6.3 HiGEM EOTs without SILO counterparts

6.3.1 ENSO-driven patterns

While HiGEM MAM EOT 3 is significantly correlated with Niño 4 SSTs, SST regressions onto the EOT time series show no substantial SST anomalies in the equatorial Pacific (Fig. 20a). This is due to weak inter-annual MAM SST variability in HiGEM in this region (not shown); even though the correlation coefficient exceeds the significance threshold (Table 1), there is very limited SST variability and hence negligible regression coefficients compared to HadISST for SILO MAM EOT 3 (Fig. 20c). The anomalous low-level circulation pattern in HiGEM (Fig. 20b) is also much weaker than observed (Fig. 20d), with no additional convergence near the Maritime Continent, as occurs in SILO MAM EOT 3. Further, the EOTs affect different regions of Queensland, with SILO EOT 3 describing coherent rainfall variability in northern Queensland, while HiGEM EOT 3 describes coherent variations in the southwest and west.

This spatial shift is consistent with the weak instantaneous correlation in HiGEM between Niño 4 and northern Queensland rainfall in MAM (Fig. 5f); HiGEM produces a stronger ENSO teleconnection with southwestern Queensland MAM rainfall, so it is not surprising that the ENSO-linked EOT would be centred there. The low MAM SST variability may be due to the overly bi-annual ENSO in HiGEM, which would lead to weak SST anomalies during the MAM transition season. In reality, some ENSO events persist through the MAM barrier; these are likely responsible for the substantial SST anomalies associated with SILO EOT 3.

Spring is the only season in SILO or HiGEM with two EOTs correlated with Niño 4 SSTs: SON EOTs 1 and 3 in HiGEM and SON EOTs 1 and 2 in SILO. HiGEM SON EOT 1 agreed well with its SILO counterpart and so was discussed in Sections 5.2.1 (for its ENSO connection) and 6.2.5 (for its SAM connection). HiGEM SON EOT 3 and SILO SON EOT 2 are associated with stagnant or decaying ENSO events (Figs. 15e and 15f), as opposed to the SON EOT 1 patterns, which are associated with growing ENSO events that peak in the following DJF. The central Pacific cooling and the anomalously warm SSTs near Australia in HiGEM (Fig. 20e) are similar to the HadISST SST anomalies for SILO SON EOT 2 (Fig. 20g).

The spatial pattern of HiGEM SON EOT 3 (Fig. 11l), however, is displaced far south and west of SILO SON EOT 2 (Fig. 24h). This south-westward displacement also occurred in HiGEM MAM EOT 3, which was also associated with weak and decaying ENSO events. Taken together, these patterns indicate that the ENSO–rainfall teleconnection during weak ENSO events is not represented properly in HiGEM: HiGEM varies the rainfall over the relatively dry interior of southwestern Queensland, rather than the wetter northern tropics. The tropical 850 hPa circulation and MSLP anomalies in HiGEM (Fig. 20f) are also much weaker than in 20CR (Fig. 20h) for this decaying ENSO EOT. HiGEM lacks the anomalous northerlies, and hence the anomalous southward moisture transport, over the Cape York peninsula, consistent with the lack of rainfall anomalies there. HiGEM SON EOT 3 is also associated with Tasman Sea blocking (Table 1), a signal which does not appear in SILO SON EOT 2.

