South Eastern Australian Climate initiative

Final report for **Project 1.2.1P**

Improved detection of the recent rainfall decline across SEA including its seasonality and spatial characteristics

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Abstract

As part of Project 1.1.1 in Phase 1 of SEACI (Timbal and Murphy, 2007a), a review of the existing literature was performed and the status of the on-going rainfall decline across south-eastern Australia was described in detail (Murphy and Timbal, 2008). It was found that the on-going drought was not the worst on record in terms of annual rainfall - south-eastern Australia (SEA) recorded a drier period from 1935 to 1945 (the World War II drought – WWII). It was also noted that at the time of the Federation of Australia, there was another very dry period. However, this was harder to quantify since most Bureau of Meteorology gridded rainfall products tend to start from 1900, while the Federation drought (from anecdotal and limited observational records) appeared to have started in the mid-1890s. A more recent analysis of updated data for the on-going drought found that SEA is now facing the largest rainfall decline in the instrumental record (Timbal, 2009), with the reduction in annual rainfall now being more severe than during WWII.

The purpose of this project is to compare these two very dry periods in more detail in the light of other findings which have emerged during SEACI – in particular:

1. The contribution of rising pressure, in particular the strengthening of the intensity of the sub-tropical ridge, (STR-I) and its relationship to global warming (GW) (from Project 1.1.2 (Timbal et al., 2007)).

2. The lack of a significant rainfall decline in 20th model simulations forced with natural external forcings and need for inclusion of anthropogenic forcings in order to explain the on-going rainfall decline (from Project 1.5.1 (Timbal et al., 2009a)).

3. The ability of climate models to reproduce the co-evolution of the GW and STR-I during the 20th century, and the need to include anthropogenic forcings to generate upward trends in both GW and STR (Project 1.1.1P (Timbal and Smith, 2009)).

In this project, the evaluation of the on-going rainfall decline in SEA has been refined by:

- Defining three climate entities: the South-West of Eastern Australia (SWEA) which is dominated by the STR influence; the northern part of the Murray-Darling basin (NMDB), which encompasses the rest of the MDB where the influence of the STR-I is less pronounced; and the eastern Sea-Board (ESB) which is located on the eastern side of the Great Dividing Range (GDR);

- Undertaking a more detailed examination of the spatial and temporal characteristics of the observed drought and comparing it to previous dry periods.

Significant research highlights, breakthroughs and snapshots

- The on-going rainfall decline is primarily due to a strengthening of the STR.

- The shift in the STR position has had no additional effect.

- Tropical SSTs (including in the Indian Ocean) are not the cause of on-going rainfall decline.

- While the current drought can be linked to global warming through the strengthening of the STR which, in turn, is attributable to anthropogenic forcings (Timbal and Smith, 2009), it is worth noting that the WWII dry decade can be seen as the first dry decade in SEA that is partially due to 20th Century global warming as a result of the intensification of the STR.

Statement of results, their interpretation, and practical significance against each objective

- The current drought is very localised to some areas (mainly in southern Australia) while, generally, the Australian continent is experiencing above average rainfall; this is in contrast with the WWII drought during which most of the continent experienced below average rainfall;

- While the spatial pattern of the current rainfall decline has a very strong similarity with the pattern of the STR-I signature on rainfall across southern Australia (Fig. 1), this is not the case in the two previous drought periods;

- The spatial and temporal signatures of the current rainfall deficit further indicate that the rainfall decline is linked to a weakening of the dominant westerly flow;

- For the current period, 80 per cent of the observed decline in SWEA can be attributed to the strengthening of the STR; the apparent shift south of the ridge in certain seasons does not appear to have (based on the analyses conducted here) an additional effect on SWEA rainfall;

- During the WWII decade, up to a third of the rainfall decline could be attributed to the strengthening of the ridge at that time;

- For the current drought, warming tropical SSTs have had no contribution overall to our rainfall since 1997 (the effect on the annual rainfall is a **positive** 0.9 per cent). In other words, due to the warming of the tropics and its spatial pattern, the rainfall decline in SWEA has been a little less than the STR intensification on its own would have produced;
- In contrast, during the WWI drought, tropical SSTs had a negative contribution to the rainfall alongside the strengthening of the ridge. The contribution of tropical SSTs in the very southern part of the Australian continent (SWEA) now and during WWII is consistent with the Australia-wide rainfall anomalies during both periods: i.e. a continent that was generally dry during the WWI decade versus a continent that is currently dominated by wet anomalies;
- While the current drought can be linked to global warming through the strengthening of the STR as a result of anthropogenic forcings, the WWII dry decade can be seen as the first dry decade in SEA that could be considered partially due to 20th Century global warming through the intensification of the STR.

Publications arising from this project

- B. Timbal, 2009: "The continuing decline in South-East Australian rainfall – Update to May 2009", *CAWCR Res. Let.*, **2**, 8pp.

Conference presentations:

- B. Timbal. 2009: "The rainfall decline in the south-east of Australia", *9th AMS southern hemisphere conference*, Melbourne, Australia
- P. Hope, B. Timbal, M. Wheeler and R. Fawcett: "A strengthening link between rainfall variability in the East and West of southern Australia", *9th AMS southern hemisphere conference*, Melbourne, Australia

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Attachment

Improved detection of the recent rainfall decline across SEA including its seasonality and spatial characteristics

Bertrand Timbal and Elodie Fernandez

As part of SEACI-1 Project 1.1.1 (Timbal and Murphy, 2007a), a review of the existing literature was performed and the status of the on-going rainfall decline across South-Eastern Australia was described in detail (Murphy and Timbal, 2008). It was found that the on-going drought was not the worst on record in terms of annual rainfall - south-eastern Australia (SEA) recorded a drier period from 1935 to 1945 (the World War II drought – WWII). It was also noted that at the time of the Federation of Australia, there was another very dry period. However, this was harder to quantify since most Bureau of Meteorology gridded rainfall products tend to start from 1900, while the Federation drought (from anecdotal and limited observational records) appeared to have started in the mid-1890s. A more recent analysis of updated data for the on-going drought found that SEA is now facing the largest rainfall decline in the instrumental record (Timbal, 2009), with the reduction in annual rainfall now being more severe than during WWII.

The purpose of this project is to compare these two very dry periods in more detail in the light of other findings which have emerged during SEACI – in particular:

- The contribution of rising pressure, in particular the strengthening of the intensity of the sub-tropical ridge, (STR-I) and its relationship to global warming (GW) (from Project 1.1.2 (Timbal et al., 2007)).
- The lack of a significant rainfall decline in 20th model simulations forced with natural external forcings and need for inclusion of anthropogenic forcings in order to explain the on-going rainfall decline (from Project 1.5.1 (Timbal et al., 2009a)).
- The ability of climate models to reproduce the co-evolution of the GW and STR-I during the 20th century, and the need to include anthropogenic forcings to generate upward trends in both GW and STR (Project 1.1.1P (Timbal and Smith, 2009)).

In this project, the evaluation of the on-going rainfall decline in SEA has been refined by:

- Defining three climate entities: the south-west of Eastern Australia (SWEA) which is dominated by the STR influence; the northern part of the Murray-Darling basin (NMDB), which encompasses the rest of the MDB where the influence of the STR-I is less pronounced; and the eastern sea-board (ESB) which is located on the eastern side of the Great Dividing Range (GDR);
- Undertaking a more detailed examination of the spatial and temporal characteristics of the observed drought and comparing it to previous dry periods.

Re-definition of the climate entities across SEA

During the SEACI program it has become increasingly obvious that the entire SEA is made of different climate entities, which exhibit different responses to remote large-scale modes of variability (El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), the Southern Annular Mode (SAM)) as well as local meteorological forcings (sub-tropical ridge (STR) intensity and position, the meridional gradient along the eastern coast as measured by the Gayndah-Deniliquin Index (GDI) and local Sea Surface Temperature (SST) anomalies).

A first attempt was made to define regions using previous work on rotated EOFs of Australia rainfall (Drosdowsky, 1993) in Project 1.1.1: three regions across the SEA were defined - the south-west of Eastern Australia (SWEA), the Southern Murray-Darling basin (SMD) and the South-East Coast (SEC). These regions were refined further in subsequent projects using the Bureau of Meteorology (BoM) Statistical Downscaling Model (SDM) in Project 1.3.1 (Timbal et al., 2008), 1.4.1 (Timbal and Fernandez, 2009) and 1.5.1 (Timbal et al., 2009a).

Here, we have refined this thinking, using the influence of the STR intensity (STR-I) on SEA rainfall as a guide. Annual correlations for the relationship between the STR-I and rainfall show the dominant influence of the STR-I across SEA and, in particular, on SWEA (Fig. 1). These correlations were calculated for annual means using detrended values from 1900 to 2008. A analysis of the relationship month by month shows that the correlations peak in early winter: May-June- July-August (more on that in Fig. 6 and later in the report).

Based on these correlations, we defined three distinct regions (Fig. 2):

1. We used the three month period with the largest correlations (MJJ) to define a continuous area in SEA where the STR-I explains more than 20 per cent of the inter-annual correlation (correlations above 0.447): this area is our new definition for SWEA;

2. The northern part of the Murray-Darling basin (NMDB), encompasses the rest of the MDB where the influence of the STR-I is less pronounced;

3. The eastern sea-board (ESB) on the eastern side of the Great Dividing Range (GDR) where indeed the STR-I influence is less marked.

In the rest of the report, these three entities (SWEA, NMDB and ESB) are used to analyse the spatial characteristics of the recent dry period spatially and to compare it to previous dry periods.

Australian pattern of rainfall decline during the Federation, WWII and the on-going protracted droughts

Rainfall deciles from these three periods are shown (Fig. 3) relative to the 1900-2008 long-term climatology. As stated earlier, the map for the *Federation drought* (from 1900 to 1908) is not ideal as it should start a few years earlier. Overall, a few points are worth making:

- The current drought is localised to some areas (southern Australia and SE Queensland) while the rest of the Australian continent is experiencing average to above average rainfall. This is in contrast with both previous drought periods where, in the case of the Federation drought, most of the continent was experiencing average to below average rainfall and, in the case of the WWII drought, below average rainfall;

- In SEA, while in the current drought the largest signal is in the SWEA area with impacts decreasing further north, during the *WWII drought* the impacts were largest further north in the MDB and, during the *Federation drought*, were largest in the ESB; and

- While the spatial pattern of the current rainfall decline has a very strong similarity with the pattern of the STR-I signature on rainfall across southern Australia (Fig. 1), this is not the case in the two previous drought periods.

