Positive Indian Ocean Dipole events precondition southeast Australia bushfires

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[1] The devastating "Black Saturday" bushfire inferno in the southeast Australian state of Victoria in early February 2009 and the "Ash Wednesday" bushfires in February 1983 were both preceded by a positive Indian Ocean Dipole (pIOD) event. Is there a systematic pIOD linkage beyond these two natural disasters? We show that out of 21 significant bushfires seasons since 1950, 11 were preceded by a pIOD. During Victoria's wet season, particularly spring, a pIOD contributes to lower rainfall and higher temperatures exacerbating the dry conditions and increasing the fuel load leading into summer. Consequently, pIODs are effective in preconditioning Victoria for bushfires, more so than El Niño events, as seen in the impact on soil moisture on interannual time scales and in multi-decadal changes since the 1950s. Given that the recent increase in pIOD occurrences is consistent with what is expected from global warming, an increased bushfire risk in the future is likely across southeast Australia. **Citation:** Cai, W., T. Cowan, and M. Raupach (2009), Positive Indian Ocean Dipole events precondition southeast Australia bushfires, *Geophys. Res. Lett.*, *36*, L19710, doi:10.1029/2009GL039902.

1. Introduction

[2] Over 170 people perished in the Victorian bushfire disaster known as "Black Saturday" on the 7th of February 2009. Fanned by 100 km hr^{-1} winds and aided by the hottest day on record in many locations (Melbourne recorded 46.4°C), a deadly line of bushfires burnt over 400,000 hectares of land, destroyed more than 2000 homes, and caused a loss of tens of thousands of livestock. In many respects, the Black Saturday bushfires were more damaging than the previously worst recorded "Ash Wednesday" bushfires (16th February 1983), when a combination of extreme heat (Melbourne recorded 43.2°C) and wind gusts empowered widespread fires across much of Victoria and South Australia, destroying approximately 2,500 homes and taking 75 lives. These two events are considered to be amongst the worst in Australia's recent history.

[3] Although southern Australia is prone to bushfires on an annual basis during summer [*Ellis et al.*, 2004], significant events are generally preceded by severe dry conditions in the months and years prior. Thus, it is important to identify the causes of these exceptional dry conditions, which are typically associated with phases of El Niño-Southern Oscillation (ENSO) [*Nicholls et al.*, 1996] and the Indian Ocean Dipole (IOD) [*Cai et al.*, 2009b; *Ummenhofer et al.*, 2009]. Both the Ash Wednesday and Black Saturday bushfires occurred amid major droughts. In the case of Black Saturday, it was preceded by the worst drought on record lasting over a decade, with a large autumn rainfall deficit and substantial reductions in winter and spring rainfall, exacerbated by an unprecedented string of pIOD events [*Cai et al.*, 2009a]. Such dipole events refer to a phase of sea surface temperature (SST) variability during which the eastern Indian Ocean (IO) is cooler than normal and the west IO is anomalously warmer [*Saji et al.*, 1999]. It usually leads to below average winter and spring rainfall over southeastern Australia [*Ashok et al.*, 2003; *Cai et al.*, 2009b], where rainfall across these seasons is critical for water availability in the southern reaches of the Murray-Darling Basin. During 2002–2008, the IO experienced five such events [*Cai et al.*, 2009b], including an unprecedented set of three-consecutive pIODs during 2006–2008 [*Cai et al.*, 2009a], with the 2007 and 2008 episodes occurring in conjunction with La Niña conditions.

[4] A commonality of the Black Saturday and Ash Wednesday fires is that they were both preceded by a pIOD event. Is there a systematic linkage between pIODs and a greater bushfire risk over Victoria? We show that this is indeed the case, and explore the mechanism.

