Understanding, Quantifying & Demonstrating the Likely Local Effects of Climate Change & Variability in the Peel-Harvey Catchment

SWCC Funded Project L2.G4, by Peter Hick, PHCC
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It is important for the reader to realise that the growth of knowledge and the extent of public awareness on the effects of Climate Change has had, and is continuing to have, exponential increase, even in the short period of this study. By their nature, the examples given to illustrate Climate Change in this study, will quickly become superseded by new interpretations and in some cases politically-driven agendas. Therefore the scope of the study should, where possible, be focused on the data presented and a very close watch kept on new data as they emerge. Realistic interpretations should be made only from the data and the basic physical characteristics of the Earth system. Use should also be made of the latest monitoring and analysis tools that are now available to assess these data.

List of Figures and Tables

Summary of study

Background

This report probably asks more questions that it answers but it does examine some of the Climate Change predictions for natural resource management (NRM) the South West of Western Australia. It also includes analysis of meteorological data with specific interest in four stations across the Peel Region. Determinations of historic trends of temperature and evaporation; decreased rainfall and runoff; rising sea level and coastal erosion; and predictions of increased seasonal intensity and variation of storm events are given.

Australia only contributes approximately 1.5% of the global Green House Gases (GHG). However WA, and the Peel Region in particular on a per capita basis, is probably one of the highest contributors of emissions any where in the world. There is compelling scientific evidence that anthropogenically-sourced GHGs are contributing to changing climate beyond the natural variability. Despite this very high variability and uncertainty in the data, the trend is now rarely credibly disputed.

For completeness this report should be read in conjunction with the report by Wilson and Hick (2006) Biodiversity Assets Assessments System, B5-04, a SWCC-funded project covering “Training NRM and Local Government Officers in the use of the Peel-Harvey Biodiversity Decision Support System”. The two projects were run in conjunction and detailed examples of quantification of the possible effects of Climate Change are covered in that report including the loss of Tuart forests on the Swan Coastal Plain, decline in Rivergums and Wandoo forests and the finding that 85% of the remnant vegetation, in the eastern part of the catchment, are in significant decline.

Both reports will be posted on the Peel-Harvey website and will be accompanied by associated raw meteorological data; and reference and source material locations.

Temperature

An increase of between1.0-2.0°C in the average annual maxima and minima over the century is recognisable in Mandurah, Dwellingup and Wandering but is not as marked at Narrogin. The warming trends are reasonably consistent for each season over the period for which records are available. However, contrary to the available long-term temperature trend, the 30 year trends from 1975 to 2005, do not conform to the longer term linear trend. The trend for this period seems to be stable or show temperature decline in most seasons, for both average maxima and minima since 1975. Therefore the data shows that the temperature trend over the past 100+ years does not always tally with the last 30 years. This is also at variance with the published data for the south west WA and may represent local climatic variability. It does tend to indicate that a major pattern shift may have occurred about 30 years ago.

Rainfall

The long-term average annual rainfall has for all four stations declined. Using the graphed linear interpolations the reduction for Mandurah (930-800) is 130mm (-14%), Dwellingup (1300-1200) is 100mm (-8%), Wandering (710-520) is 190mm (-27%) and Narrogin (530-460) is 70mm (-13%). In all cases the summer rainfall has increased, in Mandurah by 2/3rds but with very low total rainfall, and the autumn, winter and spring rainfall is in decline, apart from Dwellingup.

For the 30 years since 1975 the average annual rainfall for Mandurah shows only a 2% decline in total rainfall, for Dwellingup a 5% increase is also shared with a 2% increase at Wandering. However, Narrogin fits the SW prediction with a 14% decrease for the period 1975-2005.

The results conclude that rainfall is generally in decline in the PHC but not necessarily in the last 30 years on the Darling Plateau. Summer rainfall is increasing and winter/spring is generally declining. The relationship between total rainfall and run-off seems uncorrelated for multiple reasons. Runoff reduction from the scarp will affect the hydrology of the Swan Coastal Plain.

Stream flow represents a very small part of total rainfall. The loss of stream flow is complex and interception of rainfall and run-off by varying vegetation content, condition and management; modified land contours; possible fracturing of previously impervious horizons from mining; is further complicated by seasonal shifts in rainfall patterns and rainfall intensity.

Reduced stream flow from the scarp onto the coastal plain will reduce the ground water tables in the unconfined aquifers. These supply much of the urban and agricultural water from shallow bore fields. The effect on ephemeral wetlands will be a change in species composition and a loss of valuable diversity. A consistent trend in monitored bores seems correlated to the Tuart decline.

Lower rainfall in the eastern catchment, and a rainfall pattern that may be less concentrated in the winter and spring will reduce water-logging and may in the long-term reduce stream salinity and salinity scalding effects. The trend to more plantations will also assist this trend and some evidence that in a higher CO2 environment that is not limited by phosphate, some agricultural and silvicultural growth will be encouraged. This will be a topic worthy of more research.

Evaporation

There is a need for more work on understanding and quantifying evaporation. Better, more readily accessible models, which incorporate latest spatial, biophysical, elevation, slope and meteorological data, will be demanded by natural resource managers. Such models will be expanded into better understanding of fire risk behaviour and crop expectations.

Higher levels of summer moisture and higher summer temperatures will have significant effects on potential spread of *Phytophthora cinnamomi* (Dieback) and both the Eucalypts and proteaceous systems will be affected.

Sea Level

The +200 km of both oceanic coastlines and estuarine shorelines of the Peel Region will be affected by sea level changes. This will be attributed to isolated dramatic events, but a combination of rising sea-level, increased storm intensity, tidal and meteorological coincidence are likely to create notable incidents. This will raise community awareness and probably alarm. It will be difficult to separate the insidious sea level rise from compounding factors and planning will need to be conservative and rely on engineered mid-term solutions

The IPCC prediction is for a sea level rise by 2100 of 0.09 -0.88m. Fremantle sea level has risen 20cm since 1915 at a rate of 1.38mm/year. However, the interpolation of the data over the past 30 years produces an average figure closer to 3.0mm/year.

Estuary basin volume will increase with higher sea level, and although complex to calculate exact exchange volumes, greater tide flow and velocities (probably double) will have a significant effect on existing channel state. From an NRM perspective, coastlines and shoreline ecosystems in some cases re-establish very quickly and often with biological integrity, other situations and intertidal habitats will be lost forever and preservation efforts may prove fruitless. Some of the Ramsar wetlands may fall in the later case.

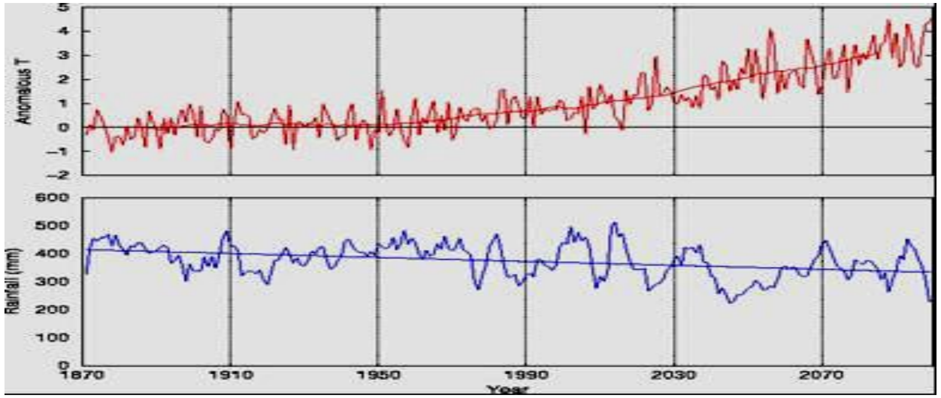

Figure 1: Projected Temperature and Rainfall change in the SW of WA (CSIRO Mk3)

The Issues in the Peel-Harvey Catchment

An example for the entire SW

The Peel-Harvey Catchment may be considered a microcosm of the SW of WA and will demonstrate most of the effects of Climate Change on physical, cultural and natural biodiversity. The insidious gradual increase in temperature can be demonstrated now but has little effect on daily routines. Altering rainfall patterns will be obvious to those whose seasonal dependence for primary production is affected, but adaptation measures may be possible. However, the more dramatic and pervasive reduction in late winter stream flow for water supply, should effect every household. Sea level effects will only be noticed when coupled with extreme weather events and excessive inundation and coastal erosion create eye-catching images.

Despite having an economy that is based significantly on mining and agriculture the Peel Harvey Catchment still retains significant natural and managed perennial vegetation. By the end of the century, Climate Change will be the dominant direct driver of Biodiversity loss and Ecosystem collapse (MEA 2005).

Ecophysical systems already stressed by clearing, salinity, introduced weeds, pests and diseases, altered management and fire will be effected. Existing habitat and biological systems will disappear; some species will adapt, emigrate or will be restricted to refuges. New ecosystems will establish, highly mobile species will compromise and some will flourish.

Stream flow represents a very small part of total rainfall. The loss of stream flow is complex and interception of rainfall and run-off by varying vegetation condition and management; modified land contours; possible fracturing of previously impervious horizons from mining; is further complicated by seasonal shifts in rainfall patterns and intensity.

There will be effects on the flora and fauna and the biological links that climate and season has on timing of floristic patterns, pollination of a changed suite of plants by a responsive suite of insects and animals. Loss of amphibian species is widely reported and fish and crustaceans have critical dependency.

Establishing baseline condition and implementing quantitative monitoring systems is a vital priority and committing long-term resources to a large system of reserves is essential.

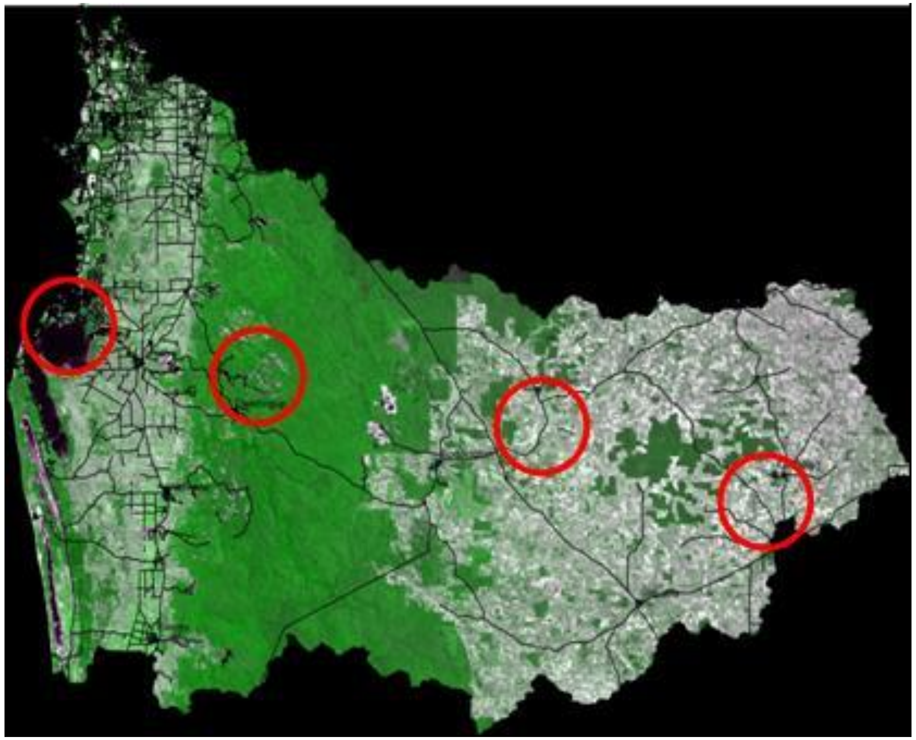

Figure 2: The Peel Region (approximately 1 million Ha extending about 170km from the coast) will be one of the first highly-populated areas of Australia to be affected by multiple elements of Climate Change; and, ecologically one of the more severely affected areas of the world. The circles show the location of Mandurah (built-up urban coastal), Dwellingup (forestry and mining), Wandering (mixed rural enterprises), and Narrogin (dry land wheat and sheep farming).

SWCC Strategies

The Peel-Harvey catchment provides a good basis upon which Climate strategies should be developed by SWCC. The four fundamental land classes are well expressed having a well developed coastal and estuarine component, an extensive coastal plain with minimal remnant vegetation with reserves, forested water catchment areas and multi-faceted dryland agriculture. Each should be treated separately and conservation and biodiversity strategies prioritised.

Arguably, this is the most important basic challenge against which all other work undertaken by SWCC will be measured. The concept of rapid adaptation to changing climate will be difficult to put into practical outcomes and scenarios without a significant change in mindset, collaboration across all sectors and policy settings that will generate long-term compromised solutions.

Ecophysical systems are already stressed by clearing, salinity, fire, introduced weeds, pests and diseases. Remnant vegetation is dominantly in upper landscape positions and will arguably be the first to be affected by a drying climate. Management for forestry, agriculture and mining will affect water resources. Existing habitat and biological systems will disappear or fall below critical group size; some species will adapt, emigrate or be restricted to available refuges. New ecosystems will establish, highly mobile species will compromise and some will flourish.

Outcomes will depend on how well we monitor and manage the existing natural resources of the Peel-Harvey Catchment. SWCC is strongly urged to adopt practical and quantitative tests within its strategic planning and Management Action Targets (MATs) that assess every investment in light of the consequences of Climate Change. This is the most important basic challenge against which all other work undertaken and by which SWCC will be judged.

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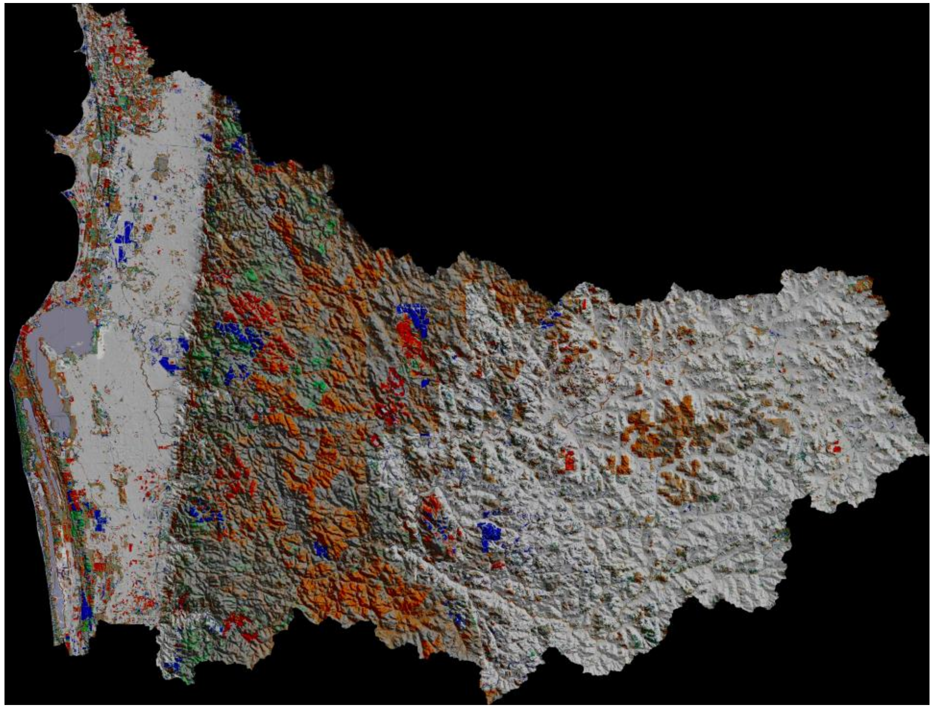


Figure 3: The status of the vegetation of the Peel-Harvey Catchment and its trends since 1988 can be mapped from the Land Monitor data. (Example taken from the PHCC DSS Toolbox includes vegetation trend and elevation data).

Raising awareness

Since the formulation of this study in 2004 the public perception of Climate Change issues has increased immeasurably. Climate Change predictions for the South West of Western Australia include increased temperature and evaporation; decreased rainfall and runoff; rising sea level and coastal erosion; and increased seasonal intensity and variation of storm events. This will, in turn, have a measurable effect on landscape, water, biodiversity and people.

The objective was to (non-hysterically) increase awareness and prepare land and biodiversity managers in the Peel-Harvey Catchment, to recognise and be ready to adapt to the effects of predicted climate change through the provision of the best-available technical and scientific information combined with local knowledge input.

To a very large extent this capacity has been put in place with the creation of the Peel-Harvey Catchment Council's Decision Support System: a toolbox, which has been externally acclaimed as the most advanced NRM Biodiversity assessment system in Australia. The practical message that comes directly from the linked technologies is that we have the capability to regionally map vegetation condition and medium-term trend that is showing Climate Change effects. From that hindcast we can start to understand better how to critically forecast, and an "adaptive" approach is taken.

The probable effects of Climate Change will have positive and negative outcomes. We must (and can in the PHC) plan and implement strategies to minimise the negative and maximise the positive effects on natural resources and biological diversification within the catchment and demonstrate that philosophy and capability to the wider SWCC community.

Before you can measure change you must understand the characteristics and the parameters of the variable system. Therefore a basic understanding of the physical character of the formation of the planet and how it sits in our solar system is offered.

In the beginning…..

The planets were formed from eddies of gas and dust in proportions corresponding to their cosmic abundance. Mostly hydrogen and some helium, the rest included all the other elements, mainly neon, oxygen, carbon, nitrogen, sulphur, silicon, magnesium, iron and aluminium. The solid Earth was a condensed rocky mixture of silicates and sulphides of magnesium, iron and aluminium, whose molecules stayed firmly together by chemical forces. The excess of iron was sinking slowly through the molten rock and formed the incandescent nucleus.

