An Investigation of the Links between ENSO Flavors and Rainfall Processes in Southeastern Australia

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ABSTRACT

The causes of rainfall variations in southeastern Australia associated with three key El Niño years (1982, 1997, and 2002) are explored. Whereas 1982 and 2002 were exceptionally dry years, 1997 had near-average rainfall. These variations in rainfall can be explained by changes in the behavior of cutoff low pressure systems. Although each year had a similar number of cutoff low events, 1997 had higher rainfall per cutoff low event when compared with the other years. In particular, rain in 1997 is attributable to five large wet events from cutoff low pressure systems. In each of these wet events, the moist air originated from the marine boundary layer off the coast of northeastern Australia. Cutoff lows in 1982 and 2002 were much drier and did not draw in moist air from the northeastern coast. In typical classifications, 1982 and 1997 are grouped together as “canonical” El Niños whereas 2002 is a Modoki El Niño. The results presented here imply that these groupings are not definitive in explaining variations in southeastern Australian rainfall.

1. Introduction

Reduced rainfall over southeastern Australia has important consequences for agriculture, bushfires, water catchments, and the health of flood plains and wetlands, and rainfall records already show a drying trend (Murphy and Timbal 2008). The trend could be attributable to global warming, large-scale climate variability, or both. The southeast is affected by a complex interplay of remote climate modes: El Niño–Southern Oscillation (ENSO), the Indian Ocean dipole, the southern annular mode, and atmospheric blocking (Risbey et al. 2009).

The interaction of these climate modes is further complicated by the different “flavors” of ENSO. As observed in the last few decades, canonical El Niños originate as a warm-water anomaly in the central Pacific Ocean, advecting eastward as described by the recharge–discharge oscillator (Jin 1997; Meinen and McPhaden 2000). A new type of ENSO—ENSO Modoki (or dateline El Niño)—has been recently documented (Ashok et al. 2007; Larkin and Harrison 2005; Kao and Yu 2009). [“Modoki” is a classical Japanese word that means “a similar but different thing” (Ashok et al. 2007).] In an El Niño Modoki the maximum warm sea surface temperature anomaly is located in the central Pacific, whereas it is farther east in a canonical El Niño, which alters the details of the Walker circulation.

There has been a recent focus on the difference between canonical El Niños, such as 1982 and 1997, and El Niño Modokis, such as 2002, and how these different flavors might affect Australian rainfall (Wang and Hendon 2007; Taschetto and England 2009). However, because only a few events of each type have been observed, the effects have not been established statistically. We have therefore taken a case-study approach to explore how these different ENSO events might manifest themselves in the broader-scale flows that influence local rainfall. If rainfall does change according to ENSO type, we should see corresponding changes in airflows and the local rainfall systems embedded in them. Would some features enable us to distinguish meaningful differences in the influence of ENSO flavors on local rainfall?

To begin to untangle these complexities, we explore the relationship between three very different El Niño
years (1982, 1997, and 2002) and their impact on synoptic weather systems and associated rainfall over the Mallee region in southeast Australia (see Fig. 1). A typical El Niño event results in lower-than-average rainfall for Australia (Nicholls et al. 1996). The strong El Niño of 1997 paradoxically resulted in rainfall that was only slightly below average, whereas the El Niños of 1982 and 2002 occurred with devastating drought (Fig. 2). The 2002 El Niño is considered to be a Modoki, whereas the 1982 event is canonical, as is the 1997 El Niño. Wang and Hendon (2007) explored the differences in broad-scale tropical circulation for 1997 and 2002 to understand the impact of ENSO flavors on Australian rainfall. We revisit this discussion and also include 1982 in our analysis because it provides an interesting contrast. The 1982 El Niño is often grouped with 1997 as a canonical El Niño; however, it had very low rainfall, similar to that in 2002 (Fig. 2).

