Understanding of the complex set of processes that make up the global climate system has advanced significantly over the last few decades. Much of this advance has been stimulated by concerns over whether the climate is changing and will change further as a result of the changing composition of the atmosphere. The mean temperature of planet earth is determined by a number of factors, but one is the existence of certain gases (water vapour, carbon dioxide, methane, for example) in the atmosphere that affect the radiative exchange between the planet surface and space, so causing the surface of the planet to be warmer than it would be otherwise. In fact, the current planetary temperature is about 30°C greater than it would be without these so-called greenhouse gases.

Thus there is a greenhouse effect that is important in determining the current climate of the earth. However, there has been growing concern over the past two decades that activities of humans are leading to an increase in the concentration of greenhouse gases, and thus an enhanced greenhouse effect. Given that the climate system can be only understood through the reductionist study of each of the contributing systems (hydrologic cycle, ocean circulations, soil-vegetation interactions, etc), and the integration of these interacting systems into an holistic representation of the systems, the science development has been both disciplinary and global, and integrative and complex. The demand by all countries to understand and make risk assessments of the issue of climate change has led to the need for a mechanism for periodically making an assessment of the status of the science.

The aim is that concurrently, governments and companies can assess the potential magnitude of the risk and decide what should be done to mitigate changes and adapt to them. This mechanism is the Intergovernmental Panel on Climate Change, established in 1988 by the UN Framework Convention on Climate Change and the World Meteorological Organisation. Thus far the IPCC has delivered two Assessment Reports, the first in 1990, the second in 1996 and the third this year.

The brief overview of the scientific basis of the enhanced greenhouse effect that follows is based on the key findings of the Third Assessment Report.

The Key Outcomes Of The Third Assessment Report Of The IPCC

Observed change

The first conclusion of the Third Assessment Report on the science of greenhouse climate change is that observations of the world's climate show convincingly that the climate is changing. Surface observations over the past 100 years (Figure 1) show that a warming of about 0.6°C has occurred since the late 1800s and that the average temperature of the surface of the planet has been greater for most of the years of the past decade than any time in the past 100 years.

Figure 1. Mean surface temperature as departure from the average temperature over the period 1961-1990
A wide range of evidence confirms this record. For example, balloon measurements have demonstrated that the warming in the past 50 years or so has occurred through the lowest eight kilometres of the atmosphere and cooling, as expected through greenhouse physics, has occurred at higher levels. Snow and ice extent have decreased, and other patterns of climate variables have been observed to have changed. One of the most telling pieces of evidence is that warming has now been observed to occur, albeit to a diminished magnitude, through the upper 1,000 m of the global oceans. This represents a huge accumulation of energy, equivalent to about 0.3 W m\(^2\) continuously for the past 30 years.

Australia is also warming. The greatest change has been in night-time temperatures (Figure 2), but significant maximum (daytime) changes have also occurred (Figure 2).

Figure 2. Warming (°C) over the past 100 years for Australia (values are in °C per decade – for total changes, multiply by 10)
Atmospheric composition change

The main driver of concern associated with climate change science over the past two decades has been the observation that some of the key greenhouse gases are increasing in concentration. The Third Assessment Report confirms that some of these changes continue to take place.

For example, continuous observations of the key greenhouse gas, carbon dioxide, at the Australian baseline observatory at Cape Grim, Tasmania, show that this gas is rising inextricably (Figure 3). Further, measurements of gases in air trapped in bubbles in Antarctic ice (Figure 4) show that concentrations of carbon dioxide are now over 30% greater than they were pre-industrially (200 years ago).

![Figure 3. Concentration of CO$_2$ in the atmosphere](image)

![Figure 4. Concentration of CO$_2$ as measured from ice-core studies](image)

Similar studies show that today's concentrations are above those observed any time in the last 400,000 years. Geologic studies suggest that they might be higher than at any time in the past 20 million years.

During the 20th century, concentrations of aerosols (dust particles) in the atmosphere rose. This fact needs to be taken into account as aerosols directly change climate by scattering sunlight and absorbing heat, and indirectly alter climate by influencing the process of formation of rain droplets and thus the reflectivity of clouds and the lifetime of droplets in the clouds.
Other factors such as volcanic eruptions contributing dust into the atmosphere and variations of the intensity of solar radiation from the sun may have caused small contributions to climate change over the past century.

**Climate models**

The third finding of the IPCC Assessment relates to the significant improvement of computer simulations of the climate system (climate models). Models produced by key research centres around the world, including the CSIRO, are able to represent in great detail the characteristics of climate including the seasonal and diurnal variations of temperature and pressure, the passage of frontal patterns, spatial patterns of precipitation, statistical patterns of extreme events, monsoons, and so on. These advances have grown out of improved understanding of the constituent processes of the system, better coupling of the processes into the models, and improved computer power and methodologies.

