connection to the vertical bores is through reverse return piping. Since the ground loops are installed well below grade, putting balancing valves to each circuit and each bore would be impossible. The reverse-return piping, though increasing the length by about one-third, assures a self-balancing system, and eliminates the need for balancing the flow through each bore individually (Figs 9, 10).

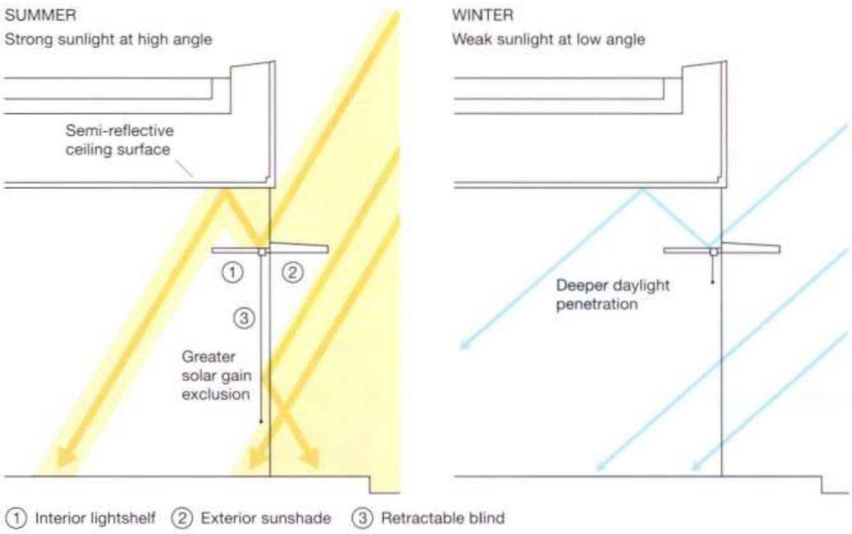
The relatively deep burial minimizes the effects of any differential settling from the parking lot above, eliminates the risk of freeze/thaw cycle stress since it is below the frost line, reduces the influence of unpredictable surface ground water movement (eg storms), and reduces heat transfer effects of the ambient air above grade.

Calculations were performed, based on the soil characteristics and empirical equations, to correlate soil temperature (which is influenced by air temperature) with a time lag appropriate for the amount of heat capacity in the ground. This allowed the team to predict soil temperature with depth. If the piping was buried 6ft (1.8m), it would not fall below 40°F (4.5°C) even in midwinter, because the soil has enough mass and volume to absorb and dampen ambient environmental fluctuations such as air temperature and solar gains. Due to the soil heat capacity, heat transfer is transient, and there is a lag from when the grade level soil experiences a load to when the piping would experience it. For this area, the time lag is 30-40 days, based on soil diffusivity characteristics. By burying the horizontal piping deeper than normal, using antifreeze in the ground loop was avoided. This increased the efficiency of the indoor equipment, reduced the number of bores needed, and eliminated an additional unnatural chemical from the site.

Water efficiency

Alongside the building's low energy measures, water is also used efficiently both inside and out, decreasing potable water use and reducing the chemicals and energy needed for wastewater treatment. Inside the building, this is achieved via low-flow and no-flow devices in the bathrooms. As these only reach full potential if correctly used, providing information was key to encouraging behavioural changes. A small plaque was posted above the waterless urinals indicating how they work and how much potable water is saved, and users also had information sessions about the two-button flush toilets.

Outside the building, pervious paving, constructed wetlands, retention ponds, and bioswales slow down stormwater runoff to help recharge the groundwater, and naturally scrub and clean the runoff water to reduce the load on the treatment facilities. Native vegetation was planted to reduce irrigation requirements and provide growing media to help filter the runoff, whilst parts of the low roof were vegetated to reduce the urban heat island effect, increase insulation, and slow down stormwater. These drought-resistant plants are irrigated through rainwater collection from the retention pond into a cistern near the barn. Soil moisture detectors activate trickle irrigation pumps (the most efficient method), so that after the initial planting and establishing, no potable water is required for irrigation.



12. "Daylight harvesting".

13. Overhang to shade summer sun.

Additional sustainable measures

The project is now seeking Gold (perhaps Platinum) certification from the US Green Building Council's LEED® rating system. As well as the measures described elsewhere in this article, other sustainable features included in the design were:

- adhesives and sealants without volatile organic compounds
- use of sustainably harvested wood materials
- use of materials that are rapidly renewable
- reuse of site demolished materials
- use of recycled materials (27%)
- lighting control that reduces energy requirements during daylight hours: the new building's orientation, with long sides facing north and south (52% glass façade, compared with only 29% of east/west façade), allows cool northern daylight and controlled southern light to penetrate, while morning and afternoon light (more difficult to control) are shaded. Exterior sunshades and interior light shelves work together to bounce indirect natural light deeply and evenly into the interior. This "harvested" light is monitored and complemented by the right amount of artificial lighting for a pleasant work experience with minimal energy use (Figs 12, 13).
- full commissioning with commentary during design, resulting in optimization/ maximization of energy savings
- retention of outbuildings to house mechanical equipment, emergency generator, and employee lunchroom
- use of native plants
- use of locally manufactured building materials, with 76% coming from within 500 miles of the site, reducing fuel consumption and expense.

The heating/cooling system in operation

Partially due to system start-up in late fall 2005, the ground did not experience a full cooling season when heat was rejected into it, so heat extraction from the ground became difficult during the peak winter months. The team therefore placed the system under a different and temporary control scheme to stabilize the units until the spring without the use of temporary boilers or heaters. Once the arrival of spring reduced the heating load, the ground temperature began to increase, allowing implementation of the original control scheme. The heating system is being put through its full paces this winter after a complete cooling season.

Once commissioning is complete, measurement and verification will also be performed to tune the computer energy model with actual energy use within the building. This will then be used to predict the future expected annual energy cost.

Conclusion

The Kresge Foundation's new headquarters symbolizes commitment to the environment, and showcases an example of an integrated approach to green building. Numerous sustainable design features, from architectural to landscaping, and a low-profile on the site both visually and environmentally, exemplify the understated presence in Troy. Collaboration and co-ordination between all members of the team helped to complete a successful project.

Jeffrey Huang is a senior mechanical engineer in Arup's New York office, and was Project Manager for the Kresge Foundation project.

Ashok Raiji is a Principal of Arup in the New York office, and was Project Director for the Kresge Foundation project.

Credits

Architect: Valerio Dewalt Train Associates **LEED® consultant:** Farr Associates **MEP engineer:** Arup - Alexander Biczak, Petronela Digeratu, Johnson Esho, Nancy Hamilton, Jeffrey Huang, Diego Lozano, Elizabeth Perez, David Powell, Ashok Raiji, Tom Smith **Structural engineer:** Robert Darvas Associates **Landscape architect:** Conservation Design Forum **Civil engineer:** Progressive AE **Lighting designer:** Lighting Design Alliance **Acoustic consultant:** Shiner + Associates **Construction manager:** JM Olson **Illustrations:** 1, 11 VDTA; 2, 4, 5, 7, 8 Jeffrey Huang; 3, 13 Ashok Raiji; 6, 9, 10, 12 Nigel Whale.

Reference

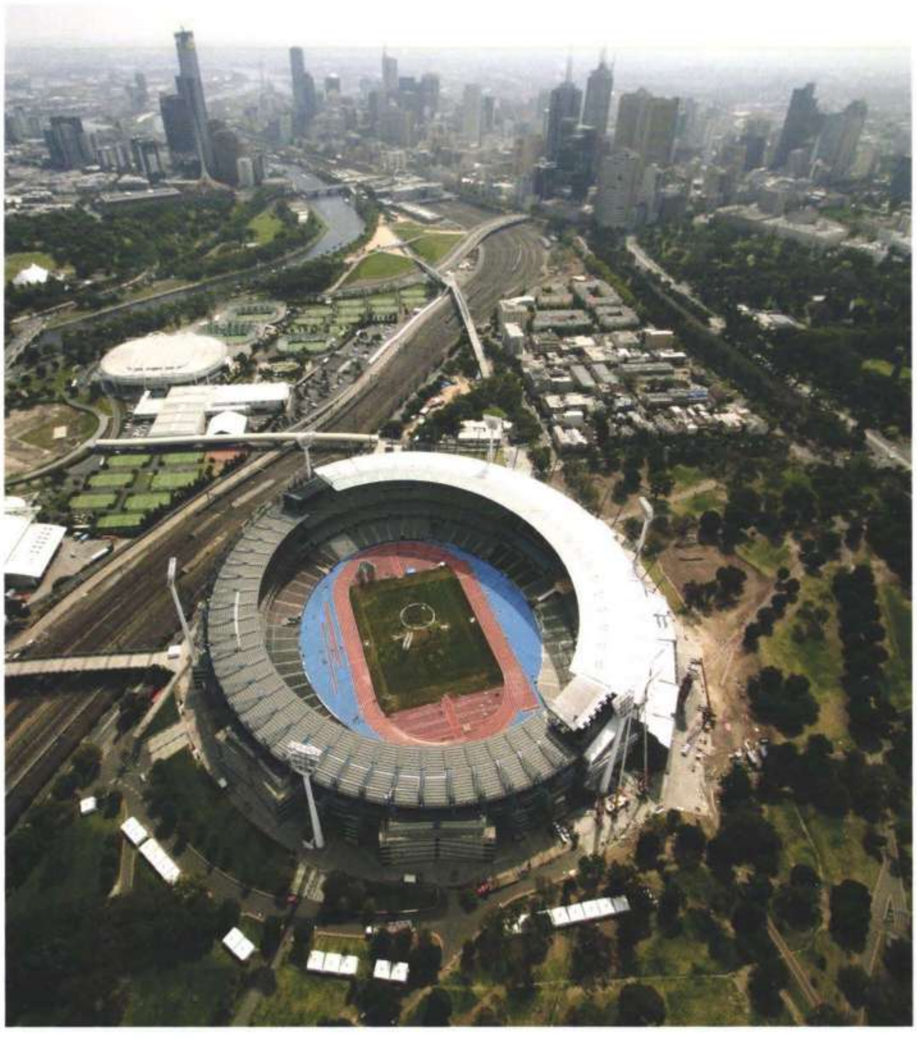
(1) http://www.doe2.com

Melbourne Cricket Ground redevelopment, Victoria

Peter Bowtell Tristram Carfrae
Frank Gargano Paul Simpson

"A large part of the success of the MCG is due to a seamless integration between engineering and architecture. The result is a light and transparent new structure that is a fitting evolution on the ongoing history of this remarkable place."

Patrick Ness, Design Director, MCG5 architectural joint venture



1. Melbourne Cricket Ground in its urban context of Yarra Park, in inner Melbourne.

History and background

Melbourne Cricket Ground (MCG) is one of the icons of Australian sport. Besides cricket, a highlight of which is the annual Boxing Day Ashes Test Match, it is used for Australian rules football during the winter, culminating in the Australian Football League (AFL) Grand Final in September. It has also hosted other world sporting occasions, most recently the 2006 Commonwealth Games, where athletics events and the opening and closing ceremonies were staged.

The MCG site at Yarra Park in inner Melbourne became home to Melbourne Cricket Club (MCC) as far back as September 1853. A Members' Pavilion and 6000-seat temporary grandstand were built in 1854, and the first cricket match was played just one year after the acquisition of the site. A long saga of building and rebuilding ensued over the years and decades that followed. A new Members' Pavilion was constructed in 1927, and another major milestone was the opening of the Southern Stand in 1936. Twenty years later the Olympic Stand was completed in time for the 1956 Summer Olympics. A new Western Stand (subsequently called the Ponsford Stand) was completed in 1968, in 1985 light towers were built to allow playing time to be extended into the night, and in 1992 the 48 000-capacity Great Southern Stand (GSS) was built as part of a major redevelopment for that year's Cricket World Cup.

In January 1996 the Australian Commonwealth Games Association began the process to decide which Australian candidate city would bid to host the 2006 Games, and in October that year the decision was made to put forward Melbourne. The city's application was prepared and presented to the Commonwealth Games Federation in March 1999, and at the CGF General Assembly in October 1999, Melbourne was chosen.

Another major redevelopment on the north side was clearly necessary to match the GSS and bring the whole facility up to the necessary standard for a 21st century sporting event of world significance, with a total capacity of 100 000 for what has now been named the "People's Ground" (Fig 1).

The client body, comprising the MCC and the MCG Trust, brought together a group of five architectural practices under the title of MCG5, and appointed Connell Mott MacDonald (now Connell Wagner) and Arup to deliver the multidisciplinary engineering design.

2. The new Northern Stand (right of the scoreboard) adds 55 000 seats to the 48 000 capacity of the Great Southern Stand.

Key design aspects

Design of the $425M MCG Northern Stand redevelopment began in 2001. To create the new 55 000-seat facility necessitated demolition of the Olympic and Ponsford Stands as well as the Members' Pavilion, and all this had to be done while maintaining an operating facility for the MCC. Minimum seat numbers of 80 000 for the AFL Grand Final in September meant that the project had to be undertaken in stages, each of which needed to deliver a functioning facility at completion, significantly increasing the complexity of delivery.

The roof over the new Northern Stand is the most striking visible feature of the stadium. The design aim was for it to be elegant, light, and transparent, enhancing the MCG's iconic status and complementing the GSS without replicating it (Fig 2).

The new back-of-house facilities had to deliver a world-class standard for Members and patrons, so that bars, concessions, committee and club rooms became key aspects of the stand. Also to be incorporated was a new Museum of Sport to display the Club's memorabilia, one of the world's best collections.

Another key aspect of the project was the need to construct the international standard athletics facility in the lead-up to the Commonwealth Games, whilst minimizing impacts on scheduling for the AFL football season and the cricket season including the Boxing Day Test. The civil engineering strategy involved the staged construction of the athletics facility in short periods between football and cricket seasons in 2004 and 2005, and finally "uncovering" the track in early 2006 in readiness for the Games.

To maintain the overall symmetry of the stadium, the GSS was extended by one bay with new giant scoreboards at each end of the ground separating the two stands.

Many sustainable principles were also incorporated into the complex to reduce the demand for energy, and meet the State Government's ESD (Ecologically Sustainable Development) Reporting Guidelines for venues for the Melbourne 2006 Commonwealth Games.

All this and more had implications for the engineering design. Though Connell Mott MacDonald and Arup worked throughout in a seamless joint venture, each firm was responsible for different aspects of the work.

Arup undertook the structural design of the main and secondary roofs and steelwork; the civil engineering for the pitch and turf; the environmental and sustainability design (ESD), including building physics, daylighting, and initiatives like the use of photovoltaics (PV), rainwater collection, and solar hot water; the fire, façade, and traffic engineering design; the environmental management plan; and the pedestrian modelling. Connell Mott MacDonald undertook the mechanical, electrical, and plumbing engineering design, and the structural engineering focused on the bowl concrete, with assistance from Arup on dynamics, the raker bowl steelwork, much of the supervision, and some 50% of the drafting.

Client requirements

Planning for the redevelopment took 12 months while Members' approval was obtained. As well as the paramount need to maintain the ground as an operating facility through all phases of the redevelopment, ensuring significant spectator capacity for the key dates of the AFL Grand Final and the Boxing Day Test Match, for the "People's Ground" the specific brief requirements were:

- a minimum 100 000 seated capacity
- an iconic and globally recognizable roof form
- new corporate entertainment suites
- new media and broadcast facilities
- upgraded security and crowd control
- enhanced Member dining and bar facilities
- a new Long Room
- member car parking at basement level
- new pitch and turf nursery
- new practice wickets and training facilities including club rooms
- extension to the GSS
- new video scoreboard facilities.

Delivering such a brief is a mammoth exercise, and the 2006 Commonwealth Games scheduled for 15-26 March placed additional requirements on the design team including:

- staged construction of the Games arena surface between the AFL Grand Final and Boxing Day during 2004 and 2005
- sustainability initiatives to meet Commonwealth Games requirements - later enhanced to become an environmental management plan for the overall operation of the MCG
- design of staging and temporary works for the opening and closing ceremonies
- delivery to an immoveable deadline, requiring tender documentation to be produced in under four months
- removal of sections of the GSS to permit competitor entry.

The Northern Stand roof

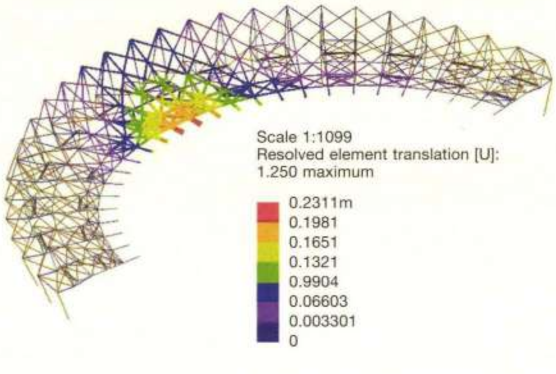
Concept and design

As this was a redevelopment, rather than a completely new construction, the final roof design needed to be not only a globally recognizable symbol for Australia's sporting citadel, but also distinctly Victorian and in harmony with the existing GSS and light towers. Several options for the structure were developed, each tested against architectural, cost, and staged construction requirements. The three main designs considered were a large single mast support, a structure suspended from two arch trusses (as with the Khalifa Stadium[1]), and a suspended roof using multiple smaller masts. Drawing on its vast experience in stadium design worldwide, the team realised that the single mast option would be too visually overbearing, while the arches would make staged construction difficult. The final innovative solution incorporated a tension structure with rafters suspended from cable stays running over individual masts and backprops (Fig 3). This created an ideal balance of unique geometry and construction practicality, which would be aesthetically complementary rather than dominating.

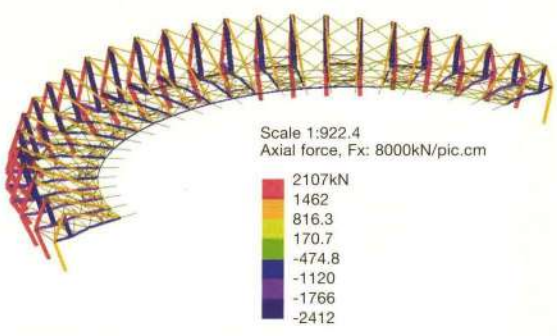
Wind tunnel testing showed that the uplift forces acting on the roof would occur in an alternating pattern of high peak regions and low troughs. Rather than design each bay to resist these peak loads individually, the team developed a supporting cablenet to distribute the load more widely and engage additional stiffness from adjacent bays. The use of counterweight to resist uplift also enabled thinner cables to be used, resulting in a visually superior design. Due to the distributing benefit of the cablenet, the amount of counterweight required was reduced by 50%.

The entire roof structure was modelled with Arup's in-house GSA (General Structures Analysis) software, which enabled various wind loads obtained from testing to be accurately analyzed and made it possible to test the impact of design and geometry changes quickly and efficiently.

3. The roof is supported from a tension structure with rafters suspended from cable stays running over individual masts and backprops.



4. GSA analysis: roof deflection.



5. GSA analysis: cablenet forces.

A lightweight structure

The key feature in making the roof structure efficient, architecturally elegant, and lightweight was the cablenet. Aside from distributing peak wind loads and reducing counterweight, it restrains the top of the individual masts, eliminating the need for bulkier bracing and once again ensuring a light roof structure, clean in appearance. The distribution of the cablenet is also a safety factor should a particular cable ever fail.

But to ensure this even force distribution, the cablenet had to be tensioned. Due to the high degree of interdependency between the cables, it would have been extraordinarily difficult and time-consuming to tension each in turn without affecting the balance of the system, so the cablenet was designed to be self-tensioning. This was achieved by having each individual cable cut to an exact length, so that when the roof load was first applied to the cables, they would naturally reach equilibrium. Sophisticated GSA analysis of the entire cablenet made this possible, by providing the cable supplier with precise estimates of the forces acting in the almost 2000 cables. In case any section of the cablenet did not reach its correct equilibrium condition, turnbuckles could increase or decrease cable tension, but these never needed to be used.

Arup's GSA model of the primary roof structure and cablenet (Figs 4, 5) was developed further so as to help the main contractor, Grocon Pty Ltd, achieve a flat roof in the final condition.

Structural analysis predicted the amount by which the roof would deflect once the steel rakers were filled with concrete, and the rakers were then given an initial upwards incline equal to this amount. The complexity of this task and the accuracy required were underscored by there being no margin for error, as once the rakers were full of concrete, they became too heavy for a crane to reposition.

The clean and lightweight appearance of the roof was enhanced by the lack of any additional counterweight. Such was the efficiency of the cablenet that only steel members already structurally required were concrete filled.

