Dates

First or last occurrence of a phenomenon in a period of time
(day of year starting from January 1st in the Northern hemisphere and from July 1st in the Southern hemisphere)

Indicator	Metric	Weather variables involved	Questions addressed	Comments	Sources
Start of growing season	First day when for five consecutive days $T_{avg} > T_c$ (e.g. T_c = 5.0 °C) (from 1 Jan)	Air temperature	Do the expected rises in average air temperatures mean an earlier start in the year of the growing season?	The arbitrary choice of T_c may give erratic predictions.	Barnett et al. (2006) Matthews et al. (2008) Confalonieri et al. (2010)
Start of field operations	First day when $\sum T_{avg} > \sum T_{avg(c)}$ (e.g. $T_{avg(c)}$ = 200 °C-d above a threshold of 0 °C)	Air temperature	Do the expected rises in average air temperatures mean an earlier start in the year of field-based operations?	Indicated as "T_{sum} 200", it is used to time the optimum application of nitrogen fertilizers to grass crops in the spring. It is an alternative representation of the start of the growing season because it produces less erratic predictions, but there is no equivalent metric for the end of growing season.	Matthews et al. (2008) Confalonieri et al. (2010) UK weekly farming newspaper (e.g. Matthews et al., 2011)
Last air frost (spring)	Last day when T_{min} < 0.0 °C (from 1 Jan)	Air temperature	Do the expected rises in minimum air temperatures mean that the last spring air frost occurs earlier in the year?	The last spring air frost occurring earlier in the year (and with a generally milder winter) raises the potential for increased crop production. For particular systems such as outdoor horticulture, soft and orchard fruits, late spring frost is a real risk factor that needs to be managed for.	Matthews et al. (2008) Confalonieri et al. (2010)
Last grass frost (spring)	Last day when $T_{min} < T_c$ (e.g. T_c = 5.0 °C) (from 1 Jan)	Air temperature	Do the expected rises in minimum air temperatures mean that the last spring grass frost occurs earlier in	The last spring grass frost occurring earlier in the year (and with a generally milder winter) raises the potential for earlier	Matthews et al. (2008) Confalonieri et al. (2010)

			the year?	grass re-growth. The arbitrary choice of T_c may give erratic predictions.	
Wettest week in the year	Mid-week date when maximum seven-day value of *P* occurs	Rainfall	Do the expected changes in rainfall pattern mean that the timing of water management is likely to change?	Wetter periods in the year may mark less irrigation requirements in those same periods. They may also indicate periods of major risk for severe thunderstorms, flooding and mudslides.	Matthews et al. (2008) Confalonieri et al. (2010)
First grass frost (autumn)	First day when $T_{min} < T_c$ (e.g. $T_c = 5.0$ °C) (from 1 Jul)	Air temperature	Do the expected rises in minimum air temperatures mean that the first autumn grass frost occurs later in the year?	The first autumn grass frost occurring later in the year (and with a generally milder winter) raises the potential for later grass re-growth. The arbitrary choice of T_c may give erratic predictions.	Matthews et al. (2008) Confalonieri et al. (2010)
First air frost (autumn)	First day when $T_{min} <$ 0.0 °C (from 1 Jul)	Air temperature	Do the expected rises in minimum air temperatures mean that the first autumn air frost occurs later in the year?	The first autumn air frost occurring later in the year (and with a generally milder winter) raises the potential for increased crop production (e.g. horticulture), and may also lead to a preference for an autumn calving system for cattle. Warmer conditions may favour the development and further dispersal of pests, pathogens and weeds.	Matthews et al. (2008) Confalonieri et al. (2010)
End of growing season	First day when for five consecutive days $T_{avg} <$ T_c (e.g. $T_c = 5.0$ °C) (from 1 Jul)	Air temperature	Do the expected rises in average air temperatures mean a later end in the year of the growing season?	The arbitrary choice of T_c may give erratic predictions.	Barnett et al. (2006) Matthews et al. (2008) Confalonieri et al. (2010)

Counts

Number of occurrences of a phenomenon
(number of days or months in a year which a criterion is met)

