Tropical influence on heat-generating atmospheric circulation over Australia strengthens through spring

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Abstract

Extreme maximum temperatures during Australian spring can have deleterious impacts on a range of sectors from health to wine grapes to planning for wildfires but are relatively understudied compared to spring rainfall. Spring maximum temperatures in Australia have been rising over recent decades and it is important to understand how Australian spring maximum temperatures develop in the present and warming climate. Australia’s climate is influenced by variability in the tropics and extratropics, but some of this influence impacts Australia differently from winter to summer, and, consequently, may have different impacts on Australia as spring evolves. Using linear regression analysis, this paper explores the atmospheric dynamics and remote drivers of high maximum temperatures over the individual months of spring. We find that the drivers of early spring maximum temperatures in Australia are more closely related to low-level wind changes, which in turn are more related to the Southern Annular Mode than variability in the tropics. By late spring, Australia’s maximum temperatures are proportionally more related to warming through subsidence than low-level wind changes, and more closely related to tropical variability. This increased relationship with the tropical variability is linked with the breakdown of the subtropical jet through spring and an associated change in tropically-forced Rossby wave teleconnections. An improved understanding of how the extratropics and tropics project onto the mechanisms that drive high maximum temperatures through spring may lead to improved sub-seasonal prediction of high temperatures in the future.
1. Introduction

Anomalously high Australian spring (September-October-November) maximum temperatures can be highly impactful. High temperatures may negatively impact health due to a lack of acclimatisation (e.g. Nairn and Fawcett, 2014), and agriculture by changing growing season length and crop yields (Cullen et al., 2009; Jarvis et al., 2019; Taylor et al., 2018). Hotter and drier spring conditions have been linked to an earlier start to (Dowdy, 2018) and preconditioning of (Abram et al., 2021) the summer fire season. Several recent springs exceeded historic temperature records, with some spring months breaking records set only the previous year (Arblaster et al., 2014; Gallant and Lewis, 2016; Hope et al., 2015; McKay et al., 2021). Much of this observed anomalous heat has been attributed to the background global warming trend (Arblaster et al., 2014; Gallant and Lewis, 2016; Hope et al., 2015; Hope et al., 2016). However, gaps remain in our understanding of the atmospheric mechanisms driving anomalous high maximum temperatures in Australia during spring, and particularly on the monthly timescale that some of these heat events occurred over.

High spring temperatures have been linked with several remote modes of variability in the tropics and extratropics. The negative phase of the Southern Annular Mode (SAM), and its associated equatorward shift of the eddy-driven jet, the positive phases of El Niño Southern Oscillation (ENSO) in the tropical Pacific and the Indian Ocean Dipole (IOD) in the tropical Indian Oceans are the strongest drivers of high spring maximum temperatures in central-southern Australia (Power et al., 1998; Jones and Trewin, 2000; Saji et al., 2005; Hendon et al., 2007; 2014; Min et al., 2013; White et al., 2014; Fogt and Marshall, 2020). Many more studies focus on the relationships between remote drivers of Australian spring rainfall variability (e.g. Nicholls et al., 1989; Meyers et al., 2007; Ummenhofer et al., 2009; Risbey et al., 2009a; Watterson, 2010; 2020; Cai et al., 2011; Min et al., 2013; Pepler et al., 2014; McIntosh and Hendon, 2018) or extreme spring fire weather (Harris and Lucas, 2019; Marshall et al., 2021). Other climate drivers may also promote anomalous high spring maximum temperatures in Australia, including the Madden-Julian Oscillation (MJO; e.g. Wheeler and Hendon, 2004; Wheeler et al., 2009; Marshall et al., 2014). Further, ENSO and the IOD co-vary strongly in austral spring (e.g. Meyers et al., 2007). As such, it can be useful to look at a single index that combines tropical SST variability, such as the tropical tripole
The drivers of anomalous maximum temperatures may vary on a sub-seasonal timescale through spring. The IOD’s influence on Australia’s temperature peaks around SON (Saji et al., 2005) compared to around NDJ (November-December-January) for ENSO (Jones and Trewin, 2000). The influence of SAM on maximum temperature changes from winter to spring, with the positive phase of SAM associated with warmer conditions across much of Australia during winter and cooler in spring (Hendon et al., 2007; Marshall et al., 2012; Min et al., 2013; Fogt et al., 2020). The climatological westerly winds over extratropical Australia shift poleward between winter to summer (e.g. Hendon et al., 2007). Further, the relationship between anomalously high geopotential height (or, synonymously, anticyclonic vorticity) over southern Australia and high spring maximum temperatures (Hope et al., 2015; Gallant and Lewis, 2016) is strongest later in spring (McKay et al., 2021). An ENSO-IOD induced Rossby wave train from the tropical Indian Ocean promotes anomalous high geopotential height south of Australia but follows different pathways from winter to spring (Cai et al., 2011; McIntosh & Hendon, 2018). These season-scale differences suggest that heat may form differently as spring evolves. As SAM, ENSO, and the IOD can only nudge spring conditions toward hotter temperatures (e.g. Hurrell et al., 2009) there is a gap in understanding spring heat, particularly on a monthly timescale.

