

Supplementary Material for Large-Scale Drivers of Marine Heatwaves Revealed by Archetype Analysis

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Archetypal Patterns

In the main text, we show only 4 of a total of 8 archetypal patterns - a choice motivated by a desire to avoid clutter of both text and graphics. For completeness, the remaining archetypes are shown in Fig. 1. The archetypes not shown in the main text are #5, #6, #7 and #8. Archetypes #1 and #2 (Fig. 1a,b and Fig. 1c,d) are discussed in the marine coldspell case study included within the this supplementary material. Archetypes labelling is arbitrary, as unlike with Principal Component Analysis, there is no ‘natural’ way to rank archetypes.

As in the main text, we also show the temporal occurrence and persistence of all 8 archetypes in Fig. 2. The archetypes not discussed in the main text show periods of persistence, such as archetype #6 during the period 1993-1995, or archetype #8, which has the signature of moderate El-Niño and was strongly expressed in 1992 and 2007.

Statistical Significance of Archetypal Patterns

In order to evaluate the statistical significance of archetypal spatial patterns and the composite fields, we employ a brute-force Monte-Carlo approach. First, we generate synthetic stochastic matrix, designed to replicate the features of the C or S matrices. The elements of these matrices is drawn from a uniform distribution between 0 and 1. The rows or columns of these synthetic stochastic

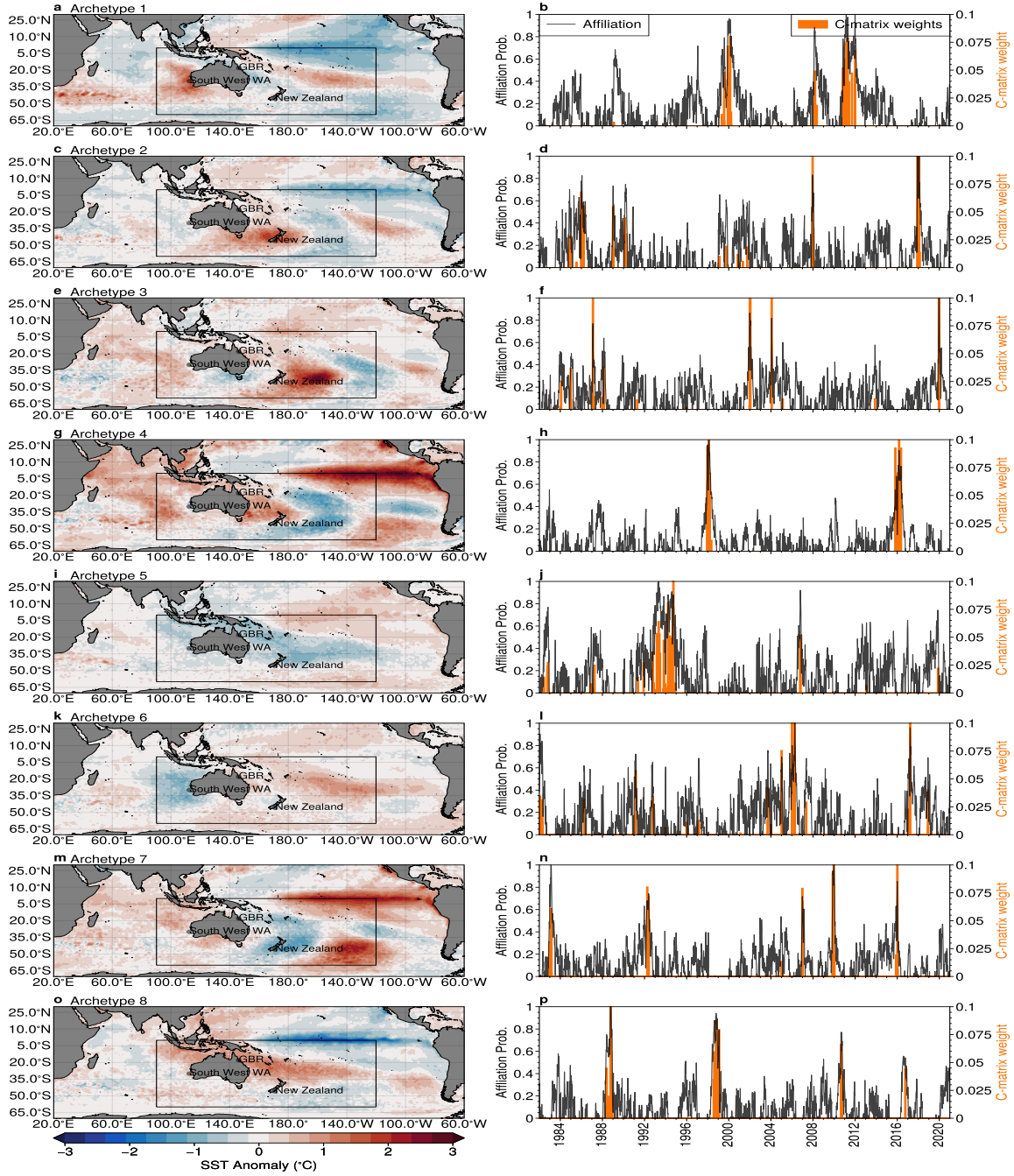


Figure 1: **Archetypal Patterns and Affiliation time-series over the South Pacific:** (left) Detrended SST anomalies for all eight archetypal patterns computed over the Australasian region (indicated by the black box), ranked from most likely to least likely to occur, and (right) associated affiliation time-series (black solid line) and the C -matrix weights applied to each time snapshot to form the archetypes (orange bars). The AA is conducted in the domain in the left-hand column. Archetypes #1 (panels a,b), #2 (panels c,d), #3 (panels e,f) and #4 (panels g,h) are used in the regional case studies in the main text (locations indicated in the text) while archetype #8 (panels i,j) is shown to illustrate classical El Niño type variability. Archetypes #5 (panels k,l), #6 (panels m,n), and #7 (panels o,p) are used in regional case studies in the supplementary material.