In term of large-scale modes of variability know to affect Australian climate, in particular the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), all three periods were marked by positive and negative events (according to Meyer et al., 2007):

- All three periods were marked by a similar number of El Niño events: 1902 and 1905; 1940 and 1941; and one more in the latter period 1997, 2002 and 2006;
- All three periods were marked by La Niña events but there were more in the latest period: 1903 and 1906; 1938 and 1942; and 1998, 1999, 2000 and 2007;
- There were very few negative IOD events: 1906, 1942 and none in the latest period; and
- There were a number of positive IOD events with the frequency increasing with time: 1906 only for the earlier period; 1935, 1944 and 1945 during the WWII period; and 1997, 1999, 2004, 2006, 2007 and 2008 for the latest period.

The larger numbers of La Niña events during the latest period is consistent with the known effect of ENSO across Australia and the latest period being generally wet Australia-wide. The increasing number of positive IOD events is likely to have an impact on Australian rainfall, although the impact of IOD on Australia peaks in spring. The annual signature of the Saji et al. (1999) Dipole Mode Index (DMI) on rainfall (Fig. 4) is interesting as it shows an impact across most of SEA. However, a close examination of the map compared to the pattern of current rainfall decline (Fig. 3C) shows differences worth mentioning:

- No impact of the IOD on the South-West of Western Australia (SWWA) which is also affected by a rainfall decline since 1997;
- The largest impact in SEA is inland of the GDR, while the largest rainfall decline since 1997 is in the SWEA;
- An extension further north of the impact of the IOD on rainfall along the GDR in New South Wales up to Queensland, an area which has not seen a rainfall decline since 1997.

A similar comparison between the maps of the STR-I impact on Australian rainfall (Fig. 1) and the current decline (Fig. 3C) does not show these discrepancies. Beyond this simple visual comparison, the joint contribution of the STR intensification and SST anomalies in the tropics in particular relative to the IOD dynamics is worth investigating further.

Seasonality of WWII and the on-going protracted droughts

Due to data limitations at the turn of the previous century, we will focus on the comparison between the WWII and current droughts in the rest of this report. As expected from earlier comments, the characteristics of the rainfall decline across the three climate entities in SEA are very different between the two periods (Table 1).

Similar (in percentage terms) anomalies were observed across all three regions during WWII and all seasons were affected (including summer): autumn and spring prominently in SWEA and NMDB, winter in ESB. The current drought is unprecedented only in SWEA. It is dominated by a strong autumn signature across all three regions, the size (and sign) of the anomalies in winter and spring explains why in SWEA the drought is record breaking. In contrast, in ESB the current drought is only half the magnitude of the WWII drought (a small negative anomaly in winter is cancelled out by a small positive anomaly in winter), and it is non existent in terms of annual rainfall anomalies across NMDB: a large spring increase cancelled out the autumn decline. Finally, it is worth noting that autumn rainfall appears as the only spatial and temporal invariant: it is sizeable across all three regions and evident during the two dry periods.

A month by month comparison of the two periods in the three regions (Fig. 5) confirms these results and highlights the continuum of eight months from March to October with rainfall deficiencies in SWEA for the current drought. These eight months include the entire wet season (May to October) where, over the 109-year long record, 60 per cent of the annual rainfall occurred. This, combined with the spatial extent of the decile 1 rainfall anomalies in the last decade, reinforces the impression that the highest rainfall decline is linked to a weakening of the dominant westerly flow as would be expected from a rainfall deficit whose temporal signature is scattered across the wet autumn/winter/spring months. Indeed, the decile 1 rainfall (Fig. 3C) region extends from the south-west across the entire SWEA and covers most of the Murray catchment. Two small pockets showing no rainfall decline are worth mentioning: the southern part of the Mt Kosciusko National Park (in the lee of the main range) and an area north-east of Adelaide in the lee of the Southern Flinders Ranges. These two small regions are relevant as they are located in the lee of significant orographic features (which tends to enhance rainfall on the western slopes and decrease rainfall on the eastern sides in westerly flows) and hence are more likely to receive rainfall from southerly or easterly flows.

The role of local MSLP indices

The role of the STR intensity (STR-I) in the rainfall decline is worth exploring further, as well as the possible additional contribution of the position of the ridge (STR-P). In addition, the slope of the Mean Sea Level Pressure (MSLP) gradient along the Eastern coast between the latitude of STR in summer and the tropical belt of low pressure is worth investigating. To do so both the Drosdowsky (2005) STR-I and STR-P monthly observed series and the Rakich et al. (2008) monthly Gayndah Deniliquin Index (GDI) are correlated with monthly rainfall across the three regions (Fig. 6). Here, for the ease of the comparison, the sign of the GDI has been reversed.

In SWEA (top right graph in Fig. 6), all three indices are significantly (at the 95 per cent level) correlated with rainfall for half of the year from April to October. The best correlation for annual rainfall is obtained with STR-I (-0.49) with both the position (-0.23) of the ridge and the GDI (-0.24) being a lesser contributor. In NMDB, correlations are low and hardly significant all year around while, along the ESB, the intensity of the STR does not appear to be relevant but its position and the GDI have a positive impact on rainfall (i.e. a ridge located further south or an enhanced South to North MSLP gradient along the East coast increases rainfall), with the GDI having a larger impact on annual rainfall (0.31) than the STR-P (0.21). This discussion and associated results illustrate that relationships between rainfall and local MSLP are not straightforward and evolve both spatially and temporally.

As one would expect, these three MSLP based regional indices are not independent. They are positively and significantly correlated almost all year around (top left graph in Fig. 6). Nevertheless, the joint contribution of STR intensity and position anomalies during the two dry epochs (WWII and on-going) is worth exploring further, in particular for SWEA. Annual cycles of the STR-I/STR-P during the two dry periods show anomalies compared to the long-term mean (Fig. 7) consistent with the rainfall anomalies in SWEA (Table 1): anomalies are larger in both intensity and position in the recent period in April to July, while during WWII they were larger in August to October.

Using the linear relationships between the STR position (STR-P) and intensity (STR-I), we computed STR-related monthly rainfall anomalies for the two dry periods in SWEA and compared them with observed values, using the following multi-linear regression model:

$$Rain_{anomaly} = a \times STR\_I_{anomaly} + b \times STR\_P_{anomaly} + c$$

With *a, b* and *c*, 3 parameters fitted on the observed values for each month, this model was used 3 times:

1. with *b=0*, to evaluate the role of the STR intensification alone;

2. with *a=0*, to evaluate the role of the shift south of the STR alone; and

3. with neither *a* or *b* equal to 0, to evaluate the joint effects of the STR intensification and shift south while taking into account the interdependence between these two variables.

For the current period the largest reconstructed anomalies were obtained with the STR-I, with rainfall anomalies being equal to 80 per cent of the observed decline. Interestingly, the percentage decreases when both STR-I and STR-P are considered (75.5 per cent); although, in the recent period, the anomalies in STR-P alone could generate sizeable reconstructed rainfall anomalies (equivalent to 30 per cent of the observed decline). Month by month anomalies (Fig. 8) compare quite well with the observations (in particular with STR-I alone), although the reconstructed anomalies are lower than observed in autumn and larger than observed in the rest of the wet season (winter and spring).

During WWII, the effects of the STR changes overall explained the dry decade to a lesser degree: reconstructed rainfall anomalies are 32 per cent of the observed decline with both STR-I and STR-P, 34 per cent with STR-I alone and 10 per cent with STR-P alone. Month by month, the underestimation is pronounced in every autumn and spring month, but the reconstructed anomalies are very accurate in winter.

It is worth emphasising that, in most months and in both periods, despite the sizeable effect of STR-P on rainfall when considered in isolation, it does not appear to have an additional effect, when combined with STR-I, in explaining the rainfall decline. The intensification of the STR is overwhelmingly sufficient to explain the part of the rainfall decline attributable to changes in the STR. This is most likely due to the high correlation (around 0.6) between STR-I and STR-P from April to November. On a cautionary note, the possibility that the shift in position has an additive but non-linear effect compared to the strengthening of the ridge cannot be ruled out completely, as the statistics used here are relatively simple and rely on linearity assumptions. More advanced non-linear statistics (such as the Classification And Regression Tree (CART) technique described in Project 1.3.1P, Timbal et al., 2009b) are needed to push this analysis further.

The role of tropical SSTs

A large number of tropical SST indices were computed using the HadSST2 dataset (Rayner et al., 2006) interpolated on 2.5º by 2.5º grid, from 1900 to 2008:

- The Saji et al. (1999) DMI, the Nicholls (1989) Indian Ocean Dipole (IOD), the Timbal and Murphy (2007) North West shelf (NWS) index; in addition, values updated to 2007 for the IOD composite from Meyer et al. (2007) were used;

- The Niño4 SST index, the Ashok et al. (2007) El Niño Modoki Index (EMI) and, in addition, values updated to 2007 for the ENSO composite from Meyer et al. (2007) were used;

- Finally, an additional index was created to maximise the influence of tropical SST on SWEA rainfall based on observed correlations (called tropical SST): this index is the difference of the SSTs north of Australia in the Eastern Indian Ocean and across the Indonesian maritime continent (0 °S -20 °S and 90 °E to 140 °E on the Equator shifted to 110 °E to 160 °E at 20 °S) minus the average of two SSTs boxes: a square further west in the Indian Ocean (10 °N to 20 °S and 55 °E to

90 °E) and a box in the Pacific Ocean (15 °N to 15 °S and 150 °E to 140 °W at the northern boundary and 180 °E to 140 °W at the southern boundary) (Fig. 9).

