3 Large-scale Climatic Changes and their Attribution

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During the last sixty years there has been a marked and continuing reduction (about 20% to date) in autumn and winter rainfall over SWWA. This negative rainfall trend has coincided with major shifts in the structure of the large-scale circulation of the Southern Hemisphere (see Frederiksen and Frederiksen 2005, 2007), which has in turn changed the nature of the prevailing weather systems, including their growth rates and likelihood of development. In IOCI Stage 2, this three-way relationship between changes in large-scale circulation, weather systems and rainfall was only investigated for July and over the period 1948 to 1994, when some of the largest changes occurred. In IOCI Stage 3, this research was extended to all months and into the 21st century. The issue of attribution (i.e., identifying the causes) of these changes was also addressed with the formulation of a new methodology to identify the forcing responsible.

This chapter summarises some of the IOCI3 research that links observed regional Western Australian rainfall changes to large-scale atmospheric changes. It also describes some of the consequences of these large-scale atmospheric changes for important weather systems, using dynamical models and mechanistic studies. The issue of attribution and future projections of changes are also discussed. The changes in the statistics of the different weather systems and their impacts on SWWA, as well as future projections of these systems, are discussed in Chapter 4.

3.1 Large-scale Changes in Climate: Subtropical Jet and Storm Tracks

Figure 3.1 Percentage change in July rainfall between the periods 1997 to 2006 and 1949 to 1968. AWAP data.

Over the latter half of the 20th century some of the largest changes in winter rainfall, atmospheric circulation and weather systems have occurred in the month of July. Figure 3.1 illustrates the percentage change in July rainfall between the periods 1997 to 2006 and 1949 to 1968. Substantial reductions (greater
than 20%) are seen over SWWA and east and south-east Australia. Conversely, substantial positive percentage changes are observed over NWWA (Chapter 5) and over parts of central Australia (Section 3.2).

Figure 3.2 Change in July zonal wind. Averaged over the longitudes of 100° E to 130° E over the two time periods 1975 to 1994 and 1949 to 1968, in metres per second. The green to blue shading just to the left of the centre of the figure illustrates an up to 9.4 metre-per-second reduction in the wind strength in the subtropics near 30° S latitude. Y axis is atmospheric pressure level in hectopascals. NCEP data.

Figure 3.3 Reduction in the equator-to-pole temperature gradient. Change in the vertically averaged potential temperature between the periods 1975 to 1994 and 1949 to 1969. Warming (yellow to red shading) in the Southern Hemisphere south of 30° S and in the Eastern Hemisphere has reduced the equator-to-pole temperature gradient, particularly in the Eastern Hemisphere. In degrees Kelvin; NCEP data.

One important IOCI3 finding was that the SWWA rainfall reductions could be explained by marked changes in the mean state of the global atmospheric circulation and temperature. Some of the largest changes occurred between the periods 1949 to 1968 and 1975 to 1994, and coincided with large reduction of inflow into Perth dams. These atmospheric changes have in turn resulted in shifts in the Southern Hemisphere storm tracks (i.e., the paths along which the storms move; Frederiksen and Frederiksen 2005, 2007 and 2011; Frederiksen et al. 2009a, b). Figures 3.2 and 3.3 show the full extent of these changes in the circulation and thermal structure of the atmosphere over time, by comparing the change in climate across two periods: 1949 to 1968 and 1975 to 1994.
Over these two periods one significant difference was a 17% reduction in the peak strength of the Southern Hemisphere subtropical jetstream over the southern Indian Ocean 'upstream' (roughly west) of Australia (Figure 3.2). The subtropical jetstream is a belt of strong, upper-level westerly winds found roughly 12 km above regions of subtropical high pressure. It is a source of potential energy in the atmosphere; it is the conversion of this potential energy into kinetic energy that drives the formation of storms. Changes in the jetstream are a signal of changes in the circulation of the atmosphere, including changes to storms and high-pressure systems.

