CLIMATE AND THE MANAGEMENT OF SUGARCANE

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WEATHER, as the short-term manifestation of climate, is one of the most frequently discussed topics among canegrowers and sugar millers. Components of weather and climate are of crucial importance for growth, harvest and economics of sugar production. Such discussions often include the complexity of the impacts of short-term weather on the crop and the unsuitability of the extremes being experienced. It is clear that solar radiation, temperature, rainfall and wind cannot be controlled to any significant extent for production of field crops. However, their impacts can be managed to some extent through better understanding of the significance of individual factors leading to adoption of improved and relevant cultural practices, based on interpretation of long-term meteorological records, or short-term strategic forecasts. This chapter defines the climate of selected regions of the Australian sugar industry. The significance and impact of climatic variables on production of cane are discussed along with management practices that might modify these impacts. Finally, a directory is provided to facilitate access to contemporary and long-term meteorological information to assist on-farm management decisions.

Weather is the expression of contemporary meteorological parameters at time scales from instantaneous through hourly, daily and weekly intervals. Forecasts for weather factors, solar radiation (mainly for the ultra-violet component at this stage), temperature, precipitation, wind, atmospheric pressure, humidity etc., are issued at these time scales because of impacts on behavioural response of the population at large and tactical needs of primary producers. Capability and capacity to supply more reliable probabilistic weather forecasts at intervals of several days to a week are improving rapidly.

Climate is the integrated consideration of weather related-factors into recognisable and recurring patterns, usually at seasonal scale. This integration leads to interpretable broad terms such as tropical, sub-tropical, temperate or mediterranean climates. We usually associate these categories with defined geographic areas. Further specification can be added with terms such as arid/dry, humid or monsoonal. Climate forecasts are a recent development, based on better understanding of control of larger atmospheric circulations by phenomena such as *El Niño, La Niña*. Climatic forecasts are more generalised than are weather forecasts and are mainly of strategic value for annual planning.

CLIMATE OF THE AUSTRALIAN SUGAR INDUSTRY

Detailed rainfall, temperature, radiation and evaporation data for 13 industry locations are shown in Appendix I. Rainfall and temperature data are real figures but radiation and evaporation data are *drilled* climate data because there are few observed data for these factors within the sugar industry. Drilled data are not actual observations, but are interpolated from existing meteorological data such as rainfall, temperature and day length.

Comparison of drilled and some actual radiation and evaporation data showed very high correlations (R^2=0.80–0.99) for monthly mean data (Appendix II). The drilled data for radiation and evaporation are provided for all sites in Appendix I (except Kununurra) for consistency and to show differences between locations. Care should be exercised in the application of the drilled data as values can vary between 0% and 20% of the actual values (Appendix II).

Rainfall

The Australian sugar industry is located in five discontinuous regions, separated by areas of unreliable rainfall or unsuitable soils, along the eastern coast, between latitudes 16.49°S and 29.48°S. Climate across these zones ranges from wet tropical through dry tropical to humid sub-tropical. The industry in the Ord River (15.65°S) is in the dry tropical zone. Rainfall data (RAINMAN database) has been analysed for 35 sites within the Australian sugar industry. For 20 of these sites, annual rainfall ranges between 1000 and 1700 mm; for 12 sites in the wet tropics, annual rainfall averages between 1700 and 4200 mm, while for Kununurra, Mareeba and Grafton, annual rainfall averages less than 1000 mm (785 911 and 980 mm, respectively).

Annual rainfall is only a broad guide to adequacy of moisture for growing sugarcane. Effective rainfall, calculated from a daily water balance, provides a more useful index of rainfall available for crop growth. Effective rainfall allows for loss of water from the root zone as run-off or deep drainage of excess water, and can be calculated by computer packages such as SOILWAT within APSIM-sugar. Effective rainfall in sugar districts is less variable than total rainfall, and may range between 21–75% of annual rainfall under irrigated conditions and 28–87% of annual rainfall under rainfed conditions. Irrigation reduces the effectiveness of rainfall because irrigation before rainfall allows less storage of rainfall in the soil profile.

Rainfall distribution

Canegrowing has evolved in areas where the rainfall distribution is predominantly in the summer growing season. This is true for the Australian industry (Figure 1), where more than 60% of annual rainfall is recorded in the period November to April. This proportion declines from more than 80% in the tropics, where there is a greater influence from cyclonic rainfall, to 60–70% in southern districts, where summer rainfall is more reliant on storm rain associated with eastward passage of surface and upper-atmosphere troughs. Irrigation is essential for production of sugarcane in the Kununurra, Mareeba and Burdekin areas because of low total annual rainfall. Variability of the summer and winter distributions in the Mackay-Proserpine and Bundaberg-Maryborough regions indicates need for significant supplementary irrigation for economic production of sugarcane (see Chapter 10, Irrigation).

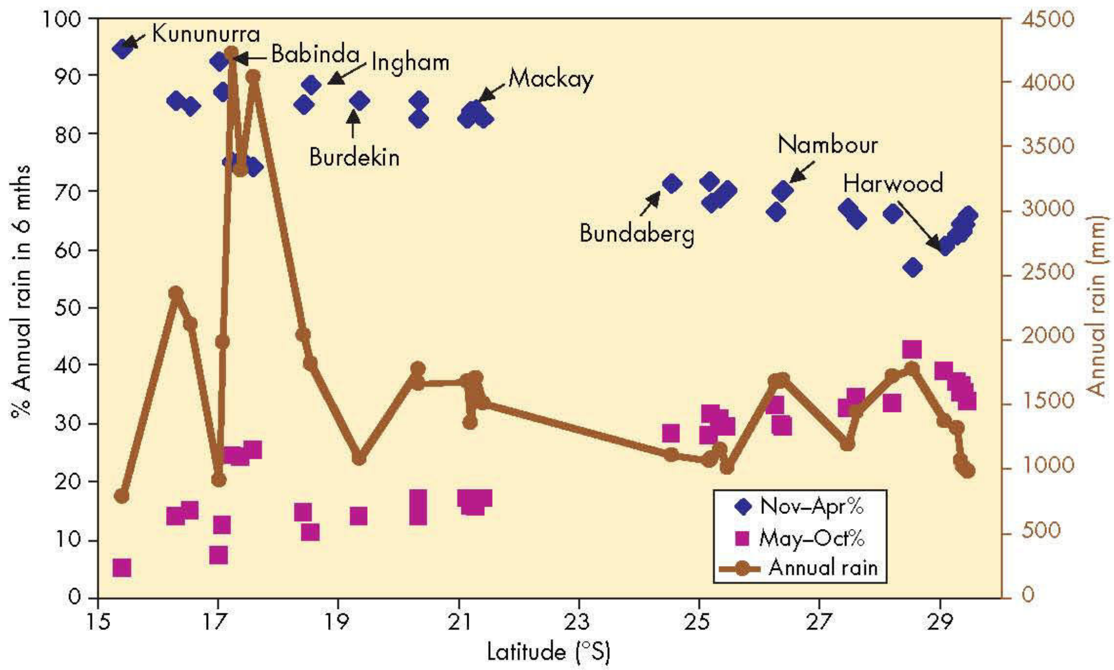

Figure 1. *Annual rainfall and percentage of annual rainfall falling in two 6-monthly periods (growing and harvest seasons), for 35 locations in the Australian sugar industry.*

