CHAPTER 13A:
AGROMETEOROLOGY AND COTTON PRODUCTION

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I. Importance of Cotton in various climates

Cotton is the world's most important fiber crop and the second most important oil seed crop. The primary product of the cotton plant has been the lint that covers the seeds within the seed pod, or boll. This lint has been utilized for thousands of years for clothing the people of ancient India, Asia, the Americas, and Africa. Cotton fabrics have been found in excavations at Mohenjo-Daro in India and in pre-Inca cultures in the Americas (Hutchinson et al., 1947). Lint, the most important economical product from the cotton plant, provides a source of high quality fiber for the textile industry. The cotton seeds, the primary byproduct of lint production, are an important source of oil for human consumption, and a high protein meal used as livestock feed. The waste after ginning is used for fertilizer, and the cellulose from the stalk can be used for products such as paper and cardboard.

Cotton is grown on every continent except Antarctica, and in over 60 countries in the world. In many countries, cotton is one of the primary economic bases which provide employment and income for millions of people involved in its production, processing, and marketing (Chaudhry et al., 2003). Worldwide, cotton production was 120.4 million bales (218.2 kg/bale) in the 2004/2005 marketing year, the largest on record (FAS, 2005). It was produced on over 35 million hectares, primarily in 17 countries. China was the world's leading producer of cotton in 2004/2005, producing an estimated 29 million bales. The United States was second with just over 23 million bales, followed by India, with 19 million bales, Pakistan, producing around 11 million bales, and Brazil, producing almost 6 million bales.

II. Agroclimatology of Cotton Production

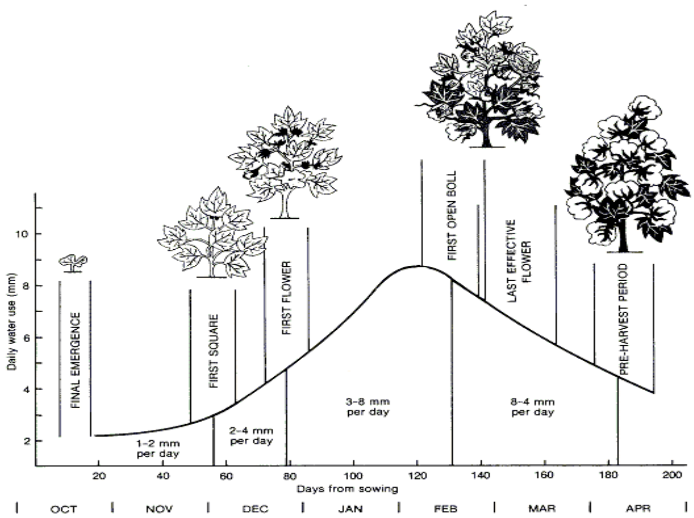
Adequate soil temperature and moisture conditions at planting are necessary to ensure proper seed germination and crop emergence. The recommended soil temperature at seed depth should be above 18° C (65° F), to ensure healthy uniform stands (El-Zik, 1982; Oosterhuis, 2001). However, soil temperatures below 20° C (68° F), when combined with moist conditions, can reduce root growth and promote disease organisms which can injure or kill the seedlings. Cotton requires a minimum daily air temperature of 15 degrees C (60° F) for germination, 21-27 degrees C (70-80° F) for vegetative growth, and 27-32 degrees C (80-90° F) during the fruiting period. Current commercial cultivars generally need more than 150 days above 15 degrees C (60° F) to produce a crop, become inactive at temperatures below 15° C, and are killed by freezing temperatures (Waddle, 1984). Mauney (1986) stated that all processes leading to square, blossom and boll initiation, and maturation are temperature-dependent. Cool nights are beneficial during the fruiting period, but extremes in temperature (low or high) can result in delayed growth and aborted fruiting sites. Gipson and Joham (1967, 1968, and 1969) documented that suboptimum temperatures retarded growth and fiber development.

