Climate Change Investigations – SAAL Region: Neales-Peake Catchment Scenario Modelling

DEWNR Technical note 2015/24

Government of South Australia
Department of Environment, Water and Natural Resources

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Summary

Recently, the Government of South Australian, through its Impacts of Climate Change on Water Resources Project, has undertaken an analysis of groundwater recharge, surface water runoff and rainfall intensity data in the South Australian Arid Lands Natural Resources Management (SAALNRM) Region to determine the potential impact of climate change on the principal water resources of the region (Gibbs et al., 2012). The SAALNRM Region contains most of the north-east of South Australia, running from the borders with the Northern Territory and Queensland as far South as Iron Magnet on Eyre Peninsula and as far East as Marla, thereby containing much of the Arckaringa Subregion. The *Climate Change Investigations – SAAL Region* project is part of the current revision of the South Australian Arid Lands Regional NRM Plan, with a key aim to integrate climate change impacts, mitigation and adaptation throughout the SAAL NRM Plan. The effect of climate change on the SAAL Region's scarce water resources is a critical factor for NRM planning in the Region. The project will fill a significant gap in the SAAL NRM planning process through applying climate change projections to filling and drying of key waterholes in the Neales River system.

Catchment floods that deliver large flows that traverse all reaches of the catchment enabling connectivity between critical refugial waterholes are vital for many aquatic fauna during periods of no flow (Hamilton et al., 2005). These floods result in substantial connection between the upstream and downstream reaches, significant floodplain inundation and a resetting of the water levels in waterholes with a high level of persistence.

The objective of this study is to provide an understanding of the likely changes to the drying-filling regime and water level persistence in waterholes that have been identified as key ecological refugia in the SAAL region under a range of possible future climate scenarios. While changes in climate are projected by General Circulation Models (GCMs), the processes controlling the conversion of changes in climate into changes in water availability occur at a smaller scale, and hence require local scale investigations on a case by case basis. The Algebuckina and Peake waterholes have been used as a case study as:

- A catchment model was recently developed to assess the climate projections (Montazeri and Osti, 2014)
- Both Algebuckina and Peake waterholes have been identified as significant ecological refugia due to their beneficial persistence times (Costelloe et al., 2004; 2005a; 2011a)
- Both waterholes have the best available stage data in the region from which catchment-scale flood events can be reasonably determined (J. Costelloe 2014, pers. comm.), so any changes in levels due to changes in climate are likely to be detected

It is not the intention of this study to predict the likely changes in waterhole flow regimes over the next century. The GCM outputs provide a projection of the changes in climate for a range of scenarios, for example high or low emissions. In climate change impact studies typically no knowledge or judgement is applied to assess the likelihood of the different projections occurring, to provide a prediction, as opposed to projections, of the future changes. As such the approach adopted in this study is to convert the climate change projections for rainfall and potential evapotranspiration (PET) from a range of current GCMs to indicate the range of possible changes in water level for those conditions.

In order to assess the impact of projected changes in climate on the water levels of Algebuckina and Peake waterholes 100 sets of downscaled rainfall and PET projections for three GCMs and two emissions scenarios, realised through use of a non-homogeneous hidden Markov model (NHMM), were incorporated into a hydrological model for Neales-Peake catchment. By combining hindcast data with projected data it was possible to run the model from 1961–2100, enabling a comprehensive analysis of projected changes to the flow regime.

An analysis of modelled water levels for Algebuckina and Peake waterholes under 40 year of historical climate show that the frequency of filling events is generally only once a year if sufficient catchment-scale rainfall events occur. The mean duration of these filling events in Algebuckina are in the order of 5–7 days and in Peake for 3–12 days, occurring mostly during the summer/spring seasons that correspond to the Northern monsoon rains influencing the SAAL region. Although high rainfall events that may result in filling events in both waterholes do occur in autumn/winter seasons, the frequency and mean duration of events is markedly less and may serve to "top-up" waterhole levels.

Three GCMs were examined representing 'best' case, 'most likely' case and 'worst' case climate futures under high and low RCP emission scenarios. Annual rainfall in the region under these GCMs and emission scenarios remains highly variable in intensity

and frequency of large events. The change in annual rainfall totals under the 'best' and 'most likely' climate projections from the historical baseline was on average small, but the range between 10th and 90th percentile totals was reduced. Under the 'worst' case climate projections a marked decline in annual rainfall from the historical baseline was apparent. Conversely, all GCMs resulted in a large increase in PET over the future time horizon for both low and high emission scenarios. With the resulting drier future climate the frequency and mean duration of high rainfall also exhibited large declines from historical baseline, particularly for the 'worst' case climate projections. Under the high emissions scenario, projected reductions in rainfall and increases in PET are more severe than the low emissions case.

The results presented indicate that changes in the frequency of waterhole filling events were strongly associated with changes in annual rainfall. The frequency of filling events in both Algebuckina and Peake waterholes under each GCM and emission scenario demonstrated trends that are in line with a projected decrease in the frequency of rainfall events during the summer/spring 'wet' season and the autumn/winter 'dry' season under a drying climate future. The mean duration of filling events is projected to be halved under the 'worst' case GCM and high emission scenario.

For both Algebuckina and Peake waterholes, the influence of the low and high emission scenarios are apparent in the 'worst' case scenario causing large decreases in frequency and mean duration of cease to flow events. The 'best' and 'most likely' case climate projections changed little from mean historical baseline, but an increase in range between 10th and 90th percentile cease to low levels is apparent. Current measured Cease to Flow (CTF) levels in Algebuckina occur approximately once each year with a mean duration of at least 70 days. For Peake waterhole CTF levels also occur at least once each year and for a mean duration of at least 100 days. Climate projection scenarios that have the potential to reduce this frequency of CTF periods and shorten the mean duration would have a detrimental effect on waterhole persistence and the ability to sustain a healthy aquatic ecosystem. Under the 'best' and 'most likely' case climate projections the frequency and mean duration of CTF levels is only slightly reduced and unlikely to be problematic in the context of ecosystem management. However, under the 'worst' case scenario it was projected that frequency of CTF levels could decrease by half and duration reduced by 20–30 days.

For all climate models and emission scenarios dry spell frequency and duration increases above mean historical baseline levels to some degree. For 'best' and 'most likely' cases this increase is not large, but under the 'worst' case climate projections there is a pronounced increases in 90th percentile dry spell frequencies, by between 3 and 5 events above historical baseline per decade, and an increase in mean duration of between 40–70 days longer than historical baseline.

The three climate models utilised in this study (noresm1m GCM as the 'most likely' case, mri.cgcm3 GCM as the 'best' case and CSIROmk3.6 GCM as the 'worst' case) all project a dryer climate over the SAAL region, with a decrease in rainfall frequency and catchment-scale flooding events and an increase in PET. This translates into different responses in drying-filling events and changes to cease to flow periods for Algebuckina and Peake waterholes. Under the 'best and 'most likely' case climate projections the climate futures show little change from mean historical baseline, but the variability of drying-filling events shows a marked increase. Under the 'worst' case climate projections, there is a marked decline in filling events and cease to flow periods, both in frequency and duration, and a substantial increase in dry spells in both Algebuckina and Peake waterholes. Managing the water availability and water dependent ecosystem health in the region within this context would benefit from ongoing monitoring and data gathering to refine the models that underpin these types of studies.

1 Introduction

1.1 Project background

Climate change is acknowledged as a potential threat to the future of South Australia's water security. South Australia's *Water for Good* plan (Government of South Australia, 2010) identified climate change as a major challenge to water resources in most of South Australia's Natural Resources Management (NRM) regions.

The CSIRO and the Bureau of Meteorology (BoM) have previously undertaken investigations which project the likely impacts of climate change on climate variables for South Australia (Suppiah *et al.*, 2006; CSIRO and BoM, 2007). Their assessment of current projections indicates that through the 21st century, South Australia may be subject to:

- increased temperatures
- reduced rainfall
- increased rainfall variability
- increased evaporation
- significantly increased frequency and severity of drought
- changes in the frequency of extreme weather events, including flooding.

Of immediate concern to South Australia will be the impacts of decreased rainfall and its increased variability. Along with higher temperatures, which increase potential evapotranspiration (PET), the combined impacts may have significant consequences for the state's natural water resources. With projected impacts of climate change leading to a generally drier outlook, the state may face reduced availability of good quality water resources and an increased risk to the security of important water resources.

Recently, the Government of South Australia, through its Impacts of Climate Change on Water Resources Project, has undertaken an analysis of groundwater recharge, surface water runoff and rainfall intensity data in the South Australian Arid Lands Natural Resources Management (SAALNRM) Region to determine the potential impact of climate change on the principal water resources of the region (Gibbs et al., 2012). The SAALNRM Region contains most of the North-East of South Australia, running from the borders with the Northern Territory and Queensland as far South as Iron Magnet on Eyre Peninsula and as far East as Marla, thereby containing much of the Arckaringa Subregion. This report found that rainfall decreases across the NRM region led to even more significant decreases in annual runoff totals, on the order of 2:1. Gibbs et al. (2012) also determined that in the Neales-Peake catchment (cf. Section 1.1.5.1.1), the length of time between flow events increased in line with rainfall decreases, i.e. a 10% reduction in annual rainfall led to a 10% increase in average length of dry periods, a statistic that is potentially more important given the intermittent nature of flow events in the region.

The *Climate Change Investigations – SAAL Region* project is part of the current revision of the South Australian Arid Lands Regional NRM Plan, with a key aim to integrate climate change impacts, mitigation and adaptation throughout the SAAL NRM Plan. The effect of climate change on the SAAL Region's scarce water resources is a critical factor for NRM planning in the Region. The project will fill a significant gap in the SAAL NRM planning process through applying climate change projections to filling and drying of key waterholes in the Neales River system. The hydrology of these waterholes is a major determinant of the ability of aquatic biota to persist in the system, as well as affecting surrounding terrestrial systems. Project findings will therefore directly inform climate change adaptation decision-making for the Neales system and indirectly assist in broader NRM planning for climate change throughout the SAAL Region.

1.2 Aims and objectives

The objective of this study is to provide an understanding of the likely changes to the drying-filling regime and water level persistence in waterholes that have been identified as key ecological refugia in the South Australian Arid Lands (SAAL) region of South Australia under a range of possible future climate scenarios. While changes in climate are projected by General Circulation Models (GCMs), the processes controlling the conversion of changes in climate into changes in water availability occur at a smaller scale, and hence require local scale investigations on a case by case basis. The Algebuckina and Peake waterholes have been used as a case study as:

- A catchment model was recently developed to assess the climate projections (Montazeri and Osti, 2014)
- Both Algebuckina and Peake waterholes have been identified as significant ecological refugia due to their beneficial persistence times (Costelloe et al., 2004; 2005a; 2011a)
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It is not the intention of this study to predict the likely changes in waterhole flow regimes over the next century. The GCM outputs provide a projection of the changes in climate for a range of scenarios, for example high or low emissions. In climate change impact studies typically no knowledge or judgement is applied to assess the likelihood of the different projections occurring, to provide a prediction, as opposed to projections, of the future changes.

As such the approach adopted in this study is to convert the climate change projections for rainfall and potential evapotranspiration (PET) from a range of current GCMs to indicate the range of possible changes in water level for those conditions.

2 Catchment overview

The Arckaringa subregion of the Lake Eyre bioregion is located in northern South Australia and contains the majority of the Neales-Peake surface water drainage catchment in addition to intersecting the southernmost watercourse in the Macumba catchment, Woolridge Creek. The Arckaringa subregion, Neales-Peake and Macumba catchments are shown in Figure 1.

The Neales-Peake catchment is an ephemeral, unregulated river system, consisting of the Neales and Peake Rivers and associated tributaries, and has a total catchment area of 34 415 km^2. The headwaters of the catchment develop on the stony tablelands forming the western rim of the Lake Eyre Basin, at an elevation of 300–370 m, with the main drainage channel running 430 km before terminating at Lake Eyre North at approximately sea level (Costelloe et al., 2005a).

Mean annual rainfall varies between 130 mm and 170 mm across the majority of the Arckaringa subregion, with higher totals in excess of 200 mm found in the higher reaches of the Stuart and Peake-Dennison Ranges. Averaged across the region, the long term mean annual rainfall is 153 mm and mean annual potential evapotranspiration is 2510 mm, resulting in significant transmission losses. Although the majority of rainfall occurs in the summer months, significant winter rains are not uncommon (Costelloe et al, 2005a). The spatial and temporal variability of rainfall over the catchment is among the highest in Australia (Allan, 1985). Key rainfall events in the Neales-Peake range from convective thunderstorms with limited spatial extent but often with high intensities, to large transient depressions of tropical origin (Allan, 1985; Croke et al., 1999) that result in catchment-wide flooding.

Characterised by complex, multiple braided, shallow channels, wide floodplains and ephemeral waterholes, the intermittent watercourses of the Neales-Peake system typically flow in response to the more localized thunderstorm-derived rainfall. Such events can be important in maintaining aquatic refugia but result in limited connectivity between waterholes. The volume of the waterholes is often quite small, with most waterholes ranging between 5 and 90 ML, though they can be as large as 280 ML (Costelloe et al., 2008). The small size of most waterholes means that small runoff events in the main channel system are capable of filling waterholes to the level at which continuous flow commences to downstream. Catchment-scale flood events that cause larger floodplain inundation occur infrequently (Costelloe et al., 2005b), but are of significant importance for recharging the alluvial/floodplain groundwater stores and allowing widespread migration of aquatic fauna.

Understanding the ecohydrology of ephemeral to intermittent arid zone rivers is greatly hindered by the scarcity of hydrological data measuring both individual flow events and the long-term flow regime in the river (Costelloe et al., 2005a). In recent years, several targeted data-gathering projects have been undertaken in the Neales-Peake catchment (Costelloe et al, 2008; Costelloe, 2011a). This has resulted in a 10 year database collating information on the persistence of waterholes in the catchment (Costelloe, 2011a). Although there is still a pronounced knowledge gap in terms of volumetric data, stage data of varying quality and length have been collected for all waterholes over the period 2000-2013 for the Neales-Peake catchment. In spite of the short time scale, missing and unreliable stage data and lack of flow data, the data collected on the Neales-Peake catchment represent the most comprehensive data set of all Western Lake Eyre Basin River Systems.

The stage data for Algebuckina and Peake Waterhole represent the most complete set of water level data in the region. The data shown represent a merging of data collected through multiple loggers installed through the ARIDFLOW project (Costelloe et al., 2004), Critical Refugia Project (Costelloe , 2011a) and a telemetered gauge installed by the South Australian Department of Environment, Water and Natural Resources in 2011.