The Indo-Pacific region subtropical jet (STJ) in the Southern Hemisphere may contribute to sub-seasonal atmospheric circulation changes through spring. The STJ is linked with SAM climate-impacts (e.g. Hendon et al., 2014) and with influencing and preventing Rossby wave propagation from the tropical Indian Ocean toward Australia (e.g. Hoskins and Ambrizzi, 1993; Simpkins et al., 2014; Li et al., 2014,2015a,b; McIntosh & Hendon, 2018; Gillett et al., in review). As the STJ decays through austral spring from its winter peak (Bals-Elsholz et al., 2001; Koch et al., 2006; Ceppi and Hartmann, 2013; Gillett et al., 2021), it may alter the teleconnection pathways from the extratropics and tropics to Australia, influencing local atmospheric circulation and maximum temperature formation as a result.
Atmospheric circulation can enhance spring heat through several mechanisms. Warmer and drier conditions can occur as a result of deflected cooling rain-bearing systems (e.g. Jones and Trewin 2000; Hendon et al., 2007; Pepler et al., 2014; van Rensch et al., 2019) away from Australia (Cai et al., 2011; Risbey et al., 2009b; McIntosh and Hendon, 2018; Hauser et al., 2020). Low rainfall correlates with high maximum temperatures (Simmonds, 1998; Jones and Trewin, 2000; Timbal et al., 2002; Hope and Watterson, 2018), and antecedent dry conditions have been found to contribute to anomalous spring heat (Arblaster et al., 2014) or heat waves (e.g. Fischer et al., 2007; Hirsch et al., 2019; Loughran et al., 2019; Hirsch & King, 2020). Anomalous heat is also associated with increased subsidence and insolation (Hendon et al., 2014; Lim et al., 2019b; Pfahl et al., 2015; Quinting and Reeder, 2017; Suarez-Gutierrez et al., 2020) or heat advection (Jones and Trewin, 2000; Boschat et al., 2015; Gibson et al., 2017). While land-surface feedbacks are important for heat formation we focus on the dynamical mechanisms that generate high spring maximum temperatures.

This study will address the influence of atmospheric processes on how extreme maximum temperatures develop in Australia through spring. In particular, the relative influence of the extratropical and tropical drivers on a monthly timescale through spring will be explored. Filling the gap between weather and seasonal time-scales is an ongoing area of research that can lead to improved sub-seasonal forecasting (Meehl et al., 2021). Given the increasing likelihood of future extreme heat events occurring through spring, it is imperative to understand how they develop now.

The remainder of the paper is structured as follows: The reanalysis datasets, Rossby wave and statistical analysis methods are described in Section 2. An overview of how Australian spring maximum temperatures are related to circulation and large-scale variability is in Section 3. How these relationships vary on a monthly timescale is assessed in Section 4 and how that relates to the subtropical jet is explored in Section 5. Section 6 describes how the drivers influence the mechanisms that promote high monthly maximum temperature. Discussion and conclusions are provided in Section 7. Our focus is on understanding the atmospheric drivers of heat, although we include some discussion of land-surface feedbacks in Section 7.
2. Methods and data

2.1 Indices and datasets

All circulation variables for September, October, November monthly-averaged data are taken from the ECMWF’s Reanalysis 5 (ERA5) (Hersbach et al., 2020) available from the Copernicus Climate Change Service (C3S, 2017) on a 0.25° grid. Here, we use data from 1979 to 2019. Low-level circulation is diagnosed using 850 hPa horizontal wind and mean sea level pressure (MSLP). Mid-tropospheric vertical motion is represented by 500 hPa velocity. Upper-level circulation is represented by 200 hPa geopotential height (200Z). 200 hPa horizontal winds are used for Rossby wave analysis. Similar results were found using ERA-Interim reanalysis (Dee et al, 2011) and the JRA-55 from the Japan Meteorological Agency (2013) (not shown).

Australian monthly-averaged daily maximum temperature data for 1979 to 2019 is taken from the Australian Water Availability Project (AWAP; Jones et al., 2009) analyses, available on a 0.05° resolution grid.

Monthly sea surface temperature (SST) is taken from NOAA Extended Reconstructed Sea Surface Temperature (ERRSST V5; Huang et al., 2017)

The impact of SAM on Australia’s climate shows some sensitivity to the method used to calculate the SAM index (e.g. Risbey et al., 2009a). To ensure consistency between the other indices and circulation variables, we calculate SAM as the difference between the standardized zonal means of ERA5 MSLP anomalies at 60°S and 40°S (Gong and Wang, 1999).