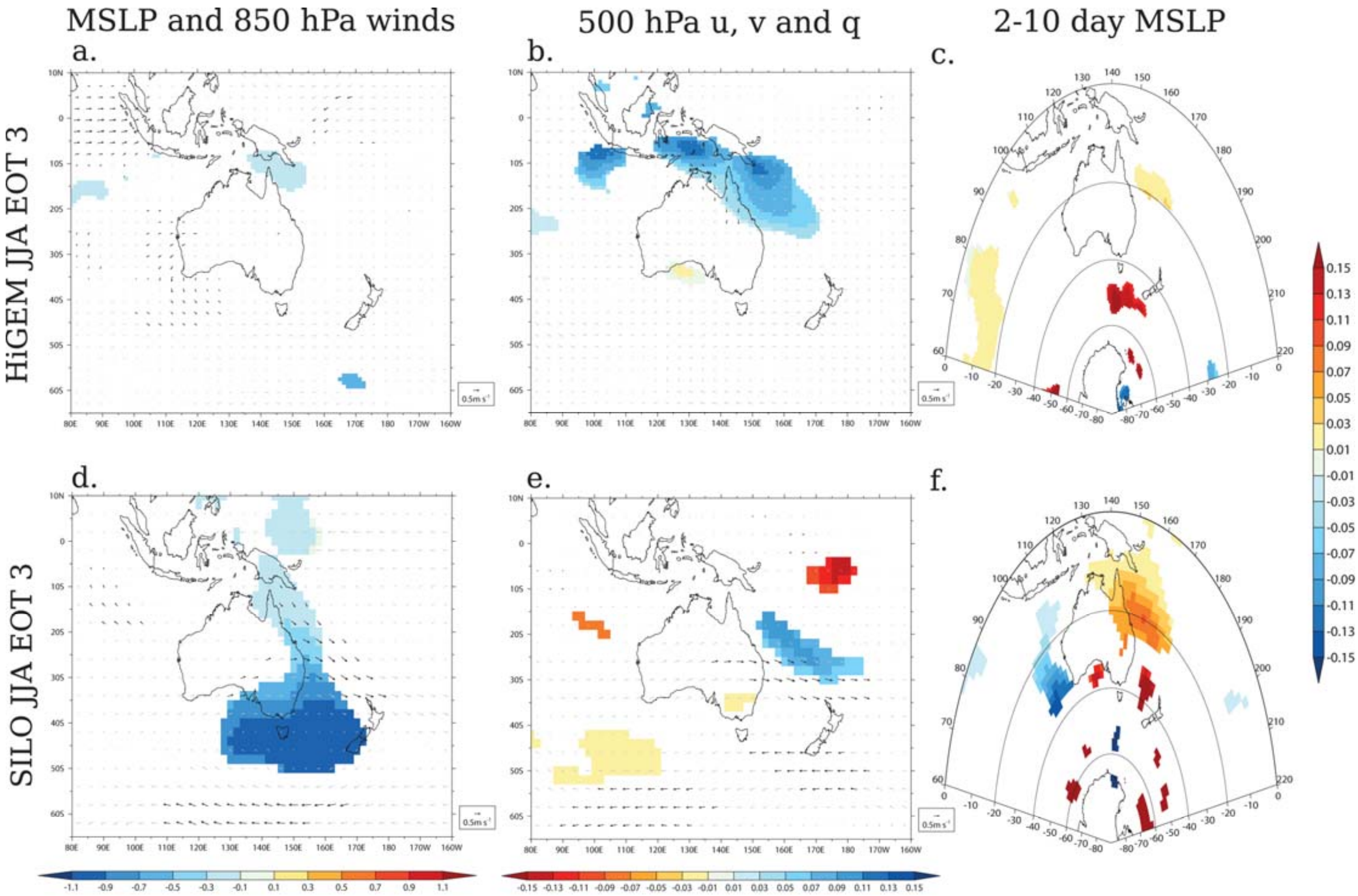

Figure 21: For (a–c) HiGEM JJA EOT 3 and (d–f) SILO JJA EOT 3, the coefficients of linear regression of (a, d) MSLP (contours) and 850 hPa winds (vectors), (b, e) 500 hPa specific humidity (contours) and 500 hPa winds (vectors) and (c, f) the standard deviation in MSLP2–10d. SILO EOTs use 20CR fields for the regressions. MSLP and 500 hPa specific humidity are shown only where the regressions are statistically significant at the 5 per cent level; 850 hPa and 500 hPa wind vectors are drawn in black (grey) where significant (not significant) at 5 per cent.