Meanwhile the solid Earth matter contained gaseous materials of helium, neon and argon, that were not combined with anything; and hydrogen atoms, that or were combined to each other by pairs to form hydrogen molecules (H2), or were combined with other atoms: with oxygen to form water (H2O), with nitrogen to form ammonia (NH3) or with carbon to form methane (CH4). Gravity pressure and the still more violent volcanic action were expelling gases with hydrogen molecules and the atoms of helium and neon being too light to be retained, escaped quickly. The Earth's atmosphere was forming with steam, ammonia, methane and some argon. Most of the steam (water) was condensed and formed the oceans.

Once the atmosphere formed from these gases, the action of ultra-violet rays on the water vapour affected the free oxygen (molecules formed by two oxygen atoms, O2). Still more intense an ultraviolet action transformed that oxygen into ozone (with three oxygen atoms O3). Ozone absorbs the radiation ultraviolet and acts of barrier.

Then, in the Earth appeared something new. It was the development of a group of forms of life able to use the visible light to break water molecules. As the ozone layer does not intercept the visible light, that process (the photosynthesis) could continue indefinitely. Through the photosynthesis carbon dioxide was consumed and oxygen was freed. Then, after 500 million years, the atmosphere became a mixture of nitrogen and oxygen, and the biosphere as we know it began.

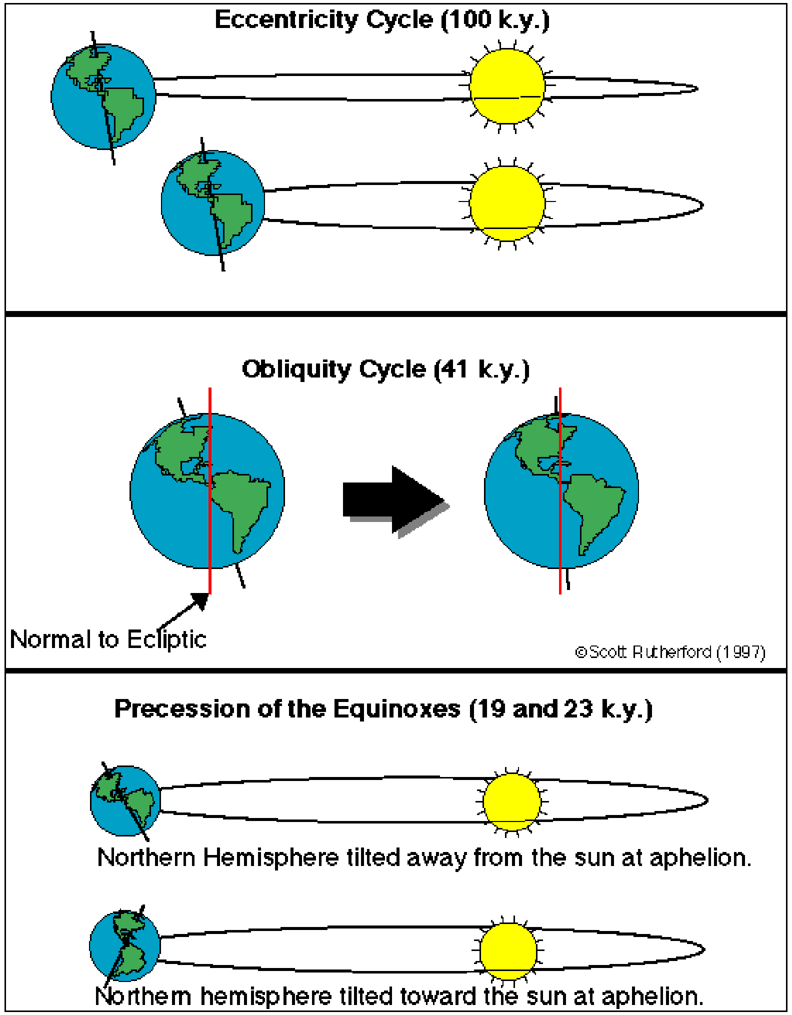


Figure 4: Orbital characteristics of the Earth do influence Climate and the extent of Eccentricity, Obliquity and Precession of the equinoxes, as predicted by Milankovitch and others, must be considered in the models.

The Seasons and the Earth's Orbit - Milankovitch Cycles

Our Climate and therefore the seasons as we know them are caused by the tilt of the axis of the Earth's rotation - the 23.4° offset of the axis from a direction perpendicular to the Earth's orbital plane. The direction of the rotational axis stays nearly fixed in space, even as the Earth revolves around the Sun annually. As a result, when the Earth is at a certain place in its orbit, the southern hemisphere is tilted toward the Sun and experiences summer. Six months later, when the Earth is on the opposite side of the Sun, our hemisphere is tilted away from the Sun and experiences winter. The solstices mark the two dates during the year on which the Earth's position in its orbit is such that its axis is most directly tilted either toward or away from the Sun.

However, there is a complication. The Earth's orbit is close to being a perfect circle, but not quite. It is elliptical, which means that the distance between the Earth and the Sun varies over the course of the year. This effect is too weak to cause the seasons, but it might have some influence over their severity. The Earth reaches perihelion - the point in its orbit closest to the Sun - in early January, only about two weeks after the December solstice. The proximity of the two dates is only a coincidence because the date of perihelion does not remain fixed, but, over very long periods of time, slowly regresses (moves later) within the year. There is some evidence that this long-term change in the date of perihelion influences the Earth's climate.

We can measure the length of the year in several different ways. The length of the year from equinox to equinox (equivalently, solstice to solstice) is called the tropical year, and its length is the basis for our Gregorian (civil) calendar. Basically, the tropical year is a complete cycle of seasons. But the length of the year from perihelion to perihelion, is called the anomalistic year. On average, the anomalistic year is about 25 minutes longer than the tropical year, so the date of perihelion slowly shifts over time, regressing by about 1 full day every 58 years. The date of perihelion thus moves completely through the tropical year in about 21,000 years.

Most of the difference in the average lengths of the two kinds of year is due to the very slight change in the direction of the Earth's rotation axis in space from one year to another. However, the Earth's axis is not quite constant, moving at a rate of a little more than a half-degree per century. This gradual change in the direction of the Earth's axis, called precession, is caused by gravitational effects of the Moon and Sun on the spinning, slightly oblate, Earth.

Because the direction of the Earth's axis determines when the seasons will occur, precession will cause a particular season to occur at a slightly different place in the Earth's orbit from year to year. At the same time, the orbit itself is subject to small changes, called perturbations. The Earth's orbit is an ellipse, and there is a slow change in its orientation, which gradually shifts the point of perihelion in space. The two effects, the precession of the axis and the change in the orbit's orientation, work together to shift the seasons with respect to perihelion. Thus, because a calendar year is aligned to the occurrence of the seasons, the date of perihelion gradually regresses through the year taking 21,000 years to make a complete cycle of dates.

The 21,000-year cycle may not be very important climatologically because the Earth's orbit is almost circular - the distance to the Sun at perihelion is only about 3% less than its distance at aphelion. However, whether perihelion occurs in January or July, it seems unlikely that our seasons would be much affected. At least, that is the case now; but the eccentricity of the Earth's orbit (how elliptical it is) also changes over very long periods of time, from almost zero (circular orbit) to about three times its current value. The eccentricity of the orbit varies periodically with a time scale of about 100,000 years. So, it would be reasonable to suppose that if the 21,000-year perihelion shift cycle were to have any effect on climate at all, it would only be during the more widely-spaced epochs when the orbital eccentricity was relatively large. That is, climatologically, the 100,000-year cycle of eccentricity should modulate the 21,000-year cycle of perihelion.

Another important cycle that affects the Earth's climate is the 41,000-year variation in obliquity. That is the tilt of the Earth's axis with respect to a direction perpendicular to its orbital plane. This variation differs from precession - the two motions are at right angles to each other. The obliquity varies by only a few degrees back and forth, and the current value of 23.4° is near the middle of the range. However, climatologically, the obliquity variation has the potential to have a fairly direct effect on seasonal extremes.

The 21,000-year perihelion cycle and the 41,000-year obliquity cycle do appear in the climatological record. But the dominant climate cycle that is seen has a period of about 100,000 years. Although this coincides with the period of change in the eccentricity of the Earth's orbit, the theory does not predict that we should see this period directly, the effect of eccentricity should appear only as a modulation of the 21,000-year perihelion cycle.
(Adapted from George Kaplan based on Milankovitch 1920, Andhermar 1842 and Croll 1875).

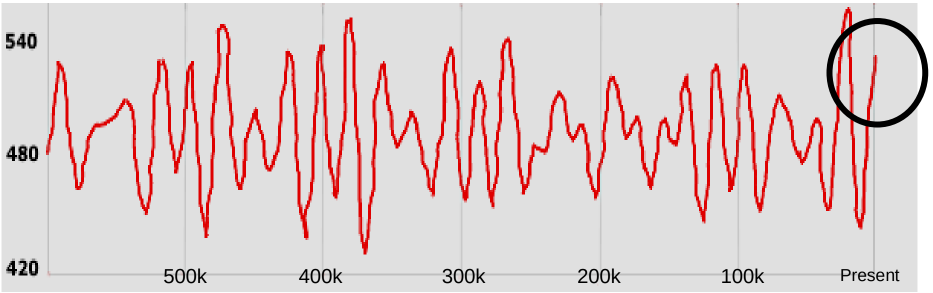


Figure 5: The incoming solar radiation over the last 600,000 years based on the eccentricity of the orbit, tilt of the axis and precession of the equinoxes is used by some to explain current cyclic warming trend. Berger and Loutre (1991).

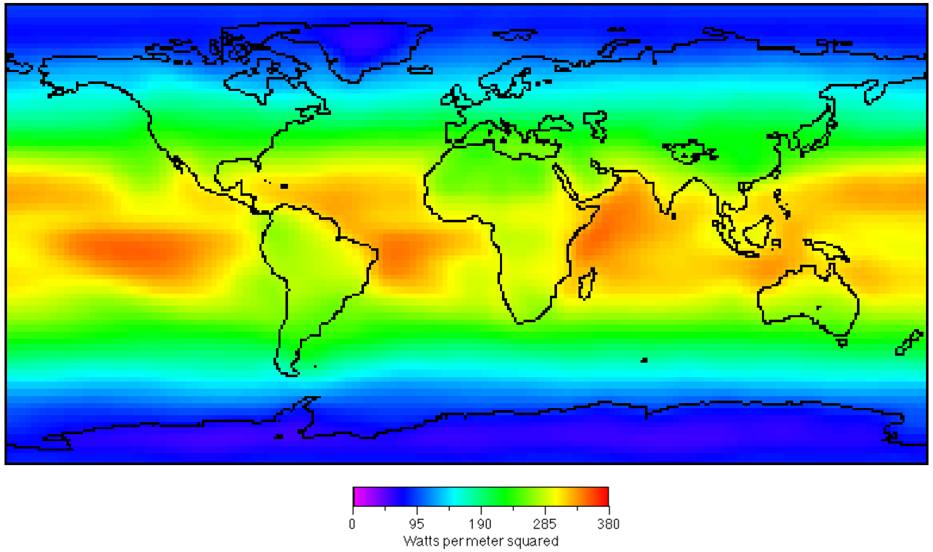


Figure 6: The annual pattern of solar radiation absorption at the Earth's surface is influenced by land cover, vegetation and cloud cover (water vapour).

Important Reference Work

The Federal Government has taken practical steps to position its policy that includes: the establishing of the Australian Greenhouse Office; support for the Indian Ocean Climate Initiative (IOCI) through CSIRO; membership of the Intergovernmental Panel on Climate Change (IPCC). The IPCC is a group of 2500 of the world's best climate scientists who meet periodically and review the research (some 6000 papers were reviewed to reach consensus for the 2006 report). Also, although not ratified, the Kyoto Protocols have set targets that the federal government has indicated that it aims to meet its targets; and, is party to the Asia-Pacific Partnership on Clean Development and Climate.

The State Government has established a Greenhouse and Energy Taskforce; supports IOCI; and within individual departments is undertaking research and management including two relevant independent projects, The Green House Strategy and SRFME that will underpin all of the work in the PHC. Links with “Climatic Scenarios & Land Use Study” project, which aims to assess potential climates variability and the effects these may have on crop and pasture suitability that is currently run by the Department of Agriculture on the Southern Agriculture Region.

The Australian Greenhouse Office produced a significant report titled “Stronger Evidence but New Challenges: Climate Change Science 2001-2005” which summarised progress and some of the observations have been included as follows with some editing:

“The evidence for a warming Earth is stronger and the impacts of climate change are becoming observable in some cases. Model-based estimates of the degree of global warming by 2100, lie between 1.4 and 5.8°C. In part, the spread in the range of estimates is due to the uncertainty about the nature and strength of processes that could dampen or amplify the initial greenhouse gas forcing. Most of the emphasis up to now has been on feedback associated with water vapour and clouds. However, over the past few years, research has yielded a better understanding of three additional effects that were recognised as being important but for which little quantitative information was available at the time.

The first of these effects is based on the radiative properties of aerosols, small particles suspended in the atmosphere that generally scatter (reflect) incoming solar radiation and thus cool the Earth's surface, acting in opposition to greenhouse gases. Estimates of the magnitude of the aerosol cooling effect have now been made, and the estimates are moving towards a higher value than earlier thought.

A second effect is associated with a decrease in albedo (the reflectivity of the Earth's surface) caused by the melting of snow and ice. The most dramatic example of this effect will likely occur in the Arctic Ocean, which is now projected to become almost totally ice-free in summer late this century. Retreating ice and snow expose darker underlying land and ocean surfaces, leading to enhanced absorption of sunlight and further warming.

Thirdly, terrestrial carbon cycle dynamics are expected to change significantly through this century, with strong amplifying effects. Several processes – the oxidation of soil organic matter, the number and areal extent of major disturbances such as fire, and the stability of carbon pools in wetlands and frozen soil – are all sensitive to climate. As temperature rises, these processes in general release further amounts of carbon to the atmosphere, forming a feedback loop that intensifies the warming.

Although much uncertainty still surrounds the timing, rate and magnitude of these effects, they all operate to amplify the initial greenhouse warming. Thus, there is now perceived to be a greater risk that the upper end of the well known IPCC TAR estimate of a 1.4 to 5.8°C temperature rise will be reached or exceeded by 2100.

Less clear are the links between climate change and two phenomena that could lead to potentially devastating impacts – droughts and tropical cyclones. Some regions of the Earth have experienced 50-year drying trends, with circumstantial evidence linking the drying with increasing sea surface temperature. Although there is no evidence for an increase in the number of tropical cyclones, some studies show an increase in the destructiveness of tropical cyclones, again related to the increase in sea surface temperature.

The observational evidence which supports the fundamental principles of climate change science has grown even stronger in the post-TAR years. The atmospheric concentration of CO2 continues to increase, and several lines of evidence, most notably isotopic analysis, attribute most of this increase to the combustion of fossil fuels. The instrumental record showing a warming Earth is supported by satellite measurements of tropospheric warming and by observations in the cryosphere and biosphere.

In summary, post IPCC TAR research has confirmed with stronger evidence the patterns of climate change described in the TAR. In addition, research over the past five years has taken a more systems-oriented approach to climate change, exploring the processes and feedbacks that affect the projections of climate change through the 21st century. A better understanding of the severity and rate of climate change over the coming decades is crucial to assessing the potential impacts on societies and ecosystems, some of which are now observable".

Greenhouse gases (GHG)

Carbon dioxide is the most discussed green house gas (GHG). However, CO2 is but one of the greenhouse gases. Methane and Nitrous Oxide have also increased dramatically in the atmosphere and are also attributable to in part to anthropogenic activities. To incoming visible solar radiation these gases are relatively transparent. However, they do absorb the reflected thermal component (infrared radiation) and as a consequence of increased amounts of these gases the atmosphere and subsequently the oceans and land will also warm.

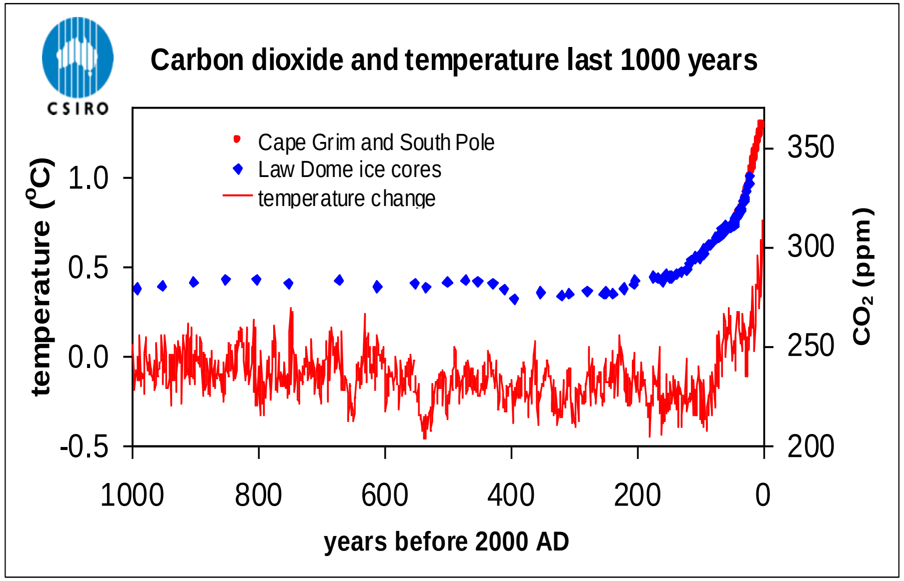


Figure 7: The main greenhouse gases (GHG) are water vapour, carbon dioxide, methane, nitrous oxide, ozone and CFCs. Since 1750, carbon dioxide has risen 35%, methane 151%, nitrous oxide 17%, tropospheric ozone 36%. The temperature of the late 20th century is the highest in at least the past 1000 years.

