

## Supplementary Material

### **Observing and forecasting the retreat of northern Australia's rainy season**

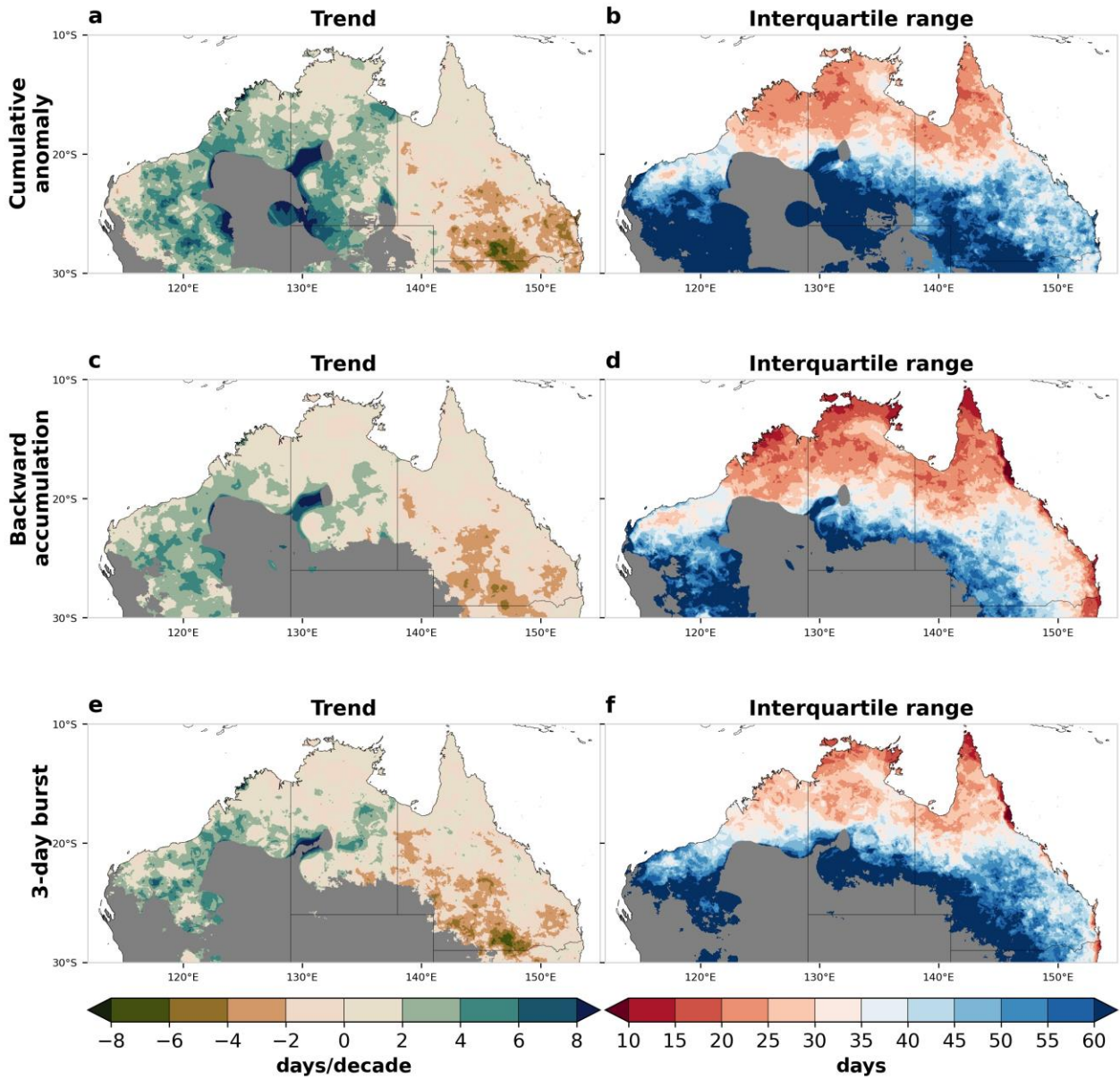
*Tim Cowan<sup>A,B,\*</sup>, Emily Hinds<sup>A</sup>, Andrew G. Marshall<sup>A,C</sup>, Matthew C. Wheeler<sup>B</sup> and Catherine de Burgh-Day<sup>B</sup>*

<sup>A</sup>Centre for Applied Climate Sciences, University of Southern Queensland, 487–535 West Street, Toowoomba, Qld 4350, Australia