The last index has the advantage of combining SSTs with a negative relationship with SWEA rainfall in both oceanic basins and contrasting them with SSTs with a positive relationship with SWEA rainfall across a large sector north of Australia. The same logic was used by Nicholls (1989) to define an IOD index. The idea is extended here across both oceanic basins. It is therefore expected to provide the strongest relationship with SEA rainfall. This index provides a broader perspective on the role of tropical SST on SEA rainfall. In particular it captures the enhanced effect of the ENSO signal on SEA rainfall when ENSO has a signature further west (El-Modoki type of ENSO) and the amplification which occurs when ENSO anomalies are transmitted through the maritime continent into the Indian Ocean. This amplification is particularly important when an IOD event occurs. It implicitly takes the view that inter-annual variability between the two oceans is linked although it will also show a signal if only one of the two oceans show an event (either ENSO or IOD). It has the disadvantage of not focusing on a particular part of the tropical oceanic dynamic (in contrast to IOD or ENSO indices). However, it has the potential to be very pertinent on long timescales (such as the decade long dry periods analysed here) as well as on inter-annual timescales. It is also important that this index is made of differences of tropical SSTs and, hence, it is unlikely that its first order trend will simply be a regional measure of global warming as is the case with single box indices (e.g. Nino4 or NWS indices). Instead, it measures the shift of warm waters and associated convection (these shifts could be due to global warming or unlinked naturally occurring variability) in the tropics which we know (based on observed correlations) have the potential to impact on SWEA rainfall.

Monthly correlations with all these indices were computed (Fig. 10) with rainfall in SWEA and a SWEA rainfall residual once the relationship between the STR-I and SWEA was removed (negative correlation are used with NWS and the tropical SST index to ensure consistency of sign between all the indices). Well known features, such as the predominant influence of the IOD and ENSO in winter and spring are clearly visible; this is also the case for our tropical SST index. All tropical indices have no significant relationship with SWEA rainfall from November to March. Three indices are particularly important: the Nicholls (1989) IOD, the Meyer et al. (2007) ENSO composite and our specifically defined tropical SST index (summarised in the third row of graphs in Fig. 10).

In general, the relationships are weaker with the rainfall residual, suggesting that part of the influence of tropical SST on SWEA rainfall is operating through circulation changes already captured by the STR intensity. Overall though, many correlations remain sizeable and significant, especially during winter and spring. In particular, the relationship with the tropical SST index remains significant (the correlation for the annual means drops from -0.53 to -0.32). As expected, it is the index with the highest correlation with SWEA rainfall, although, correlations are similar to the other indices once the relationship with the STR-I is removed.

Finally, the possible additional contribution of tropical SSTs in explaining the SWEA rainfall decline alongside the sizeable contribution from the STR intensification is evaluated using the same linear methodology described earlier, but this time STR-I and the tropical SST index were considered (Fig. 11). For the current drought, warming tropical SSTs have had no contribution overall to our rainfall since 1997 (the effect on the annual rainfall is a **positive** 0.9 per cent). In other words, due to the warming of the tropics and its spatial pattern (as captured by the complex tropical SST tri-pole), the rainfall decline in SWEA has been a little less than the STR intensification on its own would have produced (rainfall reconstructed anomalies are only 77 per cent of the observed once the tropical SST is considered compared to 80 per cent with the STR-I alone). That small but positive tropical SST influence (the difference between green and red bars in the graphs) is seen during the autumn and early winter months. The individual contributions from the tropical tri-pole (blue bars) are positive during all these months (from March to June), thus confirming that tropical SST plays no part at the time of the year when the rainfall decline is the largest (two thirds of SWEA rainfall decline occurred in these four months). On the contrary, a negative but small contribution is noticeable in late winter to spring. It is worth noting that, in general, the joint contribution of the STR-I and the tropical SST index is not a simple addition of the two individual contributions, thus confirming that part of the influence of tropical SST is occurring though the STR intensification. Overall, some very large observed monthly anomalies remain poorly accounted for: March, May, October and the lonely positive anomaly in November, which knowing the high degree of variability of local rainfall on a 12-year period - a short period from a climate/climate change perspective - is not too surprising.

In contrast during the dry WWII period in the middle of the 20th Century, tropical SST added a small negative contribution to the dry decade: the size of the reconstructed rainfall anomalies increase from 34 per cent (when only the STR-I is considered) to 37 per cent when both the STR-I and the tropical SST index are considered (the tropical tri-pole influence on its own is larger: a decline equivalent to 15 per cent of the observed values). When both effects are combined (and, as noted for the recent period, it is not a simple addition of the two effects), the rainfall anomalies during the winter months are well accounted for, but this is not the case for large monthly anomalies in autumn and in spring, the season with the largest rainfall decline during WWII (Table 1).

The influence of the tropical SST index on rainfall in the very southern part of the Australian continent is likely to involve moisture advection across the continent from the wet tropics. The last set of results (when tropical SST only played a role during the WWII dry period) is consistent with the Australia-wide rainfall anomalies shown earlier (Figs 3B and C).

Conclusions

The analysis has confirmed earlier results. The on-going current rainfall decline is largely due to a strengthening of the STR. It has been shown that the shift in position of the STR has had no additional effect. Tropical SSTs (including in the Indian Ocean) are not the cause of the on-going decline. Overall, they have had no sizeable contribution to our rainfall since 1997 overall. In details, tropical SSTs have made the rainfall decline slightly less severe in early winter while contributing slightly to the spring rainfall decline. This does not preclude the fact that, on inter-annual time-scale, some individual years or seasons can be singled out and a tropical teleconnection established: e.g. the very low rainfall during the 2006 El Niño year, or the enhanced spring rainfall decline since 2006 which is related to three positive IOD events in 2006, 2007 and 2008. The last example is essential to understanding the worsening of the rainfall decline across SEA since 2006 (Timbal, 2009).

While the current drought can be linked to global warming through the strengthening of the STR which, in turn, is attributable to anthropogenic forcings (Timbal and Smith, 2009), it is worth noting that the WWII dry decade can be considered to be the first dry decade in SEA that is partially due to 20th Century global warming through the intensification of the STR (between the 1900s and 1940s, the planet warmed by about the same amount (0.4ºC) as between the 1970s and now). However, the results presented here show that only around a third of the rainfall decline during the WWII decade can be accounted for by global warming though STR intensification, while tropical SST patterns at that time played a role, and most likely contributed to the dryness being Australia-wide during that earlier period. This contrasts with around 80 per cent of the current rainfall decline being accounted for by the intensification of the STR, with the influence of tropical SSTs during this latest period acting to reduce the severity of the rainfall decline resulting from the STR intensification.

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Appendix: Tables and figures

Table 1: *Rainfall statistics for the 3 climate entities in SEA: long term (1900-2008) mean (annual and seasonal) in mm and anomalies during the WWII dry period and the on-going protracted drought (as a percent of the long-term climatology). Positive anomalies are shown in italics; when anomalies for the recent period are the largest on record, they are shown as bold figures.*

		Annual	**Autumn**	**Winter**	**Spring**	**Summer**
	1900-2008	456 mm	103 mm	145 mm	120 mm	87 mm
SWEA	1935-1945	-10.3%	-13.1%	-7.2%	-18.2%	-1.2%
	1997-2008	**-10.7%**	**-26.5%**	**-12.1%**	-4.2%	*+1.2%*
	1900-2008	457 mm	105 mm	89 mm	106 mm	157 mm
NMDB	1935-1945	-15.4%	-17.2%	-6.3%	-29.1%	-10.1%
	1997-2008	-0.5%	-17.9%	-1.7%	*+15.0%*	*+1.6%*
	1900-2008	954 mm	253 mm	191 mm	210 mm	299 mm
ESB	1935-1945	-12.4%	-11.3%	-15.5%	-11.4%	-12.0%
	1997-2008	-6.3%	-16.7%	-7.0%	*+4.1%*	-1.4%

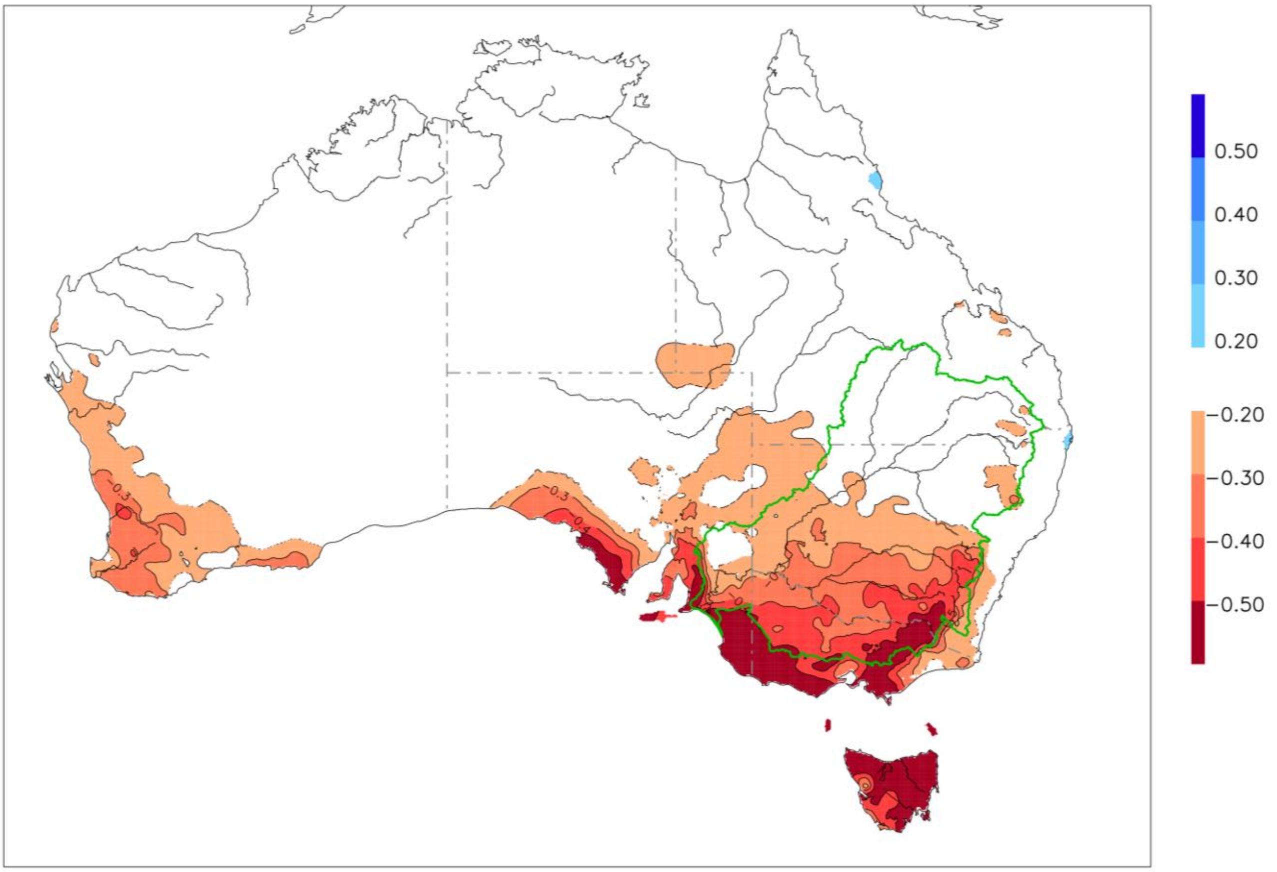


Figure 1: *Correlations between detrended values of the annual mean of the Sub-Tropical Ridge intensity and rainfall across Australia; correlations significant at the 95% level and above are colours shaded*