Figure 3.4 Trends in atmospheric instability. (a) to (l) for January to December over the period 1950 to 1999 in metres per second per year. Note the highly statistically significant negative trends 'upstream' (roughly west) of Australia (blue to purple shading), and the significant positive trends south of Australia (yellow to red), with maximum values near 60°S.

Figure 3.2 shows the elevation (in pressure units) and latitudinal cross-section of the zonal (i.e., westerly) wind, averaged over 100°E to 130°E longitude. In both periods, the zonal wind reaches a maximum strength in the subtropics (near 30°S) at an elevation that corresponds to approximately the 200-hPa-pressure level. In the later period (1975 to 1994), there was a reduction in the zonal wind of up to 9.4 m/s in this maximum. In fact, there was a hemisphere-wide reduction in the upper level zonal winds and vertical wind shear near this latitude of 30°S. However, at other latitudes the zonal winds have increased: in a hemispheric band near 50°S; in the upper troposphere near 45°S; and in the main Northern Hemisphere jet core (the jetstream maximum) near 35°N.

These changes are directly associated with changes in the Hadley circulation (not shown; the major atmospheric circulation of air from the tropics into the mid-latitudes at altitude), including a reduction in the strength of the downward branch near the core of the Southern Hemisphere jet.
The thermal structure of the Southern Hemisphere atmosphere has also changed, with significant warming south of 30° S. Figure 3.3 illustrates this change by showing the vertically averaged temperature difference between the same two periods mentioned above. This warming has reduced the equator-to-pole temperature gradient, particularly in the Eastern Hemisphere. As well, other differences in the atmospheric circulation are associated with a change in the strength of the Southern Annular Mode (SAM; not shown), which is associated with weather systems and rainfall over southern Australia (see also Chapter 4).

These changes would be expected to have a marked impact on the stability of the atmosphere and the likelihood of formation of the weather systems that affect SWWA. During winter these weather systems are associated with the Southern Hemisphere storm tracks. These storms owe their formation to an unstable atmosphere, and this unstable state is reached when the vertical difference in zonal wind is large and exceeds a critical value. However, the reduced temperature gradient between higher and subtropical latitudes tends to reduce the vertical wind shear, stabilising the atmosphere and decreasing the likelihood that storms will form.

Changes in the atmospheric circulation and thermal structure have occurred not only in winter, but in other seasons as well. This has affected the likelihood in these seasons of the formation of storms that can bring rainfall to SWWA. These changes are illustrated in Figure 3.4. It shows, for all calendar months, the linear trends in atmospheric instability for the period 1948 to 2006 throughout the mid-latitudes of the Southern Hemisphere. Of note is that the trends that are shaded in this figure are highly statistically significant at the 95% level or greater, generally at the 99% level.

Highly significant negative trends occur upstream (again, roughly west) of Australia, in regions associated with storm formation. Further south, there are significant positive trends: an increase in atmospheric instability with maximum values near 60° S. There is a clear annual cycle in the position of the greatest negative trends. The areas of greatest reduction in atmospheric instability are generally located more equatorward (25 to 30° S) from May to October, and between 35 and 50° S from November to April. Positive trends occur between 50 and 70° S in all months. Thus, in all months, storm development tends to be reduced in the mid-latitudes but increases in likelihood at higher latitudes. The net result is fewer storms impacting on SWWA, and thus a reduction and continuing downward trend in rainfall.

How do these changes in atmospheric instability impact on the structure and growth rate of weather systems associated with the storm tracks? This question is addressed in Figure 3.5, which depicts the two types of weather (storm) modes that play a dominant role during July. In the early period (1949 to 1968), storm type 1 (Figure 3.5a) was the type of weather system most likely to form. This storm mode is shown at a particular phase (or time) and consists of a series of eastward propagating troughs (blue shading) and ridges (red shading) over southern Australia. As the troughs and ridges move eastward they amplify, reaching maximum amplitude — with a greater likelihood of rainfall — over SWWA. Thus, this mode had large impact on SWWA rainfall in the earlier period. However, in the latter period (1975 to 1994) and subsequently, the growth rate (and likelihood of storm formation) of this mode decreased by more than 30%. During the period 1997 to 2006 the growth rate has decreased even further to 37% of its value in the period 1949 to 1968. This is consistent with the negative July trends in instability shown in Figure 3.4(g) upstream of Australia. This explains why rainfall has decreased and continued in this downward trend.