6.3.2 Patterns driven by local synoptic circulations

While the HiGEM and SILO JJA EOT 3 patterns describe rainfall variability in nearly identical geographical regions (northern and coastal Queensland; compare Figs. 11l and 24l), the local circulation patterns that drive this rainfall variability differ considerably. HiGEM displays few significant low-level circulation anomalies associated with this EOT (Fig. 21a), but has considerable anomalous 500 hPa northerlies across northern Queensland and high positive specific humidity anomalies in wet years (Fig. 21b). This indicates that variations in winter rainfall in northern and coastal Queensland are controlled by the anomalous moisture advection from the tropics. By contrast, Klingaman (2012b) found that SILO JJA EOT 3 was linked to low-level cyclonic anomalies in the Tasman Sea, with anomalous along shore low-level winds (Fig. 21d); there are no significant anomalies in mid-tropospheric tropical moisture or enhanced northerlies in 20CR (Fig. 21e). Further, the SILO EOT was correlated with synoptic activity over much of Queensland and just off the east coast (Fig. 21f), leading Klingaman (2012b) to hypothesise that JJA EOT 3 was driven by coastal cyclones.

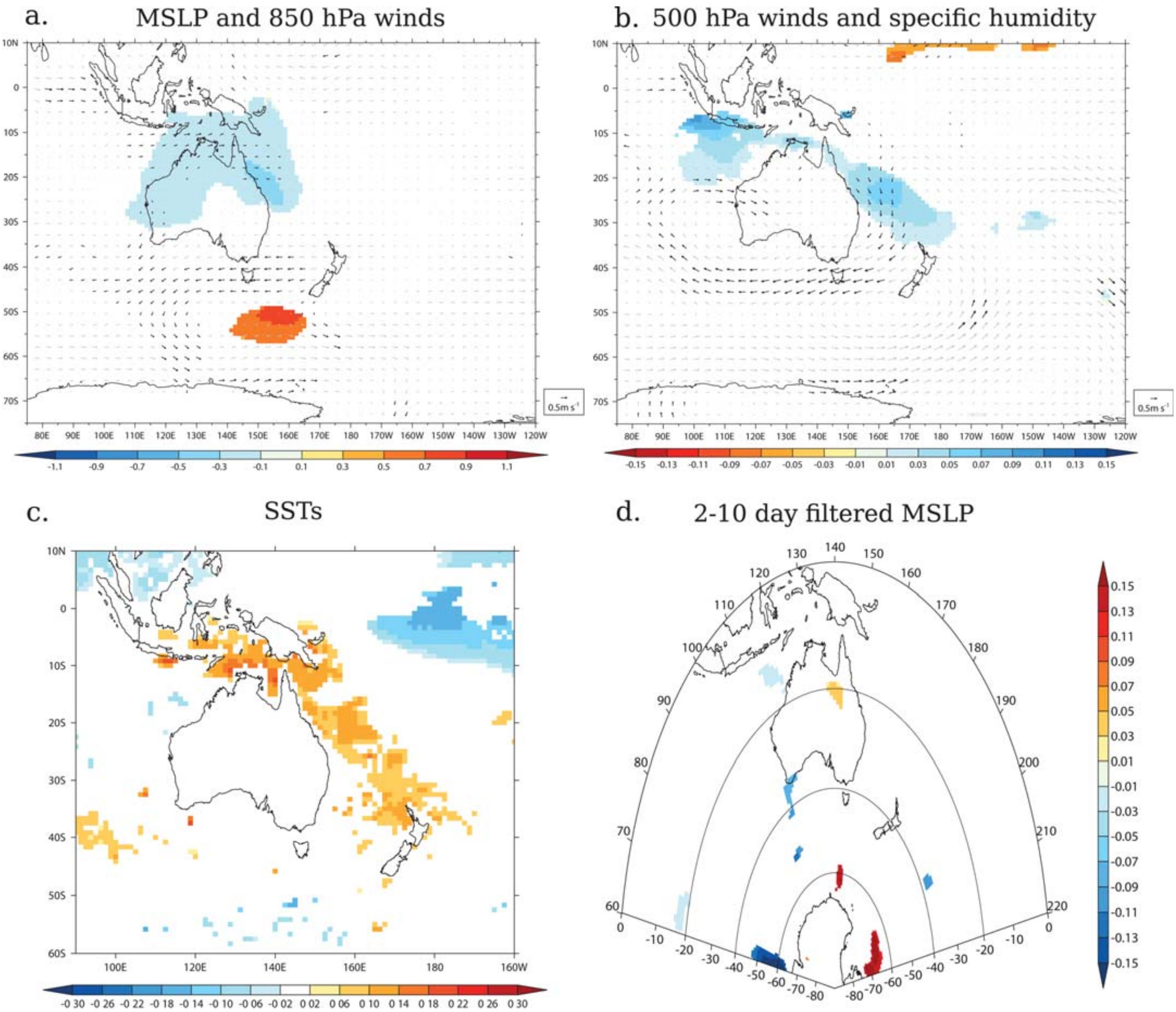

Figure 22: (a–c) As in Fig. 21a–c, but for HiGEM SON EOT 2; (d) coefficients of linear regression of seasonal mean HiGEM SSTs on HiGEM SON EOT 2, with values shown only where significant at the 5 per cent level.

HiGEM JJA EOT 3 is clearly not driven by the same mechanism, as Fig. 21c displays few significant regressions of coastal synoptic activity. Thus, JJA EOT 3 demonstrates the need to carefully examine the physical mechanisms underlying these patterns of rainfall variability in SILO and HiGEM, as similarities in the geographical regions affected alone are insufficient to determine the model's fidelity in simulating the drivers of rainfall.