Most tropical locations in the sugar industry receive less than 20% of annual rainfall in the period May to October (Figure 1). However, southern districts receive between 30% and 40% of annual rainfall in these ripening/harvesting months. This creates particular management problems with drainage and wet weather harvest in areas such as Moreton, Rocky Point and Northern New South Wales, where the winter distribution is also associated with higher annual rainfall than other parts of the southern region. Similar problems are created by the 25% of the 3000-4200 mm that falls in the Tully-Babinda area between April and October.

Radiation

Solar radiation is the energy source for photosynthesis and evaporative loss of water from soil and leaf surfaces. While most people can attribute meaning to the numbers and units used to express meteorological parameters such as rainfall, temperature and humidity, it is much more difficult to visualise the significance of a radiation measurement of 20 MJ/m^2. This is because radiation is measured only at a few sites, mainly by meteorological organisations, or plant physiologists. Most people rely on default or derived measures of radiation, such as temperature and cloudiness. Atmospheric temperature is influenced by interactions between radiation, wind and water vapour in the atmosphere.

Measurement of radiation

Total short-wave radiation is measured with a pyranometer or solarimeter. Measurement units are MJ/m^2/day (megajoules/metre squared). A reading of 28-30 MJ/m^2/day is typical of a clear sunny summer day in the tropics, with monthly averages in the range 22-25 MJ/m^2/day.The corresponding monthly value for winter in coastal Queensland is 10-15 MJ/m^2/day, while at Kununurra values range from 15-20 MJ/m^2/day (see Appendix I). Sugarcane accumulates dry matter at the rate of 1.7 g/MJ/m^2 of intercepted radiation for the rapid growth phase of plant cane, and 1.59 g/MJ/m^2 for ratoon cane.

Radiation cannot be managed or conserved for crop production. Therefore, management inputs should be directed to optimise interception of radiation by crop leaves, and minimise the fraction falling on bare earth. Relevant practices in this regard include choice of planting time, row spacing, irrigation to avoid severe water stress, adequate nutrition and protection of crops from pests and diseases. Autumn-planted cane has closed its canopy by mid-late spring and, therefore, intercepts maximum solar radiation in summer. Conversely, cane planted in spring may only achieve canopy closure well into summer. Higher yields are often achieved from similarly aged first ratoons of such crops because of more rapid canopy closure in ratoons. Sugarcane planted at 1.5 m row spacing intercepts only 60% of available solar radiation, but cane planted on 0.5 m row spacing achieves effective canopy closure about 50 days before cane at the wider spacing. The more rapid closure of canopy in close and dual-row planting is the main reason for yield increases in these planting systems.

Day length

Floral induction in plants can be stimulated by a response to day length (photoperiod). Short-day plants initiate flowers when day length reduces to a critical value, whereas long-day plants flower when a critical lengthening day is sensed. Day-neutral plants are not sensitive to day length. The photoperiod response is dependent more on the length of the day than the intensity of radiation; thus, low intensity light at dawn and dusk must be considered in managing breeding or intensive flower production systems that interrupt the photoperiod response. Choice of the correct planting time is critical for photoperiod sensitive crops, such as soybeans, where planting at an inappropriate photoperiod can reduce the juvenile stage of the crop and subsequent yield.

Sugarcane is a short-day plant. Initiation of flowering occurs in Australia between late February and early March, when days shorten from 12 hours 35 minutes to 12 hours 30 minutes. This phenomenon is currently only of significance to plant breeders for ensuring optimal management of parent canes during the natural induction period, or for implementation of longer artificial days to delay the onset of flowering. Photoperiod response in sugarcane can be destroyed, or made less effective, by night temperatures less than 20°C, day temperatures greater than 32°C, or water stress preceding and during the induction period. There is no evidence at this stage of photoperiod determining the *'earliness'* of accumulation of a higher level of sucrose in different sugarcane cultivars. However, photoperiod is one of the potential mechanisms which might be investigated to allow better understanding of this process.

Temperature

While radiation provides the energy for photosynthesis, temperature also affects growth and development of sugarcane. Rate of photosynthesis is responsive to temperature, as are other biochemical processes controlling meristematic activity for leaf and bud development, e.g. partitioning of photosynthate into components of yield.

Day degrees or thermal time

The concept of thermal-time, or accumulation of *effective day degrees*, is a useful concept for examining impact of temperature on the phenology, or growth stages, of crops. The calculation relies on determination of a base, or lowest, temperature below which there is no activity in the process of interest. The base temperature is deducted from mean day temperature to provide the effective temperature for the day. Effective day degrees are accumulated until the relevant growth process is complete, e.g. sprouting of buds, photosynthesis, emergence of a new leaf or stalk elongation. Different base temperatures apply to various biochemical and phenological events.

Photosynthesis

Rate of photosynthesis in sugarcane declines above 34°C. Daily maximum temperatures can exceed 34°C for several days at a time in northern sectors of the Queensland sugar industry, but long-term monthly means for temperature do not exceed 33°C in coastal Queensland. Longer periods of high temperature stress will occur in the Ord River region, where mean daily maximum temperature exceeds 34°C from September to April (Kununurra, Appendix I).

Photosynthetic efficiency of sugarcane increases in a linear manner with temperatures in the range from 8°C, to a plateaux of 34°C. Cool night and early morning temperatures—14°C in winter and 20°C in summer—significantly inhibit photosynthesis the next day. Mean daily minimum temperatures for Harwood (Appendix I) suggest major chill injury to photosynthesis between June and September. Minimum temperature data also show that most districts on the east coast might expect some chill injury based, on these criteria, ranging from zero at Meringa (Cairns), through 3-4 months at Ayr, 6 months for Mackay and Bundaberg, to 9 months at Harwood.