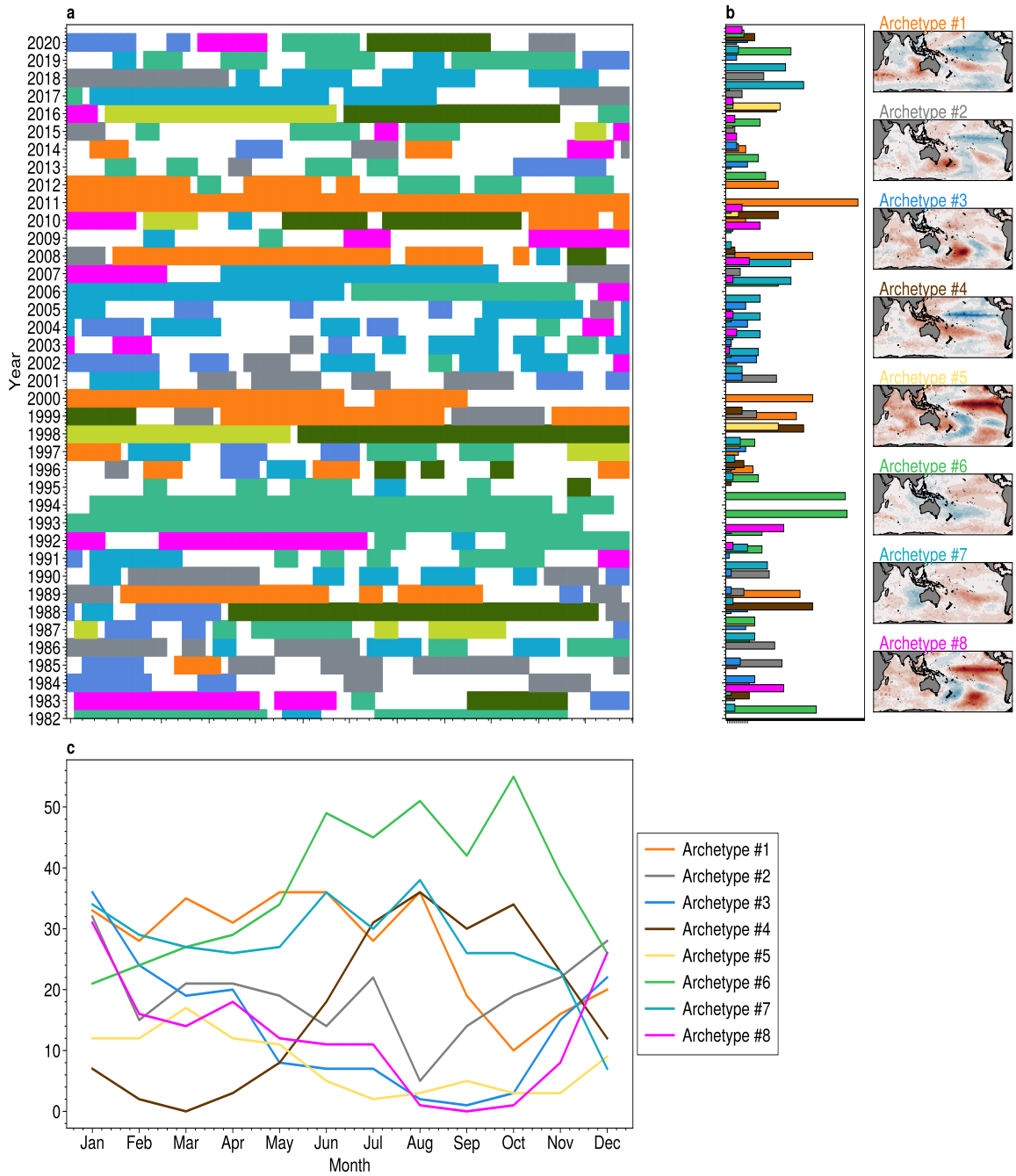


Figure 2: **Temporal Occurrence of Archetype Patterns:** **a** Coloured blocks indicate period where a particular archetype was dominant for at least 20 days. The *y*-axis indicates the year, while the *x*-axis indicates the calendar days. Blanked periods show days where no qualifying event was found; the total number of archetype event days for each archetype that occur **b** for each year; and **c** for each 5-day period over the annual cycle. Maps on far right are to remind the reader of the spatial patterns of each archetype.

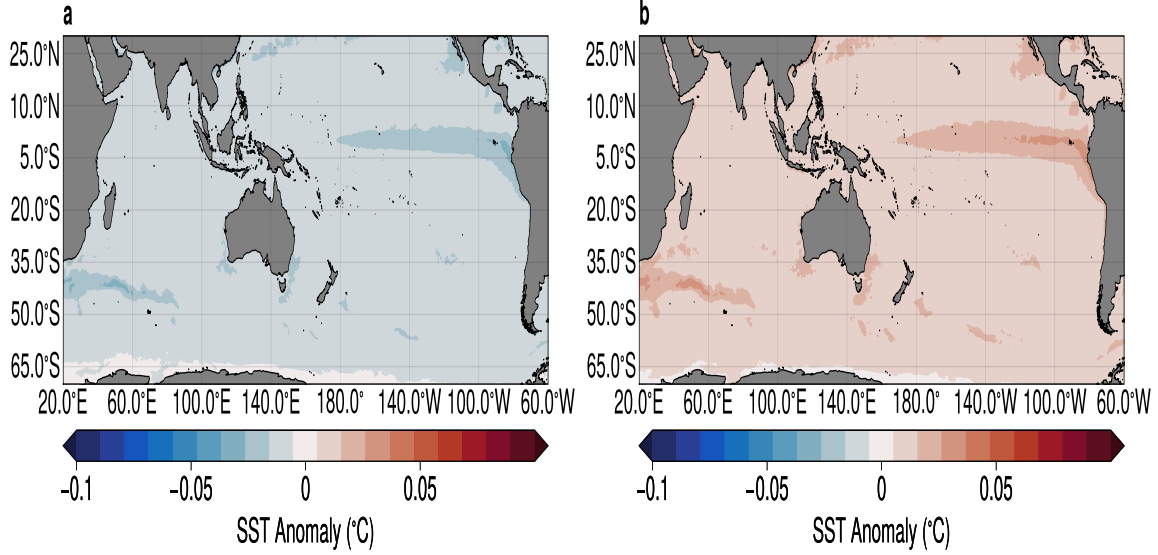


Figure 3: **Quantiles of SST used for statistical significance testing: a** 5th percentile; and **b** 95th percentile.

matrices are then normalised appropriately to ensure that the constraints. For example, in the case of a synthetic C -matrix, the normalisation is applied to rows to ensure that the constraint $\sum_t c_{t,j} = 1$ is satisfied. In the case of a synthetic S -matrix, the normalisation is performed column-wise, to satisfy the constraint $\sum_j s_{t,j} = 1$. We then form composite fields on these synthetic matrices. The procedure is repeated 1000 times and the 5th and 95th percentiles computed (shown in Fig. 3). A pixel is declared ‘significant’ if it is less than the 5th percentile, or greater than the 95th percentile.

In Fig. 4 we plot the SST archetypal patterns for all 8 archetypes, similarly to Fig. 1. Stippling indicates statistical significance. As can be seen in the figure, fields are almost everywhere statistically significant (with the exception of regions that separate warm and cold anomalies). This result might be expected from the fact that AA identifies extreme states.