If the different flavors of ENSO affect Mallee rainfall, then we ought to see this influence reflected in the synoptic processes and systems that generate the rainfall. An important synoptic feature for rainfall in southeastern Australia is cutoff low pressure systems. A cutoff low pressure system is a cold-cored, closed cyclonic circulation that typically forms in the midtroposphere and often extends to the surface over time. The systems are so named because they have become separated or cut off from the midlatitude westerlies to their south. In this region, cutoffs are responsible for at least half of all rainfall in the winter growing season (April–October) and almost all of the daily rainfall events of more than 25 mm (Pook et al. 2006). Although the role of the cutoff lows in providing rainfall is well understood, the mechanisms that alter their frequency, intensity, and rainfall efficiency are not. If ENSO flavors influence

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**Fig. 1.** Correlation of the 8-station-averaged April–October rainfall with Australia-wide “SILO” rainfall for 1950–2007 (SILO Patched Point Dataset hosted by the Australian Bureau of Meteorology online at http://www.bom.gov.au/silo; Jeffrey et al. 2001). Mallee stations are indicated by the white bullets in the state of Victoria (southeastern Australia). The 8-station Mallee rainfall is obtained from a high-quality Australian historical dataset (Lavery et al. 1997). Only values significant at the 95% level have been shaded.
Mallee rainfall differently, we might expect to see these changes in the behavior of cutoff low pressure systems.

Here we explore the differences, if any, between the characteristics of cutoff systems that occurred in the three case-study years involving two ENSO flavors. For each year we examine factors relating to rainfall differences such as the number of cutoffs and other rainfall systems and the amount of rain per system. To explore differences in the amount of rain per system, we examine the air-parcel trajectories along which moisture was entrained into each system. Cutoff low pressure systems entrain moisture from tropical oceans and thus are potentially sensitive to subtropical circulation differences wrought by different ENSO flavors. By using an air-parcel backtracking algorithm (McIntosh et al. 2007, 2009, unpublished manuscript, hereafter MPBR), we determine the origin of the air that feeds into cutoff lows.

2. Data and methods

a. Regional analysis of rainfall

Long records of rainfall were available from eight Mallee stations selected from a high-quality Australian historical dataset (Lavery et al. 1997) (Fig. 1, white dots). The stations are Mildura, Sea Lake, Swan Hill, Rainbow, Birchip, Narraport, Kaniva, and Bendigo. The period of analysis of the rainfall is April–October, which is the growing season for the predominantly winter cropping enterprises of the region. Similar rainfall mechanisms are believed to affect nearby regions of southeastern Australia as evidenced by the high correlations of yearly rainfall totals (Fig. 1).

Using the synoptic classification scheme of Pook et al. (2006) we concentrate on the most important category of synoptic system: the cutoff low. These lows are frequently associated with blocking high pressure systems and can be considered to form the cyclonic component of blocks (Taljaard 1972; Wright 1974; Coughlan 1983; Pook et al. 2006). An index of blocking action for eastern Australia shows it to be significantly correlated with ENSO (Risbey et al. 2009), which may help to elucidate the mechanisms by which the tropical Pacific is linked to cutoff low pressure behavior over southeastern Australia.

b. Backtracking analysis of air parcels

One of the ways to explore the source of moisture to synoptic systems, such as cutoff lows, is to trace the origin of air parcels that end up over the Mallee region on wet days (McIntosh et al. 2007; MPBR). Rain is typically produced from clouds in the lower troposphere, at around 700 hPa. By backtracking air parcels from this altitude above the eight chosen rainfall stations in the region we gained an understanding of the origin and coherence of air-parcel trajectories. By examining the specific humidity along the tracks, we inferred where moisture was entrained, as well as where it was lost as rainfall. This method can also be used to examine air-parcel trajectories on rainless days. The backtracking algorithm is detailed in MPBR.

The dataset we used for the backtracking analysis was the optimal model/data reanalysis produced by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; Kistler et al. 2001). This NCEP–NCAR reanalysis provides, among other variables, three-dimensional velocity, temperature, and humidity on a global grid. The horizontal grid spacing is 2.5° of longitude and latitude; the vertical spacing is variable but is on the order of 100 hPa in the troposphere, and the temporal spacing is 6 h.