Emergence of shoots

Quantitative descriptions of temperature limitations to bud development in plant and ratoon cane are scarce but base temperatures of 11.5°C and 11.8°C, respectively, apply to cultivars Q138 and Q141 for the sprouting/emergence process. Thermal time to emergence of 14 cultivars ranged between 127.5 and 233.7 day degrees. This represents a period of 9-16 days or 19-29 days for autumn and spring planting, respectively, at Bundaberg. Cultivars renowned for slow emergence must accumulate more heat units before emergence.

Leaf and stalk growth

Base temperatures of 15°C and 14°C have been used for leaf and stalk growth in Australia. However, a significant varietal effect on base temperature for leaf appearance occurs, e.g. Q138, 16.9±1.02°C and Q141, 19.66 ±0.47°C. New leaves emerged after accumulation of 105 day degrees of effective temperature, above a base of 15°C, in the tropics but 24-70 day degrees are required for leaf emergence in Q138 and Q141 at Bundaberg.

This apparent difference in elapsed thermal time for leaf emergence is attributed to non-recognition of stress caused by supra-optimal temperatures in the tropics. When mean daily temperatures in the tropical environment ranged from 20-22°C, elapsed thermal time for leaf emergence decreased to 60-70 day degrees. Cultivar effects are also embedded in the data comparison. Use of these criteria for Q138 and Q141 suggests a new leaf would be expected every 5 and 11-21 days in February and June-August, respectively, at Cairns. The contrast for Harwood is a new leaf every 8-10 days for February and no leaf emergence in June-August.

Stalk elongation of sugarcane is also sensitive to temperature, with general acceptance that the peak growth phase is terminated by onset of mean day temperatures less than 21°C. Brief periods of minimum temperature less than 20-21°C are common in southern regions of the east coast during February and March. As shown in Figure 2, this induced several cycles of reduced stalk elongation in Q141 at Bundaberg, before the general decline in temperature into the autumn (there was only one period of mild water stress when water potential at 300 mm was at 560 kPa). Stalk elongation of the variety Pindar virtually ceased at 17°C, but there is a significant difference in base temperature for stalk elongation for the varieties Q138 (18.8°C) and Q141 (19.8°C).

Temperature and CCS

When leaf growth is constrained at temperatures less than 14-19°C, the available photosynthesis is partitioned to sugar

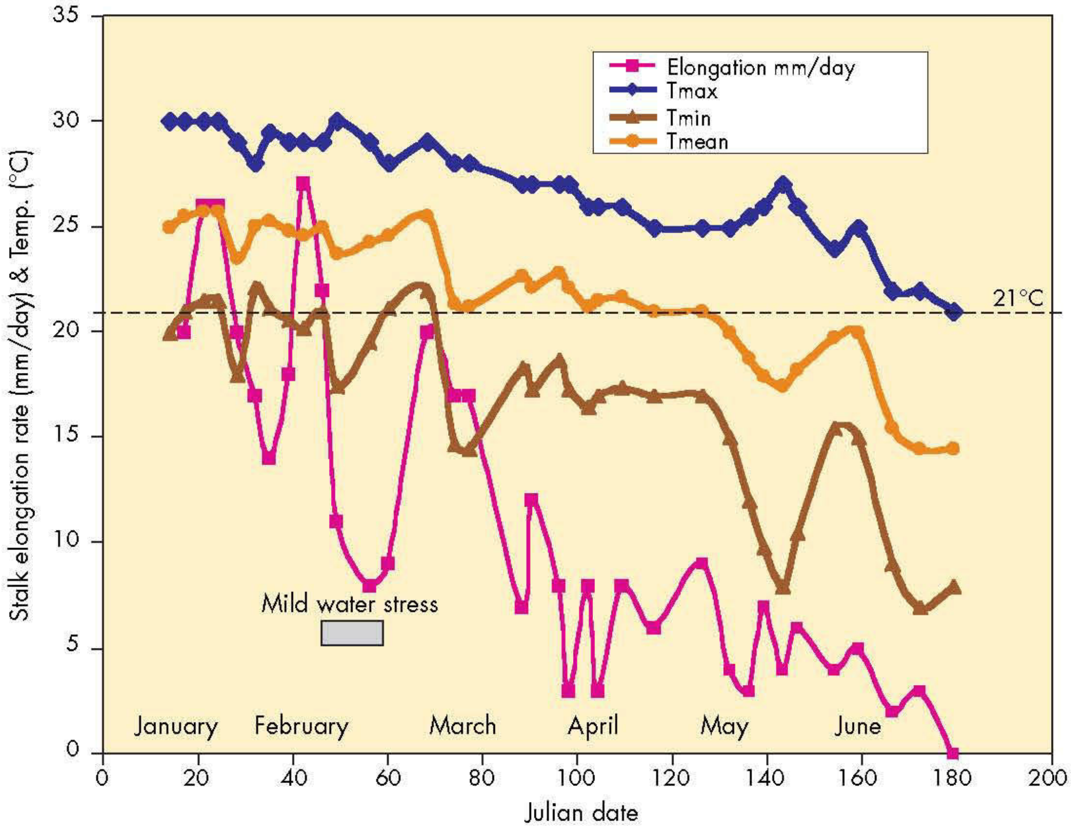

Figure 2. *Stalk elongation of Q141 at Bundaberg in relation to daily temperature (Tmax, Tmin and Tmean) between January and June 1994.*

accumulation rather than vegetative growth. This explains the role of lower temperature in ripening of sugarcane. A large range in diurnal temperatures also favours sugar accumulation. The association between mean CCS for each of 10 districts on the east coast between 1981 and 1991 and diurnal temperature range, between April and September, was not significant. There was, however, a significant association between CCS and mean annual day degrees greater than 14°C (R^2=0.47, $p<0.05$). Combination of the annual day degrees and diurnal temperature variables in a multiple regression model explained 85% of the variation in CCS.

Seasonal CCS = 5.36+0.0012 × Annual day deg. >14°C + 0.38 × Diurnal temperature range from Apr.–Sept. (R^2=0.85, $p<0.05$, n=10, Std dev. =0.37)

This model implies that CCS will generally be higher in tropical regions than in sub-tropical regions, and that CCS is enhanced by a wider range in diurnal temperatures for any given accumulation of thermal time. For example, Innisfail, Ingham and the Burdekin have similar annual thermal regimes, but CCS is ranked Burdekin > Ingham > Innisfail because of the ranking in diurnal temperature range (11.8 >10.8 >8.9°C).