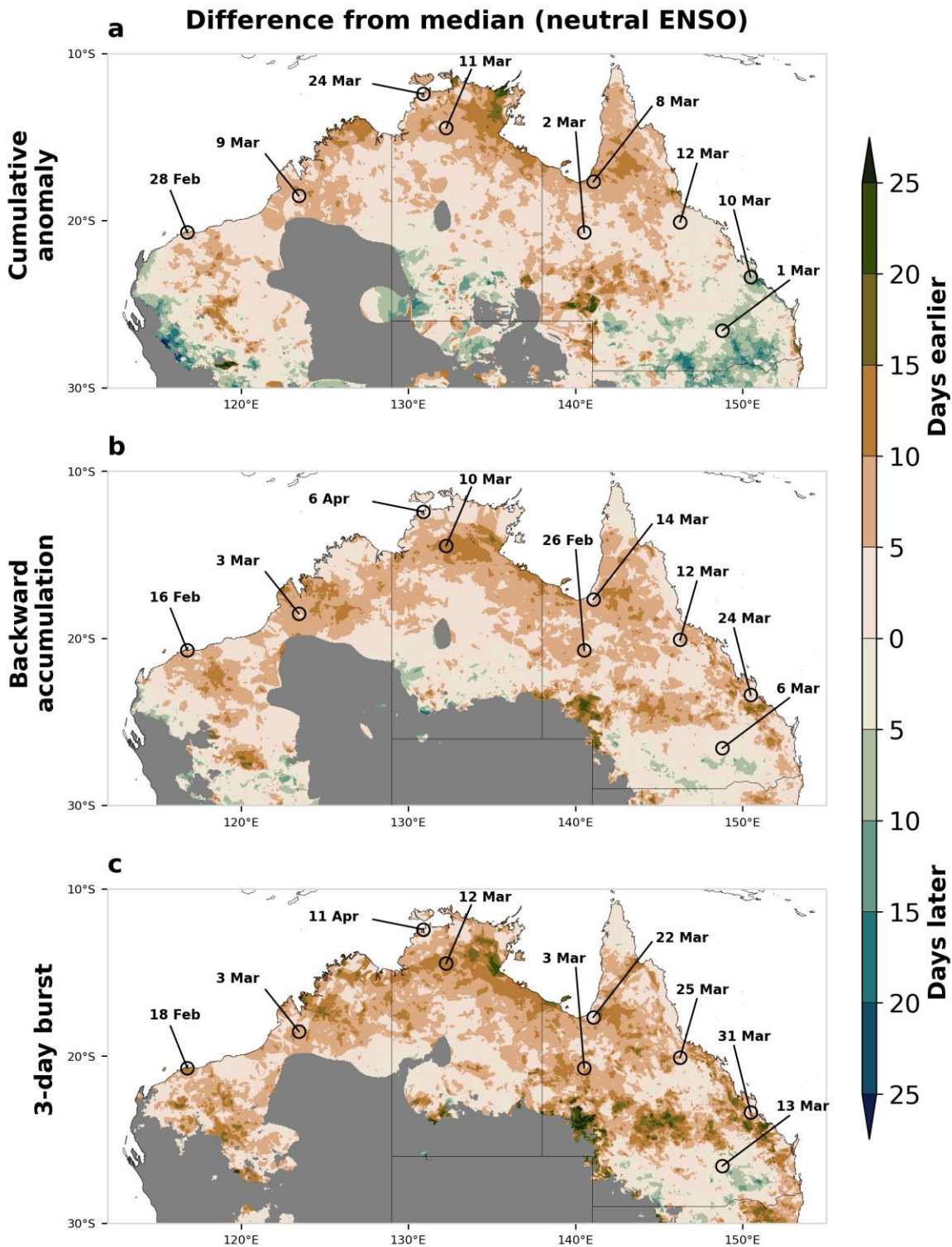
<sup>B</sup>Bureau of Meteorology, Docklands, Melbourne, Vic. 3008, Australia

<sup>C</sup>Bureau of Meteorology, Hobart, Tas. 7000, Australia

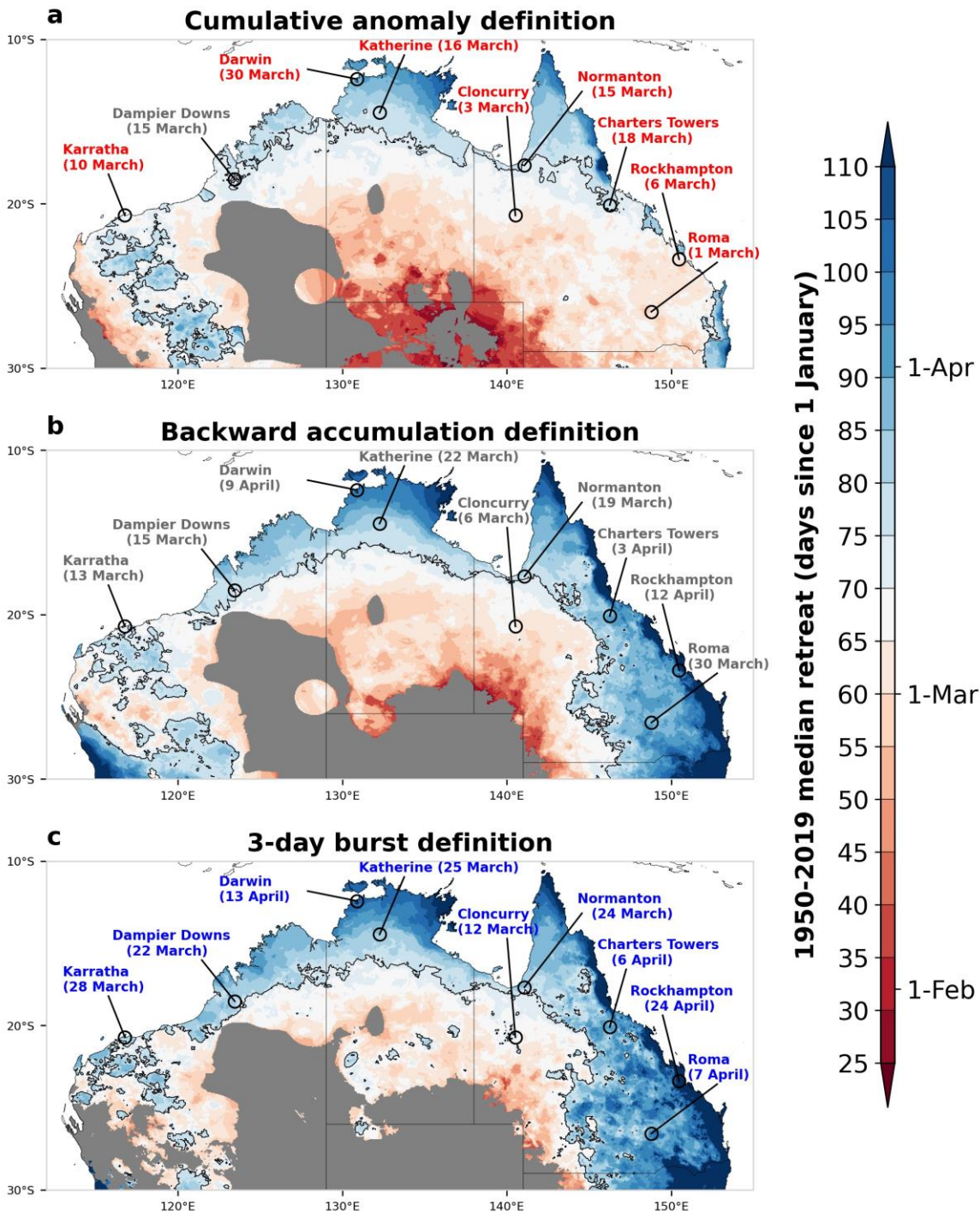
\*Correspondence to: Email: [tim.cowan@bom.gov.au](mailto:tim.cowan@bom.gov.au)