At least 500 mm (20 in.) of water (rainfall and/or irrigation) is required to produce a cotton crop. For water not to be a limiting factor on yield, cotton needs between 550 mm and 950 mm (22 to 37 in.) during the season in a consistent and regular pattern (Doorenbos et al., 1984). Untimely rainfall and/or irrigation as well as humid weather during later stages of cotton growth, primarily once the bolls begin to open, may complicate defoliation, reduce yield and quality, lower the crop's ginning properties (Freeland et al., 2004; Williford, 1992), or promote the attack of insect pests and disease organisms, such as boll rot (Boyd et al., 2004). Once the boll has opened, exposure of cotton lint to the environment causes weathering and the fibers can become stained, spotted, dark, and dull. Parvin et al., (2005) states that yield is reduced 10.10 kg of lint per hectare, per centimeter (22.897 lbs per acre per inch) of accumulated rainfall during harvest. Williford's et al., (1995) research also measured a reduction in lint yield and grade for each successive rain event at harvest. Hence, the combination of warm, dry weather conditions, abundant sunshine, and sufficient soil moisture when the bolls start opening through harvest will maximize yield and quality potential.

Optimum Climate Needs

Growth Stage	Average Daily Temperature Celsius*	Average Daily Temperature Fahrenheit*	Daily Crop Water Use (mm)*	Daily Crop Water Use (in)*
Planting (Soil)	18° Minimum	65° Minimum	>0	>0
Planting (Air)	>21°	>70°		
Vegetative Growth	21°-27°	70°-80°	1-2	0.04-0.08
1st Square			2-4	0.08-0.16
Reproductive Growth	27°-32°	80°-90°	3-8	0.12-0.31
Peak Bloom			8	0.31
1st Open Boll			8-4	0.31-0.16
Maturation	21°-32°	70°-90°	4	0.16

* Derived from listed sources



Source: ICT; Abdulmumin and Misari (1990); DPL (1998); Erie et al. (1981); Hake et al. (1996).

(Months are referent to a crop in the southern hemisphere, and days from sowing will differ based on heat unit accumulation for each location)

Photosynthesis is the driving process in determining production potential. Under optimum conditions in controlled naturally-lit plant growth chambers, a research cotton crop produced a yield equivalent to 9 bales per acre, approximately 3 times the yield of commercially grown cotton under good field production practices (Reddy et al., 1998). Lint yield is generally reduced because of reduced boll production, primarily because of fewer fruiting sites producing bolls but also because of increased fruit abscissions due to various environmental stresses (Grimes and Yamada, 1982; McMichael and Hesketh, 1982; Turner et al., 1986; Gerik et al., 1996; Pettigrew, 2004a). Environmental conditions such as overcast skies, rainy weather, water deficits, and high temperatures (day and/or night) will decrease photosynthesis and the supply of photosynthate. The decreased supply of photosynthate increases square and boll shed, and thus reduces the total possible number of harvestable bolls. Plants with the highest boll load are the most sensitive to low light intensity due to their increased requirements of photosynthates (Guinn, 1998).

Water stress caused by a deficiency of water manifests its damage as reductions in photosynthetic activity and increases in leaf senescence (Constable and Rawson, 1980; Krieg, 1981; Marani et al., 1985; Faver et al., 1996). Drought stress causes severe shedding of small squares, resulting in a decrease in flowering. Water stress during the first 14 days after anthesis also leads to boll abscission, but large squares/bolls do not shed readily and flowers seldom shed. Therefore, even under severe stress, young plants can often continue to flower. Water stress from 20 to 30 days after anthesis results in smaller bolls and reduced seed weights (Guinn, 1998). Moisture deficit stress reduces plant growth, resulting in stunted plants with reduced leaf area expansion (Turner et al., 1986; Ball et al., 1994; Gerik et al., 1996; Pettigrew, 2004b). Water deficits can reduce fiber length when the stress is severe and occurs shortly after flowering (Bennett et al., 1967; Eaton and Ergle, 1952, 1954; Marani and Amirav, 1971; Pettigrew, 2004a). Drought stress can additionally reduce (Eaton and Ergle, 1952; Marani and Amirav, 1971; Pettigrew, 2004a; Ramey, 1986), or increase (McWilliams, 2003; Bradow and Davidonis, 2000) fiber micronaire depending on when it occurs. If the drought is severe late in the season with the result that set bolls do not have the assimilates to fully develop them, then micronaire will be reduced. If the stress is during peak bloom, a reduced number of bolls will be set; if this is followed by a later season rain, assimilates will be readily available for the reduced boll load resulting in increased average micronaire of the field.