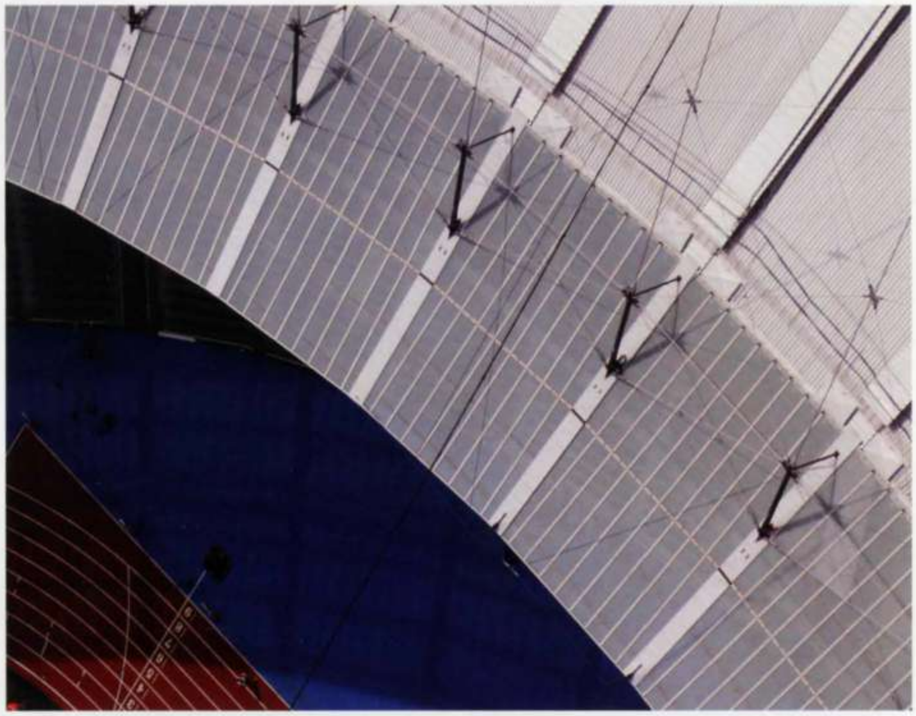
Another benefit of this solution was its suitability for staged construction, allowing the structure to be built bay-by-bay with minimal temporary support, meeting the client's tight construction programme and the need for minimal disruption to patrons. The success in meeting these construction time constraints was greatly influenced by Arup's design methodology, where consideration is always given to buildability.

The primary roof structure comprises concrete-filled prefabricated steel box section rafters, 37-42m long, located on each grid line of 16m spacing (at the rear). Each rafter is suspended from its individual fabricated steel mast, between 13m and 28m high, at the back of the roof, the masts being tapered to add to the appearance of slenderness.

The primary cables in the roof are galvanized spiral strands 65-80mm in diameter with the cablenet itself made of 22mm cables. For further

6. The extensive cantilever gives more spectator protection.

7. Cablenet supports to rafters.



8. Sophisticated analysis enabled an exceptionally clean and light appearance for the roof structure.

long-term durability, all the cables have *Metalcoat* corrosion protection. *Metalcoat* was chosen over other corrosion protection because it is flexible and could be applied to the cables prior to erection, thus saving time and reducing safety risks.

As completed, the Northern Stand roof differs from the GSS roof in several ways. Being a tension structure, it is lighter, appears more elegant, and the use of glass in it softens shadows. It also provides more coverage against rainfall than the GSS roof, with approximately 80% of the seats behind the "drip line" (Fig 6).

The bowl structural frame

The Northern Stand is a 400m long, seven-storey building with two basement levels. The team's solution for the structure makes it effectively five buildings separated by movement joints.

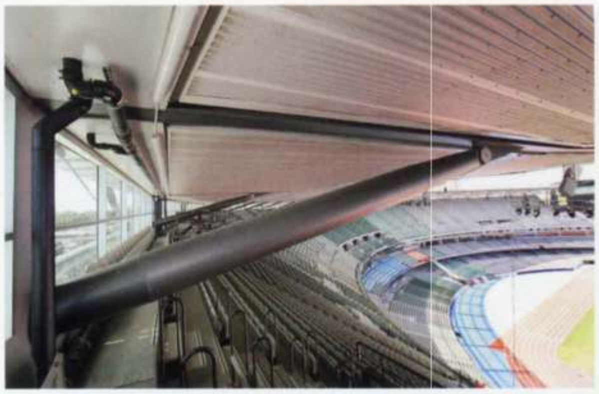
Within each building, radial shear walls provide stability and maximize ceiling zones for reticulation of services around the stand. Circumferentially, however, shear walls would hamper viewing areas so beams have been incorporated, working with the columns as a sway frame. This assists with support of the floors, which are proprietary precast prestressed *Hollowcore* planks spanning radially as the typical suspended floors of the stadium – a "win-win" situation.

The floor system

With more than 10ha of floors to construct, the team used many different flooring systems throughout the project, including conventional formed concrete, precast *Hollowcore* planks and *Bondek* composite slabs on steel.

The grandstand circumferential beams are typically post-tensioned and span approximately 16m. To maximize the services zone, the design incorporated haunches in these beams, 900mm deep at columns and stepping down to 600mm at mid-span. Beam depths were set to maximize the use of standard forms, in recognition that to speed up construction, the *Hollowcore* planks were to be supported by the formwork prior to the beams being poured.

This enabled the *Hollowcore* planks to be used as a working platform for installing reinforcement and post-tensioning tendons in the circumferential beams. The structural topping to the *Hollowcore* was poured simultaneously with the beams to minimize construction time.



9. Long cantilevering rakers support the upper seating tiers.

The seating tiers

Another feature of the stadium is the large cantilevering rakers that support the upper seating tiers (Fig 9). The latter consist of 36m long steel box girders supported on sloping tapered columns, and carry considerable forces from the roof down to the superstructure. To safely carry folded precast concrete seating flats with crowd loading, significant steel beams were required, with the additional challenge that they had to be designed for more stringent dynamic performance criteria than required for the GSS.

Modern sports stadia are increasingly used for non-sporting events like rock and pop concerts, and these crowds dancing in unison can excite a stadium structure much more than a sports crowd.

However, no Australian Standard covered dynamic response of stadium grandstand structures, and there was generally a lack of widely recognized guidance on the dynamic load produced by crowds. The "deemed to comply" approach necessitated the design of an extremely stiff structure, overly conservative and inefficient. Consequently the team adopted an advanced probabilistic method, using an in-house software program that uses inputs relating to the steel and concrete structure, as well as crowd loading variables such as crowd participation, crowd energy, and degree of crowd co-ordination. By simulating a realistic dynamic crowd load, the software could calculate the stiffness required to limit the risk of excessive vibration to 1% per event. This rational methodology provided the justification for reducing the required stiffness by 25% compared with the less sophisticated approach, saving the client more than A$1M. Given that steel beams up to 2.7m deep with 80mm thick flanges were still required, the inefficiency and visual repercussions of adopting a "deemed to comply" design can be appreciated.

In addition to providing the optimal solution for current conditions, part of the dynamic design was the provision for easy retrofit of cables to the end of the seating tier, should greater dynamic control be deemed necessary at some time in the future.

Keeping score

Rising 3m above the Northern Stand roof and 10m above the GSS roof, the scoreboards are the highest roof points of the stadium and provide an accentuated separation between the two stands. Each scoreboard is a six-storey tall structure with an 18m long cantilevered roof canopy.

The interfaces between the GSS, scoreboard and Northern Stand are glazed on each side, both to protect spectators from wind-driven rain and reduce wind loading on the main roof by making it continuously enclosed around the stadium. These interfaces posed a challenge, due to the varying deflections at these three regions. Special connection details had to be designed with enough freedom to allow movement at different rates without locking up, yet still rigid enough not to compromise structural integrity. The solution was a vertical sliding joint, with lateral resistance, that also included a "failsafe" so that the members cannot disengage.

10. Sloping tapering steel columns also form part of the building's interior structure.

Building services

The building services have to cater for many different types of spaces and also for speciality stadium facilities such as turnstiles, ticketing, scoreboards, and sports lighting. Again, a principal challenge for Connell Mott MacDonald's specialists was to design the services to allow construction and demolition to be staged while at the same time maintaining suitable services to user facilities. This required consultation with the project managers and project team before construction began and then with Grocon during the detailed design and construction.

Sports lighting

The considerably larger Northern Stand partly obstructed the existing tower sports lighting, and so additional sports lighting was needed. The team developed a virtual model of the stadium to assess the lighting and shadow effects the new stand had on the ground, a massive exercise that required aiming over 800 lights onto the pitch using lighting simulation software.

To determine the lighting for the different types of stadium use, the designers researched the requirements of the various sports codes and broadcasters, and also measured the existing light levels. This required co-ordination with the builders and the MCC to arrange for the light towers to be turned on at night without disturbing local residents. The upgraded lighting required redundant fixtures to be disconnected and the remaining fixtures re-lamped to provide an overall vertical illuminance of 2000lux.

CFD modelling

Connell Mott MacDonald used computational fluid dynamic modelling to design the various ventilation systems. Key CFD studies included:

- initial atrium smoke modelling
- spectator comfort conditions in the seated areas of the bowl
- relative changes in air movement patterns across the pitch due to the construction of the new stand
- general air movement patterns within the internal areas of the stand
- dispersion of exhaust discharges from level 4 plantrooms
- analysis of chiller air intake and discharge air movement and temperatures.

An environmentally sustainable stadium

Many sustainable principles were incorporated in the project. These involved reducing energy demand, using building systems that provided optimum operational and resource efficiency, and adopting innovative and environmentally sustainable initiatives. These measures enhance the MCG's ability to be an environmentally responsible and sustainable venue, as well as meeting the State Government's ESD guidelines for venues used for the Melbourne 2006 Commonwealth Games. In addition, an Environmental Management Plan was developed for the MCC to enable sustainable management and operational practices to be employed for the life of the facility. It is hoped that this work will eventually enable the Club to achieve *ISO14001* accreditation.

The main entry points for the new Northern Stand are through three atria (named after the replaced stands – Ponsford, Members, and Olympic). Using daylight studies and thermal modelling, the team designed the atria to use passive ventilation to cool the spaces, eliminating any use of mechanical cooling except in high heat areas like the food court.

The shading design was also optimized to provide sufficient solar heat gain control, admit sufficient daylight, but control glare in the space. To accomplish this, the three spaces have series of louvres, each differently arranged to give the best control of light within the space.

11. The Northern Stand structure at night.

The team also conducted a stormwater quality study to investigate improvement measures for the site and reuse of water. Previously all water from the site was discharged to the stormwater system that goes into the Yarra River. Rainwater from the new roof is now collected and used for washdown, substantially reducing water demand. In addition, the team devised a series of source-specific and catchment-wide water treatment methods, including the installation of gross pollutant trapping and some source-reduction measures.

Other sustainable features incorporated in the project include solar hot water and PV cell installations, which have reduced energy demand for the non-match day operational requirements.

Fire safety solutions

The team provided strategic fire safety solutions for the new Northern Stand and developed an integrated fire strategy for the redevelopment using a "first principles" design approach. The fire engineering design has enhanced the stadium's atmosphere of light and openness which derives from the architectural design's use of atria and open space planning. The building is provided with sprinkler protection and mechanical smoke control systems to control the development and spread of fire and smoke, and to maintain safe egress routes.

Timed evacuation calculations were carried out to ensure that the emergency evacuation time at control points along the emergency exit systems was within acceptable limits.

The structure is a mixture of primarily concrete for the bowl, and steel for the roof and upper seating tiers. The fire engineering permitted many of the structural elements to be expressed, relying on the inherent fire resistance of the structure without requiring additional fire protection.

12. Construction progress, April 2006, including reinstatement of stabilized turf layer.

Civil and infrastructure works

The civil engineering works included upgrades to the main entrance from Brunton Avenue (east), significant concourse works, parkland interfaces, and stormwater drainage. Alongside the traditional civil engineering, the team applied ecologically sustainable design principles in the area of water conservation and stormwater quality. As already noted, rainwater runoff from the new roof is collected, stored, and reticulated for washing down the platforms and cleaning the roof.

The design team has also had to work within a tight and limited construction timeframe that skirted around major cricket and football matches every six months while still maintaining at least 70 000 seats during the reconstruction and 80 000 for key events.

Arena and pitch works

One of the true success stories of this project was the redevelopment of the playing surface for the Commonwealth Games while still enabling the key events of the AFL Grand Final in September and the Boxing Day Test in late December to go ahead.

Traditionally the playing surface had a mounded top, falling over 1m from the pitch centre to the edges. This, however, was unacceptable for an athletics track, which must be level throughout. The solution was a totally flat grass surface to superfine tolerances, with a maximum permitted deviation from level of <10mm over the entire ground. Anything more would have permitted ponding on the pitch, potentially leading to soft spots. Beneath the grass, a sophisticated sand bedding and drainage system removes all water before it can damage the surface.

If the pitch design itself was cutting edge, the demands of programme and sequence were even more challenging. To minimize the impacts of constructing the Commonwealth Games athletics track, the works were undertaken in no less than four phases, effectively reinstating the turf over a partially completed athletics track in 2004 and 2005:

Phase 1: October to end of December 2004 (three months)

- demolition of existing field profile
- installation of conduit, drainage, and irrigation systems
- reinstatement of the profile including stabilized turf layer.

Phase 2: October to end of December 2005 (three months)

- total removal of turf and profile in athletics track and outfield areas
- construction of pavements and installation of synthetic athletics track surfaces
- relaying of temporary natural turf for Boxing Day Test.

Phase 3: January to mid-February 2006, ie from Boxing Day Test to one month before the Games (one and a half months)

- removal of temporary natural turf profile to perimeter
- completion of athletics track works including laying of final running surface
- installation of athletics furniture.

Phase 4: End of March to mid-April 2006, ie from the end of the Games to Anzac Day AFL round (three weeks)

- demolition of the athletics track and associated works
- reinstatement of profile including stabilized turf layer (Fig 12).

As if this complex and fragmented schedule was not enough, the Phase 1 works had to cope with some of Melbourne's worst ever spring thunderstorms. Nonetheless the many tasks were accomplished successfully, and to witness the total transformation from playing field to devastation and back to playing field each time for the key events seemed little short of miraculous.

Directing traffic and crowd control

As part of the Melbourne Cricket Ground redevelopment, the team reviewed pedestrian access issues with the architects to assess the suitability of internal provisions of stairs and escalators for emergency evacuation.

Alongside this, managing vehicular traffic was also a key aspect of the redevelopment. Besides buses for spectators, large broadcasting vans, rubbish trucks, and 40m long cricket wicket vehicles also need access to the stadium. Movement of the cricket wicket vehicles involved creating solutions to allow access off Brunton Avenue rather than the previous access through Yarra Park from Richmond Oval.

Through traffic surveys, the team identified that weekends and evenings were the most suitable times for large vehicles to travel without disrupting the traffic flow in Brunton Avenue. However, to ensure that traffic flow was not disrupted during these times, the team installed a signal system on Brunton Avenue.

Conclusion

Despite the complex technical and scheduling factors, Melbourne's iconic Cricket Ground was transformed as intended into a state-of-the-art international sporting stadium and the focus for the 2006 Commonwealth Games. Collaboration between the architects, the engineering team, and builder was excellent, with each party having a real desire to get the best possible solution and receptive to the ideas of the others. The design director of the MCG5 architectural joint venture, Patrick Ness, said: "A large part of the success of the MCG is due to a seamless integration between engineering and architecture. The result is a light and transparent new structure that is a fitting evolution on the ongoing history of this remarkable place."

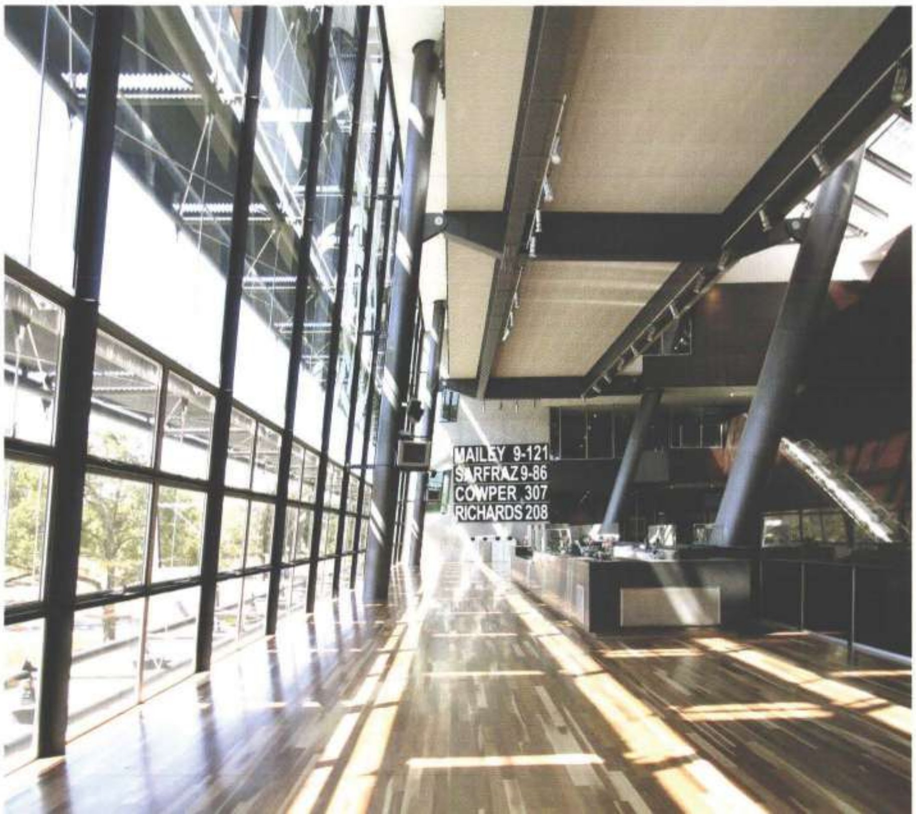
In his August 2006 MCG Trust annual report, the Chairman of the Trust, John MR Wylie, wrote:

"In 2000, the MCG Trust and the Melbourne Cricket Club undertook to redevelop the northern side of the MCG to the best standards in the world, in time for the Melbourne 2006 Commonwealth Games. This was a huge project, requiring a co-operative effort from architects, engineers, project managers, financiers, builders and unions, as well as Government, the Club and the Trust."

"Six years later, all involved can take great pride in their achievement. The new MCG is simply magnificent - reflected in the community's enthusiastic response. The ground did Melbourne proud as the centrepiece for the Commonwealth Games, and I believe all of Australia shared this pride in how well our nation's home of sport presented itself to the world for this important occasion. Once again, the MCG sets the benchmark for stadiums around the world, for both player and spectator facilities[...]"

"Our project team and builders can take great pride in the fact that, no matter what the challenge, they met it superbly. A great many people played a part over the years in this outcome and in this context I would like to acknowledge the role of [among others...] our team of talented architects working under the combined name MCG5, comprising (in alphabetical order) Cox Sanderson Ness, Daryl Jackson Architects, Hassell, HOK Sport and Tompkins Shaw Evans, together with project engineers Connell Mott MacDonald Arup JV."

13. The Northern Stand achieves lightness and transparency in its interior too.



14. Opening fireworks at the 2006 Commonwealth Games.

Peter Bowtell is a Principal of Arup in the Buildings (Australia) group in the Melbourne office. He was project director for Arup of the MCG redevelopment.

Tristram Carfrae is a Main Board member of Arup and a Principal in the Sydney office.

Frank Gargano is a Senior Associate of Arup in the Buildings (Australia) group in the Melbourne office. He was project manager for Arup of the MCG redevelopment.

Paul Simpson is a Principal of Arup in the Infrastructure (Australia) group in the Melbourne office.

Credits

Client: MCC+MCG Trust **Architect:** MCG5 (Daryl Jackson Architects, Hassell Architects, Cox Architects and Planners, HOK, Tompkins Shaw and Evans) **Multidisciplinary engineers:** Connell Wagner and Arup – Leonie Andrews, Greg Borkowski, Peter Bowtell, Stefan Brey, Ignatius Calderone, Tristram Carfrae, David Castro, Melissa Clark, Mia Cullino, Benjamin Dryne, Peter Duggan, Frank Gargano, Chris Graham, Erik Guldager-Nielsen, Nicole Hahn, Justin Hinschen, David Hunton, Paul Jannsen, Michael Kroussoratis, Daniel Lambert, John Legge-Wilkinson, Sean Maher, David Marinucci, Brendan McNamee, Betsy McWilliam, Ian Moore, John Papworth, Marzena Rolka, Olivia Ryan, Dana Shelton, David Shrimpton, Paul Simpson, Richard Vanderkley, Anna Wilson, David Young **Main contractor:** Grocon Pty Ltd **Illustrations:** 1-3, 6-11, 13 Peter Hyatt, Hyatt Associates; 4, 5, 12 Arup; 14 ©Arup/Cox Sanderson Ness

Reference

(1) CARFRAE, T, *et al*. Khalifa Stadium, Doha, Qatar. *The Arup Journal*, *41*(2), pp44-50, 2/2006.