The tropical TPI (Timbal and Hendon, 2011) is defined as the difference in SST averaged over a parallelogram located over the Maritime Continent (0°-20S, 90°-140E at the equator shifted to 110°-160°E at 20°S) from SST averaged and summed over two regions in the tropical Indian Ocean (10°N to 20°S, 55° to 90°E) and tropical Pacific Ocean (a trapezium that extends from 15°N to 15°S, 150°E to 140°W in the north and 180°E to 140°W in the
ENSO is described using the Niño3.4 index (averaged SST anomalies over 5°N-5°S, 170°E-120°W) and the IOD using the dipole mode index (DMI; the difference between the SST anomalies averaged over 10°S-10°N, 50°-70°E and 10°S-0°, 90°-110°E; Saji et al., 1999).

To highlight the influence of interannual variability, the 1981-2010 climatological mean is removed from each month.

All data are linearly detrended before analysis.

2.3 Rossby wave analysis

We use wave activity flux (WAF) at 200 hPa to trace Rossby wave group propagation and to identify source and decay regions that influence the atmospheric circulation patterns.

Following Takaya and Nakamura (2001), we calculate WAF as:

\[
WAF = p \cos \phi \left\{ \frac{U}{a^2 \cos^2 \phi} \left( \frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \frac{\partial^2 \psi'}{\partial \lambda^2} \right\} \\
+ \frac{V}{a^2 \cos \phi} \left[ \frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \phi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \phi} \right] - \frac{U}{a^2 \cos \phi} \left[ \frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \phi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \phi} \right]
\]

where \( p \) is the pressure (200 hPa) scaled against 1000 hPa, \( U \) and \( V \) are the climatological zonal and meridional wind speed magnitudes, \( a \) is the radius of the Earth, \((\phi, \lambda)\) are latitude and longitude, \( \psi' = Z'/f \) is the quasi-geostrophic perturbation streamfunction, \( Z' \) is the 200 hPa geopotential height anomaly obtained through regression onto maximum temperature or climate driver indices, \( f = 2\Omega \sin \phi \) is the Coriolis parameter with the Earth’s rotation \( \Omega \). WAF is not plotted within 10° of the equator.

WAF is parallel to the direction of quasi-stationary Rossby wave group velocity, and regions of divergence or convergence of WAF correspond to zones of Rossby wave sources or sinks respectively.
Total stationary Rossby wave wavenumber (e.g., Hoskins and Karoly, 1981) is defined as:

\[ K_s = \sqrt{\beta - U_{yy}} \]

where \( \beta - U_{yy} \) is the meridional gradient of mean-state absolute vorticity at 200 hPa. WAF should refract toward regions of higher \( K_s \) and either reflect or evanesce on regions of \( K_s < 0 \), such as in the STJ where the curvature of the flow \( (U_{yy}) \) can become larger than the planetary vorticity gradient \( (\beta) \) (e.g., Barnes and Hartmann, 2012; Li et al., 2015 a,b).

2.4 Statistical analysis

Linear, partial, and multi-linear regression and Spearman’s ranked correlation are used to assess the relationships between Australian maximum temperature, atmospheric circulation and the tropics and extratropics. Due to the large decorrelation length scales, Australian-average maximum temperature variability is representative of all but far north Australia’s spring and spring-monthly maximum temperatures (Sup. Fig. 1). Statistical significance is calculated at the 95% confidence level using Student’s (1908) t-test using 39 (41 years - 2) degrees of freedom. Pattern correlation is used to compare regression patterns.

