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INTERANNUAL VARIABILITY OF LOWER-TROPOSPHERIC MOISTURE TRANSPORT DURING THE AUSTRALIAN MONSOON

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ABSTRACT

The interannual variability of the horizontal lower-tropospheric moisture transport associated with the Australian summer monsoon has been analysed for the 1958-99 period. The 41-season climatology of moisture flux integrated between the surface and 450 hPa showed moderate levels of westerly transport in the month before Australian monsoon onset, associated with cross-equatorial flow in the Sulawesi Sea and west of Borneo. In the month after onset the westerly moisture transport strengthened dramatically in a zonal belt stretching from the Timor Sea to the Western Equatorial Pacific, constrained between the latitudes 5 and 15° S, and associated with a poleward shift in the Intertropical Convergence Zone and deepening of the monsoon trough. Vertical cross-sections showed this transport extending from the surface to the 500 hPa level. In the second and third months after onset the horizontal flow pattern remained similar, although flux magnitudes progressively decreased, and the influence of trade winds became more pronounced over northern Australia.

Nine El Niño and six La Niña seasons were identified from the data set, and composite plots of the affected years revealed distinct, and in some cases surprising, alterations to the large-scale moisture transport in the tropical Australian–Indonesian region. During an El Niño it was shown that the month prior to onset, in which the moisture flux was weaker than average, yielded to a dramatically stronger than average flux during the following month, with a zone of westerly flux anomalies stretching across the north Australian coast and Arafura Sea. The period of enhanced moisture flux during an El Niño is relatively short-lived, with drier easterly anomalies asserting themselves during the following 2 months, suggesting a shorter than usual monsoon period in north Australia. In the La Niña composite, the initial month after onset shows a tendency to weaker horizontal moisture transport over the Northern Territory and Western Australia. The subsequent 2 months show positive anomalies in flux magnitude over these areas; the overall effect is to prolong the monsoon.

Comparison of these results with past research has led us to suggest that the tendency for stronger (weaker) circulations to arise in the initial month of El Niño (La Niña) events is a result of mesoscale changes in soil moisture anomalies on land and offshore sea surface temperature (SST) anomalies, brought about by the large-scale alterations to SST and circulation patterns during the El Niño–Southern Oscillation. The soil moisture and SST anomalies initially act to enhance (suppress) the conditions necessary for deep convection in the El Niño (La Niña) cases via changes in land–sea thermal contrast and cloud cover. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: monsoon; Australia; interannual variability; NCEP reanalyses

1. INTRODUCTION

The climate of tropical north Australia is dominated by the Australian summer monsoon (ASM). As with other monsoonal regimes, the Australian monsoon is characterized by a seasonal reversal of the prevailing lower tropospheric wind; in summer this wind has a northwesterly, onshore orientation, and the resulting transport of moist maritime air across the north Australian coast helps initiate and sustain deep convection between the months of December and March. The net meridional transport of mass and momentum at low

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levels, complemented by an upper tropospheric return flow across the equator, defines the ASM as the local manifestation of a meridional Hadley cell, with large-scale subsidence occurring in the Northern Hemisphere subtropics.

Over 80% of annual mean precipitation for tropical Australia falls during the December–March interval (Bureau of Meteorology, 1988a), yet the overall amount of tropical precipitation undergoes large year-to-year variations (e.g. Holland, 1986), as do large-scale indices that measure circulation strength (Webster and Yang, 1992). Considerable effort has been devoted to understand how the strength of the ASM could be influenced by the El Niño–Southern Oscillation (ENSO) phenomenon. The extreme states of ENSO act to redistribute preferred areas of low-level moisture convergence and deep convection in the tropical Indo-Pacific region via sustained sea surface temperature (SST) anomalies and associated alteration to the zonal Walker circulation.

Given the proximity of the ascending branches of the Walker cell and ASM, the concept of an interaction between the two has an intuitive appeal. ENSO episodes are also well established and robust by the time ASM onset occurs (e.g. Rasmusson and Carpenter, 1982). This is in contrast to the Indian and South Asian monsoons, which are active between May and September — seasonal-scale prediction of these systems is hampered by the tendency of the tropical Pacific and overlying atmosphere to decouple and 'reset' itself in the March–May period, leading to a boreal spring 'predictability barrier' (e.g. Webster and Yang, 1992; Lau and Yang, 1996).

Specifically, the perceived notion is that an El Niño, which tends to relocate deep equatorial convection to the central Pacific (Hoerling *et al.*, 1997), is responsible for a weakening of the ASM, with later onset date and lower rainfall, whereas when a La Niña occurs the ascending branch of the Walker cell is intensified, leading to greater low-level moisture convergence and stronger deep convection over the equatorial Indonesian region. The implication here is for a stronger and longer ASM with higher rainfall.

A body of recent work over the past 20 years has set out to explore the validity of this monsoon–ENSO paradigm. Undoubtedly, a difference is discernible when comparing ensembles of monsoons during El Niño and La Niña events, with statistically significant alterations to rainfall patterns (e.g. Suppiah, 1993) and large-scale circulation features over tropical Australia (e.g. Drosdowsky and Williams, 1991) in evidence. However, earlier work by McBride and Nicholls (1983) suggested more complex associations, judging by the relatively low correlations between austral summer rainfall and the Southern Oscillation Index (SOI). Instead, the relationship is stronger during spring, and it has been noted that less than 10-15% of monsoon rainfall variance can be explained by SST variability in the Pacific (CLIVAR, 1997).

Part of the predictability problem lies in the growing realization that monsoon variability (both in the intraseasonal and interannual sense) is not a simple linear outcome of slowly varying, SST-related boundary forcing. Recent work has examined the nonlinearity of teleconnections between ENSO events and tropical climate anomalies (e.g. Hoerling *et al.*, 1997; Slingo and Annamalai, 2000). The latter study argues that extreme ENSO forcing may in fact stimulate local Hadley cell overturnings due to greatly enhanced subsidence in equatorial regions, leading to a *stronger* monsoon. As well as large-scale external forcing mechanisms, one must also consider smaller-scale, shorter period fluctuations in radiation transfer and hydrological processes, both at the air–sea and air–land interfaces. These mechanisms, all important in initiating and maintaining the deep convection that drives the monsoon circulation, can also interact with the larger-scale external 'forcing factors', an issue explored by Webster *et al.* (1998).