In Fig. 5, we show the statistical significance of the geopotential height patterns computed using the S -matrix weights obtained from the archetypes computed using SST. Unlike the SST patterns themselves, the geopotential height patterns are not everywhere significant. However, the regions of statistical significance typically encapsulate the broad-scale teleconnections and larger flow features.

To conclude, the spatial patterns produced by the AA undertaken in this study are robust and, nearly everywhere, statistically significant. We have also tested the statistical significance of surface atmosphere temperature and sub-

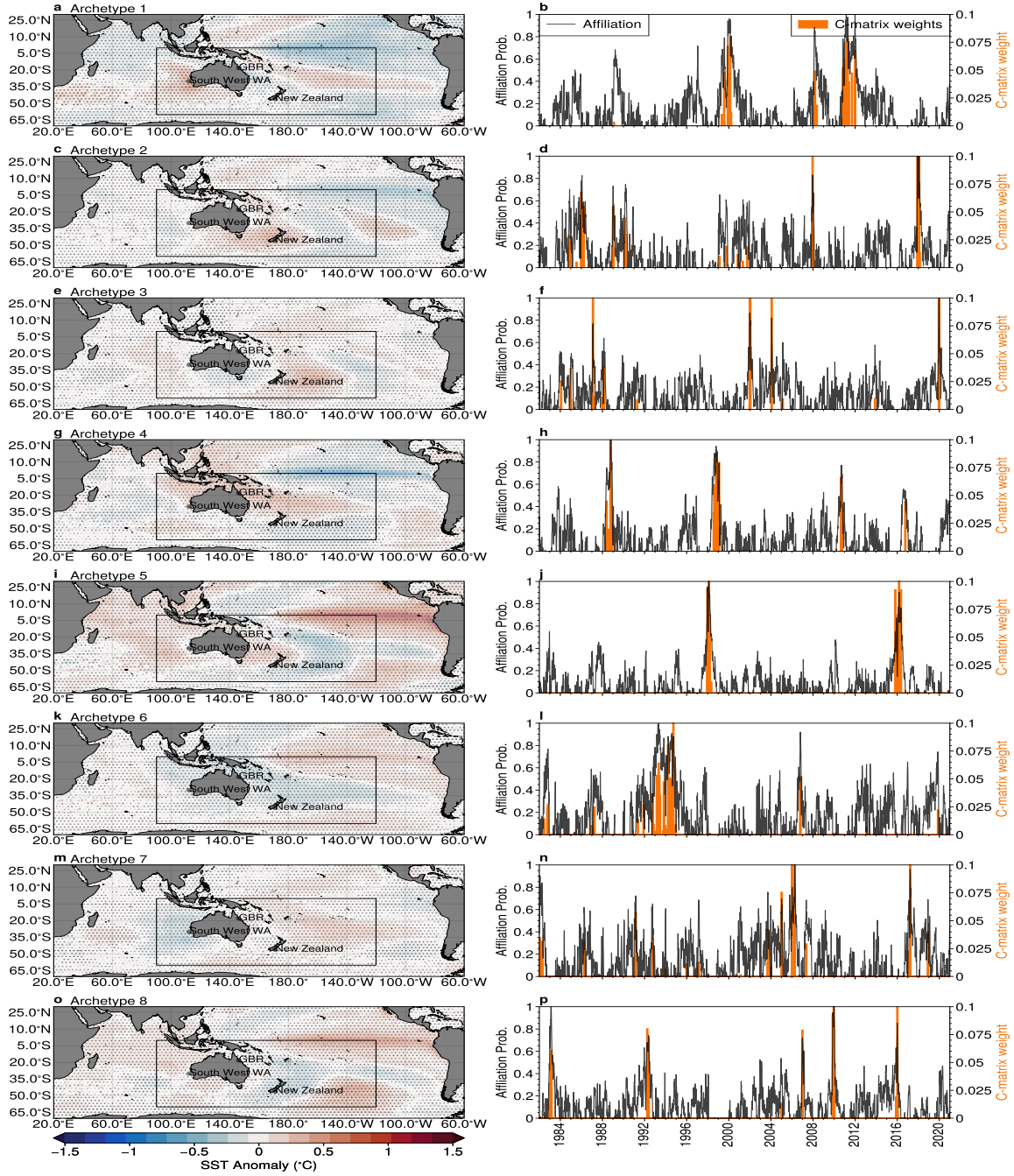


Figure 4: **Statistical Significance of Archetypal SST Patterns** : (left) Detrended SST anomalies for all eight archetypal patterns computed over the Australasian region (indicated by the black box), and (right) associated affiliation time-series (black solid line) and the *C-matrix weights* applied to each time snapshot to form the archetypes (orange bars). Stippling indicates regions where the patterns are statistically significant at the 95% confidence level (right) associated affiliation time-series (black solid line) and the *C-matrix weights* applied to each time snapshot to form the archetypes (orange bars)