Award

2006 ACEA Awards for Excellence • Category 1: Building

Australian Steel Institute : Structural Steel Design Award 2006

1. The Air Force Memorial evokes the spirit of flight as its glimmering spires soar to the heavens.

Engineering the United States Air Force Memorial, Washington DC

Leo Argiris Andrew Jackson
Patrick McCafferty Daniel Powell

"Building this Memorial took a lot of talent and creativity and determination. Like the aircraft whose flight it represents, this Memorial is an incredible feat of engineering"

President George W Bush

Design inspiration

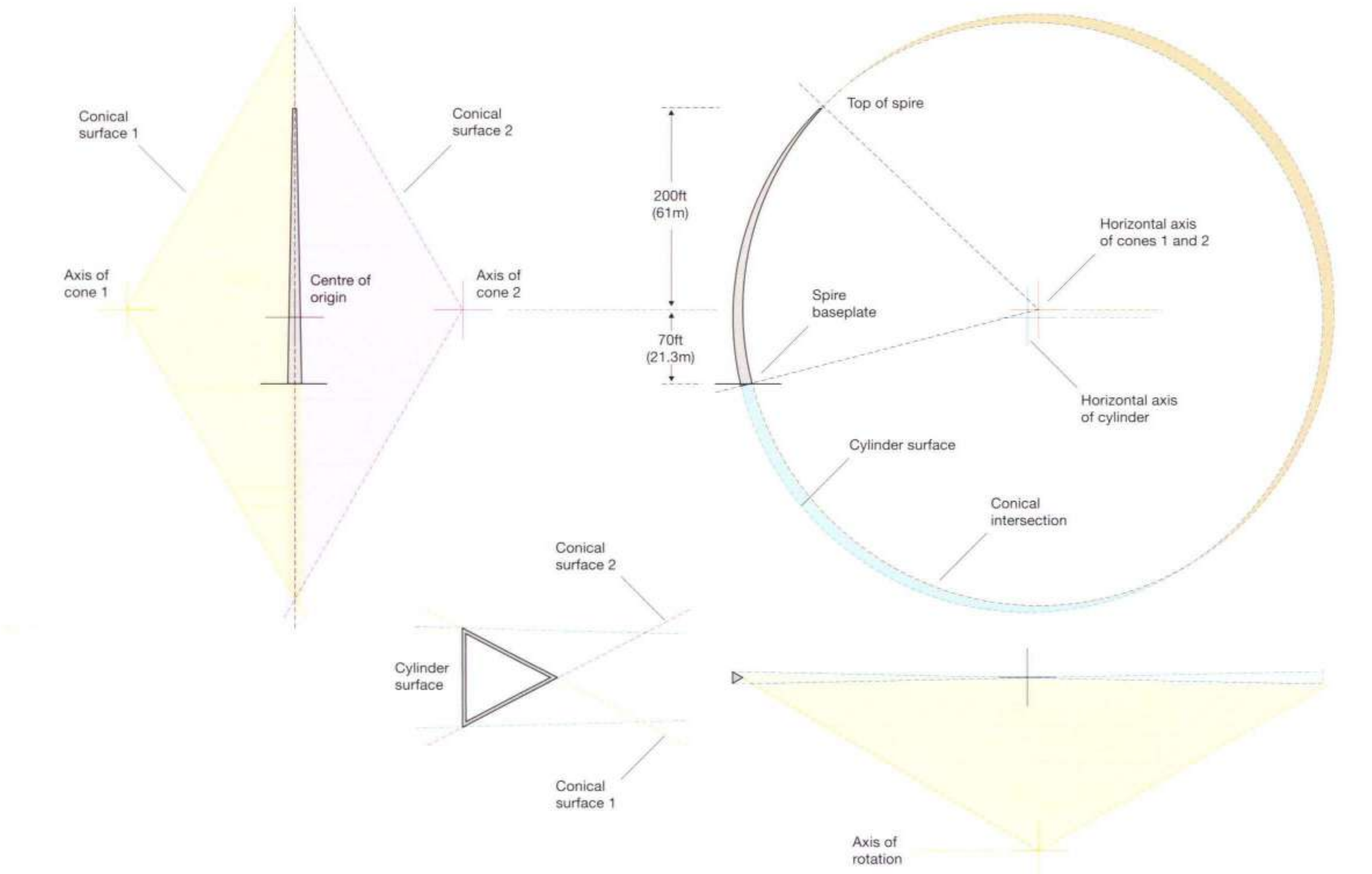
On October 14, 2006, before an audience of thousands, the President of the United States, George W Bush, accepted the United States Air Force Memorial on behalf of the Nation. Perched high atop a natural ridge overlooking the Pentagon and adjacent to Arlington National Cemetery in Washington DC, the Air Force Memorial evokes the spirit of flight as its three glimmering stainless steel spires appear to soar to the heavens. Designed by the late James Ingo Freed of Pei Cobb Freed & Partners (PCF&P), the Memorial was inspired by the US Air Force Thunderbird F-16 fighter jets' "bomb burst" flight manoeuvre. And like this jet formation, the Memorial spires soar skyward in fitting tribute to the US Air Force and its predecessor organizations.

Arup provided full engineering services in the design of the Memorial, including SMEP, fire protection, security, acoustics, and advanced technology engineering design.

Project history

The road to constructing an Air Force Memorial was long. In 1997 Arup began work with PCF&P on a design for a site just north of Arlington near the Marine Corps' Iwo Jima Memorial, but this, a star-shaped enclosure, was vetoed in a struggle between the US defence agencies. In 2001, Congress made federal land near the Navy Annex buildings available, and the Air Force Memorial Foundation (AFMF), a private organization formed to lead the design and construction, launched a second international competition. Arup again entered with PCF&P and a bold new scheme, and won the design commission for a second time.

From the earliest design charettes with Mr Freed, it was clear that the Memorial's spires were to be as sleek and slender as possible to maximize the sense of soaring they would evoke in the observer. The AFMF was led by retired Air Force Major General Edward F Grillo Jr, who was intimately involved throughout the design and regularly reminded the team that the mission was not only to commemorate the past but also to inspire the next generation of airmen.



2. The geometric form of the tallest spire is derived from the intersection of opposing horizontal cones which are sliced obliquely by a horizontal cylinder. The remaining two spires are created by rotating the tallest spire about the conical axes and truncating it at its base.

3.

The remainder of the site

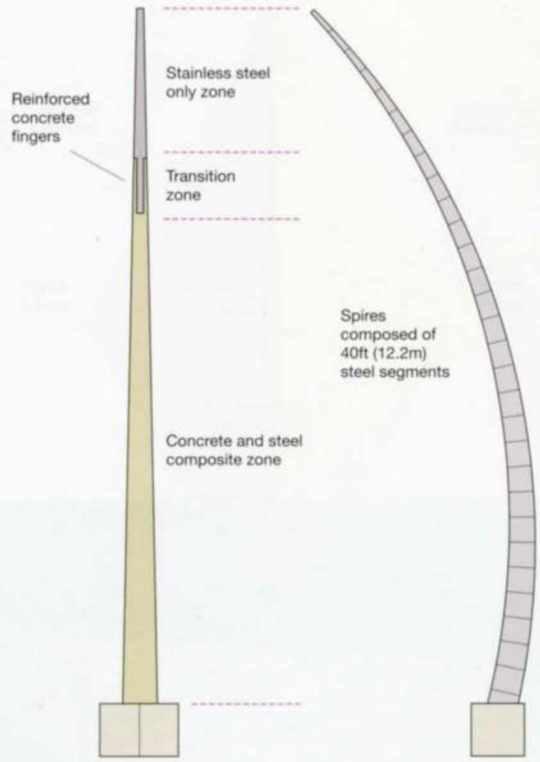
The Memorial site also includes a network of public walkways and other commemorative artworks around the base of the monument. These include black granite walls at either end of the central lawn inscribed with history, honours, and quotations, a laminated glass Contemplation Wall engraved with fighter jets in the "missing man" formation to honour fallen airmen, and a bronze Honor Guard statue by the sculptor Zenos Frudakis. In addition, a small support building, for which Arup undertook the building engineering design, services the Memorial site with administrative offices, restrooms, and kiosks.

Geometric derivation

The geometry of the tallest spire derives from the intersection of a horizontally-oriented cylinder (which forms the spire's back surface) and two horizontally-oriented and intersecting cones that oppose each other (the intersection of which forms the spire's leading edge). The resulting shape is a curved spire whose triangular section tapers towards its tip (Fig 2). Each of the two smaller spires is formed by the successive rotation of the tallest about its conical axis by specified angles.

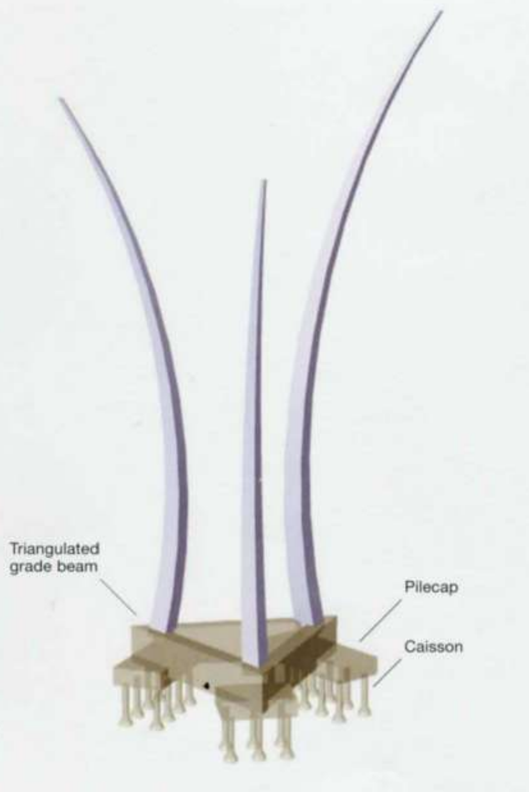
Limited by the maximum height restrictions mandated by the Federal Aviation Authority due to the Memorial's close proximity to Reagan National Airport, the spires vary in height from 270ft (82.3m) to 200ft (61m) - the tallest is only 13ft 9in (4.19m) wide at its base.

4.



5. Each spire is filled to approximately two-thirds of its height with heavily reinforced, high-stiffness concrete. Damper boxes are positioned atop the composite concrete and steel zone between reinforced concrete "fingers" at the spire corners.

6. The three spires are founded on a common triangular grade beam bearing on groups of caissons. This system ensures monolithic behaviour of the structure under lateral loads.



7. Night view at the base of the Memorial. The Washington Monument can be seen in the distance on the right.

Superstructure design

The curving, tapering shape of the spires is formed by bending and welding 3/4in (19mm) stainless steel plates into the tapering triangular shape. As two faces of each spire are sculpted along conical surfaces, these surfaces are in fact warped out of plane, creating an added degree of complexity to the nuanced form.

The spires were fabricated off-site in 40ft (12.2m) segments with the splice lines oriented along a radius to the centre of the conical surface (Fig 2). In the lower two-thirds of each spire, the segments are filled with high-strength (12ksi/80MPa) reinforced concrete for increased stiffness. These sections are heavily reinforced with #11 bars to further increase their bending stiffness; the total amount of internal reinforcement gradually reduces with the height of each spire. Each piece of more than 43 miles (69km) of internal reinforcing steel was mechanically spliced to provide the most secure and direct load path through the body of the spires.

Above the concrete zone, there is a transition zone with concrete piers, or "fingers", located in the corners; above this, the segments transition to hollow stainless steel with internal stiffeners.

Small D-shaped rings regularly spaced along the cylindrical surface of each spire accommodate abseil access for routine maintenance and inspection (Fig 19).

At every turn during the design process, the engineers were challenged to make the spires ever more slender. Conscious that every inch shaved from their profiles served to push the monument ever nearer the precipice of instability, the Arup team was nonetheless able to demonstrate through advanced non-linear structural analysis, dynamic computation, rigorous laboratory testing, and ultimately field testing that the intended slenderness was in fact achievable. Achievable, that is, provided that a unique system of custom-designed dampers was installed to augment the modest levels of natural damping inherent in the spires themselves.

Structural analysis

The spires' curved shape makes them tend to flex and slightly compress under their own self-weight, stresses that are exacerbated at times by wind loads. When the bending stresses exceed the axial compressive stresses, the internal concrete cracks slightly. The orientation and degree of this cracking directly impacts the spires' effective stiffness along their height.

The magnitude of dynamic wind load the structure experiences is a direct function of its natural frequency, which is proportional to its mass and stiffness. Since the shape and materials of each spire establish its mass, the wind loads are a function of its stiffness.

The spire's stiffness is a function of the degree of cracking within the internal reinforced concrete, which in turn is influenced by the total effective wind load imposed on the structure. A degree of iteration was therefore required to properly assess the true structural response of the spires to wind load.

The iterative analytical procedure was thus to:

(1) create an analytical model of the whole spire based on the assumed cracked cross-sectional stiffness at discrete segments along the height

(2) compute the spire's natural frequency based on the assumed cross-sectional stiffness

(3) calculate the anticipated magnitude of wind pressure acting on the spire as a function of the spire's assumed natural frequency calculated in (2)

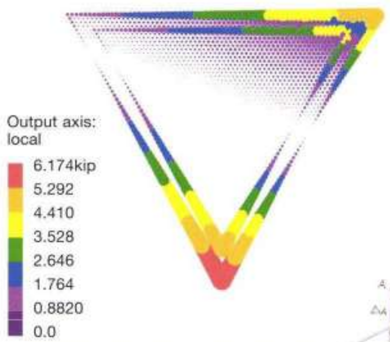
(4) apply the wind pressure calculated in (3) to a 2-D stick model and obtain internal axial and flexural forces at discrete segments along the spire's height

(5) perform non-linear computational structural analyses on 3-D cross-sectional models of each spire segment, applying the axial and flexural forces determined in (4) to each segment in turn (Fig 8); using first principles of structural mechanics and Euclidean geometry, determine the effective bending stiffness of each cross-section under each wind load case (Fig 9)

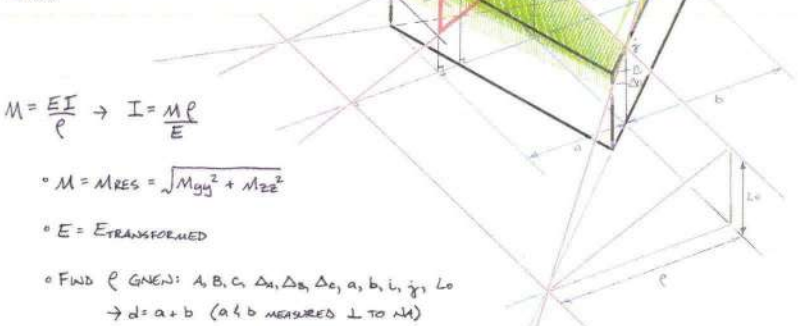
(6) modify the 2-D analytical stick model with the revised cracked cross-sectional stiffnesses determined in (5)

(7) repeat from (2) until the process converges on the calculated spire natural frequency, wind load, and resulting internal stiffness.

This procedure was used to determine the internal forces acting on all three spires. Once identified, these forces were then used to size and detail all aspects of the spires, including final skin thickness, internal reinforcement quantities, anchor bolts, and the like.



8. Structural analysis of typical spire cross section. Strain information obtained in these nonlinear analyses informed the structural stiffness of each spire along its height.



9. The geometric derivation of the effective moment of inertia of the composite cross-section of each spire is based on the nonlinear strain behaviour of the composite structure along its height. Arup developed analytical tools to identify the overall stiffness of each spire based on such derivations.

10. Each spire was pre-assembled in the fabrication shop to ensure proper fit-up and alignment of adjoining segments.

11. Every inch of weld was carefully inspected during both fabrication and erection to ensure the robustness of the structure.

12.

Of national monuments and masonry chimneys...

At their core, the structural behaviour of the spires under wind is analogous to the response of masonry chimneys to imposed wind loads, ie the taller and more slender the structure, the more susceptible it is to the non-linear dynamic effects of wind. Conversely, the stiffer the structure is, the less susceptible it will be. Thus, within the constraints of the prescribed slenderness intended by Mr Freed, the spires were made as structurally stiff as possible in order to limit the amount of wind deformations the Memorial will experience during its lifetime.

The reinforced concrete cast within each spire behaves compositely with the exterior stainless steel via closely-spaced 8in (200mm) steel shear studs welded to the inside face of the skin plate. By casting the concrete within the volume of each spire in this way, the structural stiffness was significantly increased while the dynamic effects of the wind were in turn reduced.

Robust by design

Early in the design evolution, the team decided that the spires' structure would be expressed. No architectural cladding or any such adornment would shroud the monument. The stainless steel skin would instead be ground smooth and flush, bead-blasted, etched, and polished under an exacting litany of procedures to become the Memorial's face.

Throughout the design process, the AFMF continued to impress upon the design team that the spires were to stand the test of time, serving to inspire generations to come. This philosophy of robustness permeated every aspect of the structural design.

Grade 316L stainless steel was selected for its corrosion resistance and enhanced weldability. Labour-intensive, yet fatigue-resistant, full-penetration welds were specified for all welds between spire plates, and each weld was ground to a smooth finish to eliminate crack-prone pits, burrs, and scars. Every inch was then inspected both visually and radiographically to ensure that no weld cracks or voids were accidentally created during the welding process.

Because of the cyclical nature of wind loads, the structural detailing was sensitive to weld details and their fatigue resistance (fatigue is the slow generation and growth of cracks under millions of cycles of low stress). The structural analysis thus included detailed calculations of the accumulated fatigue damage at various stress levels throughout the structure's life, which demonstrated that its anticipated design life exceeded the owner's requirements by a conservative margin.

13. Each spire was shop-prefabricated and spice-welded together on site in 40ft (12.2m) triangular segments. Reinforcing steel was inserted and spliced piecemeal within the standing hollow structure prior to placing high strength concrete through trunks inserted from top.

14. The spires under construction. The headstones of Arlington National Cemetery are visible to the north of the site.

The profile of the tallest spire was informed by the principle of robustness, as the combination of its slenderness, curvature, overhang, and extent of its internal reinforced concrete serves to balance the spire about its base. This geometric trick ensures that the foundation beneath the tallest spire is uniformly compressed under the structure's self-weight, minimizing the potential for differential settlement with time and, ultimately, reducing the load demands on the foundation's anchors, baseplates, and caissons.

Substructure design

The spires are founded on deep belled caissons to evenly distribute their overturning forces. The caissons are grouped in pilecaps – 10 caissons for the tall spire, eight for the medium spire, and six for the short spire. The three pilecaps are in turn joined together by triangulated grade beams approximately 8ft (2.44m) wide by 16ft (4.88m) deep that ensure that the foundation system is engaged as a monolithic whole. Each spire terminates in a base plate with an anchor plate deeply embedded in the pilecap below.

Dynamic response to wind

Given the inherent flexibility, low structural damping, and triangular cross-section of the spires, their form makes them fundamentally susceptible to galloping wind excitations.

Wind can cause unbalanced lateral forces on the spire surface and a resulting sway perpendicular to the wind direction. The lateral force component is proportional to the cross-wind velocity of the sway motion, and acts like damping. In some structures this damping component can be negative when the wind reaches a critical velocity, indicating inherent instability at these windspeeds.

Early wind tunnel tests of the Memorial without its dampers revealed that this critical velocity was unacceptably low (40mph/64km/hr) and that either additional damping or some equivalent measure was necessary to ensure that the total system damping remained positive and the structure continued to be stable. Subsequent analysis showed that the total damping required to avert galloping ranged from 0.8% for the tall spire to 1.0% for the short spire.

The design team and the client considered various options to mitigate potential galloping. If the spires were made stockier (and therefore stiffer), or if their corners in the upper segments were slightly chamfered to increase local wind turbulence, then the analysis indicated that galloping could be averted. However, any suggestion that the shape and slender proportions of the spires be altered in any way was strongly resisted by both architect and client as aesthetically unacceptable.

15. Thousands of USAF veterans and other guests attended the inauguration of the Memorial on October 14, 2006.

16.

The only acceptable option was to augment the inherently low damping levels of the spires mechanically, and so the team was challenged to "manufacture" sufficient damping to achieve stability without altering the form. Arup developed a bespoke system of finely-tuned internal dampers to mitigate wind-induced galloping, a passive system that utilizes the very slight sway of the spires under wind to generate sufficient levels of damping. Steel-encased lead balls 20in (500mm) in diameter roll freely within steel boxes lined with synthetic rubber, and as they impact the sides of the boxes, energy is dissipated from the spires and damping is increased. Precisely stacked arrangements of these dampers are cradled between the reinforced concrete fingers of the transition zone approximately two-thirds up each spire.

Because of the unusual shape and construction of the spires, there were several constraints on the construction and detailing of the dampers. First, the system had to provide the required amount of damping. Second, the damping scheme could not affect the shape or proportions of the spires, so it had to be contained within the slender tapering shape of the spire segments.

Ball-in-box dampers

The "ball-in-box" impact dampers installed in the spires to supress galloping are conceptually simple. Each consists of a steel-coated, 1650lb (748kg) lead sphere free to roll in a steel box with internal vertical surfaces coated in synthetic rubber. When the spire vibrates, the free rolling ball collides with the inside of the box, which moves with the structure. Each collision transfers momentum between ball and structure and dissipates energy.

Unlike some passive energy dissipation devices, impact damper effectiveness is insensitive to the structure's natural frequency. Performance depends principally on three dimensionless parameters: the mass ratio between the damper ball and the structural mode being damped; the coefficient of restitution which describes the energy dissipation in each collision; and the gap ratio - the ratio of the amplitude of structure motion, at the location of the dampers, to the width of the clearance between the ball and enclosing box. This parameter has to be sized appropriately if the impact damper is to work efficiently. If the clearance is too wide, collisions between the ball and box are intermittent and the energy dissipation per cycle of structural sway motion is relatively low. If the gap is under-sized, multiple collisions may occur per cycle but the collision velocity, and consequently energy dissipation, is low. The optimum mode of impact damper is achieved by sizing the system so that, under design operating conditions, two collisions occur per cycle of structural oscillation and the ball and structure are approximately in anti-phase.