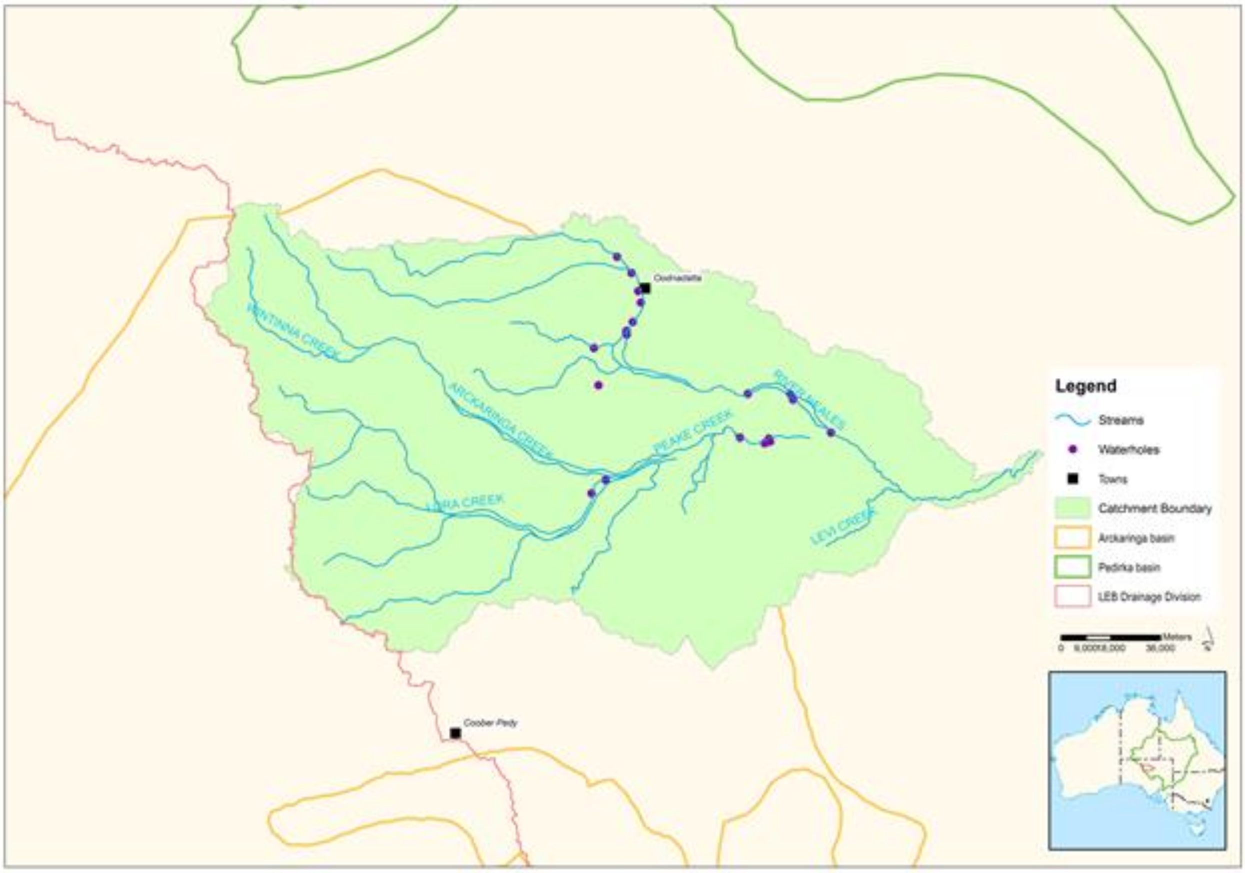

Figure 1 Neales-Peake catchment locality map

3 Climate projection scenarios

3.1 Climate data

To enable the evaluation of climate change impacts on surface water resources, it is important to identify the most appropriate climate change projections for use in these types of studies and to adopt an appropriate method to down-scale these projections to create 'future climate' data sets that are representative of each study area location.

The Intergovernmental Panel on Climate Change's *Fifth Assessment Report* (IPCC, 2013) included new climate projections from updated and revised GCMs. These new climate projections have been assessed through the Goyder Institute for Water Research project, "*Downscaling and climate change projections for South Australia*", where approximately one third of the over 40 GCMs have been identified to adequately represent the important drivers for the South Australian climate, and as such are most likely to represent the impact of a change in climate due to changes in greenhouse gas concentrations.

GCM results are too coarse to be adopted directly in water resource impact models, and downscaling of the projections to the local weather station scale is required. The Goyder Institute project has downscaled each of the GCMs selected to represent the local weather station statistics more accurately. This data represents the current best knowledge available for climate projections for the future, and as such has been adopted for this study.

The Goyder Institute project used an approach known as non-homogeneous hidden Markov models (NHMM) to undertake the downscaling, where relationships are developed to relate the large scale climate variables that GCMs can reliably simulate, such as pressures and temperatures, to the local weather station data of interest. Local scale time series of rainfall as well as temperature, solar radiation, pressure and humidity, were available, with the variables available used to derive the potential evapotranspiration (PET) time series necessary to input to the catchment model. One hundred NHMM simulations of rainfall and PET (termed realisations in this report) were made available for this study.

3.1.1 Climate futures framework for the SAAL Region

The Climate Futures Framework approach (Clarke *et al*., 2011; Alcoe *et al.* 2012) involves classifying the projected changes in climate by a suite of GCMs into separate categories (termed Climate Futures) based on the relative frequency of GCMs projecting a similar Climate Future. In the current project, the projected changes in mean annual surface temperature and mean annual rainfall are the two variables used to define the Climate Futures. The Climate Futures analysis for the Neales-Peake catchment was applied to the NHMM data based on a selection of the most representative GCMs for South Australia selected in the Goyder Institute project.

Three Climate Futures categories are used in this project:

1. The 'most likely' case, where the number of GCMs that fall in this category is at least two more than the next most likely Climate Future.
2. The 'worst case' is the Climate Future with the largest increase in temperature and the least rainfall (i.e. the driest and hottest climate).
3. The 'best case' is the Climate Future with the smallest increase in temperature and the highest rainfall (i.e. the wettest and coolest climate).

The Climate Futures analysis was undertaken for the one suitable station that had downscaled data available (Macumba, station number 17030) that is located near the study area. The time horizon of 2050 has been used to assess the projected changes in mean annual surface temperature (in degrees) and mean annual rainfall (as a percentage) derived from the downscaled GCM projections. The projected changes were calculated relative to the historic baseline period of 1990, with each period calculated using a 30-year window around the time period (i.e. for 1990 the average values are calculated over the period 1975–2005).

Two Representative Concentration Pathways (RCP) emissions scenarios were considered in this report; a low emissions (r4.5) scenario and a high emissions (r8.5) scenario, with the projected changes in rainfall and temperature for Macumba plotted in Figure 2 and Figure 3 for low and high emissions, respectively. The results are summarised in Table 1 and Table 2.

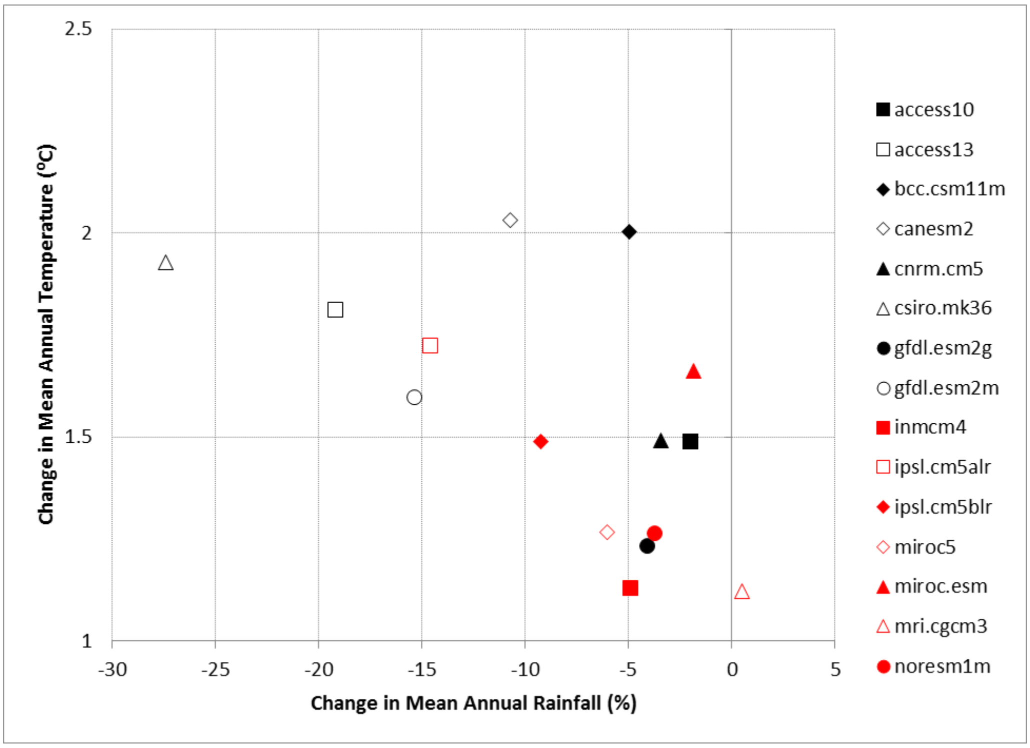

Figure 2 GCM Projections for Climate Futures for Macumba for 2050, low emissions

Table 1 Climate Future matrix for Climate Futures for Macumba for 2050, low emissions

	Mean annual temperature		
Rainfall	Slightly Warmer (0.5 – 1 °C)	Warmer (1 to 2 °C)	Hotter (2 to 3 °C)
Much Drier (> -25%)		1 of 15 models	
Drier (-15 to -25%)		2 of 15 models	
Slightly Drier (-5 to -15%)		3 of 15 models	1 of 15 models
Little Change (-5 to 5%)		7 of 15 models	1 of 15 models

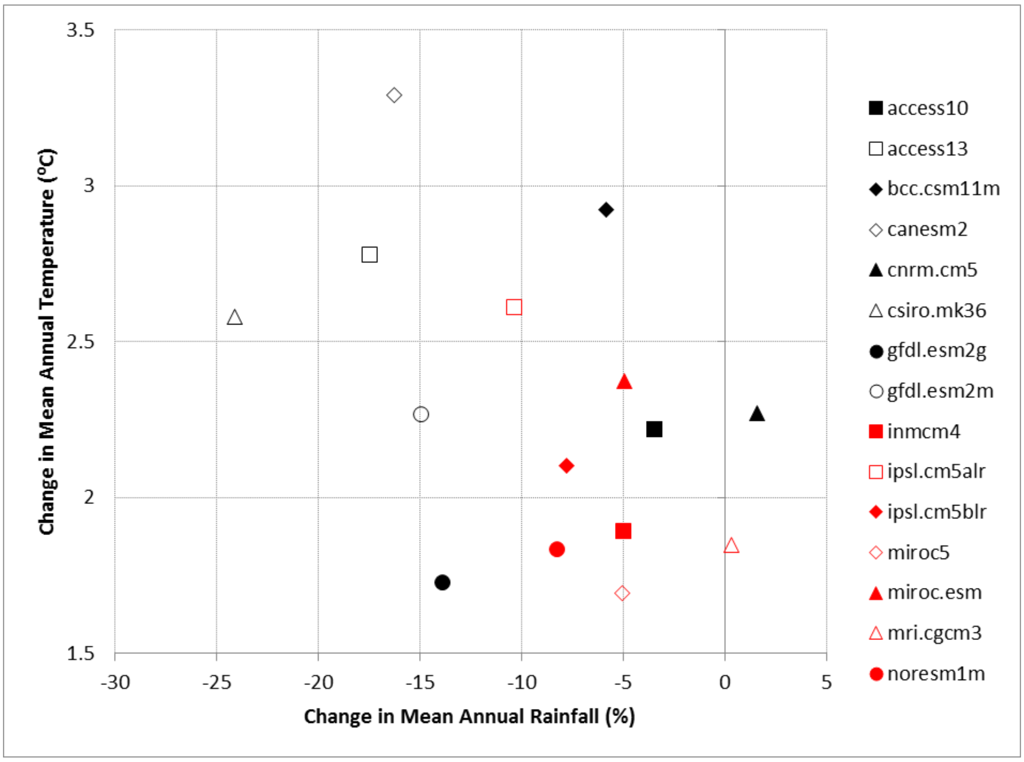

Figure 3 GCM Projections for Climate Futures for Macumba for 2050, high emissions

Table 2 Climate Future matrix for Climate Futures for Macumba for 2050, high emissions

RCP8.5*	**Mean annual temperature**			
Rainfall	Slightly Warmer (0.5 – 1 ^{o}C)	Warmer (1 to 2 ^{o}C)	Hotter (2 to 3 ^{o}C)	Much Hotter (3 to 4 ^{o}C)
Much Drier (> -25%)				
Drier (-15 to -25%)			3	1
Slightly Drier (-5 to -15%)		4	4	
Little Change (-5 to 5%)		1	3	

* Rising radiative forcing pathway leading to 8.5 W/m2 in 2100.

There is considerable range in both rainfall and temperature projections for 2050 for Macumba. For the low emissions scenario, a majority of GCMs project little change in rainfall, although multiple GCMs project slightly drier and drier conditions with one GCM projecting a much drier climate. Temperature projections under the low emissions scenario are more consistent, with 13 of the 15 GCMs projecting a warmer climate. For the high emissions case, a majority of GCMs project a hotter climate, though multiple GCMs project warmer conditions by 2050. A small majority of GCMs project slightly drier conditions under the high emissions scenario, with the remaining GCMs equally divided between drier conditions and little change. Each GCM projected greater temperature increases for the high emissions scenario compared with the low emissions scenario (average of 50% higher). In contrast, 7 of the 15 GCMs considered projected smaller reductions in rainfall under the high emissions scenario than for the low emissions scenario.

From Figure 2 and Figure 3, it can be seen that of all GCMs considered, the CSIROmk3.6 GCM projected the largest reduction in rainfall for both emission scenarios. It also projects significant increases in temperature. For these reasons it can be considered the ‘worst’ case Climate Future under the Climate Futures framework.

The MRI CGM3 GCM is the only GCM that projects increases in rainfall for both emissions scenarios. It also falls in the lowest temperature rise bin for both emissions scenarios. The MRI CGM3 will be considered as the ‘best’ case GCM in this report.

The selection of 'most likely' GCM is constrained to come from the group of seven GCMs highlighted in 1. For consistency with previous work (Osti and Green, 2014; Cetin et al., 2014), the noresm1m which falls within the highlighted box was selected for use in this work.