Oftentimes, water stress occurs concurrently with excessively high afternoon temperatures. Reddy et al. (1991; 1992; 1999) demonstrated the detrimental effect that temperatures outside of an optimal range could have on a cotton plant and its fiber growth and development in closed environmental plant growth chambers. Cotton has the ability to mitigate exposure to high temperatures by evaporative cooling of the leaves via transpiration. However, high humidity negatively impacts the plant in certain growing regions, like that found in the Mississippi Delta, and the response to irrigation can be affected by reduced evapo-transpiration efficiency of the plant. This higher humidity reduces the level of evaporative cooling, making the plant more susceptible to heat stress at lower air temperature.

Cotton lint yields and fiber quality are also impacted by the amount and quality of the solar radiation. Given adequate water and insect control, cotton grown under arid conditions such as the southwestern US, Australia, and the Middle East can routinely produce lint yields in excess of 3 to 4 bales per acre with the abundance of sunlight in each region. However, in the humid southeastern US, where clouds can be much more prevalent, lint production is limited by the amount of sunlight received (Eaton and Ergle, 1954; Pettigrew, 1994). The lint yield reduction resulting from low light situations is primarily due to fewer bolls being produced on the plants (Pettigrew, 1994). Not only is lint production reduced under low light conditions, but the fiber produced is often of inferior quality. Both Pettigrew (1995, 2001) and Eaton and Ergle (1954) found that shade treatments or reduced light conditions produced weaker fiber with a lower fiber micronaire. These fiber quality reductions were associated with alterations in various fiber carbohydrate levels, indicative of a reduction in level of photoassimilates produced (Pettigrew, 2001).

Wind can also stress the cotton plant enough to reduce yield, although some wind may be beneficial in very hot humid conditions. Wind modifies the temperature and humidity gradients around the cotton plant which in turn changes the evaporative demand. Most wind damage to cotton plants occurs during the first 3 to 6 weeks after emergence when the wind picks up soil particles and damages the young seedlings during impact. High winds can cause blowing sand that can literally cut the young plants off at the soil surface (Barker et al, 1985a and 1985b), reducing the overall stand. In regions such as the Texas High Plains where the winds blow hard and constantly, management practices which afford protection of cotton plants are designed to improve plant growth and yield. Strip cropping, where taller growing crops are planted around the cotton seedlings, offers benefits where the soil moisture can be maintained. Standing wheat and other stubble can also offer protection to the early seedlings (Barker et al, 1985a and 1985b). Extreme wind damage can sometimes occur in mature cotton crops as was evident in 2005 when Hurricanes Katrina and Rita ravaged parts of the Mid-South US cotton crop (WWCB, 2005a and 2005b). Immature bolls were beaten off of the plants and seedcotton was blown out of mature open bolls. Leaves of the non-mature plants were stripped in locations where the strongest winds occurred.

Environmental factors not only impact the growth of the cotton plant, but also that of pests and beneficial organisms. Both undesirable and beneficial plant and animal species are altered by factors which affect the crop, and should be considered during the growing season. Some climate regimes are unsuitable for beneficial plants such as rotation crops or winter cover as well as beneficial insect survival. Alternately, weather patterns alter the growth of some pest insects positively and allow their populations to expand to a crop damaging level. In areas not receiving freezing temperatures during the winter, disease and insect pests can overwinter and have a detrimental effect on young cotton. Knowledge of these interactions is essential when attempting to maximize cotton yields.