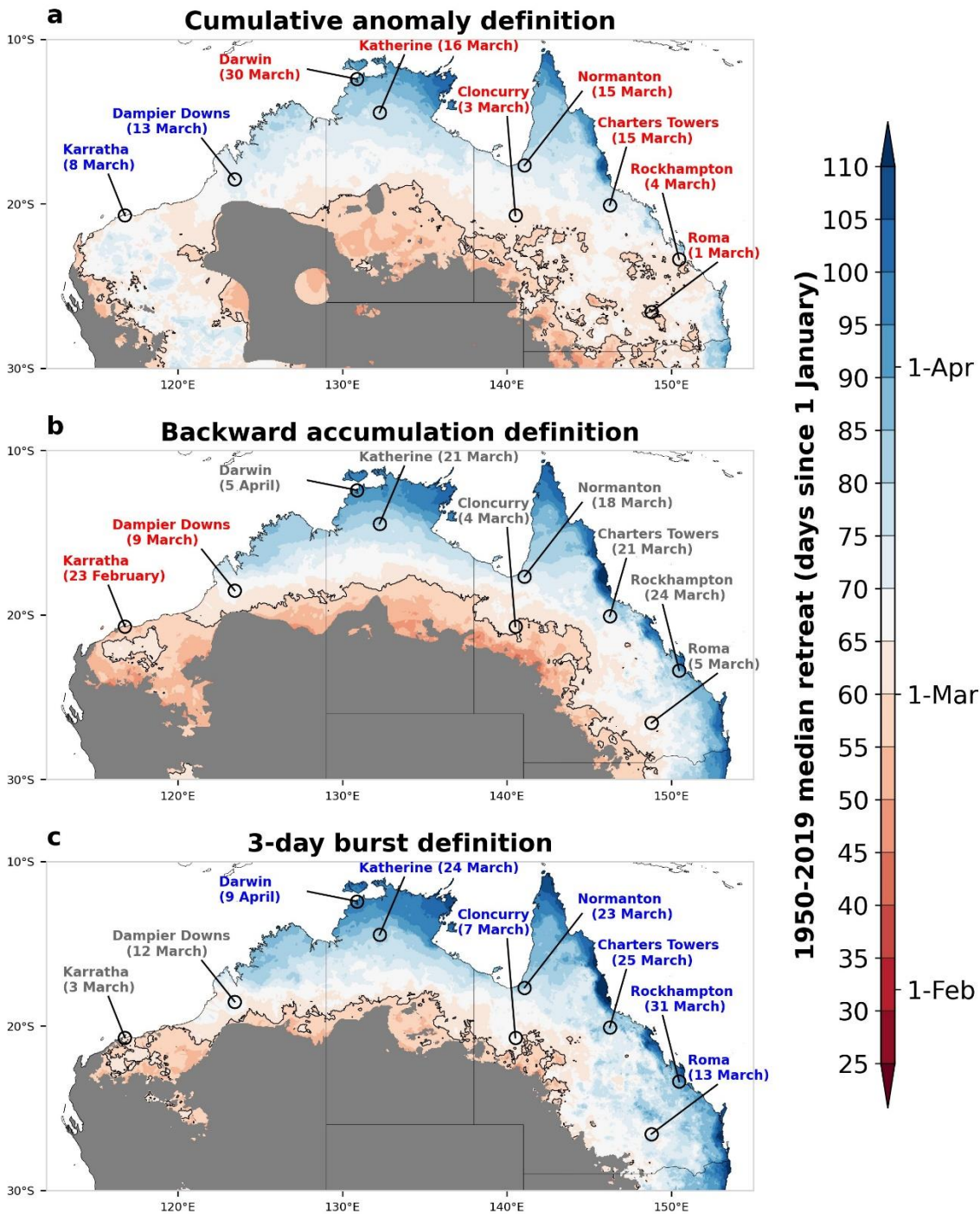
**Figure S1.** (left) Long-term trends and (right) interquartile range for the northern retreat day over 1950–2019 using the three definitions. Shown are (a,b) the peak daily cumulative anomaly, (c,d) the backward accumulation of daily rainfall from 30 April, and (e,f) the last day of the last burst event (25 mm in 3 days) before 30 April. Regions with sparse rainfall coverage or with 30% non-retreat years across the 70-year period are masked out in grey.



