CSIRO PUBLISHING
www.publish.csiro.au/journals/ajar *Australian Journal of Agricultural Research*, 2003, **54**, 599–611

Effect of climate variability on event frequency of sorghum ergot in Australia

Enli Wang[A,C], *Malcolm Ryley*[B], *and Holger Meinke*[A]

[A]APSRU, DPI/CSIRO/NRM/UQ, PO Box 102, Toowoomba, Qld 4350, Australia.
[B]Queensland Department of Primary Industries, PO Box 102, Toowoomba, Qld 4350, Australia.
[C]Corresponding author; present address: CSIRO Land and Water, GPO Box 1666, Canberra, ACT 2601, Australia;
email: Enli.Wang@csiro.au

Abstract. The significant effect of ergot, caused by *Claviceps africana*, on the Australian sorghum industry, has led to considerable research on the identification of resistant genotypes and on the climatic conditions that are conducive to ergot outbreaks. Here we show that the potential number of monthly ergot events differs strongly from year to year in accordance with ENSO (El Niño–Southern Oscillation) related climate variability. The analysis is based on long-term weather records from 50 locations throughout the sorghum-growing areas of Australia and predicts the potential number of monthly ergot events based on phases of the Southern Oscillation Index (SOI). For a given location, we found a significant difference in the number of potential ergot events based on SOI phases in the preceding month, with a consistently positive SOI phase providing the greatest risk for the occurrence of ergot for most months and locations. This analysis provides a relative risk assessment for ergot outbreaks based on location and prevailing climatic conditions, thereby assisting in responsive decision-making to reduce the negative effect of sorghum ergot.

Introduction

Ergot, caused by *Claviceps africana* Frederickson, Mantle & DeMilliano, is a non-systemic disease of the ovaries of *Sorghum* species, including *Sorghum bicolor* (L.) Moench. It is now endemic in all the major sorghum-producing countries of the world, including Australia, where it has had a significant effect on some sectors of the sorghum industry, particularly seed production and the use of sorghum as feed grain (Ryley *et al.* 2001, 2003). The high susceptibility of male sterile A-lines in hybrid seed production blocks has necessitated the regular use of triazole fungicides (Ryley *et al.* 2001). The alkaloids in the fungal structure (sphacelium/sclerotium) that replaces the ovary have been found to be detrimental to livestock (Blaney *et al.* 2000), and this has affected the acceptability of ergot-contaminated sorghum grain by many livestock producers.

Although genotypes and hybrids of *S. bicolor* have been shown to vary in their ‘resistance’ to *C. africana* (McLaren 2000; Dahlberg *et al.* 2001), there are no commercial ergot-resistant hybrids. Fertilised ovaries are generally resistant to infection by conidia of *C. africana* (Bandyopadhyay *et al.* 1998), so ergot infection is strongly influenced by the amount of viable pollen, and by humidity and temperature during the flowering period (McLaren and Wehner 1990, 1992; McLaren 1997; McLaren and Flett 1998). Low night temperatures, with a daily minimum temperature of <13°C during the flag leaf stage, can induce male sterility, reduce pollen viability (Downes and Marshall 1971; Brooking 1976, 1979), and then predispose sorghum plants to ergot infection (McLaren and Wehner 1992; McLaren and Flett 1998). In the main sorghum-growing regions in Australia this situation occurs only for very early- or late-planted sorghum. Temperature and humidity during flowering are the more important factors influencing infection (McLaren and Wehner 1990; Wang *et al.* 2000*a*). To account for the effect of temperature during the flowering period on ergot severity, Wang *et al.* (2000*a*) developed an infection factor based on hourly temperatures during that period. They showed that an infection event was likely to occur if the infection factor during the flowering period was >0.3 and the mean relative humidity at 09 00 hours was >70%.

A climatic analysis on the mean number of potential monthly ergot outbreaks indicated that there were increasing gradients of ergot events in eastern Australia from south to north as well as from west to east between December and March, when most commercial grain sorghum crops are flowering. Later in the season (April–May), when some late-planted crops may be flowering, the number of potential monthly events increased, particularly in the southern areas. The lowest number of events occurred between September and December when few commercial grain sorghum crops are flowering. The temporal and geographic distribution of the number of potential events and of ergot severity was closely related to that of relative humidity during the

10.1071/AR02198 0004-9409/03/060599

flowering period (Wang *et al.* 2000*b*). Further, it was found that the number of ergot events differed strongly from year to year, depending on the season type.

It has been well established that eastern Australia is strongly affected by the El Niño–Southern Oscillation phenomenon (ENSO), as reflected in the phases of the South Oscillation Index (SOI), a convenient and robust measure of categorising ENSO states (Nicholls *et al.* 1996; Stone *et al.* 1996). Scherm and Yang (1995, 1998) reported ENSO-related disease outbreaks and severity for wheat rust in China and the United States.

In this paper we report on the predictability of climate variability effects on the potential number of sorghum ergot events during the year. The analysis was conducted based on the findings of Wang *et al.* (2000*a*, 2000*b*) using phases of the SOI (Stone *et al.* 1996).

Materials and methods

Historical weather data and estimation of daily wetness

Long-term historical climatic data (1 January 1887–30 May 1998) from locations throughout the sorghum-growing areas of Australia were obtained from SILO patch-point data-set (Table 1). There are no recorded humidity or vapour pressure data available; hence, daily maximum vapour pressure deficit (VPD_{max}) was estimated to replace the relative humidity factor in the model developed by Wang *et al.* (2000*b*). VPD_{max} was estimated from daily minimum and maximum temperature by assuming that the daily minimum temperature equals dew point and that dew point does not change during any single day (Tanner and Sinclair 1983). Meinke *et al.* (1997) demonstrated the validity of this approach for south-eastern Queensland:

$$VPD_{max} = E_{Tmax} - E_{Tmin} \qquad \text{(hPa)}$$

$$E_{Tmax} = 6.107 \exp[17.4\, T_{max} /(239 + T_{max})] \qquad \text{(hPa)}$$

$$E_{Tmin} = 6.107 \exp[17.4\, T_{min} /(239 + T_{min})] \qquad \text{(hPa)}$$

where VPD_{max} is the maximum daily vapour pressure deficit, and E_{Tmax} and E_{Tmin} are the saturation vapour pressure at daily maximum temperature (T_{max}) and minimum temperature (T_{min}), respectively.

Simulation of the critical growth stages

For each day of the year, assumed as the first day (beginning) of flowering, the duration of flowering period, the starting date, and the length of the flag leaf period were predicted. The starting date of the flag leaf stage was simulated by assuming that the flag leaf begins to emerge when the third leaf prior to the flag leaf is fully expanded (G. Hammer, pers. comm.), and that each of the last 3 leaves requires 20 degree-days to fully expand. The end of the flag leaf stage was simulated using the APSIM sorghum model (Hammer and Muchow 1994). Anthesis was assumed to begin 100 degree-days after the flag leaf had fully expanded, and the length of the flowering period was calculated using a thermal time value of 128 degree-days with a base temperature of 3.2°C. These assumptions were based on the original data of Hammer *et al.* (1989).