3. Spring-season maximum temperatures - circulation patterns and associations with drivers

We start by giving an overview of the spring-seasonal relationships between average Australian austral spring maximum temperature and lower- and upper-level atmospheric circulation (Fig. 1a,b). Barotropic cyclones appear southwest and southeast of Australia, occurring in both the lower- and upper-level circulation regressions (Fig. 1a-b), as noted during recent extreme spring heat events (Gallant and Lewis, 2016; Hope et al., 2016; McKay et al., 2021). Weak anomalous anticyclonic low-level winds are found over Australia, as well as sinking motion across the eastern half of the continent. An upper-level anticyclone sits over southern Australia, with the wave activity flux indicating Rossby wave propagation predominantly from the subtropical Indian Ocean, through the anticyclone, and into the subtropical Pacific Ocean.
We now compare the atmospheric patterns associated with spring maximum temperature to those calculated via linear regression onto each standardised climate driver index. Note that the TPI and SAM indices have been multiplied by negative one to present positive associations with high temperatures. The pattern for SAM (x-1) shows elongated barotropic low and high anomalies lie in the middle and high latitudes respectively (Fig. 1c-d), with upper-level cyclonic nodes to the southeast and southwest of Australia. Negative SAM is associated with high maximum temperatures through much of subtropical, and particularly eastern, Australia (Fig. 1e).
The tropical modes, represented by Niño3.4 (Fig 1i-k), the DMI (Fig. 1 l-n), and tropical TPI (x-1) (Fig 1f-h) are also associated with high spring Australian maximum temperature anomalies. Each mode generates an apparent Rossby wave pattern that arcs from the tropical Indian Ocean to promote anomalous high geopotential height south of Australia, consistent with earlier studies (e.g. Cai et al., 2011; Timbal and Hendon, 2011; McIntosh &...
The tropical TPI (x-1) is a blend of both Niño3.4 and DMI circulation patterns and has a strong relationship with Australian spring maximum temperatures across all but northern Australia. Each tropical regression also shares anomalous high surface pressure over Australia, sinking motion in the east, cyclonic nodes to the southwest and east of Australia, and elongated upper-level cyclones in the subtropical Indian Ocean. These similarities are likely the result of the strong co-variability between the IOD and ENSO (e.g. Meyers et al., 2007; Risbey et al., 2009a). However, the IOD has a stronger low-level cyclone to the southeast and a poleward extension of the subtropical Indian Ocean cyclone that sets a subtly different wave train from around 50°S, 60°E that is poleward of that generated by ENSO. The positive IOD is also associated with high maximum temperatures across a broader region of southern and western Australian than is El Niño. Given the similarities and connections between ENSO and IOD teleconnections, we use the tropical TPI to represent the large-scale influence of the tropics. SAM is used to represent the influence of the extratropics. Statistical models of Australian weighted area-averaged spring maximum temperatures reconstructed through multilinear regression using either Niño3.4, DMI and, SAM or the tropical TPI and SAM as the predictors explain similar levels of maximum temperature variability (32% and 34% respectively; Sup. Fig. 2).

We next compare the atmospheric circulation associated with spring monthly high maximum temperatures to that with the large-scale modes of variability. To ensure that we are assessing the influence of the tropics and extratropics separately, we use multi-linear regression onto the monthly circulation variables.

4. Monthly circulation patterns and associations with drivers

The regression of monthly Australian maximum temperature onto the lower- and upper-level atmospheric circulation is displayed in Figures 2a-c and 3a-c respectively for September, October and November. The multi-linear regression onto the standardised monthly indices of SAM (x-1) and tropical TPI (x-1) are in Figures 2d-j and 3d-j. At first glance, these monthly circulation patterns are similar to the spring-average regression patterns. However, the details of the circulation patterns change as the months progress.
The most obvious change in atmospheric circulation through the months is in the low-level flow across Australia, particularly generated by the barotropic cyclones southwest (SWC) or southeast (SEC) of Australia (boxes in Fig 2a-b). Weak anomalous low-level anticyclonic flow around the Tasman Sea (box in Fig. 2c) also contributes to the anomalous northerly flow over eastern Australia in November in particular (Fig. 2c). Tasman Sea anticyclonic blocking patterns have previously been linked to anomalously warm conditions (Marshall et al., 2014), but here appear to only contribute to high maximum temperatures in November. The SWC and SEC vary in geographic shape and strength through the months. The SWC dominates in September but weakens through October and November, whereas the SEC is...
missing in September but is strong in October and November. Similar cyclones appear in the
monthly SAM (x-1) regressions (Figs. 2 d-f, 3d-f) and the Australian-region MSLP correlates
strongly with that associated with high Australian temperature (top-right of Fig 2d-f). Rather
than cyclones in September and October the TPI (x-1) is associated with a barotropic
anticyclone south of Australia that directs anomalous southerly low-level wind across
eastern Australia (Figs. 2 h-j); a pattern that would be associated with anomalously cooler
conditions. The September and October TPI (x-1) MSLP patterns anti-correlate with that
associated with high Australian maximum temperatures (top-right Fig. 2 g-i). It is not until
November that we see a barotropic cyclone to the southeast of Australia associated with
the TPI (x-1). So, for the majority of spring negative TPI-forced low-level atmospheric
circulation appears to counter high maximum temperatures, despite the overall positive
relationship in spring (Fig. 1h).

The anomalous southern Australian upper-anticyclone (SAA) from the spring pattern is also
associated with high maximum temperature in each of the individual spring months (Fig. 3a-
c), but its location shifts eastward across Australia through spring. The boxed region was
chosen to match earlier studies (Gallant and Lewis, 2016; McKay et al., 2021), but best
matches the November position, likely contributing to the stronger relationship between
heat and SAA in this month (McKay et al., 2021; see also section 6). The anticyclone in later
spring appears to form part of a wave train from a cyclone to the northwest of Australia
toward the southeast cyclone. While the monthly TPI regressions have anticyclones in
September and October (Fig. 3g-h), they are located too far south relative to Australia, as in
the spring-average regression. The regressions onto SAM (x-1) (Fig 3d-f) have weak
anticyclones over western Australia that are not statistically significant. It is not until
November that both SAM and TPI (x-1) (Figs 3 f, i) have an anticyclone over central-east
southern Australia. Both the upper- level SAM and TPI (x-1) regressions correlate
moderately with the maximum temperature regression in November, and the SAM and TPI
(x-1) anticyclones may form part of the same wave train associated with maximum
temperatures. However, the SAM and TPI (x-1) anticyclones are weaker and too far east
relative to that associated with high maximum temperatures, such that they may not
contribute strongly to the SAA formation. We explore this idea further in section 6.
While the southern Australian anticyclone is not well explained by SAM or TPI (x-1) through spring, much of the statistically significant 500 hPa vertical motion associated high maximum temperatures (green and magenta contours, Fig. 2a-c) matches that associated with TPI (Fig. 2h-j) and to a lesser extent SAM (Fig. 2d-f). In September, sinking motion over subtropical Australia and rising motion over the southern coasts is associated with high maximum temperatures. By November, the rising motion has largely vanished, and the sinking motion has shifted to be over eastern Australia. It was expected that the SAA would generate some of the sinking motion associated with high maximum temperature, however, this vertical motion does not correlate strongly with any of the key circulation features examined here (Sup. Table1).

