CHAPTER 14

AGROMETEOROLOGICAL ASPECTS OF DESERTIFICATION

14.1 INTRODUCTION: DESERTIFICATION AND WMO

Desertification is a highly complex set of events that poses serious threats to the environment and to the socio-economic well-being of people in various parts of the world, and climate can be a contributing factor to this process. In a general sense, the term "desertification" refers to land degradation in the Earth's dry zones. In the process of land degradation, dryland areas become much less biologically productive. Desertification can be caused by multiple interacting factors of climatic, socio-economic and ecological origin that play out through a myriad of pathways in different locales. As such, it has been difficult to precisely define the term, and over 100 formal definitions exist (Geist, 2005). The most commonly accepted definition today is that given by the United Nations Convention to Combat Desertification (UNCCD): "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities" (UNEP, 1994). Land degradation can occur in any climate, however, and some authorities call for a modified definition that encompasses all climates or better accounts for the role of plant/soil relationships in measures of aridity (for example, Riábchikov, 1976; Instituto de Meteorología, 1999; Rivero et al., 1999).

Natural oscillations in the extent of existing deserts should not be confused with desertification (UNEP, 1992). Expansion and contraction of deserts along their margins may occur over time due to inter-annual variations in precipitation, and are part of the natural spatial variability of most deserts. On the other hand, remote patches of land in dry zones sometimes hundreds of miles from deserts may become degraded and ultimately coalesce to form larger areas of desertified land. Physical attributes of such degraded land are numerous and include reductions in:

(a) perennial plant biomass;
(b) biological productivity;
(c) ecosystem biodiversity;
(d) soil fertility;
(e) stored plant and animal litter;
(f) soil organic matter;
(g) protection of soil from wind and water erosion;
(h) soil water-holding capacity, sometimes with salinization of soils or groundwater.

The resulting transformations may benefit some organisms over others, and generally result in reduced livelihood opportunities for humans, especially for the production of crops and livestock. Reduced economic output is a negative outcome from the perspective of humans. Human value judgments are at the core of the concept of desertification.

Dryland environments comprise approximately 6.1 billion ha, or about 47 per cent of all land area. Approximately 84 per cent of this area falls within the arid, semi-arid and dry sub-humid climates that are inherently susceptible to desertification (UNEP, 1997). Estimates vary widely, but about 10–20 per cent of the susceptible drylands are believed to have already undergone land degradation (Millennium Ecosystem Assessment, 2005). In 1996 the UNCCD Secretariat estimated that the livelihoods of approximately one billion people in over 100 countries are at risk from desertification, and over 250 million people are directly affected. The UNCCD notes that desertification appears to preferentially affect "the world's poorest, most marginalized and politically weak citizens" (UNCCD, 2006). Annually across the globe, it is estimated that desertification results in the direct loss of US$ 42 billion in foregone income from agriculture (Dregne and Chou, 1992). This figure does not include the likely higher costs associated with indirect economic and social impacts (for example, out-migration to other areas, health impacts, political instability, human suffering). Problems caused by desertification are not new, and are believed to be at the root of the collapse of a number of ancient societies, including those in the south-west Asian fertile crescent, upland steppe plateaus of northern China and the Tehuacán Valley of Mexico. The consequences of desertification may expand in the future, as a projected 2.0°C–4.5°C rise in global average temperature and an increase in land area affected by droughts are expected by the year 2100 (IPCC, 2007).

Desertification threatens the sustainability of land, and is believed to be one of the most serious global environmental problems. The World Meteorological Organization (WMO), as a United Nations specialized agency addressing human welfare in relation to the Earth's atmosphere, climate and water resources, considers desertification issues a high priority in its operations. In efforts to combat desertification, it has been active in improving meteorological observing networks, research and prediction capabilities related to climatic drivers of desertification; drought preparedness and mitigation plans; and knowledge transfer programmes. The purpose of this chapter is to discuss climate in relation to drylands and desertification – fundamental processes, interactions, agrometeorological interventions and WMO roles – with a view towards promoting sustainable use of global drylands.