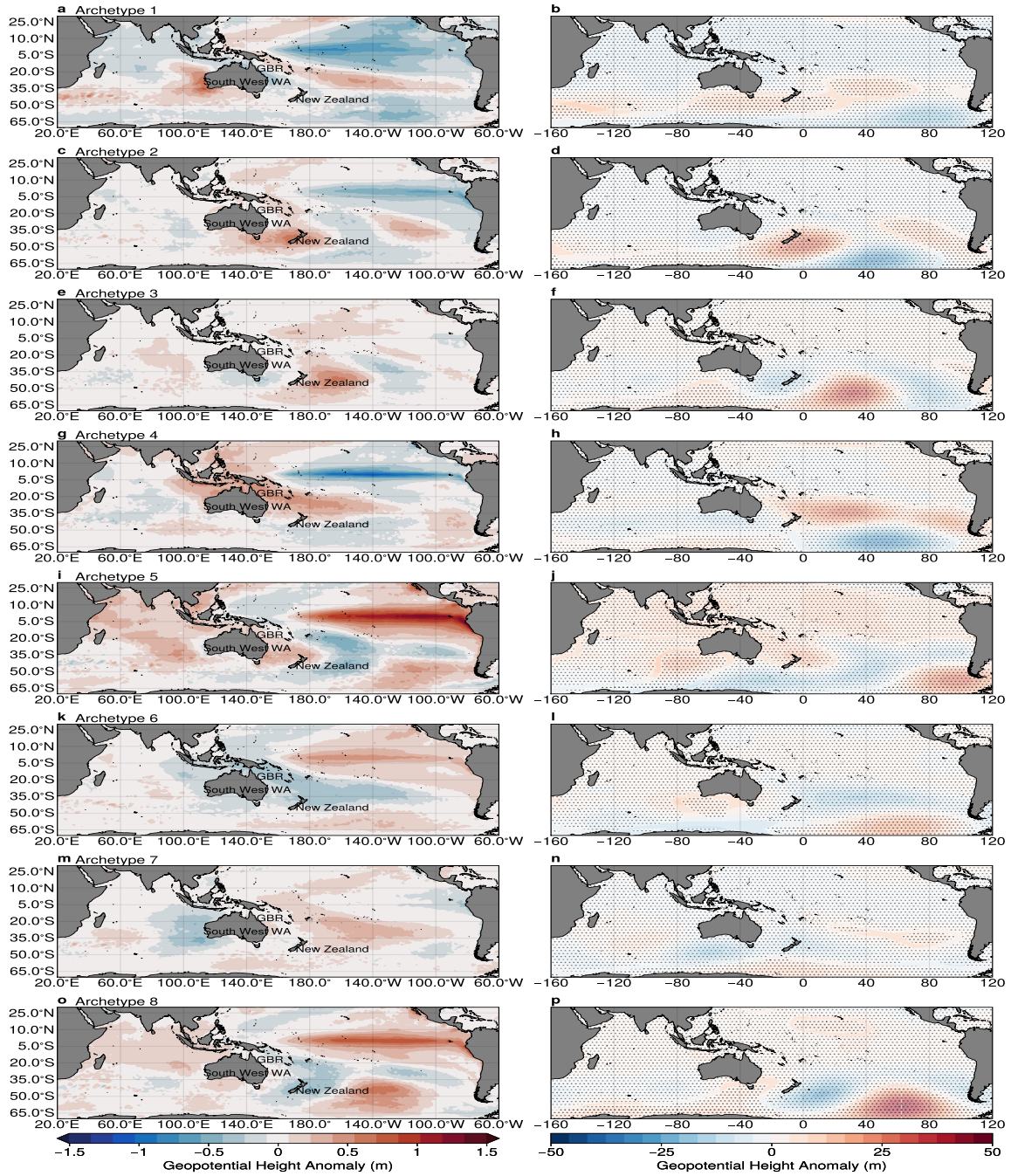


Figure 5: **Statistical Significance of Archetypal 500hPa Geopotential Patterns** : (left) Detrended SST anomalies for all eight archetypal patterns computed over the Australasian region (indicated by the black box), and (right) associated 500hPa geopotential height anomalies. Stippling indicates regions where the patterns are statistically significant at the 95% confidence level

55 surface oceanic temperatures. However, these are not shown for brevity. The
56 conclusions however, are the same, all major features of the identified archetypal
57 or composite fields are significant at the 95% confidence level.

58 Further Case Studies

59 In this section, we provide further case studies to illustrate the utility, and limits
60 of the ‘outside-in’ approach based on archetype analysis (AA). While the main
61 text focuses on marine heatwaves, here we present two case studies concerning
62 the cold extremes, known as marine coldspell, and a case study showing how
63 AA is unable to reflect regional marine extremes likely induced by small scale
64 local processes and not broad-scale processes such as El-Niño or La-Niña.

65 Marine Cold Spells in the Southeast Indian Ocean

66 In the main text, we discuss marine heatwaves in the southeast Indian ocean
67 off the coast of Western Australia. This region is often discussed in relation
68 to marine heatwaves due to the high profile of the devastating 2011 event that
69 reached the ‘extreme’ category[1]. However, recent attention has turned to ma-
70 rine coldspells in the region, as these events can also have important effects on
71 fisheries and ecological communities[2]. These analyses have shown that, much
72 like marine heatwaves in the region, marine coldspells tend to *cluster*, with mul-
73 tiple events occurring during a relatively brief period of time.

74
75 In Fig. 6, we show the composite average of marine coldspells for a repre-
76 sentative point in the south-east Indian ocean (Fig. 6a), together with the peak
77 day of two events, corresponding to the a ‘strong’ event in June 2017 (Figs.
78 6b) and a ‘moderate’ event in June 2018 (Figs. 6d), together with the two
79 best-matching archetypes (Figs. 6c,e), both of which show a broad similarity
80 the daily snapshots and the composite average.

81
82 The SST anomaly at the representative location, shown in Fig. 6f, shows
83 clear low-frequency variability, with periods of below average SST persisting for
84 months or years at a time. Examples of these periods are 1986-1988, 1990-1992,
85 1997, 2003-2004 and 2017-2019. Unsurprisingly, these periods correspond to
86 periods relatively frequent marine coldspells. The affiliation time-series of the
87 two best matching archetypes, showning in Fig. 6g, appears to capture this
88 low frequency variability, particularly archetype #1 (archetype # 2 appears to
89 correspond more commonly to isolated marine coldspell periods). For example,
90 the multi-year marine cold-spell described by Feng et al. 2021[2], that occurred
91 over the period 2016 to 2020, can be seen to correspond to a period where the
92 affiliation of both best-matching archetypes is consistently higher than 0.4.

93
94 Zooming out to investigate the teleconnection patterns, shown in Fig. 7.
95 We note that, in contrast to the marine heatwave case-study presented in the