Indicator	Metric	Weather variables involved	Questions addressed	Comments	Sources
Air frost	Days when $T_{min} < 0.0$ °C	Air temperature	Do the expected rises in average air temperatures mean a reduction in the number of air frost days?	Decreasing risks of frost is a potential opportunity for crops but also a problem with increased incidence of pests and disease likely (particularly by those concerned with organic agriculture). Warm conditions may have implications for the over-wintering survivorship of pests and pathogens, and favour their dispersal. Reduction in frost control implies a greater reliance on chemical sprays to control weeds, pests and pathogens (and treatments for animal diseases in livestock production system), with implications on the economics of food production and impacts on human and environmental health.	Barnett et al. (2006) Matthews et al. (2008) Confalonieri et al. (2010)
Plant development	Months when $T_{avg} > T_c$ (e.g. $T_c = 5.0$ °C)	Air temperature	Do the expected rises in average air temperatures mean an increased number of months suitable for plant development?	A larger number of warm months in the year raise the potential for increased crop production (e.g. horticulture).	Bellocchi et al. (2004) Confalonieri et al. (2010)
Growing season range	Days between start of growing season and end of growing season	Air temperature	Do the expected rises in average air temperatures mean an extended (potential) growing season?	An increased growing season range may occur at one or both ends of the year.	Matthews et al. (2008) Confalonieri et al. (2010)
Growing season length	Days when $T_{avg} > T_c$ between start of	Air temperature	Do the expected rises in average air temperatures	An increased growing season length may occur at one or both	Matthews et al. (2008)

	growing season and end of growing season		mean an extended (actual) growing season?	ends of the year. Length of growing season is potentially important for horticulture (for how many crops could be scheduled) and grassland systems (for the time livestock could be outside on grass, dependent of course on access). Longer growing season, and in particular the earlier start, is often seen through a change in flowering dates of plants, particularly those flowering in early spring.	Confalonieri et al. (2010)
Dryness	Days when $P < P_t$ (e.g. $P_t = 0.2$ mm)	Rainfall	Do the expected rises in average air temperatures mean an increase in the number of dry days and more marked alternation between wet and dry periods?	A larger number of dry days indicate more irrigation requirements. Dryer conditions may hinder the development of pests, pathogens and weeds.	Matthews et al. (2008) Confalonieri et al. (2010)
Wetness	Days when $P > P_t$ (e.g. $P_t = 0.2$ mm)	Rainfall	Do the expected rises in average air temperatures mean a decrease in the number of wet days and more marked alternation between wet and dry periods?	A larger number of wet days indicate less irrigation requirements. Wetter conditions may favour the development of pests, pathogens and weeds.	Matthews et al. (2008) Confalonieri et al. (2010)
Plant heat stress	Days when $T_{max} > T_c$ (e.g. $T_c = 25$ °C)	Air temperature	Do the expected rises in average air temperatures mean an increase in the number of days when heat stress (e.g. stomatal closure) will occur?	An indicator for plant heat stress identifies events with yield or quality consequences. For instance, an increase in days when heat stress will occur may inhibit biomass production. This has to be considered in respect of plant responses to	Matthews et al. (2008) Confalonieri et al. (2010)

elevated CO_2 as well. The timing of when crops become heat stressed is also critical, i.e. if at anthesis can lead to reductions in crop biomass accumulation.

Thermal units

Degree-days (°C-d) above or below a given threshold

Indicator	Metric	Weather variables involved	Questions addressed	Comments	Sources
Accumulated frost	Sum of degree-days in a year where $T_{min} < 0.0$ °C	Air temperature	Do the expected rises in average air temperatures mean a decreased accumulation of frost (snow or ice)?	The decrease in accumulated frost is a potential opportunity, but also a problem with increased incidence of pests and disease likely (particularly by those concerned with organic agriculture). A period of low winter temperatures (vernalization) is needed (chilling requirement) to many plants grown in temperate climates to initiate or accelerate the flowering process.	Matthews et al. (2008) Confalonieri et al. (2010)
Heating degree days	$\sum(T_c - T_{avg})$ in a year where $T_{avg} < T_c$ (e.g. T_c = 15.5 °C)	Air temperature	Do the expected rises in average air temperatures mean a decreased demand for energy needed to heat a home or business?	It represents the energy needed to keep a building at a constant temperature.	Barnett et al. (2006) Matthews et al. (2008) Confalonieri et al. (2010)
Accumulated degree days	$\sum T_{avg} > T_c$ in a year	Air temperature	Do the expected rises in average air temperatures mean a greater thermal time accumulation?	Autumn sowing may become preferable if an earlier harvest of the previous crop is possible due to more rapid phenological development determined by the greater thermal time accumulation.	Matthews et al. (2008)
	$\sum T_{avg} > 0$ in the first semester			Greater thermal time accumulation in the first semester	Bellocchi et al. (2004) Confalonieri et al.