At the same time, storm type 2 (Figure 3.5b) in the latter period has had a growth rate that is comparable to storm type 1. That is, both types are equally likely to occur. However, storm type 2 has a markedly different structure from storm type 1. It has very little amplitude over southern Australia, and its largest impact occurs in the South Pacific. This storm type originates south of Australia at about 60° S, and the observed increase in its likelihood of formation is consistent with the increase in atmospheric instability in that region (Figure 3.4g).
Frederiksen et al. (2011a, b, c, d) provide a more comprehensive discussion of the relationship between changes in SWWA rainfall, the climate of the atmospheric circulation and thermal structure, and the Southern Hemisphere stormtracks in all months.

3.2 North-West Cloud Bands and Intraseasonal Oscillations

Not all of Western Australia has experienced reductions in winter rainfall. As Figure 3.1 illustrates, July rainfall has increased over central north-west and central Western Australia. This region is often affected by propagating cloud bands that originate off the north-west coast of Australia. Frederiksen and Frederiksen (2011) suggest that these positive trends in rainfall are attributable to the changing nature of two types of weather systems commonly associated with these regions: north-west cloud bands and intraseasonal oscillations.

North-west cloud bands: The first of these two types is associated with eastward propagating north-west cloud bands originating in the Indian Ocean off north-west Australia. They are characterised by an extensive layer of rain-bearing cloud and constitute an important weather feature of the sub-tropics to mid-latitudes in the Southern Hemisphere, providing rainfall across much of Australia. Over the last roughly fifty years, these north-west cloud band modes have increased their growth rates by approximately 25% or more for each of the 1975 to 1994 and 1997 to 2006 periods, compared with the 1949 to 1968 period. The increasing likelihood of development of these systems would be expected to have a positive impact on rainfall over central NWWA and can partly explain the changes observed.

The leading, or fastest-developing, north-west cloud band modes have periods of about eight days throughout. These modes consist of a series of high and low-pressure anomalies (or wave trains) that originate in the Indian Ocean and propagate eastward over Australia and into the South Pacific, and affect rainfall over central Western Australia. Figure 3.6a shows the 300-hPa streamfunction for the leading north-west cloud band mode for the 1975 to 1994 period. Figure 3.6b shows the corresponding divergence field, which is proportional to rainfall and indicates the location of the largest impact on rainfall associated with this type of weather system.
Intraseasonal oscillations: A second category of weather system that impacts rainfall over central NWWA is associated with variability at the intra-seasonal timescale of between 25 and 60 days. The leading intraseasonal oscillation modes also consist of propagating wave trains of pressure anomalies extending again from the central Indian Ocean across central Western Australia. Compared to the period 1949 to 1969, the growth rates of these weather systems have also increased, by approximately 30% over each of the two periods 1975 to 94 and 1997 to 2006. Again, as with the north-west cloud bands, the increased growth rate of these modes in the latter periods is consistent with the increased rainfall over central NWWA.

3.3 Performance and Projections of Climate Models

To what extent can climate models replicate the observed changes described in the previous sections? This question is important when considering possible future changes under scenarios of increased GHG emissions. For SWWA, this would require climate models to reproduce the observed patterns for trends in atmospheric instability (Figure 3.4) and, as implied by these trends in instability, implicitly the changes in the properties of the storm track weather systems.

Figure 3.7 highlights the extent to which these models are able to capture the change in July atmospheric instability between the periods 1949 to 1968 and 1975 to 1994. Specifically, this figure demonstrates the results of observed anthropogenic forcing, including GHGs, from the pre-industrial period to the end of the 20th century. Shown are the results for 22 of the models used, which are from the IPCC Coupled Model Intercomparison Project Phase 3 (CMIP3; see Randall et al. 2007 and Meehl et al. 2007 for model nomenclature and description).