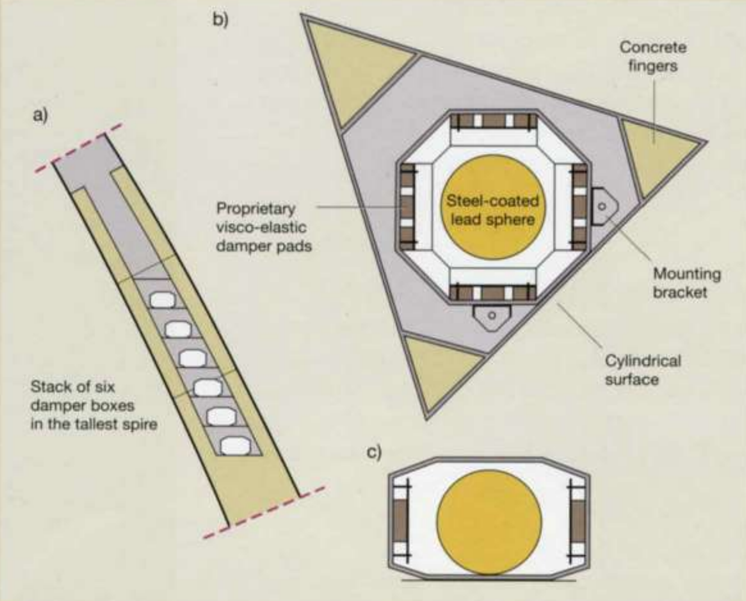
While the proportion of energy dissipation during each collision affects the damper performance, there is limited scope for tuning this as part of the design process. Suitable commercially available materials tend to have a fairly narrow range of energy dissipation characteristics. The principal concern in designing the impact pads is limiting their peak strain to a level below which the elasticity of the synthetic rubber does not degrade.

For cantilever structures such as the spires, damping devices operate more efficiently if they are higher up the structure. There was insufficient space at the spire tips, so the location selected - approximately two-thirds up - was a trade-off between individual damper box size and the total number of devices required for each spire. The required mass ratio could not be achieved using a 100% steel impactor ball, hence lead was favoured with a steel casing to prevent deformation during impact.

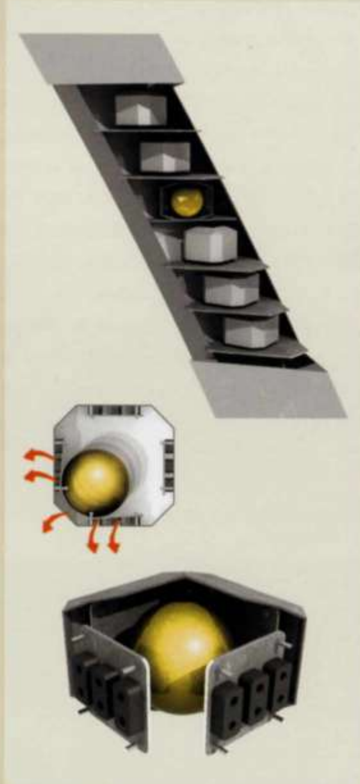
Theoretical predictions of impact damper performance can be derived for a few idealized cases, but to obtain a full understanding of the design sensitivities and ensure a robust system, a transient simulation of the structure and damper system was developed using rigid body dynamics. The simulation represented the galloping effect by applying a negative damping constant to the structure.
As the impact dampers have a non-linear characteristic, it was important to ensure structural stability at the peak displacements experienced by the spires. These were identified, in the absence of the damped galloping motions, as the peak buffeting displacements from wind tunnel tests.

Laboratory tests were performed on one damper, prior to installation, on a shake table at State University of New York at Buffalo. The purpose was to monitor the energy dissipated by the damper box as it underwent a prescribed programme of oscillating motions mimicking the sway of the spires at high wind speeds. The tests agreed very well with the performance characteristics predicted by simulation.

Additional tests were performed on the completed spires. Each was excited in the fundamental "nodding" mode by a hydraulic system connected to the tip, via a cable, and the decay of the spire motion observed to derive the damping. The site tests demonstrated that the damping levels required to prevent galloping were comfortably exceeded for all three spires. A significant observation during the test was that, in addition to damping the modes of vibration which are vulnerable to galloping, the damper impacts act to transfer energy to modes at higher frequencies. As these higher frequency motions are resistant to galloping excitation, their positive structural damping provides an additional way to dissipate in the spires, bringing further conservatism to the design.



17. (a) Section through transition zone; (b) Horizontal section through typical damper box installation within spire; (c) Vertical section through damper box.



18. Cut-away isometric of typical ball-in-box damper showing position of visco-elastic pads and motion of ball within the box.

19. Abseiler near the tip of one of the spires. Ropes are attached to engineered clips welded to the back face of each spire to accommodate such access for future testing and inspection.

20. A cherry-picker is used to access the first access clip. The abseil climber threads his rope through successive clips to prevent the ropes from sliding sideways as he ascends the curve of the spire.

Acoustic testing

Because the damping results from the impacts of steel balls against steel plates, it is noisy just as a clapper striking a church bell causes it to ring. Arup's damper test specifications included an acoustic test to assess the structure-borne noise and its impact on the memorial site.

During the shake table tests, noise and vibration from the ball impact were measured over the predicted range of structural movement. Accelerometers on the box recorded the structure-borne vibration and suspended microphones the structure-borne noise emission.

Predicting the noise level on site involved five post-processing steps from the base recordings:

(1) Filter the recording to remove the audible noise of the hydraulic shaker table.

(2) Apply a distance correction: the test noise was recorded 3ft (0.9m) from the box; the nearest distance of a ground-level visitor to one of the installed damper boxes is 120ft (36.6m).

(3) Overlap and stagger the recording multiple times to simulate the effect of multiple damper boxes.

(4) Adjust the recording to take account of the response of the spire structure. This involved predicting the plate frequency harmonics of the cladding and filtering the recording at these frequencies. Then a reverberant decay filter was applied to the recording to simulate the potential for the structure to "ring".

(5) Add the effect of site ambient noise level, which was dominated by traffic from the nearby interstate. This recording was then added to the auralization.

The client and architect were invited to Arup's New York Soundlab to listen to the predicted spire noise emission from the damper box ball impacts. They concluded that while the impacts were just audible, this was not disturbing above the site ambient level noise, and the design and installation of the damper boxes should proceed as planned.

21. Ball-in-box dampers were mechanically and acoustically tested at the State University of New York at Buffalo to verify their engineering design properties.

To be most effective, the boxes had to be as high up the spires as possible, but not so far as to unduly limit the size and travel of the lead balls. This required careful geometric studies of the shape of each box and the effectiveness of various stacked configurations within the tapering, curving spire segments (Figs 17, 18). The chamfered corners of the hexagonal boxes enabled them to be made as small as possible without impeding the travel of the internal ball, increasing the height up the spires where they could be placed for maximum effectiveness. These considerations resulted in the optimized sets of six dampers for the tall spire, four for the medium spire, and three for the short spire.

Third, the damping system had to be durable and low maintenance, which precluded the use of electro-mechanical devices or active-controlled systems in lieu of a more robust passive damping system. Furthermore, the dampers had to be easily inspected throughout the structure's lifetime, so resealable viewholes positioned through the spire skin were aligned with similar viewholes through the boxes. These enable small-diameter, hand-held orthoscopic cameras to be inserted through the spire and into each damper box for regular inspection and maintenance of the dampers.

Conclusion

The simple elegance of the Air Force Memorial belies the complex engineering mechanics that describe its behaviour and response to the environment. The intended aesthetic of the monument was preserved through the combination of advanced structural analysis applied to an innovative solution of custom-designed passive impact dampers. In so doing, the architect's vision of a soaring memorial to the United States Air Force was achieved.

22.

Leo Argiris is a Principal of Arup in the New York office. He was Project Director for the Air Force Memorial.

Andrew Jackson is a structural engineer in Arup's New York office, and was a key member of the structural design team.

Patrick McCafferty is an Associate of Arup in the Boston office, and was Project Manager for the Air Force Memorial.

Daniel Powell is an Associate of Arup in the Advanced Technology & Research Group in London, and aided the development of the "ball-in-box" dampers solution.

Credits

Client: United States Air Force Memorial Foundation **Architect:** Pei Cobb Freed & Partners **SMEP, fire protection, security, acoustics, and advanced technology engineering services:** Arup – William Algaard, Andrew Allsop, Leo Argiris, Simon Cardwell, David Farnsworth, Swan Foo, Marc-Henri Gateau, Gregory Giammalvo, Katherine Gubbins, Robert Hoffman, Andrew Jackson, Chad McArthur, Patrick McCafferty, Elizabeth Perez, Daniel Powell, Ronald Ronacher, Yet Sang, Valeriy Sokolov, Joe Solway, Aniju Varughese, Neill Woodger, Peter Young, Chelsea Zdawczyk **General contractor:** Centex Construction Co **Erector:** Cianbro **Fabricator:** Mariani Metals, Inc **Wind tunnel laboratory:** Rowan Williams Davies & Irwin Inc (RWDI) **Dynamic testing agency:** Motioneering, Inc **Dynamic testing laboratory:** The State University of New York at Buffalo **Landscape architect:** Olin Partnership **Lighting consultant:** Office for Visual Interaction (OVI) Inc **Civil engineer:** VIKA, Inc **Stainless steel consultant:** TMR Stainless **Inspection and materials testing agencies:** Terraprobe Ltd; ECS Mid-Atlantic, LLC **Illustrations:** 1, 3, 4, 7, 9, 12, 13, 16, 19, 22 Patrick McCafferty; 2, 5, 17 Nigel Whale; 6, 8, 15, 18 Arup; 10, 11, 14, 21 Andrew Jackson; 20 Rehan Siddiqui.

1. Sandridge Bridge with completed Traveller sculptures looking west over the Yarra River.

"The Travellers"

John Bahoric Peter Bowtell Paul Nicholas

Designed by the artist Nadim Karam, giant stainless steel sculptures in motion across the refurbished Sandridge rail bridge in Melbourne symbolically represent and celebrate stages in Australia's history.

Sandridge Bridge and its redevelopment

Sandridge Bridge has spanned the Yarra River in central Melbourne since 1888. An early Australian example of a steel plate girder rail bridge, it was actually the third rail bridge to be built at this location, and was also the first in the country to carry four tracks. After almost a century of use, passenger rail services over the bridge stopped in 1987 (to be replaced by alternative light rail services), the adjacent brick viaduct and line were demolished, and the five-span, 178.4m bridge itself boarded off from the public. Unusually for a rail bridge, the arches, pylons, and pediments above are intricately ornamented, and the main girders and pylons are now included as item number H0994 on the Victorian Heritage Register[1].

Facts and figures

- average weight of each sculpture: 2307kg
- heaviest sculpture: 7701kg
- total number of steel elements: 4455
- total length of steel: 3.77km

Gayip: The aboriginal period

"Since remote times Gayip has been standing on a rock. Recently Gayip has been observing travellers passing by. At night Gayip rises into the skies and spirals over the territory to ensure the wellbeing of all. Gayip has seen darkened times, thick with mistrust, and others clear and warm. Gayip is a guide to the things that have always been there."

length of steel: 223.5m
mass: 7701kg
surface area: 121.6m^2
steel elements: 198

First Settler: The convict period 1788-1868

"He came ashore with a flag and a shovel. After he planted the flag its colours began to fade in the sun. But it gave him shade and indicated wind direction, while he continued to work the land with his shovel."

length of steel: 328.7m
mass: 1383kg
surface area: 62.53m^2
steel elements : 349

The refurbishment and enhancement of the bridge and its environs as an integrated precinct were recognized as important and necessary, and in 2001 the Victoria State Government formally announced the precinct's development as a key project for the central business district. Arup was commissioned as civil, structural, mechanical, and electrical engineer for the entire project - including the design of a new deck - as well as for civil and structural works to renew the adjacent Queensbridge Square and Freshwater Place.

The artistic concept

Many Melbourne immigrants crossed Sandridge Bridge soon after disembarking at Port Melbourne, and this significance of the bridge in Australia's history led to the idea that the refurbished structure should house a commissioned artwork celebrating that history. In 2001 the Lebanese artist Nadim Karam of Atelier Hapsitus[2] submitted his sketched concept of "The Travellers", huge metal sculptures of symbolic figures moving across the bridge.

The State Government provided a $3M grant to the City of Melbourne for the project. It was to be completed before the 2006 Commonwealth Games, which gave a total project period of only 10 months. Nonetheless, within this time, and on budget, Karam's vision was realized and brought to life by the City's design and project management team and Arup, working closely with the artist, the City, and the fabricators. It is a synthesis of art and engineering - structure and sculpture becoming one in a tradition that includes such works as Antony Gormley's "Angel of the North"[3].

There are 10 Travellers, around 7.5m tall and 5-10m wide, each representing a period of indigenous or immigrant history. Nine "travel" on the bridge itself, whilst Gayip, the aboriginal figure, is symbolically fixed in Queensbridge Square on Southbank. The movement system is controlled by

2. The "Walking Sun": "... a festive wheel of prosperity, bringing together different stories and elements as it turns..."

Melbourne Beauty:
The gold rushes 1850-1890

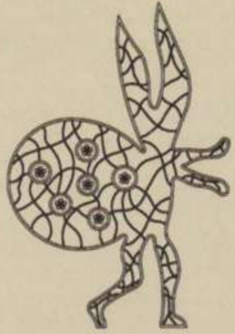
"She was such a rare beauty that the mention of her name was enough to cause a stampede. She was usually seen near the Yarra River, wearing a golden glow. No-one ever got close enough to determine whether she was real or just a mirage."

length of steel: 234.5m
mass: 1092kg
surface area: 46.99m²
steel elements : 310

Walker and his Tuckerbag:
Assisted migration 1830-1830

"He scoured the city and country in search of work. Over time he collected anecdotes from the places he visited, and putting them in his bag, wandered elsewhere to trade and collect more."

length of steel: 293.5m
mass: 1224kg
surface area: 55.05m²
steel elements : 350



Shelter: Displaced persons
1947-1953

"The shelter was a haphazard assembly of bits and pieces of old homes, dreams and memories that arrived on boat from different far away places. Pieced together with clay from the land, they multiplied to create cities.

length of steel: 345.1m
mass: 1463kg
surface area: 65.96m²
steel elements : 524

3. Sandridge Bridge from Freshwater Place on Southbank, showing the deck walkway for pedestrians and the adjacent former rail bridge section with its deck removed to expose the steel skeleton structure beneath. This view clearly reveals the bridge's marked skew across the river.

a software package operating from a computer in the City offices. The Travellers can be programmed for any configuration of movement, individually or as a group. Usually they are "parked" overnight at the southern end of the bridge, and when activated move in procession to specific locations on it and then return, three times a day. The movement starts with each figure rotating 30° to become parallel with the bridge, and then proceeding at 1.5km/hr on a bogie to its own location. Later this motion is reversed, so that the figures return to rest at the south end.

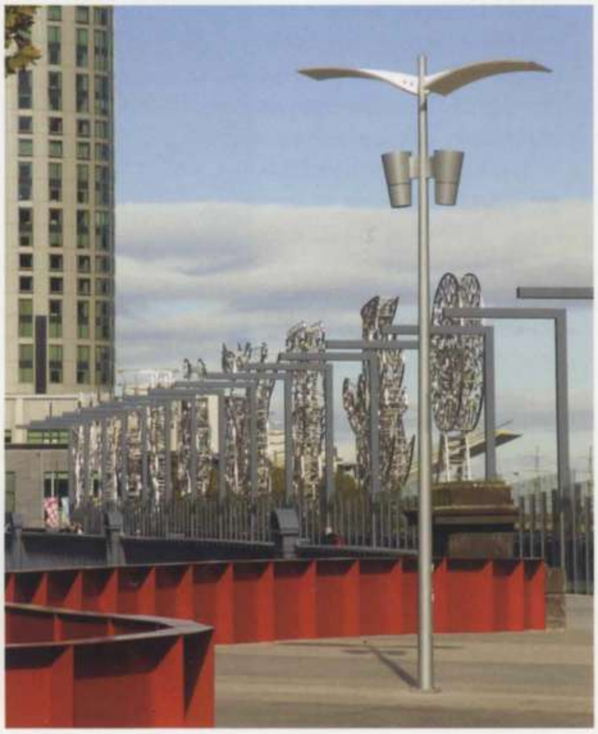
The design

The first step was to develop the artist's concept: turn drawings on paper of 10 large metal sculptures into a three-dimensional reality. As pieces of art they were beautiful but to bring Karam's complex designs to life was a challenge to the team's technical abilities, particularly as all but one sculpture would be in motion.

316 L stainless steel was chosen as the primary material. This gave the artist his desired surface finish and was appropriately corrosion-resistant, given the proximity of the Yarra River. The overall result gives each piece a sense of transparency when viewed face on, but a complex solidity from other angles.

Central to the design development process was the management of a single electronic file for each figure that was circulated in turn to the client, architect, and Arup, to be worked on/developed at each interface. The artist supplied the initial 3-D model files, and passed these to the client for onward distribution to the Arup design team. Arup firstly rationalized the proposed geometry, and then analyzed for structural adequacy. Changes were proposed as necessary to ensure the models were both buildable and structurally adequate, and these were fed back to the

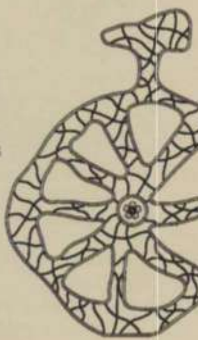
4. The Travellers from Northbank.



Urban Wheel: European migration 1947-1983

"The wheel lives in the grid. With the ability to move both horizontally and vertically, he used to scale two-storey buildings. Now he freewheels up and down the sides of skyscrapers."

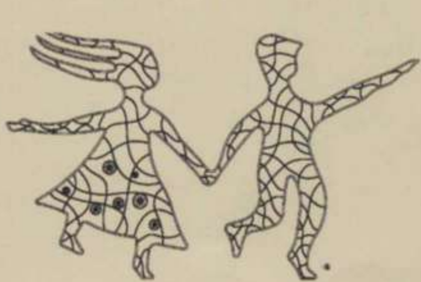
length of steel: 383.0m
mass: 1858kg
surface area: 78.08m²
steel elements: 447



Running Couple: Refugees 1958-2005

"They came from the same village far away, but never met in the haste of departure, not even on the boat. Since their encounter on the banks of the Yarra River, they now run together chasing the wind and the sun."

length of steel: 574.7m
mass: 2609kg
surface area: 111.9m²
steel elements: 655



Technoman: Students and professionals 1975-2005

"Made of electromagnetic pulses, he changes his appearance at will, but is usually recognizable from his cubist angles. He inhabits cities, speaks all program languages, and travels through data streams."

length of steel: 658.0m
mass: 2499kg
surface area: 113.3m²
steel elements: 650

client and ultimately the artist. Convergence to a solution typically required two or three iterations of this process, and the City played an important role as reviewer and in facilitating the speedy flow of information to and from the artist.

Each Traveller comprises hundreds of connecting pieces, formed from "families" of members that make up two similar planar surfaces connected by a series of diagonal curves. Each planar member and its identical "twin" in the second plane (they average 750mm apart), are joined together by a diagonal member whose curvature in turn is defined by the two planar members. The perimeter members on each face are 80mm x 80mm x 3m, internal planar members are 40mm x 40mm x 3m, diagonals are typically 31.8mm x 3.2m and orthogonal out-of-plane members are 48mm x 3.2m.

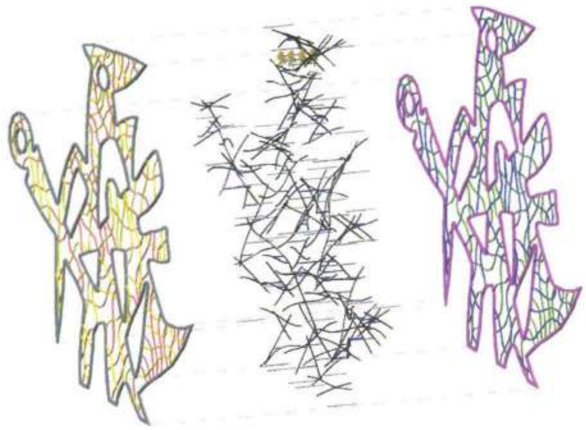
From geometry and translation to fabrication

3-D modelling and scripting were crucial to solving the geometric and communicative challenges posed by The Travellers, and a significant success factor was the fluency of both designers and fabricators in 3-D software. The initial files were supplied in Rhino, which interfaced with the other software packages used by the team - GSA, AutoCAD, and Excel. RhinoScript was used extensively, along with Visual Basic, to aid the translation of information between design, analysis, and fabrication.

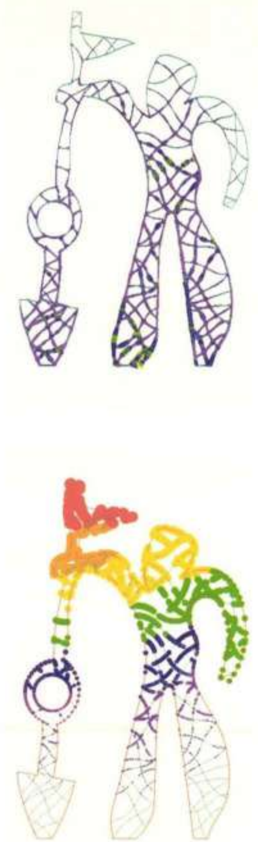
The complexity of the geometry, number of sculptures, and quantity of members required the CAD process be as automated as possible, and that design information for fabrication as well as analysis came from the single model. Additionally, the short timescale required a way to be developed to document the sculptures without drawings.