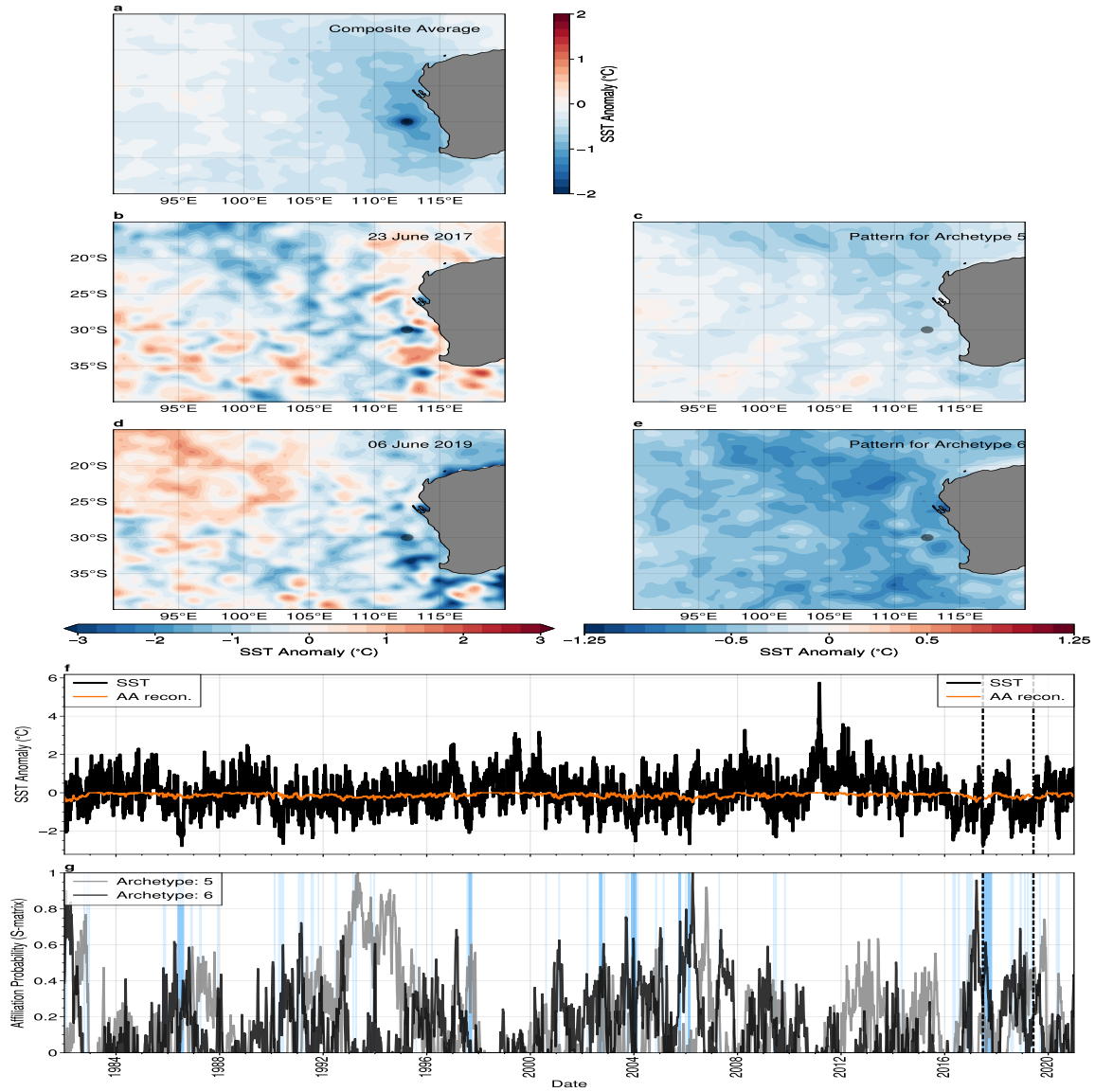


Figure 6: **The relationship between Marine Coldspells and Archetypes #5 and #6 in the southeast Indian ocean** : a SST anomaly composite average of all marine coldspells at a representative location (at 30°S,112.5°E, shown as a grey dot) in the southeast Indian Ocean; b,d snapshot of SST anomalies for the peak for the peak day of the strong marine coldspell event on the 23rd of June, 2017, and the moderate event on the 6th of June 2018; c,e the SST anomalies for best matching archetypal pattern (archetype #5 archetype #6); f time-series of SST anomalies (black) and the reconstruction from archetype 3 (orange) at the representative location shown in panels a-c ; g time-series of archetype affiliation probability for archetype 3. Colored bands in panels d,e indicate marine coldspell occurrences, coded by the severity category described in *Hobday et al. 2018*[3].

main text, there is no strong SST signature in the tropical Pacific. In fact, the affiliation time-series is positively correlated with the multivariate ENSO index at a peak lag of +10 months (Figs. 7d,e), suggestive that widespread cold temperatures in the southeast Indian ocean occur 8-12 months prior to the onset of El-Niño. The anomalous atmospheric circulation, shown in Fig. 7b, indicates widespread anomalously equatorward winds over the region of interest, and likely contributes to the cooler than average temperatures. However, correlation with the Southern Annular Mode (SAM) index is weak and the spatial patterns of mid-tropospheric geopotential height anomalies are not strongly reminiscent of the canonical SAM.

Tasman Sea and East Australian Current Marine Heatwaves

In the main text, we have employed case-studies to demonstrate the utility of archetypal analysis in identifying large-scale ‘extreme’ modes of variability that can influence local environmental conditions sufficiently to induce (or at least contribute) to the occurrence of marine temperature extremes. However, the conditions at any particular location are obviously influenced by both broad-scale (or remote) and local factors. In the following case-study, we illustrate two cases where local dynamics, not broad scale dynamics, are the dominant influence.

We take the well studied 2016 Tasman Sea marine heatwave as our first example. This event occurred in the southern Tasman Sea, centered to the east of Tasmania, starting in early September 2015 and lasting for approximately 251 days to finish in May 2016[4]. Fig. 8a shows the peak day of this event (8th February 2016) at a representative location ($42.75^{\circ}\text{S}, 148.5^{\circ}\text{E}$, shown as a grey circle in Figs 8) along with the composite average of all events at that location (Fig. 8b). Both the peak day snapshot and the composite average have similar spatial structures, which suggests that most marine heatwaves in the region have a similar spatial structure.

In contrast, the spatial structure of the best matching archetype (Fig. 8c) does not show the same spatial structure as either the daily snapshot or the composite average of marine heatwaves near Tasmania. While the time-series of the SST anomaly (Fig. 8d) and the affiliation time-series of the best-matching archetype show correlation in later part of the time-period (from 2008 onwards) with a particularly notable co-occurrence of SSTs and an affiliation probability near 1 during the 2015-2016 marine heat wave event. However, the spatial patterns associated with the best-matching archetype show little similarity to those associated with southern Tasman sea marine heatwaves. Instead of localised warm SSTs around Tasmania, the archetype shows a broad region of elevated SSTs in the Tasman and Coral Seas, extending from the east coast of the Australian continent to around 180° longitude. Prior to 2008, periods with high affiliation probabilities are not consistently associated with marine heat-