3. Results

Rainfall in the Mallee can be broadly categorized by the synoptic systems that created it: frontal systems, cutoff low pressure systems, and other systems (Pook et al. 2006). From Pook et al.’s (2006) results, the amount of rain from frontal systems in our three case-study years was almost the same (red circles in top panel of Fig. 3). Rain from cutoff low pressure systems, however, was different (blue circles; see Table 1). The rainfall totals from cutoff lows in 1982 and 2002 were around one-quarter and one-half of that in 1997, respectively. The
amount of rain from cutoff low pressure systems explains most of the difference in the rainfall totals for the three years of interest and all years in general (green circles).

Pook et al. further analyzed the rain from cutoff low pressure systems according to the number of days on which cutoffs occurred and how much rain fell on each cutoff day (lower panel of Fig. 3). It appears that in each of our three case-study years the number of days that had cutoffs was reasonably consistent (39 in 1982 and 32 in 1997 and 2002; see Table 1). However, the average rain per cutoff day in 1982 and 2002 was remarkably low (0.7 mm in 1982 and 1.3 mm in 2002 as compared with a slightly above average value of 3.1 mm in 1997; see Table 1). It appears that in each of our three case-study years the number of days that had cutoffs was reasonably consistent (39 in 1982 and 32 in 1997 and 2002; see Table 1).

Table 1. Details of cutoff-low rainfall analysis in the Mallee for three case-study years in the period from April to October averaged over the eight stations. A wet cutoff day is defined as having more than 0.2 mm of rain averaged over the eight stations.

<table>
<thead>
<tr>
<th>ENSO flavor</th>
<th>Canonical</th>
<th>Canonical</th>
<th>Modoki</th>
<th>Avg year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total rain per station (mm)</td>
<td>85</td>
<td>201</td>
<td>119</td>
<td>259</td>
</tr>
<tr>
<td>Total rain from cutoff days (mm) and as a percentage of total rainfall</td>
<td>26 (31%)</td>
<td>99 (49%)</td>
<td>42 (35%)</td>
<td>127 (49%)</td>
</tr>
<tr>
<td>No. of cutoff days</td>
<td>39</td>
<td>32</td>
<td>32</td>
<td>44</td>
</tr>
<tr>
<td>Rain per cutoff day (mm day$^{-1}$)</td>
<td>0.7</td>
<td>3.1</td>
<td>1.3</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Table 1). Therefore 1997 was a wetter year because there was higher average rain per cutoff day than in the other two years; it did not have more cutoff events. Note that each of the three years still had fewer cutoff days than an average year (see Table 1).

Each rainfall event was then looked at individually and in detail. In 1997, the high-rainfall tally was attributable to five rainfall events of at least 10 mm day\(^{-1}\), all associated with cutoff low pressure systems (Fig. 4; red stars). In 1982, there was no single rainfall event this large. In 2002, two events brought more than 10 mm day\(^{-1}\). It is interesting that 1997 began as a very dry year. It is not until August that the rainfall patterns change dramatically.

To find out why the cutoffs in 1997 produced large rainfalls but those in 1982 and 2002 did not, we examined the moisture source for each event and calculated the air trajectories that fed into the cutoff. An example of our analysis is shown in Fig. 5 for 1 September 1997. The cutoff low is expressed in both the mean sea level pressure and the 500-hPa height as a closed circulation system near the Mallee (Figs. 5a,c). The parcel of the air that “led” to the rainfall (Figs. 5b,d) traveled over the marine boundary layer off northeastern Australia (Fig. 6). In each of the other cutoff low events over the three years (rain bearing or not), the air originated from elsewhere—never from the northeastern coast of Australia. The air in the wet events in 2002 originated from southwestern Australia (not shown).

We then explored the synoptic situation that led to airflow across the marine boundary layer northeast of Australia. In all of the five cases, a high pressure system was situated off the coast of eastern Australia a few days prior to the cutoff low.

To illustrate the development, we again use 1 September 1997 in Fig. 7. In the 3 h before the rainfall (Fig. 7f), the cutoff low pressure system was adjacent to the Mallee. If the wind pattern were constant in time, the air apparently originated from near the southwestern coast of Australia (dashed line). However, if the air trajectory is traced backward according to the time-dependent winds and at the appropriate height, we find that it originated in the low levels off the east coast of Australia 3 days earlier. In each of the five wet events in 1997 we find a consistent path of air into the cutoff low. Three–four days prior to a rainfall event, air flows around an anticyclone off the east coast of Australia, where it picks up moisture from the marine boundary layer. From here, the air parcel moves inland (event day – 2).
and is advected south and up into the warm conveyor branch of the approaching cutoff low (day 1).