Given the importance of atmospheric moisture to the maintenance of monsoons, and how its distribution at low levels varies so greatly during ENSO events, a study of moisture flux variability during the ASM is timely. This study will focus on interannual variations, in particular the phases of the ASM's life-cycle, from build-up and onset to maturity and withdrawal. This method is now possible owing to the emergence of global gridded atmospheric analyses with a significant length of record. The availability of this data enables the 'moisture pathways' associated with the ASM to be identified and their variations during ENSO episodes examined in more detail than has previously been possible, particularly for the tropical Indian Ocean, where data are relatively sparse (Godfrey *et al.*, 1995).

Concerns about bias in the representation of moisture fields in global gridded analyses do exist (e.g. Trenberth and Guillemot, 1998), and these are due in large part to uncertainties in both the parameterization of hydrological processes and in wind and moisture field values (Wang and Paegle, 1996). However, the data

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assimilation schemes that create these data sets are ever improving, and this study is more intent on examining the contrast and change in bulk flow patterns during ENSO extrema, which should reduce the negative effects of systematic bias in the data.

Examination of variations in transport on the intraseasonal scale may also provide insight into why a significant number of ENSO years do not conform to the conventional notion of dry (wet) seasons during El Niño (La Niña) events. This is notwithstanding the fact that ENSO variability undergoes multi-decadal variations (e.g. Allan *et al.*, 1995; Power *et al.*, 1999), which may have an impact on the ENSO–monsoon relationship. However, the length of record available will hopefully overcome fundamental shifts to the ENSO–monsoon relationship on these decadal time scales.

As a final point, a study of moisture transport variability also allows changes to precipitation in tropical Australia to be examined, while overcoming the heterogeneous nature of tropical rainfall observations. Many past studies have explored how ASM wind patterns are modulated by ENSO; however, recent work (Wang and Fan, 1999) has shown that the relation between large-scale circulation indices depicting monsoon strength and rainfall amount can be very tenuous, particularly during ENSO episodes. By isolating moisture flux changes one can at least explicitly examine one parameter that is both fundamental to monsoon circulation maintenance and is clearly affected by ENSO-related forcing.

2. DATA AND METHODS

National Center for Environmental Prediction (NCEP) National Center for Atmospheric Research (NCAR) reanalyses (Kalnay *et al.*, 1997) are used to study the interannual variability of the 41 ASM seasons from 1958–59 to 1998–99. Other studies of regional-scale tropical climate variability have also employed this data set (e.g. Soman and Slingo, 1997). This study uses the northward and eastward wind components (u, v), specific humidity q and surface air pressure p_s to calculate moisture fluxes.

The horizontal moisture flux for one level is given by $\rho q u$ with $\rho = 1.275$ kg m⁻³ the density of air and bold type denoting a vector quantity. One can integrate the moisture flux vertically to obtain the horizontal moisture transport through a layer of the atmosphere. By substituting the hydrostatic approximation and integrating vertically with pressure, the total moisture flux F between pressure level p_1 and higher level p_2 takes the form

$$\boldsymbol{F} = -\frac{1}{g} \int_{p_1}^{p_2} q \boldsymbol{u} \, \mathrm{d}p \tag{1}$$

Since reanalysis data only exist on discrete levels, this integral must be approximated using a finite difference approach, and the same method adopted in other studies of this nature (e.g. Chen, 1985; Simmonds *et al.*, 1999) is employed here. If J separate levels are to be summed in order to determine the total moisture transport, then they must first be equated to J layers, so that

$$\boldsymbol{F} = \frac{1}{g} \sum_{j=1}^{J} q_j \boldsymbol{u}_j \Delta p_j \tag{2}$$

where Δp_j is the thickness (in pressure units) of the *j*th layer. The boundaries between layers are taken to be the midpoints between the corresponding levels. For the lowest layer the boundary is the ground, so surface pressure is used in this case.

The specific humidity q is only recorded for the lowest eight of the 19 levels of reanalysis data: 1000, 925, 850, 700, 600, 500, 400, 300 hPa. For this study, regional-scale changes in low-level moisture transport are being examined. Analysis of this data, plus the efforts of past studies (e.g. Drosdowsky, 1996) have shown that active westerly monsoonal bursts can extend up to the 350 hPa level, but, in the seasonal mean sense (which also includes 'break' phases of suppressed convection), westerly moisture transport and convergence is restricted to the lower and middle troposphere, so here the lowest six levels of the atmosphere are summed, i.e. an integration between the surface and 450 hPa is performed.

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In order to examine the 'life cycle' of moisture flux in the tropical Australian region and account for variations in the mean annual cycle, each monsoon season was adjusted in time relative to the onset date. From this reference point four consecutive 30 day 'months' formed the analysis period for each season: the month leading up to ASM onset (referred to as month -1) and three consecutive months after onset (months +1, +2, +3).

Using this method introduces two problems that are not apparent when one examines interannual variability via calendar months or seasons. The first is the practical problem of objectively determining an onset date for each monsoon. This study has opted for the methodology of Drosdowsky (1996), who defined the ASM's onset as the initial burst of deep and sustained lower tropospheric westerly flow at Darwin. The sequence of onset dates originally published in Drosdowsky (1996) covered the seasons 1957–58 to 1991–92 and was extended to 1998–99 for this study, using the same methodology applied to data at the grid point closest to Darwin (Drosdowsky's study drew on radiosonde traces from this city). The time series of these ASM onset dates is displayed in Figure 1.

ASM onset is accompanied by both an abrupt poleward shift in the Intertropical Convergence Zone (ITCZ) as well as a 'blow-up' of convection over an extensive area between the equator and the north Australian coast



Figure 1. Onset dates of the Australian monsoon for the 1958–59 to 1997–98 wet season, as determined using the objective method of Drosdowsky (1996). The vertical depicts the mean onset date of 29 December for the analysis period. Bars marked 'E' correspond to El Niño years, and those marked 'L' are La Niña years

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(Davidson *et al.*, 1983). Drosdowsky's interpretation was felt to be more compatible with these regional-scale indicators of monsoonal activity and gives a more reliable year-to-year guide as to the arrival of the true 'wet' season. Owing to the shallow convective activity and low-level westerly bursts that often mark the 'build-up' of the Australian wet season prior to widespread convective activity, using rainfall criteria to determine a sequence on onset dates may give a misleading and inaccurate picture.