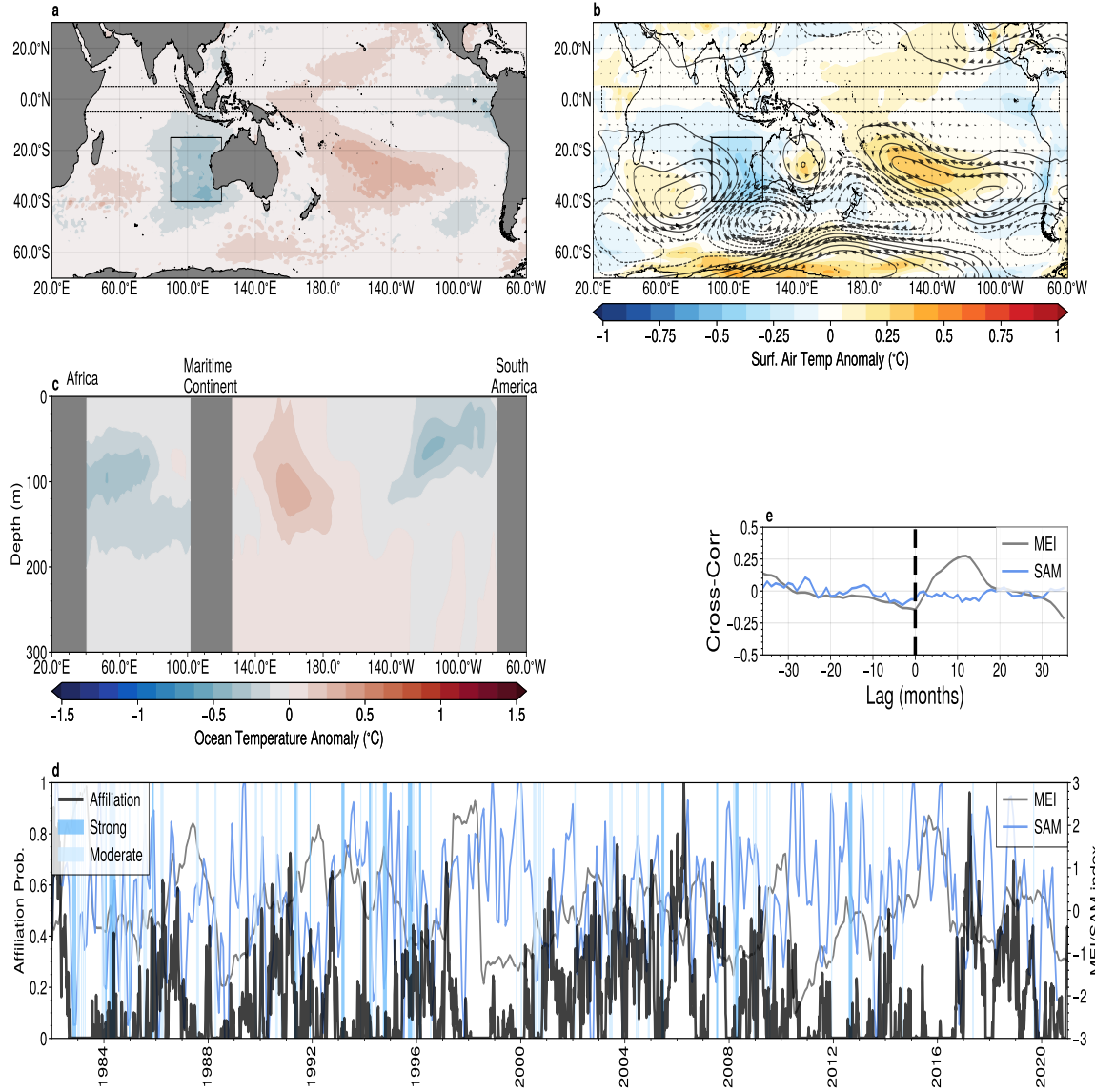


Figure 7: **Teleconnections Associated with Marine Coldspells in the Southeastern Indian Ocean:** **a** SST anomaly; **b** surface temperature (colours) with anomalous mid-tropospheric (500hPa) geopotential height (contour lines) and winds (vectors); and **c** equatorial subsurface temperatures, associated with archetype #3, the best-matching archetype for marine heatwaves in the southeast Indian Ocean. **d** The affiliation time-series (solid black) together with the multivariate ENSO index (MEI, grey) and the Marshall SAM index (blue). Periods of marine heatwaves are indicated by red shading. **e** the lagged cross-correlation between the affiliation time-series and the MEI (grey) and the Marshall SAM index (blue). Negative lags correspond to the MEI/SAM index leading the affiliation.

140 waves at the representative location. For example, the affiliation probability
141 reaches 1 in 1998, a time period associated with *lower* than average SSTs.

142 In a similar vain, we plot the same marine heatwave metric for events in the
143 East Australian Current (EAC) (Fig. 9), at 30°S, near the city of Coffs Harbour.
144 Marine heatwaves in this region have been attributed to a combination of local
145 oceanographic factors, such as eddy interaction with the EAC, and atmospheric
146 effects[5]. In this case, the spatial structure of SSTs for the peak of the most
147 intense event (4th February 2017, Fig. 9a), the composite average of all events at
148 this location (Fig. 9b) and the best-match archetype (Fig. 9c, as in the southern
149 Tasman Sea case study above) are similar, with a broad pattern of high SST
150 anomalies over the Tasman Sea region, from the eastern Australian coastline
151 to a longitude of $\sim 180^\circ$, although we note that the strongest SSTs are found
152 along the Australian coastline in both the single day snapshot and the composite
153 average of all events, which is not apparent in the SST pattern associated with
154 the archetype. However, investigating the time-series (Fig. 9d,e) shows limited
155 correlation between the affiliation time-series and the SST time-series at the
156 representative location, with the exception of the period around 1998 and, to
157 a much lesser extent, around 2010, which showed both an elevated affiliation
158 probabilities and anomalously high SSTs. Marine heatwave periods tend to
159 cluster in the later half of the time-series, consistent with the enhanced SSTs in
160 the region as a result of continued global warming[6].

161 The teleconnections associated with best-matching archetype are shown in
162 Fig. 10. The SST pattern in the equatorial Pacific, together with the peaks
163 in the affiliation time-series in the years 1998 and 2016, strongly suggest that
164 this archetype represents the variability associated with strong El-Niño events.
165 Atmospheric circulation anomalies and sub-surface temperatures strongly sup-
166 port this inference, with the characteristic weaker than average trade winds
167 evident in the atmospheric composites, and the warmer sub-surface ocean tem-
168 peratures in the eastern Pacific and cooler than average temperatures in the
169 western Pacific. However, the temperature expression is not particular strong
170 in the Tasman Sea.

171 None of the 8 archetypes obtained by our analysis strongly projects into the
172 Tasman Sea in the same way that other archetypes project into the south-east
173 Indian ocean, and the archetype that projects the most strongly (Archetype
174 #5) does not strongly reflect either the spatial or temporal structures of marine
175 heatwaves in the region. Taken together, this leads us to conclude that in this
176 complex western boundary current region, marine extremes are likely driven by
177 local process not well captured by the large scale archetypes.