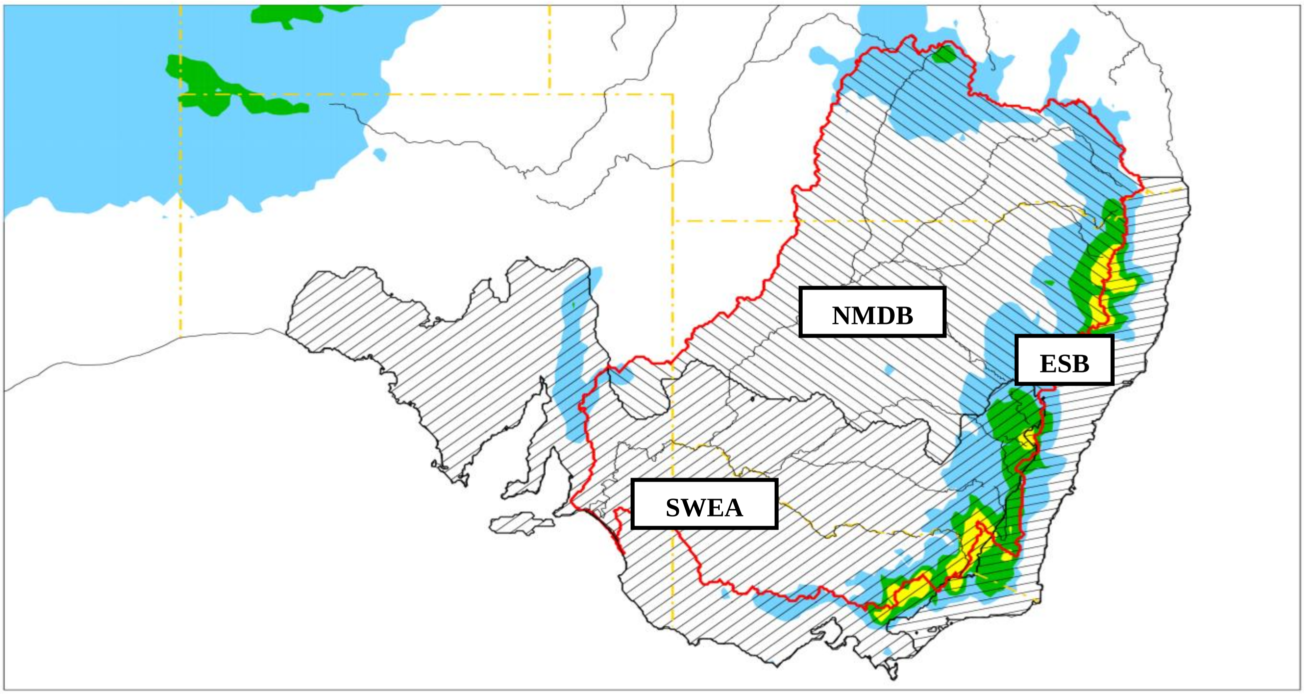
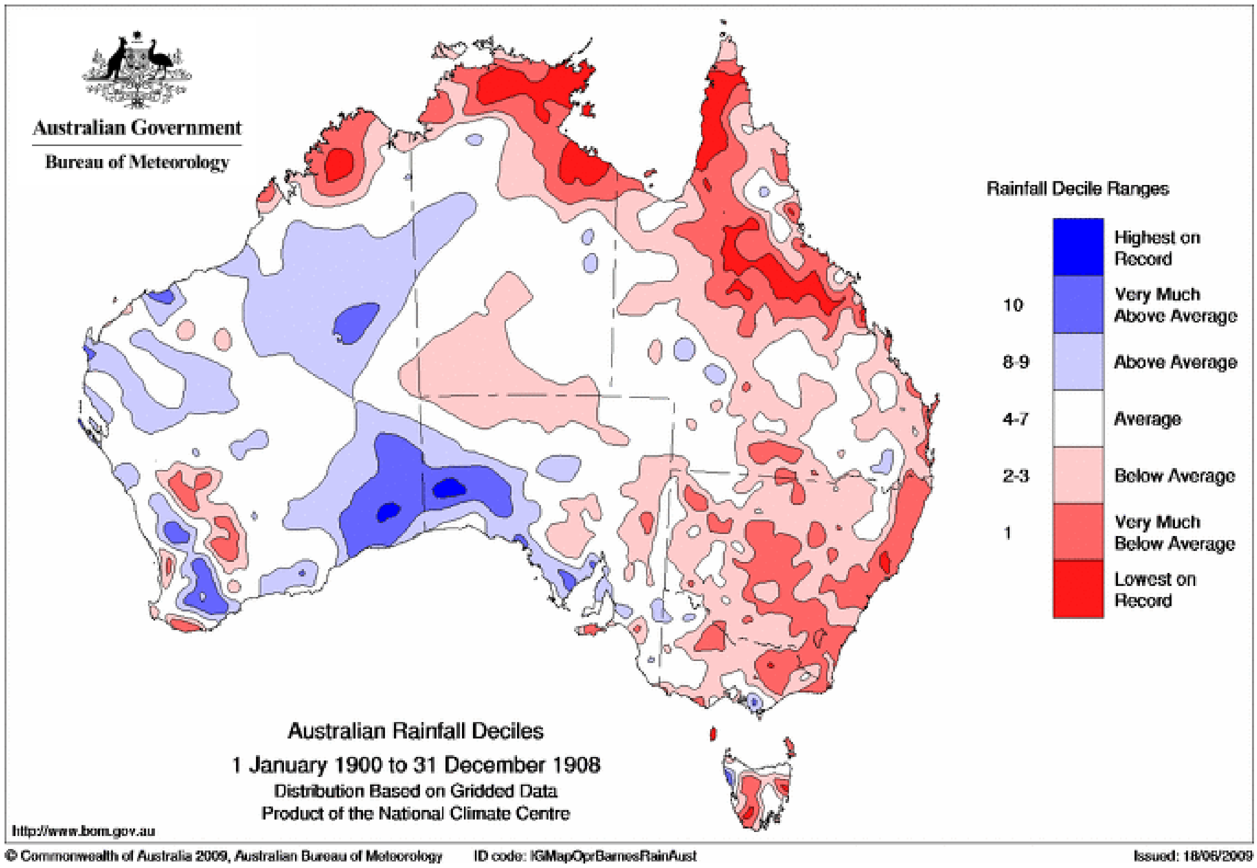


Figure 2: *The three regions of interest across the SEACI domain are shown with different stipples: the south-west part of Eastern Australia (SWEA), the Northern part of the Murray-Darling Basin (NMDB) and the Eastern Sea-Board.*