Figure 3.7 shows the extent to which the models are able to reproduce the pattern of observed changes in July atmospheric instability (Figure 3.4(g)) over the domain (longitude of 60 to 150° E, and latitude 45 to 15° S). This is the region of origin for storms that affect SWWA. The similarity in pattern between the models and observations is quantified by the use of the anomaly pattern correlation (APC). The APC indicates how much two patterns have in common. A value of 1.0 is a perfect match; a value of -1.0 is exactly the
opposite; and zero would represent an essentially random association. The APC was calculated in four different ways.

Figure 3.7 Climate models' ability to simulate atmospheric instability. Anomaly pattern correlation between the observed changes in atmospheric instability over the periods 1975 to 1994 and 1949 to 1968 and model changes for the periods: (i) 1975 to 1994 to 1949 to 1968 (black bars) and (ii) 1980 to 1999 and a pre-industrial control run (green, blue and red bars).

The black bars in Figure 3.7 represent the APCs of changes in atmospheric instability calculated for models using the same two 20-year periods described above (1949 to 68 and 1975 to 94). However, the timing of simulated changes in coupled models may not necessarily synchronise with the reanalysed observations. Therefore IOCI3 scientists have also considered whether the models can produce these changes taking into account all GHG forcing since pre-industrial times until the 1980 to 1999 period. This indicates the impact of all 20th century GHG forcing.

It is also important to understand the sensitivity of our results to the base period chosen in the pre-industrial model control runs, and how variability from one decade to another might influence the results. To explore this, IOCI3 scientists chose three adjoining 20-year periods at the end of the pre-industrial control runs, each separated by 20 years. These are designated, respectively, in Figure 3.7 by green, blue and red bars.

In Figure 3.7, the higher the models' score on the right-hand side of the figure (i.e., the closer the score is to a value of 1) the better the model captures the pattern of change in atmospheric instability. The results demonstrate that the models vary considerably in their ability to simulate the reanalysed observations. About a third of the models show a consistently negative APC in all four cases (e.g. gfdl_cm2_1, giss_aom, mpi_echam5, etc.). That is, these models actually indicate an increase in atmospheric instability that would lead to an increase in growth of the storm track modes; this is not consistent with observations. However, about a third of the models show a consistently positive APC (e.g. miroc3_2_medres, giss_model_e_r, ncar_ccsm3_0, etc.); this result is consistent with observations.
Figure 3.8 Trends in May to October atmospheric instability (2001 to 2100). (a) to (f) from the miroc3_3_hires model for SRES A1B emissions scenario; (g)-(l) from the miroc3_2_medres model for SRES A2 emissions scenario. Units are metres per second per year.

Many of the models fail to capture the necessary changes in the large-scale atmospheric circulation (e.g., in Figure 3.2) and the changes in the vertically-averaged temperature (Figure 3.3) needed to simulate the changes in atmospheric instability. Underlying these atmospheric changes in the Eastern Hemisphere are warm sea surface temperature anomalies (not shown) near 30°S, which many of the models are not able to simulate. Frederiksen et al. (2011a) showed that when natural and anthropogenic forcings are used in atmospheric-only model experiments forced by observed sea surface temperatures, all of the models they had access to produced the observed changes in the atmospheric instability between the periods 1949 to 1968 and 1975 to 1994 with similar magnitudes. This would suggest that there may be some problem with the ocean component or the coupling between the ocean and atmosphere in those coupled models that fail to produce the observed changes. Interestingly, Frederiksen et al. (2011a) also found that many of the models that did not simulate the 20th changes well showed similar patterns of changes in the atmospheric instability when forced with increasing carbon dioxide concentrations.