3.2 Climate change scenarios

Based on the Climate Futures analysis in the previous section, the projections from three GCMs have been considered in this study, to provide a representation of the range of projections available based on the AR5 GCMs selected as part of the Goyder Institute Project. Projected changes in rainfall and PET have been applied to the Neales-Peake catchment model for three GCMs:

- noresm1m GCM = 'most likely' case
- mri.cgcm3 GCM = 'best' case
- CSIROmk3.6 GCM = 'worst' case

Two Representative Concentration Pathways (RCP) emissions scenarios were considered in this report; a low emissions (r4.5) scenario and a high emissions (r8.5) scenario. The NHMM downscaling methodology produced a continuous daily time series of rainfall and PET projections from 2006–2100, with hindcast values produced back to 1961, resulting in a continuous time series of rainfall and PET from 1961–2100 that was utilised as climate inputs to the Neales-Peake Source model (for more information on the Neales-Peake model see Montazeri and Osti, 2014).

3.3 Scenario analysis framework

In order to assess the long-term impacts of climate change on catchment-scale flood events and waterhole persistence the Algerbuckina and Peake waterholes were selected as a case study. Climate projections for rainfall and PET from the three GCMs and for two emission (high – 8.5 RCP and low – 4.5 RCP) scenarios were incorporated as rainfall-runoff model inputs into the recently developed eWater Source hydrological model for the Neales-Peake catchment (version 3.6.5.) (Figure 4). Due to the lack of volumetric data from which to calibrate catchment flows, stage data was utilised to calibrate storage levels for each waterhole represented in the model. Therefore, modelled storage levels were considered more reliable as a measure to assess the impact of future climate projections. A custom batch runner interface was developed based on the BatchRunner tool from eWater, and was used to run the 100 realisations of climate data produced via the NHMM downscaling approach as inputs to the rainfall-runoff model and to each storage node model for each scenario, enabling an estimate of variability in water levels due to future climate projections (Figure 5).

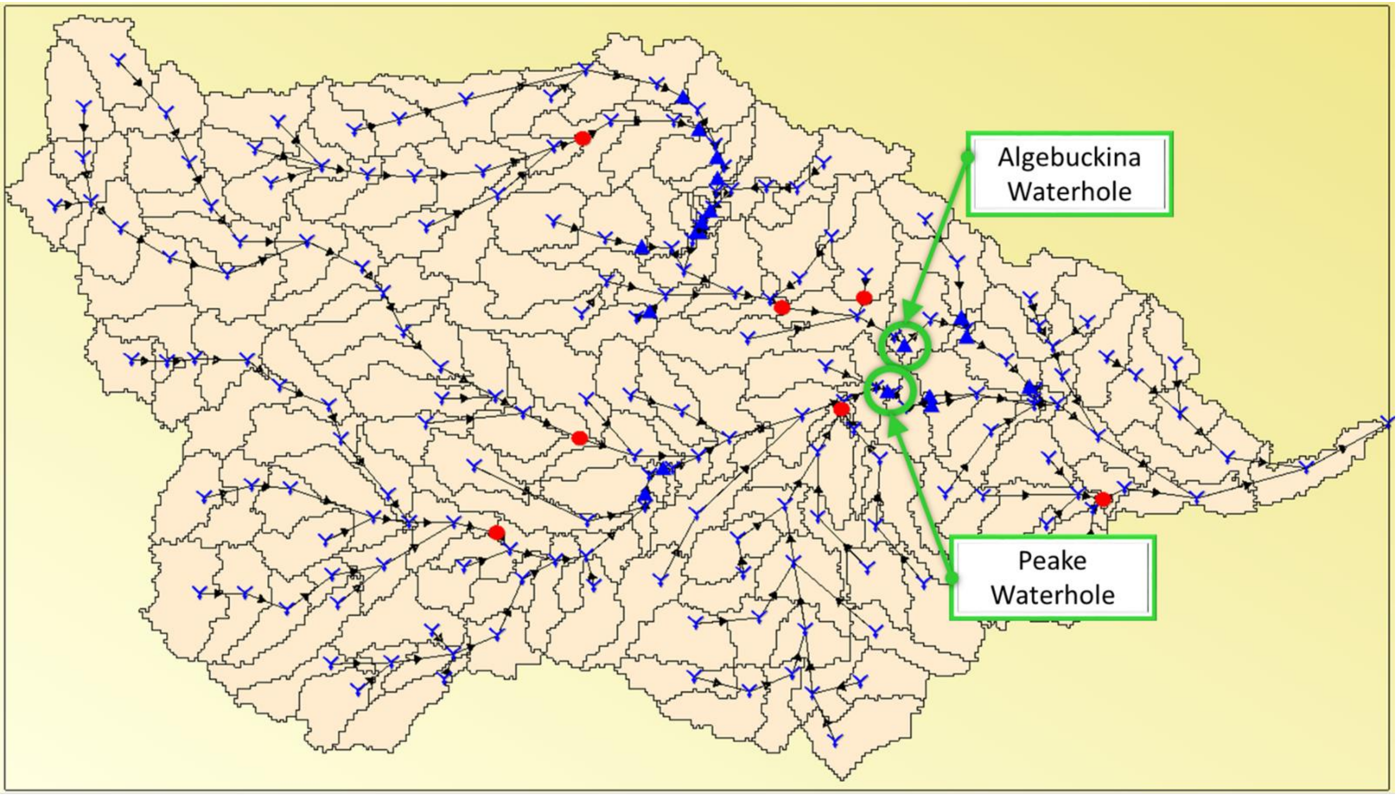

Figure 4. eWater Source model for the Neales-Peake catchment

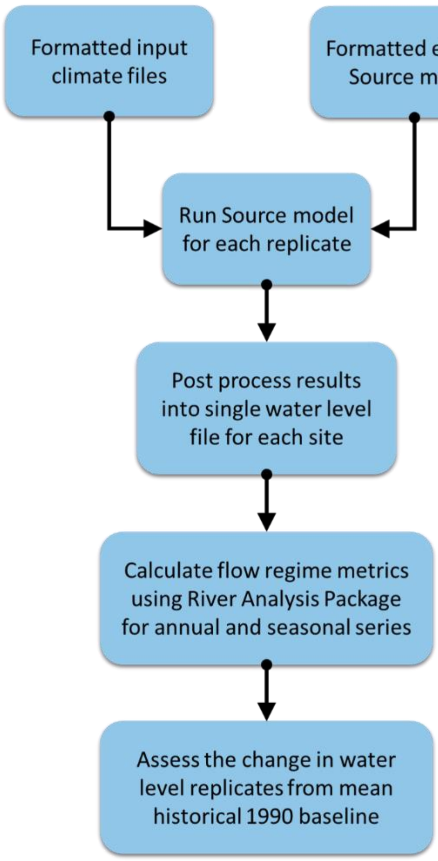

Figure 5. Conceptual representation of climate scenario analysis framework

3.3.1 Selection of metrics

Rainfall events that result in catchment-scale flood events were of particular interest in this study. Over the period 2000–10, six flows (February 2000, June 2001, February 2003, October 2005, December 2008 and December 2009) were whole catchment floods, large enough to inundate most of the floodplain, connect all major rivers and tributaries and likely flow into Lake Eyre North. Additionally, some flood data are available for the period 2010–12 which indicates that a major flood, estimated as a 1:10 year event (Costelloe, 2011a) occurred in March 2011 in response to rainfall from a rain depression associated with Cyclone Yasi. Examination of rainfall recorded during the periods identified as catchment floods indicate that a median rainfall depth of 22 mm is a conservative threshold in determining significant flooding events that enabled connectivity been waterholes (Table 3).

Table 3. Maximum rainfall depth recorded at the Oodnadatta climate station (17043) corresponding to catchment flood events identified in Costelloe (2011)

Date of event	**max rainfall (mm)** Median = 22 mm
12 June 2001	40
19 October 2005	16.2
11 December 2008	19.8
22 November 2009	20.2
25 December 2009	23.6
19 March 2011	114

Catchment-scale flood events that enable waterhole connectivity corresponded to water levels in Algebuckina above 6 meters and in Peake above 3 m, where over bank flows are likely to occur (Costelloe, 2011). In addition to catchment scale flood events that enable waterhole connectivity, the cease-to-flow depth (CTFD), which is the maximum depth of a waterhole when flow ceases, is of particular interest in this study as a measure of how long water will persist within the waterhole, which is of great significance to local biota (Costelloe et al., 2007). Data collected by Costelloe (2011) on cease to flow levels and stage recordings identified as resulting from catchment floods was used to derive threshold water levels for climate change scenario analysis (Table 4).

Table 4. Threshold gauge levels used to determine cease to flow and high levels resulting from catchment flood events (sourced from Costelloe, 2011)

Waterhole	Cease to flow levels (m)	Event levels (m)
Algebuckina	4.5	6
Peake	1.5	3

A number of metrics have been used to assess the changes in water levels for Algebuckina and Peake waterholes during 'wet' (October to March, representing the period where monsoonal rainfalls from Northern Australia contribute high, intense rainfall events to the SAAL region) and 'dry' (April to September) periods under the different climate projections:

1. The frequency of high water levels resulting from catchment flood rainfall events in a 'wet'and 'dry'period, calculated as the number of events where waterlevel is greater than the peak level (Table 4) per each 10 year block

2. Mean duration of high water levels for 'wet'and 'dry'period, calcaulated as the average number of days when water elevels are greater than the peak level (Table 4) per each 10 year block

3. The frequency and mean duration of CTF levels (Table 4) in a given 10 year block

4. The frequency and mean duration of dry spells (levels below 0.1m) in a given 10 year block.

Metrics were calculated using the River Analysis Package (RAP) Time Series Analysis tool (eWater Toolkit, http://www.toolkit.net.au/Tools/RAP)

It is important to note that previous hydrological evaluation of the NHMM utilised in climate change assessments for the Onkaparinga catchment in South Australia (Westra *et al*., 2014) have identified areas of systematic bias in the data, particularly in relation to high flow events (Westra *et al*., 2014). These biases were determined to impact on annual flow volumes, since a very large proportion of the overall flow volume in that catchment came from a small number of high-flow days. It was determined that bias was likely caused by the NHMM algorithm rather than the forcing GCM. The systematic biases in the NHMM algorithm were found to be of sufficient magnitude that Westra *et al*. (2014) suggests that they are likely to significantly affect climate change projections. Westra *et al*. (2014) recommend that the best means of addressing the systematic biases associated with the NHMM algorithm is to present future projections in terms of relative changes in future flows compared to historical flows obtained from the same climate model run with historical greenhouse gas forcings.

As a result, the absolute values for water levels, and the frequency and duration of days above or below a certain level threshold are influenced by the errors introduced by the downscaling processes. These metrics should then be interpreted as the projected change in the frequency and duration of water levels that are likely to result in changes to the waterhole drying-wetting regime when compared to the historical baseline period (1961–2000) in a given year.

For context, the variability in water levels for each waterhole simulated over the baseline period (1961–2000) is presented alongside the relevant projections. This baseline series is derived from the each climate model as recommended by Westra *et al*. (2014), therefore representing the range in the metric within the natural variability of the catchment (i.e. the water level each year is not the long term average water level) as opposed to variability introduced by the different emissions scenarios, or projections of each emission scenario represented by the three GCMs, which is presented as different series on each plot.

To illustrate the range in drying-filling metrics derived from climate projections and different RCP emission scenarios results are presented as box-plots with the format given in Figure 6.

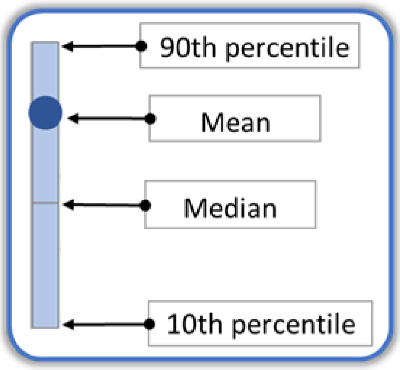

Figure 6. Box-plot configuration used to illustrate the range in flow metrics for each climate projection scenario

4 Results

4.1 Hisorical baseline conditions

To give some context to understanding the effect that climate projections from each GCM and RCP emission scenarios may have on waterhole levels and drying-filling regime an analysis of the observed climate data used as inputs to the Neales-Peake Source model was undertaken. High rainfall events above 22mm occurred in each season, with the majority of events occurring during the summer period driven by the Northern Australian Monsoon season. These rainfall events are intense with the mean duration of an event occurring within a few days (Table 5 and Figure 8).

The frequency and duration of high rainfall events for each year of the historical baseline period is presented in Figure 7 and Figure 8. Twenty-two years out of the forty-year record exhibit high rainfall events occurring in the spring/summer seasons and sixteen years have events occurring in the autumn/winter seasons, but generally only a single event occurs in years with major rainfall events.

Table 5. Summary of the mean frequency and mean duration of seasonal rainfall events for catchment averaged SILO historical rainfall (1961–2000).

	Mean frequency of events (mean number of events)	Mean Duration of events (number of days)
Spring	0.2	1.0
Summer	0.5	1.2
Autumn	0.3	1.1
Winter	0.2	1.0

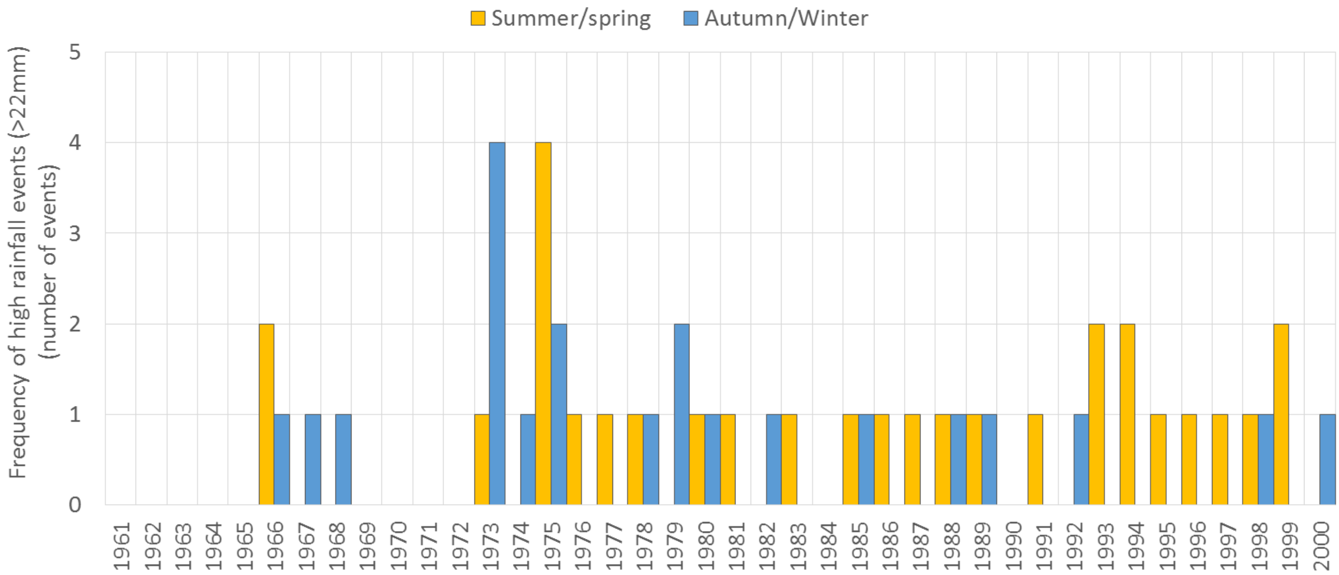

Figure 7. Frequency of high rainfall event (>22 mm) calculated from the daily rainfall data used in the Neales-Peake Source model

