PROJECT 3.2: CLIMATE EXTREMES: POTENTIAL FORECAST SKILL AND CLIMATE CHANGE SCENARIOS

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Objectives

- To identify predictors of extreme rainfall in the observed climate record and those available from climate models.
- To assess the potential forecast skill using these predictors.
- Develop scenarios for intensity-frequency-duration characteristics of seasonal rainfall under climate change, which can be used for impact and vulnerability assessments by either State agencies alone or in collaboration with IOCI's research providers.

Key Research Findings

- A literature review documenting current work on atmospheric predictors of extreme rainfall that is relevant to the South-West has been carried out.
- A climate index based on the dynamics of a normalized seasonality index called the Southwest Western Australian Circulation (SWAC) has been developed. The index describes regional circulation and its linkage to winter rainfall. Results show that the winter SWAC has a significant positive correlation with winter rainfall. The variation of the SWAC is not only responsible for the interannual variability of winter rainfall, but also for the long term trend in rainfall: decreasing trend in early winter (MJJ) rainfall due to the weakening of SWAC; and a weak upward trend in late winter (ASO) rainfall resulting from the weakly increasing strength of the SWAC in late winter. The relationship between the SWAC and SWWA rainfall is robust,

and largely independent of the influence of other large-scale circulations such as the Southern Annular Mode and ENSO.

MILESTONE 3.2.1 LITERATURE REVIEW ON PREDICTORS OF EXTREME RAINFALL

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Background

Research on rainfall extremes within IOCI Stage 2 identified a decrease in rainfall intensity for daily rainfall over a wide range of frequencies across SWWA. The research proposed extends this work by: identifying the atmospheric predictors that influence intensity-frequency-duration (IFD) relationships; examining the variability of IFD relationships with time; and providing very-high resolution climate change scenarios for rainfall extremes which can be used for impact and vulnerability assessments by either State agencies alone or in collaboration with IOCI's research providers. This milestone report comprises a literature review documenting current work on (atmospheric) predictors of extreme rainfall that is relevant to SWWA.

Literature Review

As noted in Alexander et al. (2009) there is a previous body of work that has concluded that changes in precipitation and temperature extremes have already occurred in Australia during the 20th century. This includes the works of Hennessy et al., 1999; Plummer et al., 1999; Collins et al., 2000; Haylock and Nichols, 2000; Trewin, 2001; Alexander et al., 2007; Gallant et al., 2007.

While this report focuses on atmospheric predictors, other relevant predictors that have been examined in the literature include: natural and human-induced causes; modulation of the longwave trough (Allan and Haylock, 1993); changes in the land surface vegetation, anthropogenic forcing by greenhouse gases; ozone and aerosols. It is possible/likely that these drivers may be manifested through correlated variables.

Predictors are only useful if there is data available for them. Another key requirement is that predictors should also be available from climate model output, to enable their use in the development statistical models for future scenarios. Alexander et al. (2009) examined simulations from nine coupled GCMs to assess their ability to reproduce observed trends in a set of indices: very few showed significant skill in reproducing observed spatial pattern of trends. This has important implications for the direct use of GCM output in the study of extremes in the SWWA.

Changes in extreme rainfall allow the possibility of an increase or a decrease. Alexander and Arblaster (2008) note that there has been a significant decrease in the frequency and intensity of extreme precipitation events in SWWA over the past century ", so what is causing this, can we model or 'predict' it? Alexander et al. (2009) also note that 'precipitation is not expected to respond as strongly to greenhouse gas forcing as temperature (Lambert et al., 2005). Though this Project is centred on SWWA, work covering other regions (of Australia) will also be reviewed for relevance. The question of how to characterise extreme rainfall, for example by the use of indices, or an approach directly modelling extremes using probability distributions is not discussed. Alexander et al. (2009) use extremes indices based on Frich et al. (2002), and this is one approach to characterising extremes.

It is clear that many of the possible predictors are linked, in some way, with the Indian Ocean, not surprisingly given its proximity and the direction from which rainfall in SWWA generally comes.

England[1] provides many of the most current references to work on predictors of rainfall extremes in SWWA. England classifies years as extreme or not, and concentrates on extreme years, particularly since 1970, so the sample size is small, and we quote directly: "*Rainfall over southwest Western Australia has shown a decline during winter over the past century, linked to*

[1] http://web.maths.unsw.edu.au/~matthew/swwa_rainfall.htm

1. *greenhouse gas increases*
2. *and possibly also to stratospheric ozone depletion over Antarctica*

Over these shorter time-scales, the region's interannual rainfall variability remains poorly understood, as traditional predictors for Australian climate, such as the Southern Oscillation Index, appear to resolve little of the region's variability."