The spatial pattern of HiGEM SON EOT 2 (Fig. 11h), centred along the eastern coast, does not match any of the leading three SILO EOTs for SON. The HiGEM EOT is correlated with blocking activity in the 150–180° E band with a coefficient barely above the significance threshold (Table 1), but is otherwise unrelated to any other potential driver. The relationship with blocking presents itself as a small area of significant MSLP anomalies and anticyclonic 850 hPa circulation in Figure 22a, but this anomalous circulation does not directly affect Queensland. Instead, coastal Queensland is affected by anomalous 850 hPa westerlies and reduced MSLP, particularly immediately along the coast and the central point of the EOT pattern. Coastal rainfall is also influenced by anomalously moist mid-tropospheric air to the north and east of Australia (Fig. 22b). There are no appreciable changes in synoptic activity over Queensland (Fig. 22c), but the local SSTs are warmer in wet springs along the northern and eastern coasts (Fig. 22d). The similarity in spatial pattern between the MSLP, 500 hPa specific humidity and SST anomalies suggest a role of local air-sea interactions, in which warm SSTs lead to lower pressures and increased moisture in the atmosphere. As none of the SILO SON EOTs were driven by local air-sea interactions, this HiGEM EOT has no match in observations.

6.3.3 Patterns driven by the SAM

While SILO JJA EOT 1 was correlated with Niño 4 SSTs and the SAM (Table 3), HiGEM JJA EOT 1 is linked with only Niño 4 (Fig. 1). There are few significant extra-tropical MSLP anomalies associated with the HiGEM EOT (Fig. 23a), while the 20CR MSLP anomalies corresponding to the SILO EOT show, for high JJA EOT 1 years, positive anomalies near 40°S and negative anomalies near 65°S, consistent with the positive SAM phase (Fig. 23b). It is important to note that the SAM signal in observations is not purely an extra-tropical ENSO teleconnections, as the partial correlation between rainfall and the SAM, removing the impact of Niño 4 SSTs, is also statistically significant. State-wide rainfall anomalies in winter are controlled by tropical and extra-tropical circulation anomalies in observations, but only the tropical response to ENSO in HiGEM.