III. Other Background Information on Cotton

The cotton plant is a deciduous, indeterminate perennial plant in the genus *Gossypium* of the family Malvaceae, or mallow family, and is native to subtropical climates. Two Old World diploid (2n = 2x = 26) species, *G. arboreum and G. herbaceum,* and two New World tetraploid (2n = 4x = 52) species, *G. barbadense* and *G. hirsutum,* have been domesticated independently for cultivation throughout the world. The most widely grown species worldwide is *G. hirsutum* which is grown on over 95% of the world-wide cotton hectarage, followed by *G. barbadense*. Upland cotton, *G. hirsutum,* is native to Mexico and parts of Central America, and pima, Egyptian or American-egyptian, *G. barbadense* is native to South America (Brubaker et al., 1999). India is an exception to most countries, with only 30% of its cotton production area planted to *G. hirsutum*, 17% planted to *G. arboretum*, 8% to *G. herbaceum*, and the remaining area planted to interspecific and intraspecific hybrids.

Cotton is cultivated as an annual in the temperate and even sub-tropical zones and develops in an orderly, predictable pattern. Plant development in cotton proceeds through five growth stages: germination and emergence, seedling establishment, leaf-area-canopy development, flowering and boll development, and maturation. Marur and Ruano (2001) define the growth process in four phonological phases: vegetative, squaring, flowering, and boll opening. The seed contains two well-developed cotyledons, a radicle, a hypocotyl and a poorly developed epicotyl. The cotyledons will form the seed leaves that provide energy for the developing seedling and are photosynthetically active during early seedling development. Moisture from the surrounding soil is imbibed into the seed through the chalaza, an area of specialized cells at the broad end of the seed. The water follows the tissue around the embryo to the radicle cap at the narrow end of the seed. The seed/embryo swells as water is absorbed causing the seed coat to split. Under favorable conditions, the radicle emerges through the pointed micropylar end of the seed in two to three days becoming the primary root that grows downward into the soil. The hypocotyl grows rapidly and elongates, arching near the cotyledons. The cotyledons are located at the lowest node on opposite sides of the stem. As the hypocotyl becomes longer, the cotyledons and the epicotyl are pulled/pushed through and above the soil surface. Exposed to light, the cotyledons unfold, expand, turn green and begin to manufacture food.

Much of the early growth of the cotton plant is focused on the development of a substantial root system. The primary root, or taproot, penetrates the soil rapidly and may reach a depth of up to 250 mm (10 inches) by the time the cotyledons expand. Root development may proceed at the rate of 12.5 to 50 mm (0.5 to 2.0 inches) per day, depending on conditions, such that the roots may be 1 m (39 inches) deep by the time the plant is only 305 mm (1 foot) tall (Oosterhuis and Jernstedt, 1999). The taproot continues to elongate until the plant is at maximum height soon after flowering. The bud above the cotyledon enlarges and unfolds to form the stem where true leaves and branches will develop. A fully developed cotton plant has a prominent, erect main stem consisting of a series of nodes and internodes. As the plant grows, the internode above the cotyledons extends, and a new node is formed from which the first true leaf unfolds. This process continues at 2.5 to 3.5-day intervals. A single leaf forms at each node in a spiral arrangement. At the center of this growth activity is the terminal bud. The terminal bud controls the upward pattern of stem, leaf, and branch development. About four to five weeks after planting, vegetative and reproductive branches begin to form between the leaf petiole and the main stem node (Oosterhuis and Jernstedt, 1999).

Under optimal conditions, flower buds can be seen five to eight weeks after planting as small, green, triangular structures commonly or colloquially know as squares. The first square is formed on the lowest reproductive branch of the plant located at the fifth to ninth main stem node. New squares will continue to appear on the next reproductive branch up to the top of the plant every 2.5 to 3.5 days and will appear outwardly along each fruiting branch at approximately five to six-day intervals. Bednarz' and Nichols' (2005) research on selected modern cultivars shows that the horizontal fruiting interval was 3.2 to 4.4 days. The total time from plant emergence to the appearance of the first flower bud is about six weeks. Each flower bud develops into a bloom about three weeks from the time it is visible to the unaided eye.

The cotton bloom is a perfect flower with white petals on the day of anthesis. The ovary has 3 to 5 carpels or locules. Each locule contains 8 to 12 ovules that may develop into seed. Flowers open during the morning, and pollination occurs within a few hours. Fertilization takes place within 24 to 30 hours after pollination and the fertilized ovule develops into seed (Oosterhuis and Jernstedt, 1999). The white petals of the flower turn pink after 24 hours and die the following day, usually shedding from the developing boll within a week. The growth rate of a boll is temperature dependent and a boll will reach its maximum volume in about 24 to 30 days after anthesis. After anthesis, approximately 50 days are necessary for the fibers inside the boll to mature and the boll to open.

