

Temperature Increase and Cotton Crop Phenology

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Abstract: The daily outputs of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Conformal Cubic Atmospheric Model driven by four general circulation models (GCMs) were used by a stochastic weather generator, LARS-WG, to construct local climate change scenarios at nine key cotton production areas in eastern Australia. These climate change scenarios were then linked to daily temperature-driven models of cotton phenology (the CSIRO Cotton Day Degree calculator and the Last Effective Flower tools) to examine the magnitude of the effects of increased temperature on the initiation and duration of key crop phenophases and on the occurrence of heat stress (hot days $\geq 35^{\circ}\text{C}$ maximum) and cold shocks ($\leq 11^{\circ}\text{C}$ minimum) during the growing season. The results show that when using 1 Oct. sowing (1) the timing of emergence, 1st square (flower bud), 1st flower and 1st open boll advanced 1~9, 4~13, 5~14, 8~16 days respectively for the period centred on 2030 compared to the period centred on 1990; (2) when crops were planted 10 days earlier, emergence advanced more in most of the locations while other phenological events changed only slightly (approximately 1 day) in comparison with 1st. Oct. sowing; when crops were planted 10 days later all these events generally were delayed (approximately 1.5 days) in comparison with 1st Oct. sowing depending on locations; (3) the timing of the last effective square, last effective flower and last harvestable boll were delayed 7~12, 6~9 and 3~9 days respectively across locations and GCMs; and (4) combining the effects of an earlier time of first square and a later last effective square potentially increased the time for new fruit (squares) to be produced by up to two to three weeks. This analysis highlights the challenges associated with temperature with future climate change for future cotton production in Australia. Future research will be directed to assess the combined effects of changes in temperature, rainfall and atmospheric CO_2 concentration on cotton water use, water use efficiency, cotton lint yield, fibre quality (i.e. micronaire and fibre length); evaluate the effectiveness of a range of plant-based and management-based adaptation options in dealing with climate change risks; and quantify the cost and benefits of identified effective adaptation options, especially with the use of high yielding transgenic cotton with early high fruit loads in Australian high yielding ($>2000\text{kg}$ lint /ha) irrigated systems.

Keywords: *temperature increase, cotton phenology, heat stress, cold shock*

1. INTRODUCTION

Temperature is one of the major environment factors affecting the growth, development and yields of crops, especially the rate of development (Luo, 2011). On one hand, crops have basic requirements for temperature to complete a specific phenophase or the whole life cycle. On the other hand, extremely high and low temperatures can have detrimental effects on crop growth, development and yield, particularly at critical phenophases. While cotton is morphologically indeterminate, the rate of many developmental processes such as germination, floral initiation, and development of fruiting bodies is controlled by temperature (Hearn and Constable, 1984). Daily temperature also plays an important role in determining the earliest date of sowing, defining season length which can both influence yield potential and quality (Bange et al., 2008a; Bauer et al., 2000; Dong et al., 2006), and determining where cotton can be produced sustainably. Generally the longer the growing season (GS) the greater the potential for higher lint yields (Bange and Milroy, 2004a; Stiller et al., 2004). In Australian cotton systems, the temperature requirements for the development of cotton are described by the accumulation of degree days calibrated with a base temperature of 12°C (Constable and Shaw, 1988). Other cotton systems elsewhere have used a base temperature closer to 15°C (Robertson et al., 2007).

Throughout most Australian production systems, minimum temperatures (T_{min}) ($\leq 11^{\circ}\text{C}$) experienced early in the cotton season can cause delays in development, reduction in growth, and sometimes chilling injury (Constable et al., 1976; Bange and Milroy, 2004b). As the season progresses maximum temperatures ($\geq 35^{\circ}\text{C}$, heat stress) are commonplace throughout cotton production regions and may adversely affect growth and development thus affecting water used, yield and fibre quality (Hodges et al., 1993). At the end of a cotton season cooler or cold temperature will influence the timing of crop maturity and impact on the effectiveness of chemical harvest aids, both again directly affecting yield and quality. Cotton has an optimal thermal kinetic window of 23 to 32°C in which metabolic activity is most efficient (Burke et al., 1988; Conaty et al., 2012).