Figure 1 indicates considerable interannual variability in the actual date of ASM onset, from which the second problem arises. Climatological moisture flux values obey a strong annual cycle; if this cycle is not removed, then any flux anomalies will depend partly on the timing of the monsoon for that season, since the analysis windows described above are locked to the ASM onset date.

For example, suppose the long term mean of F at a certain point is 170 kg m⁻¹ s⁻¹ in December and 200 kg m⁻¹ s⁻¹ in January. Integrated moisture flux at this point is observed to be 220 kg m⁻¹ s⁻¹ for one season. This anomaly seems significant if monsoon onset occurs in December, but it is unremarkable if onset is delayed until January. Since ASM onset date is known to relate to the phase of ENSO (Drosdowsky, 1996), this source of bias must be removed. Anomalous moisture flux for relative month i (F'_i) is therefore calculated this way:

$$F'_{i} = \frac{1}{120} \sum_{t=T}^{T+119} F_{t} - \overline{F}_{t}$$
(3)

Here, F_t is the vertically integrated moisture flux observed at time t, and \overline{F}_t is the corresponding 41 year mean value. The initial time value in the summation will depend on the ASM onset date. If i = -1 then T is 120 observations before the onset date; if i = +1, T is the onset date itself, and so on. The resulting mean flux value represents a perturbation to the climatological mean flow. The moisture flux vector magnitude $|F'_i|$ is calculated the same way:

$$|F_i'| = \frac{1}{120} \sum_{t=T}^{T+119} |F_t| - |\overline{F}_t|$$
(4)

3. RESULTS

3.1. Climatology

Figure 2 shows the climatological vertically integrated moisture flux between the surface and 450 hPa for the four relative months described above. The contours in Figure 2 represent the moisture flux vector magnitude. Figure 3 depicts vertically integrated moisture flux values with the background climatology removed, using the method described in Section 2.

Even in pre-monsoonal month -1 (Figure 2(a)), a degree of cross-equatorial moisture flow is observed, some of which is redirected onto the Northern Territory (NT) coast under the influence of a cyclonic circulation centred just off the coast of Darwin. Although the actual monthly mean vectors are relatively small off the north and north-west Australian coast, there is a substantial mean transport of approximately 200 kg m⁻¹ s⁻¹, implying quite variable local conditions. This enhanced magnitude of moisture flux could also be associated with a local sea-breeze/land-breeze regime and associated shallow convective activity that is noted during pre-monsoonal and break phases (e.g. Drosdowsky, 1996). However, the diurnal cycle of these winds causes a cancelling-out effect, and trade winds essentially dominate over this period.

Another notable feature in month -1 is the strong cross-equatorial south-east Asian 'winter' monsoonal flow, with a weaker flow also observed over the Sulawesi Sea on the eastern side of Borneo. This cross-equatorial moisture transport increases considerably in month +1 (Figure 2(b)), and feeds into the dramatic rise in zonal moisture flux over the Arafura Sea.

This zone of westerly moisture flux extends east to Cape York and the south coast of Papua New Guinea, as the zonally oriented monsoon 'shear line' shifts poleward and becomes more distinct. The corresponding



Figure 2. Climatological (1958–59 to 1997–98) surface–450 hPa vertically integrated mean moisture flux, overlaid by moisture flux magnitude, for (a) month -1, (b) month +1, (c) month +2 and (d) month +3. A maximum vector length is displayed (kg m⁻¹s⁻¹) and the contour interval for flux magnitude is 10 kg m⁻¹s⁻¹

anomaly plot (Figure 3(b)) reveals the widespread nature of ASM onset and its associated burst of deep convection. Enhanced westerly moisture flux occurs between 0-15 °S and 110-150 °E, a domain that coincides with the widespread 'convective blow-up' noted in several past studies (e.g. Davidson *et al.*, 1983; McBride, 1983). The westerly flux anomalies are also associated with the monsoon trough, which is represented clearly in Figure 2(b). The moisture flux *anomalies* of Figure 3(b) also show that increased moisture transport occurs in the Sulawesi Sea region during the monsoon's initial month, although the size of these northerly vector anomalies suggest that cross-equatorial surges in the area do not directly aid the monsoon's strength.

As the monsoon extends into months +2 and +3 (Figure 2(c) and (d)), zonally oriented transport in the Arafura Sea progressively weakens and becomes less extensive. The pattern for month +3 resembles



Figure 3. As for Figure 2, except climatological mean flux for period corresponding to each separate monthly mean has been subtracted

the pre-monsoonal month -1 in terms of vector transport, although moisture transport magnitudes are over 40 kg m⁻¹s⁻¹ higher in the Arafura Sea. Drosdowsky (1996) calculated an average monsoon length of 75.5 days at Darwin, based on the final occurrence of moist westerly winds overlaid by upper-tropospheric easterlies. Hence Figure 2(d) depicts the final active phase of the monsoon followed by the equatorward withdrawal of the ITCZ and the re-establishment of an easterly transport regime over northern Australia.

In the later monsoonal period, the anomaly plots (Figure 3(c) and (d)) revert to much lower values throughout the entire domain. The first month of the monsoon is dominated by an active phase of enhanced westerly flow, whereas subsequent months are more likely to exhibit a mixture of active and break phases, and hence not tend to stand out from the climatology that is locked to the annual cycle.

During the latter monsoonal period, the increasing importance of the trade winds for rainfall in tropical Queensland is observed — flux magnitudes increase markedly and their region of influence extends north

and west in tune with the retreating circulation 'shear line'. This is consistent with the fact that the annual rainfall maximum for tropical Queensland occurs in February-March, compared with December-January for Darwin and the surrounding area (Bureau of Meteorology, 1988b).