2. Soil Moisture and Climate Data

[5] We focus on the spring season (September, October, November, or SON) when pIOD events peak, and the summer season (December, January, February, or DJF) when the delayed impact of the IOD on soil moisture continues to be significant through a cross-season memory. The soil moisture data, developed as a part of the Australian Water Availability Project [*Raupach et al.*, 2008], consists of two layers (upper layer: surface – 0.2 m, and lower layer: 0.2 – 1.5 m), and cover from 1900 to the end of 2008. An updated version of the Global Sea Ice and SST reanalysis [*Rayner et al.*, 2003] covering the period from 1880–2008 is used to construct an index of the IOD, called the dipole mode index (DMI) [*Saji et al.*, 1999], and an ENSO index (NINO3.4). A DMI > 0 represents the positive phase of the IOD (e.g., warmer water in the western IO, cooler in the eastern IO). Observed Australian rainfall and maximum temperature data since 1950, subjected to extensive quality control from the Australian Bureau of Meteorology Research Centre [*Jones et al.*, 2006], are used to examine the relationship with the indices. In section 4, anomalies on interannual

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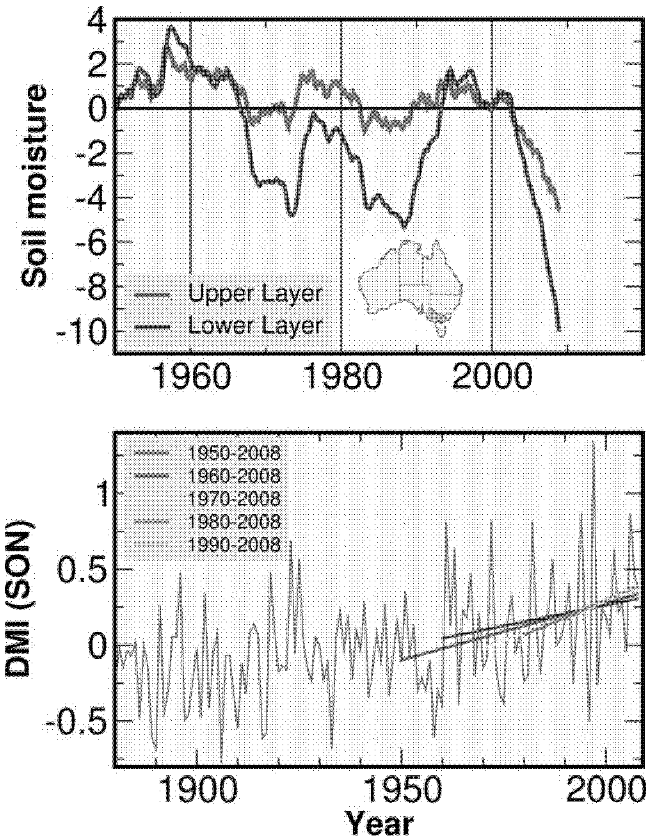

Figure 1. Raw time series of: (top) accumulative upper (top 0.2 m, red) and lower (0.2–1.5 m, blue) soil moisture anomalies (units of fraction of saturated water content in soil) over southeast Australia encompassing the state of Victoria (average over 140–150°E, 32–40°S; highlighted in map) using monthly anomalies reference to the 1950–2000 climatology, and (bottom) the DMI (°C) in spring (SON) following the definition of *Saji et al.* [1999] based on HadISST [*Rayner et al.*, 2003] referenced to the climatological mean over 1880–2008. Trend lines over several periods are superimposed.

time scales are linearly detrended before analysis to remove any relationship generated in the long-term trends.

3. Significant Bushfires and Their Relationship With ENSO and the IOD

[6] The recent dry conditions over southeastern Australia (average over 140–150°E, 32–40°S) are illustrated in Figure 1, showing the accumulative monthly upper and lower layer soil moisture anomalies from the 1950–2000 mean (Figures 1, top), calculated using a running unweighted sum. Also shown in Figure 1 (bottom) is a time series of the DMI in spring. The DMI displays upward trends over the past five decades since 1950, consistent with a skewness towards more pIODs [*Cai et al.*, 2009b]. The "off-a-cliff" behaviour in the recent 10-year reduction in soil moisture indicates how much higher the bushfire risk was leading into Black Saturday than that prior to the Ash Wednesday bushfires.