Changes in wave activity flux help explain some of the changes in the broad scale circulation changes through spring. In September, WAF predominantly diverges from the southwest cyclone toward the southern Australian anticyclone. In October, a component of WAF also diverges from the eastern tropical Indian Ocean region. By November, the tropical-
component dominates the WAF and forms part of a very different pattern to the previous
two months; continuous WAF follows a wave train that appears to propagate from the far
southwest Indian Ocean. This wave joins with a wave out of the tropical Indian Ocean, as
indicated by the tropical-origin WAF, to then continue through the southern Australian
anticyclone. The latter part of this wave train is similar to the IOD teleconnection
highlighted by Cai et al. (2011) in spring. The WAF associated with SAM and TPI (x-1) also
diverges from the extratropics toward the respective anticyclones in September and
October. While a broad region of low height in the subtropical Indian Ocean is associated
with the TPI, it does not appear to generate WAF that diverges into the extratropics. It is not
until November that WAF associated with the TPI (x-1), and weakly with SAM (x-1), appears
to diverge directly from the cyclone in the eastern subtropical Indian Ocean, indicating a
wave that joins the anticyclone over southeastern Australia.

Overall, the circulation associated with maximum temperature appears to shift from
extratropical to tropical forcing as spring progresses. SAM projects onto the atmospheric
circulation associated with maximum temperatures in September, while the TPI projects
more strongly later in spring. The change in WAF associated suggests that there may be a
blocking mechanism between the tropics and extratropics generating this change.

We find qualitatively similar results if we perform the linear regressions using maximum
temperature averaged over sub-regions of Australia, for example southwest or southeast
Australia (Sup. Fig. S3).

5. Connection between subtropical jet and atmospheric circulation

We next explore how the subtropical jet (STJ) may be influencing the WAF through the
spring months.

The STJ should effectively block direct propagation of Rossby waves from the tropical Indian
Ocean into the extratropics (e.g. Simpkins et al., 2014; Li et al., 2014;2015a,b). However, the
gradual decay of the jet through spring (e.g. see figure 9, Ceppi and Hartmann, 2013) may
reduce its effectiveness as a Rossby wave block (e.g. Wirth, 2020), allowing more direct
propagation into the extratropics by November. The STJ decay coincides with a decrease in
the area with total stationary wavenumber \((K_s)\) less than zero over southern Australia (Fig. 4).

Figure 4. Total wave number \((K_s)\) calculated September, October and November. Vectors are the wave activity flux repeated from figure 3.

The wave activity flux vectors from the maximum temperature, TPI and SAM \((x-1)\) regressions in Fig. 3 are overlaid in Fig. 4 on the monthly climatological \(K_s\) associated with the zonal winds. In September, the WAF associated with high maximum temperature indicates waves propagate through a region of low \(K_s\) over southwest Australia and are then directed along the STJ waveguide (e.g. Ambrizzi et al., 1995) \((i.e.\ from\ high\ to\ low\ latitudes)\).

As the jet weakens in October (Fig. 4b) a portion of WAF also diverges from the tropical Indian Ocean to dissipate on the jet’s equatorward flank, but mostly propagates from west to east along the STJ waveguide. WAF in November (Fig. 4c) is even more distinctive in showing Rossby waves that propagate along the jet waveguide from a region near Africa, upstream of the figure’s western edge, with further contributions from the tropical Indian Ocean.

The increase in WAF out of the tropical Indian Ocean associated with the tropical TPI \((Fig\ 4h-j)\) coincides with the STJ decay. In September and October weak WAF diverging from the central southern Indian Ocean indicates wave trains follow the eddy-driven jet waveguide \((region\ of\ locally\ higher\ wave\ number\ around\ 50^\circ S)\). McIntosh and Hendon (2018) proposed that transient eddy-feedbacks generate a secondary wave source in winter poleward of the STJ in response to IOD forcing. The high latitude wave train found in association with the TPI
may indicate that this secondary wave source is also important in early spring. The tendency for TPI-associated WAF to follow this trajectory may explain why the barotropic anticyclone associated with the TPI is further poleward than in the regression onto Australian maximum temperature. By October increased WAF diverges from the tropical Indian Ocean to divert along the region of high Ks. By November WAF diverges out of the extratropical Indian Ocean along the high Ks region, similar to the maximum temperature-WAF. This increase in tropical-origin WAF is consistent with increased wave trains propagating out of the tropical Indian Ocean associated with the TPI. WAF generated by SAM (Fig. 4d-f) also converges toward the STJ waveguide in each month.