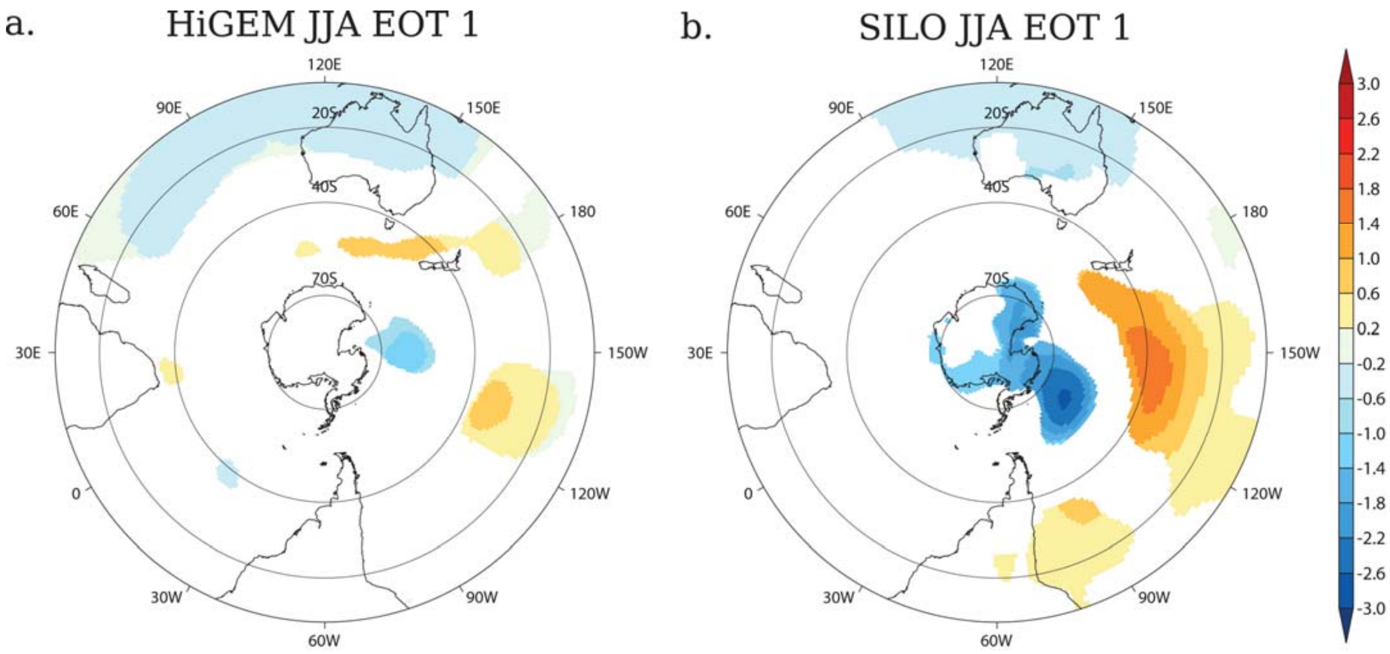

Figure 23: Coefficients of linear regression of (a) HiGEM MSLP on HiGEM JJA EOT 1 and (b) 20CR MSLP on SILO JJA EOT 1. Regression coefficients are shown only where they are statistically significant at the 5 per cent level.

6.4 Additional HiGEM EOTs

This section contains a brief analysis of the "additional" HiGEM EOTs: the HiGEM EOT for each season that does not match one of the three leading SILO EOTs and explains the least variance in the area-averaged Queensland rainfall. These patterns remain because the first four HiGEM EOTs were analysed for each season, but compared to only the first three SILO EOTs.