14.2 A GLOBAL SURVEY OF DESERTIFICATION AND ITS CAUSES

14.2.1 Drylands

This section draws heavily on a report on drylands by the Food and Agriculture Organization of the United Nations (FAO, 2004). Drylands prevail where water deficit occurs to some extent throughout a hydrological year, and may be classified on the basis of aridity. The aridity index is assessed on the basis of climate variables using the ratio of annual average precipitation to potential evapotranspiration (P/PET). According to the *World Atlas of Desertification* (UNEP, 1992, 1997), drylands have a P/PET ratio of less than 0.65 and precipitation of less than 600 mm per year. The aridity index uses the P/PET to classify drylands into hyper-arid, arid, semi-arid and dry sub-humid areas (Table 14.1). In the context of agrometeorology, FAO also assesses aridity based on how many days the water balance allows plant growth (the growing season). A negative balance between precipitation and evapotranspiration usually results in a short growing season for crops (less than 120 days). Alternatively, delimitation of climate zones can also be carried out by adopting Koeppen's classification scheme or the ecological dryness index, which relates productivity of ecosystems to actual and potential evapotranspiration (AET/PET). Useful examples are available in the scientific literature with respect to crop yields (Doorenbos and Kassam, 1988) and for natural ecosystems (Riábchikov, 1976).

Although arid zones are not restricted to any particular regions, most arid land areas of the world where agriculture is of relevance are located between latitudes 20° and 35° north and south. The main semi-arid areas occupy each side of the arid zone and include both Mediterranean-type and monsoonal-type climates. Hyper-arid and arid zones extend mostly across the Saharan, Arabian and Gobi deserts; sedentary agriculture is localized around major water bodies, as in the Nile Valley and the Nile Delta, or is intensively irrigated. Another type of dryland is the cold desert, which generally occurs in high-latitude or high-altitude continental areas and is not considered further in this chapter. Overall, Africa and Asia have the largest expanse of arid zones, accounting for almost four fifths of hyper-arid and arid zones in the world (see Figure 14.1). By definition, desertification only applies to dryland regions, despite degradation of land in other climates occurring through similar processes. Hyper-arid regions are generally not considered in discussions of desertification because, as a rule, there is no crop growth unless under intensive irrigation.

Soils are an important resource of drylands for provision of food in these areas. They provide the

Table 14.1. Dryland categories according to the aridity index classification scheme

P/PET	*Rainfall (mm)*	*Classification*	*Increasing aridity*
<0.05	<200	Hyper-arid	↑
0.05 – <0.20	<200 (winter) <400 (summer)	Arid	
0.20 – <0.50	200–500 (winter) 400–600 (summer)	Semi-arid	
0.50 – <0.65	500–700 (winter) 600–800 (summer)	Dry sub-humid	

Winter – defined as the period December to February
Summer – defined as the period June to August

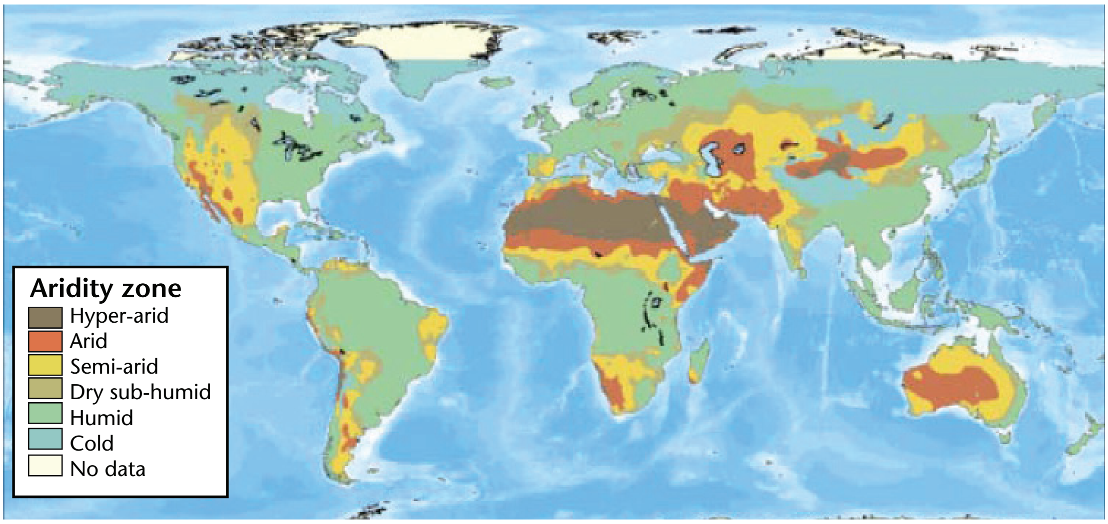

Figure 14.1. Global distribution of drylands based on the aridity index (UNEP, 1997)