Hourly temperatures were estimated from daily maximum and minimum temperatures (Wang *et al.* 2000*c*), and were used to calculate the thermal time values (degree-days) for predicting the flowering period and flag leaf stage. Estimated hourly temperatures were also used for each day during the flowering period to identify that part of the day when temperatures were favourable for infection, and to calculate

Table 1. Source of climatic records used in the analysis

Stn no.	Station name	Latitude	Longitude
033002	Ayr DPI Research Stn	–19.62	147.38
039006	Biloela DPI	–24.38	150.52
033257	Bowen Airport	–20.02	148.22
033007	Bowen Post Office	–20.02	148.25
033094	Bowen Qld Salt	–20.01	148.23
035019	Clermont Post Office	–22.83	147.64
041522	Dalby Airport	–27.17	151.27
041023	Dalby Post Office	–27.18	151.26
065012	Dubbo (Cooreena Rd)	–32.21	148.57
065037	Dubbo State Forest	–32.27	148.62
035264	Emerald Airport	–23.57	148.17
035027	Emerald Post Office	–23.53	148.16
040082	Gatton Lawes College	–27.55	152.34
040436	Gatton QDPI Research Stn	–27.55	152.33
041521	Goondiwindi Airport	–28.52	150.33
041038	Goondiwindi Post Office	–28.55	150.31
075041	Griffith Aero	–34.26	146.06
075028	Griffith CSIRO	–34.32	146.07
073128	Gundagai Ridge Street	–35.08	148.1
055023	Gunnedah Pool	–30.99	150.25
055024	Gunnedah SCS	–31.03	150.27
075018	Hay Corrong	–34.22	144.46
075134	Hay Epsom Downs	–34.88	145.29
075031	Hay Miller Street	–34.52	144.85
040112	Kingaroy Prince St	–26.55	151.85
002038	Kununurra	–15.78	128.74
002056	Kununurra Aero	–15.78	128.71
040083	Gatton Post Office	–27.56	152.28
033045	Mackay Aero	–21.17	149.18
031066	Mareeba QWRC	–17.00	145.43
042023	Miles Post Office	–26.66	150.18
039104	Monto Post Office	–24.87	151.12
012056	Moree	–31.6	119.14
053048	Moree Comparison	–29.48	149.84
053027	Moree Post Office	–29.5	149.9
054120	Narrabri Bowling Club	–30.32	149.79
053030	Narrabri West Post Office	–30.34	149.75
051115	Narromine Airport	–32.22	148.23
051037	Narromine Post Office	–32.23	148.24
002041	Ord River Regeneration St	–17.39	128.92
041082	Pittsworth Post Office	–27.71	151.63
039083	Rockhampton Aero	–23.38	150.48
043091	Roma Airport	–26.55	148.78
043030	Roma Post Office	–26.57	148.79
035065	Springsure Post Office	–24.12	148.09
043034	St George Post Office	–28.04	148.58
041103	Toowoomba	–27.58	151.93
072150	Wagga Wagga AMO	–35.16	147.46
074114	Wagga Wagga SCS	–35.13	147.31
052026	Walgett	–30.04	148.12
054029	Warialda Post Office	–29.54	150.58
041176	Warwick Dragon St	–28.22	152.03
041111	Warwick Post Office	–28.22	152.03

the value of the infection factor (*f*) on each hour using the following equation (Wang *et al.* 2000*b*):

$$f = \exp(-0.026T^2 + 1.014T - 9.8865)$$

where T is the hourly temperature (°C).

Values of daily mean infection factor were used in the analysis.

Prediction of ergot events

For each day of the year over the past 111 years, assumed as the first day (start) of flowering, the mean daily minimum temperature during the flag leaf period, the daily infection factor based on hourly temperatures during the flowering period, and the mean daily maximum vapour pressure deficit (*VPDm*) during the flowering period were calculated using the methods described above. Similar results on potential ergot events were obtained when the threshold of *VPDm* <18 hPa was substituted for the relative humidity factor in the original rules developed by Wang *et al.* (2000*b*). Consequently, *VPDm* <18 hPa was used in this analysis as the threshold for daily wetness.

Based on this information and Wang *et al.* (2000*b*) the following conditions had to be met before it was deemed likely that an ergot outbreak could occur.

(*1*) The mean daily maximum vapour pressure deficit (*VPDm*) during the whole flowering period was <18 hPa.

(*2*) Male sterility in hybrid grain sorghum was assumed to occur whenever the mean daily minimum temperature during the flag leaf stage was <13°C. In these cases, the mean infection factor (*f*) based on the hourly temperature during the whole flowering period had to be >0.05. If that mean daily minimum temperature was 13°C, the mean infection factor had to be >0.30.

When the above conditions were met, it was assumed that sorghum flowering on that day was subject to infection by ergot. That day was then counted as an 'ergot event'.

Risk analysis based on SOI phases

Understanding rainfall variability is essential for appropriate agricultural risk management (Meinke and Hochman 2000; Hammer *et al.* 2001). A considerable part of the rainfall variability in Australia is related to ENSO (Nicholls and Wong 1991; Zhang and Casey 1992). Performing principal component analysis (PCA) on long-term SOI values and then clustering these PCA scores, Stone (1992) and Stone *et al.* (1996) developed a SOI-based forecast system (SOI phases) that conveniently indexes the state of the ocean–atmosphere continuum and its effect on global rainfall. This forecast system is now used operationally for many agricultural applications throughout Australia (e.g. Potgieter *et al.* 2002; Meinke *et al.* 2003).

At each location, the total number of events in every month of the 111-year climate record was calculated. Based on the SOI phases (Stone *et al.* 1996) in the previous month, all months in the 111 years were separated into 5 classes: months with a consistently negative SOI phase (Phase 1), months with a consistently positive SOI phase (Phase 2), months with a rapidly falling SOI phase (Phase 3), months with a rapidly rising SOI phase (Phase 4), and months with a near zero SOI phase (Phase 5).

A median number of monthly infection events was calculated by sorting the events for each month for all years regardless of SOI phases. The probability of exceeding this median number of events for each month within each of the 5 SOI classes was then calculated and is presented in Figs 1–5.

The total, monthly number of events for each of the 5 SOI categories was then used to calculate the probability of exceeding a given number of monthly events for every month of the year (Figs 6–8).

Results and discussion

The effect of ENSO states (SOI phases) on the number of potential events differed strongly in different months of the year and between locations (Figs 1–5). Following an SOI Phase 1, which is frequently associated with El Niño-like conditions and below-median rainfall for much of Australia, the probability of exceeding the median number of monthly events (PEME) was <50% for almost all locations between October and February (Fig. 1). In March, PEME at most locations in New South Wales was >60%. In April, some coastal regions in Queensland had a PEME >50%, while PEME was <50% in other regions. In May, PEME in eastern Queensland and northern New South Wales was higher than 60–75%, compared with very low values (<15%) in northern Queensland and southern New South Wales (Fig. 1).

A consistently positive SOI phase (Phase 2) is often associated with La Niña-type conditions and frequently results in above-median rainfall for much of Australia. Following SOI Phase 2, PEME was much higher than that following SOI Phase 1 at almost all locations and for all months except May (Fig. 2). This result implies that a higher risk can be expected following a consistently positive SOI phase, especially from August to October (Fig. 2). During December–March, when most commercial sorghum crops are flowering, a positive SOI phase (Phase 2) resulted in the highest risk of ergot infection in most parts of the sorghum-growing areas (Figs 1–5).