The STJ acts as a waveguide (Hoskins and Ambrizzi, 1993), with the majority of WAF associated with Australian maximum temperature, and with the tropics and extratropics indicating wave trains divert to propagate along the jet. Limits around linear Rossby wave theory (e.g. Liu & Alexander, 2007) may explain why some wave activity flux cross the region of imaginary wavenumber associated with the STJ. While the breakdown of the STJ through spring may help explain the change in teleconnection pathways of the TPI toward Australia it may not directly explain the change in atmospheric circulation associated with maximum temperature.

We now look more closely into how the drivers, circulation features, and heat mechanisms relate to each other and how that results in higher Australian maximum temperatures.

6. Mechanisms and drivers of monthly maximum temperatures through spring

As with the atmospheric circulation regressions, the relationships between Australian maximum temperature and SAM and TPI (x-1) evolve through the spring months. In September, negative SAM (Fig. 5a) is associated with a broad area of high maximum temperature over subtropical Australia, that contracts in October and November (Figs. 5 b-c). Conversely, the relationship with negative TPI and maximum temperature is weaker early in spring, with statistically significant high temperatures confined to the west and east, and cool temperatures in the far north in September (Fig. 5d). The TPI’s relationship with high
maximum temperature broadens and strengthens in October and covers the majority of Australia by November (Figs. 5 e-f). Overall, these monthly relationships give the impression of a transition from extratropical to tropical drivers becoming more influential over Australian temperatures that is broadly consistent with the apparent change in atmospheric circulation through spring.

Figure 5. Multilinear regression coefficients (°C) of Australian maximum temperature regressed onto standardised timeseries of the SAMx-1 (a – c) and the tropical TPI x-1 (d - f) for September, October and November over the years 1979 to 2019. Reconstructions (blue bars) of September, October and November (i-k) Australian area-averaged maximum temperature from standardised time series of SAM and tropical TPI indices. Observed values are shown as red bars. The dashed line shows the 95% prediction interval computed as +/-1.96 standard error and the variance explained ($r^2$) of the model is in the top right of each figure.

Using the standardised SAM and TPI time series as predictors in a regression model to reconstruct the monthly Australian-averaged maximum temperature anomalies (Figs 4g-i) explains only between 18 and 36% Australian maximum temperature variance ($r^2$) through spring. The model does not substantially improve if it is calculated over southeast or
southwest Australia, or if using Niño3.4 or DMI as predictors instead of the tropical TPI (Sup. Fig.4).

To explore how the atmospheric circulation relates to some of the mechanisms that develop heat through spring, we first compose indices of the key circulation features discussed in section 4. Weighted area-averages of mean-sea level pressure (multiplied by negative one) over the southwest and southeast cyclones (SWC and SEC) and 200 hPa geopotential height over the southern Australian anticyclone (SAA) for each spring month. See Figs. 2a,b and 3a-c for regions. Creating a statistical model of Australian-averaged monthly spring maximum temperatures from these circulation features (Fig. 6a-c) explains consistently higher maximum temperature variance (around 60%) than did the model from the indices of tropical and extratropical large-scale modes of variability. Further, despite the changes in the features’ geographic shape, strength, and position across the spring months in Fig. 2, the majority of maximum temperature across Australia is well explained by at least one of these features at all times through spring (Sup. Fig. 5). We next explore how these MSLP or 200 hPa geopotential height features relate to the anomalous low-level westerly or northerly winds and vertical motion and how that relates to high maximum temperature development.

Figure 6. As in figure 4 (g-i), but using time series of key circulation features (south-west low, south-east low and southern Australian anticyclone) identified in figures 1 and 2 as predictors in the top row (a-c) and area-averaged dynamical heat mechanism components (850 hPa zonal wind and meridional wind (multiplied by -1) and 500 hPa vertical motion; see text for region averaged over) as predictors in the bottom row (d-e) for September, October, and November.
Following van Rensch et al (2019), indices of three dynamical heat mechanisms were created by weighted area-averaging of westerly and northerly wind (meridional wind multiplied by -1) anomalies over a region around southern Australia (25°S-45°S, 105°-155°E), and 500 hPa vertical motion anomalies (omega; positive is sinking motion) averaged over subtropical Australia (15°S-25°S, 120°-155°E). Regions were selected based on the areas of highest statistical significance between atmospheric circulation and Australian maximum temperature in Fig. 2a-c. A statistical model of Australian-averaged maximum temperatures that uses these mechanisms as the predictors explains a higher proportion of maximum temperature variance through spring than does the model using SAM or the tropical TPI (Fig. 6d-e). The percent variance explained is higher in September (about 80%), before dropping to around 55% in October-November. This decrease appears to be primarily associated with how strongly the anomalous westerly winds correlate with maximum temperature over southern Australia; strong positive relationship with anomalous westerly wind in September changes to insignificant or negative in October and November (Sup. Fig S6a-c). There is also an increase in negative correlation between maximum temperatures and anomalous northerly winds in north-eastern Australia (Sup. Fig S6d-e) that will partly offset the increasing positive relationship further poleward. These changing relationships between dynamical mechanisms and maximum temperature through spring are linked with the changing relationships with the circulation features (Sup. Table 1). Overall, the three dynamical heat mechanisms explain much of Australia’s monthly spring maximum temperature variability.