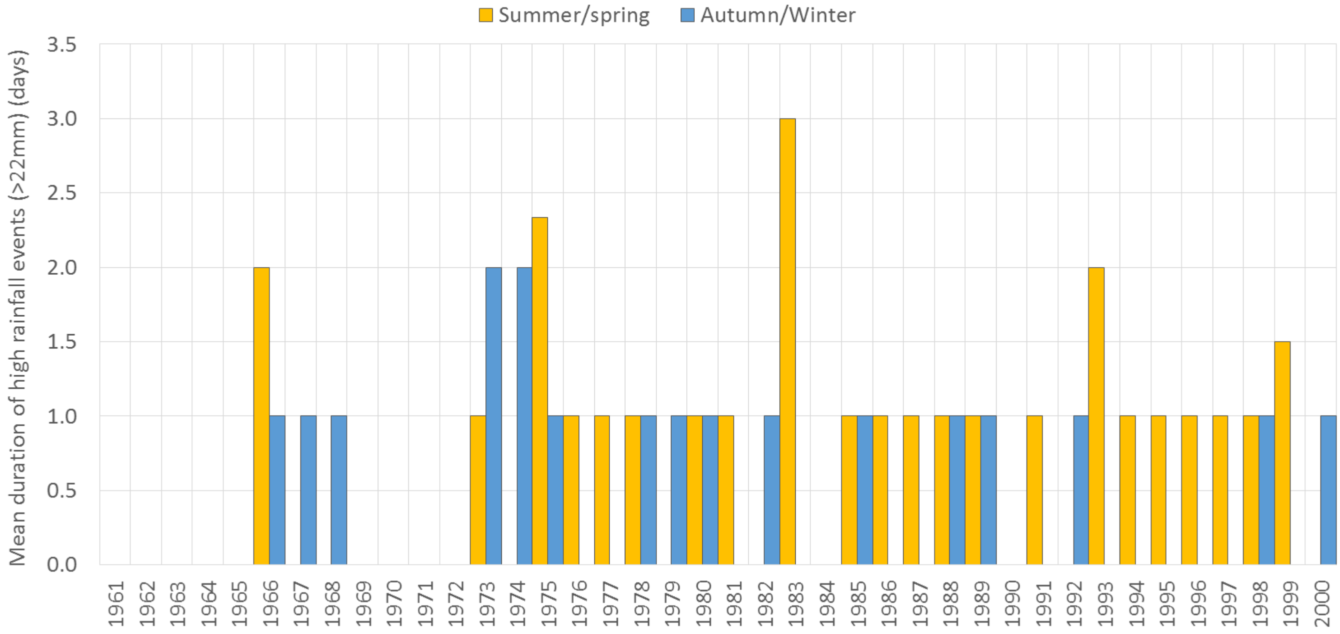

Figure 8. Mean duration of high rainfall event (>22 mm) calculated from the daily rainfall data used in the Neales-Peake Source model

In terms of the degree of changes to waterhole level under catchment averaged SILO climate data the frequency and mean duration of filling events were assessed for both Algebuckina (Table 6) and Peake waterholes (Table 7). Despite rainfall events occurring within each 10-year block this did not always translate into water levels increasing above the filling level threshold (6 m for Algebuckina and 3 m for Peake) in the 1961-1970 year block. Filling events in Algebuckina generally occurred as single annual events in a given 10 year block, with an average duration of 6 days. No peak water level events occurred during the dry season, despite large rainfall events occurring during autumn and winter in the region.

Dry periods in Algebuckina where water levels dropped below 0.1 m occurred prior to 1980 with a maximum dry spell duration of 209 days. However, between the years 1980–2000 no dry spells occurred. Cease to flow periods are between 60–70 days on average and occur at least once a year. Peake waterhole experienced more frequent high water level events compared to Algebuckina, particularly during the drier seasons. Dry spells occurred more frequently also, particularly after 1981. Cease to flow periods occurred as frequently as those in Algebuckina but lasted almost twice as long.

Table 6. Algebuckina water level metrics under historical SILO rainfall and PET data

	Year block			
	1961-1970	*1971-1980*	*1981-1990*	*1991-2000*
Frequency of high spells - "wet" period (number events in each year block)	0	**2**	**1**	**1**
Mean duration of high spells - "wet" period (mean days in each 10 year block)	0	**6.25**	**7.5**	**4.5**
Frequency of high spells - "dry" period (number events in each year block)	0	0	0	0
Mean duration of high spells - "dry" period (mean days in each 10 year block)	0	0	0	0
Frequency of low spells (number events in each year block)	**2**	**1**	0	0
Mean duration of low spells (mean days in each 10 year block)	**206**	**96**	0	0
Frequency of CTF (number events in each year block)	**10**	**19**	**18**	**18**
Mean duration of CTF (mean days in each 10 year block)	**79**	**71**	**67**	**64**

Table 7. Peake water level metrics under historical SILO rainfall and PET data

	Year block			
	1961-1970	*1971-1980*	*1981-1990*	*1991-2000*
Frequency of high spells - "wet" period (number events in each year block)	**1**	**3**	**2**	**2**
Mean duration of high spells - "wet" period (mean days in each 10 year block)	**2**	**14**	**13**	**10**
Frequency of high spells - "dry" period (number events in each year block)	0	**1**	**1**	**1**
Mean duration of high spells - "dry" period (mean days in each 10 year block)	0	**10**	**11.5**	**2.5**
Frequency of low spells (number events in each year block)	**4**	0	**1**	**2**
Mean duration of low spells (mean days in each 10 year block)	**173**	0	**52**	**12**
Frequency of CTF (number events in each year block)	**15**	**22**	**20**	**18**
Mean duration of CTF (mean days in each 10 year block)	**132**	**123**	**101**	**156**

4.2 Changes in mean annual rainfall and potential evapotranspiration

For both future emission scenarios the annual rainfall realisations over the GCM historical period up to around 2030 fluctuate within a range of ±20% change from the mean historical GCM baselines, and this is observed for all three GCMs (Figure 9 and Figure 10). For the 'best' and 'most likely' case climate projections this pattern largely continues to 2100, with the variability in annual rainfall slightly increasing. However, the 'worst' case scenario projected a general decrease from 2000 to 2050 and then levels out in line with the low (r4.5) emission concentration patterns. Under the high (r8.5) emission scenario the decline continues but reduces after 2050 to around 40% from the historical GCM baseline. The climate projections for the 'best' and 'most likely' cases produce similar results for both mean annual rainfall and mean annual PET.

Mean annual PET (Figure 11) remain similar to the historical GCM baseline until 2010 where under the low emission scenario PET increases exponentially upward to a maximum of between 4-10% higher than the historical GCM baseline. Under the high emissions scenario (Figure 12) this exponential increase is more pronounced, particularly for the worst case scenario to a maximum of 15% above the historical GCM baseline.

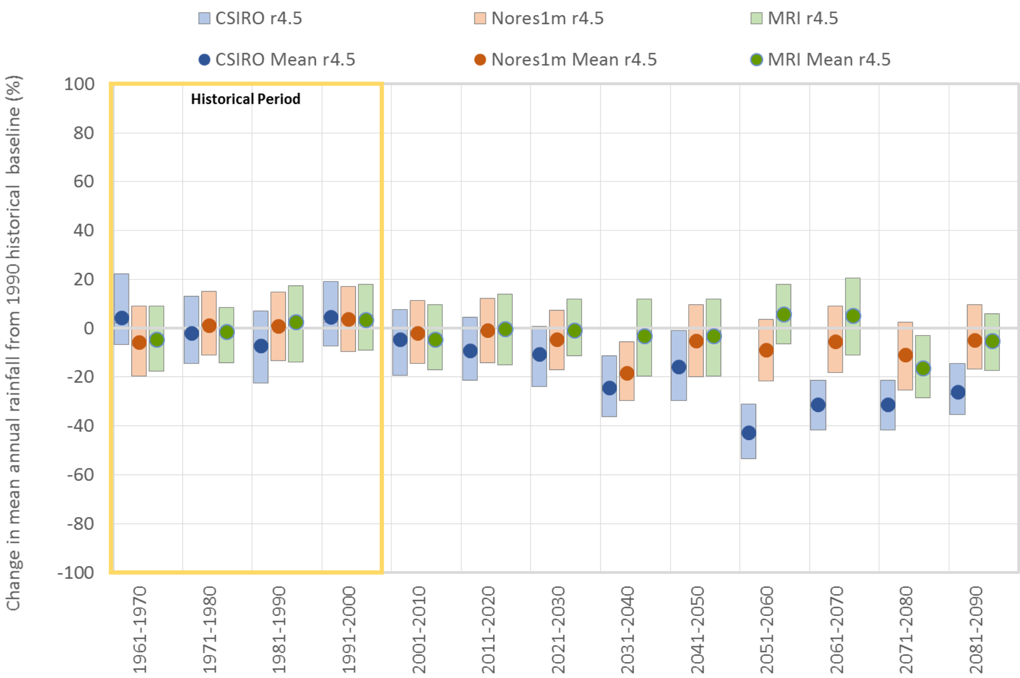

Figure 9 Change in median, mean, 10th percentile and 90th percentile annual rainfall (mm) from historical GCM baseline for each GCM projection for the r4.5 (low) future emission scenario. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

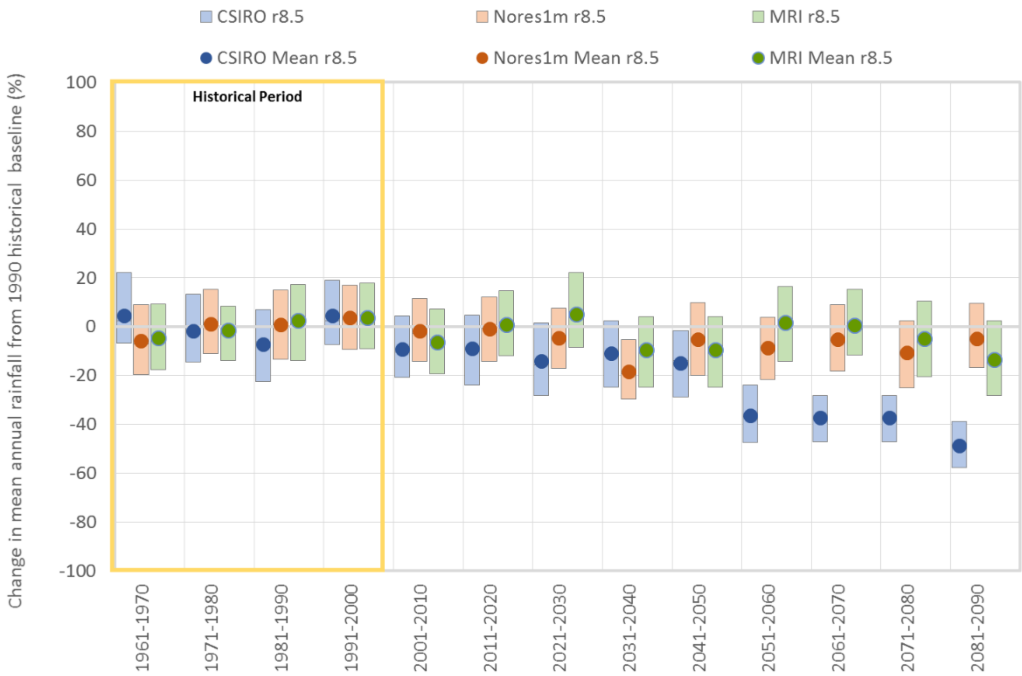

Figure 10. Change in median, mean, 10th percentile and 90th percentile annual rainfall (mm) from historical GCM baseline for each GCM projection for the r8.5 (high) future emission scenario. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

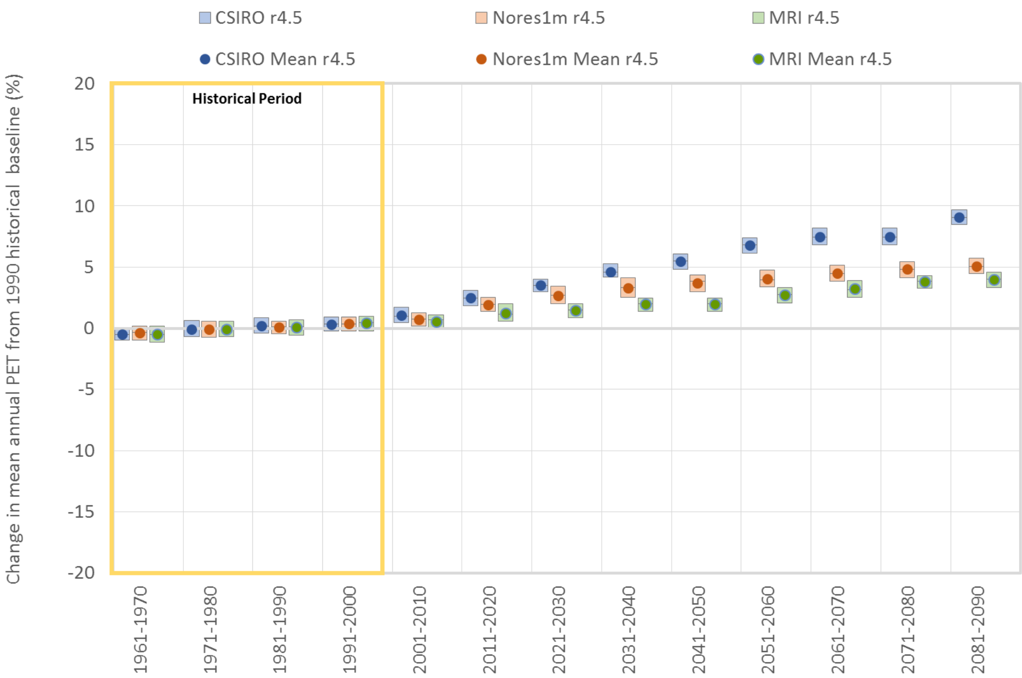

Figure 11 Change in median, mean, 10th percentile and 90th percentile annual PET (mm) from historical GCM baseline for each GCM projection for the r4.5 (low) future emission scenario. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