Under rapidly falling SOI conditions (Phase 3), PEME values for most locations were between those associated with SOI Phase 1 and 2 (Fig. 3), except for November when PEME in coastal Queensland and New South Wales was actually the highest (>60%) of all SOI categories. In February and April, PEME values in southern New South Wales also tended to be higher during SOI Phase 3 years (Fig. 3). PEME values for SOI Phases 4 and 5 were similar, except in March and August in the coastal regions of Queensland, when a rapidly rising SOI (Phase 4) resulted in higher risk of disease outbreaks (Figs 4, 5).

Figs 6–8 show the probability of exceeding a certain number of monthly events that would have been conducive to ergot infection from October to May in the past 111 years in 3 locations from north to south: Mareeba (17.00S, 145.43E), Rockhampton (23.38S, 150.48E), and Walgett (30.04S, 148.12E). At Mareeba, for 6 months (Oct., Nov., Jan., Feb., Mar., and Apr.) of the 8 months from October to May, a consistently positive SOI phase (Phase 2) in the previous month resulted in a much higher risk of ergot infection than a consistently negative SOI phase (Phase 1) in the previous month (green and red lines, respectively, Fig. 6). A high infection risk was identified for December and February following a rapidly falling SOI phase (Phase 3, blue line, Fig. 6). At this time of the year, a rapidly falling SOI phase is associated with increased mid-level atmospheric instabilities that can result in increased rainfall probabilities

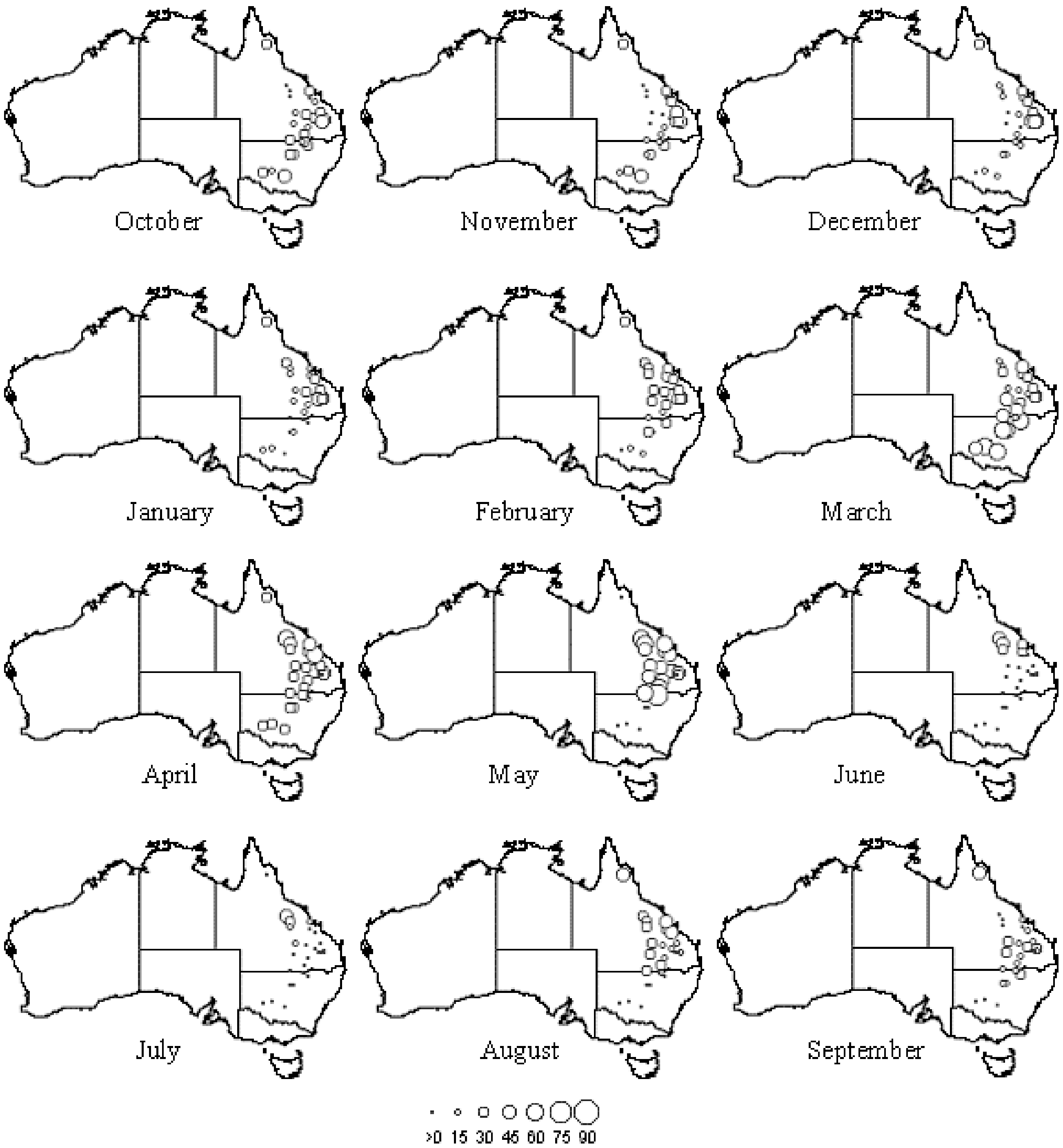

Fig. 1. Probability of exceeding median number of monthly ergot events in each month following a consistently negative SOI phase (Phase 1).