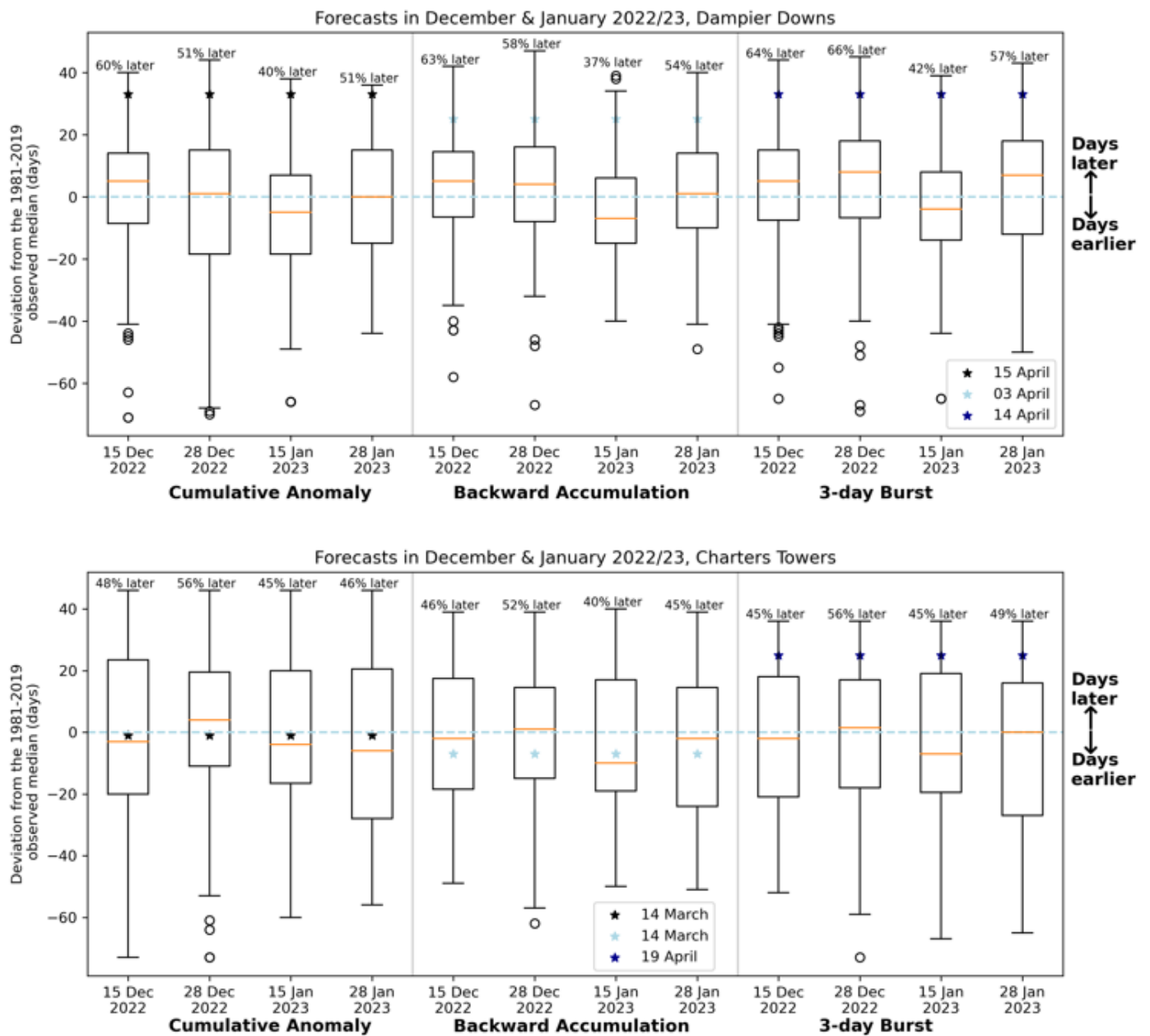
**Figure S2.** Observed difference between the 1950–2019 median retreat day and the median for neutral ENSO years for each northern rainfall retreat definition. The neutral years in this sample that cover the January to March period include 1951, 1953, 1957, 1960–63, 1967–68, 1979, 1981–82, 1986, 1990–91, 1993–94, 1997, 2002, 2004, 2013–14 and 2017. Regions with sparse rainfall coverage or with 30% non-retreat years across the 70-year period are masked out in grey.



**Figure S3.** Median retreat day over 1950–2019 using the three definitions, but with a 31 May wet season cut off. Shown are (a) the peak daily cumulative anomaly, (b) the backward accumulation of daily rainfall from 31 May, and (c) the last day of the last burst event (25 mm in 3 days) before 31 May. The black contour represents mid-March (day 74), and retreat dates for nine locations are shown across northern Australia (based on non-leap years). Blue, grey and red labels indicate the retreat definition that produces the earliest, middle and latest median retreats. Any years where the retreat day is undetermined is referred to as a non-retreat year. Regions with sparse rainfall coverage or with 30% non-retreat years across the 70-year period are masked out in grey. These mainly represent climatologically dry regions.