CO2 concentrations have grown from <u>280</u> ppm in 1750 to <u>375</u> ppm in 2003. Half of CO2 emitted by human activities is absorbed by oceans and biosphere, leaving half in the atmosphere where it has a lifetime of 50 to 100 years. It will not be possible to stabilise GHG concentrations at current levels. Stabilization at <u>450</u> ppm requires reductions of 40% by 2050 and 60% by 2090, limiting global warming to 1.2 to 2.3 ºC by 2100.

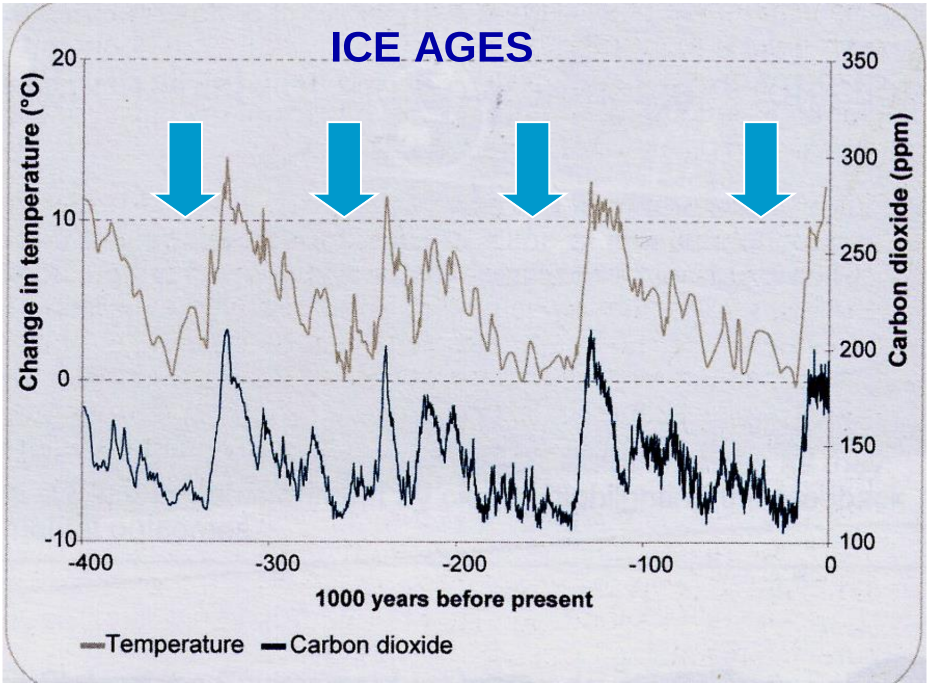


Figure 8: Temperature and CO2 are correlated

Greenhouse Gas (GHG) Sources in the PHC

The energy sector is the greatest contributor (+60%) of GHG most of which is almost entirely (98%) from coal, natural gas and oil. The net GHG emissions have risen more that 12% since 1990 and are forecast to continue to grow rapidly as demand for power for urban, industrial and especially for mining and resource benefaction are met. The production of alumina is particularly energy intensive and expansion of other mining activities and processes will contribute additional GHG loads.

To offset the increased contribution of GHG several factors have had an influence in the PHC. The virtual cessation of clearing of land for agriculture, which was initiated principally to limit the increase of salinity, and the expansion of plantations of various hardwoods and general silviculture has affected the carbon balance.

Although Australia only contributes about 1.5% of the global GHG, on a per capita basis, WA and the Peel Region in particular, is probably one of the highest contributors of emissions any where in the world.

Regardless of reductions in GHG emissions, some change is inevitable. This is based on a series of predictive models that have widely varying outcomes, but all point to some degree of global warming that has already been recorded in the SW of WA. This is predicted to keep the rain-bearing winter fronts further south-east and reduce winter rainfall.

What is Happening?

Rainfall in the South West of Western Australia comes mainly from two directions. Either from SW fronts that gather moisture from deep in the southern Indian Ocean and travel easterly around the globe, dominantly in winter months; or from the Northwest from tropical-fed systems.

The prediction is that with global warming the frequency and position of the SW fronts will change. The centres of the high-pressure systems will be further south although the NW fronts may be more frequent and the Northern part of WA may receive more rainfall from such systems.

Atmospheric circulation patterns have changed and this has been part of CSIRO and BoM studies that plotted storm development tracks between 1949-1968 against 1975-1994, and this shows a distinct shift from the SW of WA to the East (NCEP/NCAR). Clearing of native vegetation for crops, increased sea surface temperature and even reduced thermal differential cause by reduced extent of Antarctic sheets have been postulated as drivers. Natural variability could also explain this shift but the evidence is building.

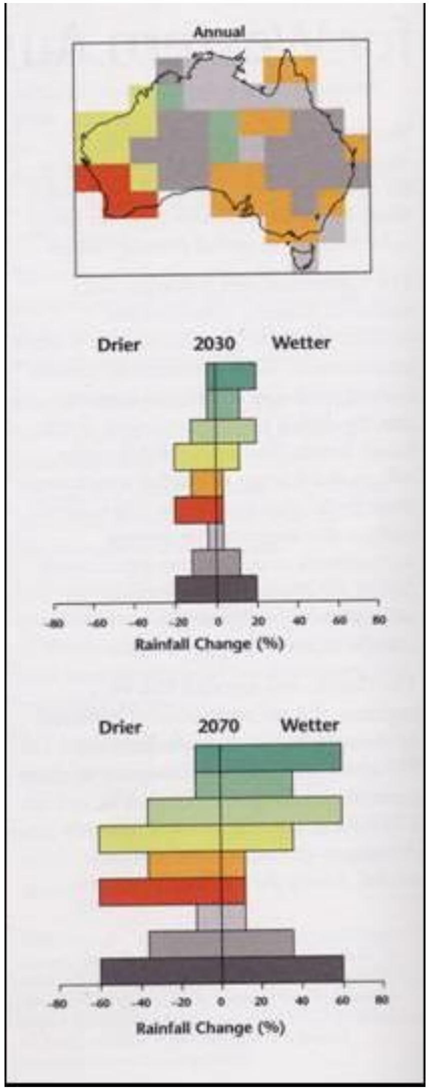


Figure 9: The CSIRO-derived long-term rainfall predictions (from Pittock, 2003) show the SW as having a range of rainfall decline as much as -20% by 2030 and -60% by 2070 relative to 1990. (note high uncertainty)

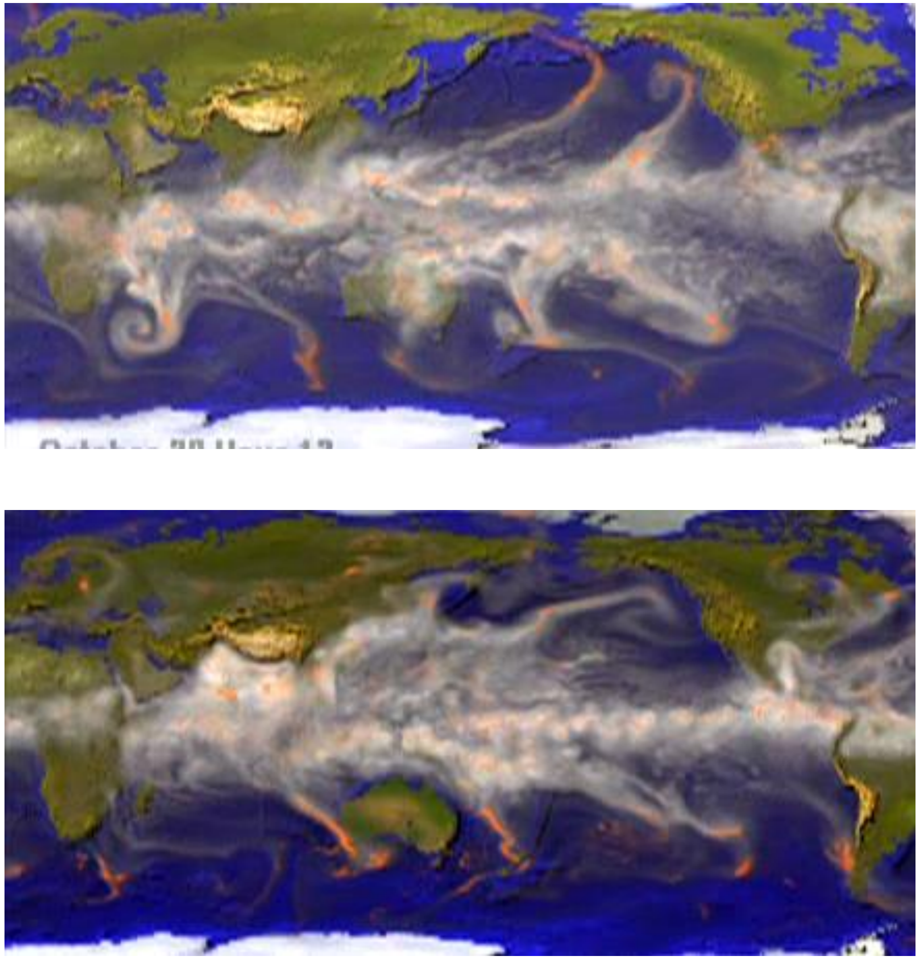


Figure 10: (Top) South-Westerly fronts bring most winter rain (orange is rainfall, white is water vapour), (Lower) North-Westerly front are less reliable although may deliver significant rainfall events.

TEMPERATURE

Tony Ashby Peel Series copyright

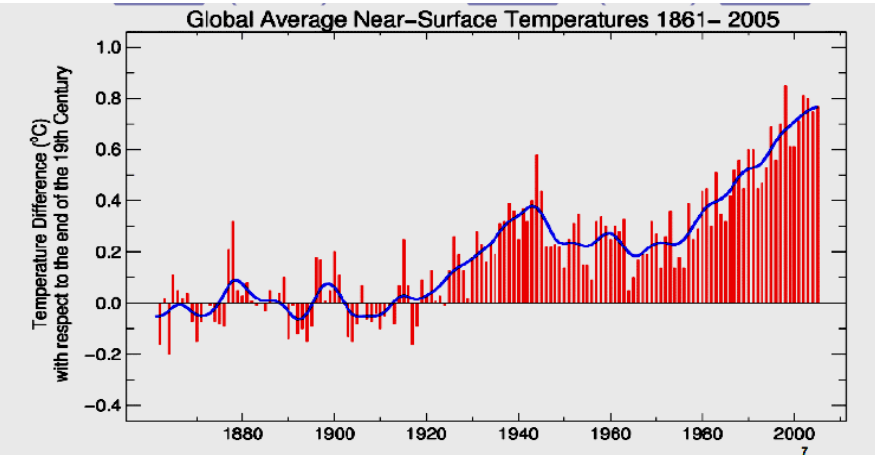


Figure 11: Global temperatures increases of the order of 0.8°C since 1900 have been also recorded in the Peel-Harvey Catchment, but the data show great variability.

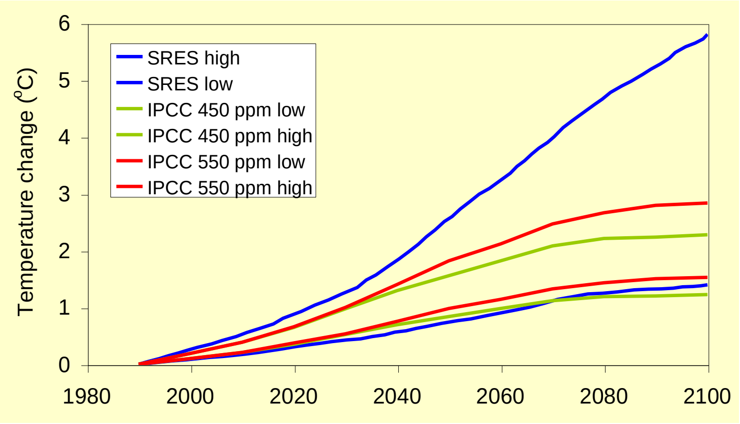


Figure 12: The results of modelling of Temperature using scenarios of CO2 limitation at both 450 and 550ppm produce wide variance when projected to 2100.

Table 1: IOCI (CSIRO Charles) predictions for 2030 from present.

Feature	**Low Global Warming**		**High Global Warming**	
	Estimate of Change	***Uncertainty***	***Estimate of change***	***Uncertainty***
Annual average temperature	+0.5 °C	±0.3°C	+1.1°C	±0.7°C
Average sea level	+3 cm		+17 cm	
Annual average rainfall	-5%	±5%	-11 %	±11%
Seasonal average rainfall Summer	-3%	±6.5%	-7.5%	±15%
Autumn	-3%	±6.5%	-7.5%	±15%
Winter	-5%	±5%	-11%	±11%
Spring	-5%	±5%	-11%	±11%
Annual average potential evaporation	+1.9%	±1.4%	+4.3%	±3.1%
Annual average number of hot days (>35°C)	+1 day		+20 days	

Temperature Pattern and Prediction

The predictions of Charles (2005) for the SW of WA give a temperature range for a low global warming scenario of an increase of 0.5°C with an uncertainty range of ±0.3°C over the next 25 years. Under a high global warming scenario the upper range is for an increase of 1.1°C with an uncertainty range of ±0.7°C. This gives the high probability of an increase in the range of somewhere between 0.2°C and 1.8°C.

Analysis of the long-term temperature trends for the four selected stations covering the Peel-Harvey Catchment has been divided into two periods; (i) the total length of record, 1900-2005 for Mandurah and Wandering and since 1935 and 1960 for Dwellingup and Narrogin respectively; and (ii), for the period 1975-2005 for all stations. The results are starkly different. It is a complex interpretation and the use of linear statistics is an attempt to simplify trends which are not simple to explain. However, it does give an example of the range and rate of the temperature variance and the gross trends are indeed, just that!

1900-2005

An increase of between1.0 - 2.0°C in the average annual maxima over the over the century is recognisable in Mandurah, Dwellingup and Wandering but is not as marked at Narrogin.

The seasonal maxima also show a consistent trend, with the exception being Narrogin especially in the summer maxima which appears to remain relatively stable over the longer period. The winter maxima for Narrogin also seem to have been more stable over time.

The seasonal minima also show the stronger increasing temperature trend nearer the coast with Narrogin again not showing the same trend and may even indicate a falling long-term trend.

1975-2005

Contrary to the longer term trend, the 30 year trends from 1975-2005 show that recent averaged trend has not conformed to the longer-term trend. Temperature trends seem to be stable or showing decline in most seasons in both average maximum and minimum trends. Therefore the data show that the temperature trend over the past 100+ years does not always tally with the last 30 years. It is at variance with the published data for the SW WA and may represent local climatic variability.

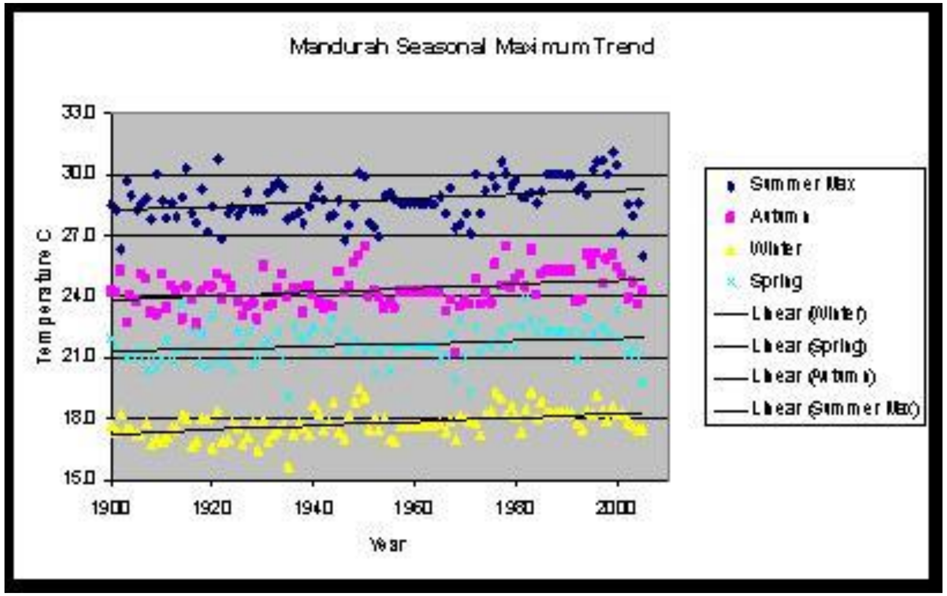


Figure 13: This example graph taken from the appendix section shows the long-term (1900-2005) seasonal maxima trends of rising temperatures in all seasons for Mandurah. (Full data in App. One)

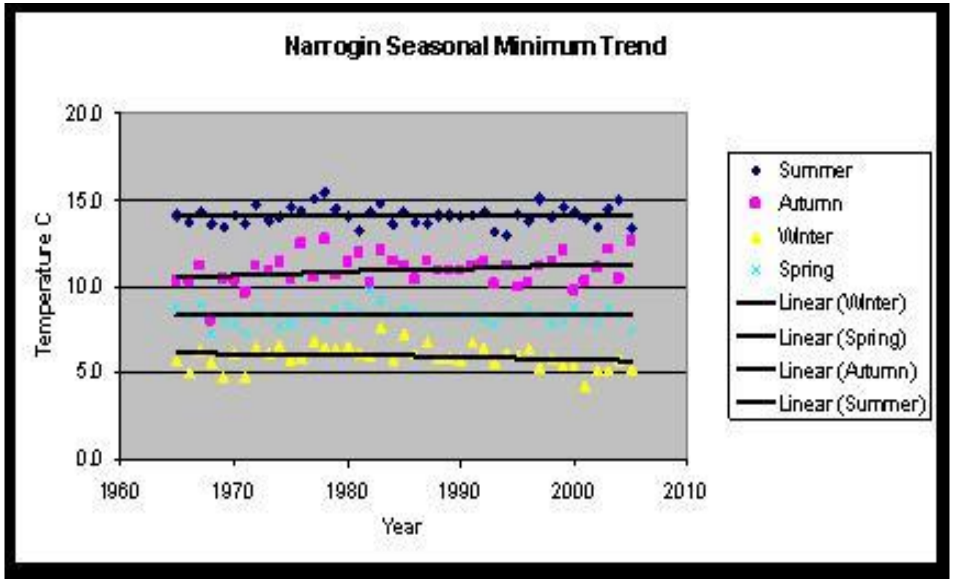
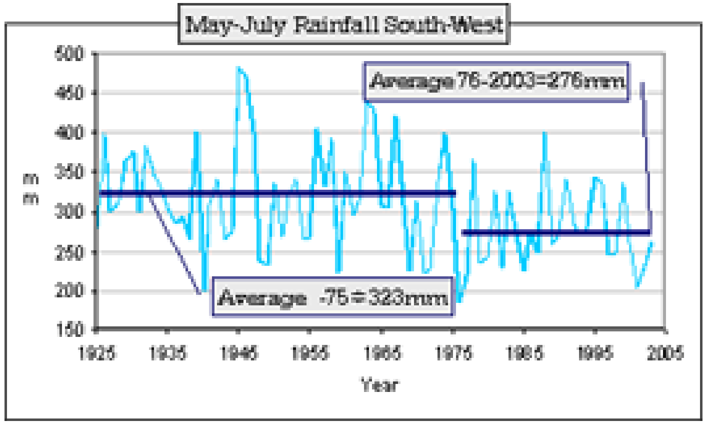


Figure 14: This example graph taken from the appendix section shows the long-term seasonal minima trends of stable or falling temperatures in all seasons for Narrogin. (Full data in App. One)

The raw data from which the graphs used in the appendices were generated is attached in Microsoft Excel format. These have been adapted and collated and in some cases interpolated between relocated rain gauges from raw data supplied by the WA Bureau of Meteorology (John Cramb) in 2006.