In the recently developed CSIRO Mark 3 model, for example, representation of the interannual variations of climate driven by El Nino, and the genesis and development of typical cyclones are realistically produced (Figure 5).

![Figure 5. Annual variation of precipitation and interannual variation in Queensland as observed, and simulated by CSIRO Mark 3 climate model](image)

It is important to realise that these models are not driven by observations, but rather generated characteristics of the global system through understanding and representation of the physics and dynamics of the processes and the system. This has been an incredible outcome for the research, and underpins our confidence in the projections of what is likely to occur in the future. Further, these developments have underpinned a new level of capability about to influence short term and seasonal weather forecasting.

Global mean temperature changes as simulated by such models take into account solar variability, changes in atmospheric aerosol concentrations and greenhouse gas concentrations.

In doing so they are able to adequately represent, retrospectively, the planetary warming of the past century (Figure 6). Again, this adds to confidence that such models, when used to test response to changes in factors that may influence climate in future, will give a believable prediction of what is likely to happen globally for given future levels of greenhouse gases.

**Attribution of change**

The conclusion of the IPCC is that most of the observed warming over the past 50 years is likely to have been due to the increase in greenhouse gas concentrations. Solar variations and aerosol concentrations have played a part in climate change, but not a dominant part.
Future human impact

In order to investigate future climate change, one needs first to establish likely future emissions of greenhouse gases and understand what the lifetimes of these gases will be (how quickly, for example, will carbon dioxide released into the atmosphere be dissolved into the oceans). Then climate models can be used to simulate how climate is likely to respond to changing levels of greenhouse gases. The major challenge with our predictions is that we have poor capacity to anticipate future release quantities of greenhouse gases, especially carbon dioxide.

So, the IPCC has established a number of emissions scenarios; that is plausible future emission profiles that reflect different views on how the global energy system will look. For example, one future is a continued growth in the use of fossil fuels, including the replacement of dwindling oil reserves by gas and coal; that there is technological improvement in efficiencies, but that these are limited. In this version of the future, the developed world rapidly raises its per capita consumption of fossil fuels, with production remaining highly coupled to increased energy consumption. Such a future would realise consistent and major growth in emission over the next 50 years. Alternatively, another view is that international acceptance of the need to control the rate of emission growth, encouraged through national legislation and business supported agreements and international agreements lead to significant end-use efficiency, and new and improved efficiency in combustion technologies. There will be significant adoption of renewable energy resources, and some lifestyle changes, all leading to much lower per capita emissions, and a stabilisation and then reduction of global emissions.

These two scenarios would lead to major differences in future emissions and thus future concentrations of carbon dioxide.

But there is another way of looking at this issue. Suppose that we start with the knowledge that there are future limits to the amount of climate change that the world should accept. That is, exceeding these changes would be 'dangerous', to use the words of the Framework Convention on Climate Change. It is not possible to conclude what this limit is, firstly because of the limitations of current modelling at the regional and local level. Secondly, even if we had the capability to make such predictions, the social, environmental and economic impacts, of such changes are still largely unknown.

But let us suppose for the moment that we know that the climate change associated with a doubling or tripling of pre-industrial carbon dioxide concentrations in the atmosphere, would be 'dangerous'. Let us also suppose that we could allow the world two centuries to bring the atmospheric concentrations to stabilisation at these levels. Then, because we have a good understanding of the carbon cycle, we can say what the emissions future would be that would be consistent with this growth in concentration. Figure 7 shows that in order to stabilise concentrations at either double or triple pre-industrial levels, future global emissions will need to be about a third of what they are today If we wish to stabilise at double pre-industrial concentrations, the trajectory of global emissions over future decades needs to rise only marginally above current emission levels before starting to come down. Even for tripling the concentration, future emissions would need to rise by less than double their current amounts before reducing.
This leads to an important conclusion. There are currently approximately two billion people who do have limited access to energy compared to those of us in the developed world. Of course, these people desire to improve their living conditions. During the next 50 years, there is likely to be a further two billion people seeking the same standards of living as those we enjoy in the developed world.

It appears almost impossible to achieve the stabilisation of concentration of carbon dioxide at double pre-industrial levels. Even tripling will be difficult to achieve, without substantial technological improvements. It is almost inevitable that something like a doubling of atmospheric concentration of carbon dioxide will occur in future.

The IPCC Third Assessment Report concluded that human influence will continue to change atmospheric composition through the 21st century, dominated by carbon dioxide, influenced by population growth, per capita demand and the inertia of exiting systems.