It is much harder to develop a general rule for why a cutoff low pressure system does not always result in rain, because trajectories can come from many directions and for a variety of reasons. We did find a tendency for such cutoff lows to be associated with trajectories directed from the southwest, south, or southeast of the Mallee region. Higher rainfall totals (all of which were still less than 10 mm day$^{-1}$) tended to be associated with eastward trajectories that traveled across the Great Australian Bight (south coast of Australia) or from the western and northwestern coasts (Fig. 8).

4. Discussion and conclusions

For our study we chose two canonical ENSO years (1982 and 1997) and one ENSO Modoki year (2002) to explore rainfall in the Mallee region of southeastern Australia (Fig. 1). The 1997 canonical year was relatively wet, whereas the canonical 1982 and Modoki 2002 years were exceptionally dry (Fig. 2). If we are to see different flavors of ENSO affecting rainfall in different ways, then we would expect these changes to occur through variations in local rainfall processes. Examination of the rainfall processes found that most of the rainfall in this region is attributable to frontal systems or
cutoff low pressure systems. Frontal rainfall is roughly constant from year to year, but rainfall from cutoff lows differs among years (Fig. 3). Therefore if ENSO flavor is to influence rainfall in the southeast, then it can be expected to systematically influence the rainfall of cutoff systems.

The reason 1982 and 2002 were so much drier than 1997 was that less rain fell on days with cutoff lows; any differences in the number of cutoff-low days were small (Table 1). Most of the rainfall in 1997 came from a few very wet events (at least 10 mm day$^{-1}$) associated with cutoffs (Fig. 4). By tracing the air trajectories backward in time from these wet cutoff events, we found a common origin in the marine boundary layer off the coast of northeastern Australia. In the 1997 wet events, the air traveled through this northeastern region (Fig. 6). In the case of drier cutoff lows the flow came from different directions (Fig. 8). The tracks from the cutoff days with no rain or less than 10 mm of rain did not travel over the marine boundary layer in northeastern Australia but rather came mainly from the northwest, west, southwest, and southeast directions.

In these case studies, the critical common ingredients for a wet event were a favorable trajectory into the cutoff low preceded by a high pressure area in the subtropical ridge off the east coast of Australia a few days before the cutoff low was over the Mallee region. In this case, air parcels would move anticyclonically through the marine boundary layer off northeastern Australia and then southward into the cutoff-low systems. The confluence of the east-coast high and cutoff low provides the ideal conditions for trajectories to gather moisture and generate heavy rainfall in the Mallee. Drier trajectories result when the high in the subtropical ridge is too far east, west, or south.

Previous studies have classified Australian rainfall according to ENSO flavor (Wang and Hendon 2007; Taschetto and England 2009). Although our case study is too small to invalidate this classification, we have shown that processes influencing rainfall are likely to be more complicated than just ENSO flavor. In particular, 1997 and 1982 are both canonical El Niños, but they have very different rainfall signatures in the Mallee. For the Mallee region, 1997 and 1982 should not be simply “grouped together” as an ENSO type, because they are very different years whose synoptic rainfall anomalies appear to be influenced by other factors.

These case studies show that Lagrangian backtracking trajectories can usefully highlight the sources of moisture.
FIG. 7. An analysis of the air trajectory (red circles) leading into the cutoff low on 1 Sep 1997 for different pressure levels and travel times upwind. Approximate positions of cyclones and anticyclones (L and H) are marked in the figure. Blocking highs are also indicated in the south. The wind field (blue arrows) is shown at the relevant time and height of the air parcel as labeled. If a constant wind field and height are used to determine the trajectory [dashed line in (f)] then the air would appear to originate from southwestern Australia.
of given rainfall systems. These moisture sources are often not what would be implied by a snapshot of winds (as illustrated in Fig. 7f and explored in MPBR). In this regard, studies that use composite winds to draw conclusions about moisture sources for rainfall may need to be revisited.