[7] Although the risk of summer bushfires exists in any given year, their severity is influenced by climate drivers. Using a bushfire definition from *Ellis et al.* [2004] (Text S1 of the auxiliary material), there have been 21 significant bushfires across Victoria since 1950, as summarised in Figure 2, which illustrates their relationship with ENSO and the IOD.[1] To compare the impact from pIODs and El Niños the 21 bushfire-years are subdivided into four groups as to those preceded (in SON) and/or concurrent with a pIOD-El Niño, pIOD alone without an El Niño, El Niño alone without a pIOD, and those not associated with a pIOD or El Niño (e.g., neutral, La Niña or negative IOD (nIOD) conditions).

[8] In total, eight major bushfires occurred in an El Niño summer (an El Niño commences in the winter-spring of the previous calendar year). Out of the eight events, six occurred in conjunction with a pIOD in the preceding winter and spring, leaving only two bushfires in an El Niño-only summer. Five bushfires occurred in La Niña summer including the Black Saturday fires, all after 1980 suggesting that the rain-inducing influence of La Niña has been diminishing. The statistics for the IOD are rather different: 11 out of 21 bushfire seasons were preceded by a pIOD event (out of a total of 16 pIODs since 1950), of which six occurred in conjunction with an El Niño, four were preceded by a pIOD alone, and one was associated with pIOD and La Niña. Only two major fires occurred in a summer following a nIOD event. This follows the notion that the lack of nIODs provides a favourable condition for historical droughts in southeast Australia [*Ummenhofer et al.*, 2009], but the increase in pIOD occurrences makes it far worse [*Cai et al.*, 2009b].

[9] Overall, the above result suggests an effective preconditioning impact from pIODs, more so than that from El Niños. We have tested the sensitivity of the statistics to changes in the IOD and ENSO definition, for example, changing the IOD definition to use anomalies averaged over July, August, September, and October, or an ENSO index over SON. The result of a greater pIOD influence than El Niño is very robust. Below we show the greater pIOD impact in terms of the associated anomalies in soil moisture and temperature (compared with those associated with El Niño), which lead to the dry conditions that increase bushfire risk.

4. Impact of ENSO and the IOD on Interannual Time Scales

[10] An important factor that determines the significant impact of pIODs compared to El Niño is that its maximum influence is in spring, coinciding with a major rainfall season for Victoria. During summer Victoria records very low rainfall totals, and as such, a dry spring usually indicates a dry summer with a high bushfire risk.

[11] Anomalous soil moisture provides a description of the impacts from the combined effects of temperature and rainfall anomalies. Lagged-correlations between the DMI/NINO3.4 with hydrometeorological fields (all linearly detrended) reveal that although there is little delayed impact on temperature, a significant "memory" exists in soil moisture, as a result of the lags induced by the soil water

[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL039902.