A meridional cross-section along 130°E of mean (unadjusted) moisture transport (Figure 4) provides a different perspective of how the belt of moist westerlies evolves. This view shows how westerly moisture transport can extend above the 500 hPa level, at least for month +1. A meridional cross-section of moisture flux with 'background flow' removed is not shown. In this case the fields for month -1 and months +2 and +3after onset do not rise above 10 kg m⁻² s⁻¹ at any point, whereas in month +1 a region of anomalous westerly transport, centred on 10°S, extends from the surface to around the 550 hPa level and attains magnitudes of up to 15 kg $m^{-2} s^{-1}$.

3.2. Anomalies associated with ENSO episodes

During the 41 seasons covered by the NCEP/NCAR reanalysis data, nine separate El Niño episodes were identified (Table I). It should be noted that three separate seasons from the protracted El Niño event of 1991–95 were chosen, the rationale being that each monsoon summer can be considered an independent entity with its own unique boundary forcing conditions.

Figure 5 shows a composite of the vertically integrated moisture flux anomalies for these El Niño seasons, with anomalous deviations from background climatology depicted (i.e. deviations from the plots in Figure 3). For example, an area of westerly vectors in Figure 3(b) indicates that climatological flow in this region during the first month of the monsoon is more westerly, compared with background climatology.

As a whole, Figure 5 shows an interesting picture of the life cycle of the ASM during an ENSO episode. Conventional notions of the low-level moisture field over the Indo-Australian region during a warm ENSO episode describe large-scale subsidence and a resultant restriction of both moisture convergence at low levels and deep convection. In month -1 (Figure 5(a)), the western equatorial Pacific is dominated by strong westerly flux anomalies, as low-level surface winds react to the shift of the regional SST maximum to the central equatorial Pacific that occurs during El Niño (Rasmusson and Carpenter, 1982), and the shift in the preferred zone of low-level convergence that occurs in sympathy. On the regional scale the moisture flux anomalies compare well with the October–November–December (OND) 'El Niño -1' surface wind anomaly composite from Reason et al. (2000), with easterly anomalies arising over the eastern equatorial Indian Ocean. Along with westerly anomalies in the western equatorial Pacific, this implies relative subsidence and moisture divergence over the Indonesian archipelago. Furthermore, the weaker than average flux magnitude in a broad equatorial area and extending south to northern Australia, compared with near-equatorial westerly flux anomalies, is symptomatic of a weaker than average cross-hemispheric flow.

> Table I. El Niño and La Niña seasons chosen for this study, with

El Niño	La Niña
1963–64	1970-71
1965-66	1973-74
1972-73	1975-76
1982-83	1988-89
1986-87	1995-96
1991-92	1998-99
1992-93	
1994-95	
1997-98	
Jan. 12	Dec. 11

mean	onset date	for	each	subset
	given on t	he la	st line	e
El Nif	io		L	a Niña

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Figure 4. As for Figure 2, except a meridional vertical cross-section of zonal moisture flux along 130°E. Contour interval is $10 \text{ kg m}^{-2} \text{ s}^{-1}$ and positive contours indicate westerly moisture transport

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Figure 5. As for Figure 3, except moisture flux anomaly for ensemble of nine El Niño events is shown. Note that deviation of 'anomalies from mean moisture flux field' is shown

During month +1 (Figure 5(b)), the flux anomalies of the previous month are maintained in the major oceans adjacent to Australia, but strong westerly flux anomalies appear in a belt that extends east from the Timor Sea and connects to pre-existing westerly flux anomalies in the western equatorial Pacific. This pattern suggests that, during a typical El Niño episode, the initial burst of the monsoon is actually stronger than average — in fact, the ITCZ is strengthened between Australia and the South Pacific Convergence Zone. The aforementioned weakening of moisture flux over the equator is still present during month +1, while immediately west of the positive flux anomalies in the Arafura Sea is a zone of strong subsidence and low-level moisture divergence. This suggests the increase of moisture flux is localized and confined to the Australian monsoon situation.

As the El-Niño-affected monsoon season progresses (Figure 5(c) and (d)), its strengthening is short-lived. Although positive anomalies in moisture flux magnitude persist over north Australia for the next 2 months, they are more indicative of east to south-easterly flow, suggesting an early conclusion to the active monsoon

season, as the Hadley cell retreats equatorward and northern Australia becomes increasingly influenced by the drier south-easterly trade wind regime.

A vertical cross-section of the El Niño composites (Figure 6) suggests there is a tendency to weaker moisture flux at mid-tropospheric levels, with easterly anomalies being consistent with a relocation in the ascending



Figure 6. As for Figure 4, except moisture flux anomaly for ensemble of nine El Niño events is shown. Stippling represents differences at greater than 95% confidence, using the *t*-test

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branch of the Walker circulation over the central Pacific. However, enhanced moisture flux occurs below 850 hPa, and in month +1 (Figure 6(b)) displaces the drier air aloft. Comparison with the climatological cross-section for month +1 (Figure 4(b)) indicates a strengthening of the monsoon trough, with intensification of the monsoon westerlies on the equatorward side of the trough, and easterly transport anomalies over Australia. Though the enhanced westerly flux is less extensive in month +2 (Figure 6(c)), it is still able to strengthen the monsoon circulation, at least in the Arafura Sea and coastal margins of NT. For month +3 (Figure 6(d)), the positive *integrated* flux anomalies seen in Figure 5(d) arise more because of stronger easterly trade winds consistent with a shorter than average monsoon season, and these are indicated in Figure 6(d) by an easterly anomaly centred over 12 °S at a height of 850 hPa.

Moisture flux anomalies during La Niña years have been examined with a composite of six austral summers selected (see Table I). The moisture flux anomalies for the ensemble are shown in Figure 7, and again



Figure 7. As for Figure 5, except moisture flux anomaly for an ensemble of six La Niña events is shown

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significant deviations from the climatological flux patterns of the Australian monsoon are in evidence. For each month, the western and central Pacific have flux anomalies that are generally opposite to those in the El Niño composite of Figure 5. Flux anomalies are easterly, as low-level convergence and convection is attracted to the warmest SST, which has shifted to the Indonesian region. In a broad band between the equator and north Australia for month -1 (Figure 7(a)), there are substantially stronger westerly moisture flux anomalies, and this contrasts neatly with the weakened fluxes for the 'build-up' month in the El Niño composite (Figure 5(a)).