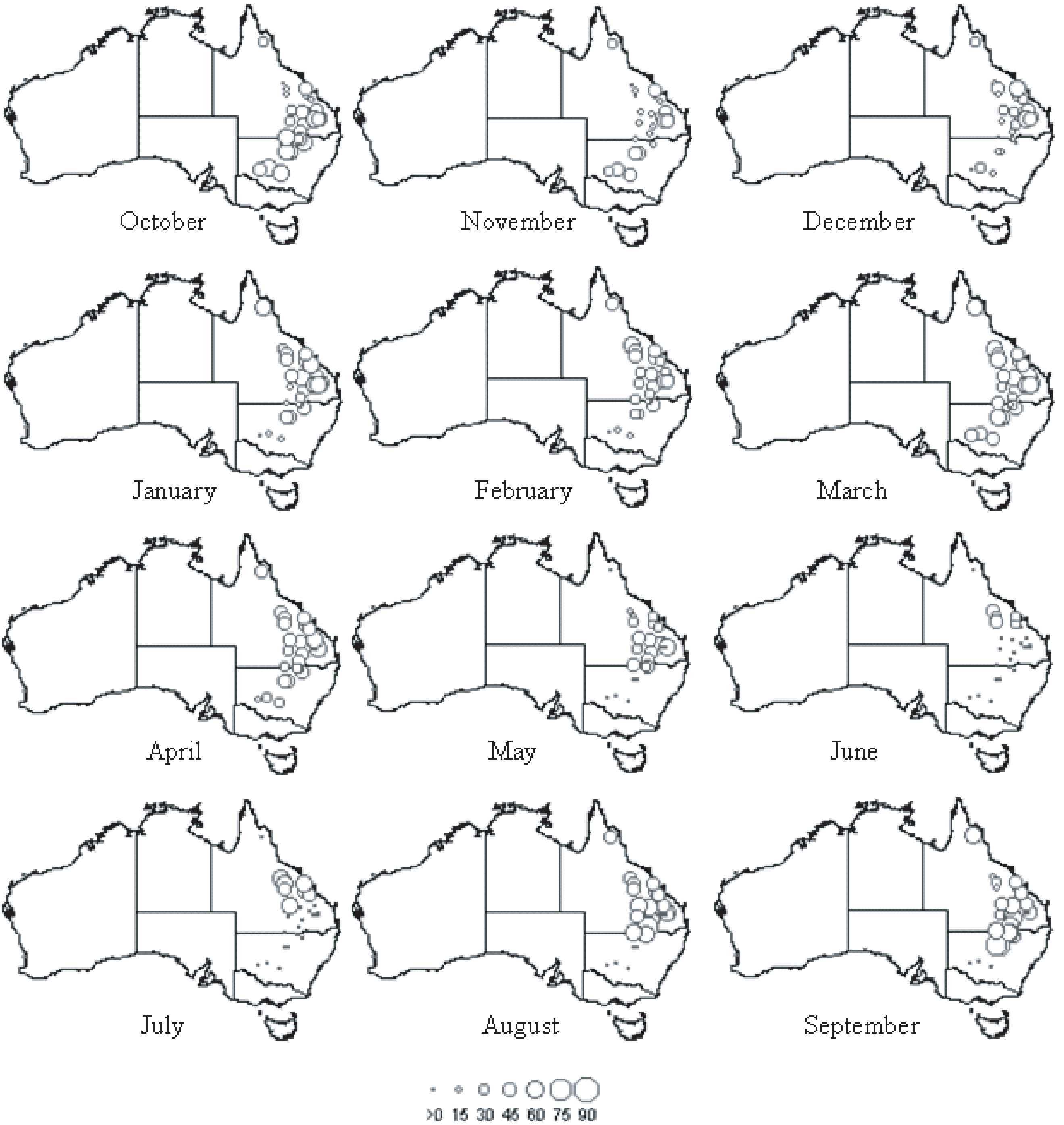

Fig. 2. Probability of exceeding median number of monthly ergot events following a consistently positive SOI phase (Phase 2).

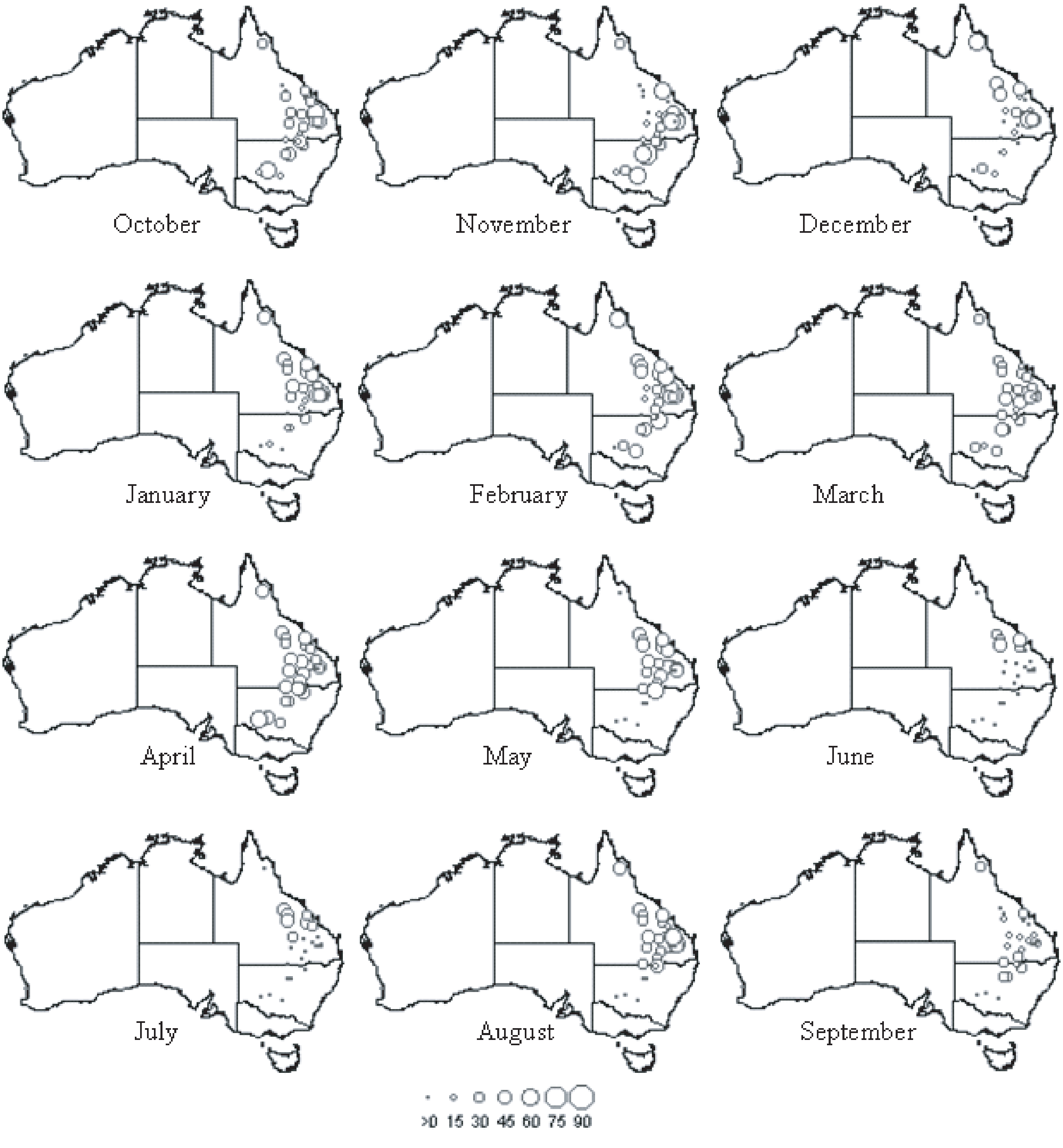

Fig. 3. Probability of exceeding median number of monthly ergot events following a rapidly falling SOI phase (Phase 3).