**Figure S4.** Median retreat day over 1950–2019 using the three definitions, but with a 1 February start date and 30 April wet season cut off. Shown are (a) the peak daily cumulative anomaly, (b) the backward accumulation of daily rainfall from 30 April, and (c) the last day of the last burst event (25 mm in 3 days) before 30 April. The black contour represents 1 March (day 60), and retreat dates for nine locations are shown across northern Australia (based on non-leap years). Blue, grey and red labels indicate the retreat definition that produces the earliest, middle and latest median retreats. Regions with sparse rainfall coverage or with 30% non-retreat years across the 70-year period are masked out in grey.



**Figure S5.** Forecasts of (top) Dampier Downs and (bottom) Charters Towers 2023 retreat date difference from the 1981–2019 observed median from 15, 28 December 2022 and 15, 28 January 2023 start dates. The stars indicate the observed date for each NRR definition. The numbers listed above the box and whisker plots indicate the percentage of 99 ACCESS-S2 forecasts (per start date) that predicted a later than observed median retreat. The January forecasts include observation from the 1 January through to the day before the start date. Long-term trends and (right) interquartile range for the northern retreat day over 1950–2019 using the three definitions. Shown are (left boxes) the peak daily cumulative anomaly, (middle boxes) the backward accumulation of daily rainfall from 30 April, and (right boxes) the last day of the last burst event (25 mm in 3 days) before 30 April.

**Table S1.** 70th percentile retreat dates for select locations across the Northern Territory that produce red meat, using observations from 1950 to 2019.

<b>Station</b>	<b>Latitude (°S)</b>	<b>Longitude (°E)</b>	<b>Cumulative definition</b>	<b>Backward definition</b>	<b>Burst definition</b>
Yambah	-23.13	133.84	8 Mar	4 Mar	5 Mar
Vaughan Springs	-22.30	130.85	13 Mar	6 Mar	16 Mar
Ammaroo	-21.75	135.24	5 Mar	3 Mar	4 Mar
Lake Nash	-20.96	137.92	18 Mar	5 Mar	7 Mar
The Granites	-20.55	130.35	9 Mar	4 Mar	-
Epenarra	-20.44	135.26	7 Mar	4 Mar	5 Mar
Avon Downs	-20.03	137.49	19 Mar	8 Mar	15 Mar
Tennant Creek Airport	-19.64	134.18	10 Mar	7 Mar	16 Mar
Gallipoli	-19.14	137.87	19 Mar	11 Mar	19 Mar
Alexandria	-19.06	136.71	19 Mar	10 Mar	13 Mar
Brunchilly	-18.87	134.50	11 Mar	9 Mar	10 Mar
Brunette Downs	-18.64	135.95	19 Mar	9 Mar	15 Mar
Helen Springs	-18.43	133.88	18 Mar	8 Mar	15 Mar
Riveren	-17.90	130.23	21 Mar	15 Mar	21 Mar
Victoria River Downs	-16.40	131.01	23 Mar	19 Mar	22 Mar
Bing Bong Port	-15.63	136.39	31 Mar	1 Apr	6 Apr
Nathan River	-15.58	135.43	1 Apr	31 Mar	6 Apr
Katherine Council	-14.46	132.26	27 Mar	28 Mar	4 Apr
Tipperary	-13.73	131.04	31 Mar	3 Apr	7 Apr
Darwin Airport	-12.42	130.89	9 Apr	10 Apr	14 Apr

Locations are listed in order of most southward to most northward (e.g., by increasing latitude). The missing "burst definition" date for The Granites is due to that particular location not experiencing a retreat date in 30% of years from 1950 to 2019 (between January and April).

**Table S2.** 70th percentile retreat dates for select locations across Western Australia that produce red meat, using observations from 1950 to 2019.