medium in which plants grow and their properties determine proportions of precipitation available for plant growth. While dryland soils vary considerably, they principally comprise aridisols and entisols, along with others including alfisols, mollisols and vertisols (Dregne, 1976). Dryland soils are characterized by frequent water stress, small water-holding capacity, low organic matter content, susceptibility to erosion and low nutrient content, particularly in nitrogen (Skujins, 1991). Vegetation supported by these soils ranges from barren or sparsely vegetated desert to grassland, shrubland and savanna or dry woodlands. Forest vegetation is sparse, with species adapted to arid soils and high water use efficiency. Plants that have adapted to drylands survive irregular rainfall, high solar radiation and periods of drought. Indeed, many plants have well-adapted strategies or characteristics to cope with the overall aridity and periods of drought (which can be defined as periods – 1 to 2 years – when rainfall is below average), such as deep root systems, waxy leaf surfaces and specific germination and life cycles. Dryland plants are also adapted to windy conditions with very low values of relative humidity. Plants also fulfil a dual role in that they protect soil surfaces from wind and water erosion and also help to stabilize mobile dune systems. Removal or loss of vegetation cover results in an increased risk of soil erosion and land degradation.

The predominant land use of drylands is agriculture, specifically pastoralism and subsistence food production. Typical crops grown under rainfed conditions are presented in Table 14.2 (FAO, 1993). A combination of meteorology (rainfall, temperature, radiation), climate and soil characteristics (water-holding capacity, organic matter content) coupled with low germination rates and high seedling mortality, results in very low plant productivity for sedentary agricultural systems in drylands. Indeed, a major constraint on agricultural development is low and highly variable

Table 14.2. Typical crops grown in drylands under rainfed conditions

Classification	*Growing season (days)*	*Typical crops*
Hyper-arid	0	No crop, no pasture
Arid	1–59	No crops, marginal pasture
Semi-arid	60–119	Bulrush millet, sorghum, sesame
Dry sub-humid	120–179	Maize, beans, groundnut, peas, barley, wheat

rainfall. Where natural and/or anthropogenic land degradation and desertification occurs, especially when these processes encroach onto marginal semi-arid environments, further environmental stress is added to cultivation and rangeland agricultural practices. Traditional systems of rainfed cropping that cope with low and erratic rainfall have evolved, however. In drier regions, livestock grazing, with regular seasonal movements, usually predominates. In areas where reasonable levels of rainfall occur and soils are relatively deep, rainfed agriculture is generally practised. Normally, several crops are sown in order to reduce the risk of total crop failure. Other agricultural strategies include the use of drought-resistant/adapted crop varieties, long fallow periods and soil protection by vegetation or other material (such as mulch or stones).

14.2.2 Causes of desertification

Although there is a widespread awareness that desertification threatens the livelihood of many people in the world's drylands, the causes of desertification remain controversial (Helldén, 1991; Lambin et al., 2001). The UNCCD definition of desertification emphasizes two main causative factors: climatic variations and human activity. It could be argued, however, that the real cause of land degradation in drylands is the removal of the natural vegetation cover. Dryland vegetation is important for maintenance of soil fertility and moisture, and for protection of the soil against destructive forces of wind and rainfall. But why does the vegetation cover become degraded? Many factors can contribute to the removal of vegetation cover. Traditionally, drought, overgrazing by livestock and exploitive use of vegetation have been blamed for dryland degradation (Dregne et al., 1991). Other factors linked to desertification include poor irrigation practices that result in soil salinization or waterlogging, overcultivation of soils, excessive pumping of groundwater and spread of bush fires.

Drought is an intrinsic feature of the world's drylands. Drought refers to a period with below-average rainfall, which can occur within a year, but multiple years may have abnormally low rainfall as well. In drylands, the natural vegetation is adapted to periods of water scarcity, and usually vegetation will quickly recover after a drought period (ecosystem resilience). In the case of a multiple-year drought (like the one during the 1970s in the Sahel), the recovery is much slower. Trees and shrubs may have died, and it may take years for the vegetation to recover. It does not necessarily follow, however, that drought per se will give rise to or cause desertification in drylands (Darkoh, 1998). Much depends on the land management practices, which either weaken or improve the resilience of the soils and natural vegetation.