IOCI

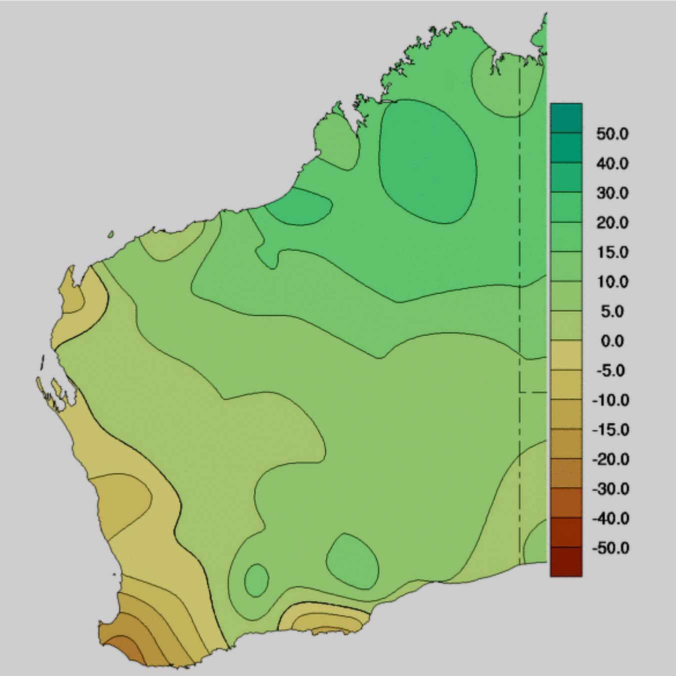


Figure 15: Changes in total average annual rainfall in SW Western Australia

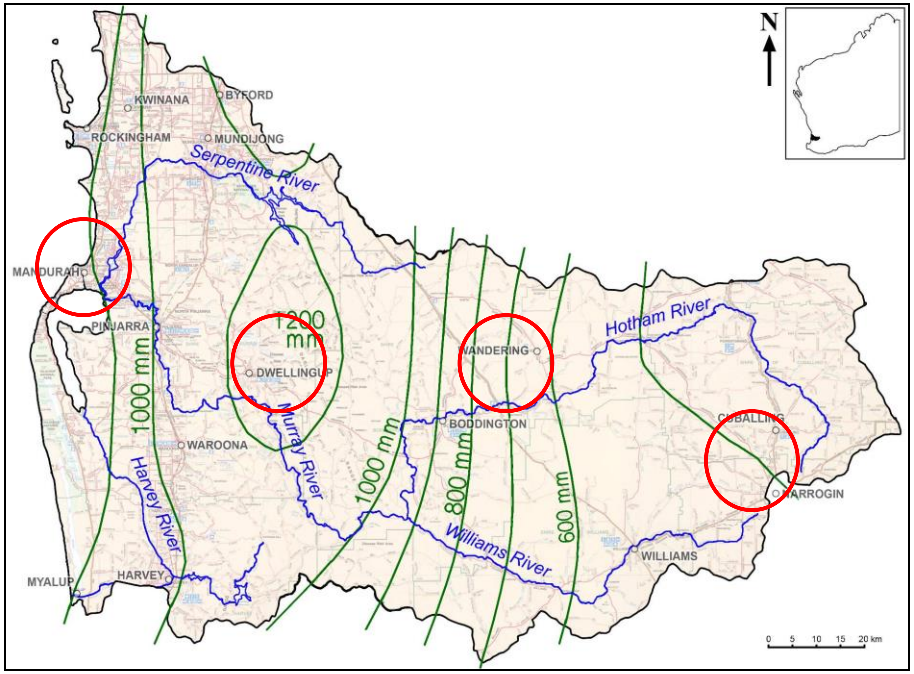


Figure 16: The Peel-Harvey catchment and historic mean average rainfall. The long term general trend shows a west to east decline across the catchment from a coastal 1000mm, apart from the geographically induced high (+1200mm) near Dwellingup and a rapid reduction to less that 600mm by Williams. This study concentrates on the long-term data from the four representative sites (circled) of Mandurah, Dwellingup, Wandering and Narrogin.

Rainfall Pattern and Prediction

IOCC and IPCC predictions for rainfall for the Peel-Harvey Catchment is that it will decline by 20-30% by 2030, and that it has already declined by 15% since 1975. Figure 17 indicates that run-off in hills catchments has declined by 64% and some estimates indicate that it could effectively cease. This study of the available records has, like the temperature analysis, been divided into annual and seasonal analysis for both the entire available record, 1900-2005, and the shorter period, 1975-2005.

1900- 2005

The long-term average annual rainfall has declined for the four stations in this study. Using the graphed linear interpolations the reduction for Mandurah (930-800) is 130mm (14%), Dwellingup (1300-1200) is 100mm (8%), Wandering (710-520) is 190mm (27%) and Narrogin (530-460) is 70mm (13%).

In all cases the summer rainfall has increased, in Mandurah by 2/3rds but based on very low total rainfall, and the autumn, winter and spring rainfall is in decline, apart from Dwellingup. The most consistent figure is the decline in winter and autumn rainfall.

Table 2 shows the results of the seasonal analysis for the four recording stations. Again some interpolation was required to cover periods when no records were available and the detail and method of this interpolation is available with the raw data files are provided from the PHCC Website.

Table 2: Seasonal rainfall changes for the period 1900-2005.

	Summer	Autumn	Winter	Spring
Mandurah	**+ 68%**	**- 9%**	**- 19%**	**- 12%**
Dwellingup	**+ 37%**	**- 9%**	**- 28%**	**+ 12%**
Wandering	**+ 18%**	**- 29%**	**- 29%**	**- 32%**
Narrogin	**+ 28%**	**- 6%**	**- 18%**	**- 14%**

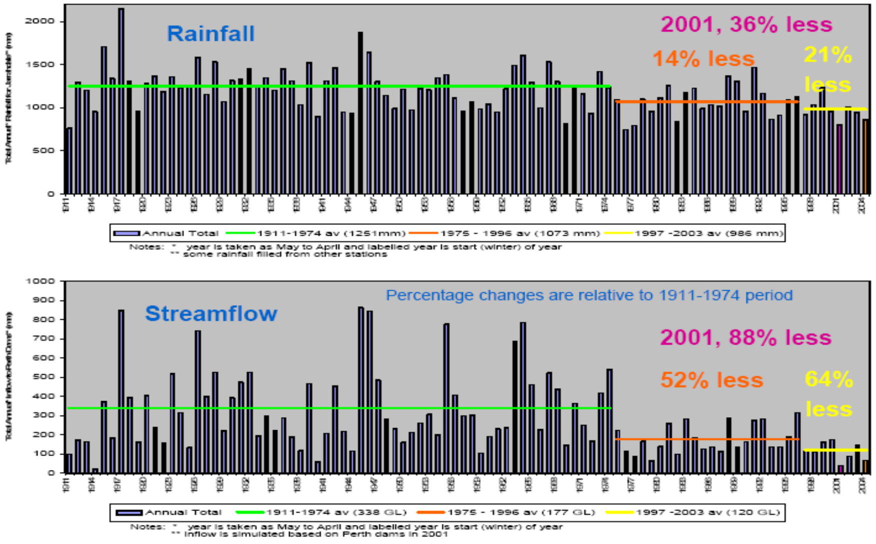


Figure 17: Stream flow data into the hills catchment is derived from Water Corp Sources and is widely used to demonstrate the dramatic consequences attributed to Climate Change and reduction of run-off.

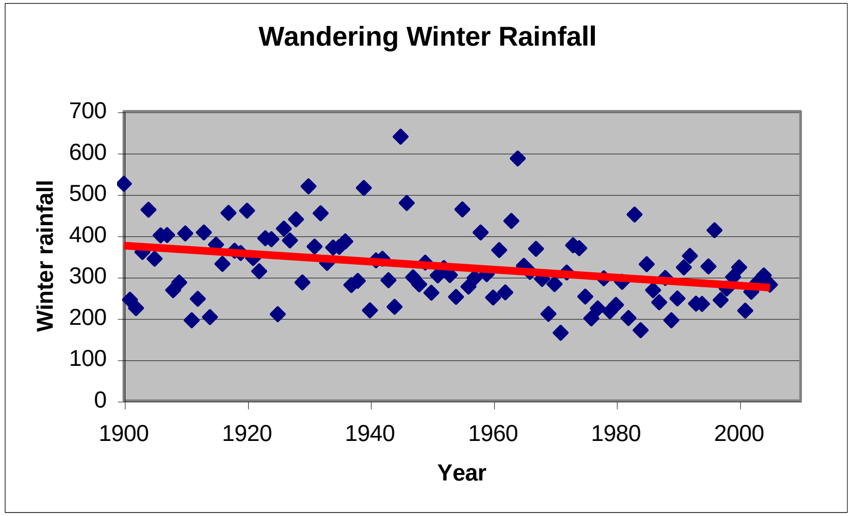


Figure 18: An example of linear trend and reduction in variability of long-term rainfall for Wandering used in this study and presented in full in the appendices

1975-2005

Similarly to the temperature data, average annual rainfall for the 30 years since 1975 the has for all four stations shown to be also partly at variance to the expected trend.

The interpolation of the linear annual trend for Mandurah show only a 2% decline in total rainfall, for Dwellingup a 5% increase is also shared with a 2% increase at Wandering. However, Narrogin fits the SW prediction with a 14% decrease for the period 1975-2005.

High variability in rainfall is to be expected and an analysis of the variability is offered in Figure 19 that plots the mean standard deviation for each quartile (25 years x 3 and 30 years) for the period 1900-2005 which showed a consistent reduction in rainfall variability for the most recent quartile period 1975-2005 for all four stations.

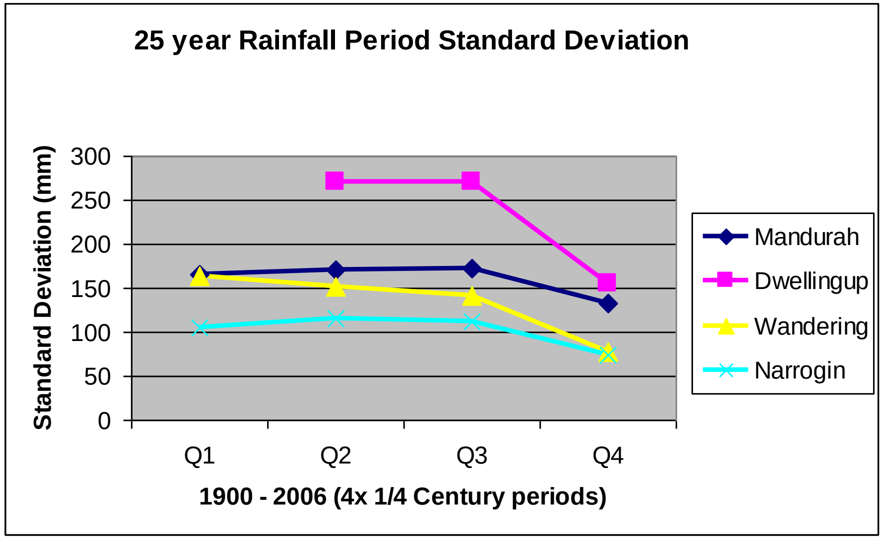


Figure 19: Standard deviation of rainfall data divided into ¼ century periods.

SEA LEVEL

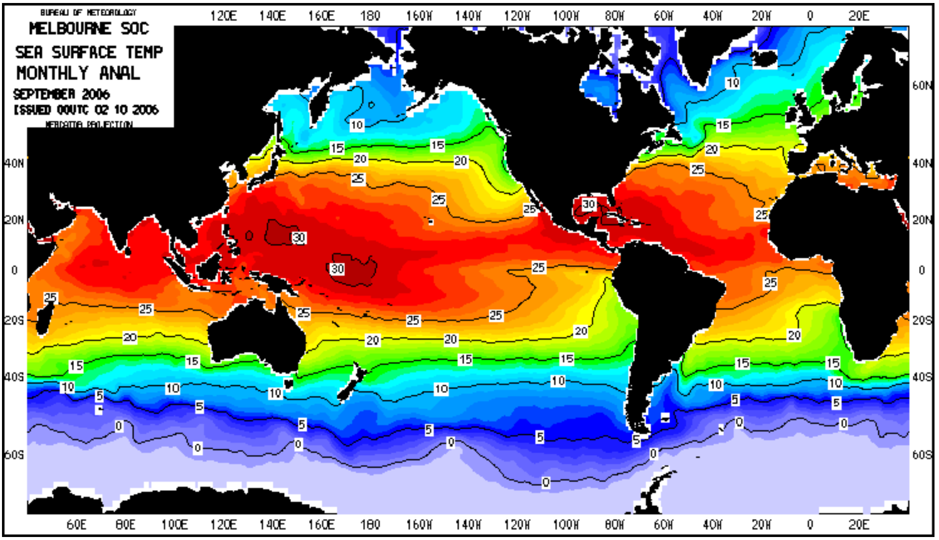


Figure 20: Satellite-derived Sea-Surface Temperature provides a basis to measure dynamic global reaction and are part of the input to predictive models.

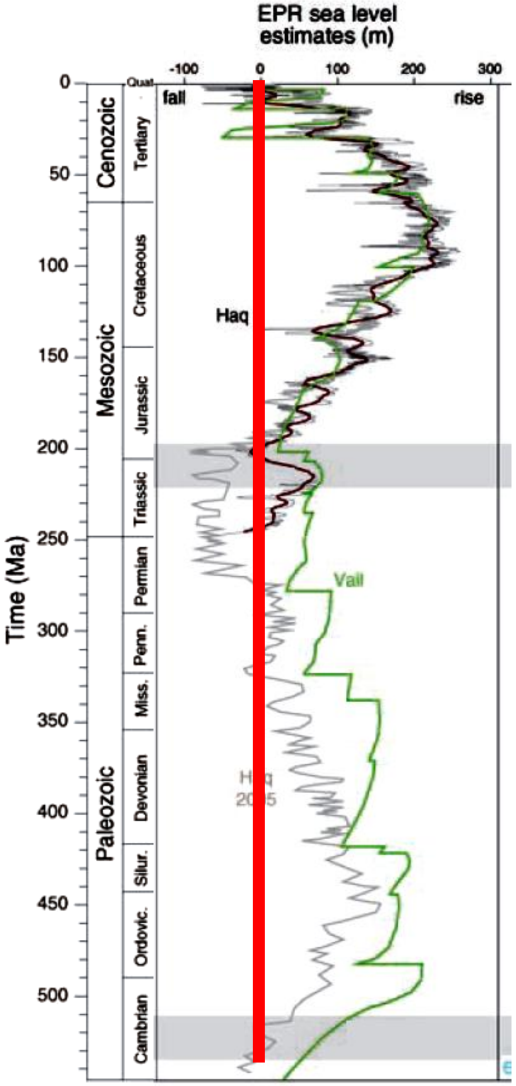


Figure 21: Historic Global Sea Level changes

Change in Sea Level

The Earth has been subjected to sea level changes over time that resulted in a sea level high of some +200m about 90 million years ago, falling through a series of ice ages to some -100 m about 125 thousand years ago. It rose to present levels with some fluctuations in the last 10 thousand years. A steady increase has been measured at Fremantle over the past 100 years of about 20 cm. An increase in sea surface temperature of at least 0.6°C since 1960 has also been measured.

Increases in sea level are produced principally by the expansion of water as it heats and the melting of ice sheets covering land masses at the poles. Floating ice does not significantly change ocean volume when it melts.

The heat content of the upper layers of the ocean is increasing, especially the upper 300 metres. A growing number of reconstructions of surface temperature over the past 1000 to 2000 years show that the sharp temperature rise over the past century is now beyond the bounds of natural variability. The imprint of greenhouse gases as the primary cause of the observed warming has also become clearer. The pattern of heat uptake in the world's ocean basins agrees well with that simulated by climate models for greenhouse gas forcing.