Australian Government
Bureau of Meteorology
Rainfall Decile Ranges
Highest on Record
10
Very Much Above Average
8-9
Above Average
4-7
Average
2-3
Below Average
1
Very Much Below Average
Lowest on Record
Australian Rainfall Deciles
1 January 1900 to 31 December 1908
Distribution Based on Gridded Data
Product of the National Climate Centre
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ID code: IGMapOprBarnesRainAust
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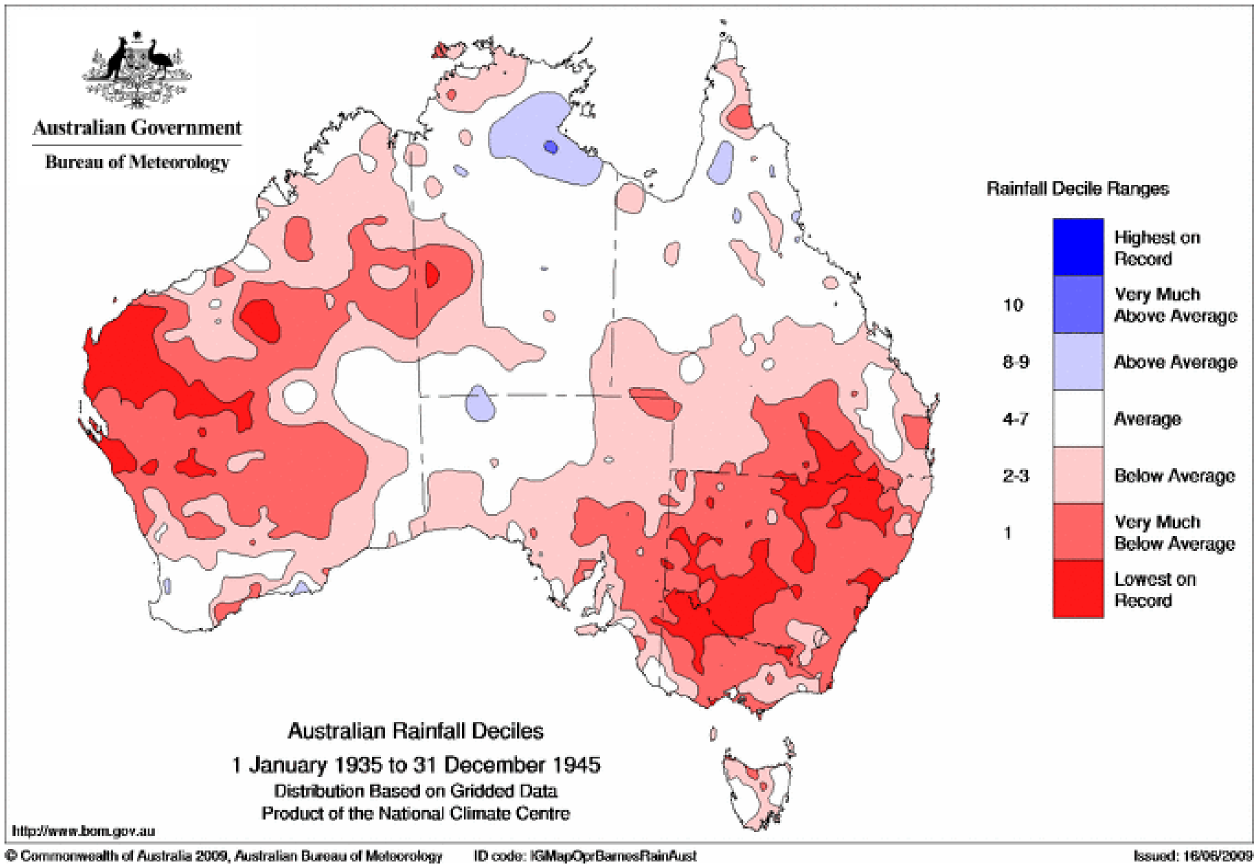
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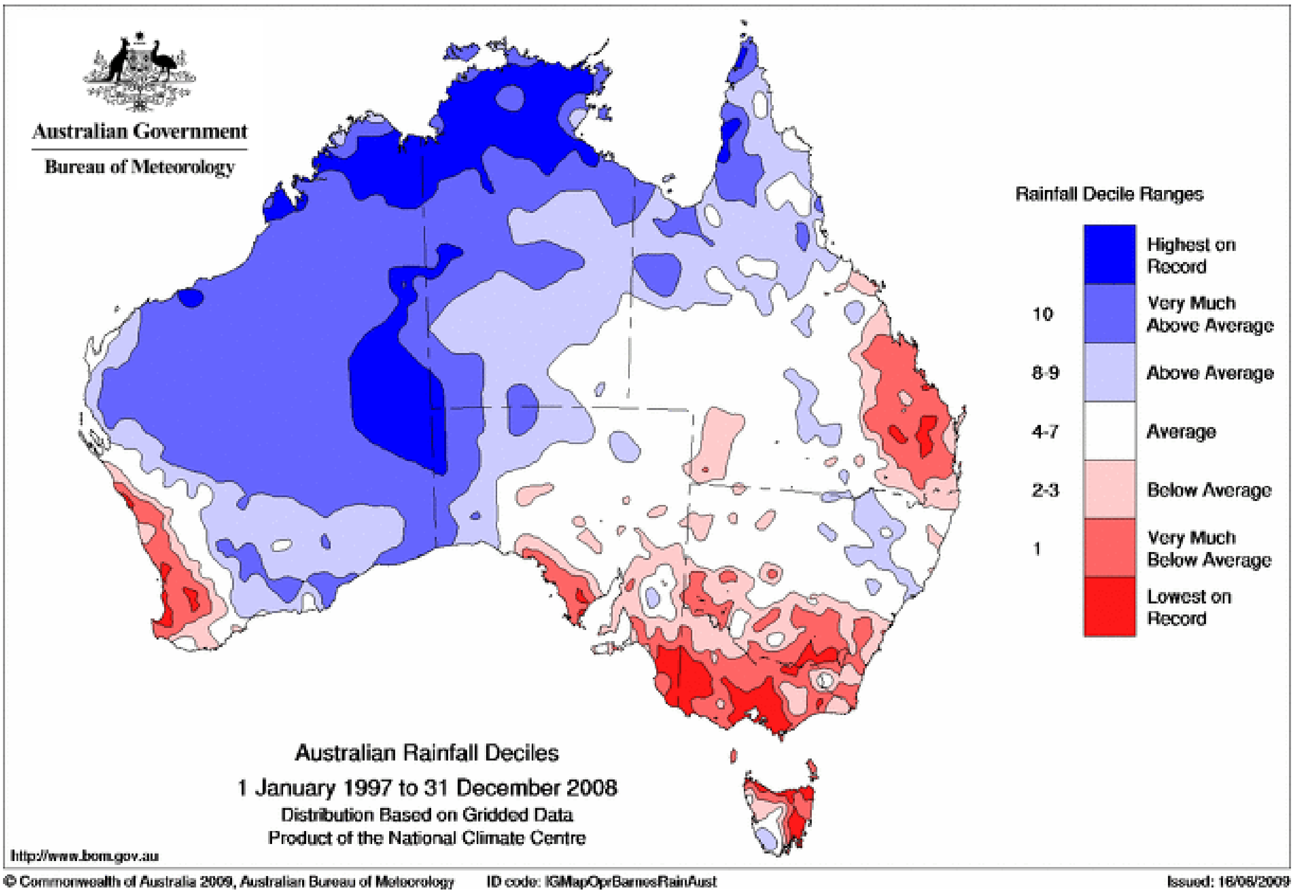


Figure 3: T*otal rainfall deciles across the Australian continent for the 1900-05 period (upper), 1935-1945 period (middle) and the 1997-2008 period (lower); deciles are expressed using the long-term climatology from 1900 to 2008 (maps courtesy of the National Climate Centre).*

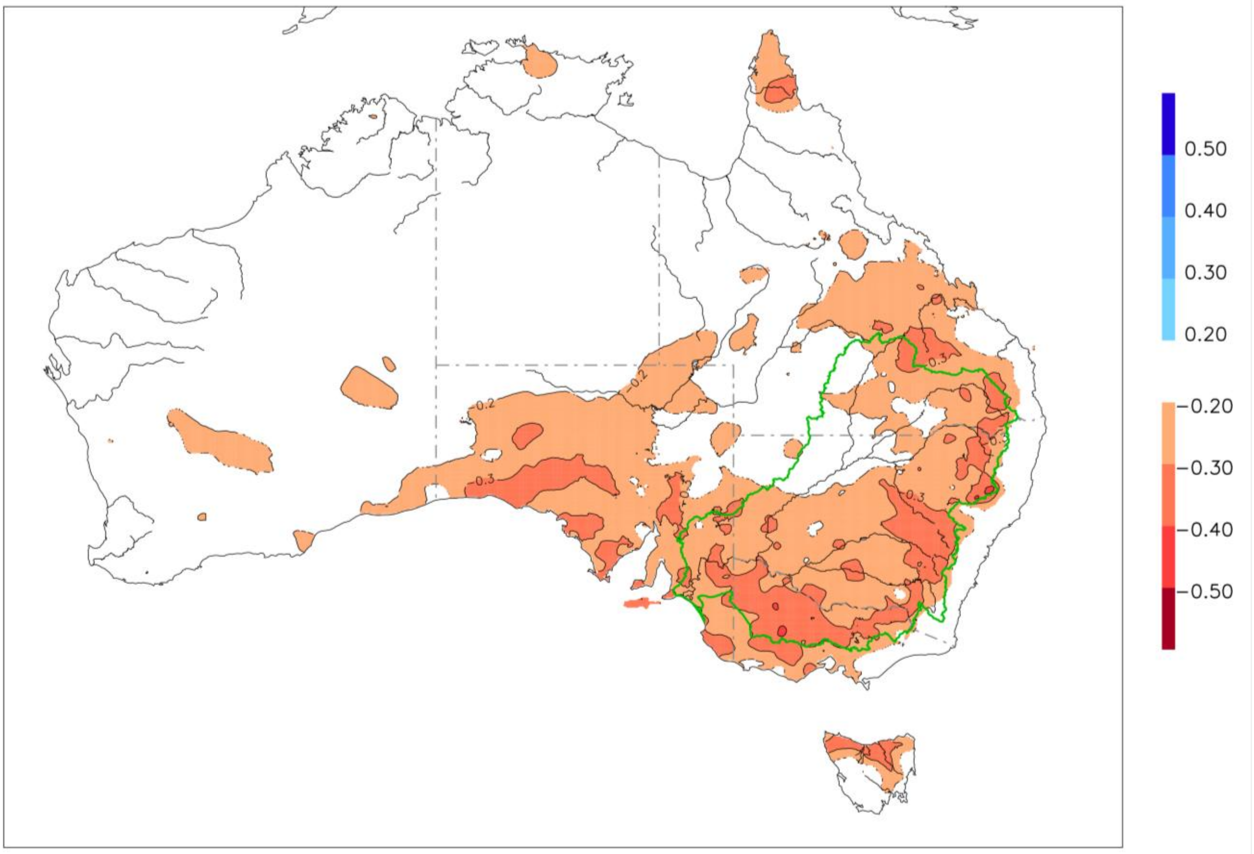


Figure 4: *Detrended correlations between detrended annual values of the Indian Ocean Dipole and rainfall across Australia; correlations significant at the 95 per cent level and above are colour shaded.*