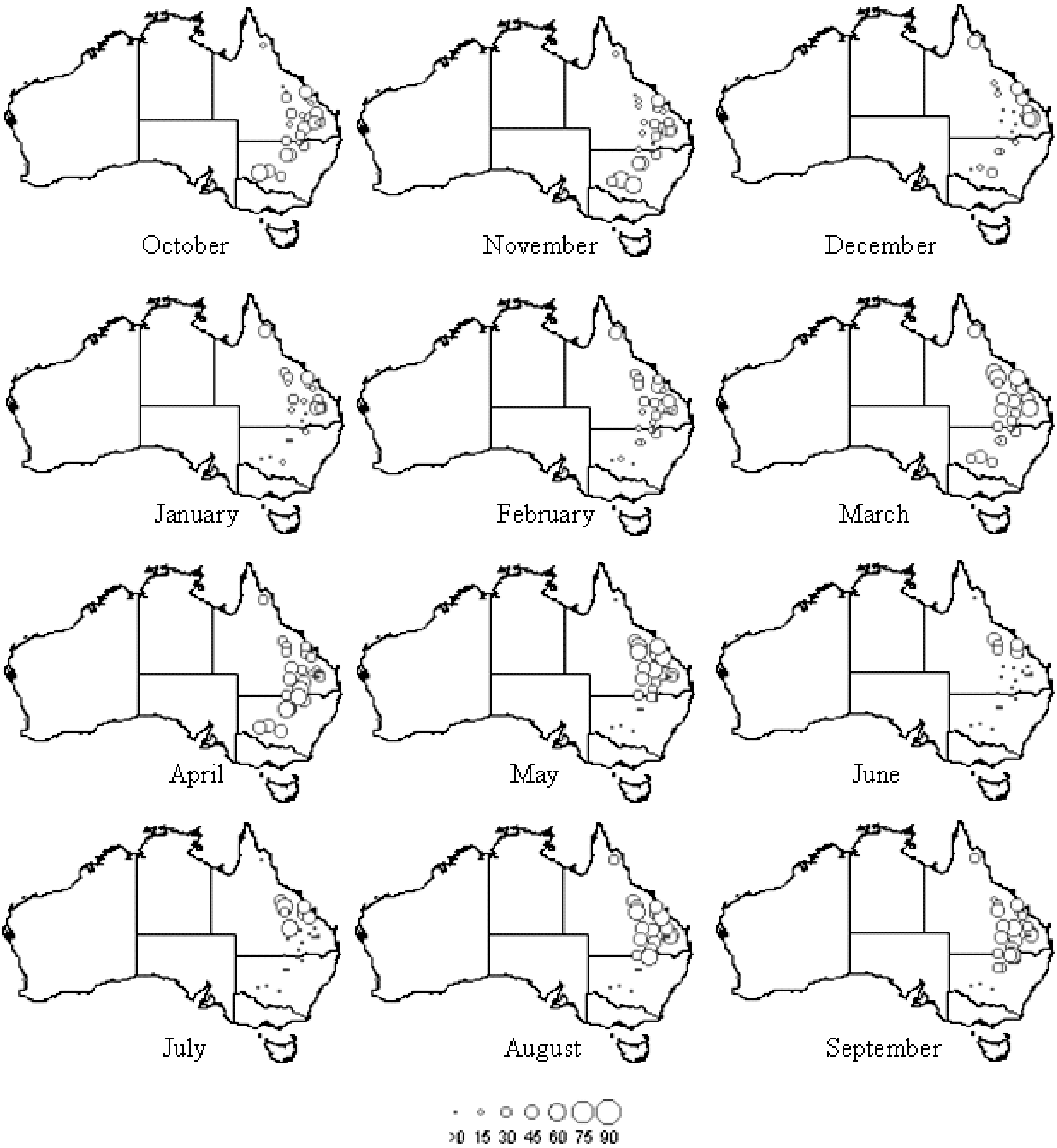

Fig. 4. Probability of exceeding median number of monthly ergot events following a rapidly rising SOI phase (Phase 4).

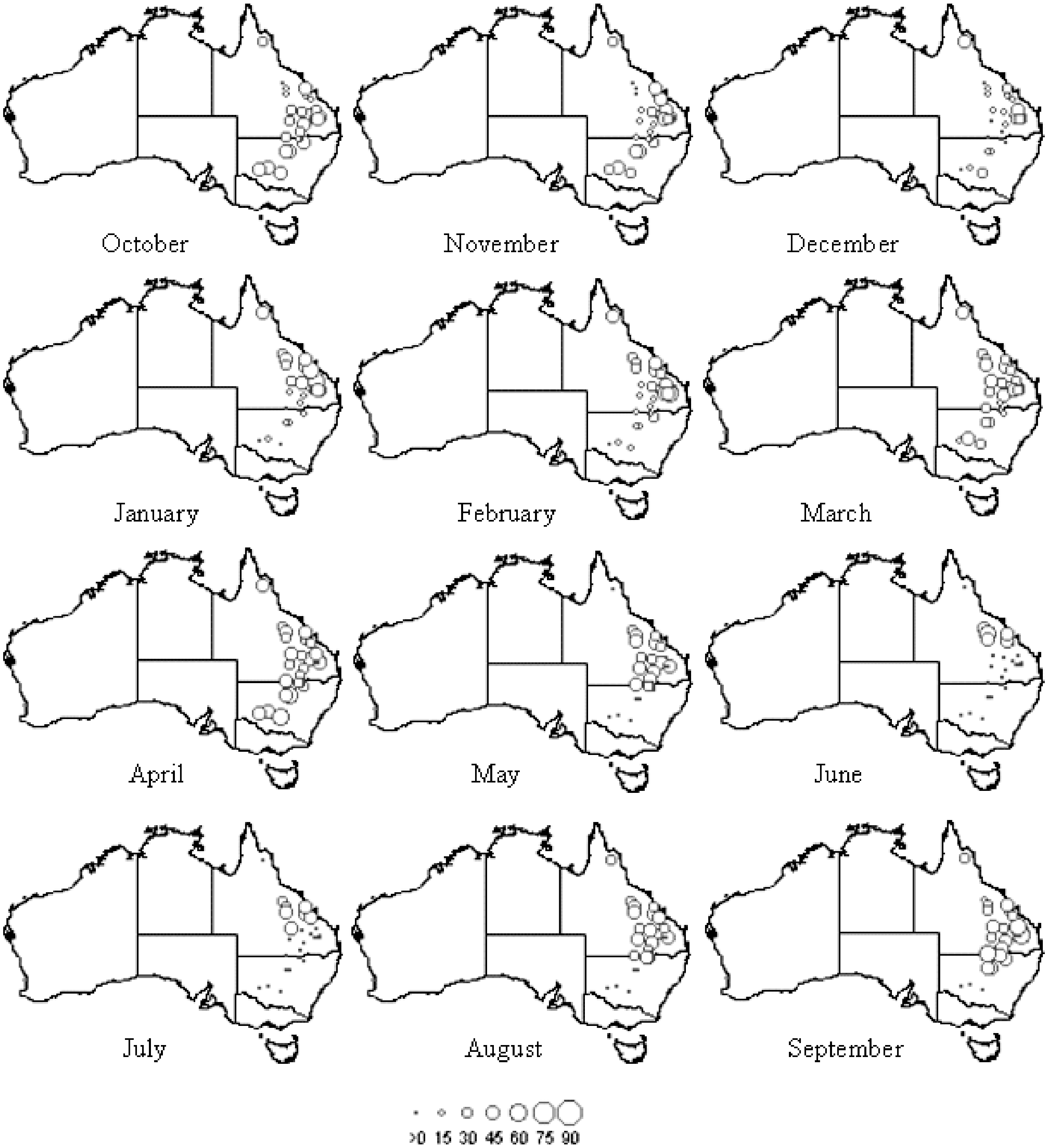

Fig. 5. Probability of exceeding median number of monthly ergot events following a near zero SOI phase (Phase 5).