		indicates climate conditions suitable for the growth of many crops.	(2010)

Water

Inputs or outputs of a water balance representing the temporal sequence of changes of water (mm)

Indicator	Metric	Weather variables involved	Questions addressed	Comments	Sources
Wettest week (amount)	Maximum amount of *P* in seven consecutive days	Rainfall	Do the expected changes in rainfall pattern mean that water access management is likely to change?	Wetter periods in the year may indicate less irrigation requirements, and opportunities to create water reservoirs. They may also indicate major risk for severe thunderstorms, flooding and mudslides.	Matthews et al. (2008) Confalonieri et al. (2010)

Waves

Cyclical occurrence of phenomena

Indicator	Metric	Weather variables involved	Questions addressed	Comments	Sources
Heat wave	Maximum count of consecutive days when T_{max} > average T_{max} (baseline period) + 3.0 °C (lasting six days or more)	Air temperature	Do the expected rises in average air temperatures mean more prolonged periods of excessively hot weather?	Prolonged period of excessively hot weather may be accompanied by high humidity. Severe heat waves may cause catastrophic crop failures If a heat wave occurs during a drought, which dries out vegetation, it can also contribute to bushfires and wildfires.	Barnett et al. (2006) Matthews et al. (2008) Confalonieri et al. (2010)
Cold spell	Maximum count of consecutive days when T_{min} < average T_{min} (baseline period) - 3.0 °C (lasting six days or more)	Air temperature	Do the expected rises in average air temperatures mean shorter periods of prolonged cold?	Shorter periods of prolonged cold mean that the snow does not stick around less long.	Barnett et al. (2006) Matthews et al. (2008) Confalonieri et al. (2010)
Dry spell	Maximum consecutive count of $P < P_t$ (e.g. P_t = 0.2 mm)	Rainfall	Do the expected rises in average air temperatures mean more prolonged periods of dry weather?	Dry spells are not as severe as a drought. Dry spells may appear interspersed with occasional large (>100 mm) rain events.	Matthews et al. (2008) Confalonieri et al. (2010)
Wet spell	Maximum consecutive count of $P < P_t$ (e.g. P_t = 0.2 mm)	Rainfall	Do the expected rises in average air temperatures mean a change in the frequency and length of rainy periods?	A large number of wet spells can lead to flooding.	Matthews et al. (2008) Confalonieri et al. (2010)

Indices

Metrics compared to standard values

Indicator	Metric	Weather variables involved	Questions addressed	Comments	Sources
Rainfall intensity and distribution	**Simple Daily Intensity** $$SDI = \frac{P_Y}{n_P}$$ Annual total precipitation, P_Y, divided by the number of wet days, n_P, for which precipitation exceeds 1 mm SDI < 2 mm d^{-1}: light 2 mm $d^{-1} \leq SDI$ < 5 mm d^{-1}: intermediate 5 mm $d^{-1} \leq SDI$: heavy	Rainfall	Do the expected rises in average air temperatures mean more intense precipitations?	Using the mean value from all wet days, SDI is little affected by strong spatial variability of individual rainfall events. Erosion risk increases with increasing SDI values.	Stone et al. (1999)
	Rainfall Seasonality $$SI_p = \frac{P_S - P_W}{P_Y}$$ P_S (mm): summer semester (May-October in the northern hemisphere, November-April in the southern hemisphere) precipitation P_W (mm): winter semester (November-April in the northern hemisphere, May-October in the southern hemisphere) precipitation	Rainfall	Do the expected rises in average air temperatures mean more differences between summer and winter precipitations?	Rainfall seasonality affects the soil and vegetation characteristics in an area. The annual distribution of rainfall can explain the vegetation distribution and composition and the sensitivity of soil to erosion processes. The measure of the rainfall seasonality sets the soil capacity to maintain water storage to be used by plants.	Matthews et al. (2008) Confalonieri et al. (2010)