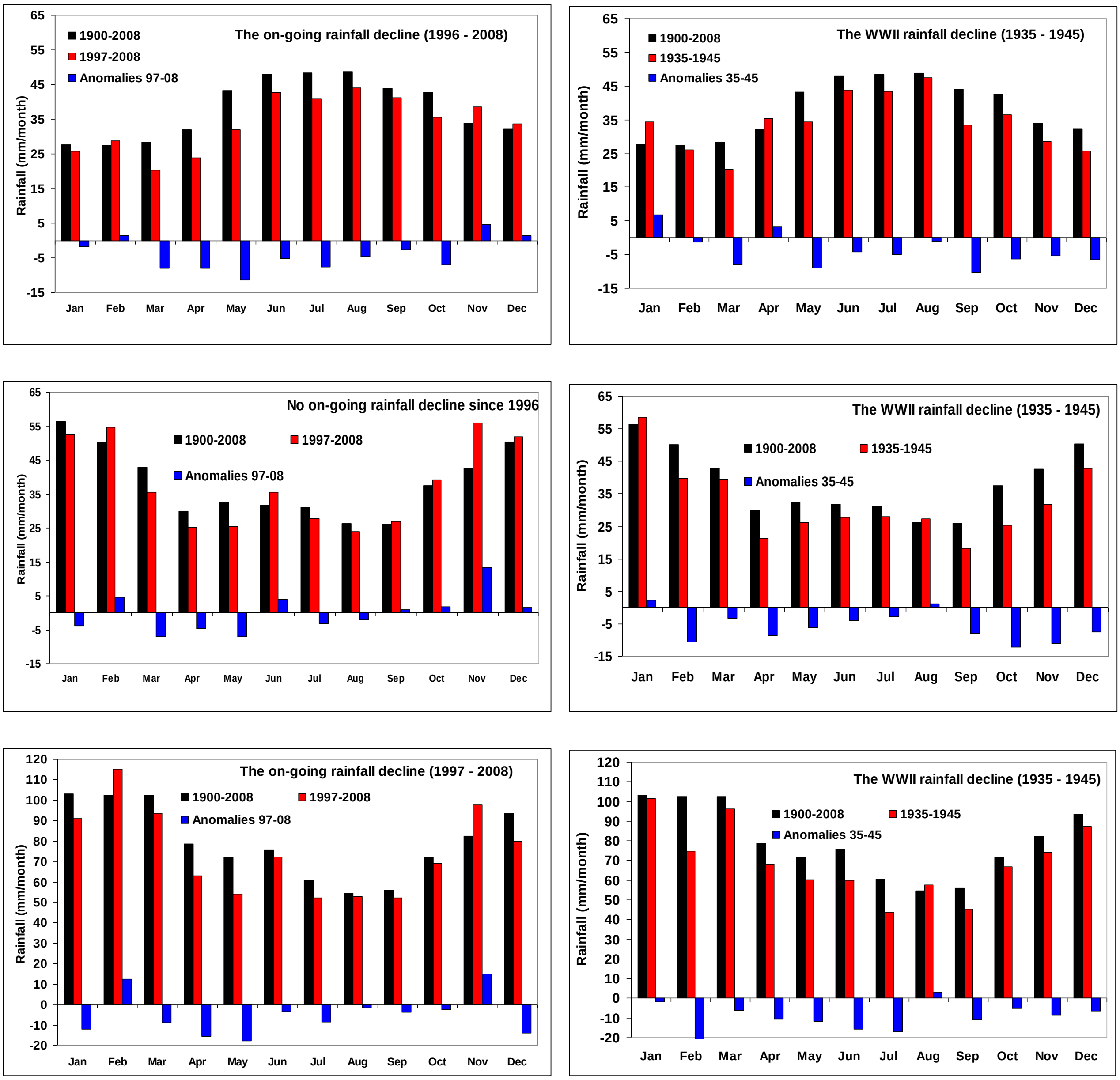


Figure 5: *Monthly mean rainfall for the long-term climatology (black bars) in SWEA (upper), NMBD (middle) and ESB (lower), for the on-going protracted drought (red bars in left graphs) and during the World War II protracted drought (red bars in right graphs); changes from the long term climatology are shown as blue bars. [Note: there is no on-going decline in rainfall in NMBD since 1996].*

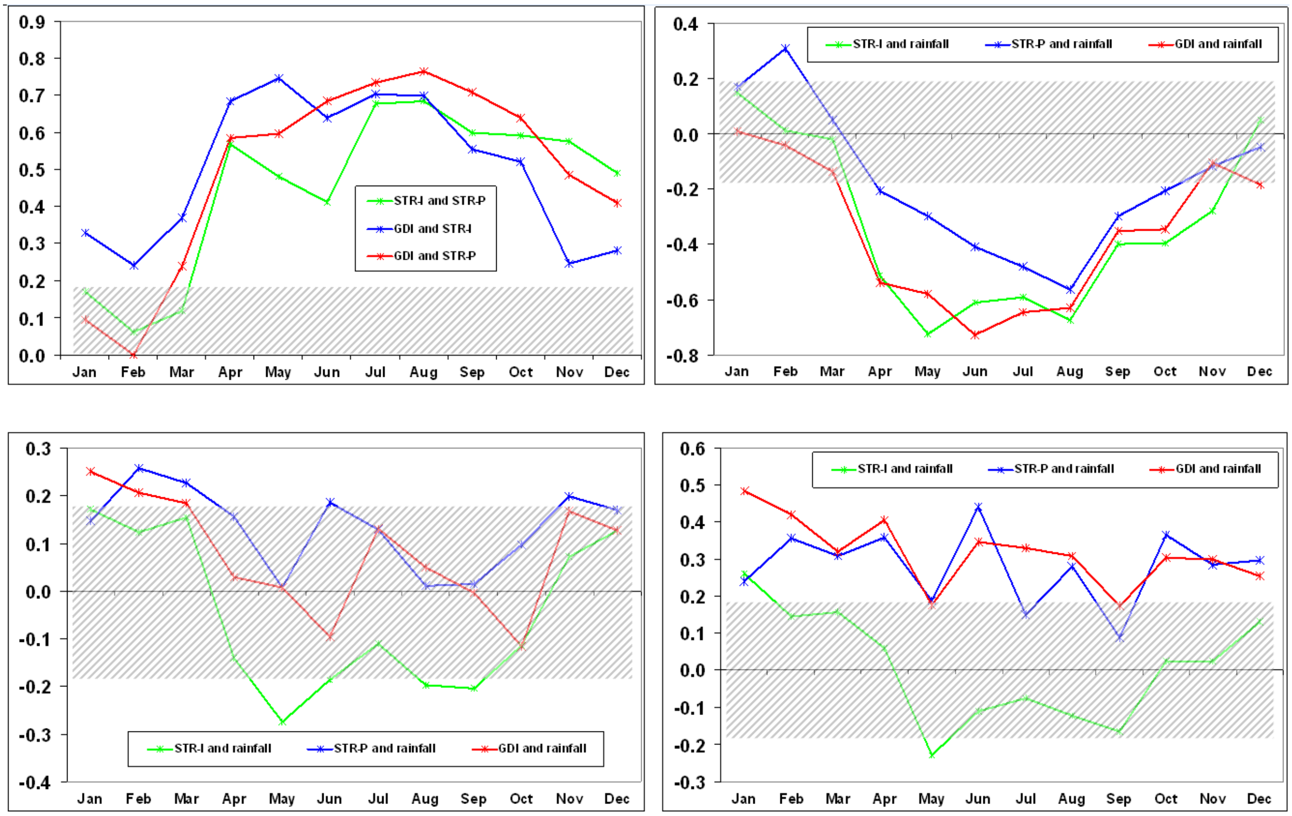


Figure 6: *Monthly correlations between rainfall in SWEA (top right), NMDB (bottom left) and ESB (Bottom right) and local MSLP indices (STR intensity and position and GDI as well as correlations between the three local MSLP indices (top left). On all graphs, correlations below the 95 per cent statistical significance level are masked by grey stipples.*

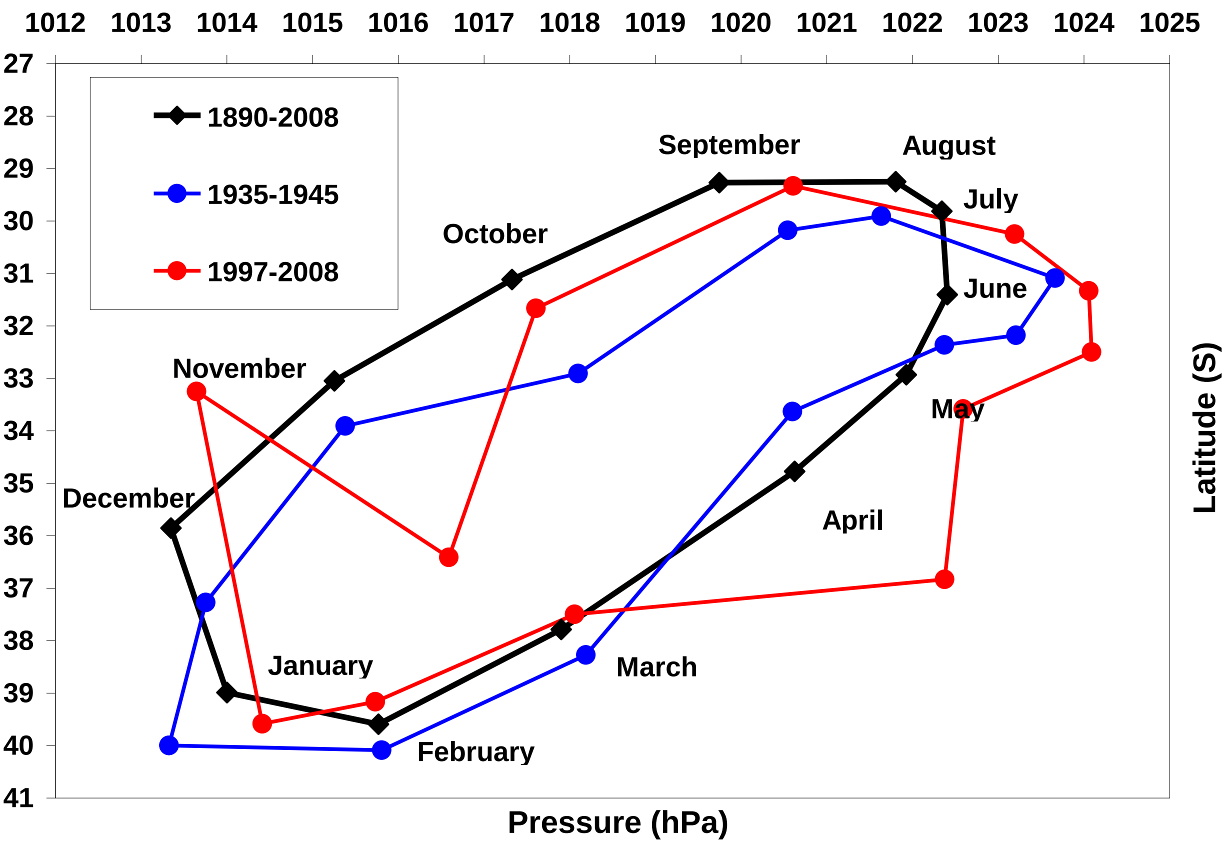
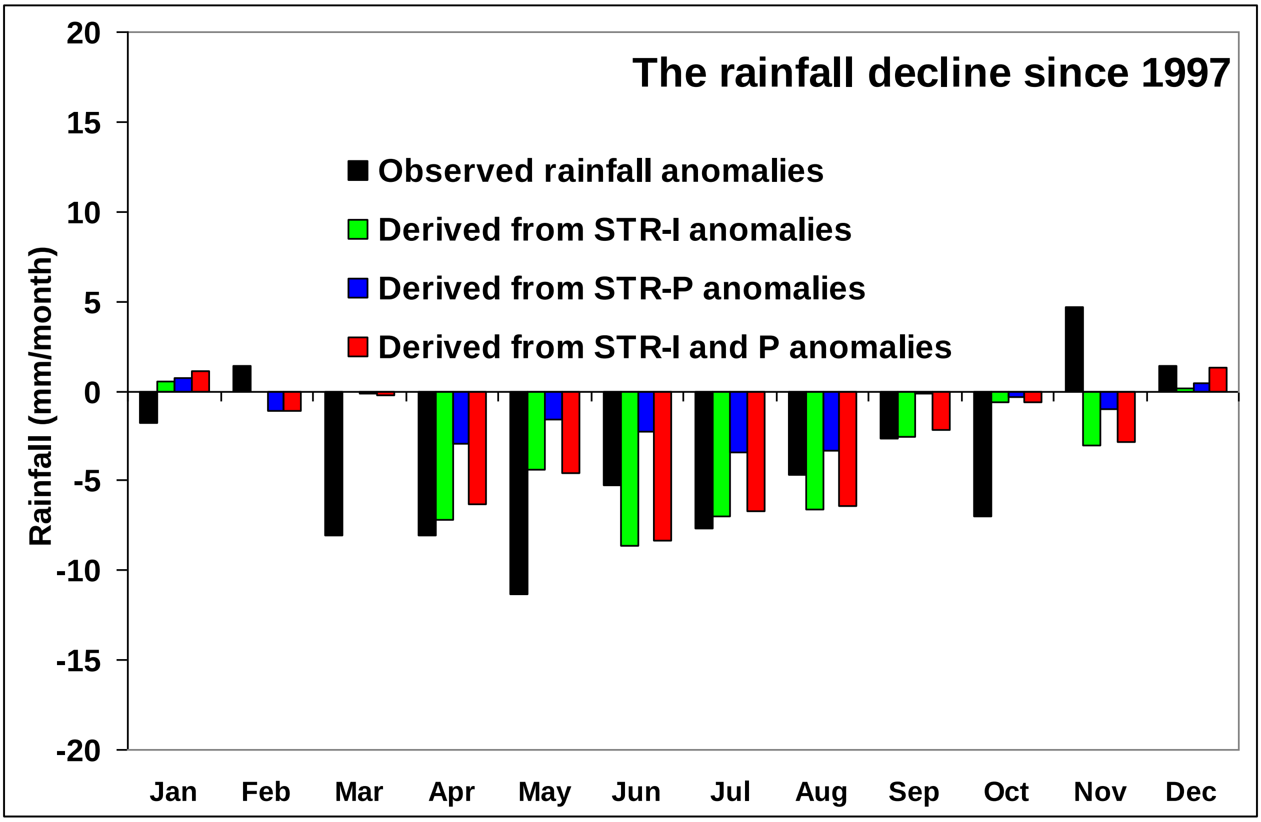