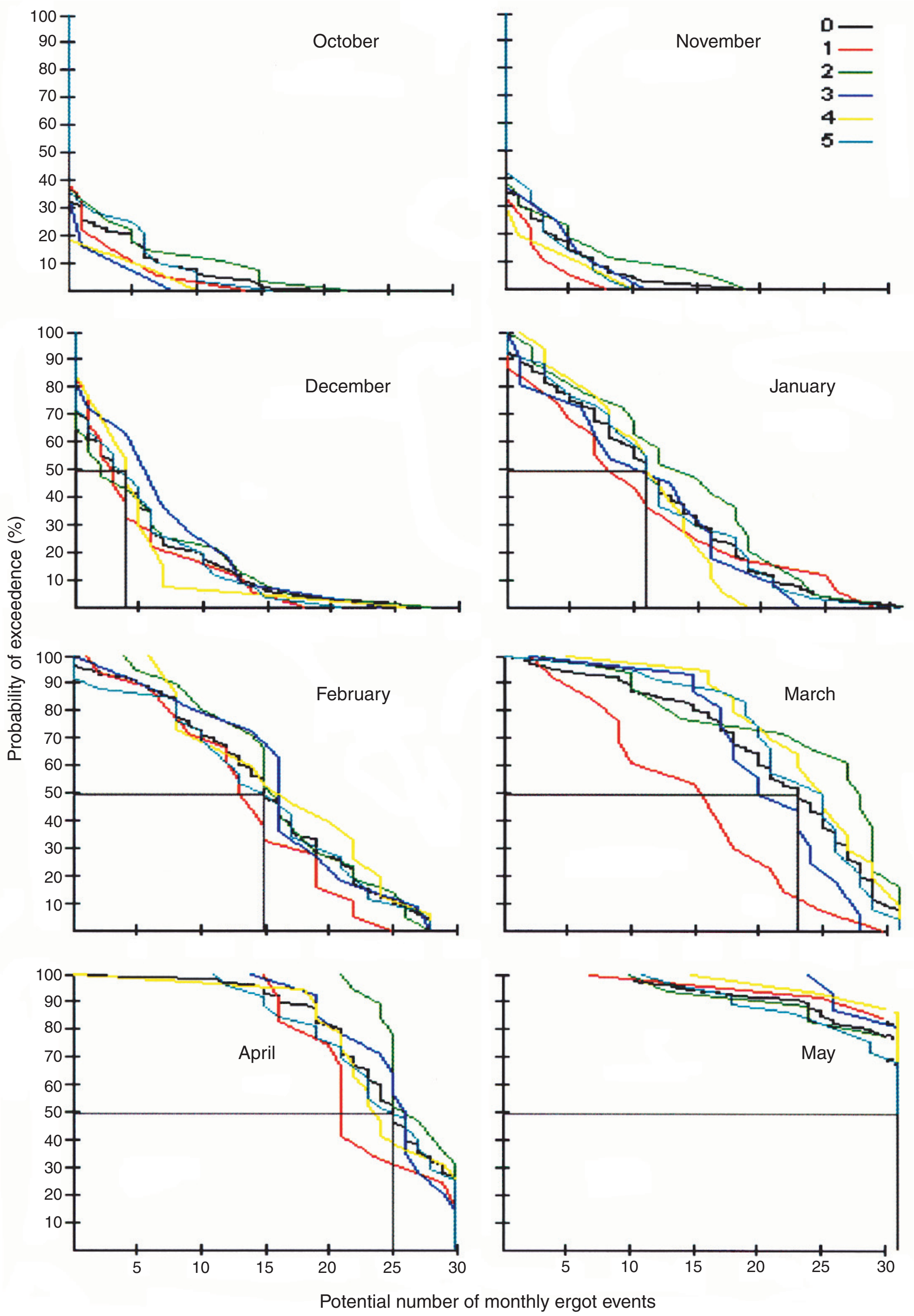

Fig. 6. Probability of exceedence for the potential number of monthly events that are conducive to ergot outbreak in Mareeba, northern Queensland, based on 111 years of climate records (1887–1998). Different line colours represent the different SOI phases: black, all years together; red, SOI phase consistently negative (Phase 1); green, SOI phase consistently positive (Phase 2); blue, SOI phase rapidly falling (Phase 3); yellow, SOI phase rapidly rising (Phase 4); light blue, SOI phase near zero (Phase 5).

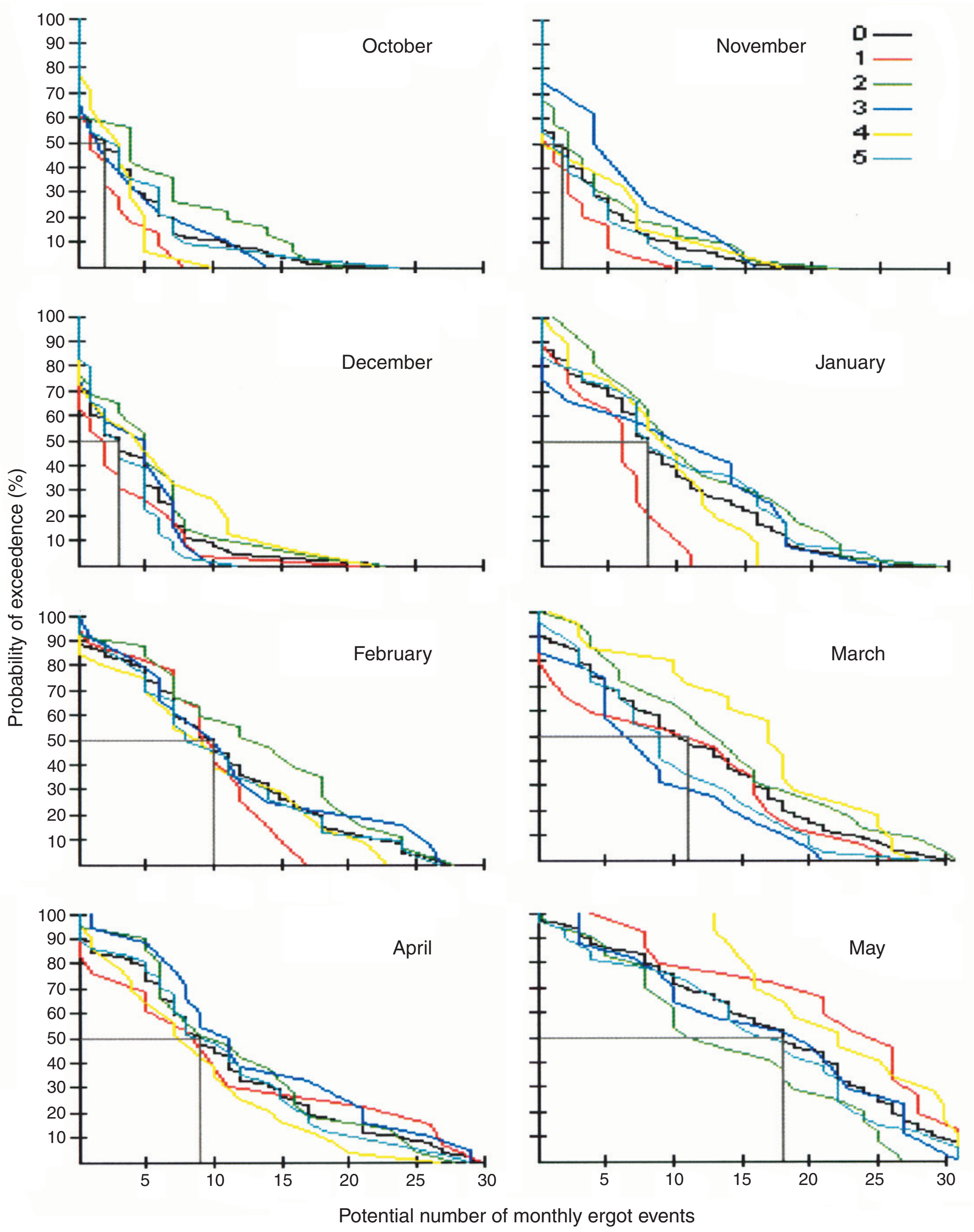

Fig. 7. Probability of exceedence for the potential number of monthly events that are conducive to ergot outbreak at Rockhampton, Queensland, based on 111 years of climate records (1887–1998). Different line colours represent the different SOI phases: black, all years together; red, SOI phase consistently negative (Phase 1); green, SOI phase consistently positive (Phase 2); blue, SOI phase rapidly falling (Phase 3); yellow, SOI phase rapidly rising (Phase 4); light blue, SOI phase near zero (Phase 5).