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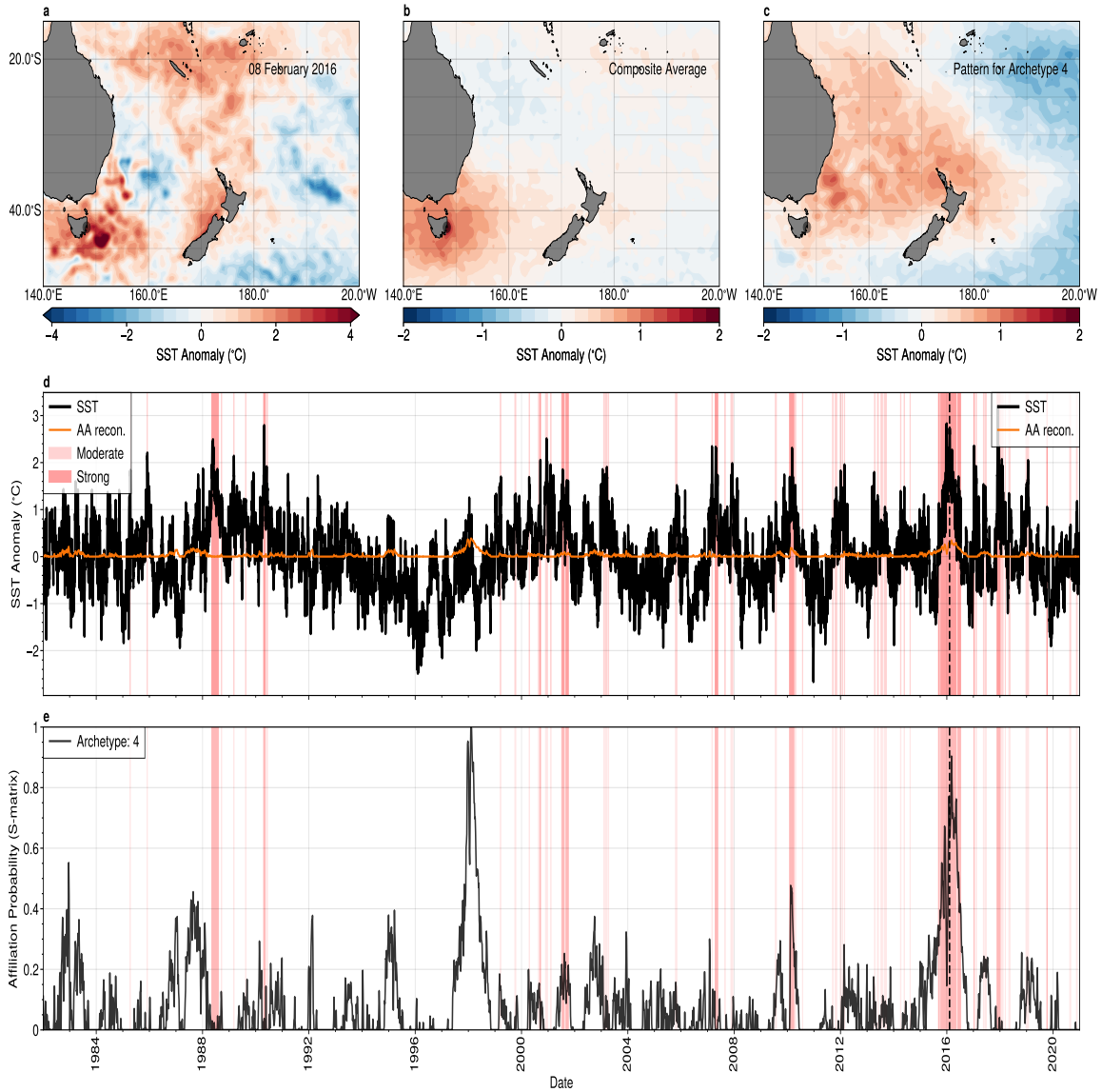


Figure 8: **The relationship between Marine Heatwaves and Archetype #4 in the Tasman Sea:** **a** a snapshot of SST anomalies for the peak of the 2016 strong marine heatwave event, which occurred on the 8th of February, 2016; and **b** SST composite average for all marine heatwaves detected at a representative location. Statistics are calculated at the representative location 45.9°S, 171°E, indicated by the grey circle. **c** the SST anomalies for best matching archetypal pattern (archetype 4); **d** time-series of SST anomalies (black) and the reconstruction from archetype 3 (orange) at the representative location shown in panels **a-c**; **e** time-series of archetype affiliation probability for archetype 3. Colored bands in panels **d,e** indicate marine coldspell occurrences, coded by the severity category described in *Hobday et al. 2018*[3].