An interesting question is how extreme daily rainfall corresponds to what might be called an extreme season. England notes that in Tasmania "*This region of wetter conditions coincides with the area of positive rainfall trends during the past century, and is likely due to a modest shift in the mean latitude of extratopical cyclones over the Southern Hemisphere since 1950."*

Variables that have shown some linkage to rainfall include:

1. *Sea Surface temperature (SST)*. Several studies have shown a link between Indian Ocean SSTs and Australian rainfall (Nicholls, 1989; Frederiksen and Balgovind, 1994; Reason et al., 1998, Li and Mu, 2001; Qian et al., 2002) and those concentrating on the SWWA include Ansell et al., (2000), Smith et al. (2000) SST, for winter, seasonally evolving trend in SST starting in summer. Luffman et al. (2009) examine the global and regional climate response to late 20th century warming over the Indian Ocean in an ensemble of atmospheric GCM experiments showing an increase in precipitation over SWWA. This seems to be an anomalous prediction due to possibly the coarseness of the model's resolution (particularly if one compares the observed and modelled annual mean precipitation, their Figure 3, for which their models does not resolve the relatively fine detail)
2. Ansell et al. (2000) :- generally observed MSLP to be more robust than correlations with Indian Ocean SSTs
3. *Fluctuations in mid-latitude frontal systems* (Allen and Haycock, 1993)
4. *Changes in land cover* (Pitman et al., 2004)
5. A CSIRO study on extreme rainfall in the Sydney basin showed that Ocean Heat Content had a correlation with changes in extreme rainfall.
6. Whilst there are connections, it appears that ENSO is not strongly linked with

SWWA rainfall

7. Southern Ocean SSTs and possibly the Antarctic Circumpolar Wave (ACW) (White, 2000)
8. The Indian Ocean Dipole (IOD) for SE Australian droughts. The Indian Ocean Dipole (IOD, see Appendix) is a coupled ocean-atmosphere mode of variability in the tropical Indian Ocean characterised by sea surface temperature (SST) anomalies of opposite sign in the east and west, coincident with anomalous large-scale circulation changes around the region (Ummenhoffer, 2009). The work of England's group has shown "*In the paper England et al. [2006] we showed a distinctive pattern of Indian Ocean sea surface temperature (SST) anomalies that characterised the southwest Australian rainfall variations, involving a dipole structure with unusually warm and cool waters adjacent to Western Australia .... Extreme events in rainfall were found to be part of a large-scale phenomenon spanning the Indian Ocean basin, extending south to 50ºS.*" and "*An analysis of the seasonal evolution of the climate extremes revealed a progressive amplification of anomalies in SST and atmospheric circulation toward a wintertime maximum, coinciding with the season of highest SWWA rainfall. The anomalies in SST can appear as early as the summertime months, however. This has important implications for predictability of SWWA rainfall extremes. This is an important aspect of the work as oceanic precursors to climate extremes are at the heart of improving lead forecast times of Australian rainfall.*" leading to "*Our discovery of an oceanic precursor to periods of unusually high and unusually low rainfall will ultimately lead to improved predictability of southwest Western Australia freshwater supply. Ensemble atmospheric and coupled climate model experiments ,..., have demonstrated that the above SST index significantly improves skill at forecasting SWWA rainfall.*"

IOD may be predictable out to several months in advance (Luo et al., 2008), and should be further investigated.

9. Moisture advection (Drost and England, 2008) '*the transport of atmospheric moisture by the wind, most notably in fronts and cyclones, is one of the main*

contributors to the occurrence of large scale precipitation' they use NCEP reanalysis data, where advection of moisture is determined as the product of specific humidity with the square root of the wind vector squared, integrated throughout the extent of the troposphere from 1000 to 500 hPa (or as the sum of the product of the specific humidity with the local mean wind at each level from 1000 to 500 hPa). They showed that there were significant correlations between advection of moisture and precipitation over Australia (including SWWA), showing significant seasonal variations. Moisture advection was also correlated (i.e. modulated by) with Southern Annular Mode (SAM) and the Southern Oscillation Index (SOI). The also speculate that changes in circulation patterns (as reflected in changes to SAM) might be reflected in changes in moisture advection, as mid-latitude weather systems are the main bearers of moisture to southern regions of Australia. They note that the correlations of moisture advection with precipitation have changed during the last part of the 20th century, and that features like ENSO, SAM and PDO affect moisture advection, and that while variability in precipitation can only be partially explained by known SST patterns, understanding moisture advection may explain observed changes in precipitation.