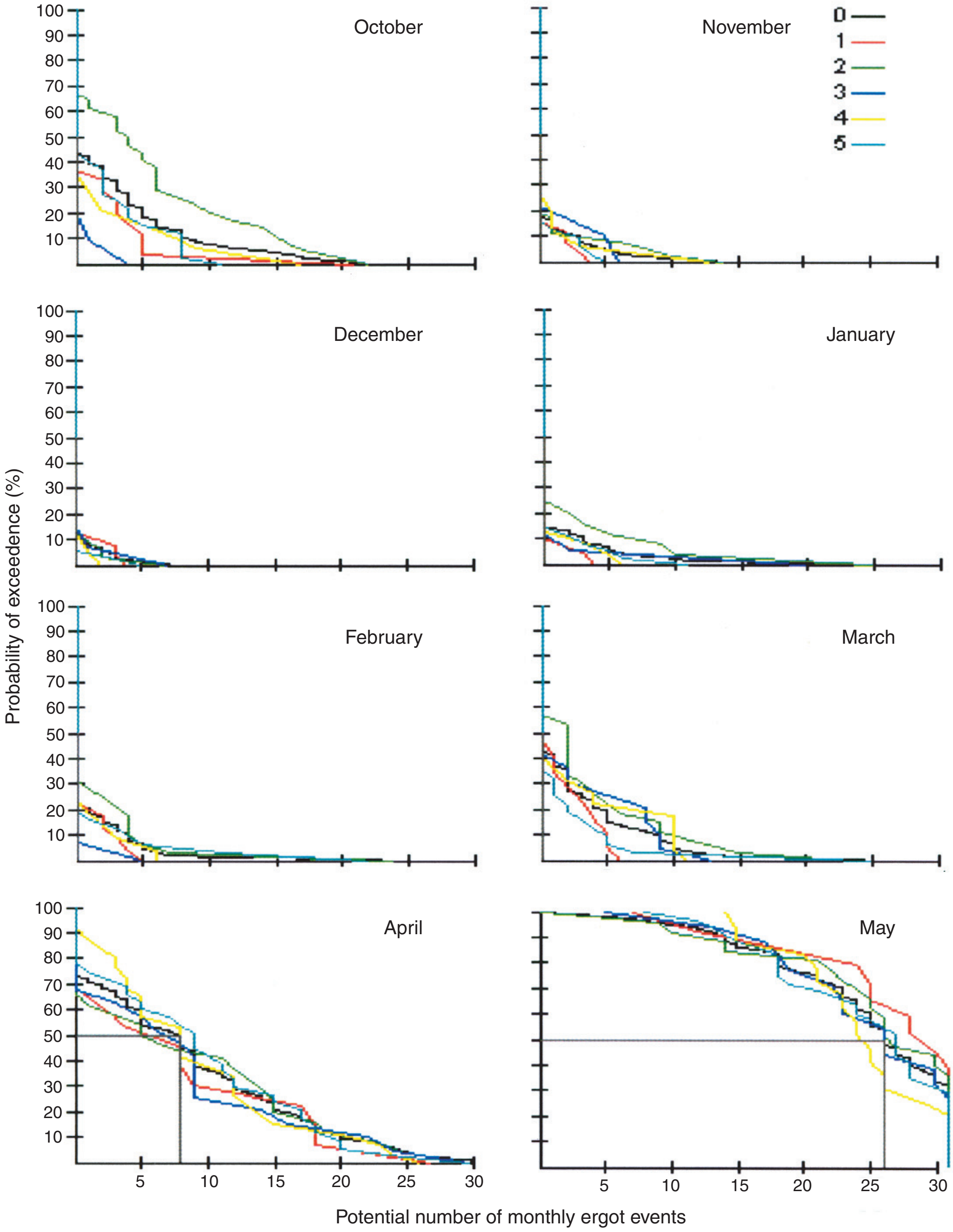

Fig. 8. Probability of exceedence for the potential number of monthly events that are conducive to ergot outbreak at Walgett, New South Wales, based on 111 years of climate records (1887–1998). Different line colours represent the different SOI phases: black, all years together; red, SOI phase consistently negative (Phase 1); green, SOI phase consistently positive (Phase 2); blue, SOI phase rapidly falling (Phase 3); yellow, SOI phase rapidly rising (Phase 4); light blue, SOI phase near zero (Phase 5).

for many parts of Australia even during El Niño years (Stone 1992). It is these non-linear relationships between the SOI and rainfall patterns that resulted in the development of the SOI phase system by Stone *et al.* (1996). In May, the ergot risk became much higher for all SOI phases.

At Rockhampton (Fig. 7), the highest infection risk occurred in October, December, January, and February following a SOI Phase 2, in November following a SOI Phase 3, and in March following a SOI Phase 4, whereas the lowest risk was associated with a SOI Phase1 from October to February (Fig. 7). From March to April, differences between SOI Phases 1 and 2 diminished. In May, a higher risk occurred following a SOI Phase 1.

At Walgett (Fig. 8), the potential number of monthly ergot events was generally low from November to February. From October to March, a SOI Phase 2 resulted in a higher infection risk than SOI Phase 1, except in December when the potential number of ergot events was very low. After March the risk following a SOI Phase 1 increased strongly.

Other locations, such as Clermont, Roma, and Goondiwindi (data not shown), showed the highest risk following a SOI Phase 2 and the lowest risk following a SOI Phase 1.

Ergot was first recorded in Australia in April 1996. The above results are generally consistent with the limited, observed ergot outbreaks over the past few years. In 1996, late April–early May was wet in southern Queensland and the disease rapidly spread (Ryley *et al.* 2001). The SOI phase for March–April 1996 was ‘near zero’ (Phase 5), implying a medium high risk for ergot outbreaks relative to the other SOI categories (Fig. 5). However, the absolute number of potential events so late in the season is always very high, regardless of SOI phases (Figs 6–8). In February 2000, ergot was widespread in most crops on the eastern Downs (Ryley *et al.* 2001). This followed a ‘consistently positive’ SOI phase in January 2000. This is consistent with our analysis. However, little ergot was observed in summer 2000–01 despite the consistently positive SOI phases from September 2000 to March 2002. The available data are too sparse to independently validate or test these probabilistic forecasts.