Targets currently being debated within the Kyoto Protocol would make very little difference in the longer term to carbon dioxide concentrations and thus climate change. In that sense, the Kyoto targets as they stand can only be regarded as a first step in a massive re-engineering of world energy systems.

**Future climate**

Applying the IPCC IS92a scenario of future emissions to change carbon dioxide concentrations in the CSIRO model, we get an indication of the magnitude of global warming possible over the next 100 years. The Third Assessment Report, concludes that global temperatures and sea level will rise under all IPCC emission scenarios. The projected warming will be between 1.4°C and 5.8°C between 1990 and 2100. At least half of the uncertainty represented by this range relates to uncertainties in future emissions and the rest to uncertainties in climate science.

The Assessment also concluded that, because of the long effective residence time of carbon dioxide in the atmosphere, the changes will persist for centuries. Sea level rise will be primarily due to thermal expansion of the oceans as water gradually warms. As warm water slowly penetrates to the deeper ocean, sea-level rises will continue well beyond the time that stabilisation of greenhouse gas concentrations is achieved.

The various scenarios and the range of climate change that they suggest present a range of choices. If the global community chooses to follow a fossil fuel, energy intensive future, then the likely temperature changes are going to be more in the upper range (towards the 5.8°C change). Whereas, if technology and community will bring about the kinds of energy futures described in the lower emissions future, then temperature changes can be limited to something like 1.4°C.
As the potential consequences of the impacts of such changes become better understood, it is likely that this choice of climate future will be the driving influence on the probabilities associated with each of the emission scenarios.

I again emphasise that there are serious shortcomings when it comes to using climate models to describe local to regional change. This is a far more demanding task than estimating the global mean change, and gross feature of the system. We are hopeful that new models, such as the CSIRO Mark 3, will assist in this regard, but it is indeed challenging science and represents where much research is focused.

Given the nature of the climate system, first substantive impacts of climate change will be seen at the local to regional level. Some places will be more sensitive to impacts of warming than others.

Similarly, because we do not yet have this forecasting confidence at the regional level, it is possible that there will be changes to the climate system that are currently unpredictable. This is perhaps particularly likely given the limitations of the representation of the ocean component of the climate system in the models.

Thus the current approach that has been used by CSIRO is to establish and periodically update scenarios of climate change for Australia. Our objective is that the community will have available some idea of the nature and magnitude of change that might occur in future decades. The scenarios published in another document are based on the combined output of some nine international climate models. That is there is an attempt to weight our view of what is likely to happen by the degree of consistency that exists between model predictions. These scenarios suggest that Australia will warm close to the global average. There will be drying trends over large parts of the country influenced both by precipitation reductions in the southern parts and increased evaporation across the nation. Rainfall will occur in heavier events.

**Climate And The Energy Cycle**

In Australia, the main sources of greenhouse gas emissions are energy production, much of which is from electricity generation and transportation. It is this connection that makes the national and international response to the threat of climate change so difficult. Historically, energy generation has been closely linked to wealth generation and economic growth. Thus, as the developing world seeks to improve its standard of living, there is pressure to continue to increase in the use of fossil fuels, with the consequent growth of greenhouse gas emissions.

The costs of impacts of climate change are not yet easily calculable so the costs' and benefits of letting the change happen or not are incompletely understood. There are major issues of international equity involved in the way in which we seek to address climate change.

The real impact of the climate change issue is on the energy cycle. As a result, the debate concerning a protocol within the Framework Convention on Climate Change - the Kyoto Protocol - is really about how the world is going to handle the transition between energy economies. In this sense, the climate change debate could be regarded as the world's first major challenge in the transition to a sustainable future. I speak here about sustainability in terms of current generations meeting their triple bottom-line responsibilities (economic, social and environmental) in such a way that this generation does not jeopardise the capabilities of future generations to do the same.

The technological opportunities to address these challenges are now appearing. Opportunities exist in at least the following areas:

- new automobile technologies
- land use changes
- renewable fuels
- recycling
- energy efficiency
- clean combustion

The future holds significant changes and opportunities at every step of the energy value chain. Significant parts of the private sector are seeking advantage by early exploitation and implementation of changes to the way in which their businesses use energy. Opportunities are being based on new technologies. Governments may need to be involved to ensure that market conditions support a move to a new energy economy.
Conclusions

The recent Third Assessment Reports of the Intergovernmental Panel on Climate Change states that whilst there is still much to be learnt about climate change and what we can expect in the future, by and large, greenhouse science is well based. It shows that there is a likelihood of significant global warming in the next 50-100 years. The details of how that will impinge on regional and local climate are less clear. This is a very demanding requirement on the science to answer these questions. But, given the difficulties (inertia, third world demand and population growth), some warming is unavoidable. The impacts of this warming will be widespread sectorally and geographically.