The miroc3_2_medres and miroc3_2_hires models capture the changes in atmospheric instability, storm track modes and rainfall particularly well. These two models were used to project future changes in atmospheric instability for the end of the 21st century. Figure 3.8a-f shows the projected trends in atmospheric instability over the period 2001 to 2100 for the months of May through October using the miroc3_2_hires model for the SRES (Special Report on Emissions Scenarios; see Box 3) A1B GHG emissions.
Both simulations show negative trends for atmospheric instability near $30^\circ$ S and positive trends further south. Thus they project a continuation of the patterns already observed (shown in Figure 3.4). The magnitude of the projected trends is about half that of the observed negative trend, but is similar to that modelled for the 20th century (see below for a discussion of this issue). This suggests that the trends seen in the 20th century are likely to continue into the 21st century. That is, these results imply a continuation of the downward trend in SWWA rainfall already observed, as the following results on the corresponding rainfall impact indicate.

Figure 3.9 Projected changes in May to October rainfall between the two periods 2080 to 2099 and 1980 to 1999. Projections are made using: (a) to (f) the miroc3_2_hires model under the SRES A1B emissions scenario; and (g) to (l) the miroc3_2_medres model under the SRES A2 emissions scenario. Rainfall is given in millimetres, with yellow to red shading indicating a projected reduction, and blue to violet indicating a projected increase. SWWA is projected to undergo May to October rainfall reductions in every month over this half-year under both scenarios; some reductions could exceed 20 millimetres.

Figure 3.9 shows the results of the above two model projections for trends in May to October rainfall between the two periods 1980 to 1999 and 2080 to 2099. The results are consistent with trends in atmospheric instability. The projections show hemispheric reductions in rainfall in a zonal band north of $40^\circ$ S, and increases in rainfall further south. Differences in rainfall between the periods 1980 to 1999 and 2080
to 2099 vary between -40 millimetres (mm) to +40 mm. Over SWWA, rainfall is projected to decrease in all months over this half of the year (Figure 3.10). In some months reductions exceed 20 mm, with these large reductions being especially prevalent in the SWWA region. Note, however, that the model results for the 20th century produce changes in rainfall which are about half those actually observed, and so may also be underestimating the projected changes.

Figure 3.10. Projected changes in Australian May to October rainfall. As per Figure 3.9, but showing in more detail projected changes in Australian rainfall in millimetres. Yellow through red indicates areas of rainfall reduction, green through blue, areas of rainfall increase.

3.4 The Causes of Large-Scale Changes in Climate: Attribution

Determining the causes of the changing climate during the last half-century and the likely drivers of further change into the 21st century is of great importance for policy development. To attribute these causes one
must disentangle the anthropogenic component from natural internal variability across various time scales. Important driving forces for climate change, known as forcing agents, include GHGs, aerosols, changes in solar radiation and volcanic activity, and changes in surface albedo, roughness and evaporation due to land use.

Determining the impact of changes in external forcing on the climate is a very complex problem. This is because, as the climate changes in response to the forcing, this change influences the nature of the weather systems, which in turn feedback onto the climate. This feedback needs to be accounted for before the impact of the forcing agents can be determined for each climate variable, such as the circulation, temperature, or rainfall; this impact can be described by a forcing function. Zidikheri and Frederiksen (2011) have developed a methodology to estimate the feedback and directly calculate the forcing functions responsible for circulation and temperature changes. This provides a way to attribute this aspect of climate change. This method is the first capable of achieving this. The scheme was used to determine the anomalous temperature and circulation forcing functions responsible for the changes in the Southern Hemisphere circulation during the second half of the 20th century.

Figure 3.11 shows the anomalous temperature forcing function at an elevation equating to the 500-hPa pressure level. This is the forcing function associated with the changed temperature (Figure 3.3) and circulation (Figure 3.2) between the July periods 1949 to 68 and 1975 to 94. The figure demonstrates how the Southern Hemisphere circulation changes have been driven by a temperature forcing anomaly (change) that is largely zonally symmetric\(^9\), i.e., is largely consistent across a given band of latitude. These temperature forcing anomalies have enhanced warming in the mid- to high latitudes while at the same time reducing warming in the tropics and subtropics. The effect is a reduction in the horizontal temperature gradients over mid-latitude regions such as those over southern Australia and SWWA in particular. In turn, this has: reduced the instability of the Southern Hemisphere atmosphere in the mid-latitude regions; reduced the intensity of storm formation; and reduced the resulting rainfall, as discussed earlier.