Cotton exposed to low temperatures takes longer to develop, and accumulates biomass at a slower rate (Gipson, 1974; Mauney 1986). Cold temperature responses (below 10°C) in early post-emergent seedlings can permanently arrest growth and development (Christiansen, 1967; Christiansen and Thomas, 1969). Bange and Milroy (2004b) also found that negative effects on development exist when plants were exposed to at least 10 nights at 10°C, or for 5 nights at 5°C on post emergent cotton. In Australia, to account for early season cold temperature effects on cotton development, a 'cold shock' effect is applied to day degree (DD) accumulation. A 'cold shock' is defined as an event when the daily minimum temperature falls to 11°C or less, which is assumed to cause chilling injury and thus delays development.

Late in the season, cold temperatures ($\leq 2^{\circ}\text{C}$) can signal the end of the GS. These low temperatures may force bolls to open affecting lint fibre quality (colour and maturity), and will severely impede the efficacy of chemical harvest aids (optimal temperature $\sim 18^{\circ}\text{C}$) to remove leaf from the plant prior to harvest (Bange et al., 2009). The optimum sowing time aims to reduce the incidences of 'cold shocks', while in-season management aims to ensure that fruit has adequate time to mature and that harvest aids are applied prior to the onset of cold temperature.

Increase in temperature associated with climate change will change crop phenology including the start and the duration of phenophases. These changes may have significant implications for cotton lint yield and fibre quality. Hence this work aims to understand local climate change in Australian cotton regions and quantify its impacts on cotton crop phenology.

2. MATERIALS AND METHODS

2.1. Study Locations

This study focused on major cotton production areas in Queensland (Emerald, Dalby, St George and Goondiwindi) and New South Wales (Moree, Bourke, Narrabri, Warren and Hillston), Australia (Table 1). These cotton production areas also represent different growing environments: with Emerald, Bourke and St George being classified as being hot; Dalby, Goondiwindi, Moree, Narrabri and Warren as being central; and Hillston as cool. Classification of these climates for cotton production was based on the analysis of McMahon and Low (1972) using growing DD. These different environments have resulted in adoption of different crop management practices and cultivars.

Table 1 Study Locations

Locations	Latitude (°S)	Longitude (°E)
Emerald	23.55	148.24
Dalby	27.18	151.26
St George	28.04	148.58
Goondiwindi	28.55	150.31
Moree	29.49	149.85
Bourke	30.09	145.94
Narrabri	30.34	149.76
Warren	31.78	147.77
Hillston	33.49	145.52

2.2. Local Climate Change & Climate Change Scenarios

In this study, the outputs of the CSIRO Conformal Cubic Atmospheric Model (CCAM), a dynamic downscaling approach, for baseline (1980-1999) and future period (2020-2039) were used by a stochastic weather generator, LARS-WG, to derive local temperature change including changes in the mean and in variability. The CCAM model was driven by four general circulation models (GCMs), specifically GFDL, CSIRO Mark 3.5, MPI, and MIROC, under A2 emission scenario. The local temperature change information for each location were then reapplied to the LARS-WG with the historical daily temperature data to construct long time series (100 y) temperature scenarios including baseline and future scenarios for impact assessment. More information on these procedures can be found in Luo et al (2013).

2.3. Performance of the LAS-WG

To have confidence in the performance of the LARS-WG, a statistical t-test was carried out to examine the difference in the mean of observed (historical datasets) and LARS-WG-generated temperature including Tmax and Tmin for the period 1980-1999. The observed climate data were obtained from Specialised Information for Land Owners Patched Point Dataset (<http://www.longpaddock.qld.gov.au/silo>) (Jeffrey et al., 2001).