To achieve this, the Arup team began by working closely with the steel fabricator to understand the requirements of the fabrication process and the geometric constraints that needed to be taken into

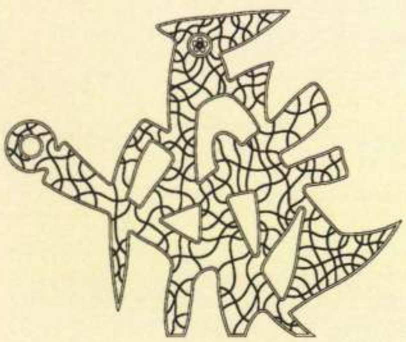
5. Detail of the "First Settler".



6. Exploded isometric model of "Technoman", showing the relationship between planar faces and diagonal members joining the two planes.



7 Developing the "First Settler".



Butterfly Girl: Asian and Middle East migration 1975-2005

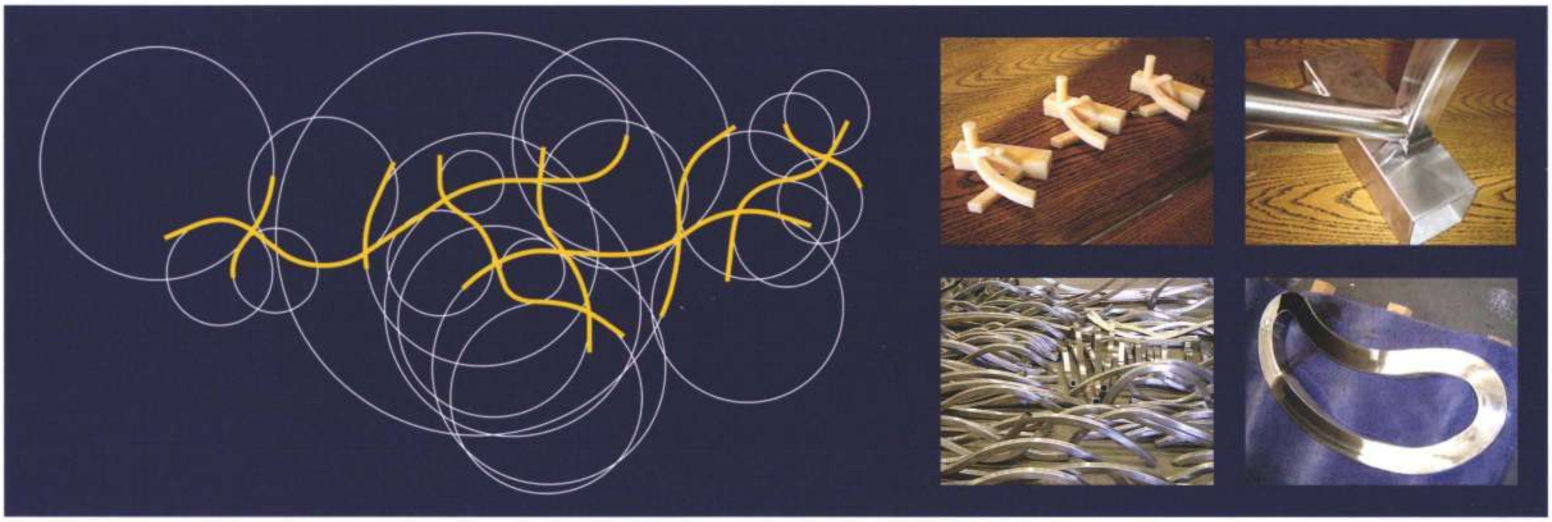
"She collects butterflies, but never keeps them for longer than a day. She brought her favourites with her, coloured with strange and beautiful patterns, and released them into the Bush."

length of steel: 356.6m
mass: 1531kg
surface area: 68.58m^2
steel elements: 494

Walking Sun: Australian multiculturalism

"The walking sun is a festive wheel of prosperity, bringing together different stories and elements together as it turns."

length of steel: 368.2m
mass: 1715kg
surface area: 71.56m^2
steel elements: 468



8. Parametric curve modelling, wax prototyping of connections, and resultant fabricated steel members after the linear induction bending manufacturing process.

9. Gayip atop his rock on Southbank.

10. The public walkway on Sandridge Bridge.

account. The process of developing a modelling and representation strategy that best fit fabrication and analytic requirements was supported by wax prototyping different options. Models were created early on to aid understanding of the relationship between incoming members at connection nodes. These were used by the artist and fabricator for comment/review, enabling decisions to be made that both met the artist's creative intent and were buildable. The knowledge gained about geometry, representation and documentation was fed and encoded into the overall design process.

The artist's models used spline geometry, which could immediately provide rough schedules and costings, but needed to be approximated with a standard series of arcs and straights for fabrication. To automate the rationalization process, a script was written within Rhino to find the inflexion points along each spline, split the spline at these points, and then match each fragment with the closest arc from a catalogue of 47 different radii. Arcs were separated with a line tangential to each: by inserting a straight line of a minimum length, each member could be rolled as a continuous piece, greatly minimizing welding and polishing time in the shop.

A second script generated each diagonal member. Geometrically, each sculpture is defined by its two planes and the diagonal members that move between them, and any diagonal member could be generated directly from the corresponding members on the top and bottom planes by determining the diagonal plane that lay between them and projecting onto it. This process approximated the original spline geometry to a high degree in nearly all cases, and automation greatly decreased the time needed to model each sculpture.

Complicating the task was the need to make the geometry as GSA-friendly as possible, and the Rhino model was suitably prepared prior to export. All arcs were prefaceted to control their GSA approximation, and the collection of curves was intersected against itself and then split at the resultant points to ensure nodal connections both within members and between intersecting members. The model was exported as a DXF file; later design iterations and refinement generally involved tweaking, deleting, and inserting individual members, not re-exporting the entire model.

Documentation for each sculpture consisted of the 3-D model (a centreline model) and an eight-page spreadsheet, one page per section type. A Visual Basic routine extracted length and radius information from each member to the spreadsheet, simultaneously tagging each member and element numerically within the 3-D model. The spreadsheets could be fed directly into the bending machinery, the time to extract each one being less than half-an-hour per sculpture. One interesting effect of documenting non-visually - necessary because of the sheer quantity of information - was that it became difficult to quickly locate information visually within the 3-D model. A Visual Basic routine had to be written to select and zoom to any given member within Rhino from the spreadsheet, where it was easier to locate - showing that an automated and streamlined process to communicate spatial information needs to include mechanisms for making sense of it quickly when the fabricator calls!

As well as the early wax models, 1:1 steel prototypes were created to develop the geometries of the intersection points, the number of curves in each figure being limited to the maximum of 47 different radii; the smallest curve was 120mm and the largest 2m. This simplified fabrication and ensured that all sculptures were kept within the assessed structural limitations. The steel models also enabled confirmation of the finish quality to welds and polishing to the steelwork, as well as to gauge the visual appearance of the adopted section sizes to ensure they were aesthetically appropriate. All stainless steel to stainless steel connections were full strength butt welds using TIG welding.

The sculptures had to be strong enough to withstand directional wind, their own self-weight, and "unauthorized" people loading. Each Traveller essentially behaves as a freestanding column, and was assessed in terms of its buckling capacity at the ultimate limit state, fatigue, deflection under serviceability, wind, and natural frequency (this was to ensure that the entire figure did not become excited under wind loading and that individual elements did not "flutter").

Bogies

How would The Travellers move along the length of the Sandridge Bridge? The design team's solution encompassed the development of both a bogie system and a rail support system. The concepts were initially developed so that the fabricator, Danfab, could build full-scale prototypes of the systems that needed to comply with the very tight spatial constraints of the Sandridge Bridge's dimensions.

A prototype bogie was duly built and tested in the factory, initially as a working motor and later with a completed figure installed, simulating how the designed solution would work on the bridge. The bogie system was refined from these tests to produce a smooth gliding motor system for the nine figures in movement. Each sculpture is fixed to a welded platform which in turn is bolted to a 323mm diameter spigot member. This is supported by roller taper bearings at the base (to support vertical loads) and roller thrust bearings at the top (to support horizontal loads).

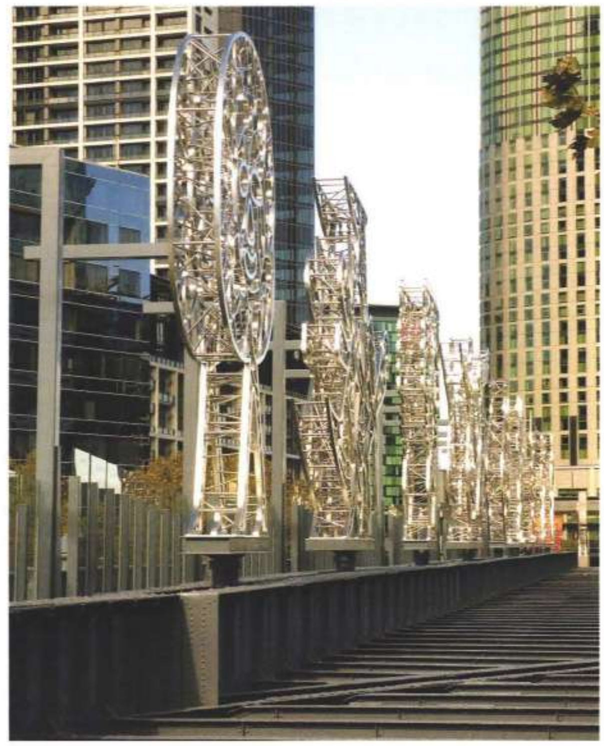
Conclusion

Work commenced in April 2005, and the project was completed on time and on budget. The Travellers first met their public at the refurbished Sandridge Bridge's official opening on 12 March 2006.

Karim's work drew enormous interest both then and during the ensuing period of the Commonwealth Games, when thousands of Melbournians and visitors crossed the bridge and experienced the scale, movement, and inclusive message of The Travellers. The Victorian Government's expectations for an iconic, engaging and modern work of art, to help highlight the aesthetics of the refurbished industrial-age bridge have clearly been met, as the sculptures continue to attract, intrigue and, it is hoped, inspire passers-by during their daily journeys across the bridge.

11. Prototype load-testing of Traveller bogies at the Danfab workshop. (Garry Ormsten, project architect, in background).

12. The Travellers on their bogies.



Awards

- Australian Institute of Project Management Awards 2006: Community Service and/or development category: The Travellers
- Australian Property Institute, Excellence in Property Awards 2006 - Heritage Property category: Sandridge Bridge refurbishment
- Planning Institute Australia (Victorian Division) awards 2006 - Urban Design Certificate of Commendation: Sandridge Precinct Redevelopment
- Planning Institute Australia, Australia Awards for Urban Design 2006 - Public Domain Award: Sandridge Bridge Precinct

John Bahoric is an Associate of Arup in the Buildings (Australia) group in the Melbourne office. He was the senior structural engineer for The Travellers.

Peter Bowtell is a Principal of Arup in the Buildings (Australia) group in the Melbourne office. He was project director for Arup of the Sandridge Bridge refurbishment and The Travellers.

Paul Nicholas is an architect from the Royal Melbourne Institute of Technology working in Arup as part of his PhD programme. He was responsible for the scripting, 3-D modelling, and rapid prototyping for The Travellers.

Credits

Client and architect: The City of Melbourne **Artist:** Nadim Karam **Civil, SME, and environmental engineer:** Arup – John Bahoric, Peter Bowtell, Peter Duggan, Stephen Dunstone, Marissa Kretsch, John Legge-Wilkinson, Sean Maher, Brendan McNamee, Derek Powell, Nathan Smith, Barry Steinmeyer, Paul Trantallis, Debbie West **Bogie fabricator:** Danfab Metal Fabrication **Steelwork fabricator:** Silverstone Engineering **Illustrations:** 1-5, 9, 10, 12: Martin Saunders; 6-8, 11: Arup.

References

(1) http://www.heritage.vic.gov.au/

(2) http://www.hapsitus.com/

(3) BROWN, M *et al*. The Angel of the North. *The Arup Journal*, *33*(2), pp15-17, 2/1998.

Climate as a driver of change
Part 1: Global warming - the evidence and the causes

1. Deforestation in the Amazon, from cattle ranching, soyabean cultivation, and small-scale subsistence agriculture, is contributing to global warming.

Jake Hacker

Climate change is our greatest challenge, a problem so immense that it can radically alter the natural world and human societies, and make the world of 2100 unrecognizable from that of today. Despite the claims of sceptics, a scientifically robust, evidence-based analysis indicates that we should take this prognosis very seriously.

Introduction

This is the first of two articles about anthropogenic climate change, the idea that major climate change can be produced by human actions. These articles describe the context of climate change as a driver of change by examining the scientific evidence for its reality and its likely consequences. They continue the "drivers of change" theme already explored in *The Arup Journal* for the two key and related issues of energy[1] and water[2].

The global warming hypothesis

The concept of anthropogenic climate change is succinctly expressed by the two-part global warming hypothesis (GWH):

(1) The Earth's climate is getting warmer due to the build-up of additional greenhouse gases (GHGs) in the atmosphere from human activities, principally carbon dioxide (CO_2) released by burning fossil fuels and deforestation.

(2) If humans continue with their present path of economic (and social and technological) development based on fossil fuel energy, anthropogenic climate change will continue and accelerate, with possibly very damaging consequences for both the human and natural world.

If the GWH is correct, what will the world look like at the end of the century because of climate change? We can distinguish two scenarios (see Box I) at either end of a spectrum of possibilities.

I. The GWH scenarios

Scenario A: the carbon-constrained world

We get our energy primarily from low and zero-carbon sources. Our lifestyles are highly efficient in energy terms, with all the precious zero-carbon energy, and every ounce of damaging CO_2 from carbon-based fuels, accounted for. The ways we operate our homes, manage our travel plans, design our cities, and grow and source our food are very different from today.

This has been a world of increasingly erratic and variable weather, with sea levels rising steadily. Our relationship with climate and the nature of climate risk are necessarily highly optimized. Every drop of water is accounted for, and buildings act as passive climatic modifiers, not relying on mechanical heating and cooling. There are large-scale programmes to protect natural systems undergoing environmental stress as their ecological niches shift with the shifting climatic zones.

Scenario B: the climate-constrained world

We have continued to fuel rapid economic growth through the use of fossil fuels, and the ensuing climate change has led to widespread environmental degradation. 60% of species existing at the turn of the millennium are lost. In Amazonia the once-widespread rainforests have died out due to persistent drought. Half the Greenland and Western Antarctic ice sheets have melted, raising ocean levels by 7m.

Many of the world's coastal cities are abandoned; the acidic CO_2-rich oceans are anoxic and the last wild fish stocks gone. The world is polarized into two factions: one trying (somewhat helplessly) to reduce the level of GHGs in the atmosphere and halt or reverse the impacts of global warming, the other simply retreating to higher latitudes and building new cities on higher ground to maintain the old way of life. The two factions are fighting over the world's dwindling resources of food and fresh water.

In both scenarios...

... the world is very different from today. In the former, the era of readily-available cheap energy has ended through our own conscious choice. In the latter, the period of relatively stable and benign climate humans have experienced during civilization's development has ended.

The two parts of the GWH are now widely believed to be proven beyond reasonable doubt, so we would appear to have a choice about how to influence our future - proactive action leading towards Scenario A, or reactive action towards Scenario B. To most, Scenario B does not seem a viable option, making some level of proactive action a necessity, but how strongly the GWH is held to be proved will determine the vigour with which that is pursued.

To understand the extent to which climate change will be a driver for change in the future, it is necessary to assess the robustness of the evidence for the GWH.

These two articles aim to present this evidence. Here we consider Part 1 of the GWH, focusing on contemporary climate change and why it is happening. The second article will examine the evidence for Part 2, the implications for the future.

Development of the GWH

Contrary to general perception, the GWH is not a new concept. It was first put forward in an earlier form by the Swedish scientist Svante Arrhenius in around 1904[3,4]. Arrhenius was fascinated, like many 19th century scientists, by the problem of explaining the Ice Ages – the great northern hemisphere glaciations for which evidence had been emerging. In 1896 he published a paper proposing that past climate changes may have been produced by alterations in atmospheric CO_2 levels. Through painstaking hand calculations, and building on earlier work by Fourier, Tyndall, and other 19th century scientific pioneers, he showed that a doubling of atmospheric CO_2 could have produced a change in global average temperature of around 5°C, what we now know to be the difference between our present climate and that of an Ice Age. This was a major intellectual step, as there was scant evidence then for a link between changes in CO_2 in the atmosphere and the Ice Ages.

Arrhenius' most prescient step came, however, a few years later. He argued that burning coal to power the factories and engines of the industrial age would one day lead to a further increase in atmospheric CO_2 and that a doubling would produce global warming of around 5-6°C, similar to that at the end of the last Ice Age. He wasn't unduly disturbed by this prospect, thinking the change would take 3000 years based on the then rate of coal use. Indeed, it would benefit mankind, the warming world being a more amenable place for humans to live and prosper.

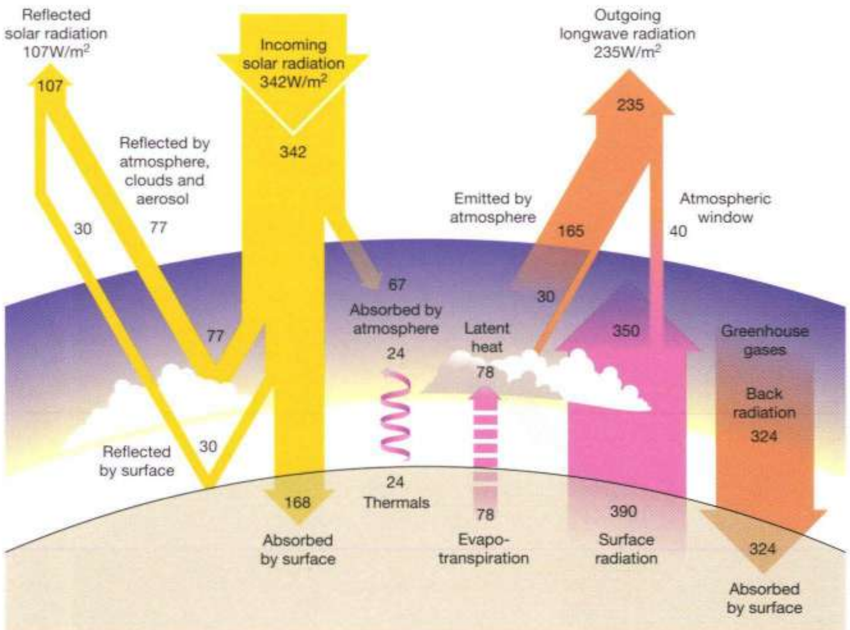
The GWH was recast in its modern, more ominous form in the late 1950s, by scientists who were beginning to be concerned about the accelerating increase in fossil fuel use. Even as these trends developed, they thought the CO_2 released into the atmosphere would simply be absorbed into the Earth's natural stores of carbon, the world's forests and oceans. But in 1957, two prominent US climate scientists, Roger Revelle and Hans Seuss, published a paper[5] showing that CO_2 released from burning fossil fuels was building up in the atmosphere and, further, that the oceans had much less capacity to absorb it than previously thought. They commented that "the accumulation of CO_2 in the atmosphere may become significant if industrial fuel combustion continues to rise exponentially... human beings are now carrying out a large-scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future"[3, 5].

This statement was the first expression of the current form of the GWH and the start of its modern investigation. The atmosphere was monitored through the 1960s and 1970s to see if atmospheric CO_2 was continuing to rise – which it did, steadily year on year – and computer models were developed to indicate what the consequences would be. This first phase culminated in the 1979 Geneva World Climate Conference and the publication of a US Academy of Sciences report[6] in the same year that concluded: "It is highly credible that a doubling of CO_2 in the atmosphere will bring 1.5-4.5°C global warming."

This range of temperature change, slightly lower than but consistent with Arrhenius' earlier predictions, has remained essentially unchanged to the present day as the most likely range of outcomes for a doubling of atmospheric CO_2[7].

How, then, has climate science developed over the last 25 years? The problem in 1979 was that two major areas of uncertainty remained. The first was that the predicted climate changes were only just starting to occur, so there was no observational confirmation of the GWH. The second was that while the effects of changes in CO_2 were understood with some confidence, other factors can also influence climate; it had to be ruled out that no other process would cancel out the effect of the rising GHG levels. Before discussing the GWH further, therefore, the factors affecting the Earth's climate should be examined.

Table 1. Analogy between factors affecting the Earth's climate and a room heated only by the Sun.	
Earth climate	**Room climate**
Sun	Sun
temperature of lower atmosphere/Earth surface	room air temperature
greenhouse effect	insulation
sea and land ice	reflective blind
clouds	curtains
ocean	thermal mass of building fabric



2. Schematic[8] of the Earth's radiation budget, showing estimates of heat flux from measurement. The units are W/m².

Factors that determine climate

Climate is the time-averaged properties of weather. The factors determining day-to-day weather are enormously complex and notoriously difficult to predict more than a few days ahead, but the factors affecting climate are more robust and simpler to understand. Of these, the most robust are those factors that determine the average temperature of the lower part of the atmosphere – the average surface climate.