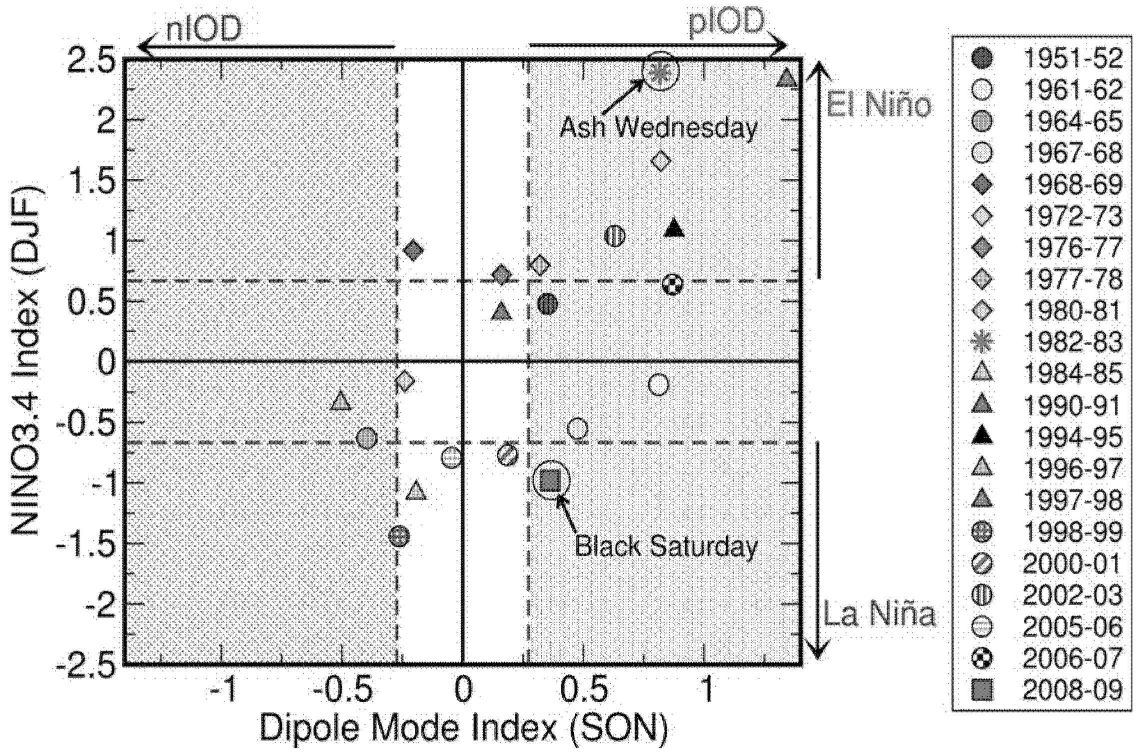

Figure 2. Scatterplot of historically significant Victorian summer bushfire seasons [*Ellis et al.*, 2004] from 1950–2009 in terms of the preceding IOD and concurrent ENSO conditions. The IOD is shown by a DMI (°C) in spring (SON), and ENSO by a NINO3.4 index (°C) in summer (DJF). An El Niño or pIOD is defined when their indices exceed 0.75 of their long-term standard deviation [*Cai et al.*, 2009b], indicated by areas outside the blue dashed lines.

capacitance. In the upper layer, significant correlations extend only into the next season, but in the lower layer, this memory can last up to three seasons. Over Victoria, both the simultaneous and lagged correlations associated with the DMI are larger than those associated with ENSO (figure not shown) despite the amplitude of the IOD being far smaller than that of ENSO. To reflect the actual difference in the impacts between the IOD and ENSO we calculate the one-standard deviation anomaly pattern of soil moisture (both upper and lower) associated with the IOD and ENSO.

[12] Because we are interested in the fire season, we focus on soil moisture anomalies over SON and DJF. An IOD event dies out by December, and as such, the associated anomalies in DJF arise from the delayed impact discussed above. In effect, this means using the SON DMI to calculate the IOD-congruent anomalies in DJF. For ENSO the delayed impact in DJF from SON is accounted for by the DJF NINO3.4 index, which shares variations of the SON index (correlation of 0.92). The congruent anomalies accumulated over the two seasons may be calculated as the sum over SON and DJF using their respective seasonal anomalies and indices, or by using anomalies accumulated over the two seasons and an index averaged over the two seasons. The two approaches produce almost identical results, and we display the results from the latter approach (Figure 3), as is the case for the long-term trends (section 5).

[13] Several features emerge. Firstly, the IOD-congruent upper and lower layer soil moisture anomaly patterns are largest and with the highest negative correlations (indicated by white contours) over Victoria (Figures 3a and 3b). Secondly, the ENSO-congruent anomalies are broader in scale and largest over the eastern and northeastern Australia, with correspondingly significant negative correlations over these regions (Figures 3d and 3e). However, over Victoria, the ENSO-congruent anomalies (and correlations) are far smaller than for the IOD case. This is one of the factors why pIODs are more effective in preconditioning Victoria bushfires.

[14] Another contributing factor is the IOD-congruent maximum temperature anomalies. Because there is no delayed impact on temperature, the associated anomalies are calculated using synchronised seasonal anomalies with the indices. In SON, the IOD-congruent anomalies (Figure 3c) are far greater than those congruent with ENSO (Figure 3f) across Victoria. Indeed, although large over northeastern Australia, the ENSO-congruent temperature anomalies are only statistically significant (95% confidence level) across northern Victoria, in the fire season itself the correlations drop below significant values (DJF, Figure 3g). Thus, in spring, pIODs contribute more strongly to higher spring maximum temperatures than El Niños which exacerbate the associated dry conditions, increasing the summer fuel load.