However, the intuitive notion of a strong monsoon (with implied stronger westerly moisture transport) during La Niña does not carry over into the month *after* the monsoon's onset, as seen in Figure 7(b), nor is this plot a linear reflection of the corresponding El Niño composite in Figure 5(b). The trend of enhanced low-level moisture convergence over Indonesia–Papua New Guinea can be seen from the respective westerly (easterly) flux anomalies in the equatorial Indian (Pacific) oceans, but the implied availability of more moisture does not necessarily translate to more vigorous westerly moisture flux. Flux anomalies are relatively weak off the north and northwest Australian coast, and the lower mean flux magnitudes suggest a weakening of day-to-day variability.

As with the El Niño composite, the more conventional picture reasserts itself as the monsoon season continues. In month +2 (Figure 7(c)) an area of north-westerly anomalies extends westward to cover Cape York and the Gulf of Carpentaria, although the change is more marginal over coastal NT. Westerly anomalies predominate in a broad band, with a stronger cross-hemispheric flow over the South China Sea also occurring. Further widespread positive anomalies in month +3 (Figure 7(d)) and an influx of moisture into the Australian land mass point to enhanced monsoon activity and an extended season.

The vertical cross-section along $130 \,^{\circ}$ E (Figure 8) of these flux anomalies indicates differences in the structure of anomalous zonal moisture flow for the various months considered. In month -1 (Figure 8(a)) the westerly anomalies attain a maximum at the surface and are indicative of a more active and more poleward displaced monsoonal circulation than average, whereas month +1 suggests a weakening of the zonal monsoon shear line with a near-surface dipole anomaly opposing the climatological pattern of Figure 4(b). At the surface in the Southern Hemisphere tropics there are slight negative anomalies in zonal transport during months +2 and +3, although these are counteracted by the meridional orientation of the integrated flux anomalies. Also in month +2, part of the strong westerly flux anomalies in the Northern Hemisphere tropics is redirected southward towards tropical Australia.

3.3. Intraseasonal distribution of 'active' and 'break' episodes

Like other monsoonal systems, the ASM is divided into alternating phases of 'active' and 'break' activity, when deep convection (and by implication, rainfall) is respectively enhanced and suppressed. Large-scale circulation differences accompany these distinct convective regimes, as the zonal shear line retreats equatorward away from the north Australian coast, and the vertical shear between low-level westerlies and upper tropospheric easterlies weakens (McBride, 1986). Coherence between this intraseasonal activity and the phase of the equatorial, zonally propagating Madden–Julian Oscillation has also been noted (e.g. Hendon and Liebmann, 1990), with a dominant period of 30–50 days.

The large-scale changes to moisture transport that occur throughout the ASM season, and which are associated with the evolving ENSO signal, must surely have their crux in the configuration of these active and break phases. Specifically, variations in the length or distribution of these phases and the relative amounts of rainfall that either phase brings to tropical Australia are likely to be important in better understanding the nature of ASM variability.

The mean number of days of net westerly surface-450 hPa vertically integrated moisture transport in the grid box co-located with Darwin is shown in Table II along with corresponding amounts for the El Niño and La Niña composites defined in the Section 3.2. This study has preferred to examine the overall patterns of lower tropospheric transport instead of explicitly addressing the composition of the 'active' and 'break' monsoonal phases. Thus, it should be noted that while 'net westerly moisture flux at Darwin' generally corresponds to an active monsoon phase, this is not exclusively the case. Westerly flow is not necessarily



Figure 8. As for Figure 6, except moisture flux anomaly for an ensemble of six La Niña events is shown

overlaid by easterly flow in the upper troposphere, which is one criterion used by Drosdowsky (1996) and in this study's calculation of Australian monsoon onset dates. If this rule had been employed then, by definition, there would always be zero days of net westerly transport in month -1.

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are indicated					
	1	Months relative to onset date			
_	-1	+1	+2	+3	
41-season mean	11.5	18.6	16.7	13.7	60.5
El Niño events La Niña events	10.9 12.2	22.1 18.5	14.2 16.5	5.3 [‡] 17.5	52.6 [†] 64.7

Table II. Average days of net westerly moisture transport from surface to 450 hPa (at Darwin) for each 30 day 'month' (as defined in the text) and overall 120 day monsoon season, for the 41-season mean, and the composite of El Niño and La Niña events. Deviations from the mean at statistical confidence of 95% ([†]) and 99% ([‡]) confidence are indicated

Furthermore, the bias of moisture towards the lowest three or four discrete pressure levels might lead to situations of westerly *moisture transport* but not overall westerly deep layer mean *wind flow*, another criterion employed in Drosdowsky's study. A comparison of the number of 'deep westerly' and 'westerly moisture transport' days for each of the four 30 day months showed correlations of 0.80, 0.83, 0.93 and 0.95 between the two parameters in chronological order, so it is reasonable to assume that days of westerly moisture transport generally correspond to active phases of the monsoon in the months following monsoon onset.

During El Niño, the presence of much stronger westerly moisture transport over the Arafura Sea in month +1 is consistent with a higher than average number of net westerly transport days (Table II), whereas the near identical number of days in month +1 for the La Niña compared with the mean echoes the small vector anomalies in Figure 7(b). Applying a *t*-test to the relevant departures from the climatology yielded only two that were statistically significant, due largely to the large standard deviation of the samples. In month +3, the tendency for monsoon seasons to be shortened during El Niño is supported by a decrease in the number of westerly days. Though not statistically significant, the value in the La Niña composite for the same month is also higher, again supporting an extended monsoon.

As active and break phases are distinguished by quite different regional circulation (and hence moisture flux) regimes, it is possible that global-scale background forcing in the form of an El Niño/La Niña may not act in a consistent way on the two separate patterns. To analyse this, the moisture flux climatologies were decomposed into two separate maps depicting integrated moisture flux patterns during net westerly (active) and easterly (break) flux at Darwin, with the two resulting patterns for month +1 shown in Figure 9. As in previous plots, 'perturbation' flux is depicted, i.e. how the moisture transport differs from the overall climatological flow.