Future work in this area needs to address what proportion of wet events in all years (not just El Niños) occurs because of flow over the marine boundary layer in northeastern Australia. An exploration of trajectories from cutoff lows in all years suggests that flow in wet events often travels in an anticyclonic direction over northeastern Australia (McIntosh et al. 2007). In our case studies, a critical feature to generate such flow is the occurrence of a high pressure system in the subtropical ridge east of Australia. If this is usually the case, what controls the position of these systems? We illustrated here differences in the way in which synoptic processes entrain moisture into cutoff-low systems for different cases and years. Such differences could reflect the random variations of weather, or they may be the result of broader influences on weather processes from remote drivers such as ENSO. If the former, it would be difficult to generalize the influence of particular ENSO flavors on rainfall.

In addition to ENSO, southeastern Australian climate is driven by the Indian Ocean dipole and the southern annular mode (Risbey et al. 2009). Each of these drivers could be expected to alter the structure of synoptic systems over Australia and hence cutoff lows. A further extension of this study would be to explore in detail the different effects of these drivers in contributing to flow trajectories into the Mallee.

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APPENDIX

The Backtracking Algorithm

To explore the source of moisture to synoptic systems such as cutoff lows, we trace air parcels, associated with rainfall, backward in time [following the methods of McIntosh et al. (2007) and MPBR]. Rain emanating from the slow widespread ascent that occurs with cutoff lows is characteristically produced from clouds in the lower midatmosphere, typically around 700 hPa. We backtrack air parcels from this altitude above a number of rainfall stations in the Mallee region. By examining the specific humidity along the tracks, we can infer where moisture is entrained as well as where it is lost as rainfall.

The data used were obtained from the optimal model/data reanalysis produced by the National Centers for Environmental Prediction–National Center for Atmospheric Research (Kistler et al. 2001). The NCEP–NCAR reanalysis provides, among other variables, three-dimensional velocity, temperature, and humidity on a global grid. The horizontal grid spacing is 2.5° of longitude and latitude, the vertical spacing is variable but on the order of 100 hPa in the troposphere, and the temporal spacing is 6 h.

Air-parcel trajectories are obtained by solving the kinematic differential equation

\[ \frac{D \mathbf{x}}{D t} = \mathbf{v}, \]

where \( D/Dt \) is the material derivative following the flow, \( \mathbf{x} \) is the unknown three-dimensional position \((x, y, p)\) of an air parcel, and \( \mathbf{v} \) is the specified three-dimensional velocity \((u, v, \omega)\), with \( \omega \) being vertical velocity in pressure coordinates. The equation is solved backward in time starting at the location of one or more rainfall stations in the Mallee. Once the air-parcel trajectory is calculated, specific humidity is interpolated from gridded values onto the trajectory.

The trajectory Eq. (A1) is solved using a semi-Lagrangian algorithm to ensure numerical stability given
the lack of fine-resolution data in time (Staniforth and Côté 1991). The basic algorithm is

1) linearly interpolate velocity to the starting point,
2) use this velocity to take an Euler step backward for half of a time step, giving an estimate of the midpoint of the trajectory for this time step,
3) use cubic-spline interpolation to find the velocity at the midpoint,
4) iterate steps 2 and 3 to find a better estimate of the midpoint position and velocity (we use three iterations), and
5) use the midpoint velocity to take a step backward by the entire time step of 6 h.

In this study we used the method to calculate air-parcel trajectories for a maximum of 10 days backward in time.

One further refinement involves the precise timing of daily rainfall and therefore the appropriate 6-h trajectory to examine. Our rainfall data are extracted as daily totals but the NCEP–NCAR reanalysis data are generated every 6 h. Most rainfall events are concentrated in a few hours rather than over a day (although there are exceptions). The 6-h band in which the rainfall most likely occurred was chosen as the one that had the greatest “uplift” or change in pressure over the last 6 h.

We emphasize that using a Lagrangian backtracking method is crucial for determining the correct trajectory. Unless the changing state of the winds is considered at each 6-hourly step, then the final trajectory can be vastly different over 10 days. Further analysis of this method, tests for sensitivity, and case studies are given in MPBR.

REFERENCES