<b>Station</b>	<b>Latitude (°S)</b>	<b>Longitude (°E)</b>	<b>Cumulative definition</b>	<b>Backward definition</b>	<b>Burst definition</b>
Glen-Ayle	-25.27	122.04	8 Apr	22 Mar	23 Mar
Turee Creek	-23.62	118.66	29 Mar	15 Mar	21 Mar
Newman Aero	-23.42	119.80	1 Apr	20 Mar	26 Mar
Emu Creek Station	-23.03	115.04	25 Mar	17 Mar	23 Mar
Cheela Plains	-22.94	116.97	3 Apr	14 Mar	9 Mar
Bonney Downs	-22.18	119.94	31 Mar	12 Mar	25 Mar
Mount Florance	-21.79	117.86	19 Mar	15 Mar	20 Mar
Yalleen	-21.68	116.39	24 Mar	16 Mar	10 Mar
Onslow Airport	-21.67	115.11	12 Mar	5 Mar	15 Mar
Mallina	-20.88	118.03	23 Mar	11 Mar	21 Mar
Warrawagine	-20.85	120.70	23 Mar	9 Mar	12 Mar
Karratha Aero	-20.71	116.77	20 Mar	12 Mar	20 Mar
Pardoo Station	-20.11	119.58	24 Mar	13 Mar	22 Mar
Mandora	-19.74	120.84	24 Mar	21 Mar	29 Mar
Sturt Creek	-19.16	128.16	16 Mar	11 Mar	20 Mar
Larrawa	-18.84	126.53	21 Mar	10 Mar	11 Mar
Bidyadanga	-18.68	121.78	23 Mar	20 Mar	25 Mar
Margaret River Airstrip	-18.62	126.88	19 Mar	11 Mar	14 Mar
Dampier Downs	-18.51	123.46	24 Mar	19 Mar	25 Mar
Gogo Station	-18.29	125.59	8 Apr	22 Mar	23 Mar
Halls Creek Met. Office	-18.23	127.66	29 Mar	15 Mar	21 Mar
Fitzroy Crossing Comp.	-18.19	125.56	1 Apr	20 Mar	26 Mar
Broome Airport	-17.95	122.24	25 Mar	17 Mar	23 Mar
Kimberley Downs	-17.39	124.36	3 Apr	14 Mar	9 Mar
Derby Aero	-17.37	123.66	31 Mar	12 Mar	25 Mar
Country Downs	-17.28	122.57	19 Mar	15 Mar	20 Mar
Marion Downs	-17.07	126.85	24 Mar	16 Mar	10 Mar
Warmun	-17.02	128.22	12 Mar	5 Mar	15 Mar
Kununurra Aero	-15.78	128.71	23 Mar	11 Mar	21 Mar
Drysdale River Station	-15.70	126.38	23 Mar	9 Mar	12 Mar

Locations are listed in order of most southward to most northward (e.g. by increasing latitude).



**Table S3.** 70th percentile retreat dates for select locations across Queensland that produce red meat, sugar or dairy, using observations from 1950 to 2019.

<b>Station</b>	<b>Latitude (°S)</b>	<b>Longitude (°E)</b>	<b>Cumulative definition</b>	<b>Backward definition</b>	<b>Burst definition</b>
Biggenden Post Office	-25.51	152.05	26 Mar	4 Apr	10 Apr
Maryborough	-25.51	152.72	4 Apr	13 Apr	15 Apr
Windorah Airport	-25.41	142.66	21 Mar	6 Mar	27 Mar
Eidsvold Post Office	-25.37	151.12	18 Mar	29 Mar	4 Apr
Childers South	-25.26	152.28	25 Mar	10 Apr	15 Apr
Cordalba Store	-25.16	152.21	24 Mar	10 Apr	14 Apr
Walla Tm	-25.14	151.98	18 Mar	5 Apr	15 Apr
Gin Gin Post Office	-24.99	151.96	24 Mar	4 Apr	14 Apr
Theodore	-24.95	150.08	22 Mar	24 Mar	1 Apr
Bingera Sugar Mill	-24.93	152.2	25 Mar	4 Apr	10 Apr
Bundaberg Aero	-24.91	152.32	28 Mar	5 Apr	13 Apr
Tambo Post Office	-24.88	146.26	22 Mar	26 Mar	4 Apr
Monto Township	-24.86	151.13	23 Mar	1 Apr	3 Apr
Monkira	-24.82	140.56	9 Mar	21 Feb	8 Mar
Bargara	-24.8	152.45	31 Mar	11 Apr	18 Apr
Fariymead Sugar Mill	-24.79	152.36	28 Mar	9 Apr	18 Apr
Charnwood	-24.65	151.63	24 Mar	8 Apr	13 Apr
Rosedale Post Office	-24.63	151.92	25 Mar	7 Apr	12 Apr
Moura Post Office	-24.57	149.97	22 Mar	28 Mar	4 Apr
Bauhinia Downs Store	-24.57	149.29	24 Mar	28 Mar	2 Apr
Thangool Airport	-24.49	150.57	17 Mar	26 Mar	30 Mar
Rolleston Airport	-24.46	148.63	14 Mar	27 Mar	1 Apr
Makowata	-24.44	151.65	25 Mar	7 Apr	14 Apr
Blackall Airport	-24.43	145.43	20 Mar	26 Mar	2 Apr
Biloela - Valbona	-24.41	150.52	23 Mar	27 Mar	31 Mar
Seventeen Seventy	-24.16	151.89	4 Apr	14 Apr	22 Apr
Springsure Comet St	-24.12	148.09	16 Mar	30 Mar	4 Apr
Calliope Station	-24.02	150.97	18 Mar	4 Apr	13 Apr
Gladstone Airport	-23.87	151.22	25 Mar	4 Apr	13 Apr
Dululu Post Office	-23.85	150.26	24 Mar	28 Mar	6 Apr
Blackwater Airport	-23.6	148.81	18 Mar	24 Mar	2 Apr
Emerald Airport	-23.57	148.18	21 Mar	30 Mar	2 Apr
Gracemere - Lucas St	-23.46	150.46	14 Mar	2 Apr	13 Apr
Longreach Aero	-23.44	144.28	26 Mar	22 Mar	1 Apr
Rockhampton Aero	-23.38	150.48	19 Mar	4 Apr	13 Apr
Yeppoon The Esplanade	-23.14	150.75	29 Mar	14 Apr	20 Apr
Capella Post Office	-23.09	148.02	16 Mar	29 Mar	4 Apr
Aramac Post Office	-22.97	145.25	30 Mar	28 Mar	3 Apr
Boulia Airport	-22.91	139.9	14 Mar	1 Mar	12 Mar
Glenormiston	-22.91	138.8	16 Mar	28 Feb	12 Mar
Clermont Post Office	-22.82	147.64	25 Mar	29 Mar	5 Apr
Marlborough Helipad TM	-22.82	149.89	23 Mar	29 Mar	5 Apr
Clermont Airport	-22.78	147.62	24 Mar	29 Mar	5 Apr
Winton Post Office	-22.39	143.04	9 Mar	11 Mar	17 Mar
Carmilla	-21.92	149.44	28 Mar	8 Apr	13 Apr
Carmila Beach Road	-21.92	149.44	28 Mar	8 Apr	13 Apr