Figure 7: *Annual cycle of monthly mean sub-tropical ridge position and intensity from the long-term climatology (black curve) and for the two dry periods: WWII (blue curve) and current (red curve).*



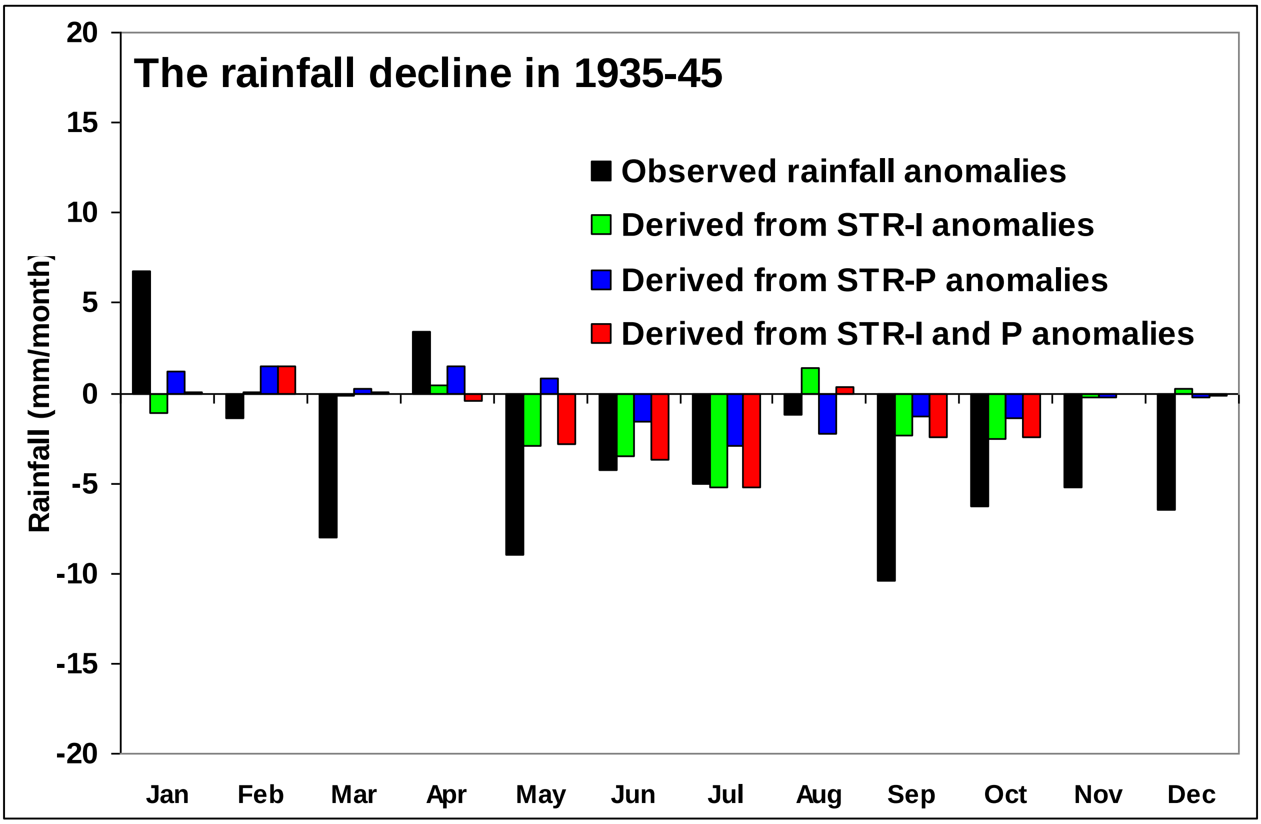


Figure 8: *Monthly rainfall anomalies for the on-going drought (upper graph) and the WWII drought (lower graph) as observed and reconstructed using the linear relationship between rainfall and the sub-tropical ridge intensity (STR-I in green), position (STR-P in blue) and both intensity and position combined (in red).*

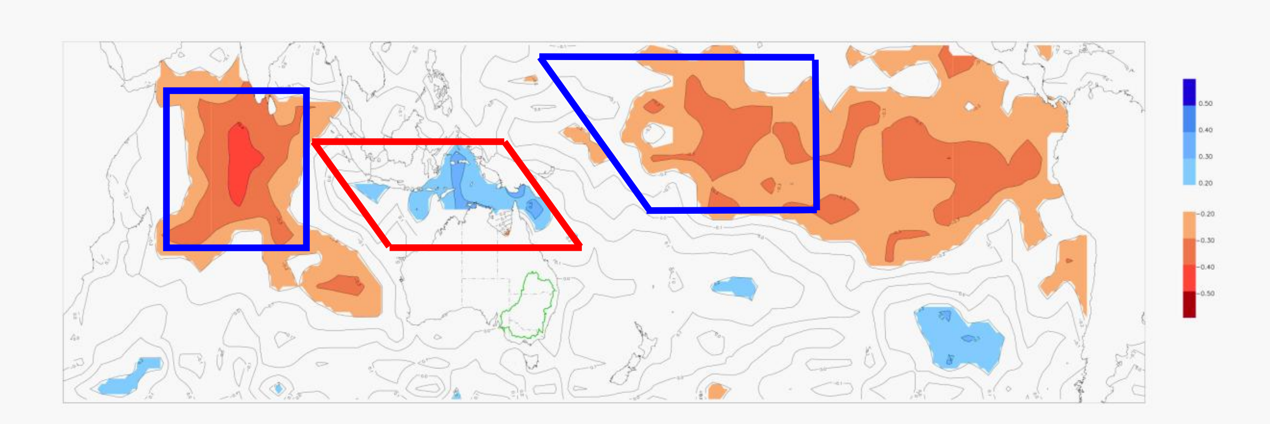


Figure 9: *Map of the annual correlation of SSTs with SWEA rainfall (correlation significant at the 95 per cent level are shaded). The boxes used to define the tropical tri-polar SST index are shown: the index is the difference between SST in the central red box minus the average of the SST within the two blue boxes.*