6.4.1 Patterns driven by tropical cyclones

HiGEM MAM EOT 4 describes coherent rainfall variability in coastal northeastern Queensland (Fig. 11n). It has no significant correlations with any of the potential drivers considered (Table 1), but as for DJF EOT 4, it is associated with substantial variations in tropical-cyclone activity near the Queensland coast. Regressions of track density on MAM EOT 4 show increases in the number of cyclones tracking across northern Queensland in high MAM EOT 4 years (Fig. 24a), with genesis-density regressions indicating more cyclones forming east of Queensland in the Coral Sea and west of Queensland in the Gulf of Carpentaria (Fig. 24b). More cyclone tracks end across northern Queensland in wet autumns along the coast(Fig. 24c), with lower lysis densities just to the south of the region encompassed by this EOT. Vertical windshear is reduced throughout northern Australia in high MAM EOT 4 years (Fig. 24d), which would promote tropical-cyclone development and maintenance. Finally, composites of cyclone tracks in seasons in which MAM EOT 4 is above (Fig. 24e) and below (Fig. 24f) one standard deviation of its mean emphasise the substantial increase in the number of tropical cyclones near or crossing the Queensland coast in high MAM EOT 4 seasons.

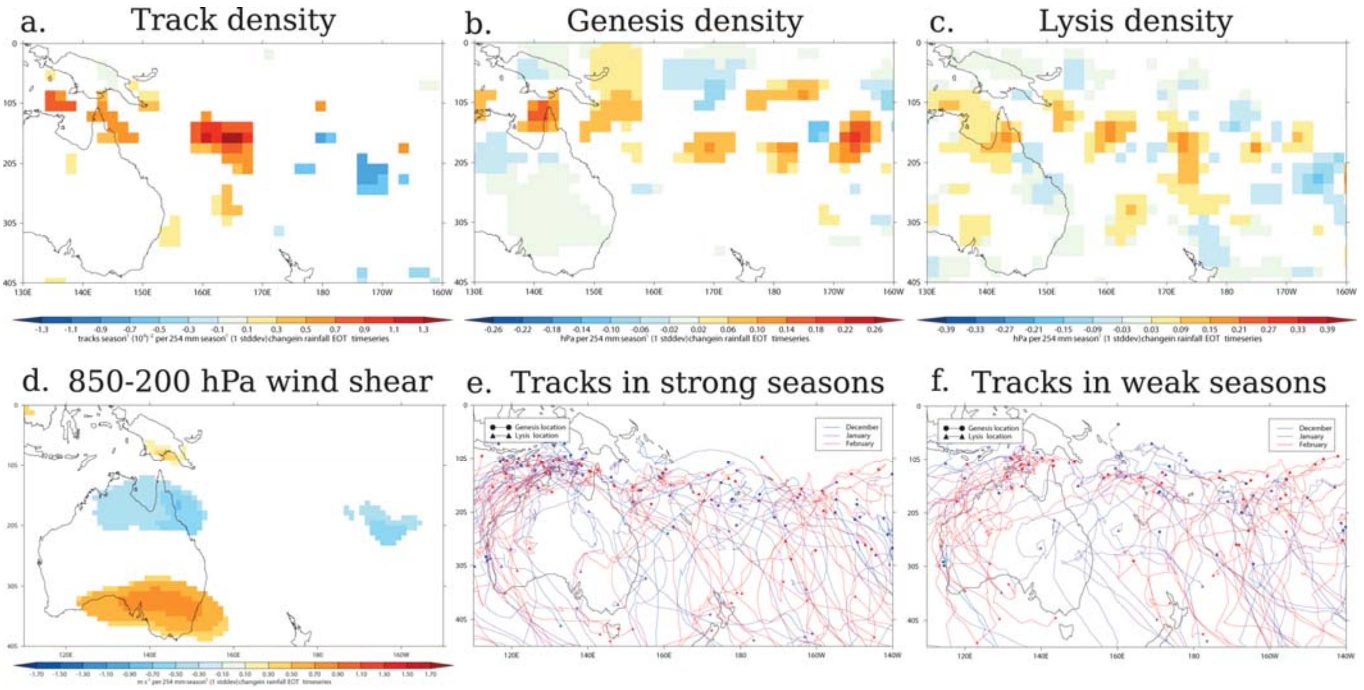

Figure 24: (a–c) As in Figs. 16a–c, but for HiGEM MAM EOT 4; (d–f) as in Figs. 16g–i, but for HiGEM MAM EOT 4.