Figure 7 summarises the relationship between Australian maximum temperatures, circulation features, dynamical heat mechanisms and climate drivers through the spring months. The correlation between the SEC and Australian maximum temperature is strongest in September and rapidly decreases through October and November, and simultaneously the correlations with the SWC and particularly the SAA increase. As expected from Fig. 2, the SEC and SWC are more closely linked with the extratropics. Linearly regressing out the SAM component from time series of the SWC and SEC reduces the correlation strength with Australian maximum temperature (Fig. 7a), particularly in September. Conversely, linearly removing the tropical TPI slightly increases the correlation between the cyclones and temperature, with the partial-correlation only weakening in
November. As SAM is strongly related to the barotropic cyclones it is also strongly related to how temperature changes with the anomalous westerly wind. Linearly removing SAM from the westerly wind time series nearly halves the correlation with maximum temperature in September and weakens the correlation in October and November (Fig. 7b). Conversely, linearly removing the tropical TPI actually slightly increases the correlation with the westerly wind anomalies in September and October but decreases the correlation in November.
The relationships with anomalous northerly wind and sinking motion and Australian-averaged maximum temperature do not change as dramatically with the removal of SAM or the TPI. Anomalous northerly wind is not strongly influenced by the tropics or extratropics in September or October, but the correlation strengthens and weakens in November with the removal of the TPI and SAM, respectively. While removing SAM and TPI from the SAA
had relatively little influence on the correlation with Australian maximum temperatures, removing SAM from sinking motion in September and both TPI and SAM in October and November reduced the correlation. Overall, it appears that the heat mechanisms associated with high maximum temperatures in spring are influenced differently by the different influence of the extratropics and tropics on the local atmospheric circulation features through spring.

7. Discussion and conclusions

The sources of the atmospheric circulation patterns associated with high monthly-maximum temperatures in Australia appear to change from primarily extratropical in early spring to tropical in late spring. Examination of three dynamical heat mechanisms (anomalous low-level winds broken into westerly and northerly components, and anomalous mid-tropospheric sinking motion) indicates that this shift may be due to a change in how heat develops. In early spring, the low-level wind plays a greater role in maximum temperatures, advecting relatively warmer air from the oceans over the cold landmass. This wind correlates strongly with the extratropics (here, SAM), as SAM projects strongly onto the southwest and southeast cyclones that direct a lot of the low-level flow around Australia. Conversely, the atmospheric circulation associated with the TPI (x-1) acts to counter the low-level flow that drives higher temperatures. Thus, in early spring we have a closer association with heat production and the extratropics. By late spring, the circulation patterns associated with high temperature have changed and the wind does not correlate as strongly. As such adiabatic sinking over subtropical Australia has a proportionally stronger correlation with high temperatures. Both SAM and TPI (x-1) regressions show sinking motion in the subtropics through spring. While El Niño can promote negative SAM from late spring (L’Heureux and Thompson, 2006; Hendon et al., 2007; Lim et al., 2016; Lim et al., 2019a), the TPI that better matches the sinking motion over eastern Australia in November. Hence, the apparent change from extratropical to tropical forcing in the circulation pattern is likely because the tropics promotes more of the heat developing mechanisms later in spring. However, much of the atmospheric patterns associated with heat through spring are explained by neither the tropical TPI nor SAM.
The subtropical jet appears to play a greater role in Australian spring heat by acting as a wave guide (Hoskins and Ambrizzi, 1993) that directs quasi-stationary Rossby waves toward Australia, rather than as a block that limits direct propagation of Rossby waves from the tropical Indian Ocean to the southern hemisphere extratropics (e.g. Simpkins et al., 2014; Li et al., 2015 a,b). While wave activity flux appears to indicate wave propagation occurs directly out of the tropical Indian Ocean later in spring, the upper-level atmospheric anomalies are broadly consistent with IOD-forced wave trains identified in the literature (Cai et al., 2011; McIntosh and Hendon, 2018; Wang et al., 2019). As such, the secondary wave source in the high latitudes of the Indian Ocean proposed by McIntosh and Hendon (2018) may be key for promoting the TPI-forced atmospheric circulation in early spring. Overall, the STJ decay appears to be a lesser factor than the dynamical heat mechanisms in the apparent change from extratropical to tropical forcing of maximum temperatures through spring. Consistent with this idea, wave activity flux calculated by first regressing 200Z onto the three dynamical heat mechanisms (Sup. Fig. 7) also indicates waves change extratropical or tropical forcing through spring, that then propagates along the jet wave guide toward Australia.