Cold chlorosis

Low temperatures can induce a chlorotic banding pattern on cane leaves (cold chlorosis, Figure 3). This results from damage to chlorophyll by low, but non-freezing, temperatures while leaves are still elongating in the leaf roll.

Frost

Frost damage to sugarcane in Australia is usually confined to low-landscape positions of inland sections of the Bundaberg, Isis and Maryborough districts and inland sections of the Broadwater and Harwood areas of New South Wales. Young autumn plant cane may suffer light leaf damage in some years in parts of the Bundaberg to Maryborough region. Significant frosting of millable cane occurs in some years in the Burnett Valley, near Wallaville and the inland sections of the NSW industry.

Figure 3. *Cold chlorosis — chlorotic zones on sugarcane leaves induced by non-freezing low temperatures.*

There are two types of frost. *Radiation frosts* occur on clear, cold nights with little wind, when outgoing radiation is excessive and air temperature generally increases with height in a micro-layer near the ground. *Wind or advection frosts* occur when wind or topography brings cold air into a location. The two types of frost can occur together, with an advection frost re-inforcing effects of a radiation frost. While frost damage to the growing point of sugarcane begins at −2.0°C, an air temperature of at least −3.5°C is required at 1 m height outside the crop for frost damage to occur. A well-grown canopy helps to retain heat in the crop and prevent cold air from descending onto the growing point. Thus, management issues such as nitrogen rate, avoidance of waterlogging or moisture stress and crop age are important in minimising impact of frost. Differences in canopy habit and structure and genetic variation in freeze tolerance are important in conferring different frost reactions across varieties (Figure 4). Presence of a trash blanket under partially canopied cane dramatically increases susceptibility to frost damage by reducing capacity of soil to radiate heat into the cold night air. The effect on frost damage to sugarcane of trash retention under a closed canopy has not been measured.

Figure 4. *Frost damage to sugarcane Q111 (L) and CP44-101 (R) at Wallaville in 1982.*

A light frost will cause leaf scorch. A more severe frost kills the green leaf and the growing point. Frozen internodes begin to deteriorate after the thaw, causing a drop in juice pH and an increase in alcohols and dextran in juice. It is important to exclude rotting material from the cane supply by lowering the topping height. Side shoots will develop from the uppermost one or two buds not killed by the frost. Severity of the frost is assessed from the number of frozen internodes. A four-stage classification is used: *Class I* frost kills all green leaf, the growing point and all buds on the stalk; a sour rot is developing; basal stalks should be harvested immediately. *Class II* frost kills the green leaves, the growing point and the top 3–10 eyes on the stalk; stalks should be topped at the side shoots. *Class III* frost kills up to three green leaves, the growing point and buds 1–3 on the stalk. *Class IV* frost causes some leaf damage, but stalks will resume normal growth. Deterioration will usually be significant within 2–3 weeks after the frost. Highest priority for harvest is allocated to most severely frosted cane.

Hail

Hail damages sugarcane by shredding the leaf blade and in severe cases there may be some breakage of immature upper stalk sections. Leaf growth will resume if the growing point is not damaged.

Lightning

Lightning damage to sugarcane is a reflection of localised high temperature stress. Damage in young cane is usually restricted to small areas (30–60 m) in diameter, with effect grading from severe in the centre to little or no effect on the margin. Leaves are scorched. Lightning strike can ignite trash blankets if there is little rain associated with the storm.

Wind

Wind interacts with the sugarcane production system through direct impact on the plant and also through impact on management operations.

Wind can affect sugarcane through at least three mechanisms: transpiration, carbon dioxide uptake and mechanical damage to leaves and stems. Transpiration of sugarcane is likely to increase with wind speed up to the point where stomatal conductance is unable to satisfy the vapour deficit at the stomatal surface—stomata should then start to close to reduce transpiration. There are no additional benefits of wind on carbon dioxide uptake through turbulent mixing in plant canopies at wind speeds above 6 km/h. Physical damage to leaf blades and mid-ribs inhibits photosynthesis and translocation of products of photosynthesis.

Wind damage

Strong winds induce apparent pruning effects on plant canopies. This is reflected in shorter leaves and stalks on the windward side of cane fields. This is probably a reflection of reduced growth from stomatal closure induced by excessive vapour pressure deficit.

Physical damage to sugarcane from strong wind ranges from leaf shredding, leaf desiccation (wind burn), stalk breakage, lodging and stool tipping. Leaf shredding is usually associated with cyclones when all other wind damage effects, except wind burn, are also present. Wind burn is the rapid desiccation of the spindle leaf caused by hot, dry winds during periods of rapid growth in summer—only a few varieties are susceptible to wind burn (Figure 5).

Stalk breakage from strong wind can occur in immature sections of the stalk, while brittle varieties break at ground level. Sugarcane is classed as lodged when the canopy of well grown cane is loaded with rainfall and the stalks are blown down by wind. A response to light usually results in immature sections of most stalks re-erecting an incomplete canopy within 7–10 days of lodging. Lodging usually occurs in late summer or autumn in crops of more than 80 t/ha which respond to the turning moment under stormy conditions. Varieties with higher resistance to lodging may accumulate 120 t/ha in stalk yield before lodging. Lodging can limit further accumulation of biomass and may cause loss

Figure 5. *Wind burn causes desiccation of the spindle leaf of some varieties.*

of CCS. Some stalks may die in crops which lodge heavily in one direction, rather than sprawling which allows more general access of individual tops to radiation.

Stool tipping occurs in similar circumstances to lodging, but rigidity of stalks and limited root mass causes the whole stool and root mass to tip from the ground. Stool tipping results in reduced accumulation of biomass, increased soil and extraneous matter in mechanically harvested cane and gaps in the subsequent ratoon crop.

Managing for climate

Climate cannot be controlled. However, successful canegrowing is largely about managing the crop to optimise the beneficial effects of climate and to minimise the adverse impacts. Some of these opportunities, several of which will be explained in more detail in subsequent chapters, are outlined in the following text. Improvements in climate and weather forecasts can be used by growers to reduce risk associated with selected management operations—guidelines are shown for access to this information.

Timeliness of operations

Traditional planting and harvest seasons have developed in response to the long-term appreciation of weather patterns. For instance, planting in the tropics usually commences in late autumn to early winter when soils are dry enough for seed-bed preparation after the wet season. Late spring planting in the tropics is undesirable because the stool and canopy are not sufficiently established before the wet season. Conversely, in the Bundaberg to Maryborough region, the climate provides a fairly even split between autumn and spring planting. In New South Wales, a late finish to the wet season and cold winters restrict planting to spring.