Cotton fibers are formed from individual cells located on the seed epidermis. While firmly attached to the seedcoat, the fiber elongates for 20 to 25 days after fertilization and then grows in diameter for another 20 to 25 days. The developing cotton fiber is like a hollow tube, with successive layers of cellulose deposited on the inner surface of the fiber wall in a spiral fashion. The amount of cellulose deposited determines the fiber strength, fineness, and maturity. Micronaire, a measurement of both fiber maturity and fineness, can be more heavily influenced by the environment than other fiber traits. High temperatures or drought during the elongation phase of fiber development can shorten fiber length and reduce fiber uniformity, and can cause high, or even under extreme conditions, low micronaire (Ramey, 1999). Cotton lint is creamy white to white when the boll opens. Fiber quality is at its maximum as soon as the boll opens, and declines thereafter until harvest due to environmental interactions.

IV. Management Aspects of Cotton Production

There are various management practices that should be followed to help mitigate some of the environmental risks associated with growing cotton. They include selection of adapted cultivars, planting within the recommended range of favorable planting dates and environmental conditions, use of seed and seedling protectants to avoid stress or early season diseases and insects, use of effective pest management tactics to avoid competition and damage by weeds and insects, management for optimal soil moisture, proper fertility management, and management for maturity and readiness for harvest at optimum times. There is an abundance of university extension service recommendations and other government agency sources of information to assist a cotton grower in making good management decisions to avoid or minimize risk. These sources include environmental and climatological monitoring and forecasting services. Some risks will never be avoided unless the cotton is grown in a protected, controlled environment such as growth chambers or greenhouses; however, this is not economical for commercially grown cotton at this time.

One of the tools used in reducing environmental risks and increasing the possibilities of a profitable yield is cultivar development through breeding and genetics. Successful cultivar development incorporates risk aversion into the genetic code of adapted varieties. Traditional breeding methods are used with aggressive selection pressure to develop genotypes for favorable traits for environments of interest. New cultivars are selected in the breeding programs based on their yield, fiber quality, and other traits of interest. The selection process ensures that new cultivars are developed within the current climate cycle or pattern and therefore have those recent environmental risks built into their genetics. When a new cultivar is released for commercial production, its primary selling trait is its high and consistent yield. Producers are primarily paid for their crop based on yield, and therefore should choose to plant cultivars based on their yield history over the past few years in their locality. One needs to remember that genotypes bred in one location, or environment, may not be the ideal cultivar for another location, or environment.

Breeding also allows for traits to be bred into a genotype, or cultivar. For example, as reported above, extreme heat results in delayed growth and loss of squares and fruit. Heat tolerance can be genetically manipulated in cotton. Certain cultivars have been identified that perform better under hot temperatures. Therefore, breeders have been successful in selecting for and developing heat tolerant (Feaster, 1985; Lu et al., 1997) and drought tolerant lines (Basal et al., 2005). For example, higher yielding pima lines have been developed by selecting for increased stomatal conductance, thus allowing these lines to keep their leaves cooler (Radin et al. 1994 and Percy et al. 1996). Salt tolerance is also an inherited trait which cotton breeders have been successful in incorporating into new cultivars (Higbie et al. 2005). These cultivars will give growers greater success in increasing germination in salty soils. Cotton seeds with enhanced emergence force that break through soil crusts have also been selected for by breeders (Bowman, 1999), with expectations that a higher percentage of the seedlings will emerge to produce even and uniform plant stands.