Area-averaged anomalous low-level wind and vertical motion were used to understand how the atmospheric circulation relates to Australia-wide maximum temperatures and explain much of the spring maximum temperature variability. However, it was not always clear how the atmospheric circulation features influenced those heat mechanisms. The southern Australian anticyclone and 500 hPa subtropical-Australian sinking motion, while important for heat, appear to be largely uncorrelated with the other circulation features and mechanisms. Greater insight into how remote forcing of the atmospheric circulation results in high Australian temperatures could be gained by including other heat mechanisms in future analyses, including: insolation (Lim et al., 2019b), changes to synoptic weather systems (Cai et al., 2011; Hauser et al., 2020), and land-surface feedbacks linked to antecedent moisture (e.g Seneviratne et al., 2010; Arblaster et al., 2014; Hirsch and King, 2020). Including the preceding month’s Australian-averaged rainfall anomaly as an additional predictor of Australian monthly maximum temperatures did increase the percent variance explained by the statistical model (Sup. Fig. 8), but only in later spring. Dry conditions have been noted as an important factor in Australian summer heat waves (Hirsch...
et al., 2019; Loughran et al., 2019; Hirsch & King, 2020), and may be important for extreme heat in late spring.

While simplifying heat mechanisms into three separate indices was useful, geographic differences across Australia and interactions between mechanisms should also be considered. The combination of poleward advection of adiabatically warmed air after it descends anticyclonically over the Tasman Sea has been identified as a key mechanism for summer heatwaves in southeast Australia (e.g. Quinting and Reeder, 2017). This combination of mechanisms may generate heat through spring, particularly in the east and in November. The rising motion over southern Australia requires further investigation as it may be another factor in the combination of heat-mechanisms. Air diabatically warmed in association with storminess just to Australia’s south may then be advected and descend toward Australia.

We used the tropical TPI to represent tropical variability relevant to Australia’s maximum temperature, but other indices or drivers may highlight different Rossby wave pathways or heat mechanisms. Reconstructing Australian maximum temperature time series with more commonly used indices for the IOD and ENSO did not change the effectiveness of the statistical models overall (Sup. Fig. 4). However, this model did show a stronger relationship between temperature and the IOD in early spring and ENSO in later spring, consistent with earlier studies (Jones and Trewin, 2000; Saji et al., 2005). As such, monthly IOD regressions onto atmospheric circulation may produce different wave trains earlier in spring than found with the tropical TPI. The MJO may also influence the atmospheric circulation associated with monthly maximum temperature development. MJO-initiated Rossby wave trains from the western Pacific promote low winter minimum temperatures in Australia (Wang and Hendon, 2020), and from the tropical Indian Ocean to promote high spring maximum temperatures in Australia (personal communication: Wang and Hendon, 2021). The positive phase of the IOD suppresses MJO activity across the Indian Ocean (Wilson et al., 2013), possibly restricting the MJO’s influence on Australia’s maximum temperature. However, MJO activity in the tropical Indian Ocean has recently been found to counter the wetting influence of La Niña during spring (Lim et al., 2021b). As such the MJO may be an important
factor for spring maximum temperatures, particularly when the tropical SSTs are not otherwise conducive for high temperatures.

As the trend toward higher Australian spring temperatures is projected to continue into the future, a better understanding of what drives maximum temperatures over the months of spring is critical. A combination of extreme values in remote tropical and extratropical drivers of variability, exacerbated already dry and hot conditions in spring 2019 to promote one of Australia’s deadliest fire seasons (Watterson, 2020; Lim et al., 2021a; Abram et al., 2021, Marshall et al., 2021). Further, projected trends toward positive IOD (Cai et al., 2014; Abram et al., 2020) may contribute to higher maximum temperatures in the future, particularly in later spring when the tropics exert greater influence on Australia’s dynamical heat mechanisms. As we have shown just how different the atmospheric circulation and heat mechanisms can be through a season in Australia, other regions and seasons could also benefit from similar analysis, particular as the world continues to warm (e.g. Collins et al., 2013).

Code and data availability
The code for analysis is available from the corresponding author on request. ERA5-reanalysis data are available from Copernicus Climate Change Service at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. AWAP data is available from the Australian Bureau of Meteorology.

Author contribution
R.C.M. produced the figures and wrote the initial draft manuscript. All authors contributed to analysis and editing of the manuscript.

Competing interests
The authors declare that there are no conflicts of interests.
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