5. Impact of ENSO and the IOD on Long-Term Changes

[15] Since 1950, maximum temperature in SON and DJF over Victoria has increased by 1.23 and 0.80°C, respectively, with SON values statistically significant at the 99% confidence level (DJF is significant at the 90% confidence level). Rainfall reductions since 1950 for the two seasons are 40.5 mm (SON, mean = 185 mm) and 5.7 mm (DJF, mean = 122 mm), although neither is statistically signifi-

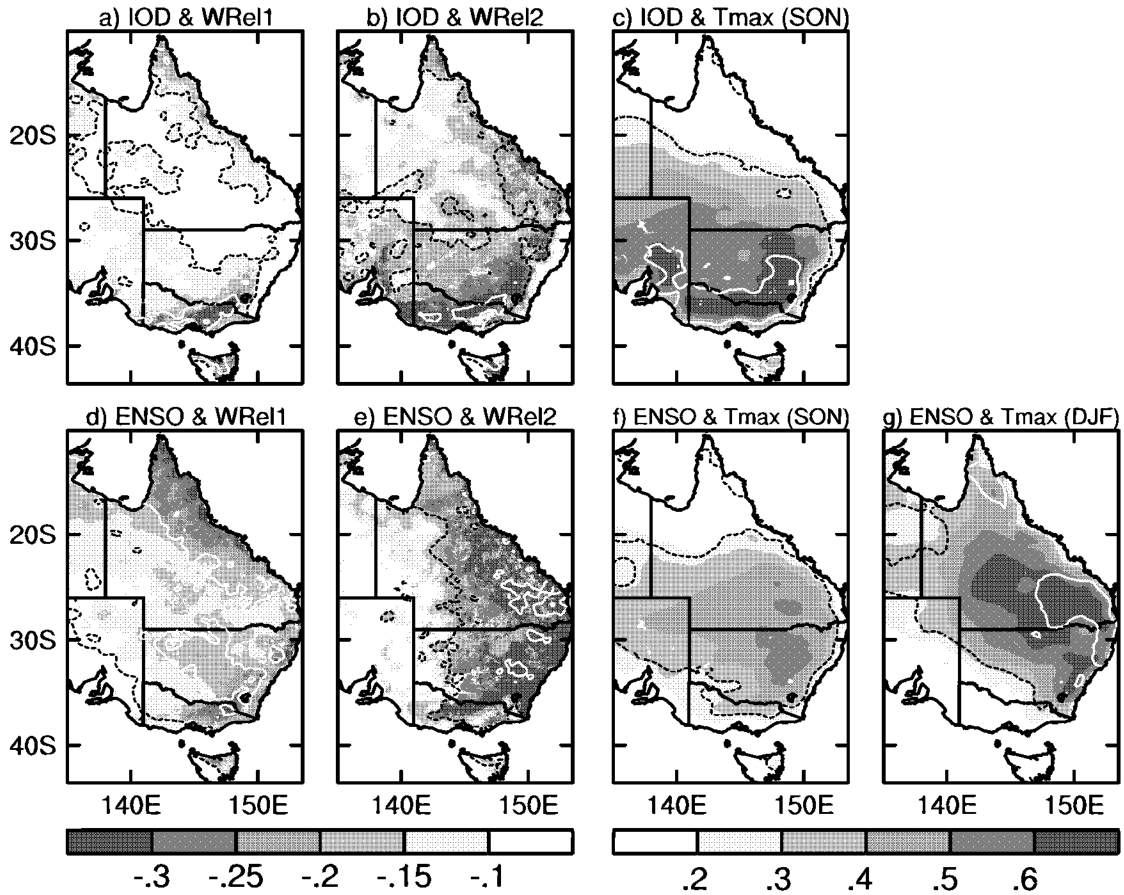

Figure 3. One standard deviation anomaly pattern of (a) upper and (b) lower soil moisture (fraction, 0–1) accumulated over the SON and DJF seasons, and (c) SON maximum temperature (Tmax) associated with IOD (°C). (d–f) Same as Figures 3a–3c, but associated with ENSO, (g) with an additional Tmax for DJF plotted. These patterns are calculated by regressing detrended soil moisture onto the respective detrended index and multiplying by the index standard deviation (see text for further details). The contours are the associated correlations with the dotted line corresponding to a coefficient of −0.26 (95% confidence level) and the white line to a coefficient of −0.50 (above the 99.99% confidence level).