2.4. Cotton Crop Phenology

Cotton sowing in the Australian industry occurs around 1 Oct. (Bange et al., 2008a). In this analysis, we chose three sowing times: 20 Sep., 1 Oct. and 11 Oct. We then defined the GS as the period from these sowing dates until 21 May, 31 May and 10 Jun respectively. For the central and cool locations these sowing dates generally represent a range of sowing dates currently used.

Cotton crop phenology stages considered in this study include the dates of emergence, first square (flower bud), first flower, first open boll, last effective square (LES), last effective flower (LEF), and last harvestable boll (LHB). The DD targets corresponding to the first four stages are set to 80, 505, 777 and 1527 DD respectively (Constable and Shaw, 1988). The last harvestable boll is associated with the occurrence of the first frost which is defined as the Tmin of $\leq 2^{\circ}\text{C}$. The date of the last effective square, flower, and boll can be used to determine target ‘cutout’ dates that assist in ceasing production of new fruiting sites to allow crops (and all bolls) to be mature in time for harvest. The DD differences between the dates of the LHB and LEF (LHB period) and between the LEF and LES (square period) are set to 750 and 430 degree days respectively (Constable, 1991). The DD were derived using a base temperature of 12°C (Constable and Shaw, 1988).

As mentioned in the Introduction, to account for cold temperature on early season cotton development a ‘cold shock’ effect is applied to DD accumulation for predicting the first square and first flower. A ‘cold shock’ is defined as an event when daily Tmin falls to 11°C or less, and extends the DD accumulation by 5.2 degree days for each cold shock event (Hearn and Constable, 1984).

To quantify the effects of climate change on crop phenology, the on-line Day Degree calculator and Last Effective Flower tools (<http://cottassist.com.au>), developed by CSIRO, were modified to be used with baseline (1980-1999) and future period (2020-2039) temperature scenarios for the study locations. Changes in cotton phenology were presented in multi-model ensemble means, which is the average derived from the four driving GCMs.

3. RESULTS

3.1. Performance of the LARS-WG

Table 2 shows the p-values associated with t-tests comparing the mean monthly values of Tmax and Tmin between observed and LARS-WG modelled data for the 1980-1999 time period. It can be seen that the overwhelming majority (about 95% of cases across locations, months and temperature variables) has p-values of greater than 0.05, indicating that the LARS-WG performs reasonably well in simulating monthly mean Tmax and Tmin. This demonstrated the robustness of the weather generator used in this study.

Table 2 p-values associated with t-tests between the mean values of monthly temperatures calculated from daily observed and modelled temperatures using the LARS-WG. The bold values in the table highlight the instances where there were significant differences ($p \leq 0.05$) between the observed and predicted data.