Within each of the planting windows, there is opportunity for good management to optimise the result. Investment in field drainage, good fallow management, attention to quality of planting material, and recognition of benefits of earliest planting opportunities are usually reflected in good establishment of plant cane. Cane planted before, or towards the end, of the optimal period is subjected to greater risk of germination failure from waterlogging, on-set of cold weather or attack from wireworms or fungi.

The harvest season for sugarcane in Australia has developed around suitable weather conditions to promote maturation of the crop and also to allow access to the fields. The adverse effects of weather on crop maturation have not been managed to any significant extent within the Australian sugar industry.

In several overseas industries, failure of a climatic stimulus to ripening is managed by use of chemical cane ripeners. This technology is being re-evaluated in Australia because of increased interest in harvesting cane in the late-autumn and early winter months. Impacts of wet weather on the cane harvest can be minimised by improved in-field and whole-farm drainage design. Wider inter-spaces to match track width of in-field equipment, combined with mound planting of dual rows, will also minimise the impact of wet weather on the harvest operation.

While climate cannot be managed, there are several management operations that modify the effective climate/weather conditions experienced by the crop. For instance, irrigation increases the effective rainfall received by the crop. This effect can also be achieved from the moisture conserved beneath a green-cane trash-blanket. This mulch also insulates the soil surface from incident radiation, resulting in slower emergence of ratoon shoots, particularly in sub-tropical regions. Raking trash from the stool provides a compromise between adverse effects of insulation from radiation and moisture conservation.

Improved climate/weather forecasts

Weather conditions influence the timeliness and efficiency of many operations on the farm, such as land preparation, planting, cultivation, weed control, irrigation and harvest. Risk associated with such operations could be reduced with access to more reliable short- and medium-term weather forecasts. Weather forecasts are now available for up to five days in advance, but their use for management is limited by lack of probability information. Such improvements are being developed along with assessment of utility of improved forecasts for improved management of irrigation water in particular. Seasonal forecasts of climate (more than three months for rainfall) are now available and are based on status and trends in the Southern Oscillation Index (SOI). Such forecasts allow canegrowers with limited supplies of irrigation water to think more strategically about opportunities for use of such resources. This strategic advice cannot be translated into tactical decisions until linked with more reliable weather forecasts for up to 30-day intervals.

Weather and the Web

The explosion in information technology media has seen the Internet overtake newspapers, radio and television as the source of more advanced weather/climate products. These Internet sites (Table 1) also provide the more familiar weather services. Weather channels on cable or pay television are now offering a series of refined weather products.

Satellite images commonly seen as a once daily snap shot on weather pages in newspapers or in television weather bulletins are also published on Internet sites, with frequent updates during the day. The updates are of interest for tracking progress of cyclones or storm fronts.

Other sites are linked to the Bureau of Meteorology and provide current and forecast synoptic charts. The Bureau of Meteorology site on climate contains a useful summary of historic climate information for many key sites in Australia. This information is also contained in the Australian RAINMAN database, where graphical output can be used to simplify presentation of the information.

Real time displays of rainfall activity from Doppler radar stations are available on the Internet for the United States of America. Similar information is available from the Bureau of Meteorology in Australia for a monthly or annual fee and on the Weather Channel of cable or pay television. This information is of value to canegrowers for assessing risk and opportunity associated with application of fertilisers and herbicides.

Internet sites are useful for examining outlooks for weather for periods up to 10 days. The outlook prognosis is based on simulation models. Outlooks are generally regarded as experimental at this stage and it is therefore desirable to look at the output of at least two outlook simulations to assess commonality of forecast. Output from such sites can be in map or meteogram format. A meteogram is a time-based graphical (line or bar chart) representation of the selected weather parameter.

Internet sites for climate tend to specialise in impact of larger atmospheric circulation models on projection of climatic patterns for the coming season. This includes the *El Niño* and Southern Oscillation Index phenomenon. These sites often provide forecasts and educational information about climate.

Table 1. Internet addresses for sites with relevant information about weather and climate.

Comments	Site location
Weather	
General index	
Index of major Australian weather sites — has links	http://australiansevereweather.simplenet.com/links/index.html
Satellite Images	
Image of the Australian continent	http://www.ece.jcu.edu.au/JCUMetSat/aushlast.gif
Visible spectrum image of Austral-Asian hemisphere	http://www.ghcc.msfc.nasa.gov/GOES/gms5vis.html
Infra-red image of Austral-Asian hemisphere	http://www.ghcc.msfc.nasa.gov/GOES/gms5ir.html
Water vapour image of Austral-Asian hemisphere	http://www.ghcc.msfc.nasa.gov/GOES/gms5wv.html
Synoptic charts	
Mean sea level pressure — current & forecasts	http://www.bom.gov.au/weather/national/charts
Outlook sites	
Bureau of Meteorology — weather for Australia	http://www.bom.gov.au/silo/
Bureau of Meteorology experimental 7-day outlook	http://www.bom.gov.au/bmrc/medr/mslpTH8.html
Interactive forecast maps and meteograms — use AVN191 or MRF	http://www.arl.noaa.gov/ready/cmet.html
GRADS 5 & 10 day rainfall probability	http://grads.iges.org/pix/prec7.html
GRADS MRF model rainfall outlook to 120 hours	http://grads.iges.org/pix/aus.pw.html
FNMOC NGR & AVN model outlook — use Aust & NZ	http://www.fnoc.navy.mil/PUBLIC
UNISYS weather service aviation forecasts	http://weather.unisys.com/aviation
Cyclones and other warnings	
Bureau of Meteorology	http://www.bom.gov.au/weather
Climate	
Climate outlook QDPI /Dept Nat. Resources	http://www.dnr.qld.gov.au/longpdk/
Climate models 6-9 month outlook	http://www.bom.gov.au/climate/ahead/ENSO-summary.shtml
Current season, season ahead, Aust. Maps, Climate averages & extremes, Climate education & information	http://bom.gov.au/climate/
Sea surface temperatures and anomalies	http://www.bom.gov.au/climate/current
NOAA Climate Diagnostics Centre — research into climate variability, including *El Niño*	http://www.cdc.noaa.gov/

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APPENDIX 1

Meteorological data for selected locations in the Australian sugar industry. Data are a combination of long-term records from the RAINMAN data base[1], drilled data[2], or means from the site[3]. Radiation and temperature data are not available for all locations.