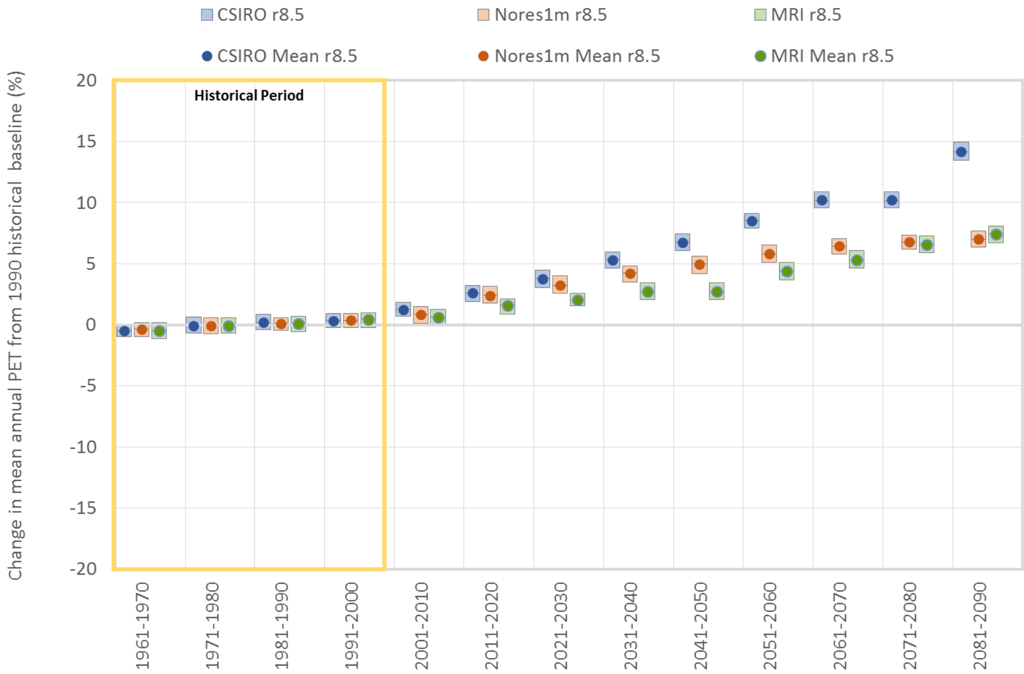

Figure 12. Change in median, mean, 10th percentile and 90th percentile annual PET (mm) from historical GCM baseline for each GCM projection for the r8.5 (high) future emission scenario. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

4.3 Seasonal changes in frequency and mean duration of high rainfall events

An analysis of the frequency and mean duration of historical baseline rainfall events derived from each GCM was assessed for the spring/summer ('wet') and autumn/winter ('dry') period in order to ascertain the likely trends observed in water level assessments. The difference in frequency of events between wet and dry seasons is clear when comparing historical rainfall data (Figures 7 and 8) which indicates the majority of catchment flood inducing rainfall events occur in spring/summer.

The change in frequency of large rainfall events greater than 22 mm rainfall depth during the 'wet' spring/summer seasons unsurprisingly follow similar trends as described for mean annual rainfall climate projections, particularly showing the decrease in rainfall frequency in line with the trends attributed to the high and low emission scenarios.

Rainfall in the region occurs infrequently but when it does occur it can have high intensity, reflecting the wide range in rainfall frequencies across all climate models and emission scenarios. The mean difference in rainfall frequency from baseline changes only slightly for the 'best' and 'most likely' GCM cases, but the 'worst' case GCM declines after 2040 in line with trends observed by the low and high RCP scenarios (Figure 13a). Although the mean duration of high rainfall events for each GCM does not appreciably change from historical GCM baseline for the 'best' and 'most likely' case GCMs, the range in mean duration captured by the 10th and 90th percentiles declines somewhat over the future projection time horizon (Figure 13b).

Large catchment-scale rainfall events are not uncommon during the autumn/winter seasons, as shown in Figure 7. The change in frequency of autumn/winter rainfall events from the historical GCM baseline (Figure 14a) strongly increases in range during the future climate time period in comparison to spring/summer frequency of events (Figure 13). In a similar fashion to the change in mean duration of summer/spring events, the mean duration of autumn/winter events does not markedly change between emission scenarios (Figure 14b).

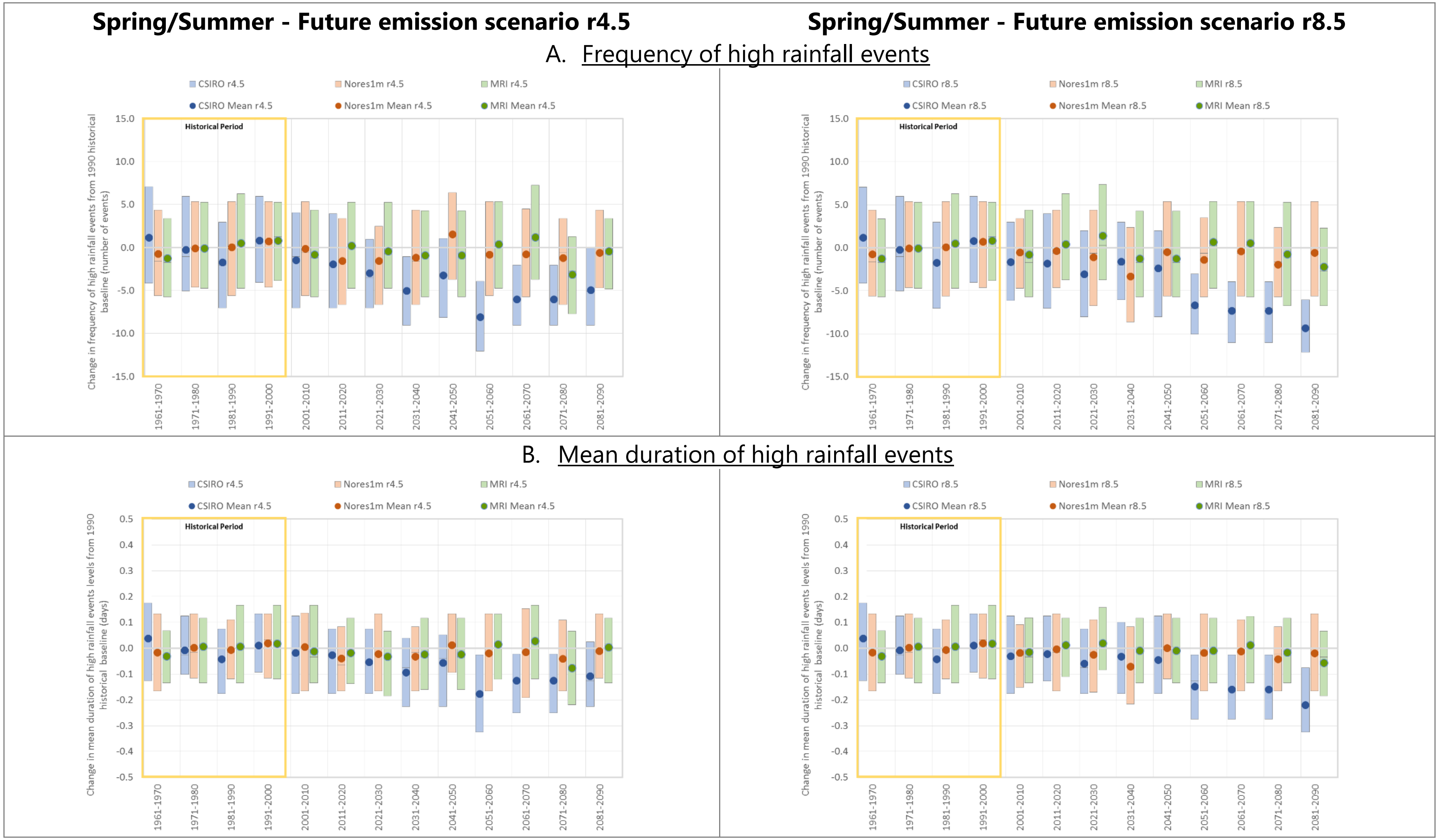

Figure 13. Change in median, mean, 10th percentile and 90th percentile (A) frequency and (B) duration of high rainfall events (>22 mm) during Oct-Mar ("wet" season) for each GCM projection and emission scenario from historical GCM baseline. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

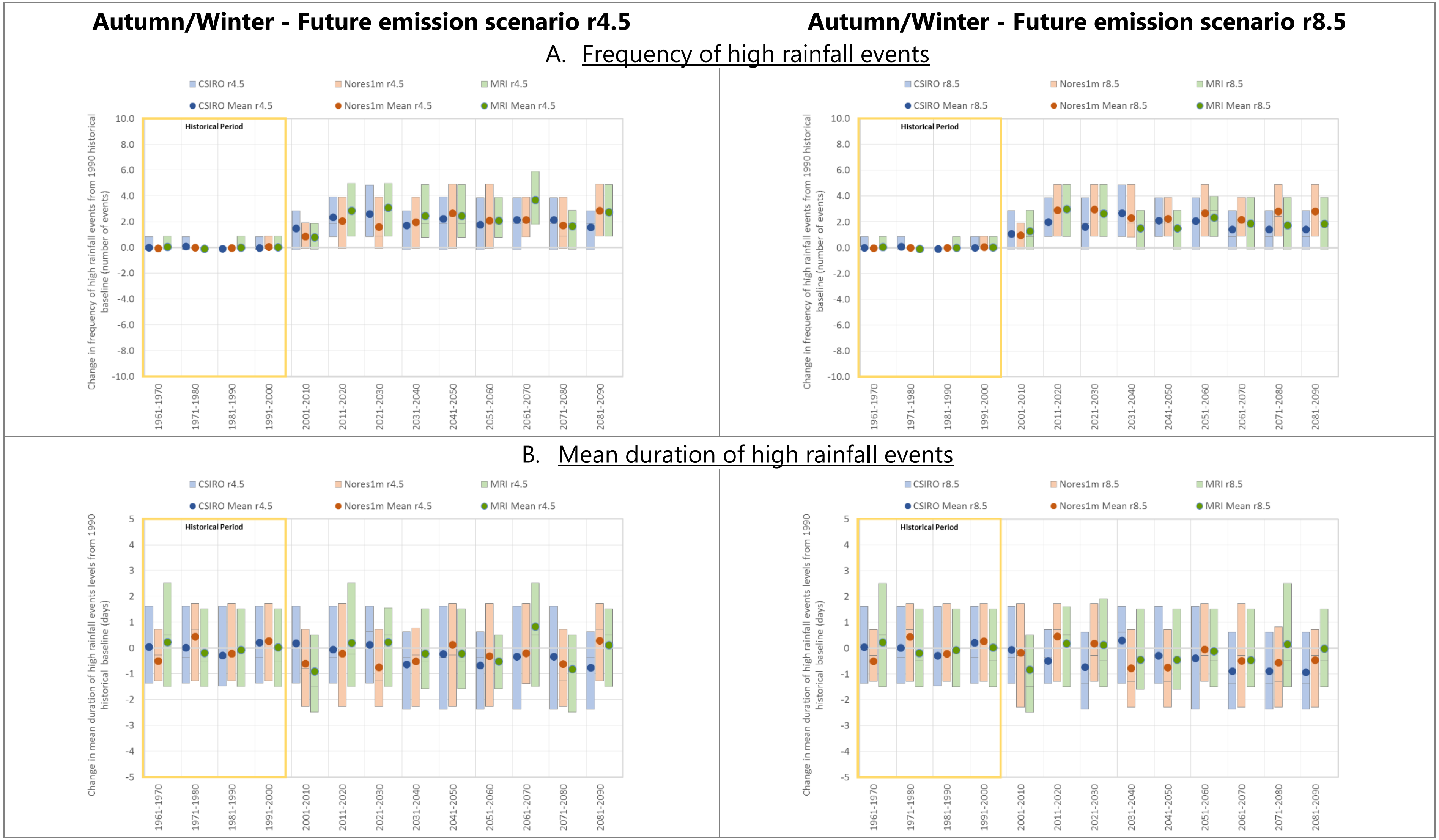

Figure 14. Change in median, mean, 10th percentile and 90th percentile (A) frequency and (B) duration of high rainfall events (>22 mm) during Apr-Sept ("dry" season) for each GCM projection and emission scenario from historical GCM baseline. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

4.4 The change in Algebuckina waterhole levels under climate projections

Over the historical baseline period the number of modelled high water level events greater than 6 m occurs between 0 and 2 events in a given decade (Table 6). The historical replicates derived from each GCM generally falls within this range in terms of change from the historical mean baseline (Figure 15).

Under future climate projections there is a general decline in the range of frequency of events (Figure 15a) over the 100–year time horizon for all GCMs and emission scenarios, with some decades experiencing a change of ± 1 event in a given decade. Considering the typical number of filling events in Algebuckina in any given 10–year period is between 1 and 2 events, this is a large change in frequency of events. For both low and high emissions scenario, the 'best' and 'most likely' cases, on average, change little from the historical baseline, however, for the 'worst' case climate projections show a marked decline in frequency of events. Overall, the change in mean duration of filling events for the 'best' and 'most likely' cases changes little from the historical GCM baseline under both emission scenarios. However, the 'worst' case climate projections suggest a consistent decrease in mean duration of filling events from about 2040 onwards, reducing by approximately 2–4 days from historical GCM baseline (Figure 15b).

Analysis of Source model outputs for the number of filling events and the mean duration of these peaks during autumn/winter in Algebuckina shows there were no filling events calculated over the modelled 40-year historical period (Table 6). Under the 'worst' and 'best' climate projections, the change from historical GCM baseline shows a small increase in the range of filling events, but on average there is little change from the mean historical GCM baseline (Figure 16). Under both low and high RCP emission scenario the mean duration of filling events is markedly different from the trends exhibited during the summer/spring seasons. Mean durations during the 1961–2000 period are less than 1 day with little change from mean historical GCM baseline.

The frequency of cease to flow periods modelled under historical catchment average rainfall and PET is between 10–19 events in a given decade (Table 6). In comparison, the change in CTF frequency of events under each GCM from historical baseline is in the order of ±7 events (Figure 17a). Under the low emission scenario the 'best' case climate projection show only a slight variation from the mean historical GCM baseline overall. The 'most likely' climate projections show a decrease in the change in frequency of events from mean historical GCM baseline after 2050 and under the 'worst' case climate projections the decline is more strongly in line with trends observed for the low RCP emission scenarios. Under high emission scenarios the decline in frequency of events is more pronounced for all GCMs, but particularly for the 'worst' case GCM projections to a reduction in CTF events by half by 2090.

Overall there is only a small difference in the range of mean durations of CTF periods under the 'most likely' and 'best' case climate scenarios compared to the historical GCM baseline (Figure 17b). This trend is apparent for both low and high emission scenarios. In contrast, the 'worst' case climate projections show a marked decrease is duration of CTF levels from the historical GCM baseline under both low and high emission scenarios, suggesting a decrease in mean duration of between 10 to 25 days from the historical GCM baseline. Modelled CTF period durations are in the order of 60-80 days, therefore, a significant decrease of 10th percentile CTF periods may impact on waterhole persistence.