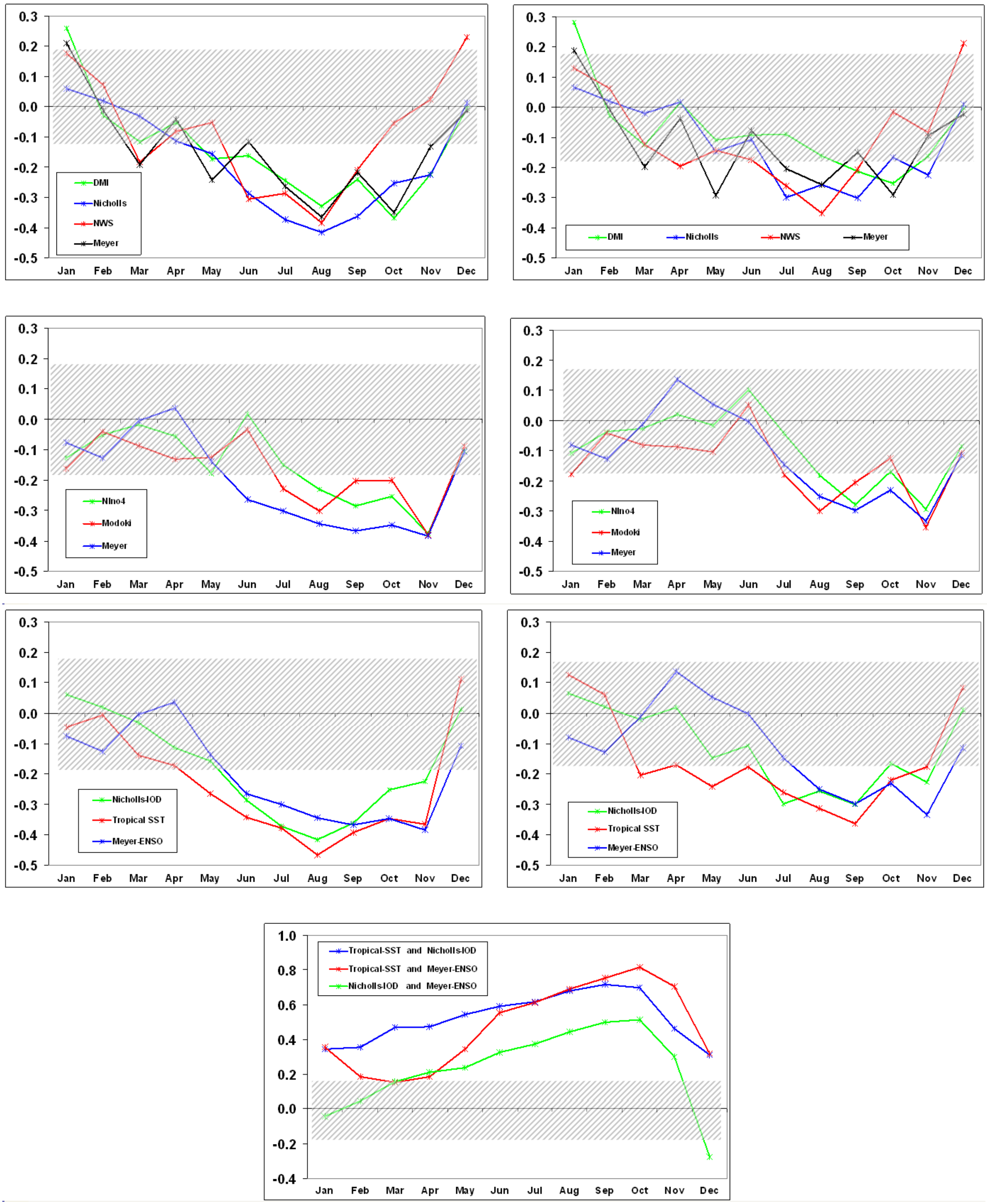
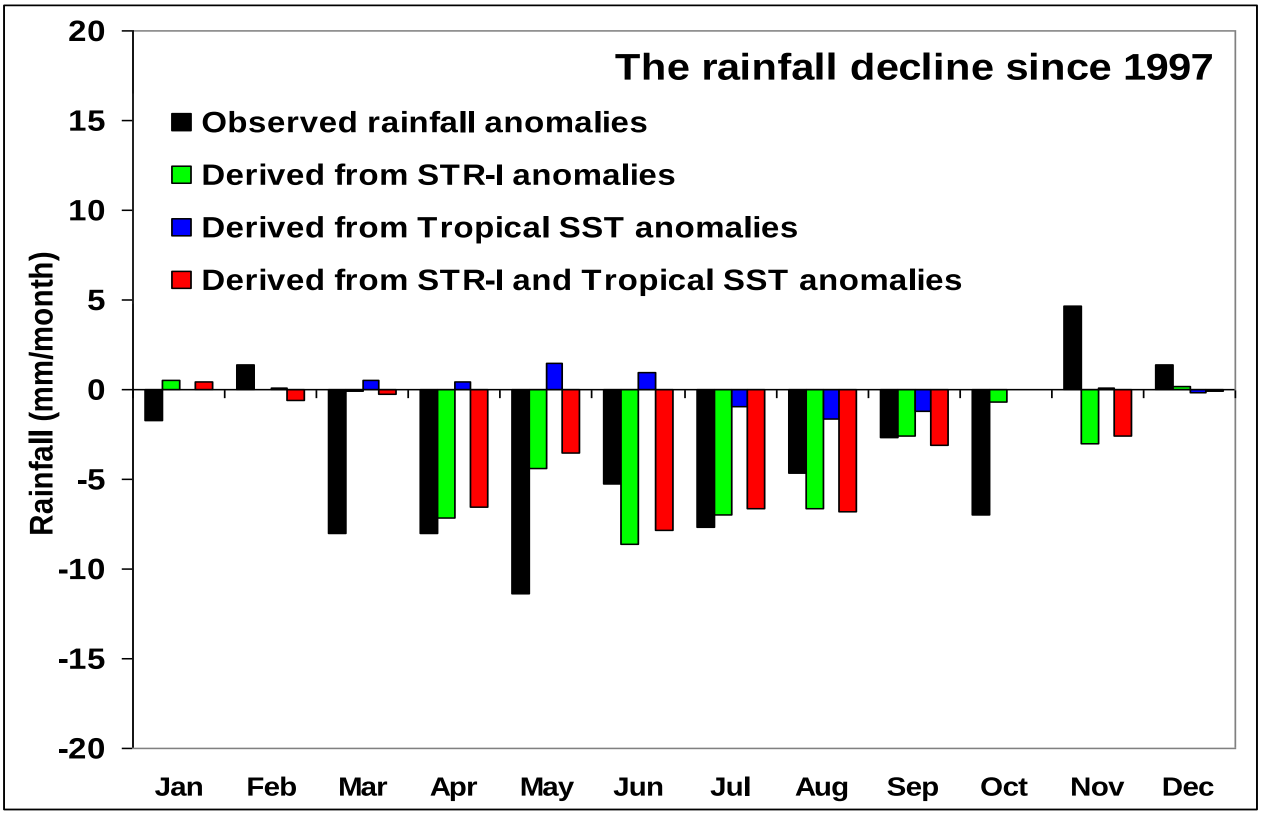


Figure 10: *Monthly correlations between tropical indices for the Indian Ocean (top row), Pacific Ocean (second row), the best three tropical indices (third row, see text for details) and rainfall in SWEA (left column) and SWEA rainfall residual with the STR-I influence removed (right column); correlations between the three most relevant tropical indices (bottom graph). On all graphs, correlations below the 95 per cent statistical significance level are masked by grey stipples.*



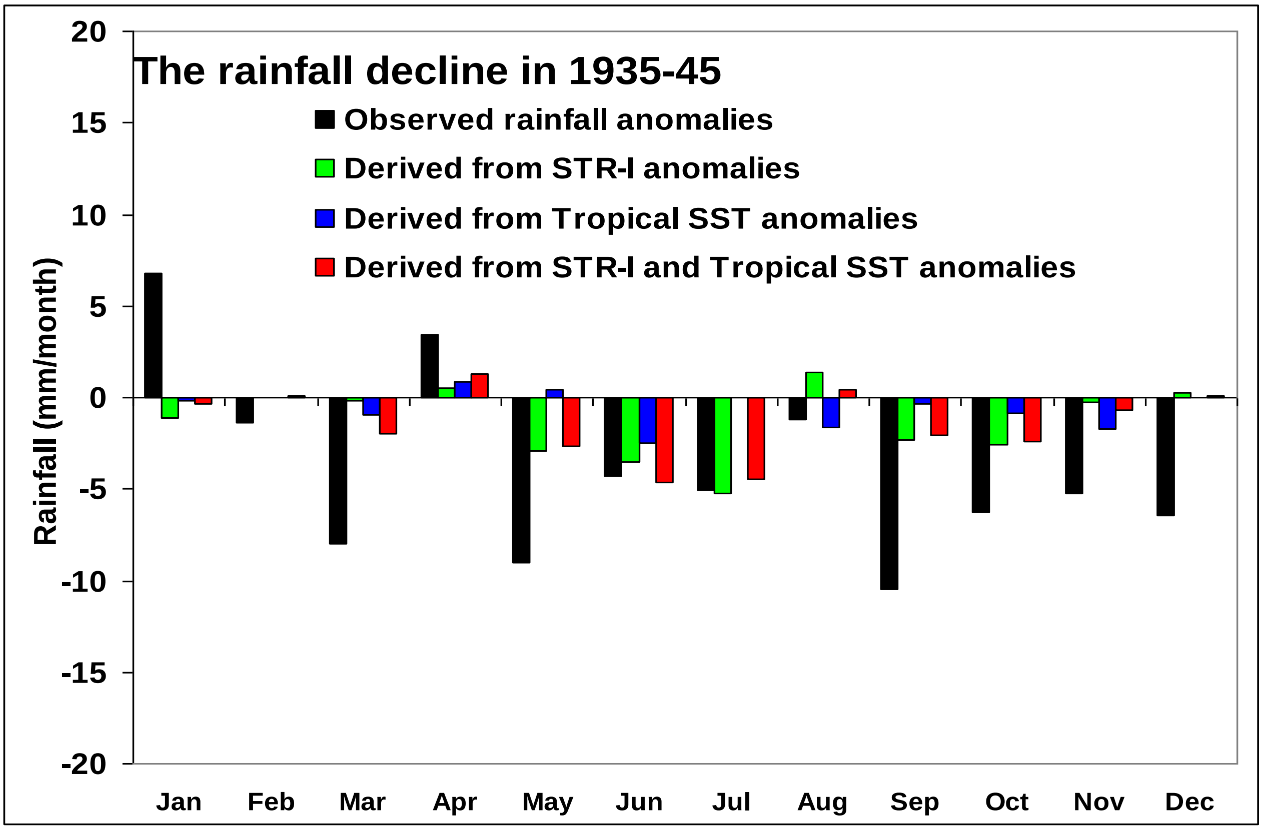


Figure 11: *As per Fig.8 but for the sub-tropical ridge intensity (STR-I in green), and the tropical SST index (in blue) and both the combination of both (in red).*