Figure 9(a) shows how active phases of the ASM occur in harmony with a large-scale increase in monsoonal westerlies over tropical Australia and an associated convective 'blow-up' (as noted in Gunn *et al.* (1989)), whereas break phases (Figure 9(b)) are linked to a temporary resumption of dominant easterly trade winds and associated subsidence over tropical Australia. Figure 9(a) also suggests that cross-equatorial flow might play an indirect role in feeding monsoonal deep convection, since northerly anomalies are noted in the Sulawesi Sea area, a region that receives cold surges originating in China; see Suppiah and Wu (1998).

Anomaly plots of net westerly and easterly flow during month +1 of the El Niño composite (Figure 10) depict widespread alterations to the moisture flow field for both intraseasonal phases, indicating that the El Niño does not simply affect the monsoon through changing the number of days a monsoon is permitted to be active.

The anomaly plots in Figure 10 are departures from the corresponding plots in Figure 9. Thus, the large area of westerly flux anomalies and positive flux magnitude changes over north Australia in Figure 10(a) suggest that active periods in month +1 are even stronger than average during the El Niño. Days of easterly moisture transport (at this stage of the season associated with the retreat of the monsoon shear line and reintroduction of south-east trade winds and large-scale subsidence), show no overall trend in large-scale moisture flux, but the widespread negative anomalies in flux magnitude imply weaker synoptic activity and convection.



Figure 9. As for Figure 3(a), except monthly mean field has been decomposed into a composite of all days within a month that has net (a) westerly and (b) easterly moisture transport over Darwin



Figure 10. As for Figure 9, except moisture flux anomaly for an ensemble of nine El Niño events is shown

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The decomposition of month +3 in the El Niño composite shows interesting variations too. The moist westerly days (Figure 11(a)), although fewer in number, still seem to import moisture via northerly anomalies over NT. For easterly moisture transport periods (Figure 12(b)) the signal is more ambiguous, although an area of westerly flux anomalies and heightened flow activity is seen over the Arafura Sea. Space does not permit month +2 anomalies to be shown, though a similarity with month +1 is evident.

Analysis of corresponding daily rainfall totals at Darwin, which have also been split into 'active' and 'break' components, a useful counterpoint to the decomposed moisture flux plots, and provide a measure of how these plots agree with observed rainfall. Both totals and mean daily averages are shown in Table III. In month +1 of the El Niño subset, apart from the increased precipitation that can be attributed to moist westerly days, the rainfall strength is heavier than average as well. The proportion of rain that falls during 'break' periods is much lower, a function of both the lower number of easterly flux days and slightly lower rainfall strength.

By month +3 the total rainfall has become lower than average for the El Niño subset, but a higher proportion falls on days of 'break' easterly flow. Comparison of mean daily strengths suggests that this is actually due to the relative number of moist westerly days decreasing (Tables II and III), thus making it more likely for precipitation to occur on a 'break' day, as a reduction in the mean rainfall for each easterly day is noted as well. However, on those 'active' westerly days rainfall is slightly heavier than average, as suggested by the local north-westerly flux anomalies in Figure 11(a). So, slightly lower rainfall towards the end of the monsoon in an El Niño year is attributable to an early withdrawal of the active monsoon trough and weaker post-monsoon rains and not to an actual decline in the strength of the monsoon itself.

For the La Niña composite, Figure 7(b) indicated month +1 was characterized by negative flux anomalies over northern Australia. When this plot is decomposed, the 'active' plot (Figure 12(a)) reveals westerly anomalies associated with a stronger monsoon in the Timor and Coral Seas, but not immediately north of Australia. Instead flux anomalies are slight and an extensive area of weaker flux magnitude prevails, implying weaker synoptic activity, similar in theme to the combined plot of Figure 7(b). The 'break' portrait (Figure 12(b)) is interesting because both this figure and its 'active' companion show reinforcing north-west



Figure 11. As for Figure 10, except month +3 is shown

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		Months relative to onset date				Seasonal total
		-1	+1	+2	+3	
41-season n	nean					
Westerly	Amount	102.4	297.2	242.7	179.0	821.4
	Daily avg	8.9	14.3	13.9	13.8	13.6
Easterly	Amount	160.4	116.2	136.4	116.3	529.4
	Daily avg	8.8	10.4	12.7	8.0	9.2
El Niño eve	nts					
Westerly	Amount	106.8	443.0	166.9	123.6	840.3
	Daily avg	9.3	18.7	11.0	15.9	16.1
Easterly	Amount	164.0	52.8 [‡]	135.0	138.0	489.1
	Daily avg	8.3	8.1	8.7	6.3	7.2^{\dagger}
La Niña eve	ents					
Westerly	Amount	76.3	129.0 [‡]	328.9	271.5^{\dagger}	805.7
	Daily avg	5.2	6.7^{\ddagger}	19.7^{+}	16.2	12.4
Easterly	Amount	226.7	56.5 [‡]	136.6	164.1	583.9
	Daily avg	13.5	5.8 [‡]	10.6	13.9 [†]	10.8

Table III. As for Table 2, except rainfall totals and monthly mean average daily rainfall $(mm day^{-1})$



Figure 12. As for Figure 10, except ensemble of six La Niña events is shown

anomalies in the Coral Sea. The overall weakness of the active monsoon during month +1 of a La Niña year might have led some supposedly 'active' days to be classified as easterly, due to westerly monsoonal flow not extending fully to the 500 hPa level. The net integrated flux over Darwin could, therefore, be easterly, whereas more vigorous westerly flow was still occurring in the Coral Sea sector of the ITCZ.



Figure 13. As for Figure 12, except month +3 is shown

Figure 12(a) in particular is suggestive of weaker than average rainfall, and Table III indicates mean rain strength in both westerly and easterly categories to be significantly weaker than climatology for month +1. The amount of precipitation attributable to 'active' flow is much lower: 129 mm over 1 month, compared with 297.2 mm for climatology.

As suggested earlier, much of the monsoon rainfall during La Niña falls in the latter months, as the ASM is extended. Month +2 showed higher than average rain falling on westerly days (see Table III), with a significant increase in daily strength. The corresponding integrated flux anomalies (not shown) indicated northerly flux anomalies in the Arafura Sea. This trend continues during month +3 (Figure 13(a)). The area of positive flux magnitude, and meridional anomalies, extends in a zonally oriented belt stretching across the north Australian coast and extending into adjacent seas. However, this is a local effect — no direct correspondence with cross-equatorial flow was noted; in fact, extra moisture seems to be supplied from the equatorial western Pacific, a product of an enhanced Walker circulation.