For all GCM projections the change from historical GCM baseline of the frequency of dry spells is not large and tends to decline during the 1990 and 2000 decades, as is observed under the modelled baseline conditions for Algebuckina with no dry spells simulated during this time period (Figure 18). Following 2040, only the 'worst' and 'most likely' cases show an increase in dry spells, with the 'worst' case GCM showing a marked increases in 90th percentile dry spells between 3–5 events per decade. This trend is exacerbated under the high emissions scenario. The mean duration of dry spells for all GCM projections changed little from historical GCM baseline. An increase in mean duration is observed under future climate projections, increasing by around 20–30 days longer for the 'best' and 'most likely' scenarios, but under the 'worst' case the increase in mean duration is more pronounced with 90th percentile dry spells reaching a mean duration of between 40-70 days longer than historical GCM baseline.

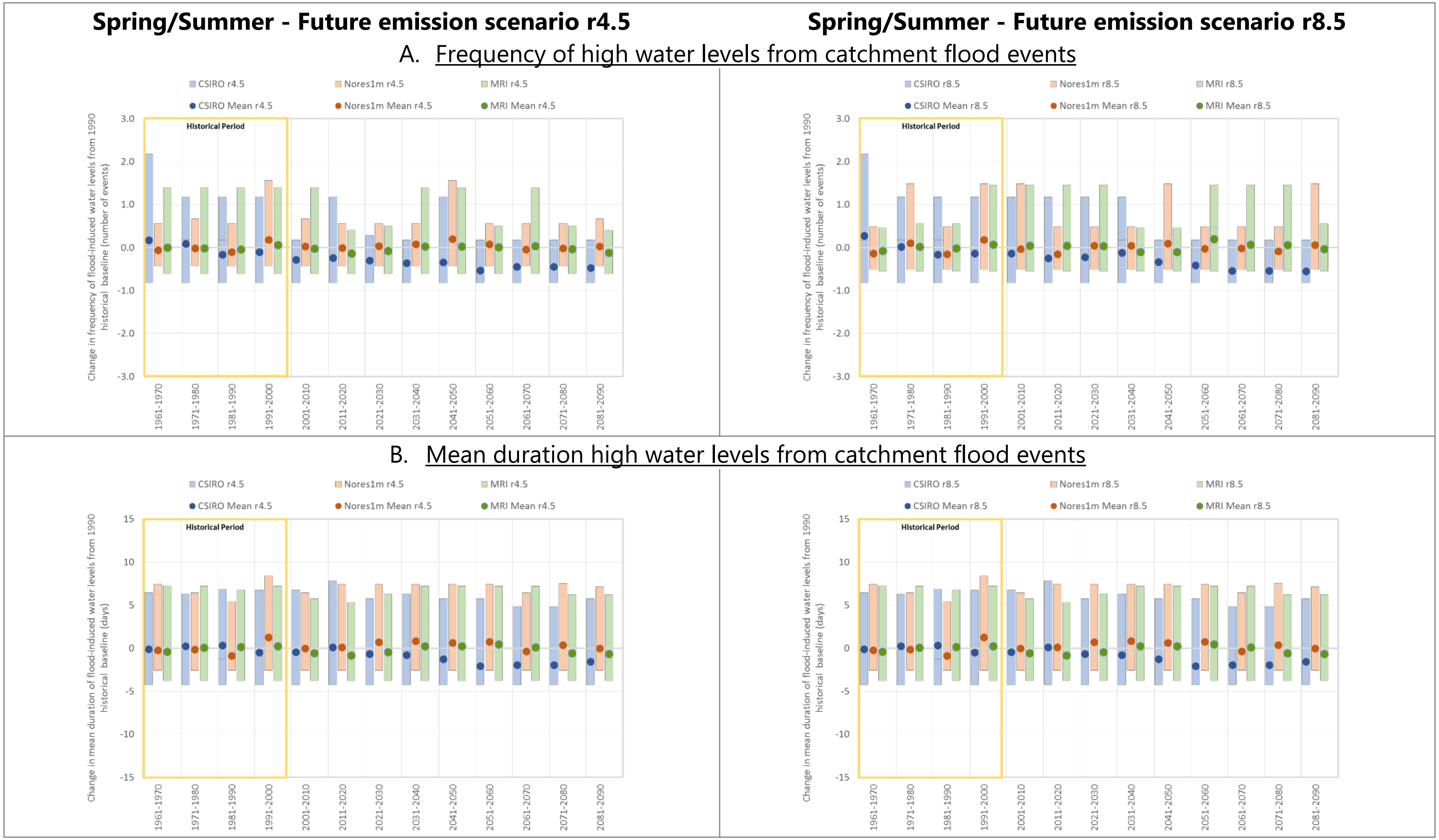

Figure 15. Change in Algebuckina median, mean, 10th percentile and 90th percentile (A) frequency and (B) duration of significant inundation events (>6 m) during Oct–Mar ("wet" season) for each GCM projection and emission scenario from historical GCM baseline. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

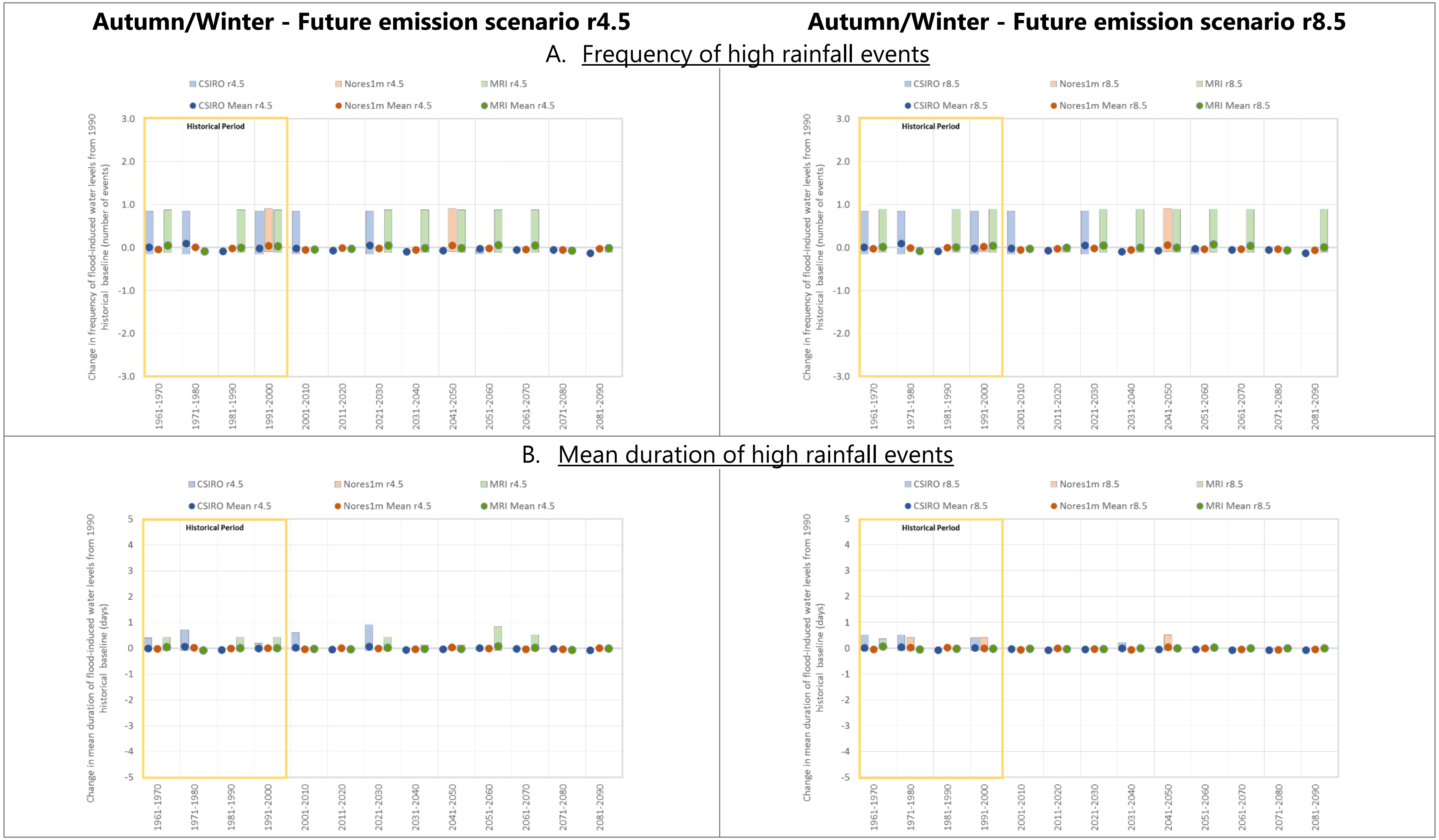

Figure 16. Change in Algebuckina median, mean, 10th percentile and 90th percentile (A) frequency and (B) duration of significant inundation events (>6 m) during Apr–Sept ("dry" season) for each GCM projection and emission scenario from historical GCM baseline. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

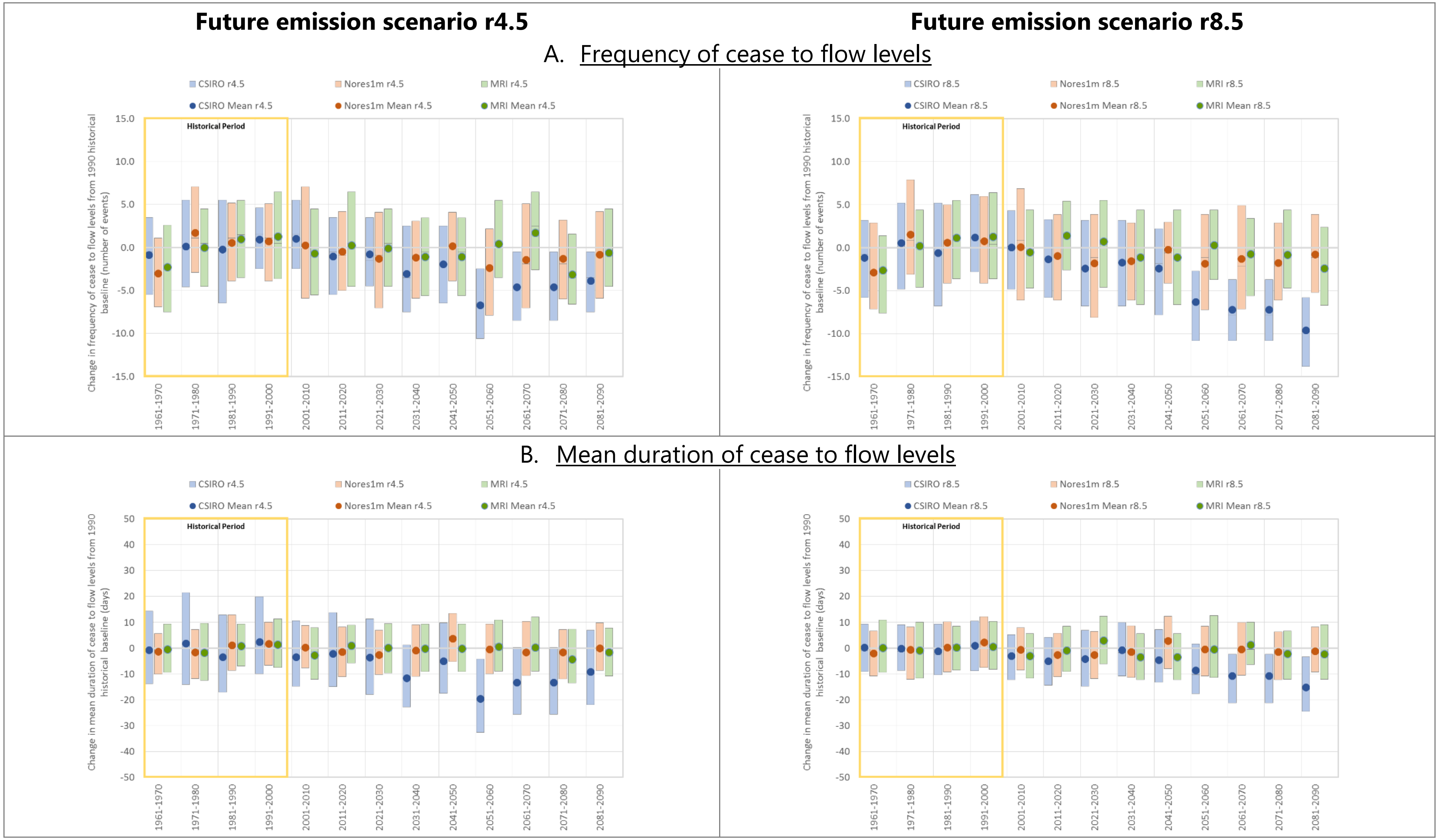

Figure 17. Change in Algebuckina median, mean, 10th percentile and 90th percentile (A) frequency and (B) duration of CTF levels (4.5 m) for each GCM projection and emission scenario from historical GCM baseline. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