$SI_P < -0.13$: wetter winters than summers $-0.13 \leq SI_P \leq 0.13$: uniform distribution $SI_P > 0.13$: wetter summers than winters			It also determines the water stress that occurs in the drier and warmer months and can determine the presence or absence of vegetation. It is also important when viewed in the light of runoff generation.	
Modified Fournier $$FI_m = 12 \cdot \sum_{1}^{12} \frac{p^2}{P_Y}$$ p (mm): monthly precipitation P_Y (mm), annual total precipitation $FI_m < 1300$: uniformity $1300 \leq FI_m < 1800$: fairly poor uniformity $1800 \leq FI_m < 2200$: poor uniformity $2200 \leq FI_m < 2500$: irregularity $2500 \leq FI_m < 2700$: fairly high irregularity $FI_m > 2700$: high irregularity	Rainfall	Do the expected rises in average air temperatures mean precipitations more unevenly distributed throughout the year?	Uneven distribution decreases the extent of effective rainfall. It can be used to estimate the rainfall erosivity.	FAO/UNEP (1977)
Mediterraneity index $$MI_2 = \frac{P_w}{P_s}$$ P_s (mm), summer trimester (July-September in the northern hemisphere, January-March in the southern hemisphere) precipitation P_w (mm), winter trimester (January-	Rainfall	Do the expected rises in average air temperatures mean more differences between summer and winter precipitations?		Le Houérou (2004)

	March in the northern hemisphere, July-September in the southern hemisphere) precipitation $MI_2 < 1.5$: non seasonal, non-Mediterranean climate (tropical or temperate) $1.5 \leq MI_2 < 2$: sub-Mediterranean climate $MI_2 > 2$: typical Mediterranean climate				
Continentality indices	**Emberger-derived Index** Difference between the mean of the maximum temperatures of the hottest month (*M*) and the mean of the minimum temperature of the coldest month (*m*) in a year $M - m < 15$ °C: oceanic insular zones $15 \leq M - m < 25$ °C: lowland littoral zones $25 \leq M - m < 35$ °C: semi-continental zones 35 °C $\leq M - m$: continental zones	Air temperature	Do the expected rises in average air temperatures mean a change in the annual variation of temperature?	Evaporation is represented by the temperature range "*M* - *m*" because it frequently increases with it. More continental climate is characterized by cold winters and hot summers. Less continental climate may mean relatively cool summers and relatively moderate winters.	Emberger (1930)
	Gorczinski Index $K = \frac{1.7 \cdot A}{\sin(L)} - 20.4$ *A* (°C), difference of monthly mean temperature of warmest and coldest month *L* (°), absolute value of the latitude	Air temperature		It is affected by the annual cycle of incoming solar radiation, which depends on latitude.	Gorczinski (1920)

	(out of the range of ±10 degrees) $K \leq 12.4$: maritime $12.4 < K \leq 18.4$: weakly maritime $18.4 \leq K < 27.4$: neutral $27.4 \leq K < 33.4$: weakly continental $33.4 \leq K$: continental				
Aridity Indices	**De Martonne-Gottmann Index** $b = \frac{1}{2} \cdot \left(\frac{P_Y}{T_Y + 10} + 12 \cdot \frac{p_a}{T_a + 10} \right)$ P_Y (mm), annual precipitation T_Y (°C), mean annual air temperature p_a (mm), precipitation of the most arid month T_a (°C), mean air temperature of the most arid month $b < 5$: extreme aridity $5 \leq b \leq 14$: aridity $15 \leq b \leq 19$: semi-aridity $20 \leq b \leq 29$: sub-humidity $30 \leq b \leq 59$: humidity $b > 59$: strong humidity	Air temperature, rainfall	Do the expected rises in average air temperatures and changes in precipitation/solar radiation/evapotranspiration patterns mean an expansion of arid conditions?	These indices indicate the relative dryness of an ecosystem and thus contain vital information regarding the crops that can be grown in the area. Temperature increases are likely associated with stronger and more prolonged drought periods and a northward extension of arid conditions (desertification). Soil structure may be degraded due to reduction in organic matter. The resultant decrease in aggregate stability would lead to reduced water retention and increased erodibility of soils. The potential for erosion (both through water and wind) raises particularly in relation to bare soils in dryer autumns.	De Martonne (1942), Diodato and Ceccarelli (2004)
	Budyko Index $Q = \frac{R_n}{\lambda \cdot P_Y}$	Solar radiation, rainfall			Budyko (1974)