Monthly rainfall[1], mean maximum and minimum temperatures[1], radiation[3] and pan evaporation[3] for KUNUNURRA (KIMBERLY RESEARCH STATION), 15° 38' S, 128° 41' E

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	200	194	119	41	9	3	5	0	3	22	62	131	784
Rain median	175	181	100	22	0	0	0	0	0	11	44	117	756
Rain stand. dev.	108	103	86	78	23	12	15	2	7	27	51	66	219
Highest rain	576	503	325	541	131	87	79	14	33	125	229	323	1450
Lowest rain	21	32	5	0	0	0	0	0	0	0	11	30	425
Mean rainy days	14	14	9	3	1	0	0	0	1	3	7	10	62
No. of years	55	55	55	55	54	54	54	54	54	54	54	54	54
Mean max. °C	36.1	34.8	34.9	35.1	32.9	30.5	30.1	33.3	36.1	38.2	38.7	37.8	34.9
Mean min. °C	24.8	24.6	23.7	20.7	18.5	15.7	14.5	16.5	19.9	23.0	24.7	25.0	21.0
Lowest min. °C	14.4	15.7	13.2	10.4	8.1	6.2	4.4	2.9	10.6	11.5	14.8	14.4	na
Radiation $MJ/m^2/day$	23.6	23.1	21.4	21.8	18.1	17.8	19.1	20.8	22.9	23.8	23.6	25.2	21.8
Pan evap. mm/day	7.8	6.7	6.4	7.7	7.1	6.7	7.2	8.4	9.9	10.6	9.7	8.7	8.1

Monthly rainfall[1], mean maximum and minimum temperatures[1], radiation[2] and pan evaporation[2] for BSES , MERINGA, 17° 04' S, 145° 46' E

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	428	429	413	196	83	50	27	27	27	40	84	190	1986
Rain median	355	362	319	146	62	39	18	18	14	25	54	145	1920
Rain stand. dev.	312	271	295	163	67	43	28	31	30	54	99	181	640
Highest rain	1813	1507	1275	856	369	234	134	159	113	373	489	835	3804
Lowest rain	35	12	8	12	0	0	0	0	0	0	0	0	649
Mean rainy days	15	16	17	14	12	8	6	6	5	6	8	11	124
No. of years	100	100	100	100	99	99	99	99	99	99	99	99	99
Mean max. °C	31.5	31.3	30.4	28.8	27.4	25.7	25.5	26.5	27.7	29.1	30.6	31.6	28.8
Mean min. °C	23.6	23.7	23.0	21.5	19.8	17.6	17.1	17.4	18.6	20.3	22.2	23.4	20.7
Lowest min. °C	18.2	17.9	18.6	13.9	10.1	6.2	7.3	7.8	11.1	12.4	14.6	17.1	Na
Radiation $MJ/m^2/day$	20.3	18.6	17.8	16.5	14.6	14.6	15.3	18.1	21.1	23.5	232.5	22.3	18.8
Pan evap. mm/day	6.1	5.4	5.2	4.9	4.1	4.0	4.2	4.9	6.1	7.1	7.1	6.9	5.5

Monthly rainfall[1], mean maximum and minimum temperatures[1], for MAREEBA QWRC COMPOSITE, 17° 00' S, 145° 25' E

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	220	230	189	52	18	15	7	7	5	15	45	109	910
Rain median	195	220	155	29	10	9	3	2	2	4	24	92	879
Rain stand. dev.	125	130	152	69	20	19	10	13	7	22	50	85	306
Highest rain	734	556	683	563	95	95	51	80	37	110	217	343	1864
Lowest rain	4	0	3	0	0	0	0	0	0	0	0	0	349
Mean rainy days	14	14	13	8	5	4	3	2	2	2	5	9	81
No. of years	105	105	105	105	104	104	104	104	104	104	104	104	104
Mean max. °C	31.1	30.7	29.8	28.4	26.8	25.2	25.1	26.4	28.1	30.4	31.9	32.0	28.8
Mean min. °C	21.1	21.3	20.2	17.8	15.2	12.3	11.1	11.7	13.6	16.0	18.9	20.2	16.6
Lowest min. °C	11.1	16.7	13.9	10.4	1.7	0.4	0.7	1.7	5.4	7.0	7.0	12.9	na

Monthly rainfall[1], mean maximum and minimum temperatures[1], radiation[2] and pan evaporation[2] for INNISFAIL (SOUTH JOHNSTONE EXPT STATION, 17° 37' S, 146° 00' E).

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	529	598	635	399	279	160	109	88	88	88	137	237	3329
Rain median	444	572	611	367	256	133	97	68	54	55	105	168	3290
Rain stand. dev.	395	296	337	233	163	107	72	77	82	90	118	210	770
Highest rain	2749	1497	1577	1084	825	503	442	414	393	431	575	1049	5252
Lowest rain	12	146	69	44	9	8	4	5	0	0	15	19	1709
Mean rainy days	19	20	22	21	20	17	16	15	14	12	12	14	202
No. of years	80	80	80	80	79	79	79	79	79	79	79	79	79
Mean max. °C	31.3	30.6	29.8	28.2	26.1	24.3	23.9	25.3	27.0	29.0	30.6	31.2	28.1
Mean min. °C	22.4	22.5	21.9	20.4	18.5	15.5	14.8	15.4	16.6	18.8	20.7	21.8	19.1
Lowest min. °C	14.4	16.0	15.0	12.8	7.4	5.4	3.3	6.8	7.3	9.6	10.8	14.9	na
Radiation $MJ/m^2/day$	20.1	18.2	17.4	15.8	13.6	14.0	14.6	17.4	20.6	23.0	23.1	22.1	18.3
Pan evap. mm/day	6.2	5.5	5.2	4.8	4.0	3.8	4.1	4.7	5.9	6.8	7.0	6.8	5.4

Monthly rainfall[1], mean maximum and minimum temperatures[1], radiation[2] and pan evaporation[2] for INGHAM COMPOSITE, 18° 38' S, 146° 10' E