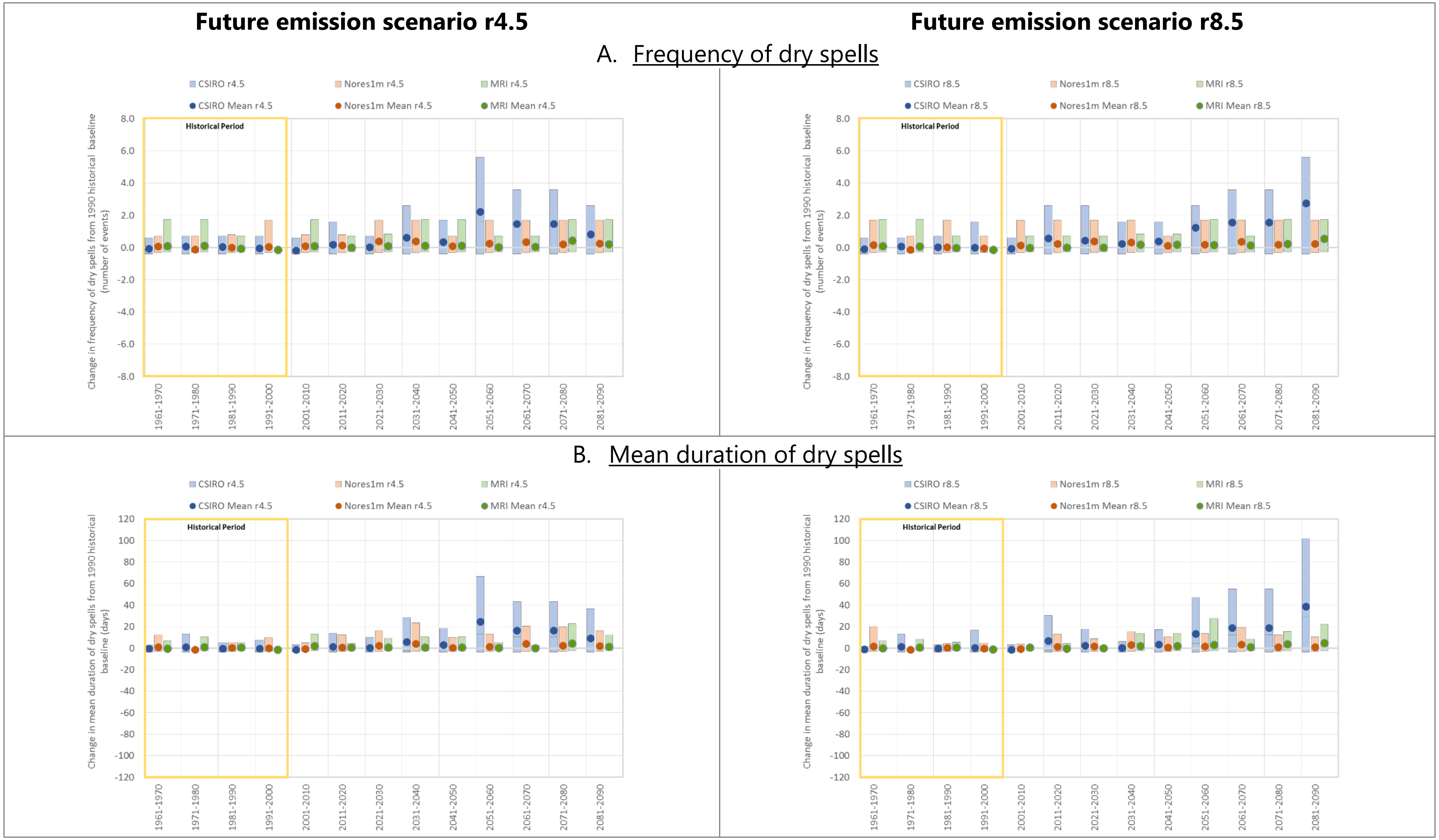

Figure 18. Change in Algebuckina median, mean, 10th percentile and 90th percentile (A) frequency and (B) duration of dry spells (levels <0.1 m) for each GCM projection and emission scenario from historical GCM baseline. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

4.5 The change in Peake waterhole levels under climate projections

Over the historical baseline for summer/spring period the number of high water level events greater than 3 m occurs between 1 and 3 events in a given decade, more frequent than spilling events in Algebuckina waterhole (Table 7). The historical replicates derived from each GCM generally falls within this range in terms of change from the historical mean baseline (Figure 19). Under future climate projections there is a general decline in the range of frequency of events (Figure 19a) over the 100 year time horizon for the 'worst' case scenario, but for the 'best' and 'most likely' case scenarios there is little overall change in terms of the mean change from historical GCM baseline and the range in 90th percentile events. For the 'worst' case scenario the decline is in the order of 1–2 filling events per decade but levels out after 2050 under low RCP emission scenario. Under a high RCP emissions scenario, for the worst' case GCM projections, this decline follows a similar trend. In addition, the range in frequency of events for the ''best' and 'most likely' cases increases for 10th percentile events.

Overall, the change in mean duration of filling events for the 'best' and 'most likely' cases changes little from the historical GCM baseline under both emission scenarios. However, the 'worst' case GCM projections suggest a consistent decrease in mean duration of filling events from about 2040 onwards, reducing by approximately 2–4 days from historical GCM baseline (Figure 19b). In comparison, modelled mean duration of high water levels in Peake are in the order of 10–14 days, but could be as low as 2 days.

Analysis of modelled outputs for the number of filling events in Peake waterhole during autumn/winter shows there were no filling event between 1961-1990, but every subsequent decade experienced at least one filling event with a mean duration of between 2–12 days (Table 7). Under all GCM climate projections and emission scenarios there is little change from historical GCM baseline up to 2040 (Figure 20a). Within the 2050 year block for the low emission scenario the range in events increases under the 'most likely' case only, and within the 2070 and 2090 year blocks the 'best' case climate projections increase in range from historical GCM baseline. Conversely, under the 'worst' case climate projections there is little change from the historical GCM baseline. The range in frequency of high flow events under high emission scenario shifts somewhat for the 'best' case scenario where there is an increase in 10th percentile events in the 2080 year block only.

Under both low and high RCP emission scenario the mean duration of filling events is markedly different from the trends exhibited during the summer/spring seasons (Figure 20b). For the low emission scenario, the variability of changes in mean durations compared to historical GCM baseline increases during the autumn/winter seasons. Generally, the difference in mean duration from the historical GCM baseline is small, but 10th percentile durations are more variable from decade to decade. This trend is exacerbated under high emission scenarios from about 2060 onwards where the mean duration days decrease more strongly.

The frequency of cease to flow periods modelled under historical catchment average rainfall and PET is between 15–22 events in a given decade (Table 7). In comparison, the change in CTF frequency of events under each GCM from historical baseline is in the order of ±5 events in a given decade (Figure 21a). Under the low and high emission scenarios both the 'best' case and 'most likely' case climate projections exhibit an increase in the variability of 10th percentile CTF events compared to historical GCM baseline. This variability is also observed for the 'worst' case climate projections up to 2050 and for subsequent decades decrease in frequency of CTF events to around 2-4 event in a similar trend as observed by low RCP emission patterns. Under high emission scenarios the decrease in frequency of CFT events is more pronounced with a continuous decline in CTF events of on average 5 CTF events less than historical GCM baseline.

Overall there is only a small difference in the range of mean durations of CTF periods under the 'best' and 'most likely' cases climate projections compared to the mean historical GCM baseline (Figure 21b), and the variability from decade to decade remains similar to baseline. This trend is apparent for both low and high emission scenarios. In contrast, the 'worst' case climate projections show a marked decrease is duration of CTF levels from the historical GCM baseline under both low and high emission scenarios, suggesting a decrease in mean duration of between 20–40 days from the historical GCM baseline. Modelled CTF period durations are in the order of 100-150 days, therefore, a significant decrease of 10th and 90th percentile CTF periods of around 40-60 days may impact on waterhole persistence.

For all GCM projections the change from historical GCM baseline of the frequency of dry spells is variable decade to decade and declines between 1991 and 2000 year block. Under the modelled baseline conditions for Peake dry spells are simulated in each decade, except for 1971–1980 (Table 6), and vary in frequency between 1 and 4 events. From 2040 onward all GCM climate projections show an increase in the frequency of dry spells from the historical GCM baseline, with the 'worst' case GCM showing a marked increases in 90^{th} percentile dry spells between 5–7 dry spells per decade. This trend is exacerbated under the high emissions scenario for GCM climate projections.

Based on modelled outputs for Peake waterhole, dry spell duration exhibit a wide range, between 12–173 days on average. The mean duration of dry spells for all GCM projections changed little from historical GCM baseline until 2040 for the 'worst' case climate projections, and 2070 for the 'best' and 'most likely' climate projections. An increase in mean duration is observed by around 20-30 days longer for the 'best' and 'most likely' 10^{th} percentile dry spells, but under the 'worst' case the increase in mean duration is more pronounced with 10^{th} percentile dry spells reaching a mean duration of between 60–100 days longer than historical GCM baseline.

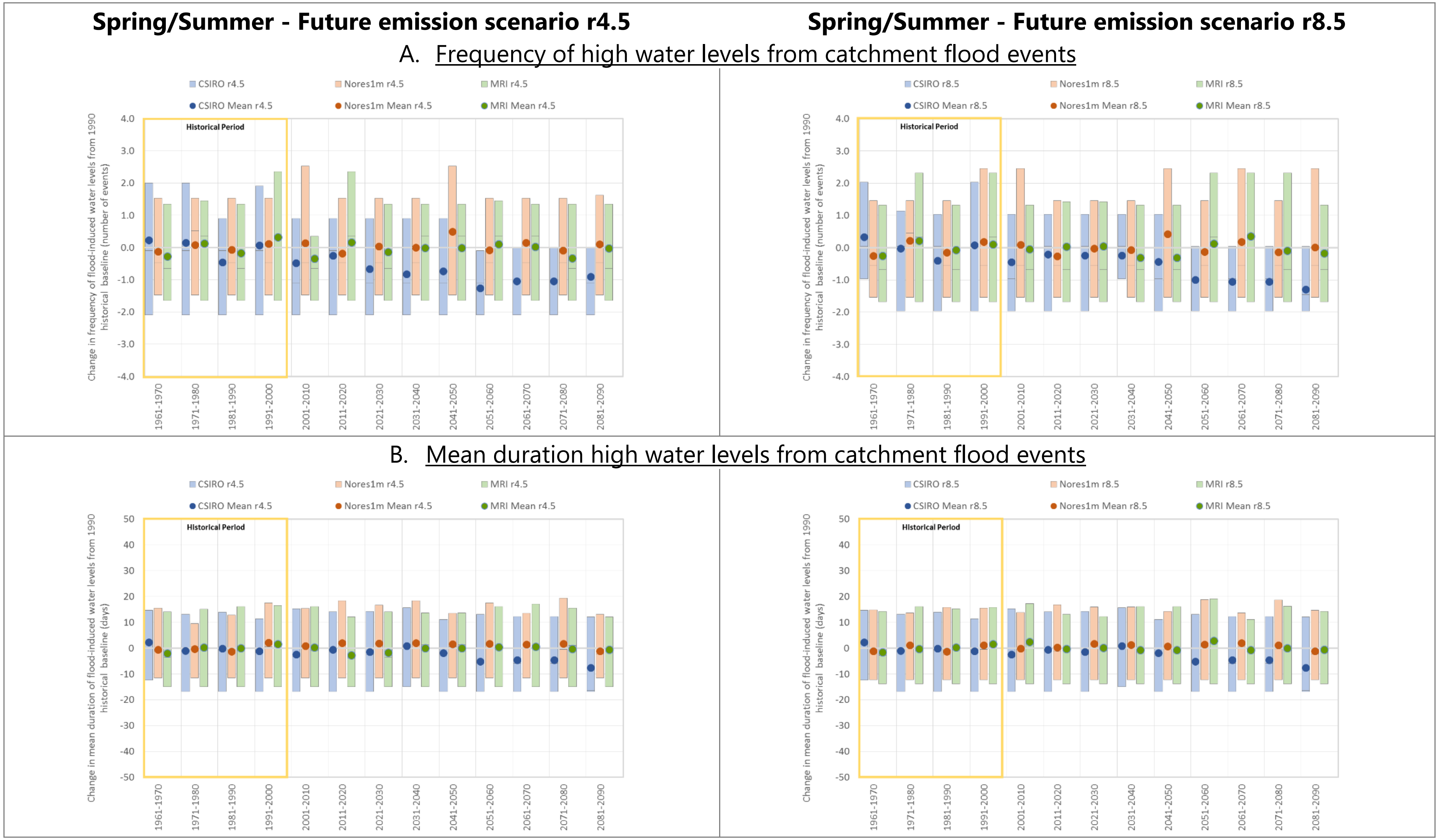

Figure 19. Change in Peake median, mean, 10th percentile and 90th percentile (A) frequency and (B) duration of high rainfall event (>3 m) during Oct-Mar ("wet" season) for each GCM projection and emission scenario from historical GCM baseline. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

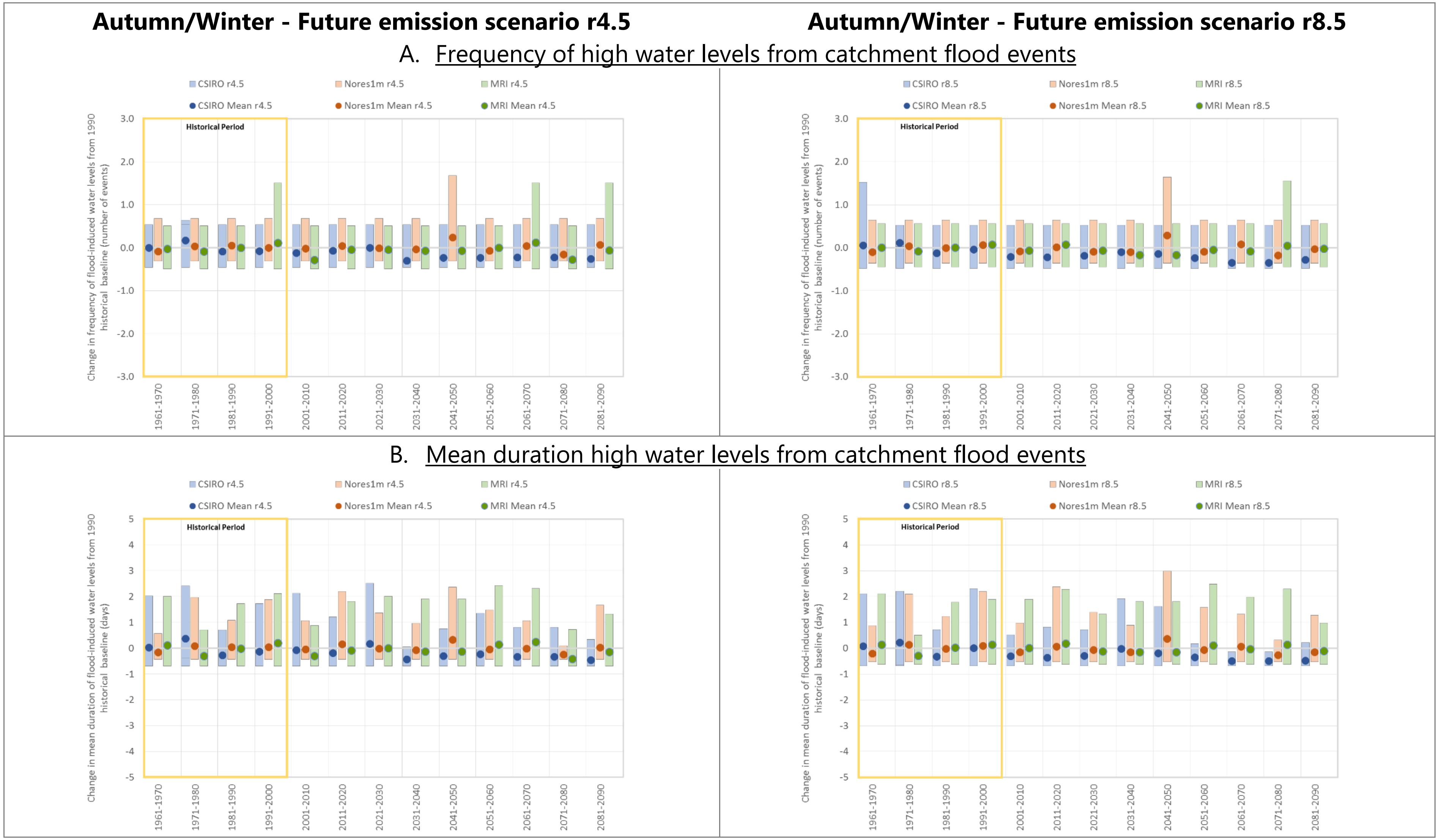

Figure 20. Change in Peake median, mean, 10th percentile and 90th percentile (A) frequency and (B) duration of high rainfall event (>3 m) during Apr-Sept ("dry" season) for each GCM projection and emission scenario from historical GCM baseline. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