10. Alexander et al. (2009) note that a number of studies have attributed portions of the drying in SWWA to
    a. Anthropogenic forcing (Cai and Cowan, 2006; Hope, 2006; Timbal et al. , 2006)
    b. Impact of natural variability (Cai et al., 2005)
    c. Land cover change (Pitman and Narisma, 2005; Timbal and Alexander, 2006)
    d. BoM research finds Australian precipitation trends consistent with decadal variability in tropical Pacific SSTs

Technical Details

A Climate Index May Explain the Rainfall Decrease Over SWWA

We have used the monsoon concept to describe regional circulation patterns influencing rainfall variations in SWWA (Figures 3.2.1 and 3.2.2) and explored the impacts of SAM on the climate of this region. We found that the climate of SWWA is controlled by a monsoon-like circulation over the wider SWWA based on the characteristics a monsoonal system (Feng *et al.*, 2009): alternate wet and dry seasons, the seasonal reversal of wind and the evident land-sea thermal contrast. A climate index (based on the dynamics of a normalized seasonality index) called the Southwest Western Australian Circulation (SWAC) was developed to describe this circulation and its linkage to rainfall over SWWA. Results show that the winter SWAC has a significant positive correlation with SWWA winter rainfall. The variation of the SWAC is not only responsible for the interannual variability of SWWA winter rainfall, but also for the long term trend in SWWA rainfall: decreasing trend in early winter (MJJ) rainfall due to the weakening SWAC, and weak upward trend in SWWA late winter (ASO) rainfall resulting from the weakly increasing strength of the SWAC in late winter. The relationship between the SWAC and SWWA rainfall is robust, and largely independent of the influence of other large-scale circulations such as the SAM and ENSO.

Ongoing work in Project 3.2 will investigate how the SWAC influences extreme rainfall and temperature by integrating the SWAC index as a predictor into the statistical models for rainfall and temperature extremes over SWWA.