Estimates of sea level change vary significantly and include some predictions that sea level may increase by as much as 7m by 2100. However, the Intergovernmental Panel on Climate Change (IPCC) initially based their estimate on an increase of Global Temperature between 1.4 to 5.8°C by 2100 giving a range of sea level rise of 0.09 to 0.88m relative to 1990. (Note: The 2007 IPCC report has revised this figure down). This range represents an estimated 0.8 to 8.0mm per year and when compared with the recorded average for Fremantle of 1.38mm per year for the period 1915-1998 gives some perspective to the estimate for the last century being in the lower quartile. However, this may be escalating.

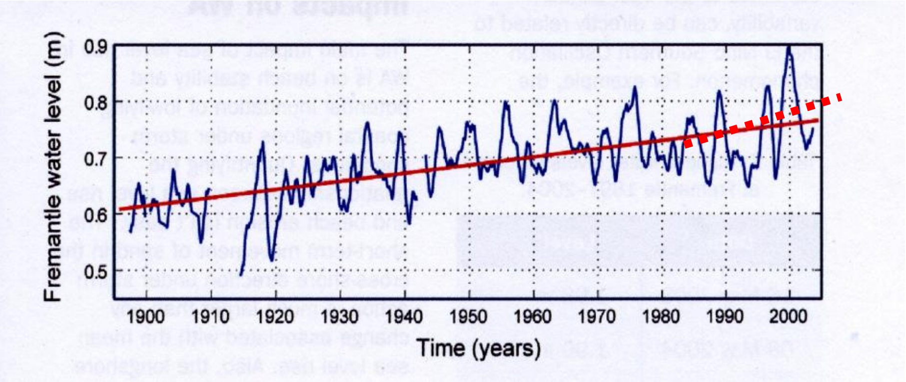


Figure 22: Change in Sea Level at Fremantle, WA 1900-2005 with an estimate of possible increases over the last 30 years. (Interpolated post-1975 trend dotted line)

There are some fundamental considerations that must be understood when trying to determine what the effect of sea level change is likely to have on the Peel Region and the Leeuwin Current. There is a complex relationship between the temperature of the atmosphere; the exchange of that thermal energy with the surface and the deeper ocean; the currents that deliver flows of thermally different waters pole-ward; and the long-term effect that may have on melting of the icecaps; and, frequency and intensity of storm events.

The Leeuwin Current: The western coast of Australia is like no other in the world with land on the escarpment having been untouched by major effects of Eustacy (changes from the effects of sea level) and Tectonism (changes from upheaval or wrenching of the Earth's crust) for much of the past 90 million years. This ancient plateau has thus provided a habitat and isolated adaptation for a very special range of plants and animals. The climate has been modified by the anomalous counter current that brings warm, nutrient deficient waters south and then east around the SW of Australia. This current flows mainly in the winter months and is anomalous in the fact that it flows against the natural anti-clockwise gyres present in the Indian, South Pacific and South Atlantic Oceans. It produces a milder climate for WA than on the west coasts of Africa and South America at similar latitudes (estimated +3°C) and has a major controlling influence in our weather systems, rainfall and natural marine and coastal biodiversity.

IOCI predictions indicate that the warm, south-flowing Leeuwin Current may experience slight increases in strength by 2100 although the increase may be small relative to the inter-annual variability which is driven by the ENSO signals from the Pacific.

The Tide: Another confusing layer of more predictable sea level change occurs in daily, monthly and longer time cycles, and that is the tide. Tide is affected by the long and short-term non-coincidental relationship of the sun and the moon and the gravitational effect on the ocean, this is compounded by atmospheric pressure and wind direction and strength. It is important to isolate these influences in planning the strategy to manage for the inevitable change that has already commenced.

Tide range on the coast of the Peel Region fits a general pattern of +0.10 to +0.90m AHD in spring tides and +0.40 to +0.70 AHD in the neaps, with the estuary following about 55% of the exchange with about a 1-2 hour lag. This has changed considerably since the opening of the Dawesville Channel in 1996 and the removal of the Fairbridge Bank in 1986 (although the Fairbridge Bank is rapidly returning as sediment enters the mouth following the failure of sand bypass measures to trap sediment).

The Coastline of the Peel Region is protected to some extent by two parallel offshore reef systems that are remnants of two earlier post-glaciation "still-stands" of older shorelines that have the effect of mitigating some of the wave energy. However, rises in sea level would remobilise significant sandy sediment that forms the barrier dune and beach system and generate a long-shore littoral drift, probably in a net northerly direction. The areas between the reef lines and the coast also contain significant quantities of readily re-suspendable sand deposits that have established in the relative calm of the "lagoon". Increased storm severity could also potentially remobilise those sediments and contribute to near-shore redistribution and reef smothering.

All of the +200km of both oceanic and estuarine Peel Region coastline will be affected by changes in sea level that will be attributed to a combination of all of the fore-mentioned influences. These areas are perceived to represent the most desirable places to live and the expectation that there will be a long-term solution to maintaining both desirable habitat for both humans and natural biological diversity is unlikely to be satisfied.

The Bruun Rule

Numerous examples are available in the international literature showing that there are linear relationships between sea level rise and coastal erosion ("more than 2/3rds of the world's sandy coastlines have retreated in the past few decades, Bird, 1996"). Perhaps the most relevant work to the Peel Region has been undertaken by Jones and Hayne (2002) at Swanbourne WA. Swanbourne Beach has many similar attributes to much of the ocean coastline in the Peel Region.

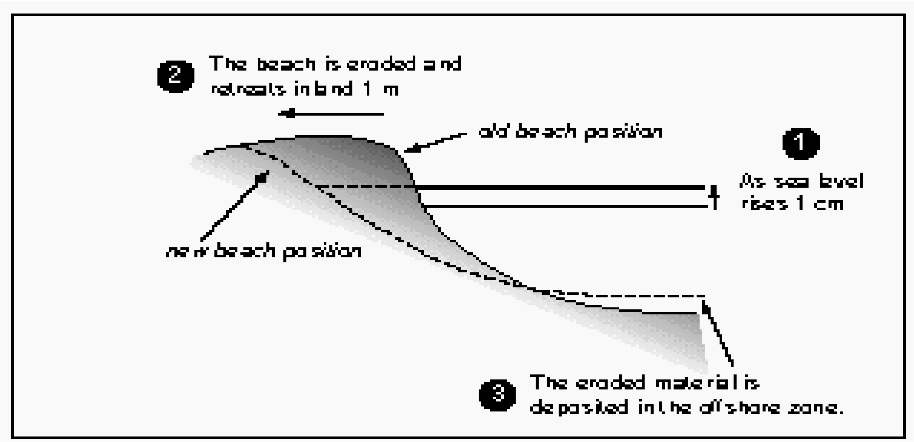


Figure 23: The Bruun Rule when applied to a coastline in the Peel could determine the amount of landward erosion caused by increasing sea level.

The Bruun Rule is the best known and most commonly used model for estimating potential loss of coastline as a result of sea level rise. Simply, it calculates shoreline Recession (R), due to a Sea level rise (S), where (L) is the cross-shore distance to water depth (h) to which near-shore sediments exist and (B) is the height of the dune.

$$R = (L / B + h) S$$

The potential erosion and recession of Swanbourne Beach using this model exceeds 40 metres in 50 years (assuming a moderate 18cm) and over 100 metres (assuming 48cm) by the next century.

These conservative figures are approximately 2.5 times higher than the setback values currently used in planning in WA. Pilkey (2004) and others have been critical of the uncontrolled use of Bruun's Rule to estimate shoreline recession in more complex coastal situations and a word of caution is noted in unvalidated blanket use of such models.

Adaptation to estuary situations

Adaption of Bruun's rule to an estuarine situation is proposed by translating landwards and upwards, with the erosion at the landward end of the profile supplying the material to raise the lower portion of the profile.

Overall the approach assumes a net sediment balance, so that simple geometry gives the landward translation (Recession), R as:
where S is the amount of sea level rise, L is the active length of the profile, hd is the closure depth and f is the freeboard.

$$R = \frac{S * L}{h_d + f}$$

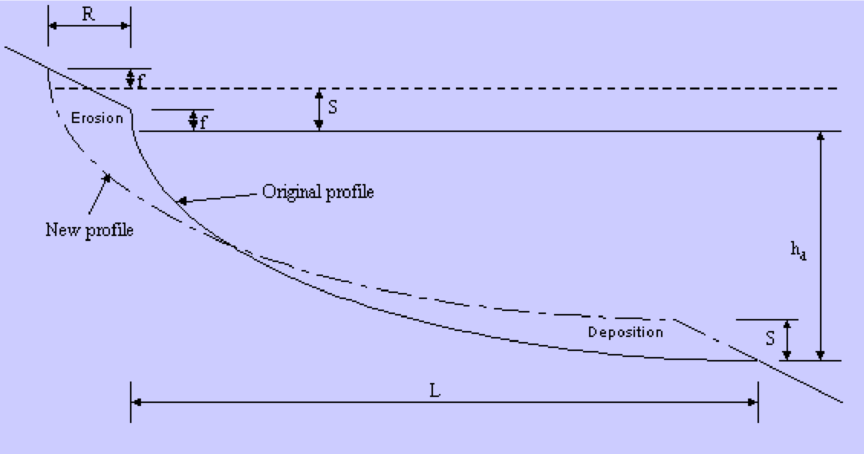


Figure 24: An adaptation of Bruun's rule to Estuaries is needed

The Bruun Rule applies only in a 2-D sense to the cross-shore profile and takes no account of 3-D effects such as longshore transport (Bruun, 1980). There is also very little field validation of the concept as applied to muddy shores especially in the gently sloping Peel-Harvey Waterways where hd and f is usually very small, L is large and longshore transport is minimal. Adaptation of Bruun's Rule to estuarine and low relief coastlines needs some more detailed analysis and validation.

Expected Peel-Region Coastal Effects

Climate models indicate that the region is likely to receive less frequent, but more intense storms. Such storms are often accompanied by storm surges that are caused by the combined effects of lower atmospheric pressure and the main driver, wind direction. (Approximately 10mm of sea level increase for each hectopascal fall). Storm surges are also affected by the shape and sea floor gradient of the coast line which can have the effect of concentrating the surge. The shape of Comet Bay and the offshore reef system would have the effect of intensifying a storm surge generated by a NW storm and the effect on the Mandurah CBD could be magnified.

Erosion of soft sediments is also closely linked to sea level and storm events. Both oceanic and estuarine shorelines in the Peel Region have dunal and sedimentary deposits that will redistribute as a function of the combined effects of rising sea level and storm-related events.

Bruun's Rule indicates that sea level rises create landward horizontal erosion of the order of 50 to 100 times that of the vertical rise. Should the maximum IPCC prediction occur, an erosion front on the sandy beaches of the Peel Region could be as much as 88 metres further inland than at present. Similar or greater outcomes are likely on the estuarine shorelines and deltaic features.

This will also have significant bearing on how planning for natural coastal resources and conserving important habitat, especially the internationally-recognised Ramsar Wetlands of the Peel-Yalgorup system. Very small changes in sea level will change the vast intertidal flats and surrounding vegetation, freshwater refuges will likely become saline, lacustrine and estuarine biota diversity will be threatened and the intrinsic avian qualities will be altered.

The obvious outcome for Local Government planning and provision of infrastructure is being realised. The insurance industry has factored in the probability of future problems and risk premiums have been incorporated into policies.

To demonstrate this possible "worst-case scenario", a section of the Peel-Harvey Catchment Council's Decision Support System Toolbox has included an interpolated line that (within the cadastral limits of the contour data) indicating the land that is 1m above the Australian Height Datum (AHD). A 100m lateral buffer line is also interpolated away from that line to demonstrate possible outcomes. Average tide conditions are approximately 0.3-0.5m above AHD so the line may represent the potential areas of inundation and erosion. As Elevations models improve the potential to improve the spatial and vertical resolution will also follow.

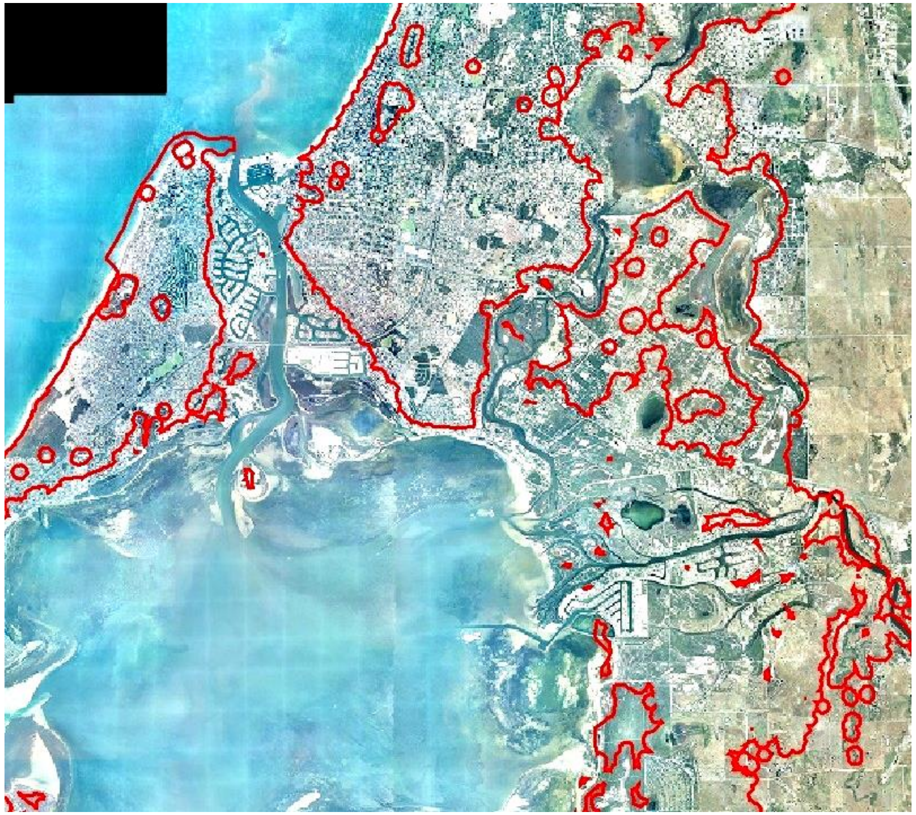


Figure 25: The interpolation contour for a 1m sea level rise coupled with an approximate lateral buffer zone of 100m overlaid on aerial photography that has already been incorporated into the PHCC DSS. This line indicates possible infrastructure and natural resources that would be directly affected by such a change in the Peel Region.

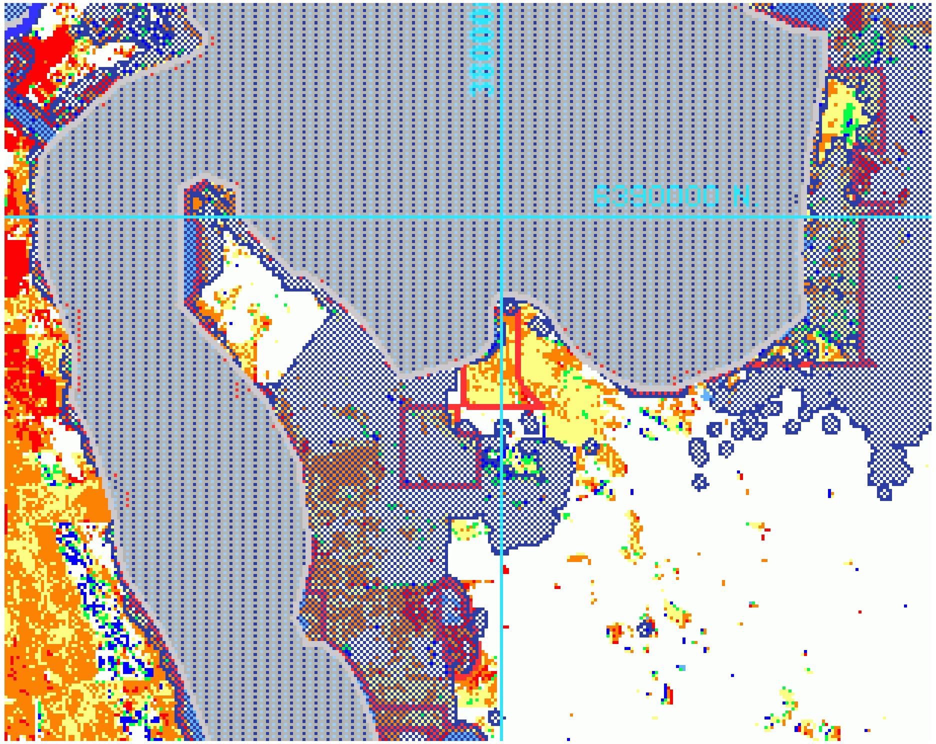


Figure 26: This example from the DSS shows the remnant vegetation trend classes that indicate the changed status of the vegetation since 1990 and the Ramsar boundaries *(red lines)* overlaid with the inundation contour *(light blue fill).*

Relevant reading and reference sites

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Hick P Biodiversity in the Peel-Harvey Catchment. PHCC website

Jones and Hayne 2002

Wilson and Hick (2006) Biodiversity Assets Assessments System, B5-04, a SWCC-funded project covering “Training NRM and Local Government Officers in the use of the Peel-Harvey Biodiversity Decision Support System”.