\(^9\) Zonally symmetric: the pattern seen at a given latitude tends to circle around the globe, across all longitudes.
very similar to those actually observed (Frederiksen et al. 2010, 2011a, b). Furthermore, the 21st century projections of these models, when forced by increasing anthropogenic gases under SRES B1, A1B and A2 scenarios, show a continuation of observed trends into the second half of the 21st century.

**Knowledge gaps and future directions**

The majority of the work described in this section focused primarily on SWWA and predominantly on the winter season. There is a great need to build on and expand existing methods of detection and attribution developed as part of IOCI3, and broaden their application to more phenomena affecting Western Australia, including over central and northern Western Australia, and in all seasons. There is also a need to provide confidence in understanding the causes of observed changes and in projections.

An important aspect of future research should be to identify the physical processes and mechanisms responsible for these changes. In particular, one important objective is to disentangle the roles of anthropogenic forcing (e.g., GHGs, ozone, aerosols; see Chapter 5) and natural variability in the changing climate of Western Australia. An evaluation of the latest Coupled Model Intercomparison Project Phase 5 (CMIP5) climate simulations would help identify models that embody the correct physical processes and mechanisms, and are skilful in reproducing the observed climate and rainfall trends of the 20th century. Such an analysis would add confidence to future likely projections of Western Australian climate change and seasonal extremes, and provide guidance on which models are suitable for studies of climatic extremes, extreme weather and regional projections.

The impact of large-scale drivers on extremes of climate and weather is an important area that needs to be better understood. For example, possible causes of extreme events include low-frequency modes of variability such as the El Niño – Southern Oscillation (ENSO), the Indian Ocean Dipole, and weather systems such as Intra-seasonal Oscillations (e.g., the Madden-Julian Oscillation), north-west cloud band disturbances, monsoon, mid-latitude storms, TCs, and their interactions. Future research should focus on both dynamical and statistical techniques to elucidate the three-way interactions between systematic trends in climate change, low-frequency variability (teleconnections, or large-scale drivers) and weather systems in current and future climates under IPCC Fifth Assessment Report scenarios.

In particular, an area which should be studied is the future likelihood, risks and impacts of persistent severe weather events of prolonged heat waves and high or low rainfall, similar to those seen over east Australia during 2010/2011, where extremes in natural variability (e.g., ENSO) reinforce or act against climate change trends, and which can last from months to many seasons. Also, results from IOCI3 have shown that the rainfall deficit over SWWA is due to the decreased growth rate and southward shift in storms, and is associated with the observed expansion of the tropics. At the same time, there has been an increase in weather systems and rainfall associated with north-west cloud band disturbances and intraseasonal oscillation modes. This raises the issue of whether the continued expansion of the tropics under future climate change may cause these weather systems to intrude further south and make up the rainfall deficit caused by changes in the mid-latitude storms. This is something that needs to be explored.

The attribution of the causes of current and future climate change has major implications for policy development on climate adaptation. To solve the attribution problem, future research should use climate model simulations with different combinations of radiative forcing (e.g., GHGs, aerosols and ozone) and inverse modelling techniques developed in IOCI3. Novel dynamical and statistical methods developed by IOCI3 scientists could be used to analyse a wide range of weather systems and important large-scale modes of variability in the atmospheric circulation relevant to Western Australian climate and weather. These weather systems and modes of variability would include extra-tropical storms, blocking, north-west cloud band disturbances, intraseasonal oscillations (e.g., the Madden-Julian Oscillation), ENSO, SAM, Indian Ocean Dipole and modes related to trends in the large-scale Southern Hemisphere circulation.