<b>Station</b>	<b>Latitude (°S)</b>	<b>Longitude (°E)</b>	<b>Cumulative definition</b>	<b>Backward definition</b>	<b>Burst definition</b>
Corfield-Manuka St	-21.71	143.38	11 Mar	12 Mar	15 Mar
Nebo	-21.69	148.69	24 Mar	29 Mar	31 Mar
Koumala	-21.63	149.24	31 Mar	12 Apr	18 Apr
Sarina Post Office	-21.42	149.22	4 Apr	18 Apr	23 Apr
Hay Point	-21.3	149.26	4 Apr	19 Apr	25 Apr
Mackay Te Kowai Research Station	-21.19	149.11	4 Apr	17 Apr	23 Apr
Homebush	-21.17	149.01	31 Mar	17 Apr	20 Apr
Mackay Aero	-21.17	149.18	5 Apr	18 Apr	24 Apr
Mirani	-21.16	148.86	31 Mar	16 Apr	20 Apr
Mount Jukes	-21.01	148.91	4 Apr	17 Apr	22 Apr
Mount Jukes	-21	148.94	8 Apr	19 Apr	25 Apr
Pindi Pindi	-20.86	148.74	1 Apr	16 Apr	19 Apr
Hughenden Airport	-20.82	144.23	11 Mar	11 Mar	29 Mar
Glendower Station	-20.74	144.49	13 Mar	11 Mar	21 Mar
Richmond Post Office	-20.73	143.14	15 Mar	12 Mar	21 Mar
Cloncurry Mcillwraith St	-20.71	140.52	16 Mar	13 Mar	19 Mar
Mount Isa Aero	-20.68	139.49	18 Mar	12 Mar	22 Mar
Julia Creek Airport	-20.67	141.72	13 Mar	9 Mar	10 Mar
Lethebrook	-20.54	148.66	12 Apr	17 Apr	23 Apr
Proserpine Airport	-20.49	148.56	12 Apr	16 Apr	20 Apr
Crystal Brook	-20.34	148.5	5 Apr	16 Apr	18 Apr
Foxdale/Koolachu	-20.33	148.51	5 Apr	16 Apr	18 Apr
Dalbeg	-20.23	147.3	29 Mar	1 Apr	5 Apr
Millaroo DPI	-20.06	147.28	26 Mar	31 Mar	4 Apr
Charters Towers Airport	-20.05	146.27	3 Apr	1 Apr	4 Apr
Bowen Airport	-20.02	148.21	24 Mar	4 Apr	9 Apr
Camooweal Township	-19.92	138.12	19 Mar	8 Mar	10 Mar
Clare	-19.79	147.23	27 Mar	30 Mar	5 Apr
Inkerman Station	-19.76	147.46	24 Mar	29 Mar	2 Apr
Home Hill Osborne School	-19.7	147.35	23 Mar	29 Mar	9 Apr
Ayr Research Station	-19.62	147.38	27 Mar	31 Mar	9 Apr
Shirbourne Park	-19.6	147.1	25 Mar	2 Apr	9 Apr
Giru	-19.52	147.1	23 Mar	2 Apr	9 Apr
Kalamia Estate	-19.52	147.42	27 Mar	2 Apr	10 Apr
Canobie	-19.48	140.93	20 Mar	13 Mar	19 Mar
Alva Beach	-19.46	147.48	30 Mar	5 Apr	11 Apr
Townsville Aero	-19.25	146.77	30 Mar	5 Apr	6 Apr
Oak Park Station	-19.25	144.15	18 Mar	20 Mar	29 Mar
Rollingstone	-19.04	146.41	1 Apr	14 Apr	15 Apr
Bambaroo	-18.88	146.17	3 Apr	15 Apr	16 Apr
Helens Hill	-18.79	146.11	6 Apr	17 Apr	20 Apr
Poverty Hill Alert	-18.75	146.12	9 Apr	18 Apr	21 Apr
Upper Stone Excelby	-18.72	145.92	9 Apr	17 Apr	20 Apr
Forrest Beach	-18.71	146.3	13 Apr	19 Apr	21 Apr
Boodjamulla - Lawn Hill NP	-18.7	138.49	20 Mar	16 Mar	17 Mar
Toobanna	-18.69	146.15	13 Apr	19 Apr	26 Apr
Upper Stone	-18.69	145.96	11 Apr	19 Apr	21 Apr
Warrens Hill (Molonga)	-18.69	146.22	14 Apr	20 Apr	26 Apr