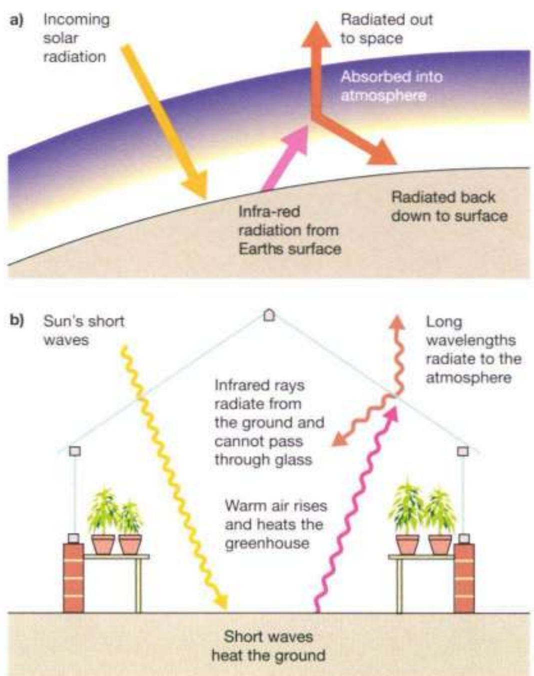
The temperature of a planet's surface is not determined solely by distance from the Sun. Two other fundamental factors are the amount of sunlight prevented from reaching the surface, and the rate of heat loss from the surface to space. These are analogous to two key factors governing the temperature inside a building – shading and insulation. In fact, a broader analogy can be drawn between the factors determining the Earth's temperature and those determining the temperature inside a passive (solar-heated) building, such as a greenhouse (see Table 1).

Effectively the atmosphere is like a room, a "box" where heat enters and leaves by various processes (Fig 2) - mainly thermal radiation from the Sun (sunlight) and thermal radiation emitted from the top of the atmosphere into space (infrared). The temperature in the box is stable - in thermal equilibrium - when all the heat flows are equal: energy in = energy out. Any imbalance will lead to a change in temperature until a new thermal equilibrium is reached.

The Earth's "shading" is the reflection of sunlight from the tops of clouds and from snow and ice.* Currently clouds reflect about 25%, and land and sea ice 5%, of the Sun's thermal radiation back into space without it having a chance to warm the Earth's surface or atmosphere.

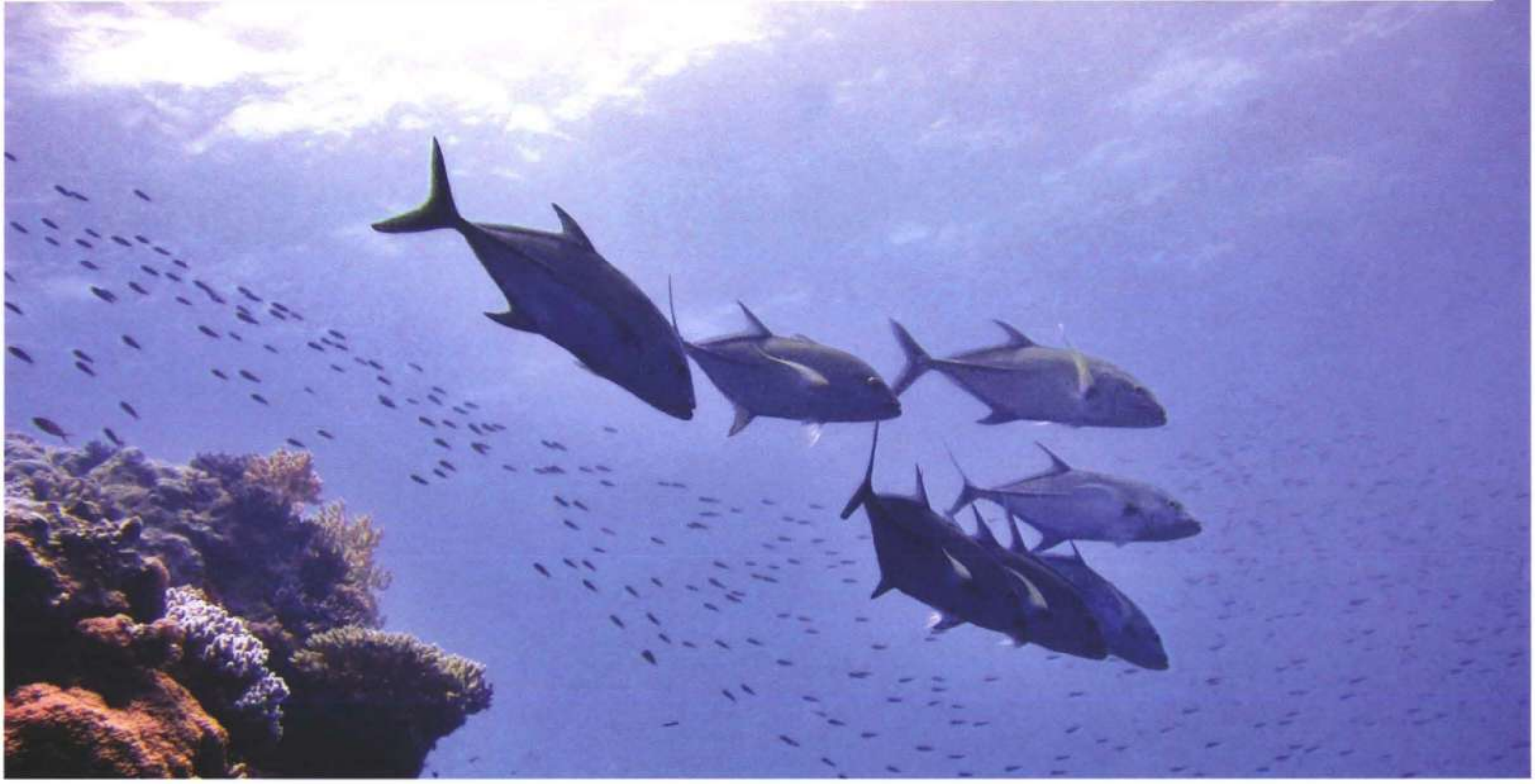
Another important shading factor is the effect of aerosols – atmospheric particulate pollutants. Aerosols have natural sources, mainly volcanoes throwing dust and ash into the upper atmosphere, but also anthropogenic sources, principally burning biomass and fossil fuels. Light-coloured aerosols reflect sunlight, so have a cooling effect, but dark-coloured aerosols (eg soot from coal and biomass burning) are warming. Aerosols also promote cloud formation, which generally has a cooling effect by increasing "shading". Aerosols persist in the atmosphere for one or two years at most following emission, so have a short-term effect.

The Earth's "insulation" is the "greenhouse effect" (Fig 3), so called because of the similarity between how glass and the atmosphere transmit thermal radiation. Both are largely transparent to sunlight, which lies in the shortwave (visible) part of the electromagnetic spectrum, but mostly opaque to infrared radiation emitted by the Earth's surface. In both a building and in the atmosphere, for thermal equilibrium to be established the amount of infrared radiated away from the "box" must equal the thermal radiation entering from the Sun.



3. The greenhouse effect: a) Earth b) greenhouse.

* Formally, the effect of snow and ice, and part of the effect of clouds, is "reflectance", but this can be thought of as "shading" for argument's sake.



4. The oceans form the climate system's "thermal mass".

Table 2. The main GHGs in the atmosphere today, with approximate contributions to the elevation of the Earth's surface temperature[9].	
Greenhouse gas	**Contribution to temperature change**
water	+21°C
CO_2	+7°C
O_3	+2°C
others (CH_4, N_2O, CFCs)	+3°C
Total	+33°C

The greenhouse effect means that for thermal equilibrium to be reached, the air in the room or the atmosphere must become warmer than would otherwise be the case, to force enough infrared radiation out through the thermal barrier provided by the glass or atmosphere. As John Tyndall explained in 1862: "As a dam built across a river causes a local deepening of the stream, so our atmosphere, thrown as a barrier across the terrestrial [infrared] rays, produces a local heightening of the temperature at the Earth's surface."[3]

In the atmosphere, absorption of infrared radiation is caused by the GHGs (Table 2). The most important is water (in vapour and liquid form in clouds), followed by the atmospheric trace gases CO_2, ozone (O_3), methane (CH_4), nitrous oxide (N_2O), and CFCs and their replacements. Together the GHGs raise the Earth's surface temperature by about 33°C; without them it would average around -18°C and the Earth would be largely covered in snow and ice[9]. The greenhouse effect is therefore crucially important to life; indeed, there is a symbiotic relationship, life having had a crucial role in establishing the atmosphere's chemical composition and hence the global climate.

While water vapour is the most important GHG, its role in climate change differs from the others. The amount the atmosphere can carry is determined by its temperature (warm air can hold more moisture than cool air), and moisture content changes rapidly with temperature. Water vapour is thus a passive gas that cannot initiate climate change. In contrast, the processes determining concentrations of other GHGs are somewhat outside the climate system, and so can initiate and drive forward climate change. These gases also typically have long lifetimes in the atmosphere, so changes in their concentrations have long-lasting effects. Water vapour is therefore not normally considered a greenhouse gas in the same sense as the other GHGs, but it is a vital part of greenhouse effect-driven climate change because it constitutes a positive feedback. If air temperature increases through some other process, the amount of water vapour in the air will grow and the associated increase in the greenhouse effect will amplify the warming trend, and vice versa.

The Earth's radiation balance (Fig 2) is the fundamental control on climate, but there are some other important factors. The first is the oceans. They form the climate system's "thermal mass", like a big stone wall. Their capacity to store heat far outweighs that of the atmosphere and their heat content changes on much longer timescales, from years to decades to millennia. How solar heating is divided between atmosphere and oceans is thus another important factor affecting climate. The oceans play a major role in short-term climate fluctuations (eg El Niño in the Pacific, and the North Atlantic oscillation in the Atlantic) and provide thermal inertia in the system that slows change if climate change is occurring.

The second important factor is that the Earth is not a box but a sphere, heated more strongly at the equator than at the poles. This creates vigorous circulations in the atmosphere and oceans that transmit heat poleward from the equator. The form of these circulations is governed by the rotation of the Earth and the shapes of the continents, producing the complex pattern of climate types found across the globe.

The greenhouse effect is indisputable. It is the fundamental concept in climate science, and doesn't affect just the Earth's climate but is important in most planetary atmospheres. Indeed it can be a lot larger than it is on Earth. On Venus, for example, it is so strong that it elevates the surface temperature by around 500°C[10]. The Earth's greenhouse effect could thus be much larger that it is today were the atmosphere's chemical composition to change. If the energy coming in, ie the Sun's intensity and "shading", stays the same but the greenhouse effect increases, the Earth will warm up. This brings us to the first part of the GWH.

Part 1 of the hypothesis:
The Earth's climate is getting warmer due to the build-up of additional GHGs in the atmosphere produced by human activities, principally burning fossil fuels and deforestation.

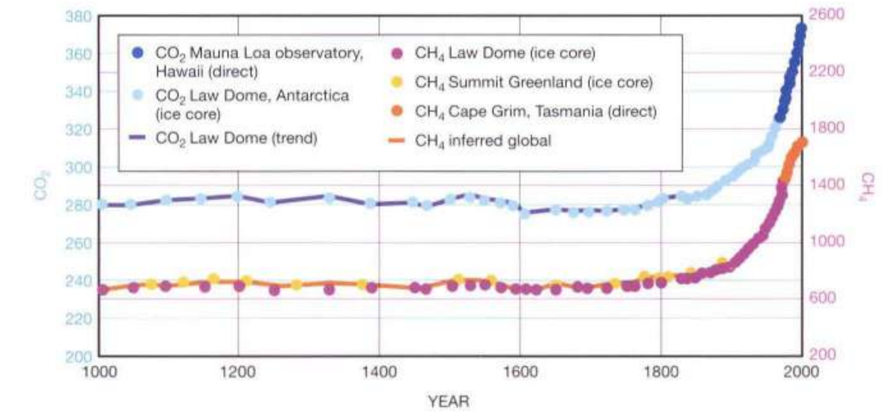
The (circumstantial) evidence for anthropogenic climate change

Two pieces of evidence are usually cited to support the concept of anthropogenic climate change. The first is that atmospheric GHG concentrations have been increasing since around 1750, the start of the European Industrial Revolution (Fig 5): CO_2 by around one-third and CH_4 more than doubling. Previously the concentrations of both gases had been fairly constant for several thousand years. It is reasonable to ascribe these changes to human activity, since the industrial period is when humans have been adding CO_2 to the atmosphere by burning fossil fuels and massively clearing forests, and releasing CH_4 and other GHGs from industrial and agricultural processes.

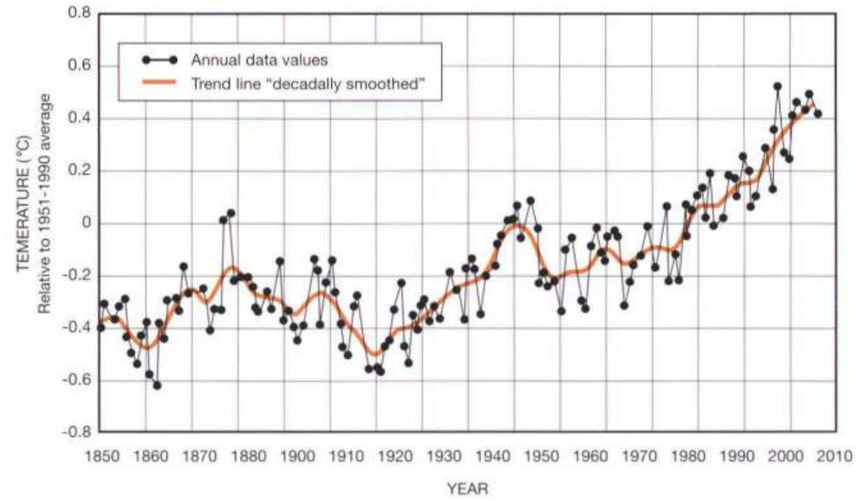
The second piece of evidence is that the average land and sea-surface air temperature* has increased over the same period, in accord with the expected impact of the increased greenhouse effect. The global coverage of thermometer measurements is good enough from about 1850 onwards to construct a global average near-surface air temperature (Fig 6). The change over the last 100 years is 0.74˚C ±0.18˚C[12]. The changes have not been uniform: they were larger over land than over the oceans, more in higher latitudes than lower, with the Arctic and parts of Antarctica warming at over twice the rate of the world as a whole. Since 1860, 19 of the 20 warmest years have occurred since 1981, and the five warmest since 1998[13].

These changes in near-surface temperature have also been accompanied by increases in the temperature of the lower atmosphere and the oceans, and several other changes associated with a warming world: dramatic loss of sea ice and retreat of nearly all the world's mountain glaciers; earlier springs and later winters; changes in the ranges of migratory birds and other animals; and rising sea levels[12].

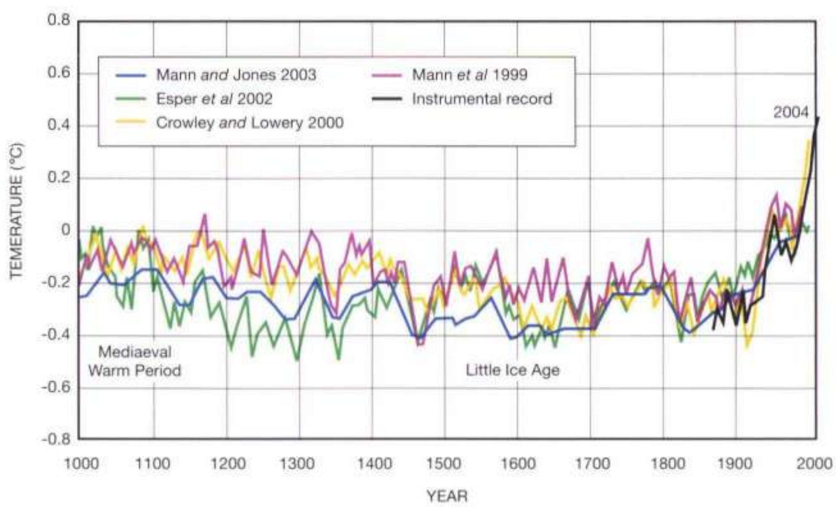
* In climate change studies, "surface air temperature" is the temperature 2m above the ground or sea surface. It should not be confused with the physical surface temperature, ie the surface of the ground or the surface water of the oceans. The surface air temperature data in Fig 6 were measured directly using thermometers at meteorological weather stations, on land, ships and ocean buoys.



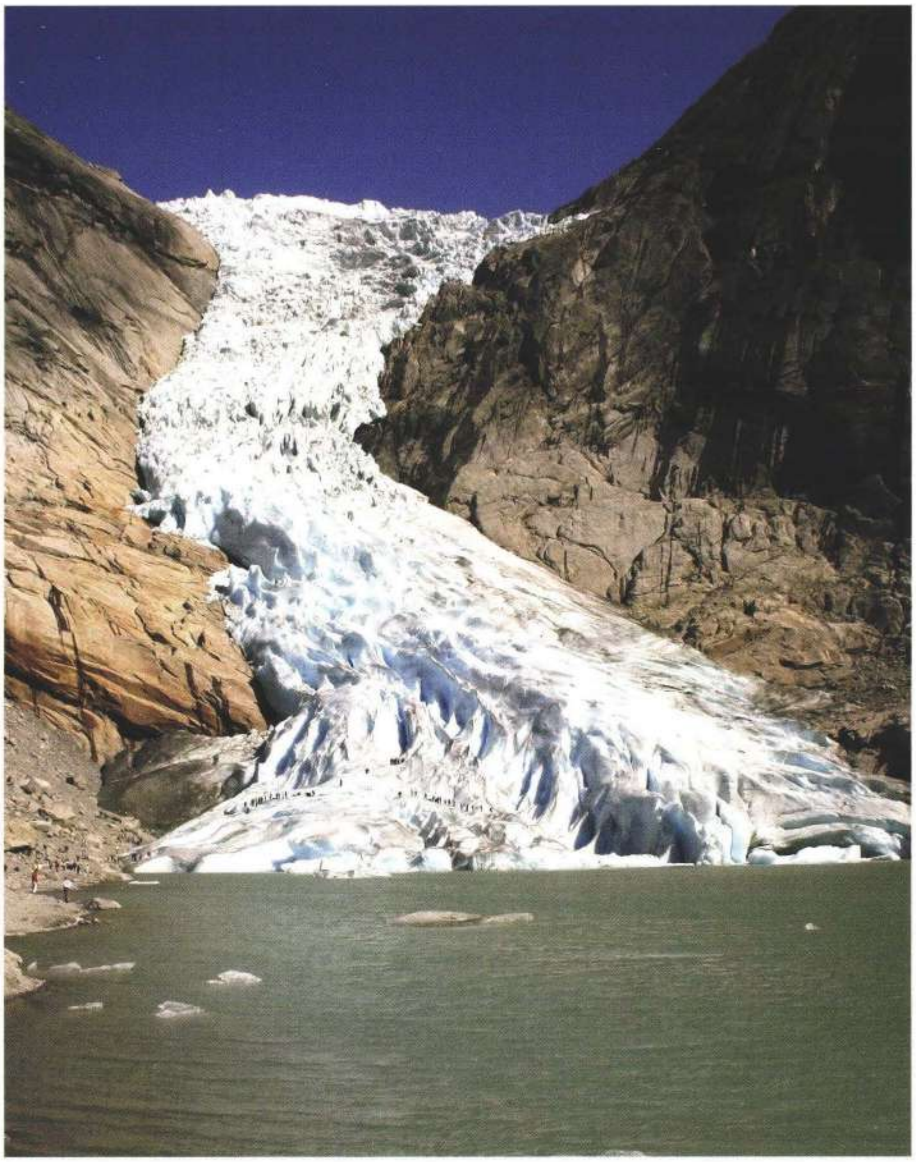
5. Variations in atmospheric CO_2 and CH_4 since the start of the Industrial Revolution. The data for the last few decades are from direct measurements, the remainder from analysis of Greenland and Antarctic ice cores. Because CO_2 and CH_4 are well-mixed and long-lived gases in the atmosphere, point measurements give a good indication of global average values[11].



6. Global average land and sea surface temperature from direct thermometer measurements since 1850.



7. Northern hemisphere temperatures inferred from climate proxies (tree rings, ocean corals, lake sediments and other available climate proxies and records) and direct thermometer measurements since 1860 (red curve)[11]. The graph's overall shape has been dubbed the "Hockey Stick".



8. Nearly all the world's mountain glaciers are in retreat.

There have also been changes in climate and weather patterns not directly linked to the changes in global average temperature but consistent with a warming world: more prolonged droughts; heavier rainfall and greater flooding; more intense heatwaves; and stronger hurricanes and typhoons.

Although the direct observational record over the last 150 years shows a clear warming trend, climate actually fluctuates naturally on timescales of decades and longer. Are these changes unusual in the context of the past? The Earth's climate has sometimes undergone huge variations, but over the last 10 000 years or so, since the end of the last Ice Age, it has been relatively stable and similar to the climate of the pre-industrial period. A key era is the last 1000 years, when both modern civilization and human historical memory of climate developed.

Although there are few direct thermometer measurements of temperatures over this period, we can infer what climate might have been like from so-called "climate proxies" – biological and physical artefacts that contain memories of conditions prevailing when they were formed. Examples are tree rings, ocean corals, pollens in lake sediments, and ice-cores.