Locations		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Emerald	T _{min} ¹	0.610	0.574	0.418	0.865	0.718	0.398	0.465	0.570	0.586	0.666	0.482	0.513
	T _{max} ²	0.983	0.716	0.602	0.811	0.911	0.077	0.941	0.471	0.073	0.044	0.248	0.852
Dalby	T _{min}	0.689	0.491	0.130	0.745	0.716	0.855	0.418	0.790	0.314	0.890	0.868	0.873
	T _{max}	0.328	0.233	0.881	0.324	0.735	0.373	0.973	0.045	0.029	0.258	0.952	0.875
St George	T _{min}	0.647	0.739	0.859	0.181	0.695	0.265	0.586	0.750	0.131	0.071	0.155	0.353
	T _{max}	0.768	0.530	0.932	0.089	0.648	0.684	0.747	0.725	0.045	0.006	0.076	0.269
Goondiwindi	T _{min}	0.972	0.454	0.401	0.675	0.908	0.182	0.748	0.706	0.171	0.701	0.426	0.441
	T _{max}	0.488	0.878	0.719	0.869	0.198	0.955	0.635	0.252	0.015	0.055	0.119	0.467
Moree	T _{min}	0.426	0.833	0.630	0.197	0.862	0.600	0.725	0.103	0.210	0.529	0.246	0.944
	T _{max}	0.318	0.648	0.307	0.730	0.522	0.662	0.410	0.714	0.111	0.082	0.199	0.274
Bourke	T _{min}	0.900	0.784	0.429	0.211	0.226	0.304	0.405	0.910	0.180	0.050	0.110	0.186
	T _{max}	0.826	0.455	0.538	0.727	0.928	0.684	0.091	0.532	0.079	0.124	0.174	0.667
Narrabri	T _{min}	0.474	0.796	0.963	0.174	0.030	0.771	0.732	0.736	0.828	0.475	0.456	0.947
	T _{max}	0.637	0.477	0.829	0.743	0.534	0.701	0.802	0.239	0.038	0.040	0.169	0.375
Warren	T _{min}	0.301	0.966	0.756	0.219	0.350	0.613	0.528	0.880	0.828	0.244	0.138	0.547
	T _{max}	0.649	0.612	0.510	0.782	0.884	0.846	0.965	0.701	0.314	0.413	0.063	0.875
Hillston	T _{min}	0.403	0.908	0.267	0.123	0.590	0.338	0.931	0.960	0.951	0.304	0.150	0.660
	T _{max}	0.866	0.036	0.122	0.580	0.453	0.670	0.809	0.838	0.352	0.205	0.104	0.159

3.2. Temperature change

Figure 1 shows the multi-model ensemble mean changes between the periods centred on 2030 and 1989 in Tmean for GS and for each location. From this figure it can be seen that Tmean increased 1~1.2°C across locations. The largest change in average temperature occurred in Dalby associated with a considerable shift in both Tmax and Tmin. The least change in Tmean was at Hillston associated with the lowest changes in both Tmax and Tmin across locations.

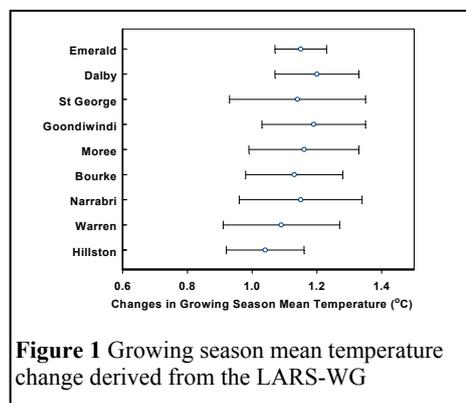


Figure 1 Growing season mean temperature change derived from the LARS-WG

3.3. Changes in crop phenology

Normal sowing

Figure 2 shows the multi-model ensemble mean changes in key phenological events for the period centred on 2030 in comparison with the baseline period 1980-1999. From this figure, it can be seen that temperature increase accelerated the phenological development of all phases across all locations. Emergence, first flower, and first open boll individually were advanced 1~9, 2~8, 1~2, and 1~5 days, respectively (Figure 2a). The biggest changes were in the period from sowing to emergence, especially for the locations further south. In general the smallest effect across all phases was associated with the most northern growing region of Emerald, while the largest change for all phases was associated with the most southern growing areas of Warren and Hillston. This translated into the smallest overall cumulative change for Emerald (8 d) and greatest change for Hillston and Warren (16 d).

For the end of season, the timing of the phenological stages of the LES, LEF and LHB were delayed 0.3~3, 1.8~6.8 and 2.5~9 days respectively across locations, except Warren where the LEF was unaffected and St George where the LHB advanced slightly (Figure 2b). The greatest variability in delays was associated with the LHB (at $T_{min} \leq 2^{\circ}C$) with the largest changes projected for Warren (9d), followed by Dalby (7d) and Narrabri (6d). The smallest changes for LHB were for St George (-0.3d) and Bourke (2.5d). Across all locations, LES and LEF were also later as the periods between LHB to LEF, and LEF to LES were shorter. Overall this meant that the smallest overall delays in season end were for Bourke (6.5d), Hillston (7.3d) and St George (7.5d). The projected longest delays in season end was for Dalby (11.8d) followed by Moree (10d).