Australian Greenhouse Office
http;//www.greenhouse.gov.au/

Environment Australia
http;//www.ea.gov.au/biodiversity/science

Bureau of meteorology
http://www.bom.gov.au/climate/

CSIRO
http://www.csiro.au/news/issues/climate.htm

http://www.dar.csiro.au/impacts/future.html

Indian Ocean Climate Initiative
http://www.ioci.org.au/

http://www.grida.no/climate/ipcc/regional/275.htm

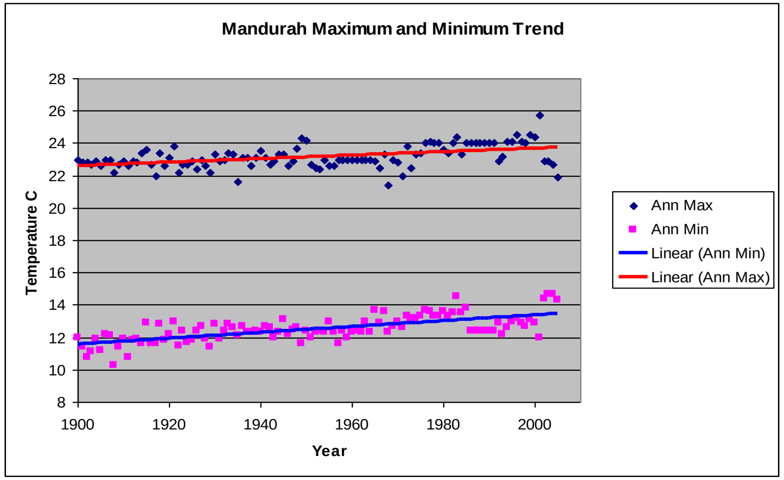
Future Climate
www.futureclimate.com.au

Western Australian State of Environment
www.soe.wa.gov.au

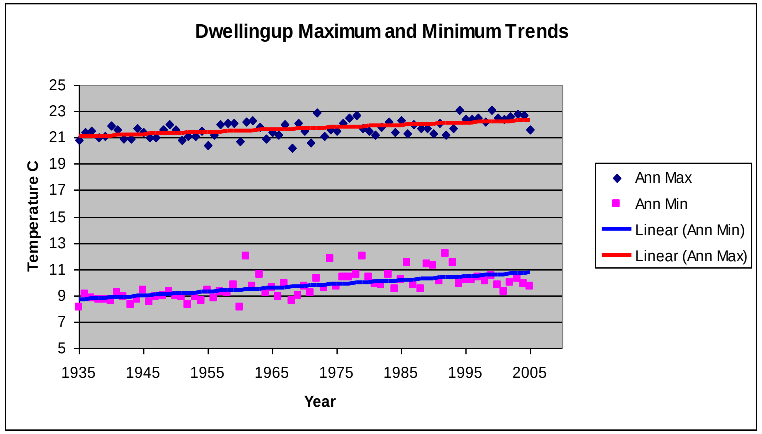
Appendix 1 Temperature Graphs

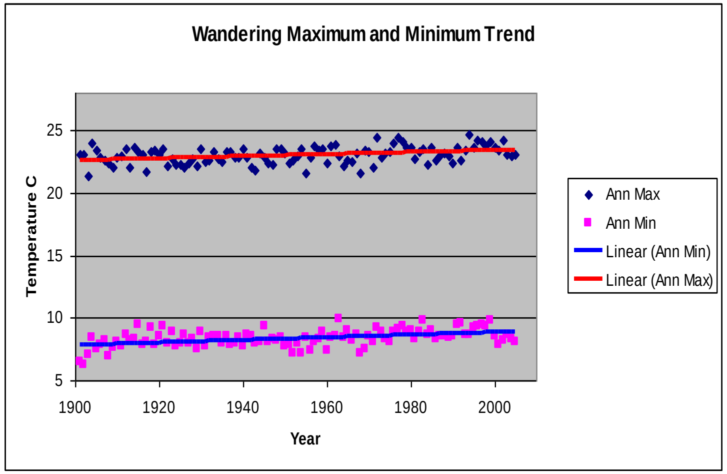
The raw data from which the graphs used in the appendices were generated is attached in Microsoft Excel format and have been adapted and collated from raw data supplied by the WA Bureau of Meteorology (John Cramb).

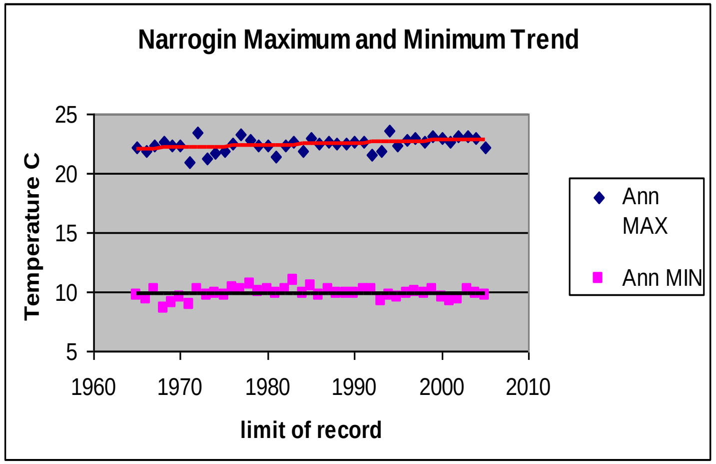
Figure A1.1: **Annual Average Long-term Maximum and Minimum Temperatures.** This group of figures graph the long-term 1900-2005 (or as available and adapted from BoM records) for Mandurah, Dwellingup, Wandering and Narrogin for annual Maximum and Minimum temperatures. These have been graphed using a linear interpolation.



Mandurah and Dwellingup minimum trend is of the order of 2°C







With the exception of the minimum trend for Narrogin all four stations appear to have an increase in temperature. The stability of the minimum at Narrogin could be associated with less rainfall and potential for less cloud cover.

Figure A1.2: **Seasonal Maximum Long-term Temperatures** show increasing trend for four stations although variability in summer maxima range from nearly +2°C in Dwellingup to negligible in Narrogin, and lower but more uniform trend in winter maxima for the long-term (1900-2006) period.

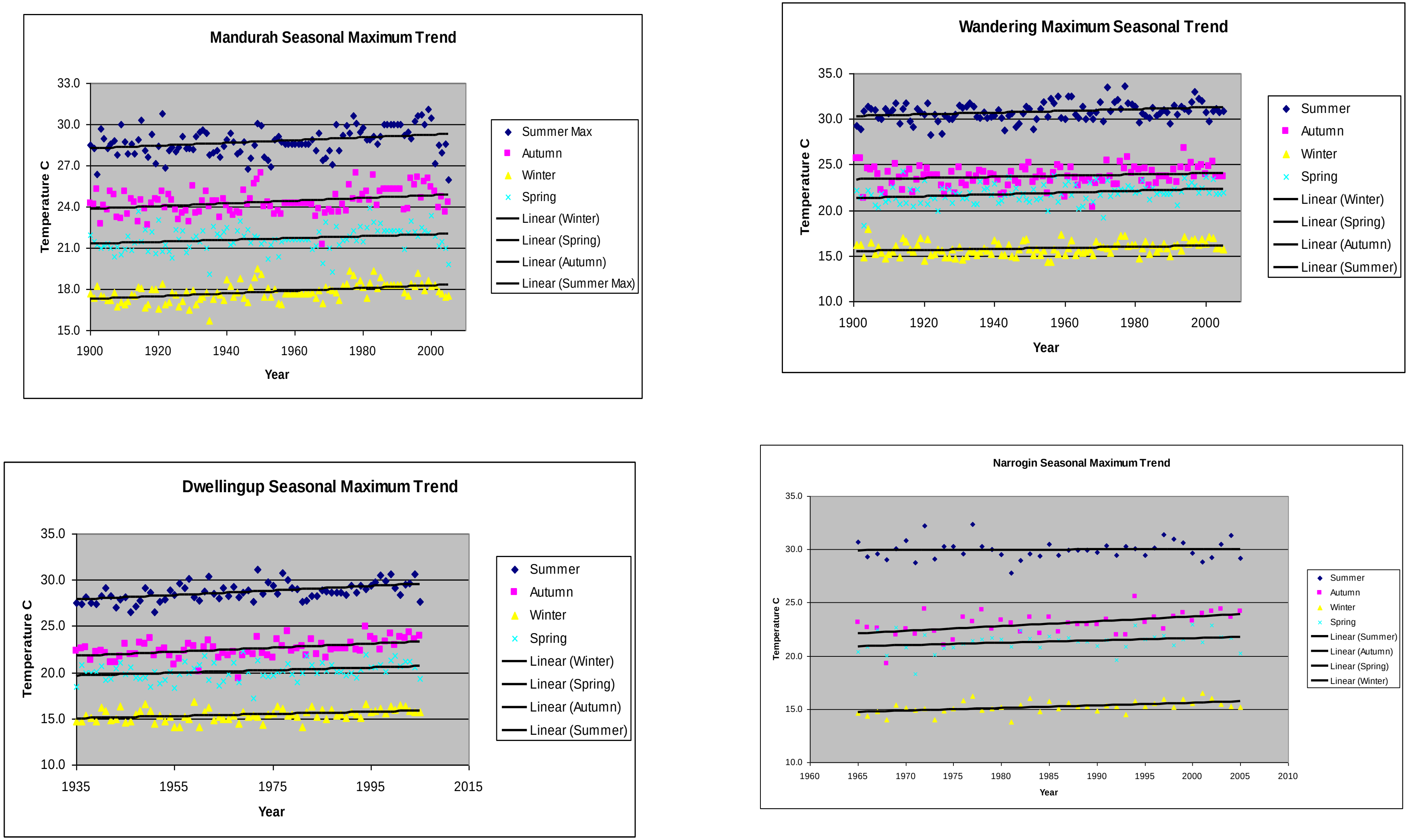
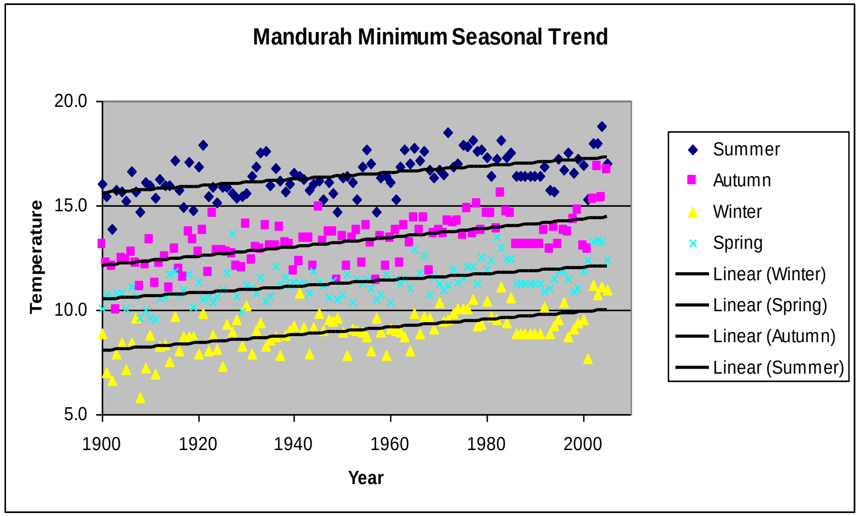
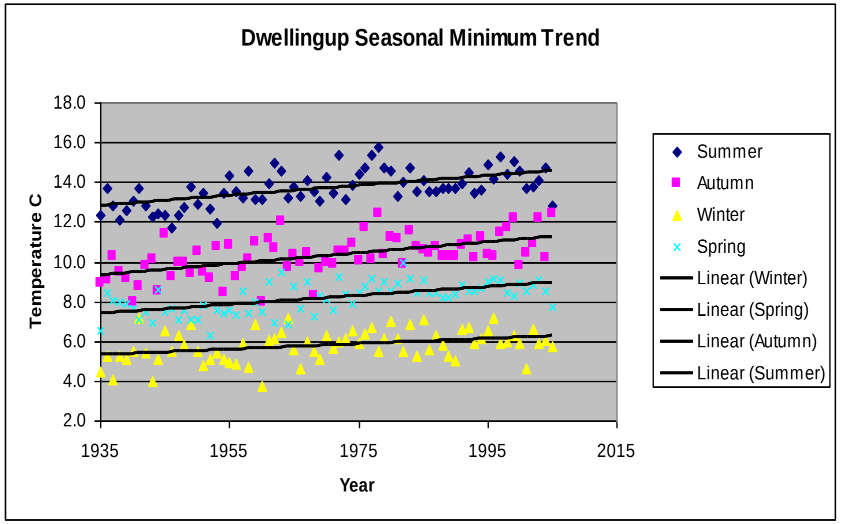
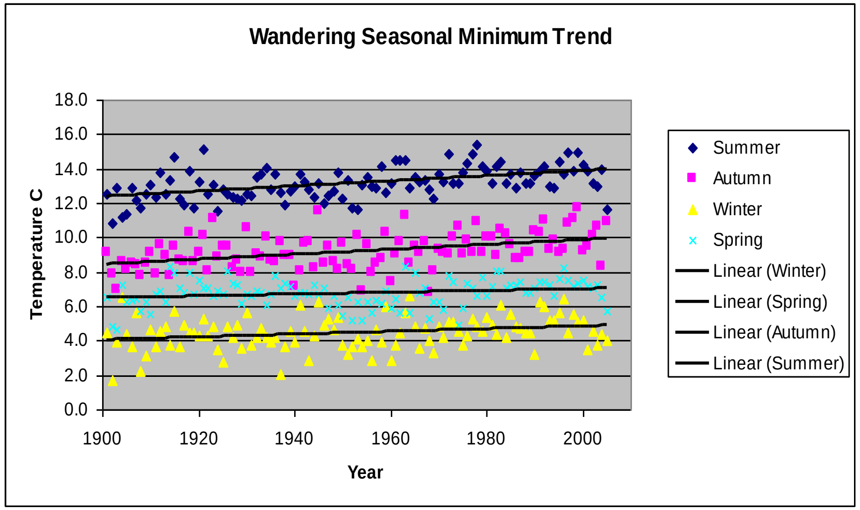
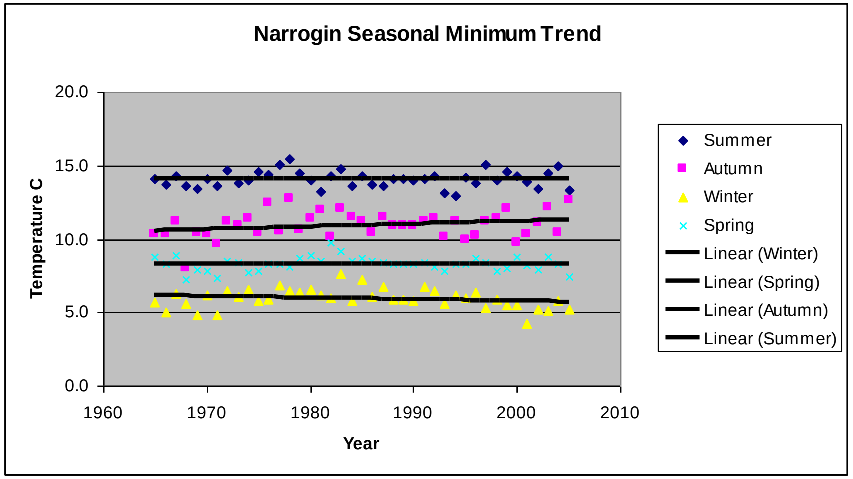


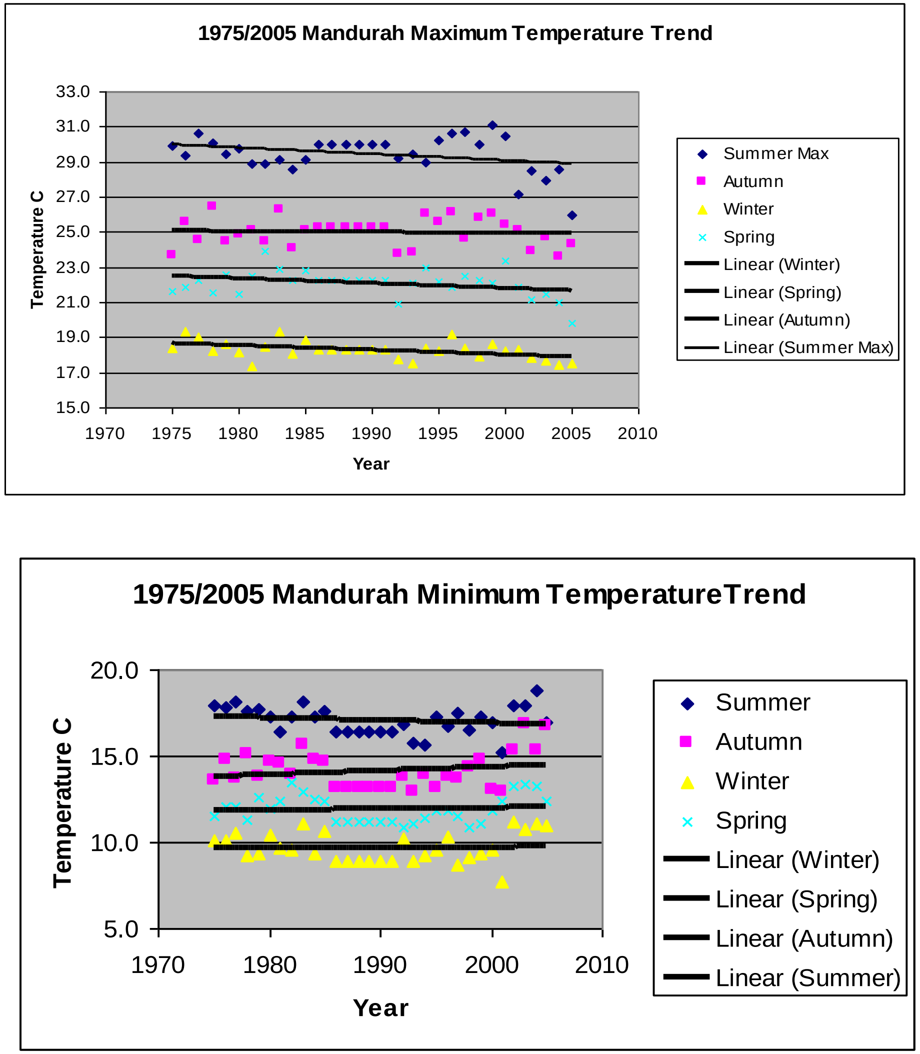
Figure A1.3: **Seasonal Minimum Long-term Temperature** trends for four stations shows consistent increases again except for Narrogin which appears to have remained more stable or colder winters, but note the shorter record.