One of the largest contributions breeding has made to current US Mid-South Cotton production has been the development of earlier maturing cultivars. These cultivars were bred to better fit the climate of this area and mature as much as 30 days earlier than historical cultivars. These cultivars take better advantage of the normal weather pattern of the area by being in the fruiting stage while there is still moisture available in the soil, starting the maturation process during the dryer times of the summer, and being harvestable prior to the normal rainy period of the late fall and winter. These cultivars have also been created to produce yield despite the intense pest pressures of the area. A secondary contribution breeding has made was the introduction of pest tolerant traits into the cultivars. These cultivars can produce toxins or tolerate toxins in order to control specific pests that previously would reduce yield. These cultivars were bred in the Mid-South, so were selected based on their capability to adapt to that environment.

Weather conditions often determine the type of pests that will have to be controlled in a given growing season as well as the efficacy of control procedures. Weed pests of cotton change according to regional climatic conditions, cultural practices, and local weather variables. Herbicides often require actively growing plants to achieve good control. Moisture and temperature generally control how actively weeds grow. Plant pathogens and insect pests in most cases require alternate hosts. The alternate host's growth is dictated by regional climatic differences and local weather variations. Insect pests for example move from the alternate hosts into cotton when that host is less attractive to the pest than cotton, mostly when the host is dying or senescing. Spider mites, for example, generally require dry weather. The dry weather prevents beneficial fungi from producing an epizootic thus eliminating the spider mite population. Effective pest control requires good timing to be beneficial, and one of the largest obstacles to properly timed crop protection applications is weather. If improperly timed, crop protection products may fail and the resulting uncontrolled pest population could damage the crop. Each crop protection product is only active within a certain environmental regime or during a certain life stage of a pest. Temperatures too high or low, or rain prior to or after application may cause failures. Moisture and/or high winds can prevent the timely application of products and thus reduce control and yield.

Following local extension recommendations or governmental guidelines will help reduce environmental risks to producers. These recommendations and guidelines usually include planting and harvesting dates that consider risks of temperature and precipitation extremes and other general environmental factors. They also may include timing suggestions for certain practices which would have adverse effects if done at alternate times. Soil sampling is one of those recommended tasks which will identify many soil issues that could limit production. Sampling is a tool that can be used to identify limiting nutrient, pH, or salinity factors that can reduce yields and/or fiber quality.

Since cotton plants are killed by freezing temperatures, the crop has to be grown between the last spring and first fall freezes. Climatological records can identify the growing period for a location and be used to compute the statistical probability of a freeze occurring before or after certain dates. Growers must realize and take advantage of these data in order to reduce the risk of the crop being killed by freezing temperatures after planting in the spring, or prior to maturation in the fall. The National Climatic Data Center computed this dataset for many sites across the United States and is available for producers to utilize (Koss et al., 1988). This dataset provides three probability levels (10, 50, and 90 percent) of a certain temperature (-2°, 0°, and 2° C) (28°, 32°, 36° F) occurring after a certain spring and before a certain fall date. Producers have to weigh those risks and decide whether or not to plant. Even though the current weather is ideal for planting, producers should not plant if there is a higher percent chance of a freeze occurring after that date than that percent of risk they are willing to accept. Also producers have to utilize this information to determine the last day they are willing to plant, as the crop has to have enough time prior to the first fall freeze to mature. Other data derived from climatological data are also beneficial to growers, such as the number of days a grower has to complete tillage and non-tillage operations during a season (Bolton et al., 1968; and Zapata et al., 1997).

There are also certain cultural practices that may be utilized to reduce some of the environmental risks associated with growing a cotton crop. Seeding rates need to be sufficient to achieve an ideal plant population for all location. Plant populations of 68,000 to 101,000 plants per hectare (27,500 to 41,000 plants per acre) are recommended on bedded rows and populations of 197,000 to 247,000 plants per hectare (80,000 to 100,000 plants per acre) are typical in ultra narrow row or broadcast cotton production. When planting, seed depth is critical and seeds should be placed at 10 to 25 mm (½ to 1 in.) depending on soil type, crusting potential, and moisture levels. If planting immediately precedes a rain, certain soils will crust and seal over, depriving the seedling of oxygen that is required for germination and root development, and making it more difficult for the seed to push through the soil for emergence. Planting seed at the shallower depth is recommended under these conditions to improve emergence (Anonymous, 2006). Even planting seed at deeper depths, up to 30 mm (1.5 in.), is not uncommon when planting to the moisture level in the soil in arid and dry areas. This however is not the ideal situation as more seed may have to be planted to achieve the desired final plant stand. Strip-cropping and interplanting may be utilized to reduce wind effects on seedlings. Skip-row planting may be utilized for better soil water utilization and a higher field level drought tolerance.