cant. Because upper and lower soil moisture are sensitive to changes in hydroclimatic fields particularly rainfall, the reductions over Victoria are also not statistically significant. However, the multi-decadal changes are quite substantial, up to 30% over much of Victoria (based on the 1950–2008 average). These patterns (Figures 4a and 4b) measure changes in the background soil moisture condition for the 59 years prior, upon which recent interannual variability superimposes.

[16] Over Victoria, the ENSO-congruent change is small, reflecting the small trend in the NINO3.4 index and the weak ENSO influence over Victoria (Figures 4e and 4f). By contrast, the IOD-congruent change over Victoria is large (Figures 4c and 4d), accounting for more than half of the observed change (Figures 4a and 4b). This is due to the strong IOD influence discussed above, and the strong trend in the IOD index. We have tested the sensitivity of the IOD trend to the choice of the commencement decade for the IOD trend calculation (e.g., 1960, 1970 and moving forward). This always produces an upward trend in the index (Figure 1b), and hence IOD-congruent trends. Further, over any of these periods, the IOD-congruent trend is always greater than that congruent with ENSO.

[17] In a warming climate, higher risks of bushfires may arise from several factors. These include a global-scale rise in temperatures that project onto extreme hot weather, an increased frequency of dry conditions exacerbated by low rainfall totals occurring in the months prior to a significant bushfire, and local-scale anomalously high temperatures. Climate models project a warming pattern in the tropical IO that features a slower warming rate in the eastern IO than in the western IO [*Shi et al.*, 2008]. Over the past decades, consistent mean circulation changes in the IOD prevalent season (SON) have emerged featuring an SST trend pattern reminiscent of a pIOD state, increasing easterly winds and a shoaling thermocline in the eastern IO [*Cai et al.*, 2009b]. These changes have manifested as a steadily increased frequency of pIOD events [*Cai et al.*, 2009b], and a reduction in the number of nIOD events [*Ummenhofer et al.*, 2009]. Over the past decade, these features have contributed to the dry conditions in spring over Victoria; in six out of the past seven years (2002–2008) SON rainfall has been anomalously low. Given the effectiveness of pIOD's in preconditioning Victoria bushfires, if the projected IO warming pattern continues to manifest as an increased frequency in pIOD occurrences, it will lead to higher bushfire