<b>Station</b>	<b>Latitude (°S)</b>	<b>Longitude (°E)</b>	<b>Cumulative definition</b>	<b>Backward definition</b>	<b>Burst definition</b>
South Ingham (Marina Parade)	-18.66	146.18	17 Apr	21 Apr	26 Apr
Sunnybank	-18.66	146.27	17 Apr	20 Apr	26 Apr
East Ingham	-18.65	146.17	17 Apr	21 Apr	26 Apr
West Ingham	-18.65	146.14	17 Apr	21 Apr	26 Apr
Lower Stone	-18.63	146.04	17 Apr	21 Apr	24 Apr
Tara	-18.63	146.15	17 Apr	21 Apr	26 Apr
Victoria Plantation	-18.63	146.18	17 Apr	21 Apr	26 Apr
Mt Cordelia	-18.6	146.24	17 Apr	20 Apr	26 Apr
Hawkins Creek	-18.59	146.07	17 Apr	22 Apr	24 Apr
Macknade Sugar Mill	-18.59	146.25	17 Apr	20 Apr	26 Apr
Halifax	-18.58	146.28	14 Apr	19 Apr	26 Apr
Macknade Mill	-18.58	146.24	17 Apr	20 Apr	26 Apr
Ripple Creek	-18.58	146.2	17 Apr	21 Apr	27 Apr
Augustus Downs Station	-18.54	139.87	20 Mar	14 Mar	17 Mar
Lucinda	-18.54	146.34	16 Apr	19 Apr	24 Apr
Gregory Downs Station	-18.5	139.29	20 Mar	13 Mar	17 Mar
Gowrie	-18.48	145.93	17 Apr	21 Apr	26 Apr
Zatta's Alert	-18.45	145.83	17 Apr	20 Apr	24 Apr
Croydon Township	-18.2	142.24	22 Mar	21 Mar	27 Mar
Mount Surprise Township	-18.15	144.32	24 Mar	22 Mar	28 Mar
Tully Sugar Mill	-17.94	145.93	23 Apr	27 Apr	29 Apr
Burketown Post Office	-17.74	139.55	24 Mar	21 Mar	23 Mar
Cowley Beach	-17.69	146.11	25 Apr	26 Apr	29 Apr
South Johnston	-17.61	146	25 Apr	27 Apr	29 Apr
Evelyn State Forest	-17.54	145.48	20 Apr	21 Apr	25 Apr
Innisfail	-17.52	146.03	25 Apr	26 Apr	29 Apr
Babinda	-17.34	145.92	25 Apr	27 Apr	29 Apr
Petford	-17.34	144.93	24 Mar	23 Mar	23 Mar
Miranda Downs Station	-17.33	141.88	23 Mar	23 Mar	28 Mar
Walkamin Research Station	-17.14	145.43	29 Mar	7 Apr	9 Apr
Gordonvale	-17.09	145.79	19 Apr	22 Apr	26 Apr
Mareeba	-17	145.43	29 Mar	7 Apr	11 Apr
Cairns Racecourse	-16.95	145.75	18 Apr	21 Apr	25 Apr
Mossman	-16.47	145.37	17 Apr	20 Apr	23 Apr
Maitland Downs Station	-16.22	144.71	3 Apr	4 Apr	4 Apr
Palmerville	-16	144.08	31 Mar	3 Apr	7 Apr
Shiptons Flat	-15.8	145.24	18 Apr	21 Apr	22 Apr
Kowanyama Airport	-15.48	141.75	30 Mar	31 Mar	7 Apr
Merluna	-13.06	142.45	8 Apr	9 Apr	11 Apr
Lockhart River Airport	-12.79	143.3	16 Apr	18 Apr	24 Apr
Weipa Eastern Ave	-12.63	141.88	10 Apr	14 Apr	15 Apr
Moreton Telegraph Station	-12.45	142.64	14 Apr	15 Apr	16 Apr

Locations are listed in order of most southward to most northward (e.g. by increasing latitude).

**Table S4.** Lead-lag correlations of NRR dates (averaged over 10–20°N and 120–148°E), and seasonally averaged Oceanic NINO index (ONI) from 1950 to 2019.

	<b>Cumulative anomaly, <i>R</i> (<i>P</i>-value)</b>	<b>Backward accumulation, <i>R</i> (<i>P</i>-value)</b>	<b>3-day burst, <i>R</i> (<i>P</i>-value)</b>
DJF-1 (ONI leading)	0.08 (0.50)	0.11 (0.35)	0.12 (0.33)
MAM-1	-0.11 (0.39)	-0.03 (0.83)	-0.04 (0.73)
JJA <sub>0</sub>	-0.41 (<0.001)	-0.30 (0.01)	-0.33 (0.006)
SON <sub>0</sub>	-0.38 (0.002)	-0.26 (0.03)	-0.28 (0.02)
DJF <sub>0</sub>	-0.37 (0.002)	-0.25 (0.04)	-0.28 (0.02)
<b>MAM<sub>0</sub></b>	<b>-0.41 (&lt;0.001)</b>	<b>-0.35 (0.003)</b>	<b>-0.38 (0.001)</b>
JJA+1 (NRR leading)	-0.30 (0.01)	-0.39 (<0.001)	-0.37 (0.002)
SON+1	-0.26 (0.03)	-0.36 (0.002)	-0.33 (0.005)
DJF+1	-0.25(0.04)	-0.33 (0.006)	-0.31 (0.008)
MAM+1	-0.29 (0.02)	-0.35 (0.004)	-0.35 (0.003)
JJA+2	-0.10 (0.40)	-0.12 (0.30)	-0.15 (0.20)

Both the ONI and NRR dates are linearly detrended prior to the correlation analysis. Shown are correlation coefficients *R* and *P*-values.