Earlier sowing and Later Sowing

With earlier sowing (21st Sept.) in comparison with 1st Oct. sowing, emergence advanced by 1~3d or was unchanged across locations except for St George where a 3d delay was found (Table 3). First square was advanced by 1~4d in northern cotton production areas (with warmer climate), but was delayed ~1d in southern areas (with colder climate). In general there was little effect by the 1st open boll as there was no more than 1d advancement or delay (Table 3). With later sowing (11th Oct.) in comparison with 1st Oct. sowing, emergence was delayed 1~4d except at Hillston where a 0.3d advancement was found. First square was advanced by 1~2d in warmer locations while delayed 0.3~3d in colder locations. 1st flower and 1st open boll were advanced or delayed in the range of 0~1.5d depending on locations (Table 3).

Table 3 Changes (days) in early phenological events of an earlier (21 Sep.) and later sowing (11 Oct) in comparison with 1 Oct. sowing in a changing climate

Locations	Emergence	1 st Square	1 st Flower	1 st Open Boll
Earlier Sowing				
Hillston	-1.5	0.8	0.5	-0.5
Warren	-1.0	0.0	0.3	-0.3
Narrabri	-1.5	0.8	0.5	0.0
Bourke	-3.0	0.5	-0.5	0.5
Moree	-2.3	0.8	0.3	0.0
Goondiwindi	0.0	-2.0	0.5	0.5
St George	3.0	-3.8	-0.8	1.0
Dalby	-1.5	-0.5	0.5	0.5
Emerald	0.0	-0.8	0.8	-0.3
Later Sowing				
Hillston	-0.3	0.3	1.3	-1.5
Warren	0.0	2.8	0.8	-0.8
Narrabri	2.8	0.3	-0.5	0.0
Bourke	2.3	-1.0	-0.5	-0.3
Moree	4.0	-1.5	0.3	-0.3
Goondiwindi	0.5	0.5	-0.5	1.0
St George	2.3	0.0	-0.5	0.5
Dalby	3.3	-1.5	-0.5	0.0
Emerald	0.5	-0.5	0.5	-0.3

Table 4 Change in the length of fruiting period (the difference in days between the first square to last effective square)

Locations	Earlier sowing	Normal sowing	Later sowing
Hillston	19.5	18.8	18.8
Warren	22.0	21.0	18.3
Narrabri	18.5	17.8	14.8
Bourke	15.8	13.3	12.0
Moree	18.5	17.0	14.5
Goondiwindi	16.8	14.8	13.8
St George	16.8	16.0	13.8
Dalby	20.5	18.5	16.8
Emerald	13.8	13.0	13.0