From these, we can estimate average near-surface air temperatures. Spatial coverage of climate proxies is typically only good enough to do this in the northern hemisphere; coverage in the southern hemisphere is sparse.

While different reconstructions vary to some extent, all show two climate periods well documented in historical records: a relatively warm time around 1000AD, known as the "Mediaeval Warm Period", when the Vikings colonized Greenland and grapes are reputed to have been grown in northern England, and a relatively cold period around 1600AD - the "Little Ice Age" - when winters were very harsh in northern Europe and "Frost Fairs" were regularly held in London on the frozen River Thames (Fig 7). Much of the climate variability over this period can be attributed to variations in solar output and atmospheric aerosols from volcanic eruptions.

Despite differences between reconstructions (due to different and typically sparse data, and varying statistical methods of drawing inferences from them), all indicate that northern hemisphere temperatures between the Mediaeval Warm Period and the Little Ice Age varied by not more than around 0.6°C, a temperature change similar to that experienced during the 20th century. In this sense recent climate change is not unusual. But, crucially, it is unusual in two important respects. First, the recent change has happened relatively quickly. Secondly, it shows no sign of shifting to a downward (cooling) phase; already global temperatures are higher than they are likely to have been over at least the last 1300 years[12].

These two factors - increasing GHG concentrations and concurrently rising temperatures - are often cited as THE evidence for global warming. However, this evidence is really only circumstantial. More work needs to be done to establish a causal link between the two and an anthropogenic case for global warming.

Three questions

The following three questions are key to establishing the validity of the first part of the Global Warming Hypothesis:

(1) Have humans actually caused the increase in GHG concentrations, or is some other process responsible? It could be a coincidence that the changes began at the start of the Industrial Revolution.

(2) Is the increase in GHG concentrations sufficient to explain the rise in global temperatures?

(3) How large is the effect of natural variability within the climate system and could this provide an alternative explanation for the warming, or swamp out the effect of the increased GHGs?

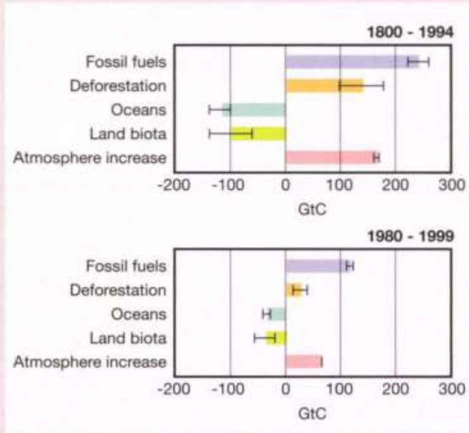
Much of the climate science work over the last 50 years has been focused on addressing these questions. How far have they been answered?

II. The carbon cycle

The level of atmospheric CO_2 is determined by the carbon cycle[10] (Fig 9). Carbon has four main stores - the atmosphere (CO_2 in the air); the land biosphere (living organic matter and organic debris held in soil); the oceans (organic matter, calcium carbonate and dissolved CO_2); and fossil fuel deposits - and four pathways through which carbon is continually transferred between these stores. Two are natural: absorption and release by the land biosphere (from photosynthesis and respiration) and release and absorption at the surface of the ocean (by photosynthesis and respiration of marine life, and chemical absorption and release into sea water); and two are entirely anthropogenic: deforestation and fossil fuel burning. (A fifth process, outgassing from the mantle by volcanic activity, was very important during the Earth's long past, but has been small in recent geological time.)

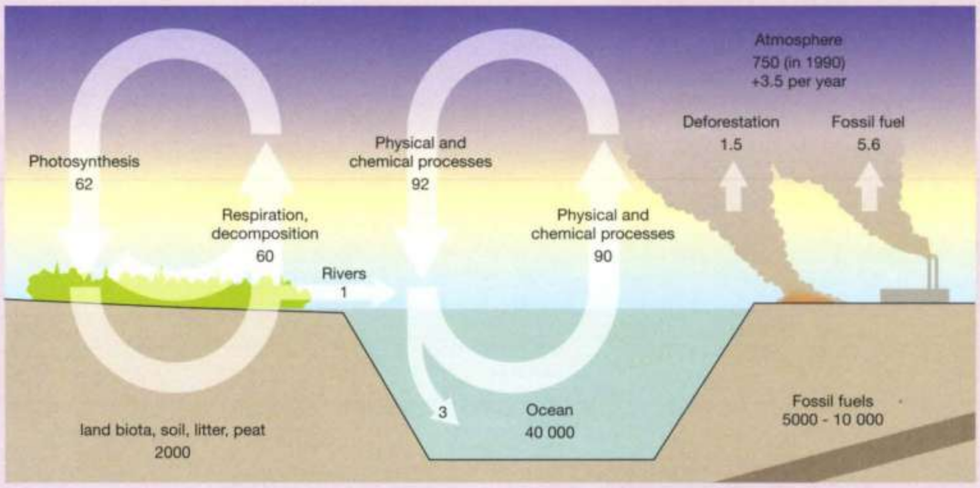
The carbon cycle resembles the Earth's radiation budget discussed earlier: the level of CO_2 is determined by the size of flows in and out, and reaches an equilibrium when they balance each other. Currently, humans add around 7GtC (gigatonnes of carbon* (1000M tonnes)) to the atmosphere each year through burning fossil fuels, and about 1.5GtC from deforestation. This is about 1% of the total atmospheric carbon and around 0.5% of the total natural flow of carbon through the carbon cycle each year. Early GWH sceptics argued that this anthropogenic perturbation was too small to make any possible difference and that any excess would simply be absorbed into the land biosphere and the ocean. It has now been established, due to improvements in chemical analysis techniques over the 1980s and 1990s, that both these natural carbon stores have been net absorbers of CO_2 over the industrial period[14,15] (Fig 10). However, rates of uptake respond slowly to changes in the atmospheric CO_2 concentration. Currently only around half the additional CO_2 being added to the atmosphere is absorbed in this way, the remainder staying in the atmosphere. Hence while small, the anthropogenic addition, like compound interest, builds up year on year.

It is sometimes stated that CO_2 has an atmospheric lifetime of 100 years. This is not true, strictly speaking, because CO_2 is an inert gas in the atmosphere.



10. Carbon transfers to and from the atmosphere, 1800-1994 and 1980-1999[14]. Horizontal bars indicate uncertainty estimates.

Its concentration is set by the relative size of the transfers of CO_2 to and from the atmosphere in the carbon cycle. If the size of one of these flows changes, then the carbon cycle eventually reaches a new equilibrium with a different level of atmospheric CO_2. It is this process that is thought to take around 100 years. Because the carbon cycle has already been perturbed, there is no reason to expect that, if anthropogenic emissions of CO_2 stopped today, atmospheric levels would return to where they were before the Industrial Revolution. In this sense, the effects of anthropogenic emissions are permanent, or at least very long lasting. Also of much concern is that while the oceans and the land biosphere currently act as sinks for anthropogenic CO_2, in the future they could become net sources of CO_2 to the atmosphere, due to changes in climate causing positive feedbacks on the carbon cycle, such as forest fires and out-gassing of dissolved CO_2 from a warming ocean. If this were to occur it would constitute a positive feedback for warming that could take climate beyond a point where change can any more be limited by reducing anthropogenic GHG emissions – "runaway global warming".



9. The carbon cycle: exchange of carbon between the atmosphere (as CO_2), on the land (in the bodies of plants and animals and in organic matter in soil and peat), in the ocean (as dissolved CO_2 and calcium carbonate), and in fossil fuel (reserves)[10]. Fluxes are in gigatonnes of carbon (GtC) per year; stores in GtC.

Considering the first question, the increase in GHGs can be split into CO_2 and non-CO_2. CO_2 is a stable gas in the atmosphere, its concentration determined by the size of sources and sinks at the land and ocean surface (see Box II). It is now known[14,15] that the only net source of additional CO_2 to the atmosphere over the industrial period has been human beings, meaning the increase is 100% anthropogenic (Fig 10). But although CO_2 is the most important single GHG, emissions of the non-CO_2 GHGs are also important, being equivalent to around 60% of the total CO_2 emissions (Table 3). It is difficult to prove conclusively, because of their complex chemistry, that increases in concentrations of these gases over the industrial period are due to humans, but anthropogenic emissions of these gases are currently comparable to or exceed natural emissions (see Box III).

The second question can be addressed using the concept of "radiative forcing" (Table 4), a measure of the additional amount of heat prevented from leaving the top of the atmosphere by a particular effect. Radiative forcings are calculated using atmospheric radiation theory and are independent of complex climate models.

For the increase in all the GHGs combined, the radiative forcing over the 20th century was about 3W/m^2 of the Earth's surface – divided approximately equally between increases in CO_2 and in non-CO_2 GHGs. This is a dull background heat, equivalent to only around 1% of the solar radiation received at the top of the atmosphere, but it is a sustained and persistent perturbation to the Earth's thermal equilibrium, requiring an adjustment of the Earth's surface temperature. Evidence from observations of past climate change and modelling studies indicate that it is

*Weight of carbon is used when discussing the carbon cycle because a common unit is needed that relates its different forms in the different stores (carbon is in the form of CO_2 only in the atmosphere, generally). To convert from weight of CO_2 to weight of carbon one needs to divide by 44/12 = 3.7, the ratio of the molecular weights of a CO_2 molecule and a carbon atom (ie 1tC = 3.7t CO_2).

III. The non-CO_2 GHGs

The non-CO_2 gases are all stronger GHGs, molecule per molecule, than CO_2*. Their impact can be compared to that of CO_2 using the concept of global warming potential (GWP). This is a measure of their effect on climate relative to CO_2 over a defined period, usually 100 years[7]. For example, if a gas has a 100-year GWP of 10, a molecule of it released into the atmosphere has 10 times the warming influence on climate of a CO_2 molecule over the same period. Using this concept, emissions of non-CO_2 GHGs can also be expressed as equivalent emissions of CO_2 (Table 3).

The synthetic non-CO_2 GHGs include the halocarbons (CFCs, HCFCs, PFCs, HFCs, halons) and sulphur hexafluoride (SF_6). Most of these compounds have long lifetimes in the atmosphere; GWPs are typically around 10 000 for the halocarbons and 22 000 for SF_6.

The main naturally-occurring GHGs are CH_4, N_2O, and O_3. All three have anthropogenic sources. Unlike CO_2, they are broken down by chemical reactions in the atmosphere and so have finite atmospheric lifetimes. CH_4 is the most important, and the second most important GHG overall after CO_2. Its atmospheric concentration has more than doubled in the industrial period (Fig 5). Around 40% of current CH_4 emissions are estimated to still be from natural sources, mainly decomposition of organic material in wetlands. The remaining 60% are anthropogenic, divided more or less equally between: (1) leakage of natural gas during extraction of natural gas, coal, and petroleum; (2) cattle and other livestock; (3) rice agriculture; (4) biomass burning, waste treatment, and decay of waste in landfill sites. The 100-year GWP of CH_4 is 23. However, a CH_4 molecule only persists on average in the atmosphere for around 10 years, being broken down by sunlight in a series of reactions (that ultimately lead to a molecule of CO_2 that joins the main part of the carbon cycle). Most of the impact over 100 years, therefore, is concentrated at the start of that period and the 100-year GWP somewhat under-emphasizes the importance of CH_4 as a GHG.

N_2O occurs naturally as a result of ocean and soil processes, but has an anthropogenic source from nitrogen fertilizers and other agricultural practices, currently estimated to be about the same size as the natural source. Its atmospheric concentration has also increased over the industrial period, from around 270ppb to 310ppb. It has a lifetime in the atmosphere of around 120 years and a 100-year GWP of 296. It is broken down in the atmosphere by sunlight to form nitrogen and oxygen.

O_3 in the upper atmosphere (stratosphere) acts to cool climate slightly by screening out incoming solar radiation (in the ultraviolet).** However, in the lower atmosphere (the troposphere) it is a GHG and its concentration here is estimated to have doubled over the industrial period. O_3 doesn't have a direct anthropogenic source but is produced in the troposphere by the action of sunlight on certain "precursor" gases, which include the anthropogenic pollutants carbon monoxide, nitrogen oxides (emitted by the combustion of fossil fuels, particularly in vehicle emissions), and volatile organic compounds. These precursor gases thus have an indirect greenhouse effect. Both O_3 and its precursors have short chemical lifetimes in the atmosphere. O_3 itself isn't usually assigned a GWP.

The presence of the long-lived non-CO_2 GHGs (ie excluding tropospheric O_3 and its precursors) in the atmosphere is currently equivalent to an additional 60ppm of CO_2 based on 100-year GWPs[16]. Since the current actual level of CO_2 in the atmosphere is around 385ppm, the total level of atmospheric GHGs is currently nearly 450ppm CO_2 equivalent.

Table 3. Emissions of CO_2 and non-CO_2 GHGs from anthropogenic sources expressed as 100-year CO_2 equivalent emissions over the 1990s[15]. CFCs are not included; these are controlled under the Montreal Protocol and emissions have declined since the early 1990s. Direct CO_2 emissions have increased since the 1990s averaging 7.2±3 GtC/yr from 2000-2005[13].

	GtC/yr CO_2-eq		Percentage of direct CO_2 emissions
CO_2 (all anthropogenic):			
fossil fuels	*6.4*		*80%*
deforestation	*1.6*		*20%*
Total		8.0	100%
Non-CO_2 (known anthropogenic sources)			
CH_4	*2.2*		*28%*
N_2O	*1.0*		*13%*
fluorocarbons and SF_6	*0.1*		*1.3%*
carbon monoxide	*1.5*		*19%*
nitrogen oxides (NO_X)	*0.2*		*1.5%*
Total		5.0	63%
Total		13.0	163%

Table 4. Radiative forcings averaged over the industrial period (1800-2003)[12].

Forcing agent	Forcing (W/m^2)		
Greenhouse gases (GHGs)			
Well-mixed GHGs:			
CO_2	*1.66*		
CH_4	*0.48*		
N_2O	*0.16*		
halocarbons	*0.34*		
Total well-mixed GHGs		2.64	
Tropospheric O_3		0.35	
Stratospheric O_3		-0.05	
CH_4-derived stratospheric H_2O		0.07	
Total GHGs			3.01
Solar irradience		0.12	
Land use		-0.2	
Snow albedo (black carbon on)		0.1	
Aerosols			
direct effect	*-0.5*		
indirect effect (cloud albedo)	*-0.7*		
Total aerosols		-1.30	
Linear contrails		0.01	
Sum of individual forcings		1.74	

more than enough to account for the observed increase in global temperature[17].

Of the other effects listed in Table 4, the next largest is also anthropogenic. This is the aerosols associated with atmospheric pollution, particularly from burning fossil fuels. Overall this has been a cooling effect, sufficient to cancel out about half the GHGs' warming, and has been termed "global dimming". Without this effect, ironically, increases in global temperatures over the 20th century might have been significantly larger than they were.

The only other positive (warming) radiative forcing on climate over the industrial period has been a small increase in solar output, equivalent to about 5% of the GHGs' effect.

The third question is perhaps the hardest to answer. Since we only have one climate system, which is affected by both anthropogenic and natural factors, it is impossible to know what might have happened without the anthropogenic perturbation. The only way to address this question is to use a computer model of the whole climate system – a so-called global circulation model (GCM)[10]. The UK Meteorological Office's state-of-the-art GCM, HadCM3, modelled three cases: no external radiative forcing (internal climate variability alone); with natural radiative forcing factors (solar output changes and volcanic eruptions); and with both natural and anthropogenic radiative forcing (Fig 11).

*This is partly because the concentrations of these gases are so much lower than CO_2. The wavelength bands in which they absorb infrared radiation are less "saturated", ie there is a larger change in relative absorption for a given increase in concentration.

**CFCs destroy O_3 in the stratosphere, and so exert a warming influence on climate, but they are also powerful GHGs themselves; the "ozone hole" is mainly a health risk issue, and has relatively minor effect on climate.

In the first, the model maintains an almost steady-state climate. In the second, with anthropogenic forcing (GHGs and aerosols) there is reasonable agreement with the observations, but the warming is over predicted in the middle part of the century. But in the third case, with natural forcing (volcanoes and solar variations) added, good agreement with the observations is found. This and other similar modelling studies[12] - not just comparing with observations of global mean temperature, but also looking at patterns of change across the surface of the Earth and through the depth of the atmosphere - indicate that the increase in GHGs is necessary to explain the observed warming. Natural variability within the climate system, such as changes in cloudiness or in ocean circulation, would have been too small to cancel out the effect of rising GHG concentrations.

All this evidence led the Intergovernmental Panel on Climate Change (IPCC), the UN body charged with reviewing the state of understanding of climate science, to conclude in 2001 that: "The balance of evidence indicates that most of the warming observed over the last 50 years is due to human activities [through the increase in GHG concentrations]"[7]. To many, this statement was taken to conclude the investigation of the first part of the GWH.

Scepticism

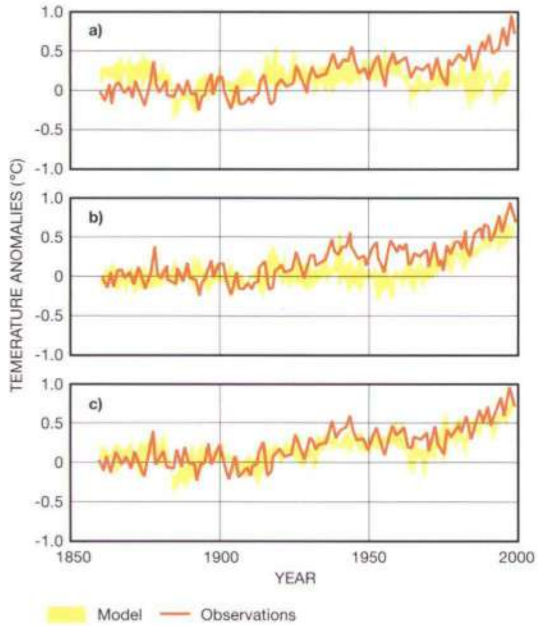
The IPCC's 2001 conclusion was formally acknowledged by many leading scientific bodies. In the same year a group of 16 national science academies issued a statement endorsing the report[18]. In 2005, the national science academies of the G8 nations plus those of Brazil, China and India followed up with a signed statement acknowledging the reality of anthropogenic climate change and endorsing the IPCC assessment[19]. And yet the concept of anthropogenic global warming is frequently portrayed in popular media – newspapers, films, and even novels – as something around which there is still considerable scientific uncertainty and debate. Where does this so-called "scepticism" originate from?

One unwitting source may have been the climate science community itself. Although very few practising climate scientists doubt the reality of anthropogenic climate change, to some there is something unsatisfactory about the proof outlined above, because at its end it relies on GCM models, not observed data. This is of concern because the length of time over which data are available to scrutinize the GCMs (not just for ability to predict global temperature but a range of climate factors, such as the horizontal and vertical temperature structure of the atmosphere and oceans) is only the last 50 years or so during which extensive monitoring networks have been in place. It is impossible to benchmark the models in any detailed way against a period that contained only natural forcing, as opposed to the more recent period of natural + anthropogenic forcing.

This situation is summed up well by Carl Wunsch, a wise head amongst US climate scientists: "It is very difficult to separate human induced change from natural change, certainly not with the confidence we all seek. In these circumstances, it is essential to remember that the inability to prove human-induced change is not the same thing as a demonstration of its absence... Public policy has to be made on the basis of probabilities, not firm proof."[20]

Climate scientists have generally been cautious in the language used to communicate probabilities to policy makers. This situation is changing, however, partly because trust in the models, and in the observational evidence base, has grown so dramatically in recent years.

Shortly before this article went to press, the IPCC released the summary of its Fourth Assessment Report[12], updating the 2001 report[7]. The wording of the key statement on 20th century climate change is very similar, but the phrase "balance of evidence" has been replaced by "very likely", which in IPCC terminology means "more than 90% probable": "Most of the observed increase in globally average temperatures since the mid 20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."



11. Simulated and observed global mean near-surface air temperatures: a) with natural variability only (including no radiative forcing); b) with natural variability + anthropogenic radiative forcing; c) with natural variability + anthropogenic radiative forcing + natural radiative forcing (volcanoes and solar output changes)[7].

In the lay community, sources of scepticism are somewhat different. It is very difficult for the lay person to form a judgement because of the extent and complexity of information available. Scepticism is widespread, however, and often appears to be based simply on intuitive feelings that "it just shouldn't be so".

As will be discussed in the second article, some projections for global warming are truly terrifying and call into question the whole basis of our modern lifestyles, so it is unsurprising that this "intuition" is seductive. But in other cases this type of scepticism takes on a more sinister tone, in which scientific "facts" are invoked, often out of context, to try to disprove the GWH. The aim of such efforts appears not to be to genuinely inform, but rather to confuse. The somewhat emotive term "climate change denial" has come into common usage to denote this type of scepticism.

What are these arguments? Space precludes discussion of them all (whole websites[21, 22] have been set up to address them), but here we consider five key sceptical arguments/misunderstandings.

1. The trend in atmospheric temperatures is not real.

One type of climate change scepticism is to dispute that a warming trend actually exists. This "trend scepticism" is rare nowadays, as the observational evidence has become so irrefutable and palpable, but it still crops up sometimes.