The most obvious and beneficial cultural practice that can be utilized to reduce environmental risks is irrigation. Supplemental irrigation should be applied if needed during dry periods. Field drainage is also very important as cotton can not remain in saturated soil. Any practice that can improve the surface or subsurface drainage is very beneficial. Tillage operations such as bedding or sub-soiling, or inserting drainage tiles may be utilized to improve field drainage.

V. User Requirements for Agrometeorological Information in Cotton

User requirements for agrometeorological information will vary depending on the climate, cultivar, and soil type of the region where the crop is grown. Commercial cotton production worldwide is in a constant battle to keep the cotton plant unstressed and retaining its fruit while environmental factors are constantly stressing the plant and certain requirements need to be followed in all locations. Current cultivars require between 1195 and 1275 Degree Day (DD15.5C) heat units based on 15.5 degrees C (2150-2300 DD60F) from planting to harvest to produce an acceptable yield (Anonymous, 2006). The degree day baseline is based on a very large pool of research that studied temperature effects on different growth stages (Mauney, 1986; Anderson, 1971; Young et al., 1980; and Bilbro, 1975). Recent research has shown that a higher baseline temperature combined with other weather variables may predict boll maturation better (Viator et al., 2005) Degree Day heat units are calculated by taking the daily average temperature, (Max + Min)/2, and subtracting the base, either 15.5 for Celsius or 60 for Fahrenheit, from the daily average. The resulting number is the number of heat units accumulated for that day. High yielding cotton also requires between 508 and 1016 mm (20-40 inches) of water during the growing season. If a location normally has little or no precipitation during the growing season, irrigation is necessary. Cotton also requires a soil with excellent water holding capacity, aeration, and good drainage, since excessive moisture and water logging is detrimental to production.

Growth Stages Indicated by Accumulation of Degree Day Heat Units*

	DD15.5 - °C	**DD60 - °F**
From Planting to Emergence	25 – 35	50 – 60
From Emergence to First Fruiting Branch	165 – 190	300 – 340
From Emergence to First Square	235 – 265	425 – 475
From Square to White Bloom	165 – 195	300 – 350
From Emergence to Peak Bloom	770 – 795	1385 – 1435
From White Bloom to Open Boll	415 – 610	750 – 1100
From Emergence to a Mature Crop	1165 – 1250	2100 – 2250

*Compiled from: Anonymous, 2006; Boyd et al., 2004; Kerby et al., 1987; Young et al., 1980.

During germination, the soil must have reached a minimum soil temperature of 18° C (65° F) and have moisture available, but not be saturated. Soil temperatures below 20° C (68° F) reduce root growth and when combined with moist conditions promote disease organisms which can injure or kill the seedlings. Forecasted daily average temperatures should be above 21° C (70° F) for the 5 days immediately following planting in order to assist in quick germination and the establishment of a healthy plant stand. These requirements increase the possibility of growing a good radicle. Damage to the radicle at this point will cause a shallow root system, leaving the plants more susceptible to water and drought stresses (El-Zik, 1982; Oosterhuis, 2001).