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	426	459	409	192	103	54	37	36	37	46	92	176	2064
Rain median	357	428	344	148	84	40	23	25	20	30	70	121	2079
Rain stand. dev.	292	255	269	171	78	52	38	39	47	62	99	173	661
Highest rain	1712	1222	1223	1351	377	338	188	248	282	486	518	793	4558
Lowest rain	28	39	29	7	2	0	0	0	0	0	0	5	816
Mean rainy days	14	16	16	13	11	7	6	6	5	5	7	9	115
No. of years	108	108	108	108	107	107	107	107	107	107	107	107	107
Mean max. °C	32.3	31.4	30.6	29.0	27.0	25.2	24.8	26.2	28.1	30.3	31.8	32.4	29.1
Mean min. °C	23.0	23.2	22.2	20.2	17.5	14.1	13.5	14.5	15.9	18.3	20.8	22.0	18.8
Lowest min °C	16.7	18.3	15.0	12.2	6.2	5.2	2.2	5.0	4.4	9.5	13.3	15.6	na
Radiation $MJ/m^2/day$	20.5	18.8	18.1	16.5	14.4	14.3	16.6	17.8	21.1	23.3	23.4	22.5	18.8
Pan evap. mm/day	6.5	5.8	5.4	5.0	4.1	3.7	3.9	4.7	6.1	7.1	7.3	7.1	5.5

Monthly rainfall[1], mean maximum and minimum temperatures[1], radiation[2] and pan evaporation[2] for AYR (BURDEKIN SHIRE COUNCIL), 19° 34' S, 147° 23' E

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	258	259	182	62	38	31	18	15	21	25	44	114	1070
Rain median	198	211	136	32	17	14	6	3	4	9	23	67	1034
Rain stand. dev.	228	219	158	91	56	43	39	25	49	37	55	123	446
Highest rain	954	1681	689	524	422	223	315	115	419	237	317	738	2432
Lowest rain	8	3	2	0	0	0	0	0	0	0	0	0	261
Mean rainy days	11	11	9	5	4	3	2	2	2	3	4	7	63
No. of years	113	113	113	113	112	112	112	112	112	112	112	112	112
Mean max. °C	32.7	32.1	31.6	30.1	27.8	25.7	25.4	26.9	28.6	30.1	31.8	32.7	29.6
Mean min. °C	23.2	23.0	22.0	19.6	16.7	13.5	12.6	14.3	16.5	19.1	21.5	22.4	18.7
Lowest min. °C	18.3	18.3	14.7	13.1	5.3	3.3	4.2	6.7	8.9	13.0	16.1	11.1	na
Radiation $MJ/m^2/day$	21.6	19.9	18.8	17.2	14.9	14.5	15.6	18.3	21.5	23.9	24.2	23.4	19.5
Pan evap. mm/day	6.7	6.0	5.6	5.0	4.1	3.7	4.0	4.8	6.0	7.0	7.4	7.2	5.6

Monthly rainfall[1], mean maximum and minimum temperatures[1], radiation[2] and pan evaporation[2] for MACKAY SUGAR EXPT STATION, 21° 10' S, 149° 07' E

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	348	348	289	142	93	61	37	31	29	45	78	180	1679
Rain median	258	276	243	111	84	48	20	17	17	33	57	138	1614
Rain stand. dev.	315	267	209	126	82	56	50	43	41	49	69	184	584
Highest rain	1988	1567	1035	607	575	367	325	296	235	263	421	1311	3455
Lowest rain	26	37	16	1	0	0	0	0	0	0	0	1	631
Mean rainy days	15	16	16	14	12	9	7	6	6	6	8	11	126
No. of years	110	110	110	110	109	109	109	109	109	109	109	109	109
Mean max. °C	30.6	29.9	29.2	27.6	25.3	23.5	23.0	24.6	26.5	28.3	30.1	30.8	27.5
Mean min. °C	21.9	22.0	20.8	18.1	15.0	11.2	10.0	11.5	13.5	16.7	19.6	21.1	16.8
Lowest min. °C	16.7	17.2	10.8	10.5	3.3	1.5	0.5	1.5	5.0	6.1	12.5	15.0	na
Radiation $MJ/m^2/day$	21.6	19.9	18.8	16.9	14.4	14.2	15.2	17.0	21.6	23.6	24.3	23.5	19.3
Pan evap. mm/day	6.6	6.1	5.5	4.8	3.8	3.4	3.6	4.4	5.7	6.8	7.3	7.2	5.4

Monthly rainfall[1], mean maximum and minimum temperatures[1], radiation[2] and pan evaporation[2] for BUNDABERG SUGAR COMPOSITE sites 24° 50' S, 152° 22' E

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	195	172	136	82	73	62	51	33	37	63	84	127	1117
Rain median	140	124	107	55	52	36	27	25	25	48	67	97	1045
Rain stand. dev.	178	156	109	74	67	78	69	30	41	53	68	97	369
Highest rain	1162	816	519	346	397	499	466	142	277	281	354	490	2362
Lowest rain	4	3	2	0	0	0	0	0	0	1	2	0	340
Mean rainy days	12	12	12	8	8	6	5	5	5	7	8	9	97
No. of years	117	117	117	117	116	116	116	116	116	116	116	116	116
Mean max. °C	30.1	29.9	29.1	27.5	24.7	22.4	21.8	23.2	25.2	26.9	28.3	29.6	26.6
Mean min. °C	21.6	21.5	20.4	18.0	14.9	12.0	10.5	11.5	14.0	17.0	19.3	20.8	16.20
Lowest min. °C	13.9	16.0	14.6	10.4	3.9	3.5	2.5	3.8	6.7	8.3	11.9	12.5	na
Radiation $MJ/m^2/day$	22.1	20.3	19.0	16.8	13.8	13.0	14.4	17.0	20.4	22.3	23.4	23.3	18.8
Pan evap. mm/day	6.3	5.7	5.1	4.2	3.1	2.8	2.9	3.6	4.8	5.7	6.3	6.5	4.7

Monthly rainfall[1], mean maximum and minimum temperatures[1], radiation[2] and pan evaporation[2] for MARYBOROUGH COMPOSITE, 25° 32' S, 152° 40' E

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	167	173	153	90	78	67	52	40	43	74	86	128	1152
Rain median	137	134	126	69	64	45	38	32	35	61	76	108	1117
Rain stand. dev.	129	151	122	71	64	69	59	38	36	68	55	85	332
Highest rain	764	899	548	339	344	348	406	323	165	498	302	551	2250
Lowest rain	5	8	5	5	3	0	0	0	0	0	3	8	324
Mean rainy days	13	14	14	11	10	8	7	6	6	8	9	10	116
No. of years	129	129	129	129	128	128	128	128	128	128	128	128	128
Mean max. °C	30.3	29.9	29.0	27.1	24.4	22.1	21.6	23.1	25.4	27.5	28.7	30.1	26.6
Mean min. °C	20.5	20.6	19.3	16.7	13.2	9.9	8.0	8.7	11.4	15.1	17.6	19.4	15.0
Lowest min. °C	13.3	14.4	11.8	6.7	2.2	-0.6	-1.4	-4.4	1.5	4.6	8.2	12.2	na
Radiation MJ/m^2/day	22.0	20.0	18.7	16.4	13.4	121.6	13.6	16.6	20.1	21.9	23.0	23.1	18.4
Pan evap. mm/day	6.0	5.4	4.8	4.0	3.0	2.7	2.8	3.5	4.7	5.5	6.1	6.3	4.6