In the 1970s, Charney (1975) related the Sahelian drought to a positive climate–land cover change feedback mechanism. He speculated that overgrazing causes less vegetation cover, which increases the surface albedo. Less solar radiation is absorbed and the Earth's surface becomes cooler, leading to less precipitation and a further decline in vegetation cover. In a recent study, however, Giannini et al. (2003) showed that oceanic forcing played an important role in the Sahelian drought. Sahelian rainfall is closely related to a tropical sea surface temperature anomaly pattern that spans the Pacific, Atlantic and Indian oceans. This is not to say that sea surface temperatures are the whole story. There could be additional land–atmosphere feedback mechanisms that enhance drought conditions initiated by sea surface temperature anomalies (Zeng, 2003). But at this point the role played by changes in land use and vegetation cover in climate variability and change is poorly understood and will require more research.

Global climate change could result in more frequent and prolonged droughts in the world's drylands. But it remains unclear what the exact impact of global climate change will be in the drylands (WMO, 2003*a*). This obviously may differ from region to region, and could result in more favourable conditions in some places and worse conditions in other areas. For example, recent model predictions for Sahelian Africa range from increasing precipitation (Haarsma et al., 2005) to more dry conditions (Held et al., 2005). Despite such contradictory model predictions, most climatologists seem to agree that weather will become more extreme, with higher temperatures, stronger winds and more erratic rainfall patterns (WMO, 2003*a*). If drought increases in a certain region, this could result in shifts of entire vegetation zones. If the number of people relying on the land in those areas remains the same, drought will enhance the risk of desertification, and adapted land management that reduces vulnerability to more erratic rainfall and drought will be needed.

Livestock keeping is traditionally an important economic activity in many dryland areas. When the land is non-degraded, grazing can be sustainable as long as livestock numbers are relatively low. But in many of the world's drylands, rural populations have grown substantially over the last decades, leading to increased livestock numbers. At the same time, much former rangeland was converted into cropland. When populations and land pressure increase, grazing may lead to degradation of the rangeland vegetation, and soils can become prone to wind and water erosion processes. Overgrazing often occurs around wells or other places where the herds gather for drinking. This somewhat negative view of livestock grazing as a cause of serious vegetation degradation was reconsidered during a conference on soil fertility management in West Africa (Renard et al., 1998). The meeting concluded that "livestock are no longer described as agents of destruction but instead as agents of positive change. Rather, livestock is a crucial and integral part of the soil fertility cycle; principal vectors of nutrient redistribution across the landscape" (Webb, 1998). Hence, in many cases livestock grazing should not be blamed for causing desertification. Livestock keeping is an integral part of the land use in drylands, and only contributes to land degradation if the animal numbers exceed the threshold for sustainable use of the land. The latter may vary from location to location, depending on soils, climate and land management practices, and it is therefore difficult to determine when and where overgrazing is a serious problem.

Another factor that has been blamed for causing desertification is the removal of natural vegetation by local communities. Wood is needed for construction and for fuel, and growing population numbers increase the demand for wood. Also, the expansion of cropland has often caused clearance of trees and shrubs. But again, the destruction of natural vegetation by local communities is a more complicated issue than previously thought. While deforestation for fuelwood and charcoal production can have serious effects, recent research has shown that these effects are usually confined to densely populated settlement areas (Darkoh, 1998). Little evidence exists to suggest that rural household energy consumption is responsible for large-scale deforestation. Instead, it is the urban demand, usually for charcoal, that is responsible for deforestation of large rural areas. The economic value of charcoal makes it an interesting commodity for entrepreneurs who can derive income from its production and distribution (Darkoh, 1994).

It is tempting to conclude that an expanding rural population is the ultimate driving force behind vegetation degradation and desertification. The dependence of more people on the resources in an area exerts more pressure on those resources. Sometimes the pressure is indirect, such as in the case of a high demand for charcoal in urban areas. But the causes of desertification are complex, and the relationship between population growth and desertification is not clear-cut (UNCCD, 2005). Other factors can be of equal importance. For instance, poverty prevents people from investing in improved land management and rehabilitation, often resulting in soil-mining practices. Also, national policies may be more oriented towards cash crop production than towards maintaining the self-sufficiency of agricultural production systems in many dryland zones. Other human factors may also contribute to desertification problems. Examples are unfavourable land tenure arrangements, which may lead to insufficient investments in the land, or war zones, which can cause large-scale migration and the establishment of refugee camps, such as in Darfur, western Sudan, where thousands of people fled the country and settled in refugee camps in neighbouring Chad. Such concentration of many people in a small area places great pressure on the surrounding land, especially when wood is collected for fuel and construction material.