In a previous paper we predicted the mean number of monthly ergot events and ergot severity in the period from 1957 to 1998 across the sorghum-producing areas of Australia (Wang *et al.* 2000*b*). The results presented here show that the number of potential ergot events in any month differed strongly between years, depending on the season type and location. Generally, a SOI Phase 2 or 4 (often associated with La Niña-type climate patterns) resulted in a higher number of potential infection events. Using cross-spectral analysis, Scherm and Yang (1995) also showed that long-term (>40 years) interannual variations in the development of wheat rusts in China and the United States were associated with the SOI at temporal scales characteristic of the ENSO. Their further analysis indicated that there are consistent and significant coherence relationships between the Western Atlantic pattern and stripe rust severity in North China at a periodicity of 3 years (Scherm and Yang 1998). Our results, which are obtained based on the biophysical relationships between ergot infection processes and weather factors (Wang *et al.* 2000*a*, 2000*b*), provide a more mechanistic basis to assess the effect of climate variability on ergot disease outbreaks. These results indicate that it is important to take the climate variability into account when conducting risk analyses of disease outbreaks. Such information could be an important component of the management of sorghum ergot in Australia and overseas. Hybrid seed producers and grain growers could be alerted to the potential of a high ergot risk based on SOI phases, and be more prepared to undertake appropriate management practices that could reduce ergot infection and contamination levels in harvested grain.

References

Bandyopadhyay R, Frederickson DE, McLaren NW, Odvody GN, Ryley MJ (1998) Ergot: a new disease threat to sorghum in the Americas and Australia. *Plant Disease* **82**, 356–367.

Blaney BJ, McKenzie RA, Walters JR, Taylor LF, Bewg WS, Ryley MJ, Maryam R (2000) Sorghum ergot (*Claviceps africana*) associated with agalactia and feed refusal in pigs and dairy cattle. *Australian Veterinary Journal* **78**, 102–107.

Brooking IR (1976) Male sterility in S*orghum bicolor* (L.) Moench induced by low night temperature. I. Timing of the stage of sensitivity. *Australian Journal of Plant Physiology* **3**, 689–696.

Brooking IR (1979) Male sterility in S*orghum bicolor* (L.) Moench induced by low night temperature. II. Genotype differences in sensitivity. *Australian Journal of Plant Physiology* **6**, 143–147.

Dahlberg J, Bandyopadhyay R, Rooney B, Odvody G, Madera-Torres P (2001) Evaluation of sorghum germplasm used in US breeding programmes for sources of sugary disease resistance. *Plant Pathology* **50**, 681–689.

Downes RW, Marshall DR (1971) Low temperature induced male sterility in *Sorghum bicolor*. *Australian Journal of Experimental Agriculture and Husbandry* **11**, 352–355.

Hammer GL, Hansen JW, Phillips JG, Mjelde JW, Hill H, Love A, Potgieter A (2001) Advances in application of climate prediction in agriculture. *Agricultural Systems* **70**, 515–553.

Hammer GL, Muchow RC (1994) Assessing climatic risk to sorghum production in water-limited subtropical environments. I. Development and testing of a simulation model. *Field Crops Research* **36**, 221–234.

Hammer GL, Vanderlip RL, Gibson G, Wade LJ, Henzell RG, Younger DR, Warren J, Dale AB (1989) Genotype-by-environment interaction in grain sorghum. II. Effects of temperature and photoperiod on ontogeny. *Crop Science* **29**, 376–384.

McLaren NW (1997) Changes in pollen viability and concomitant increase in the incidence of sorghum ergot with flowering date and implications in selection for escape resistance. *Journal of Phytopathology* **145**, 261–265.

McLaren NW (2000) Resistance of sorghum hybrids to ergot caused by *Claviceps africana*. *South African Journal of Plant and Soil* **17**, 1–5.

McLaren NW, Flett BC (1998) Use of weather variables to quantify sorghum ergot potential in South Africa. *Plant Disease* **82**, 26–29.

McLaren NW, Wehner FC (1990) Relationship between climatic variables during early flowering of sorghum and the incidence of sugary disease caused by *Sphacelia sorghi*. *Journal of Phytopathology* **130**, 82–88.

McLaren NW, Wehner FC (1992) Pre-flowering low temperature predisposition of sorghum to sugary disease (*Claviceps africana*). *Journal of Phytopathology* **135**, 328–334.

Meinke H, Hammer GL, van Keulen H, Rabbinge R, Keating BA (1997) Improving wheat simulation capabilities in Australia from a cropping systems perspective. Water and nitrogen effects on spring wheat in a semi-arid environment. *European Journal of Agronomy* **7**, 75–88.

Meinke H, Hochman Z (2000) Using seasonal climate forecasts to manage dryland crops in northern Australia. In 'Applications of seasonal climate forecasting in agriculture and natural ecosystems: the Australian experience'. (Eds GL Hammer, N Nicholls, C Mitchell) pp. 149–165. (Kluwer Academic Publishers: Dordrecht, The Netherlands)

Meinke H, Wright W, Hayman P, Stephens D (2003) Managing cropping systems in variable climates. In 'Principles of field crop production'. 4th edn (Ed. J Pratley) pp. 26–77. (Oxford University Press: Melbourne)

Nicholls N, Drosdowsky W, Lavery B (1996) Australian rainfall variability and change. *Weather* **52**, 66–72.

Nicholls N, Wong KK (1991) Dependence of rainfall variability on mean latitude and the Southern Oscillation. *Journal of Climate* **3**, 163–170.

Potgieter AB, Hammer GL, Butler D (2002) Spatial and temporal patterns in Australian wheat yield and their relationship with ENSO. *Australian Journal of Agricultural Research* **53**, 77–89.

Ryley MJ, Henzell RG, Chakraborty S, Bhuiyan S, Herde D (2001) The biology and management of sorghum ergot in Australia. In 'Proceedings 4th Australian Sorghum Conference, 5–8 February 2001, The Kooralbyn Hotel Resort'. (Eds AK Borrell, RG Henzell) (Range Media Pty Ltd: Toowoomba, Qld) CD Rom ISBN: 0724221638.

Ryley MJ, Persley D, Jordan DR, Henzell RG (2002) Status of sorghum and pearl millet diseases in Australia. In 'Sorghum and millets diseases 2000'. (Ed. JF Leslie) pp. 141–150. (Iowa State University Press: Ames, IA)

Scherm H, Yang XB (1995) Interannual variations in wheat rust development in China and the United States in relation to the El Nio/Southern Oscillation. *Phytopathology* **85**, 970–976.

Scherm H, Yang XB (1998) Atmospheric teleconnection patterns associated with wheat stripe rust disease in North China. *International Journal of Biometeorology* **42**, 28–33.

Stone RC (1992) SOI phase relationships with rainfall in Australia. PhD Thesis, University of Queensland, Brisbane, Australia.

Stone RC, Hammer GL, Marcussen T (1996) Prediction of global rainfall probabilities using phases of the Southern Oscillation Index. *Nature* **384**, 252–255.

Tanner CB, Sinclair TR (1983) Efficient water use in crop production: research or re-search? In 'Limitations to efficient water use in crop production'. (Eds HM Taylor, WR Jordan, TR Sinclair) pp. 1–27. (ASA: Madison, WI)

Wang E, Meinke H, Ryley MJ (2000*a*) On the relation between weather variables and sorghum ergot infection. *Australian Journal of Agricultural Research* **51**, 313–324.

Wang E, Meinke H, Ryley MJ (2000*b*) Event frequency and severity of sorghum ergot in Australia. *Australian Journal of Agricultural Research* **51**, 457–466.

Wang E, Ryley MJ, Meinke H (2000*c*) Prediction of sorghum downy mildew risk in Australia using daily weather data. *Australasian Plant Pathology* **29**, 108–119.

Zhang XG, Casey TM (1992) Long-term variations in the Southern Oscillation and relationships with Australian rainfall. *Australian Meteorological Magazine* **40**, 211–225.

Manuscript received 1 November 2002, accepted 25 March 2003