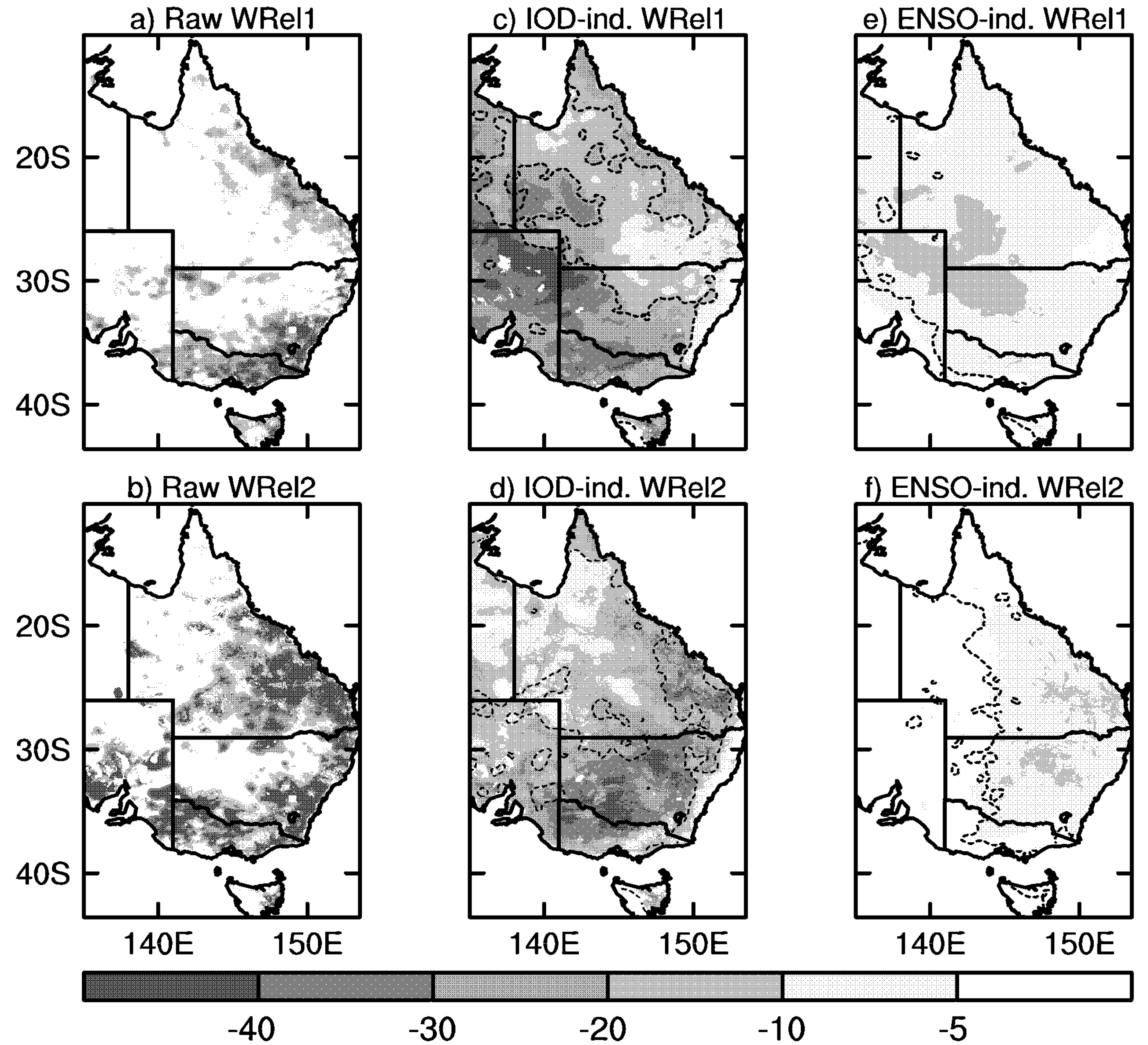

Figure 4. Multi-decadal trends of (a) upper and (b) lower layer total soil moisture for SON and DJF, and the corresponding (c and d) IOD-congruent and (e and f) ENSO-congruent trends over the 1950–2008 period (% of climatology per 59 years). The IOD and ENSO congruent trends are calculated by regressing grid-point soil moisture anomalies onto the respective index, and multiplying by the trend in each index. Correlation coefficients of −0.26 (95% confidence level) between detrended soil moisture anomalies and the detrended index are shown as dotted lines in (c–f).

risks across Victoria, assuming that the IOD-rainfall teleconnection for Victoria persists into the future.

6. Conclusions

[18] Bushfires that occurred on "Black Saturday" (7th February 2009) and "Ash Wednesday" (16th February 1983) across the southeastern Australian state of Victoria were preceded by a pIOD event. By contrast, these devastating bushfires occurred during a La Niña and El Niño summer, respectively. The present study shows that there is a systematic linkage between pIOD events and Victorian bushfires. Of the 21 significant bushfires since 1950, 11 were preceded by a pIOD. This is from a total of 16 pIOD events. In spring, one of Victoria's main rainfall seasons, a pIOD contributes to lower rainfall and higher temperatures exacerbating the dry conditions and increasing the available summer fuel load. As such, it is pIODs, more so than El Niño events, that are effective in preconditioning Victoria bushfires, as seen in the impact on soil moisture on interannual and longer-term time scales. Given that the recent systematic increase in pIOD occurrences is consistent with what is expected from global warming, a possible scenario is that climate change will lead to a higher bushfire risk across Victoria, as a consequence of the IO's response to global warming, in addition to any impact from rising temperatures.

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