R_n (MJ m^{-2} year^{-1}), annual sum of net solar radiation (~$0.45 \cdot R_g$, annual sum of incoming solar radiation, MJ m^{-2} year^{-1}) $Q \leq 1.0$: no water deficit $1.0 < Q \leq 3.4$: limited water deficit $3.4 < Q \leq 10.0$: severe water deficit $Q > 10.0$: desert climate		
Desertification Index $I_D = \frac{P_Y}{ET_Y}$ P_Y (mm), annual total precipitation ET_Y (mm): annual total reference evapotranspiration $I_D < 0.05$: very arid $0.05 \leq I_D < 0.20$: arid $0.20 \leq I_D < 0.50$: semi-arid $0.50 \leq I_D$: dry sub-tropic	Evapotranspiration, rainfall	UNEP (1992)
Moisture Index $I_M = \frac{W_S - W_D}{ET_Y}$		Carter and Mather (1966)

W_S (mm), annual surplus of water (sum of positive differences between precipitation and reference evapotranspiration)

W_D (mm), annual deficit of water (sum of negative differences between precipitation and reference evapotranspiration

ET_Y (mm): annual total reference evapotranspiration

$I_M < -66.7$: arid
$-66.7 \leq I_M < -33.4$: semi-arid
$-33.4 \leq I_M < 0$: dry sub-humid
$0 \leq I_M < 20$: moist sub-humid
$20 \leq I_M < 100$: humid
$100 \leq I_M$: perhumid

References

Barnett, C., J. Hossel, M. Perry, C. Procter, and G. Hughes. 2006. A handbook of climate trends across Scotland. Scotland and Northern Ireland Forum for Environmental Research, SNIFFER Project CC03, Edinburgh, United Kingdom.

Budyko, M.I. 1974. Climate and life. Academic Press, New York, USA.

Carter, D.B., and R. Mather. 1966. Climatic classification for environmental biology. C.W. Thornwaite Association, Publications in Climatology, 19:305-395.

Confalonieri, R., Bellocchi, G., Donatelli, M. 2010. A software component to compute agrometeorological indicators. Environmental Modelling & Software, 25, 1485-1486.

De Martonne, E. 1942. Nouvelle carte mondiale de l'indice d'aridité. Annales de G éographie 51:242-250.

Emberger, L. 1930. Sur une formule applicable en g éographie botanique. Comptes Rendus de l'Academie des Sciences de Paris, 19:389-390.

FAO/UNEP. 1977. Assessing soil degradation. In: FAO Soils Bulletin, vol. 34, FAO, Rome, Italy.

Gorczinski, W. 1920. Sur le calcul du degré de continentalisme et son application dans la climatologie. Geogr. Annaler 2:324-331.

Le Houérou, H.N. 2004. An agro-bioclimatic classification of arid and semiarid lands in the isoclimatic Mediterranean Zones. Arid Land Research and Management 18:301-346.
Matthews, K.B., Rivington, M., Buchan, K., Miller, D., Bellocchi, G., 2008. Charecterising and communicating the agro-meteorological implications of climate change scenarios to land management stakeholders. Climate Research, 37, 59-75.
Stone, D.A., A.J. Weaver, and F.W. Zwiers. 2000. Trends in Canadian Precipitation Intensity. Atmosphere-Ocean 38:321-347.
UNEP. 1992. World atlas of desertification. Edward Arnold, London, United Kingdom.