For the 'break' component in month +3, however (Figure 13(b)), easterly flux anomalies cover the north Australian coast, although the moisture flux magnitude decreases over NT and the Arafura Sea. Referral to corresponding rainfall amounts (Table III) shows that total precipitation over Darwin due to moist westerly transport increases by nearly 50% over climatology in month +3 during La Niña and the daily average is stronger for both phases, and statistically significant for the easterly 'break' phase. Thus, the existence of easterly moisture flux anomalies during break phases is not exclusively associated with subsidence and suppression of convection.

4. DISCUSSION

As alluded to in Section 3, the El Niño and La Niña composites of moisture flux variability show distinct and often surprising departures from the climatological mean *as well* as a large variability within samples. This is not surprising given the significant interannual variability in the Australian monsoon. However, an examination of the actual composition of the two composite groups shows that there is a structure to this seemingly large spread of values.

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Figure 14. Moisture flux of ensemble members for (a) El Niño and (b) La Niña composites. Crosses show ensemble members, bold line the climatological mean, and bold dashed line the ensemble mean. Units are kg m⁻¹ s⁻¹

The (climatologically adjusted) integrated moisture flux for the Darwin grid point is shown for both ensembles in Figure 14. In the El Niño case (Figure 14(a)), month +1, which according to Figure 5(b) showed the largest anomalies in terms of both flux magnitude and vector differences, also shows the highest variance. Nonetheless, a consistency of signal is observed, with seven of the nine ensemble members being higher than the long-term average. Variance is noticeably smaller for months +2 and +3, and the majority of values are less than the long-term average in month +3. In the La Niña composite (Figure 14(b)) the variance of the ensemble members in month +1 is actually smaller than in the following 2 months, and only in the pre-monsoonal month -1 are a majority of the seasons higher than average. Though only half of the six La Niña seasons are higher than average in months +2 and +3, it should be noted that the positive flux anomalies for these composites were attributable to meridional flux anomalies (see Figure 7(c) and (d)).

There is also a general lack of month-to-month memory in flux values, which echoes the rainfall analysis of Simmonds and Hope (1997). However, correlating the relative months with each other over the 41 seasons (Table IV) uncovers associations. For example, a strong link between month -1 and month +1 is noted, and month +3 is also positively correlated with month +1 to a statistically significant degree. These correlations generally hold for the El Niño and La Niña subsets (not shown), and notwithstanding that the dominant time

Table IV. Cross-correlation (×100) ofzonal integrated moisture flux at Darwin for41 year climatology. Critical values at the(†) 95% and (‡) 99% confidence levels areindicated

	-1	+1	+2	+3
-1		-49 [‡]	19 11	31 [†]
+1 + 2			11	-42

scale of intraseasonal monsoon variability is similar to the time interval used in this study and will account for a percentage of this signal, the significant correlations noted above suggest physical processes giving rise to the apparently counter-intuitive results of Section 3.

The first point to consider is the fundamental notion of a monsoon circulation arising initially through a thermal contrast between moist, cooler ocean and dry, warmer land, which is then maintained by moist processes; see Webster (1987). The actual condition of the land mass in terms of albedo, vegetation and soil moisture content is known to be very important in determining a monsoon's strength and timing (e.g. Fennessy *et al.*, 1994), as the increase in soil moisture effectively makes the land's bulk radiative and thermal properties more 'ocean-like', greatly increasing the complexity of the relationship between the two media (Webster *et al.*, 1998).

One way a thermal balance between land and ocean can be altered is via a change in the date of the onset of the monsoon. As indicated in Table I, the mean onset date of the ASM in an El Niño year is 1 month later than for a La Niña. Given the connection between El Niño and springtime drought in northern Australia (McBride and Nicholls, 1983), along with an extra month of deficient rain brought about by the delayed onset of the monsoon, a dominance of dry soil moisture anomalies is implied, and this effect is intensified by the fact that maximum solar input is located over the north Australian interior at this time of year. The moisture deficit establishes positive feedback, with deficient soil moisture known to impede the development of deep convection in the local, short-term sense (Clark and Arritt, 1995). Conversely, a La Niña brings higher pre-monsoonal rains to north Australia, and thus an enhancement of soil moisture, which would aid local-scale deep convection, the type of synoptic activity seen in tropical Australia during pre-monsoonal and 'break' phases (Keenan and Carbone, 1992).

In the month -1 plot of the El Niño ensemble (Figure 5(a)) easterly flux anomalies predominate, suggesting an enhanced trade wind inversion and stronger low-level divergence. However, the corresponding rainfall values for Darwin in month -1 indicate no change in overall precipitation in the month leading up to monsoon onset. A similar contradiction occurs for the La Niña case: despite anomalous westerly transport for month -1 (Figure 7(a)), the rainfall on 'westerly' days is lower, as well as the daily strength.

The contradictory value of month -1 rainfall in both cases indicates the highly complex nature of the interactions involving moisture transfer between land and atmosphere at the local scale. Intensification of deep convection via evapotranspiration anomalies caused by changes to cloudiness and the surface's albedo could also result, and these mechanisms may become more important over longer spatial and temporal scales than the nullifying effect drier soil has on local deep convection.

There is evidence from global circulation model (GCM) experiments that deficient soil moisture can help to *increase* precipitation. Simmonds and Hope (1998) demonstrated that in tropical settings an initial condition of dry soil leads to a transient response of higher precipitation. Furthermore, this result was most significant during the ASM period. Also, an earlier GCM investigation (Simmonds *et al.*, 1992) showed how the imposition of a negative pressure anomaly at the surface in tropical Australia led to increased precipitation, regardless of local soil or atmospheric moisture content. Such a scenario could be produced by extended diabatic heating brought about by negative cloud and soil moisture anomalies.

These two findings can be related to the El Niño case of abrupt transition from average or deficient premonsoonal rain (and assumed soil moisture deficiencies) to a significantly enhanced monsoon circulation in month +1.