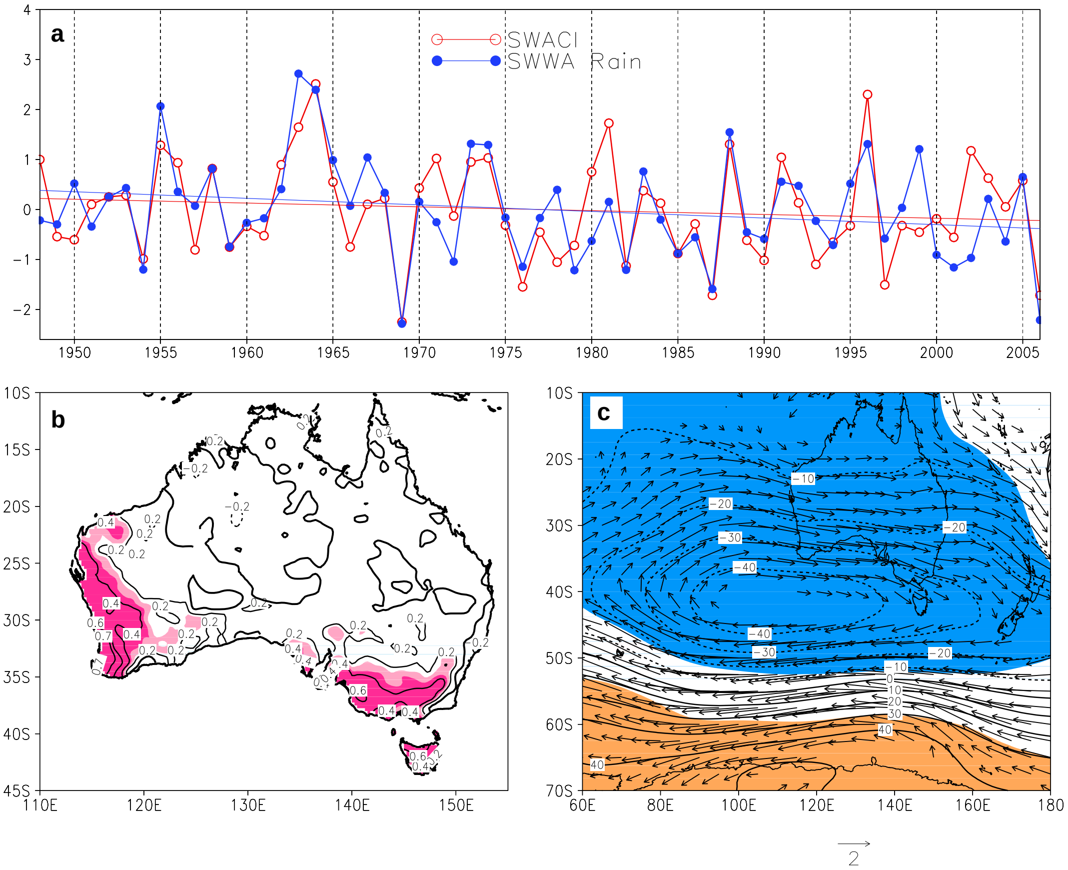

Figure 3.2.1 (a) Normalized time series of the winter SWACI and SWWA rainfall for 1948-2006. The line with hollow dots is the SWACI and the one with solid dots is SWWA rainfall. The thin lines are the linear trends for the corresponding periods, blue for SWWA rainfall and red for the winter SWACI, respectively. (b) Correlation map between the winter SWACI and rainfall in Australia. The shaded areas indicate significant at the 0.05 level. (c) The composite differences of geopotential height and winds at 850 hPa between the strong (more than 1 standard deviation) and weak (less than -1 standard deviation) winter SWAC years, only the values significant at the 0.05 level is given out. The significant positive/negative correlations at the 0.05 level between the winter SWACI and 850 hPa geopotential height is shaded in yellow/blue.

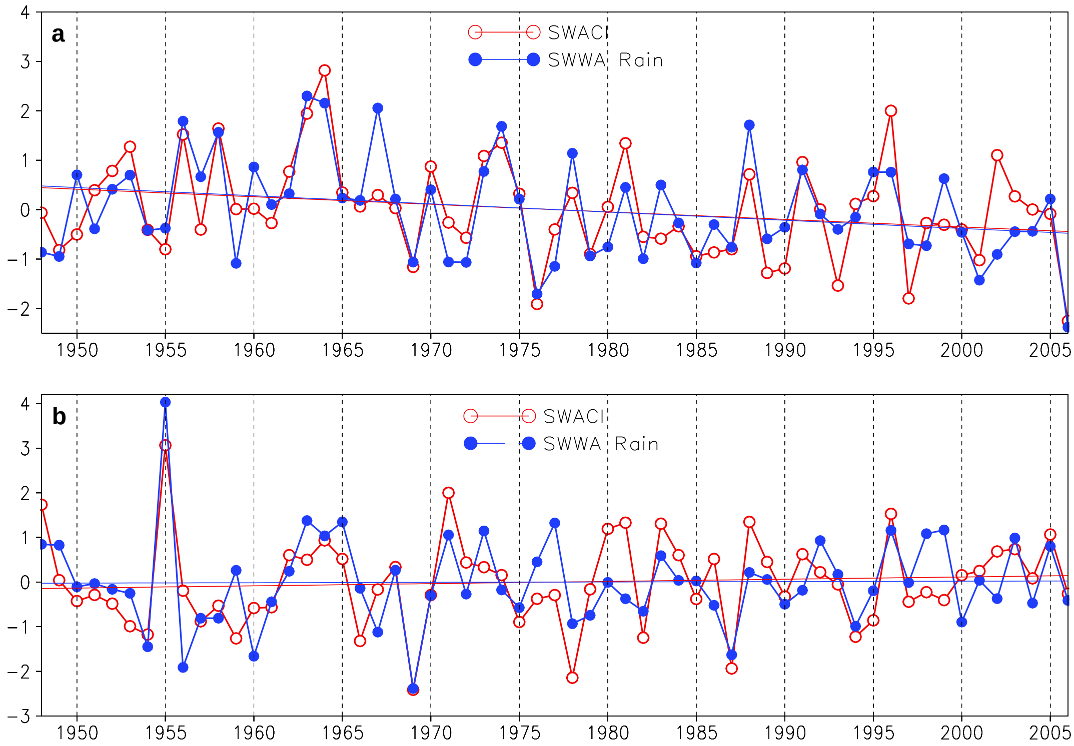

Figure 3.2.2 (a) Same as Error! Reference source not found.**(a) but for the early winter (MJJ). (b) Same as (a) but for the late winter (ASO).**

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Appendix: Indian Ocean Dipole

The Indian Ocean Dipole (IOD) is an oceanographic phenomenon affecting climate in the Indian Ocean region. For a brief introduction with a range of references see http://en.wikipedia.org/wiki/Indian_Ocean_Dipole.