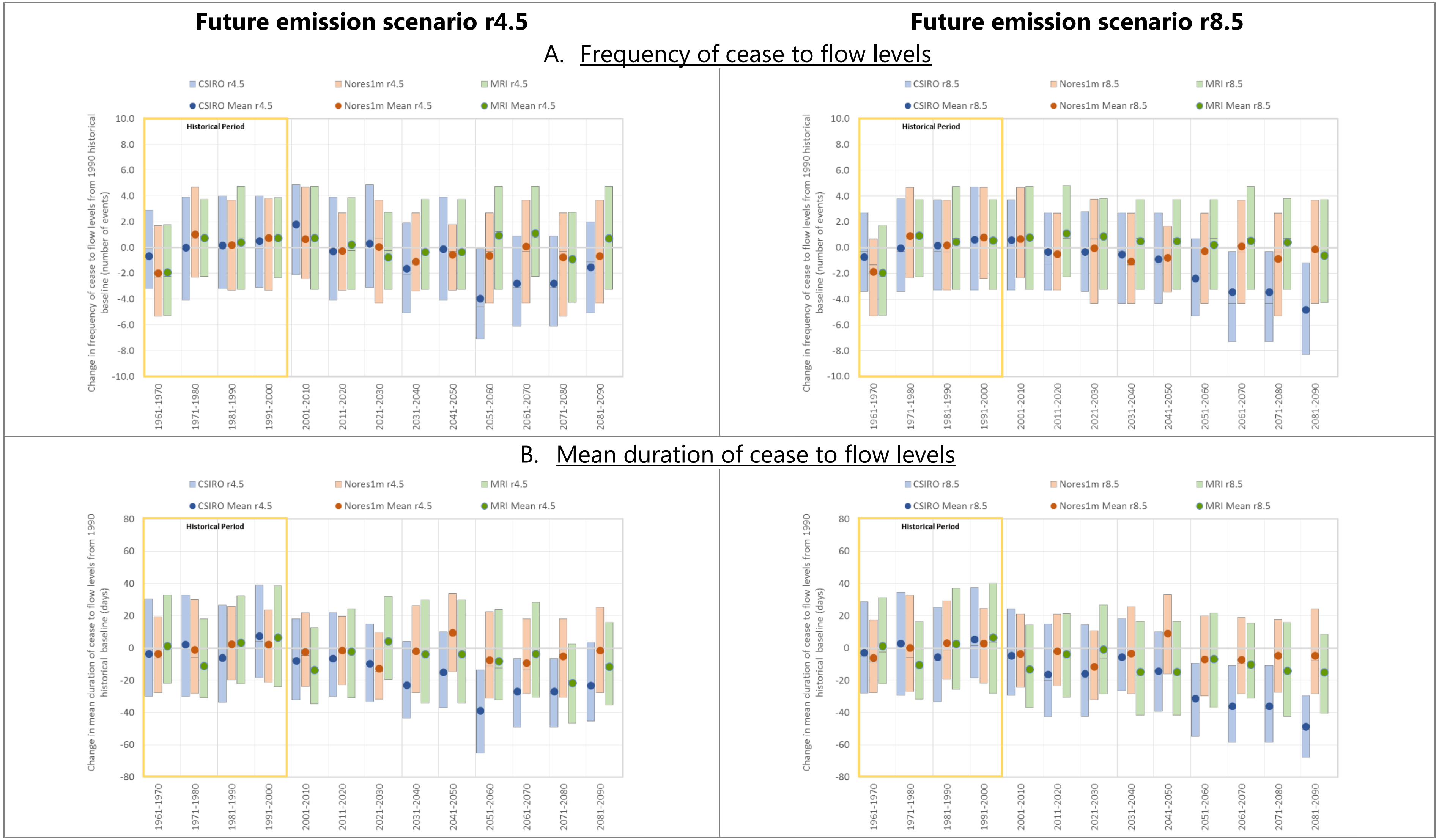

Figure 21. Change in Peake median, mean, 10th percentile and 90th percentile (A) frequency and (B) duration of CTF levels (1.5 m) for each GCM projection and emission scenario from historical GCM baseline. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

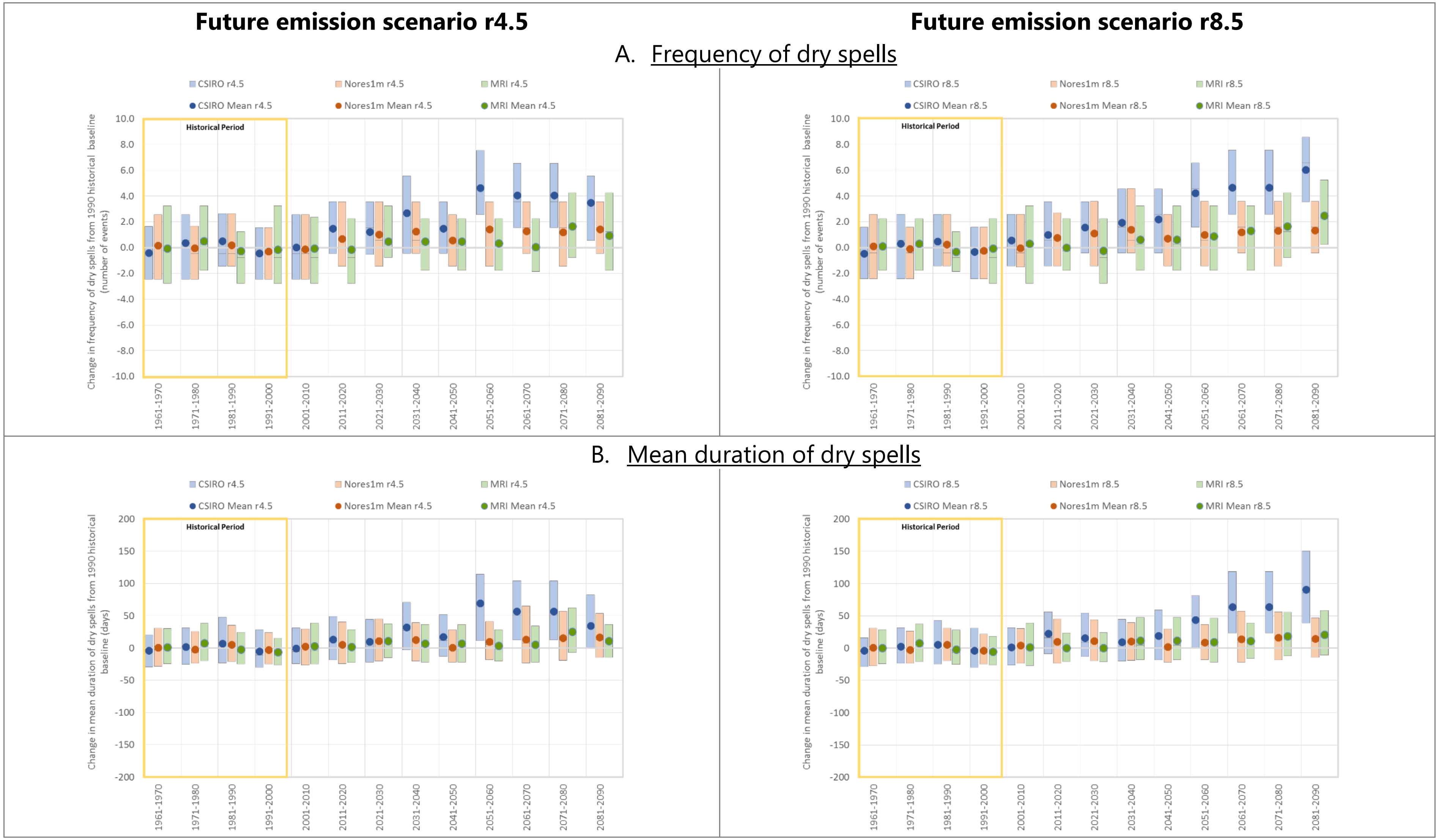

Figure 22. Change in Peake median, mean, 10th percentile and 90th percentile (A) frequency and (B) duration of dry spells (levels <0.1 m) for each GCM projection and emission scenario from historical GCM baseline. 'Best' case = mri.cgcm3 GCM; 'most likely' case = noresm1m GCM and 'worst' case = CSIRO GCM.

5 Discussion and summary

Catchment floods that deliver large flows that traverse all reaches of the catchment enabling connectivity between critical refugial waterholes are vital for many aquatic fauna during periods of no flow (Hamilton et al., 2005). These floods result in substantial connection between the upstream and downstream reaches, significant floodplain inundation and a resetting of the water levels in waterholes with a high level of persistence.

Costelloe (2011) states that a useful definition of a waterbody that has potential as refugia for aquatic fauna has a "maximum cease to flow depth of >4 m and an approximate annual flow frequency. Such a waterhole would retain sufficient water to sustain key biota in the event of a complete flow year occurring without inflow, resulting in an 18–24 month period of no flow". Water extraction from waterholes during periods of no flow and low flow can potentially have serious effects on the persistence of waterholes and subsequently on the sustained aquatic health of a reach or catchment (Costelloe, 2011). Therefore, it is beneficial to developing management strategies to have a thorough understanding of how a future climate under anthropogenic pressures may impact on waterhole drying-filling cycles and the persistence a waterhole has between flow events.

In order to assess the impact of projected changes in climate on the water levels of Algebuckina and Peake waterholes 100 sets of downscaled rainfall and PET projections for three GCMs and two emissions scenarios, realised through use of a non-homogeneous hidden Markov model (NHMM), were incorporated into a hydrological model for Neales-Peake catchment. By combining hindcast data with projected data it was possible to run the model from 1961–2100, enabling a comprehensive analysis of projected changes to the flow regime.

An analysis of modelled water levels for Algebuckina and Peake waterholes under 40 year of historical climate show that the frequency of filling events is generally only once a year if sufficient catchment-scale rainfall events occur. The mean duration of these filling events in Algebuckina are in the order of 5–7 days and in Peake for 3–12 days, occurring mostly during the summer/spring seasons that correspond to the Northern monsoon rains influencing the SAAL region. Although high rainfall events that may result in filling events in both waterholes do occur in autumn/winter seasons, the frequency and mean duration of events is markedly less and may serve to "top-up" waterhole levels.

Three GCMs were examined representing 'best' case, 'most likely' case and 'worst' case climate futures under high and low RCP emission scenarios. Annual rainfall in the region under these GCMs and emission scenarios remains highly variable in intensity and frequency of large events. The change in annual rainfall totals under the 'best' and 'most likely' climate projections from the historical GCM baseline was on average small, but the range between 10th and 90th percentile totals was exacerbated. Under the 'worst' case climate projections a marked decline in annual rainfall from the historical GCM baseline was apparent. Conversely, all GCMs resulted in a large increase in PET over the future time horizon for both low and high emission scenarios. With the resulting drier future climate the frequency and mean duration of high rainfall also exhibited large declines from historical GCM baseline, particularly for the 'worst' case climate projections. Under the high emissions scenario, projected reductions in rainfall and increases in PET are more severe than the low emissions case.

The results presented indicate that changes in the frequency of waterhole filling events were strongly associated with changes in annual rainfall. The frequency of filling events in both Algebuckina and Peake waterholes under each GCM and emission scenario observed trends that are in line with a decrease in the frequency of rainfall events during the summer/spring 'wet' season and the autumn/winter 'dry' season under a drying future climate. The mean duration of filling events is potentially halved under the 'worst' case GCM and high emission scenario.

For both Algebuckina and Peake waterholes, the influence of the low and high emission scenarios are apparent in the 'worst' case scenario causing large decreases in frequency and mean duration of cease to flow events. The 'best' and 'most likely' case climate projections changed little from mean historical GCM baseline, but an increase in variability between 10th and 90th percentile cease to low levels is apparent. Current measured CTF levels in Algebuckina occur approximately once each year with a mean duration of at least 70 days. For Peake waterhole CTF levels also occur at least once each year and for a mean duration of at least 100 days. Climate projection scenarios that have the potential to reduce this frequency of CTF periods and shorten the mean duration would have a detrimental effect on waterhole persistence and the ability to sustain a healthy aquatic ecosystem. Under the 'best' and 'most likely' case climate projections the frequency and mean duration of CTF levels is only slightly reduced and unlikely to be problematic in the context of ecosystem management. However, under the 'worst' case climate projections it is likely that frequency of CTF levels could decrease by half and duration reduced by 20–30 days.

For all climate models and emission scenarios dry spell frequency and duration increases above mean historical GCM baseline levels to some degree. For 'best' and 'most likely' cases this increase is not large, but under the 'worst' case climate projections there is a pronounced increases in 90^{th} percentile dry spell frequencies, between 3-5 events above historical GCM baseline per decade, and an increase in mean duration of between 40–70 days longer than historical GCM baseline.

Comparing a deep waterhole such as Algebuckina (4m) with a shallow waterhole like Peake (2m) the frequency of dry periods is higher for Peake by 1–2 dry spells per decade. Compared to historical dry spells for each waterhole, which occur once or twice per decade, this would be a significant increase in the frequency of drying out periods, exacerbated under a higher emissions scenario. 'Worst' case future climate projections from 2040 onwards show a marked increase in the duration of dry spells for both Algebuckina and Peake waterholes, with a large range in duration of dry periods observed for Peake. Under a higher emission scenario with higher temperatures and more evaporation, the 10th percentile dry spells durations are between 60–100 days longer than under historical conditions.

The three climate models utilised in this study (noresm1m GCM as the 'most likely' case, mri.cgcm3 GCM as the 'best' case and CSIROmk3.6 GCM as the 'worst' case) all project a drier climate over the SAAL region, with a decrease in rainfall frequency and catchment-scale flooding events and an increase in PET. This translates into different responses in drying- filling events and changes to cease to flow periods for Algebuckina and Peake waterholes. Under the 'best and 'most likely' case climate projections the climate futures show little change from mean historical GCM baseline, but the variability of drying-filling events shows a marked increase. Under the 'worst' case climate projections, there is a marked decline in filling events and cease to flow periods, both in frequency and duration, and a substantial increase in dry spells in both Algebuckina and Peake waterholes. Managing the water availability and water dependent ecosystem health in the region within this context will require ongoing monitoring and data gathering to refine the models that underpin these types of studies.

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