Decreased cloudiness associated with less rain will lead to enhanced surface heating. In the short period leading up to a later monsoon onset, while convection is relatively inactive, land-based conditions are adjusting in a way that will enhance regional land-sea contrast, allowing (a) the anomalous subsidence brought about by ENSO-enhanced trade winds to be overcome and (b) a stronger than usual monsoonal circulation to develop.

Aiding this hypothesis is evidence of a shift in SST patterns between austral spring and summer in the north Australian region (Reason *et al.*, 2000). This study's analysis of ENSO composites over the past 130 years indicated SST anomalies of up to -0.3 °C during OND of an El Niño, which would increase the degree of land-sea contrast, although the immediate impact would be a retardation of off-shore deep convection. However, negative anomalies in cloud occur at the same time, and as noted in several studies of tropical convective activity (e.g. Lau and Sui, 1997; Flatau *et al.*, 1997), cloud shielding and mixing of the upper ocean layer play fundamental roles in regulating SST on the regional scale. By January–February–March of an El Niño episode, Reason *et al.* (2000) showed that the aforementioned SST anomalies had become positive; negative cloud anomalies in OND allow greater heat transfer into the ocean, and weaker low-level winds associated with weaker convection prevents this additional heat from being mixed down to any great depth. Thus, as in the case of the negative changes to soil moisture, conditions off-shore set the scene for a stronger monsoon circulation.

For a La Niña, local changes to evapotranspiration brought about by soil moisture anomalies can again be used to explain observed alterations to moisture transport, as can changes to SST and cloudiness. On the local scale, Reason *et al.* (2000) show how SST anomalies in a La Niña are generally opposite to those observed in a warm episode. Positive SST anomalies in the OND period help feed the observed higher than average rainfall (Table III) and increase soil moisture levels on land. This results in a negative feedback between ocean and atmosphere via greater cloudiness and surface winds, and a resulting decline in SST seen in the following season. Over land, there is evidence from numerical modelling experiments that an initial positive anomaly in soil moisture can lead to decreased precipitation on time scales of up to 90 days as well as positive surface pressure anomalies (Yang, 1995).

The observation in this study of average to decreased precipitation in month +1 of a La Niña again supports this line of thought, although caveats must be attached. As seen in Figure 14(b), there is an equally high probability of above-average as there is below-average moisture transport in month +1 of a La Niña, which highlights the complexity and non-linearity of the interactions outlined above, a point stressed by many of the authors previously cited. The presence of soil moisture, particularly after monsoon onset, when deep convection is more directly attributable to a large-scale contrast between land and ocean, increases the 'degrees of freedom' of the monsoon (Webster *et al.*, 1998), and there are presumably several mechanisms that can lead to the initiation of deep convection.

Although changes to SST and large-scale atmospheric overturnings brought about by ENSO events undoubtedly alter the transport patterns of atmospheric moisture as it relates to the ASM, the tendency for the same event to cause mesoscale changes to evapotranspiration and radiative transfer suggests other, less direct methods by which a monsoon's strength and persistence can be altered during austral summer. However, the indirect monsoon influences of anomalies in soil moisture, albedo and solar input are essentially negative feedback loops, whereas the large-scale SST anomalies in the central tropical Pacific and associated changes to the Walker circulation provide steady forcing throughout the length of the wet season (as can be seen by the composite integrated flux anomaly plots of Figures 5 and 7) and appear to exert a more substantial influence on the monsoon circulation during months +2 and +3. Nonetheless, the interplay between the two sets of forcing factors implies great complexity in the structure of the ASM variability patterns.

5. SUMMARY

This study has examined regional-scale patterns of lower-tropospheric horizontal moisture transport in relation to the Australian monsoon. In order to study the ASM's 'life-cycle', each season's suite of monthly averages

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were calculated relative to the onset date of the monsoon for the season in question. After this step the relevant climatological mean for each period was removed, allowing the 'perturbation' that the monsoon causes in the general horizontal moisture flow to be isolated.

Comparison of ensembles of El Niño and La Niña seasons showed considerable changes to moisture transport patterns both prior to actual monsoon onset and during the following 3 months. Analysis of moisture flux anomalies for the ensemble of El Niño seasons revealed a tendency towards *stronger* flow in the Arafura Sea region during the initial month of the ASM, and then a shorter than average duration of the monsoon season overall. Conversely, a typical La Niña season begins with a weaker than average initial burst of monsoonal westerlies. This is then compensated by an extended season and positive westerly flux anomalies over tropical Australia, accompanied by widespread positive anomalies in moisture flux magnitude. This implies a higher than average kinetic energy. Consistent with this, substantially higher rainfall at Darwin was noted over the same period, as well as during month -1, the monsoon's build-up.

Decomposition of these monthly moisture flux anomalies into periods when westerly or easterly flow prevailed at Darwin provided further insight into the modulation of moisture transport in concert with large-scale regional alteration to SSTs and the equatorial Walker cell. These results suggested that, at least for month -1 of an El Niño, the enhanced moisture transport through the Timor and Arafura Seas could be attributed to both a greater than usual number of 'active' days, which were also stronger than usual in terms of both the amount of moisture transported, and also to the rain that fell. The same was found to occur during the extension of the monsoon season that typically occurs during a La Niña. Overall, a study of the intraseasonal monsoon changes provided a level of insight not possible when considering the ASM as a whole — average *seasonal* rainfall for both El Niño and La Niña cases did not differ greatly from the mean (see Table III).

Further work on this topic must centre on the role that land-sea contrasts may play in influencing this variability, and how this contrast is modulated by changes in the thermal and radiative properties of the Australian land mass, both as a boundary forcing condition and also in the interactive sense during the course of a 'wet' season. ENSO events can exert powerful influences on these particular variables, and also lead to wide-ranging shifts in SST and cloudiness over the Indian/Pacific Ocean warm pool (of which tropical Australia comprises the southern border). These background forcing conditions, combined with coherent alterations to the date of the monsoon's onset that are related to the state of ENSO, are mechanisms suggested to be causing the counter-intuitive observation of stronger (weaker) periods of monsoon circulation occurring during El Niño (La Niña). Such findings can be explored in more detail with the help of GCMs, with the hope of revealing some of the crucial processes that underpin this complex and highly interactive climate system.

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