6.4.2 Patterns driven by local synoptic circulations

Centred in northwestern Queensland, HiGEM DJF EOT 3 (Fig. 11i) also shows no correlation with the potential drivers considered in Table 1. There are no significant anomalies in MSLP or 850 hPa winds associated with this EOT (Fig. 25a), but the 500 hPa and humidity fields (Fig. 25b) reveal a strong tropospheric anomalous cyclone over continental Australia that draws anomalously moist air south from the tropics across western Queensland. There are no substantial changes in synoptic activity near Queensland (Fig. 25c). Thus, it appears that coherent summer rainfall variations in western Queensland in HiGEM are driven by local variations in the strength of the monsoon cyclone that control the advection of tropical moisture across the region at mid-tropospheric levels.

6.4.3 Patterns with no clear driving mechanism

The remaining two HiGEM EOTs - JJA EOT 4 (Fig. 11o) and SON EOT 4 (Fig. 11p), both focused in south-eastern Queensland - have limited significant regression coefficients with all variables considered in this study; these EOTs do not have clear driving mechanisms. Regressions of each against MSLP and 850 hPa winds (Fig. 26a, d), 500 hPa winds and specific humidity (Fig. 26b, e) and the standard deviation in $MSLP_{2\text{-}10d}$ (Fig. 26c, f) are shown for completeness, but the results are inconclusive. It is worth noting that Klingaman (2012) failed to find a driving mechanism for similar south-eastern Queensland EOT in SON-SILO SON EOT 3 - which suggests that coherent south-eastern Queensland rainfall variability in spring, cannot be explained using these analysis techniques. It is also possible that, as these EOTs are artificially constrained to be orthogonal in time, these EOT 4 patterns are unphysical and unrepresentative of rainfall variability in this region.