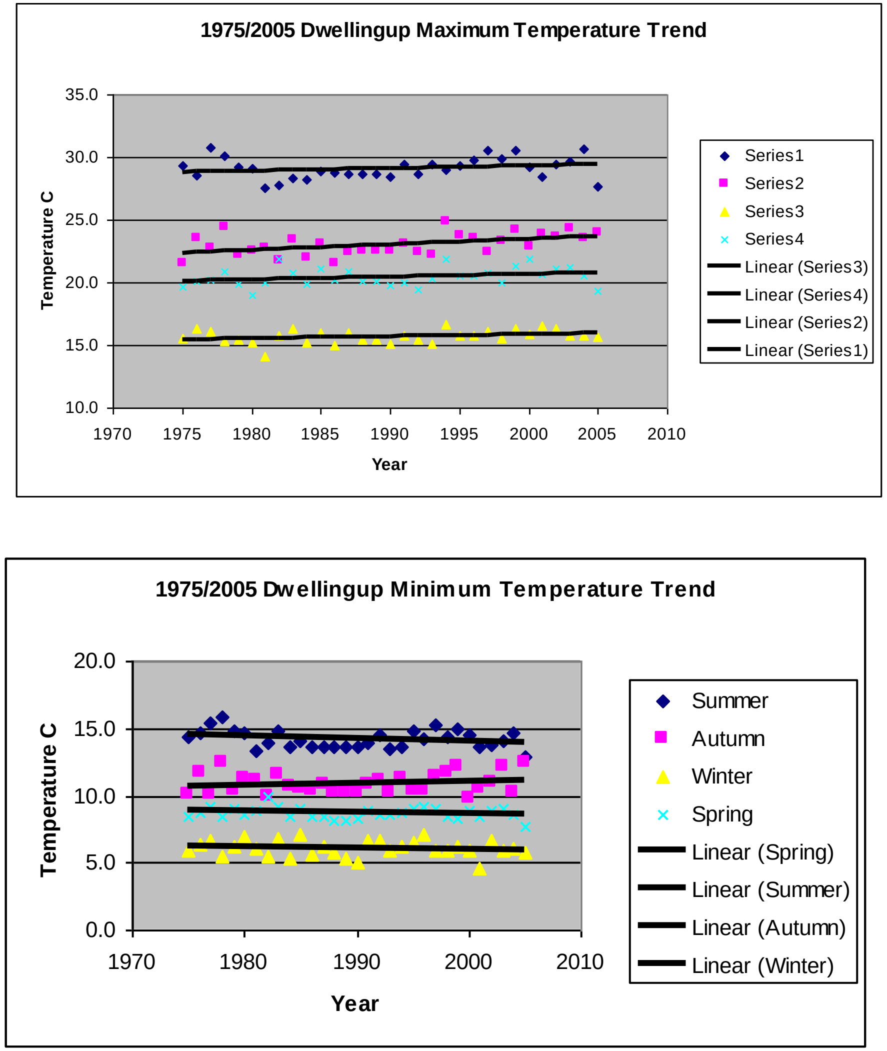




1975/2005 Mandurah Maximum Temperature Trend

1975/2005 Mandurah Minimum TemperatureTrend

Figure A1.4: **1970-2005 Seasonal Maximum and Minimum** trends for Mandurah shows an anomaly from the other 3 stations for the period 1975-2005. Maximum average temperature in all seasons apart from autumn appear to be stable or falling by up to 1°C.



1975/2005 Dwellingup Maximum Temperature Trend

1975/2005 Dwellingup Minimum Temperature Trend

Figure A1.5: **1970-2005 Seasonal Maximum and Minimum** trends for Dwellingup. Show stable maximum trend and comparable minimum trends to that in Mandurah.

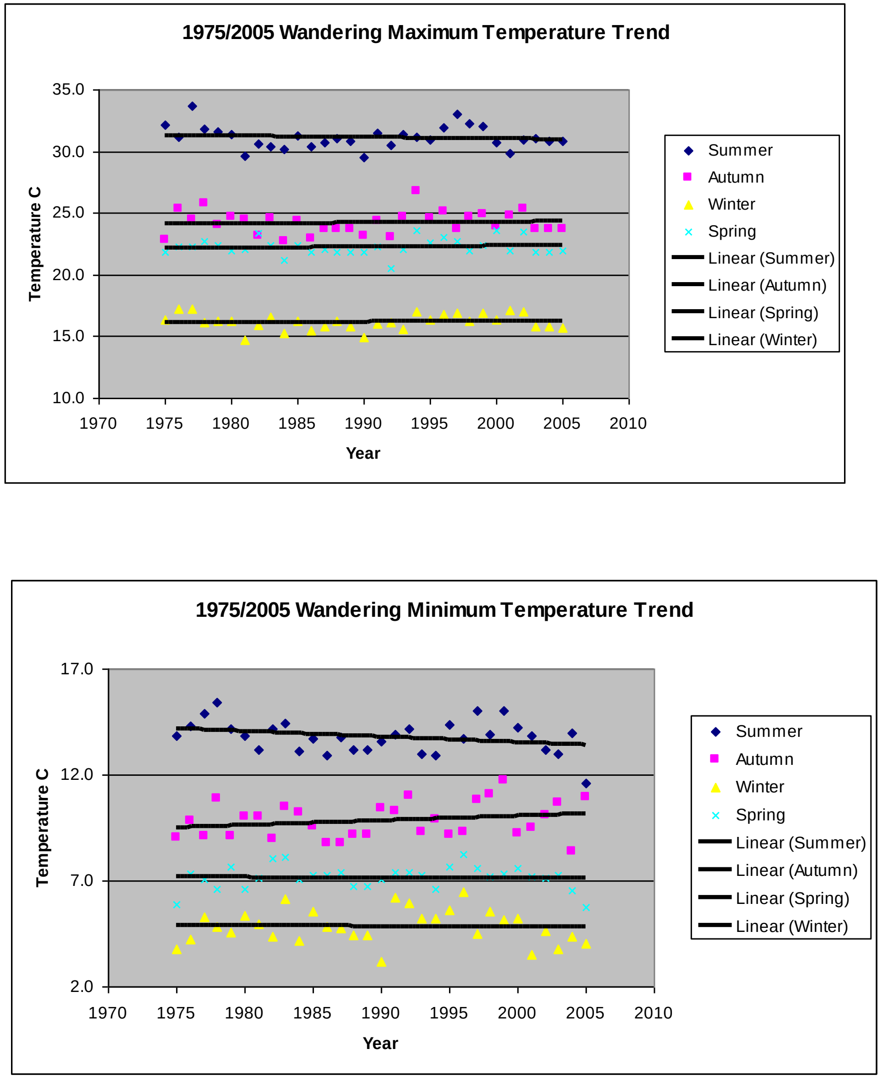


Figure A1.6: **1970-2005 Seasonal Maximum and Minimum** trends for Wandering show stable or declining trends apart from the autumn minimum trend.

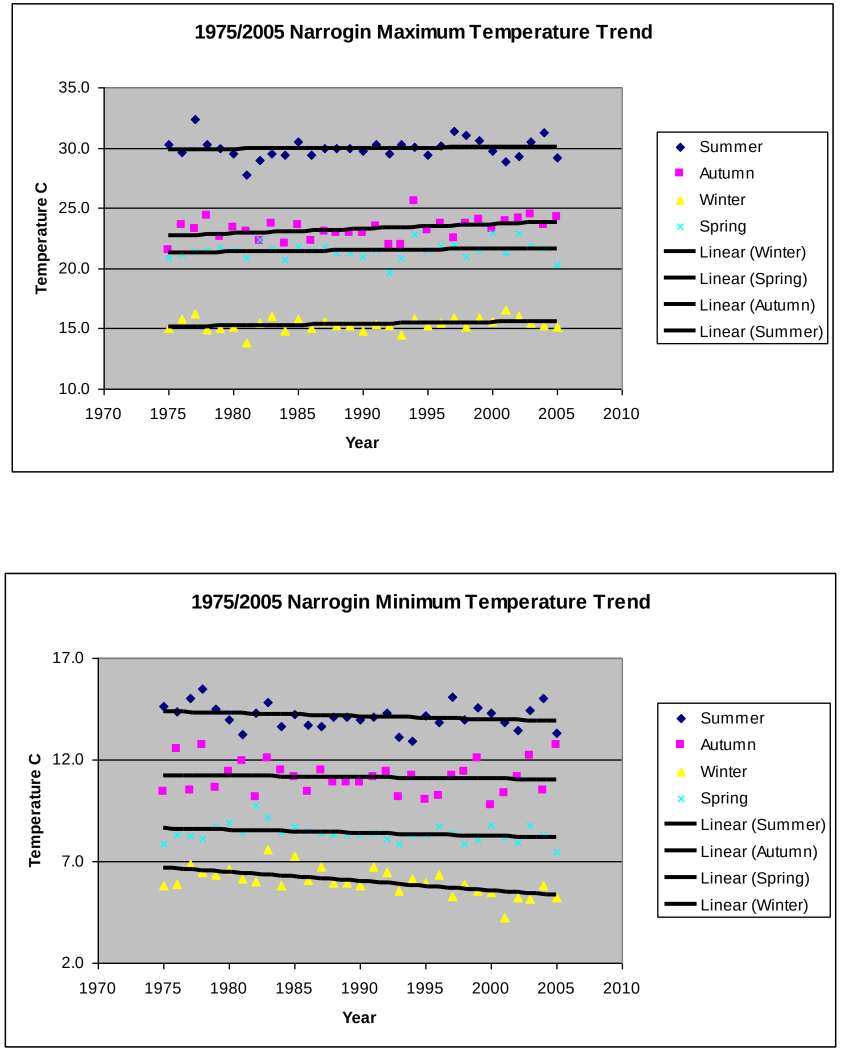
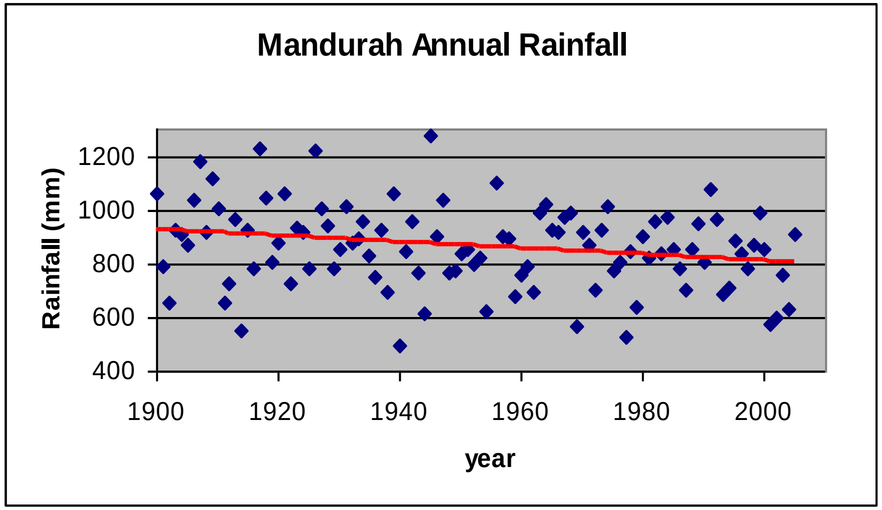
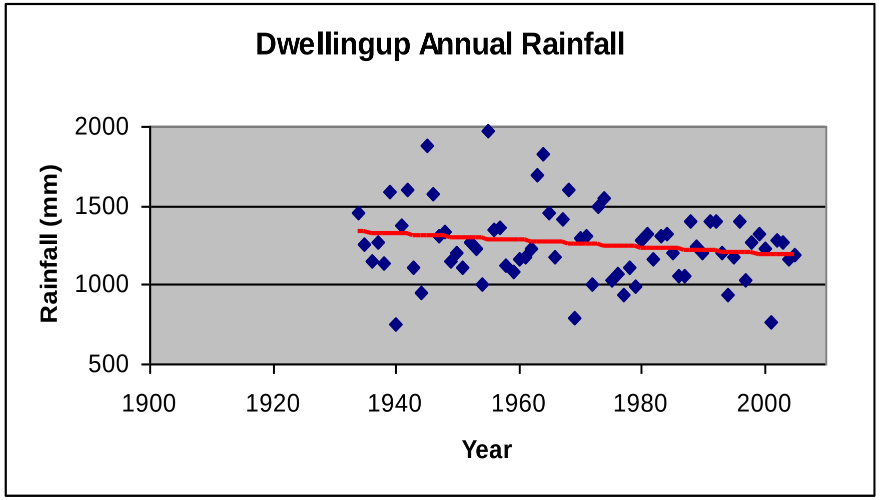


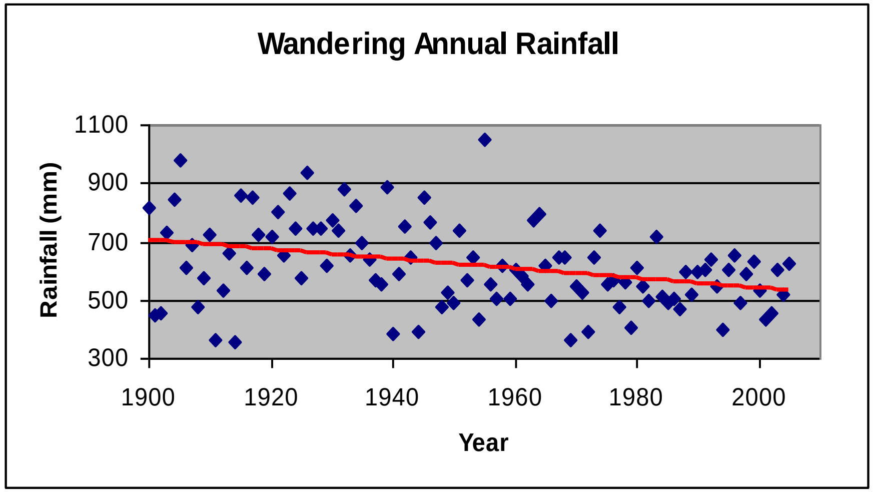
Figure A1.7: **1970-2005 Seasonal Maximum and Minimum** trends for Narrogin show a similar trend apart from the sharp decline in winter minimum trend.

Appendix Two: Rainfall Graphs

The raw data from which the graphs used in the appendices were generated is attached in Microsoft Excel format and have been adapted and collated from raw data supplied by the WA Bureau of Meteorology (John Cramb).







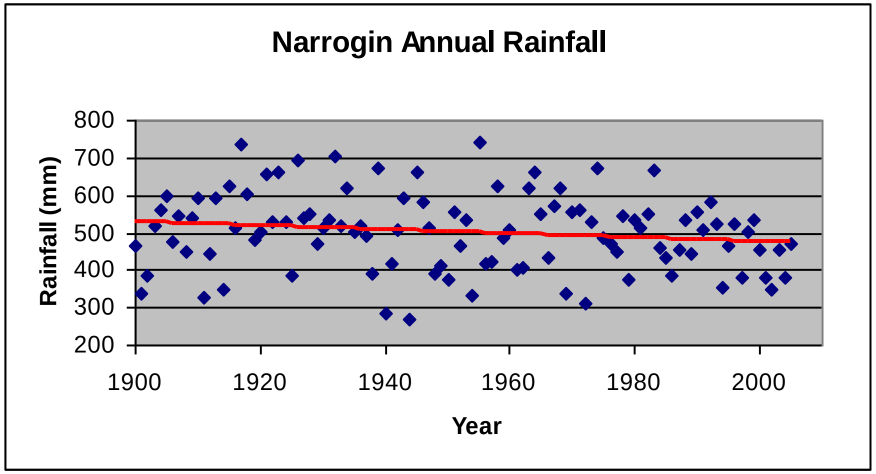


Figure A2.1: Long-term annual rainfall, four stations.