Basically, the human causes of desertification are not fully understood. Changing paradigms and varying views among researchers mean that there is no consensus yet on how human factors play a role in desertification (Darkoh, 1998). According to Geist and Lambin (2004), a limited suite of recurrent core variables, of which the most prominent are climatic factors, economic factors, institutions, national policies, population growth and remote influences, drive desertification. These factors give rise to cropland expansion, overgrazing and infrastructure extension. For each location, a set of causal factors, in combination with feedback mechanisms and regional land use, make up specific pathways of land change that could trigger desertification.

Desertification can be considered and studied at different spatial scales, varying from arable fields (microscale) to the scale of entire nations (macroscale). When studying desertification at those different spatial scales, several processes may act as the causative factors driving desertification. In addition, indicators of desertification may depend on the scale that is considered. Table 14.3 summarizes major causes and indicators of desertification at three different spatial scales.

14.2.3 Distribution of areas affected by desertification and relative importance of causes

Arid zones occupy a diverse range of regions on Earth and are not restricted by latitude, longitude

Table 14.3. Desertification causes and indicators at different spatial scales

Spatial scale	*Desertification*		
	Natural causes	*Human causes*	*Indicators*
Macroscale (2 000–10 000 km)	Global climate change Increasing drought Shift of vegetation zones	Large-scale migration Population increase	Land use changes Reduced vegetation cover
Mesoscale (2–2 000 km)	Local climate change Disturbed rainfall patterns Increasing temperatures	Population increase Forced migration Settlement of herders Deforestation Urbanization	Reduction in forest cover Decrease in grasslands Increase in cropland Declining yield statistics Sediment load in rivers Duststorm frequency
Microscale (<2 km)	Erratic rainfall pattern Increased temperatures More extreme events Disturbed water balances Increased erosion	Poor land management Bad irrigation practices Soil nutrient depletion Tree removal Overgrazing	Poor vegetation cover Low crop yields Water erosion features Wind erosion features Crusted soils Bare soils

or elevation (see Figure 14.1). For example, China has both the highest desert, the Qaidam Depression at an altitude of 2 600 m, and one of the lowest deserts, the Turpan Depression, at 150 m below sea level. This ubiquitous distribution of arid regions indicates potential widespread vulnerability of environments to desertification processes from various human and natural factors. Figure 14.2 provides at least some indication of the potential vulnerability of areas to desertification and its global pattern (after USDA-NRCS, 1998). There are many uncertainties regarding the extent, causes and seriousness of desertification, however. For example, in terms of desertification vulnerability, what criteria should be used to identify vulnerability to desertification? Emphasis, for the environmental scientist, is usually centred on physical processes, such as potential for wind erosion, water erosion or changes in vegetation cover. For social scientists investigating desertification, however, human factors such as