12. Sceptics will cherry-pick figures from locations around the world to indicate a cooling trend.

One tactic is to cherry-pick particular temperature time series from locations around the world that don't clearly show warming, or possibly even indicate a cooling trend. Some time series have shown local cooling and many others are short in duration with inter-annual and decadal climate variability swamping underlying global trends. This is why global and regional averages are usually discussed when considering climate change, because averaging reduces the "noise" of local climate variability, allowing underlying trends to be revealed. The exception is the Central England Temperature record begun in 1659, a key data source as it is the world's longest temperature/time series. From it a clear signal is now emerging[23] of warming that can only be accounted for by the inclusion of man-made sources.

Another such argument is that the global trend is not due to underlying climate change, but to the data being biased by urbanization (urban areas on the whole being warmer than rural surroundings). But this is also spurious. The data come from all over the globe, including many from ship and ocean buoy-based observations, and the data that do come from stations subsumed by urbanization have had bias corrections applied. A recent study[24] looked for perceptible differences between global average temperature trends for windy as opposed to calm nights, since this would reveal any effects of "urban heat islands" (mainly a night-time effect), but none were found.

Until recently, the only piece of credible evidence to question the significance of the global surface air temperature trend was a discrepancy in the vertical structure of temperature changes in the atmosphere compared to the predictions of GHG theory. Under GHG forcing, the atmosphere should get warmer at the surface, warm by a similar amount in the troposphere, and cool in the stratosphere. Surface and stratospheric trends were in line with this picture, but satellite measurements for the mid-troposphere did not show the warming expected. The 2001 IPCC report[7] noted that it wasn't known then whether this was due to genuine discrepancies with the theory or measurement error, but the latter is now known to be the case, due to a fundamental error in the way the satellite measurements were calibrated[25]. This, therefore, is no longer a source of uncertainty.

2. The global warming trend is real but it is not due to GHGs.

Another sceptical tack is not to deny global warming itself, but to suggest it is not caused by GHG increases. A problem with this "attribution scepticism" is that it must first disprove that anthropogenic GHGs affect climate, at least to the extent given by accepted theory. It is sometimes argued that anthropogenic GHGs are not important because water vapour is the most important GHG, but, as noted above, water vapour plays a very different role in the radiative forcing from the other GHGs. Indeed, the radiative theory of climate forcing is now so well established that it is really flying in the face of the laws of physics to argue against the importance of GHGs as agents of climate change.

The main approach by attribution sceptics, then, is not to tackle the GWH head-on, but to propose some other mechanism for the observed warming trend, perhaps in the hope that if a convincing alternative case can be made, the GHG theory will be forgotten.

The main natural agents of climate variability are volcanic eruptions and variations in solar output[10]. The former put aerosols into the stratosphere that persist and have a cooling effect for one to three years. As they are episodic, it is hard to make the case for volcanic eruptions as a mechanism for sustained warming.

Solar radiative output is relatively constant, but varies on a variety of timescales as a result of fluctuations in the solar magnetic field. These changes have a direct radiative forcing effect on climate through the change in total solar irradiance (TSI) at the top of the atmosphere. Such changes are thought to have contributed to past fluctuations, like the Little Ice Age. Changes in the geographical distribution of solar irradiance due to variations in the Earth's orbit are also thought to have led to large climate changes in the past, such as the Ice Ages (see discussion overleaf).

TSI has been measured directly from satellites since around 1980. Before then, less accurate data can be inferred from sunspot numbers and isotope records, which provide proxies for TSI. Intriguingly, solar output increased from a relative minimum around the time of the Little Ice Age to the middle of the 20th century, the period of the initial rise of temperatures and GHGs over the industrial period. Since around 1980 TSI has been relatively constant although oscillating with an 11-year sunspot cycle.

Some attribution sceptics claim that changes in solar output can explain fully all the warming since the start of the 20th century, but there are two problems. Firstly, while the IPCC concluded in 2001 that TSI changes can account for some warming in the first half of the 20th century[7], these changes are not consistent with warming over the last three decades. Secondly, the magnitude of TSI changes is relatively small: the net change over the industrial period is only about 1/25th the size of the GHG forcing (Table 4) and the amplitude of the 11-year oscillations is around 1/10th of the GHG forcing.

For these changes to be as important as the GHGs, either there must be something basically different about how the climate system responds to solar radiative forcing compared to other types of radiative forcing, or these changes in solar activity have an indirect effect on Earth's climate unrelated to changes in TSI. One possible mechanism is that changes in the ultraviolet part of the TSI spectrum (which are larger than the mean) affect O_3 production. A proposed indirect mechanism is that changes in the solar wind and solar and terrestrial magnetic fields cause changes in the amount of galactic cosmic rays received in the atmosphere, changing in turn the Earth's cloudiness through the effect on cloud nucleation processes[7]. While these ideas are intriguing, they currently lack an established theoretical and experimental basis and remain controversial.

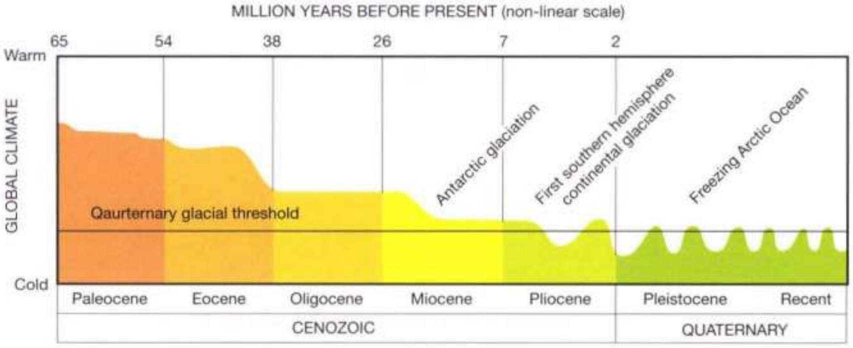
Earth's climate may yet be shown to be influenced more strongly by solar variations and other extraterrestrial effects than currently believed, but it seems very unlikely that this would be to an extent to disprove current theory. We already have a well-established theory that does a good job of explaining present and past climate change without the need for indirect solar forcing effects, suggesting that the latter are small. And if that were not the case, then the established theory must be somehow fundamentally wrong, requiring wide-ranging reappraisals in other areas of science. For example, if the GHG part of the theory is the cause of the error, then the quantum theory that describes how light and matter interact - a well-established foundation of modern physics - must also be wrong.

Ruling out these possibilities, the possible existence of such processes should only give us comfort if they have the capacity to become significant cooling effects in the near future. Otherwise, they will just be supporting the warming influence of the rising GHG concentrations.

3. Global warming is just part of natural variability, and therefore it would have happened anyway.

Another attribution sceptic approach is to point to past climate changes, implying climate can alter naturally without human intervention, so there is no need to assign blame to ourselves.

A major battleground for this type of argument has been the "near past" climate records based on proxies (Fig 7), now colloquially referred to as the "Hockey Stick" (the graph shape resembles an ice hockey stick on its side, with the blade pointing upwards as the period of recent temperature increases). Several such studies emerged in the late 1990s, but at the time of the 2001 IPCC report only one, by Mann *et al*, covered the whole of the last millennium[26]. This loomed large in the IPCC report and underpinned the statement that "the 1990s were the warmest decade and 1998 the warmest year of the millennium"[7]. This caused a furore in sceptic circles and was vehemently attacked, notably in a paper[27] by McIntyre & McKitrick (M&M) claiming that the Mann *et al* methodology was flawed, and that northern hemisphere temperatures in the 15th century were warmer than today (despite this date being closer to the start of the Little Ice Age than the accepted timing of the Medieval Warm Period). The debate then heated up considerably, as the sceptics now had some "firm evidence" to discredit the IPCC.



13. Schematic showing cooling following the end of the dinosaur period.

Things came to a head in the US in 2005. Congress commissioned an independent review from the National Research Council (NRC). In the House of Representatives, Rep Joe Barton, chair of the House Energy and Commerce Committee and a prominent climate change sceptic, launched a major investigation into the scientific activities of Mann and his co-workers and commissioned the statistician Edward Wegman to head a review panel. Both reports were released in 2006 and took widely differing tones. The NRC broadly endorsed Mann *et al*'s work, though suggested that the period 900-1400AD contained high uncertainty, due to data sparsity, and the IPCC may have been too quick to give key prominence to the emerging findings[28]. In contrast, the Wegman report was critical of Mann *et al* and supportive of M&M[28].

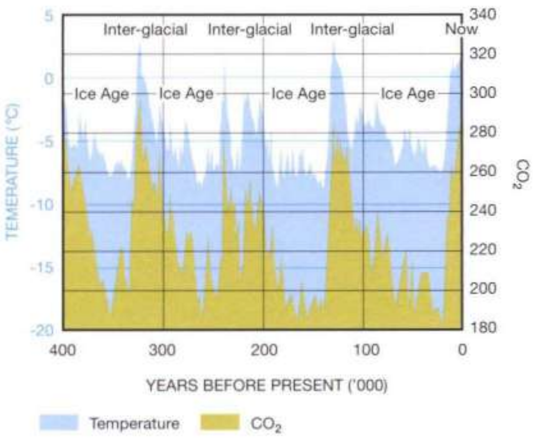
Meanwhile, other studies had appeared, broadly consistent with the Mann *et al* reconstructions, including one by a group at the US National Centre for Atmospheric Research which concluded that M&M's different results arose because they had "censored" key data[29]. Despite this, the sceptics remain unrepentant and continue to state, citing M&M, that "it has been proved beyond doubt that the Hockey Stick is a fake".

The IPCC is also unrepentant. Its 2007 statement is stronger than in 2001[12]: "Average Northern Hemisphere temperatures during the second half of the 20th century were likely to be the highest in at least the past 1300 years."

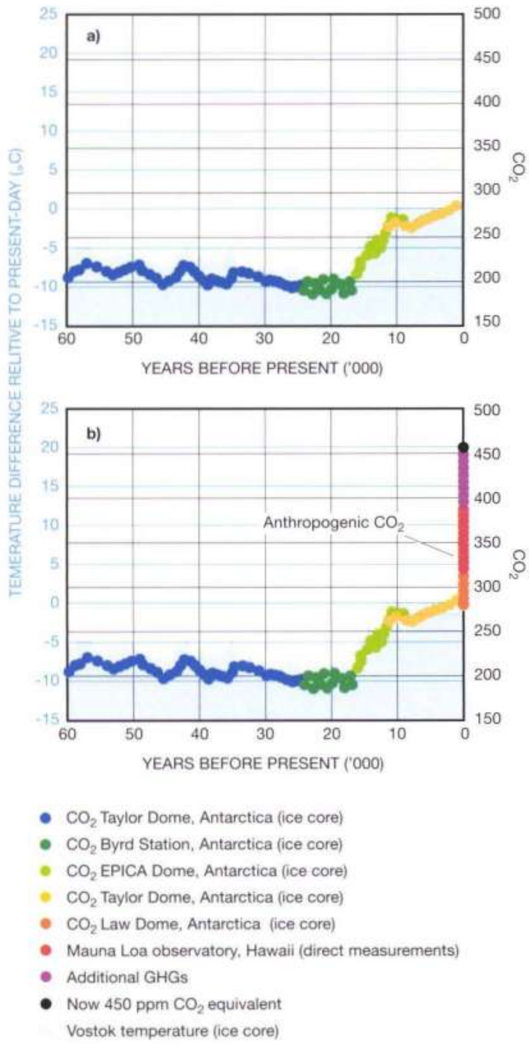
The Hockey Stick graph controversy provides interesting insights into the potential politicization of climate change science, but its intensity is completely out of proportion to its significance as evidence relating to anthropogenic global warming. The important thing is to understand why contemporary global warming is happening, and where it will lead in the future. What happened in the past is largely irrelevant if the current drivers of climate change are of a very different nature. Also, if one wishes to point to the climate system's ability to change naturally without human intervention, there are much more dramatic examples than those that occurred (or potentially occurred) over the last 1000 years or so.

In the dinosaur era (230M-65M years ago), the Earth was at times much warmer than today, by up to 10°C degrees, primarily because of the very high level of atmospheric GHGs. What would now be considered tropical conditions existed at the poles and the globe was ice-free. Following the dinosaur extinction, the Earth underwent several warming and cooling phases, but general cooling prevailed (Fig 13) as GHGs were taken out of the atmosphere by chemical and biological processes, culminating in the development of the Antarctic ice sheets

14. Changes in GHGs today are known to be driven by anthropogenic sources.



15. Temperature fluctuations for the last 400 000 years (the last four Ice Ages) from Vostok ice core data, Antarctica[30].



16. Temperature and CO_2 changes: end of the last Ice Age, the Holocene, and the Anthropocene:
a) ice core measurements up to 1600AD;
b) with CO_2 concentrations from ice core measurements from 1600 and direct measurements from 1958 on, + CO_2 equivalent concentrations for the non-CO_2 GHGs[11, 16].

around 20M years ago. Around 4M years ago northern hemisphere glaciation developed. For the last 2M years there have been oscillations between relatively extensive northern hemisphere glaciations (Ice Ages) and warmer periods (Interglacials) like our present (or at least pre-industrial) climate, with about 5°C difference in global average temperature between the two. At first these oscillations had periods of around 40 000 years, and then around 100 000 years (Fig 15).

The accepted theory for these cycles is that periodic variations in the Earth's orbit (so-called Milankovitch cycles) lead to variations in the distribution of solar radiation (insolation) on its surface[9, 10]. These are small in magnitude but are thought to produce climate change by causing changes in the carbon cycle and thereby atmospheric GHG levels. This is the only known process able to produce such large climate fluctuations, although the exact nature of the coupling between carbon cycle and insolation is still not well understood.

This type of process is not occurring today, because the Earth's orbit is not in a phase where we would expect orbital variations to be driving a warming (or cooling) trend. Moreover, as already shown, the changes in GHGs today are known to be driven by anthropogenic sources, not natural release of carbon.

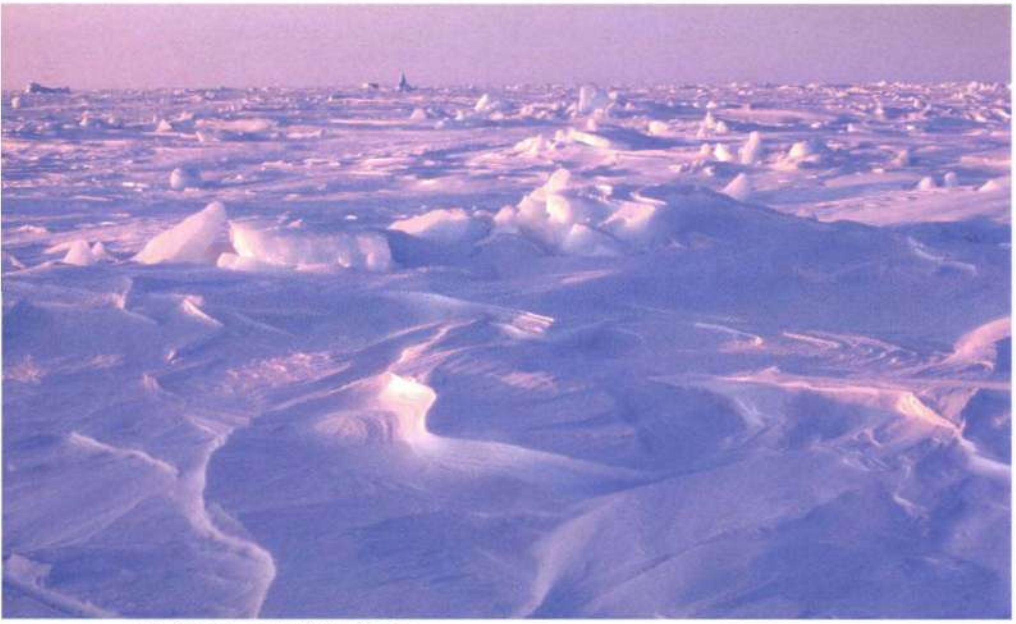
At the end of the last Ice Age there was an increase in CO_2 and associated warming, before levelling off in the last 10 000 years or so of relatively stable climate, called the Holocene. The increase in GHGs over the industrial period is quite striking in this context (Fig 16). The changes now occurring in GHG levels are quite different from those in the past, because they are being produced by humans. It is unlikely that any past natural agent could have produced such rapid changes, except perhaps outgassing from the Earth's mantle.

For this reason, it has been suggested that the present climate period is no longer part of the Holocene, but a new geological period, the Anthropocene.

4. Global warming will lead to a new Ice Age by the Gulf Stream switching off.

Many sceptical arguments are becoming less and less tenable, and so new ones have had to be found. One is that global warming might lead to a new Ice Age. This appeals to sceptics, as it suggests future planning for climate change is futile.

The concept of warming leading to cooling is counter-intuitive and needs some explanation: Ice core measurement from the Greenland ice sheet indicates that during the last Ice Age several warming episodes preceded quite rapid cooling[31]. These have been correlated with changes in North Atlantic ocean circulation. In the far North Atlantic and the Arctic Ocean, surface water flowing up from the south is cooled and sinks (because it becomes more dense). This process is called the thermohaline circulation (THC) and causes the Gulf Stream waters to travel further north than would otherwise be the case (the Gulf Stream is a major ocean current that carries warm water from the equator north along the east coast of America, spewing out into the North Atlantic at Cape Hatteras[32]).


17. Sea ice on the Arctic Ocean.

It has been argued[33] that at times of strong warming when lots of meltwater flows into the Arctic Ocean and precipitation increases, the THC weakens because the surface water, being less salty, is no longer dense enough to sink (cold fresh water can be less dense than warmer saltier water). If this were to happen it would reduce the amount of warm water flowing north in the THC and act to cool the northern hemisphere. The popularized version of this theory has the weakening THC create a dramatic "shutting down" of the Gulf Stream, causing western Europe to become as cold as eastern Canada.

Two myths inform this description. The first is that the Gulf Stream is produced by the THC - it isn't. It is a "western boundary current", produced by the Earth's rotation and the action of the prevailing winds on the ocean surface (other currents of this type are the Kuroshio, flowing north along the east coast of Japan, and the Agulhas, flowing south along the coast of east Africa). If the THC were to shut down, the Gulf Stream might weaken a bit but it wouldn't stop.

The second myth is that Western Europe is warmer than Eastern Canada because of the Gulf Stream. In fact the main reason that London is warmer than Quebec is that London's prevailing winds (from the west at that latitude) blow from over the relatively warm ocean, rather than the frozen steppes of north America.

Something else is needed to make the theory work, and the missing ingredient is sea ice. Because the Arctic is nearly all ocean, it can freeze very rapidly if its temperature falls below seawater's freezing point. This would increase the albedo (reflectivity) and insulate the ocean surface, cutting off heat transfer to the atmosphere. This would give Western Europe bitterly cold winds from over a vast expanse of ice and snow, rather than relatively warm ocean water, causing a dramatic cooling over land.

Through much of the last Ice Age the North Atlantic was probably very close to freezing for much of the time, and this was probably a major cause of the highly variable Ice Age climate seen in the Greenland ice cores[31]. Something like this might also have happened to some degree during the Little Ice Age.

Today, the situation is very different. Much less of the North Atlantic is close to freezing; in fact the amount of sea ice is decreasing year on year. The more that global warming continues, the further we depart from this "tipping point" for sudden cooling[33]. In fact, although all current GCMs predict a weakening of the THC under global warming, none shows that even a regional cooling in the north Atlantic would follow[12, 34], suggesting that we are not currently close to this tipping point. Reports that the THC is actually weakening have also been found to be premature, the "weakening signal" being due to greater than expected fluctuations in what is a highly turbulent circulation[35].

5. Global warming won't actually be that bad.

This is "impact scepticism". It relates to the second part of the GWH, and so will be covered in the second article.

Conclusion

In this article the scientific basis for the global warming hypothesis has been outlined and the main scientific evidence to support its first part – the attribution of contemporary global warming to anthropogenic GHGs – has been presented.

It has been shown that this evidence is now robust. The increase in GHGs is anthropogenic and provides an entirely credible explanation for the observed warming trends; no known processes provide an alternative explanation, and none are overriding the GHG warming effect or are likely to in the future. The corollary is that if human beings continue to produce GHGs in large quantities, the warming trend will continue. We will look at the implications of that in Part 2.

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Credits

Illustrations: 1 Brasil2/iStockphotos.com; 2, 3, 5, 6, 7, 9-11, 13, 15, 16 Nigel Whale; 4 Pufferfishy/Dreamstime.com; 8 Svetlana Privezentseva/Dreamstime.com; 12 Sandra Henderson/iStockphotos.com; 14 Natalia Bratslavsky/Dreamstime.com; 17 Bernardbreton/Dreamstime.com; 18 NASA.

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18. "Blue Marble" - the Earth from 45 000km distance, photographed by a member of the *Apollo 17* lunar mission on its outward journey, 7 December 1972.

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Arup is a global organization of designers, founded in 1946. It has a constantly evolving skills base, and works for local and international clients throughout the world.

To celebrate its 60th anniversary in 2006, Arup partnered with the international charity WaterAid in the Arup Cause initiative, which focused Arup's mission to "shape a better world" on the provision of safe domestic water, sanitation, and hygiene education to the world's poorest people.

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Front cover: The US Air Force Memorial at Arlington, Washington DC, was inspired by the Thunderbird F-16 fighter jets' "bomb burst" flight manoeuvre, which was performed overhead during the Dedication Ceremony (Photo: Patrick McCafferty).

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