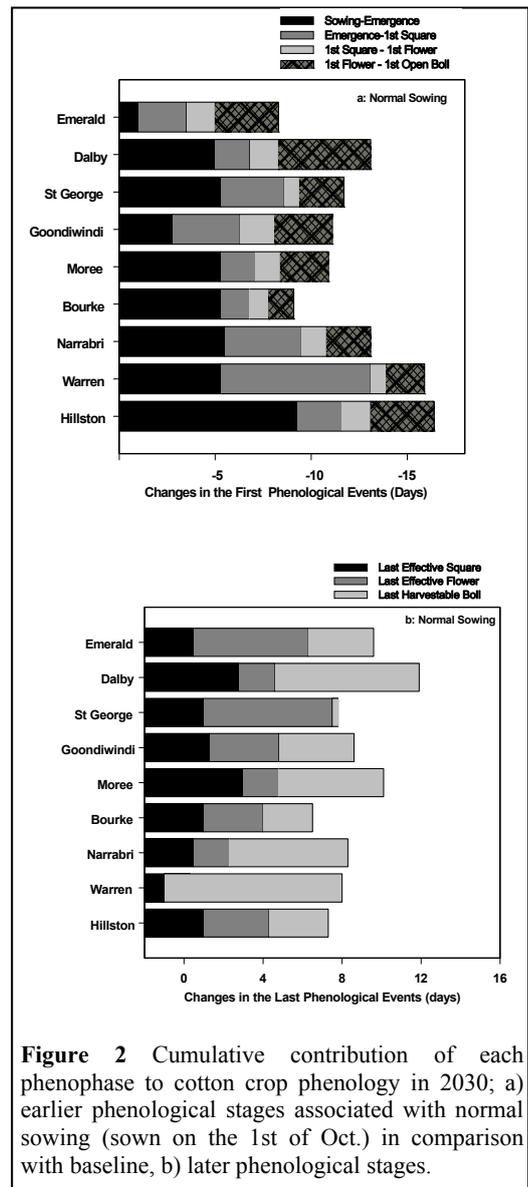


Figure 2 Cumulative contribution of each phenophase to cotton crop phenology in 2030; a) earlier phenological stages associated with normal sowing (sown on the 1st of Oct.) in comparison with baseline, b) later phenological stages.

4. DISCUSSION AND CONCLUSIONS

These results show that the start of key phenological events such as the emergence, first square, first flower and first open boll advanced across locations and GCMs (Figure 2a). Positive impacts on changes in development were related to advancement in emergence and a potential increase in the reproductive (fruiting) period as a result of earlier first square and delayed last effective square. The delay in the last effective square was a result of both a delay in the onset of first frost ($\leq 2^{\circ}\text{C}$) event in the autumn and a more rapid increase in boll development.

Advancement in germination at all locations will lead to increased crop vigour and allows crops to be better established with a more flexible sowing window (Bange et al., 2008b; Braunack et al., 2012). The period from first square to last effective square is effective the period when fruit is developed. This study showed that the period (Table 4) could be increased by two to three weeks, which would result in increased fruit production. Earlier sowing increased the period 1~2 days while later sowing reduced the period 0~3 days (Table 4).

Potential negative effects associated with changes in development may be associated with reductions in the time for vegetative growth to support reproductive growth, and a loss of reproductive capacity associated with reduced boll filling periods and increase fruit shedding from high temperature-stress days. For first square and first flower a more rapid advancement in all locations means that reproductive growth will occur earlier, placing greater demands on overall growth. If less vegetative growth is produced without proper management or cultivars to suit, this may cause crops to 'cutout' more quickly and reduce yield potential. Reduction in the time to 'cutout' will bring on earlier maturity, thus reducing yield (Bange and Milroy, 2004b). There was also evidence that boll periods will be less as demonstrated by the periods from first flower to first open boll and from last effective flower to last harvestable boll. This is a similar finding to Reddy et al. (1999) where cotton boll development was shortened. As a consequence, fibre properties were influenced and boll size was smaller. Despite potential increases in the fruiting periods which may result in more fruit (bolls) the impact on yield maybe tempered by the reductions in boll size.

Future research will be directed to (1) assess the combined effects of changes in temperature, rainfall and atmospheric CO₂ concentration on cotton water use, water use efficiency, cotton lint yield, and fibre quality; (2) evaluate the effectiveness of a range of plant-based and management-based adaptation options in dealing with climate change risks; and (3) quantify the cost and benefits of identified effective adaptation options.

Acknowledgement

We thank Drs McGregor and Nguyen, CSIRO Marine and Atmospheric Research for providing us the high resolution climate change projections from four GCMs and Mr Chris Bull for putting extracted data onto the tape. Thanks also go to Dr Semenov, Rothamsted Research, UK for providing us the weather generator, LARS-WG, and Mr Peter Devoil for letting us access long times series of historical climate datasets. This project is financially supported by the Cotton Research and Development Corporation with project number: UTS1301.

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