At the beginning of the last century, research on the Indian Summer Monsoon (represented by the All-India Rainfall) led to the discovery of the Southern Oscillation, which is the atmospheric phenomenon associated with El Niño. Recently, however, findings have indicated a mysterious weakening in the correlation between the Indian Monsoons and ENSO (El Niño/Southern Oscillation). Consequently, based on the observational data from 1958 to 1997, an investigation was conducted into the influence of the Indian Ocean Dipole (IOD) phenomenon on interannual variability of the Indian Summer Monsoon rainfall.

The Indian Ocean Dipole (IOD) is a coupled ocean-atmosphere phenomenon in the Indian Ocean. It is normally characterized by anomalous cooling of SST in the south eastern equatorial Indian Ocean and anomalous warming of SST in the western equatorial Indian Ocean. Associated with these changes the normal convection situated over the eastern Indian Ocean warm pool shifts to the west and brings heavy rainfall over the east Africa and severe droughts/forest fires over the Indonesian region.

The IOD involves an aperiodic oscillation of sea-surface temperatures, between "positive" and "negative" phases. A positive phase sees greater-than-average sea-surface temperatures and greater precipitation in the western Indian Ocean region, with a corresponding cooling of waters in the eastern Indian Ocean—which tends to cause droughts in adjacent land areas of Indonesia and Australia. The negative phase of the IOD brings about the opposite conditions, with warmer water and greater precipitation in the eastern Indian Ocean, and cooler and drier conditions in the west.

The IOD also affects the strength of monsoons over the Indian subcontinent. A significant positive IOD occurred in 1997-8, with another in 2006. The IOD is one aspect of the general cycle of global climate, interacting with similar phenomena like the El Niño-Southern Oscillation (ENSO) in the Pacific Ocean. The positive IOD in

2007 evolved together with La Niña which is a very rare phenomenon that happened only once in the available historical records (in 1967). Also consecutive positive IOD events are extremely rare, with only one such precedence within the records (1913–14).

The IOD phenomenon was first identified by climate researchers in 1999. Yet evidence from fossil coral reefs demonstrates that the IOD has functioned since at least the middle of the Holocene period, 6500 years ago. The name " Indian Ocean Dipole (IOD) " was coined by Prof. Yamagata, Dr. Saji and other researchers of the Climate Variations Research Program (CVRP) of Frontier Research Center for Global Change (FRCGC) to represent the zonal dipole structure of the various coupled ocean-atmosphere parameters such as SST, OLR and Sea Surface Height anomalies. Generally, this configuration is also called positive IOD. In fact, a negative IOD also evolves preceding/following a positive IOD, with reverse in the configuration of the positive IOD.

The intensity of the IOD is represented by anomalous SST gradient between the western equatorial Indian Ocean (50E-70E and 10S-10N) and the south eastern equatorial Indian Ocean (90E-110E and 10S-0N). This gradient is named as Dipole Mode Index (DMI). When the DMI is positive then, the phenomenon is refereed as the positive IOD and when it is negative, it is refereed as negative IOD. This dataset can be downloaded in a netcdf format here. Since, IOD is a coupled ocean-atmosphere phenomenon it can also be represented by any other atmospheric (pressure, OLR) or oceanographic (sea surface height) as well. DMI derived from OLR anomalies can be downloaded from here.

Between 1958 - 1997, whenever the correlation of the Indian Summer Monsoon rainfall with ENSO (El Niño/Southern Oscillation) is low, the correlation with the Indian Ocean Dipole (IOD) is high, and vice versa. In the 1990s, intense and frequent Dipole Mode events occurred, resulting in a weak correlation between the Indian Monsoon and ENSO (fig.1). The IOD event not only affects the zonal (east-west) circulation in the troposphere, but also impacts on the meridional (north-south) circulation (fig.2). The simulations using the Frontier atmospheric general circulation model (FrAM1.0) clearly showed that a positive Dipole Mode Event, in particular, produces a positive rainfall anomaly along the monsoon trough prevailing across Northern India, and over the Bay of Bengal (ref. 3). During a typical El Niño period the amount of precipitation accompanying the Indian Monsoons is reduced, but a positive Dipole Mode Event counteracts this effect when they occur together (ref.4). The mechanism that causes the complementary impact of these two main phenomena on Indian Monsoon rainfall has now been clarified for the first time. These findings will considerably improve the short-term prediction of climate change in various countries affected by the Asian Monsoon in addition to India. (http://www.jamstec.go.jp/frcgc/jp/press/yamagata/011129/eng/index_e.html

LIST OF FIGURES