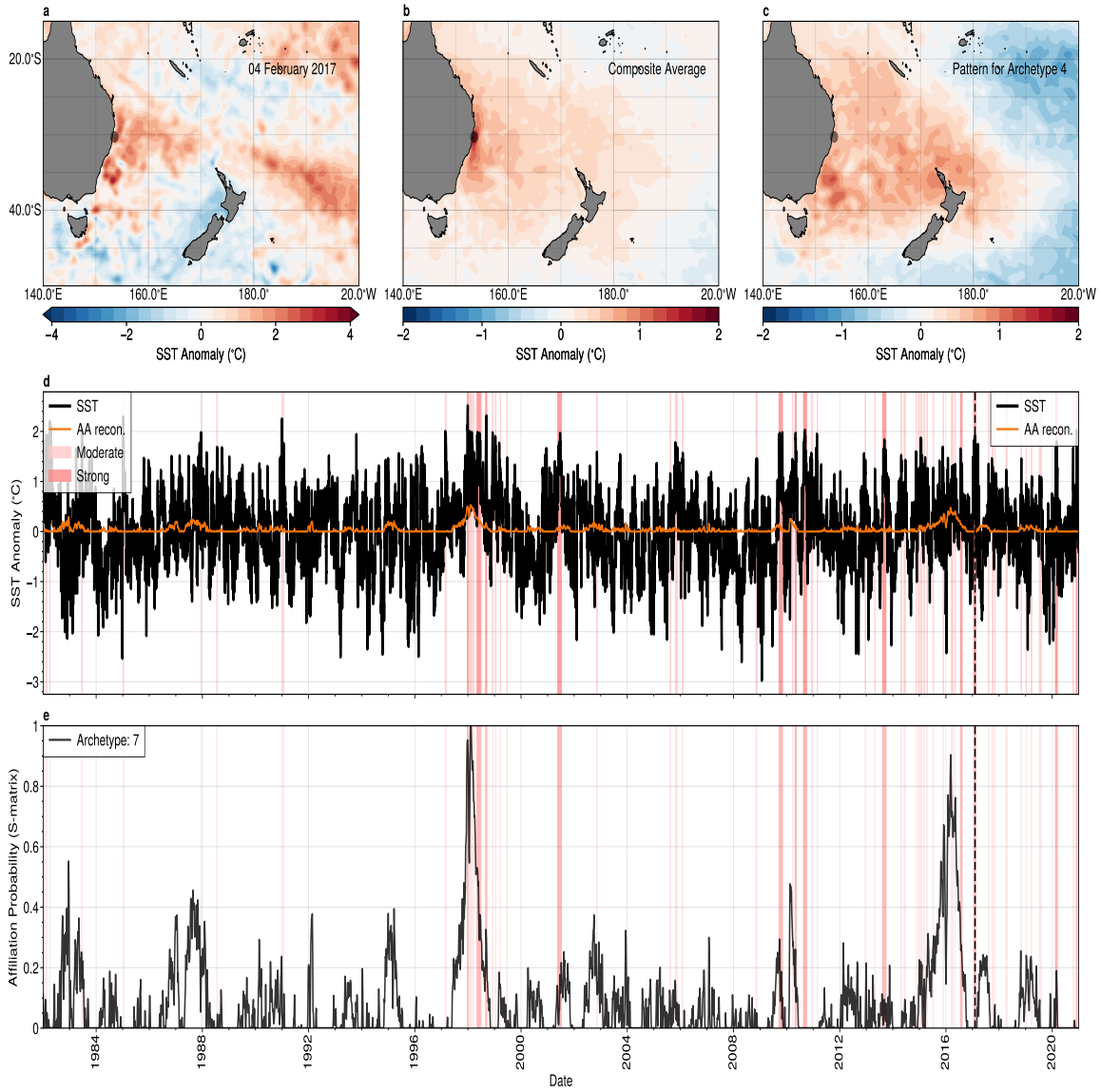


Figure 9: **The relationship between Marine Heatwaves and Archetype #7 in the East Australian Current:** **a** snapshot of SST anomalies for the peak of the 2017-2018 severe marine heatwave event, which occurred on the 5th of December, 2017; and **b** SST composite average for all marine heatwave detected at a representative location. Statistics are calculated at the representative location $30^{\circ}\text{S}, 152^{\circ}\text{E}$, indicated by the grey circle. **c** the SST anomalies for best matching archetypal pattern (archetype 4); **d** time-series of SST anomalies (black) and the reconstruction from archetype 3 (orange) at the representative location shown in panels **a-c**; **e** time-series of archetype affiliation probability for archetype 3. Colored bands in panels **d,e** indicate marine heatwave occurrences, coded by the severity category described in *Hobday et al. 2018*[3]

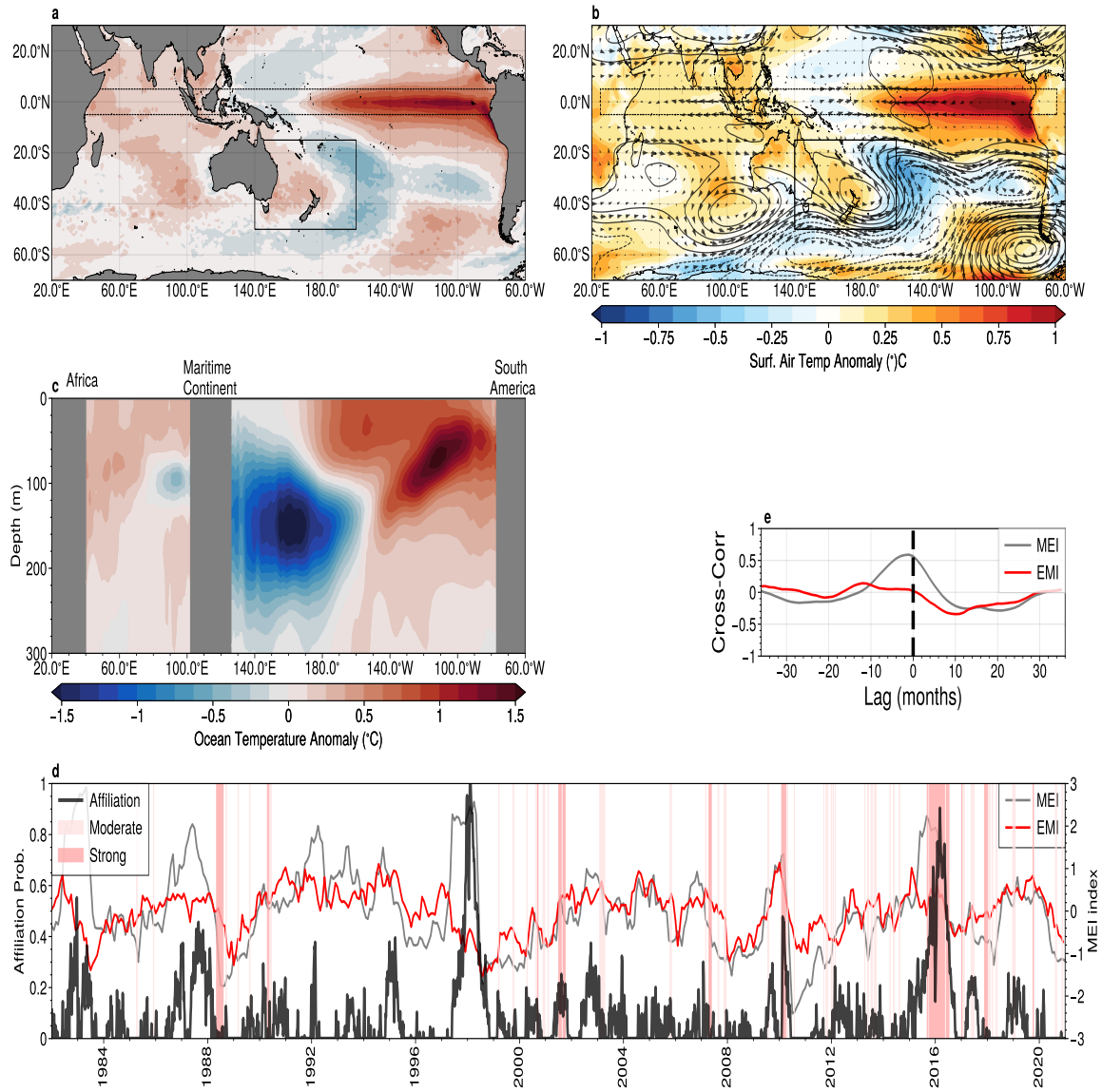


Figure 10: Teleconnections Associated with Marine Coldspells in the Southeastern Indian Ocean: **a** SST anomaly; **b** surface temperature (colours) with anomalous mid-tropospheric (500hPa) geopotential height (contour lines) and winds (vectors); and **c** equatorial subsurface temperatures, associated with archetype #6, the best-matching archetype for marine heatwaves in the southeast Indian Ocean.

The affiliation time-series (solid black) together with the multivariate ENSO index (MEI, grey) and the Marshall SAM index (blue). Periods of marine heatwaves are indicated by red shading. **e** the lagged cross-correlation between the affiliation time-series and the MEI (grey) and the Marshall SAM index (blue). Negative lags correspond to the MEI/SAM index leading the affiliation.

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