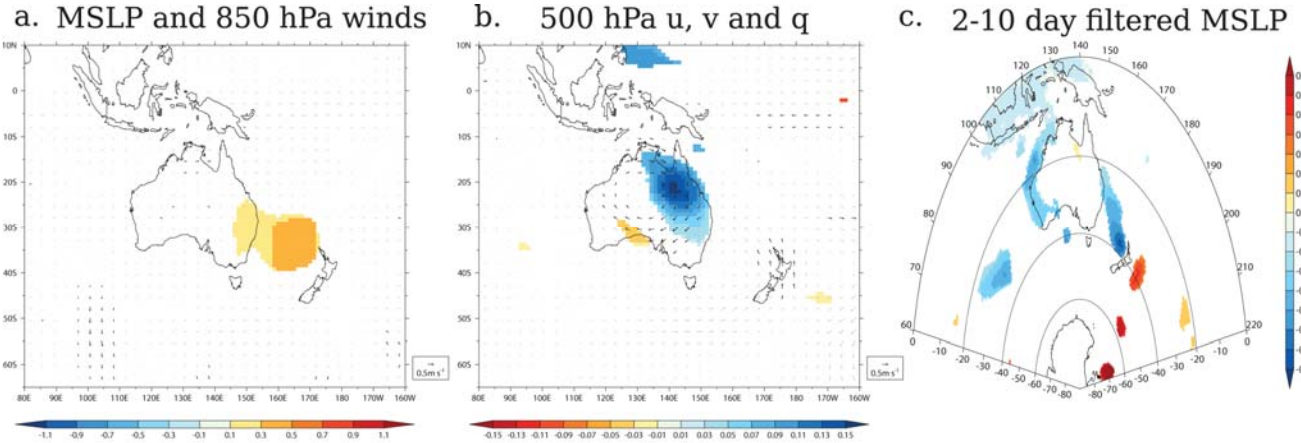

Figure 24: As in Fig. 18a–c, but for HiGEM DJF EOT 3

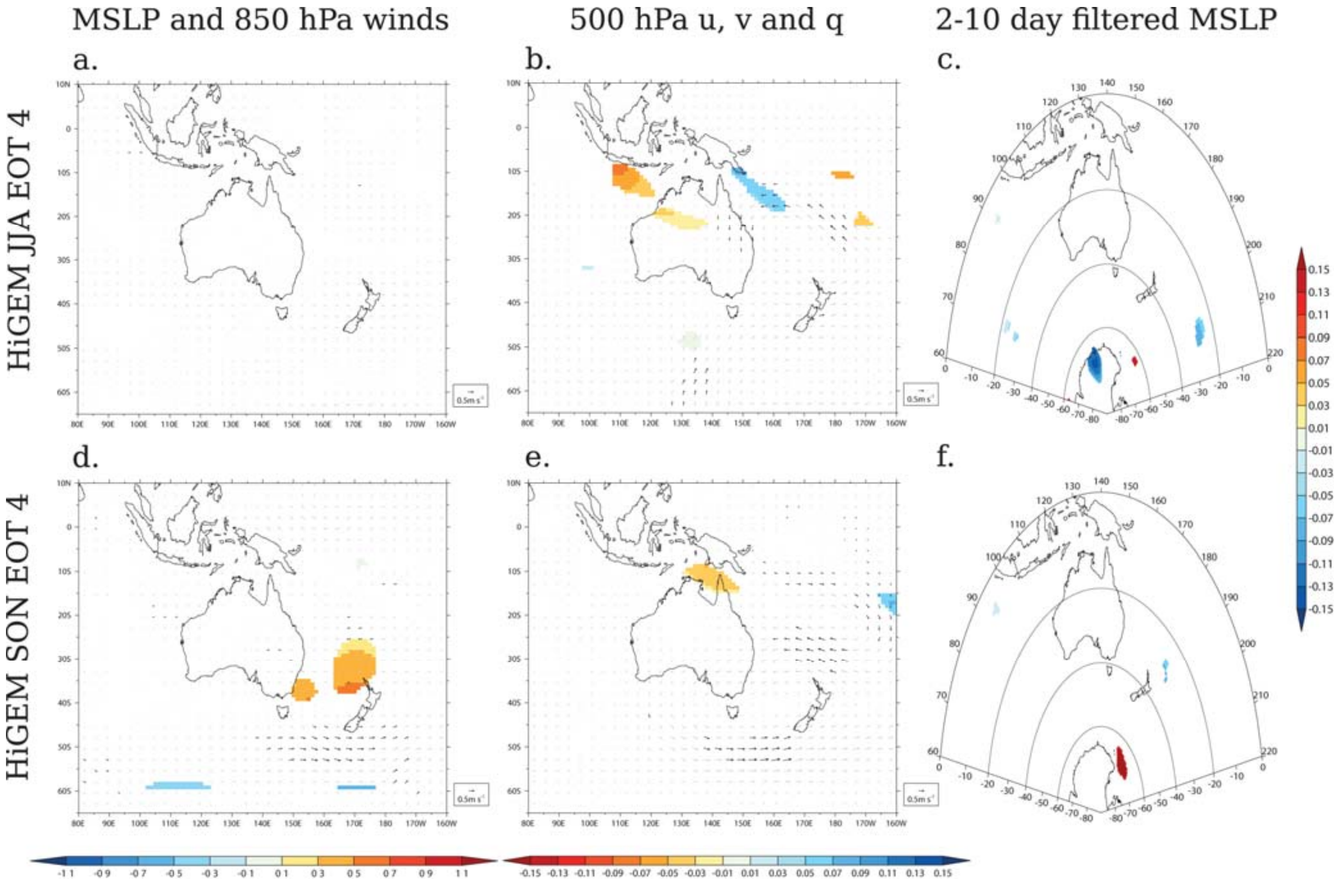

Figure 25: As in Fig. 18a–c, but for (a–c) HiGEM JJA EOT 4 and (d–f) HiGEM SON EOT 4.