After planting, optimum daily maximum temperatures for vegetative growth are 21-27 degrees C (70-80° F) with sufficient moisture. During fruiting, daily maximum temperatures of 27-32 degrees C (80-90° F) with sufficient moisture are optimal. Each boll requires 415-610 DD15C (750-1100 DD60F) heat units to mature from a white bloom into an open boll. High temperatures above 32 degrees C (90° F) may decrease boll size and increase the amount of time for bolls to reach maximum weight (El-Zik, 1982; Oosterhuis and Jernstedt, 1999). Too much water from rain or irrigation early in the plant's growth will cause the plant to set its first reproductive branch too high on the main stem as a result of excessive internode elongation. On the other hand, water stress or drought early will cause the setting of reproductive branches too low on the stem because internode length is reduced. Rain, cloudy weather, and excessively high temperatures can cause an increase in square and boll shedding (Reddy et. al., 1998; Guinn, 1998; Eaton et al., 1954; Pettigrew, 1994). Rain or irrigation on open flowers during the pollination process can rupture the pollen resulting in poorly pollinated flowers and subsequently, square shed (Burke, 2003; Pennington and Pringle, 1987). Even without rain, cloudy weather decreases photosynthesis and may result in square and small boll shed. High temperatures prior to anthesis can prevent the production of viable pollen (Meyer, 1969) and cause the stigma to extend so fertilization is prevented resulting in young square abortion. When the temperature rises above 35° C (94° F), more of the anthers produced are sterile and therefore flower survival and fruit production is poor during that time.

As this shows, there are numerous abiotic stress factors, particularly moisture surpluses and deficits, high and low temperatures, and low light, that impose limitations to the growth and development, and therefore yield of a cotton crop. Monitoring these factors is a requirement that allows growers to understand why yields may be reduced due to certain environmental effects. Climate and environmental monitoring should be done at the local level. The normal climate of a location remains more consistent over time and therefore needs to be considered prior to the season. The normal weather patterns during the production season have to be identified and then taken advantage of in order to maximize production and profitability. Knowledge of the location's climate, both atmospheric and edaphic, verifies the location's suitability for sustaining crop production. Soil moisture and temperature need to be monitored prior to planting to promote quick and healthy germination and establishment of a healthy, uniform plant stand. Soil moisture during the entire season is critical in order to maximize yields and either extreme of too much or too little stresses the plant and potentially limits the plant's yield. Air temperatures are important throughout the growing season, but are most critical at planting time.

VI. Agrometeorological Services Available for Cotton Production

Cotton that is grown commercially has to produce yields that are at or above a point at which a sustainable economic profit is attained. The economics of a particular region will ultimately determine what yield is acceptable. In order for growers to be able to monitor in-season environmental conditions, utilize historical climatic information, and attempt to take advantage of or divert ill effects of weather, pertinent weather and crop information needs to be made available to them. Research on the interactions between existing and new cultivars with environmental conditions need to be completed and released to growers in a timely and continuous manner. Agrometeorological information and products are vital tools for growers to have available for management and economical decision making. Governments, agencies, universities, and organizations are ideal groups to make these data and products available to individual growers. Many countries or areas have groups such as these providing these services to growers and some countries are developing programs. These agrometeorological services need to be developed and maintained in all cropping areas, worldwide.

Locations to access local weather include the Internet, national or regional weather services, and local meteorological professionals. Data may be collected near population centers, and thus may not represent local agricultural interests or needs. However, several areas have established agricultural weather station networks and their data are available through the supporting group or agency. In the US, agricultural weather networks are supported by individuals, cooperatives, corporations, agencies, universities, and organizations. The data are available usually via the Internet and agrometeorological products are made available to their users. Users may monitor current or historical weather data, depending on the network's capabilities, for decision making in cotton production from planting, utilizing soil temperatures, to harvest, monitoring heat units after a cracked boll for defoliation applications. Producers may also utilize the data in-season for monitoring square and boll shed or crop protection applications.

One example of a product provided to cotton producers by a university is a cotton planting recommendation map that graphically depicts over the entire state when the next 5-day forecasted temperatures are suitable for cotton planting (MSU-DREC, 2006). Another example of a researched agrometeorological tool is monitoring maturity of the cotton plant utilizing the Node Above White Flower (NAWF) mapping technique (Bourland et al., 2001). NAWF can be utilized effectively to plan and schedule sequential events, such as termination of crop enhancing and protection applications, defoliation, and harvest by monitoring both the physiological stage of the cotton plant and heat unit accumulation (Harris et al., 1997; Tugwell et al., 1998; Siebert et al., 2006). On a global scale, world-wide weather and crop information is being compiled and distributed by the United States Department of Agriculture (**USDA**), World Agricultural Outlook Board (**WAOB**) in its publications available through the mail or the Internet at **http://www.usda.gov/oce/weather/pubs/index.htm**.

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