Monthly rainfall[1], mean maximum and minimum temperatures[1] for NAMBOUR BOWLING CLUB, 26° 37' S, 152° 58' E

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	247	255	251	151	131	91	80	48	56	96	123	172	1695
Rain median	179	180	220	120	98	51	53	41	44	85	104	149	1630
Rain stand. dev.	213	214	196	118	109	105	105	37	49	77	90	122	495
Highest rain	1256	1082	1228	553	679	542	835	136	227	372	442	618	3778
Lowest rain	23	21	5	5	0	0	0	0	0	2	6	14	379
Mean rainy days	13	14	15	11	10	7	6	6	6	8	9	11	116
No. of years	106	106	106	106	105	105	105	105	105	105	105	105	105
Mean max. °C	29.0	28.5	28.0	26.2	23.4	21.4	20.8	22.3	24.5	26.0	27.9	29.0	25.6
Mean min. °C	19.0	19.3	18.0	14.7	11.4	8.4	6.8	7.3	9.8	13.0	15.9	17.8	13.5
Lowest min. °C	13.4	11.9	10.0	5.8	1.3	-2.3	-2.9	-0.9	0.3	2.2	5.6	5.9	na

Monthly rainfall1, mean maximum and minimum temperatures[1] for SOUTHPORT, 27° 56' S, 153° 23' E apply to Rocky Point 27° 52' S, 153° 23' E

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	178	189	200	137	133	93	74	55	58	85	104	134	1441
Rain median	129	131	170	105	102	61	54	43	50	63	81	105	1408
Rain stand. dev.	147	167	142	121	120	102	79	48	44	74	86	90	403
Highest rain	776	880	712	639	592	691	406	229	198	515	476	440	2670
Lowest rain	9	5	1	5	2	0	0	0	0	5	9	3	584
Mean rainy days	13	13	15	11	10	8	7	7	7	9	10	11	121
No. of years	119	119	119	119	118	118	118	118	118	118	118	118	118
Mean max. °C	28.6	28.4	27.6	26.1	23.4	21.2	20.6	21.5	23.4	25.2	26.7	28.0	25.1
Mean min. °C	20.4	20.4	19.1	16.7	13.6	10.8	9.2	9.8	12.1	15.0	17.4	19.3	15.3
Lowest min. °C	14.4	15.0	8.3	8.9	3.3	0.6	-3.9	0.6	2.8	5.5	8.0	5.6	na.

Monthly rainfall[1], mean maximum and minimum temperatures[2], radiation[2] and pan evaporation[2] for CONDONG SUGAR MILL, 28° 19' S, 153° 25' E

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	220	250	264	148	138	120	92	76	65	88	107	150	1711
Rain median	164	175	226	121	106	64	47	47	53	75	82	135	1637
Rain stand. dev.	165	218	192	116	113	134	109	77	48	64	94	99	474
Highest rain	856	1043	1035	540	502	767	446	391	166	318	536	519	3256
Lowest rain	20	4	8	11	2	1	0	0	0	3	6	8	693
Mean rainy days	15	16	18	14	12	9	8	8	9	10	11	12	142
No. of years	86	86	86	86	86	86	86	86	86	85	85	85	85
Mean max. °C	28.7	28.4	27.5	25.8	23.1	20.9	20.4	21.5	23.6	25.4	26.8	28.2	25.0
Mean min. °C	20.1	20.1	18.7	16.2	13.3	10.5	9.0	9.7	12.0	14.8	17.1	19.0	15.0
Radiation $MJ/m^2/day$	22.1	20.0	18.1	15.6	12.3	11.4	12.6	15.6	19.2	21.1	22.6	23.1	17.8
Pan evap. mm/day	5.6	5.0	4.3	3.5	2.6	2.3	2.6	3.2	4.3	4.9	5.6	5.9	4.2

Monthly rainfall[1], mean maximum and minimum temperatures[2], radiation[2] and pan evaporation[2] for HARWOOD SUGAR MILL, 29° 25' S, 153° 14' E

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Rain mean	141	167	170	137	135	107	76	52	51	69	93	113	1308
Rain median	118	121	155	114	94	66	43	36	31	55	72	91	1251
Rain stand. dev.	91	124	108	115	131	115	94	53	53	66	77	77	374
Highest rain	437	591	673	637	590	574	593	242	220	519	405	379	2452
Lowest rain	8	4	7	7	0	0	0	0	0	1	0	14	479
Mean rainy days	12	12	14	12	11	9	7	6	7	8	9	10	117
No. of years	85	85	85	85	84	84	84	84	84	84	84	84	84
Mean max. °C	27.8	27.6	26.1	25.0	22.3	20.1	19.5	20.7	22.9	24.6	25.9	27.3	24.2
Mean min. °C	20.0	20.0	18.6	15.9	12.7	9.9	8.4	9.3	11.7	14.6	16.7	18.7	14.7
Radiation $MJ/m^2/day$	22.0	19.9	17.7	15.1	11.8	10.7	12.0	15.1	18.8	20.9	22.4	23.0	17.4
Pan evap. mm/day	6.0	5.4	4.6	3.8	2.7	2.4	2.6	3.4	4.5	5.1	5.9	6.2	4.4

Appendix 2

Comparison of drilled data from 1957–1999 with actual mean monthly data for solar radiation and Class A pan evaporation for different periods at selected sites in the sugar industry.

Parameter	Location	Period of observations	Function	R^2
Radiation	Bundaberg	1989-94	Drilled = 1.13×Actual Rad'n – 3.25	0.97
Radiation	Bundaberg	1992-98	Drilled = 0.94×Actual Rad'n + 2.13	0.97
Radiation	Ayr	1991-93	Drilled = 0.93×Actual Rad'n + 3.27	0.80
Evaporation	Bundaberg	1966-93	Drilled = 1.10×Actual Evap'n – 0.36	0.96
Evaporation	Bundaberg	1992-98	Drilled = 1.05×Actual Evap'n + 0.08	0.96
Evaporation	Mackay	1974-90	Drilled = 1.15×Actual Evap'n – 0.61	0.99