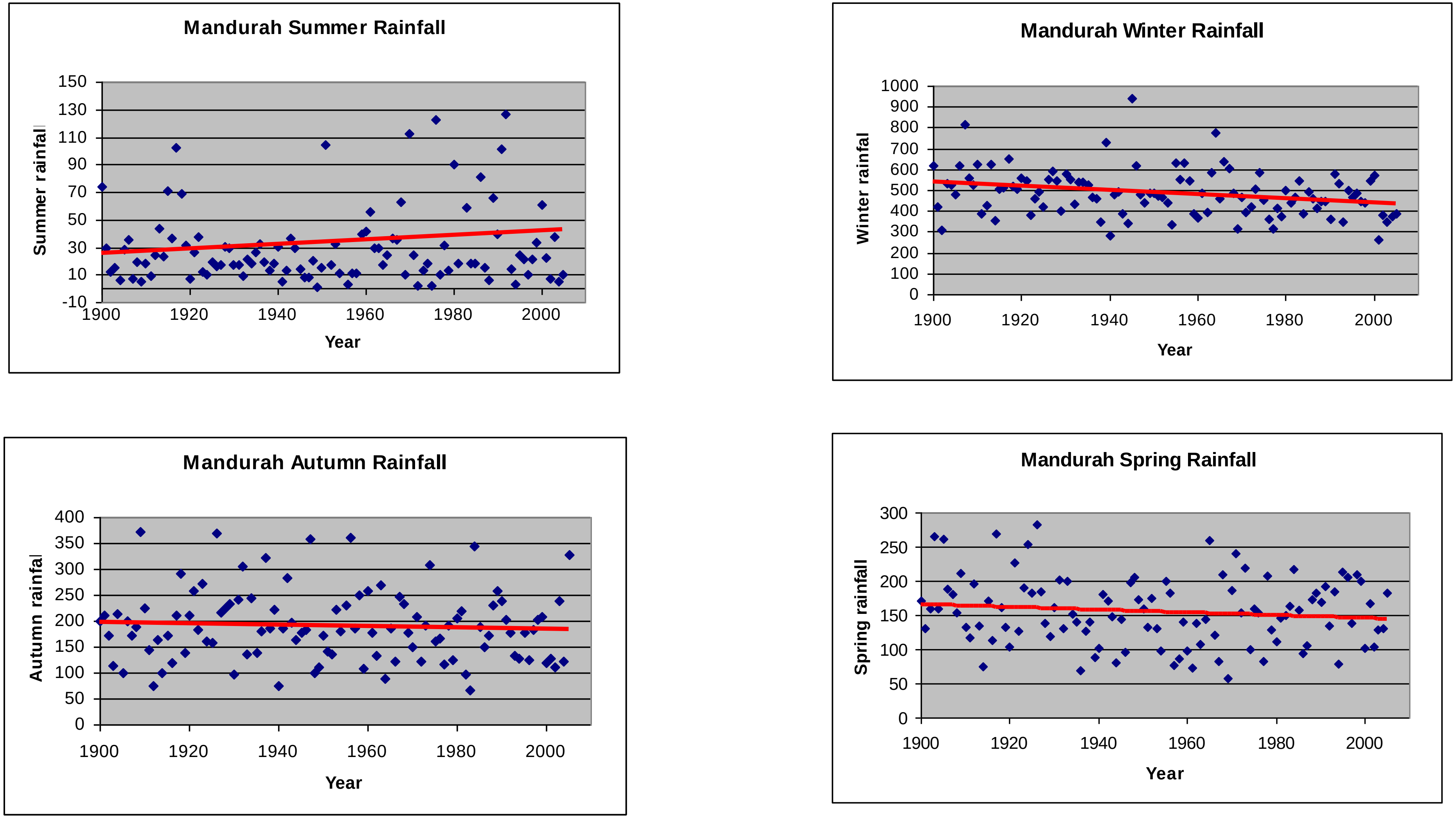


Figure A2.2: Mandurah long-term seasonal rainfall.

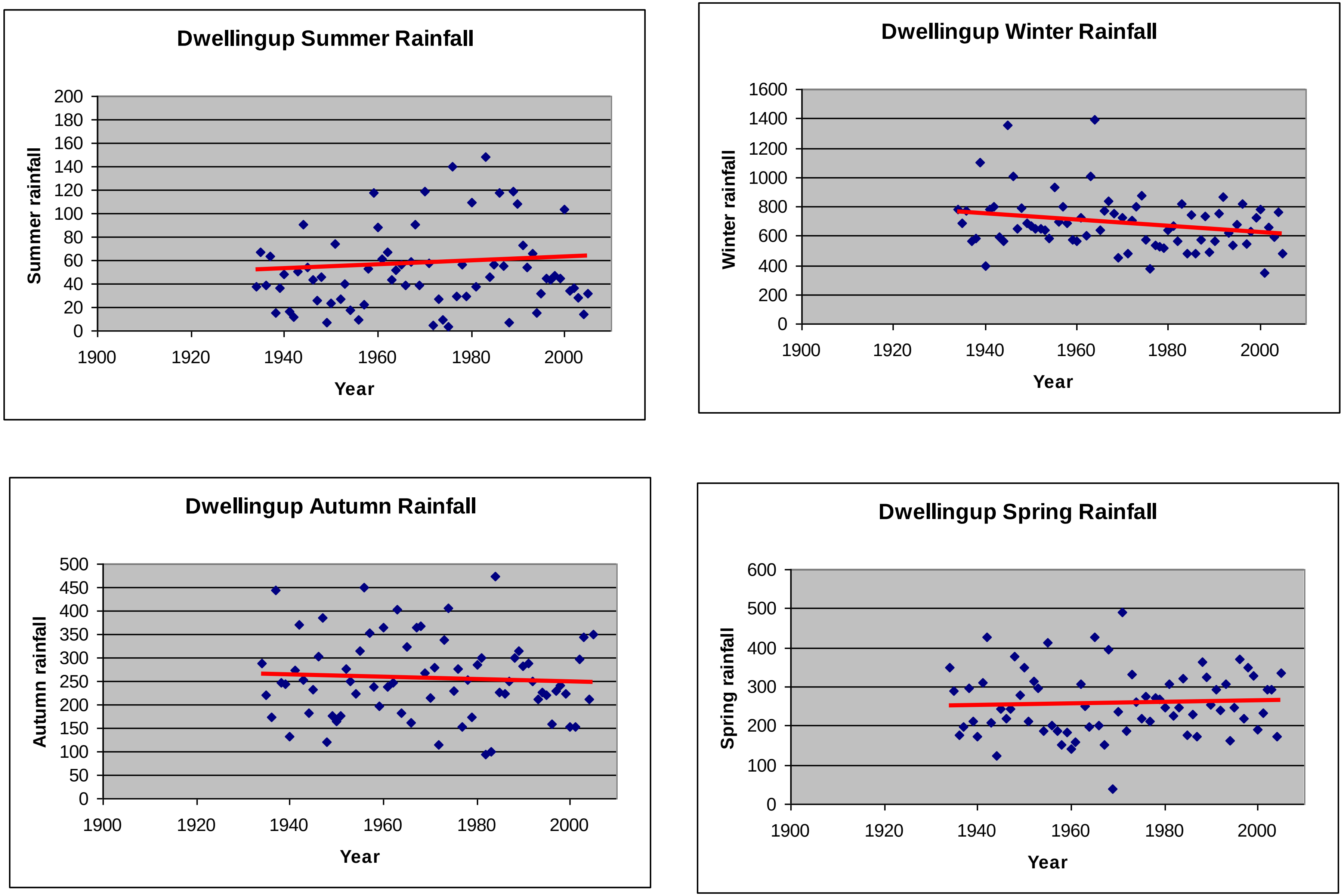


Figure A2.3: Dwellingup long-term seasonal rainfall.

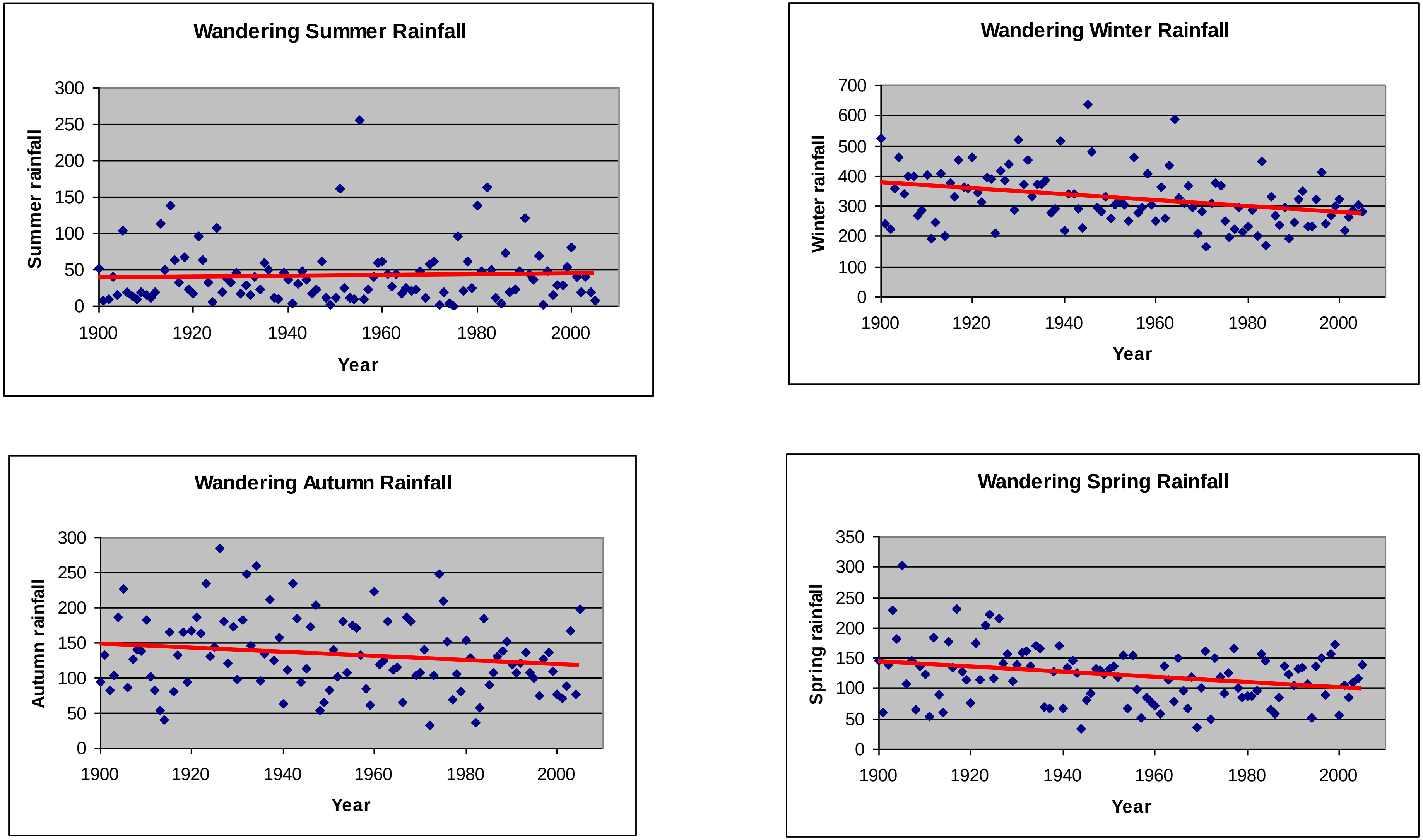


Figure A2.4: Wandering long-term seasonal rainfall.

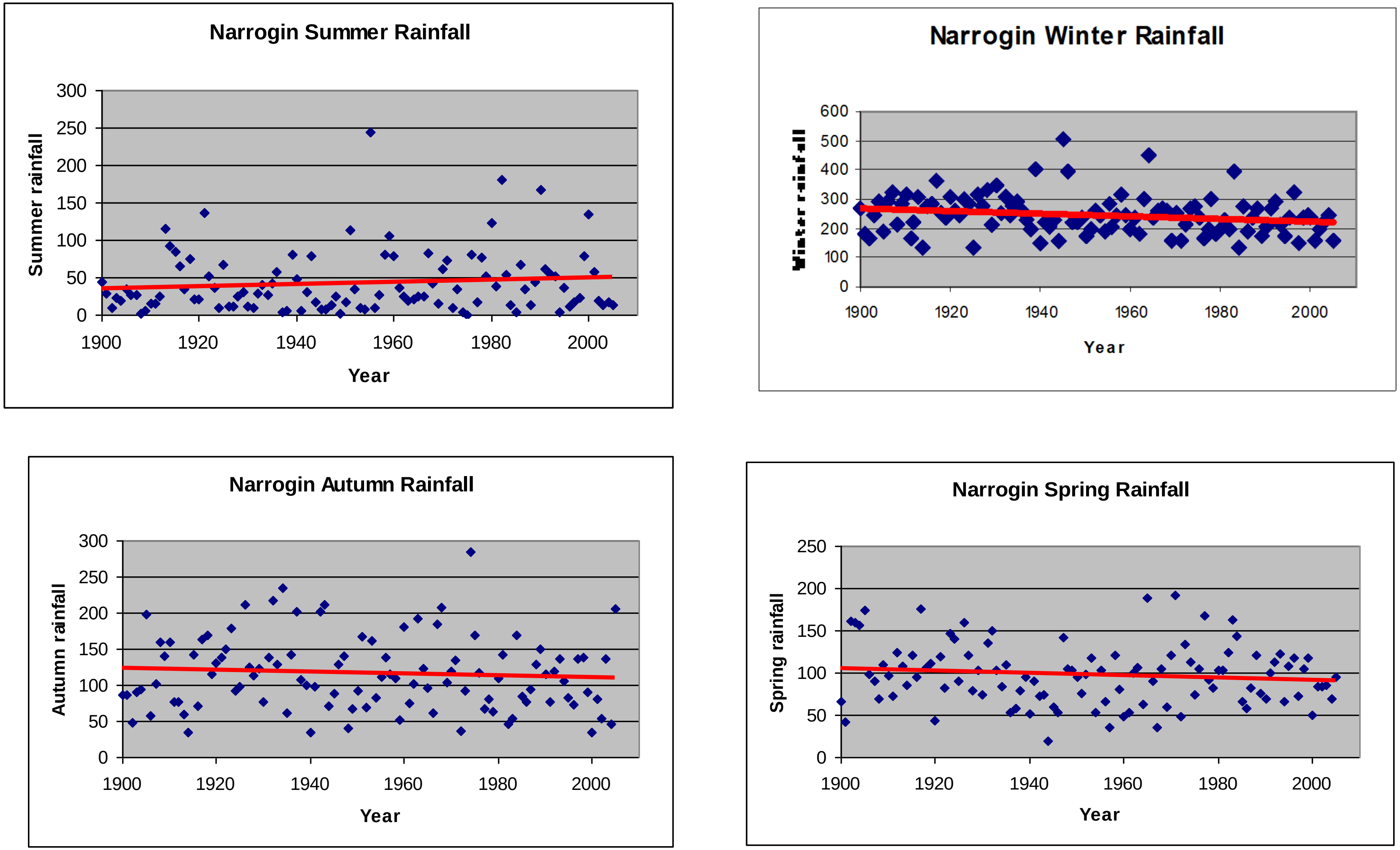


Figure A2.5: Narrogin long-term seasonal rainfall

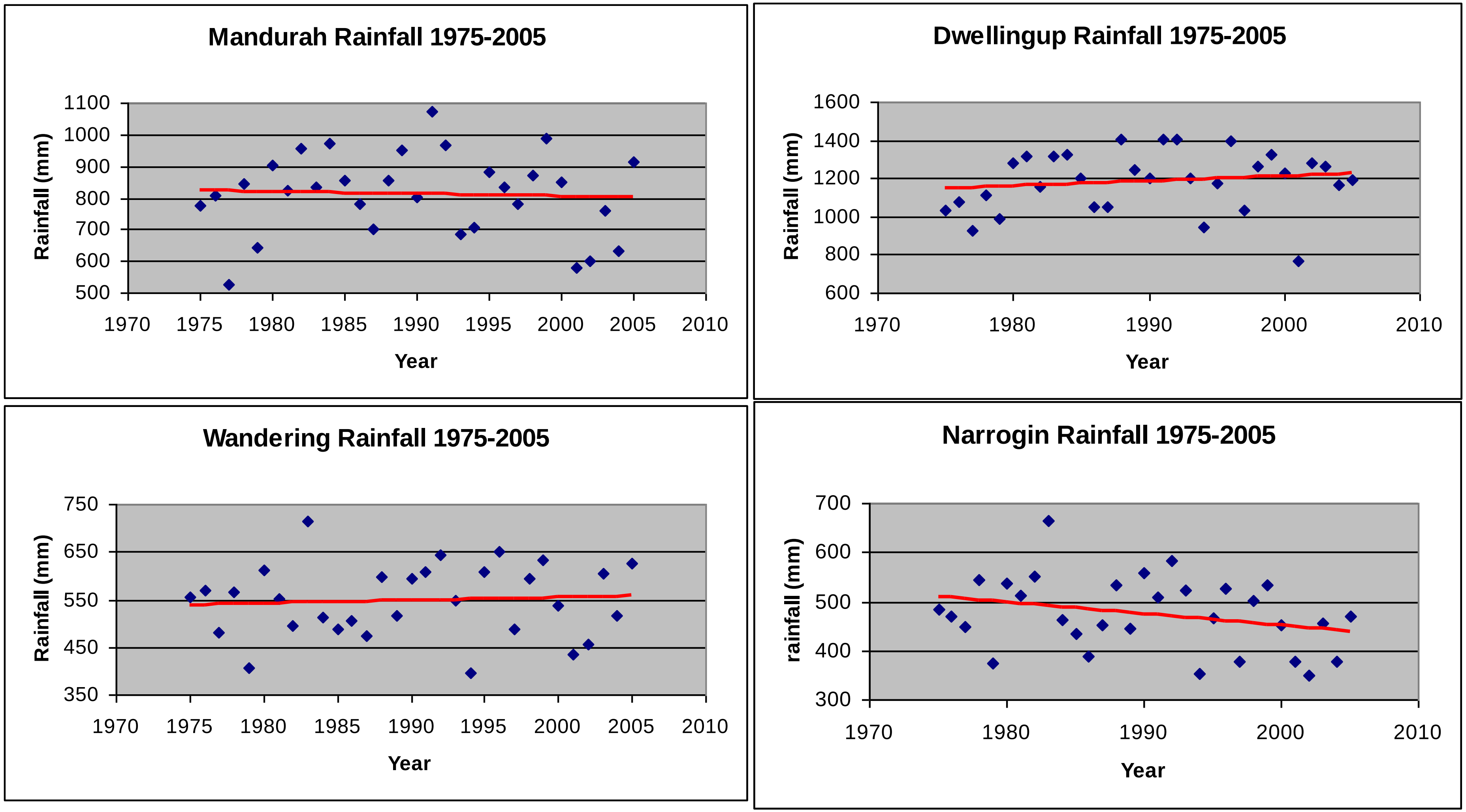


Figure A2.6: Total annual average rainfall for the 1975-2005 period.