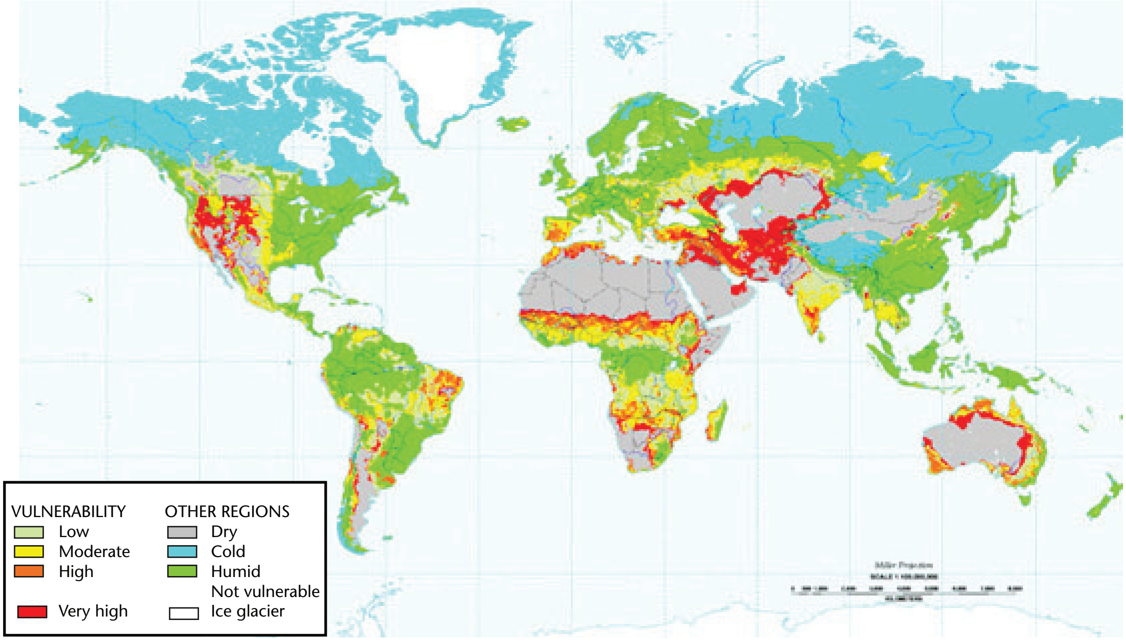

Figure 14.2. Global distribution of desertification vulnerability based on reclassification of the global soil–climate map and global soil map (USDA–NRCS, 1998)

political stability, demographics, poverty, market and trade systems, and technological utilization also affect processes of desertification and are normally absent from maps of desertification vulnerability. Indeed, despite large global assessments and international policies that have been initiated and developed in response to desertification (for instance, the Global Assessment of Human-Induced Soil Degradation (GLASOD), the United Nations Environment Programme (UNEP) and UNCCD), the phenomenon is still poorly documented and largely unmeasured. The extent and severity of desertification, vulnerable locations and the dynamics of desertification under future climate change scenarios are poorly understood at the global scale (Dregne, 2002). Furthermore, previous global assessments have been restricted to a large extent by disagreement over the definition and criteria for scientific investigation of desertification. A lack of synthesis among scientific disciplines regarding the complexity of causes and effects of desertification has also limited understanding of desertification, in terms of both natural and anthropogenic factors. Such institutional and scientific limitations have hampered policy development and planning for mitigation in areas experiencing desertification, and measures to reduce desertification risk in locations vulnerable to land degradation. A more recent global programme on land cover change – the Millennium Ecosystem Assessment (MEA) – has attempted to provide a more focused assessment of land cover change to meet the needs of decision-makers, government bodies and the public. The MEA has been charged with providing scientific and practical information for the sustainable management of ecosystems for human well-being. Its approach differs in many respects from previous global programmes in that it is performing multiscale and diverse assessments of land cover change, from the village level to a global scale. In addition, findings conducted at a given scale are informed by the assessments at other scales, which further emphasizes the diverse range of causes associated with land degradation.

While the causes of desertification are numerous and complex, one can conclude that desertification is driven by a limited group of core variables, which are above all climatic, technological, political (both institutional and policy-based) and economic factors. While drylands exist naturally because of background environmental conditions (such as atmospheric circulation patterns or sea surface temperatures), additional influences of human-induced land degradation (including deforestation, overgrazing, and salinization in irrigated areas) or changes in climate encourage desertification through expansion of dryland ecosystems in marginal areas. Therefore, the relative importance of these natural and anthropogenic factors in affecting the global distribution of desertification can vary and is dependent upon pressures faced by people and agricultural systems in a particular location. To highlight this, two examples of the relative importance of different factors influencing the distribution of desertification in different areas of the Earth (Southern Africa and northern China) are described below:

(a) Southern Africa: Relative impacts of changes in aridity, temperature and rainfall can alter the extent and seriousness of desertification. Arid regions are principally formed as a result of atmospheric circulation, through development of semi-permanent high-pressure systems formed by cool descending air from the poleward flow of air from the Equator (around 30° north and south latitude). In the context of climate change, changes in patterns of atmospheric circulation may intensify and broaden desert areas, resulting in an expansion of desert-type conditions. For example, episodes of aridity and changes in rainfall variability on the African continent linked to fluctuations in large African desert basins (such as the Kalahari and Namib deserts) have been shown to be connected with changes in sea surface temperatures, influencing both atmospheric moisture content and the strength of the African monsoon (Stokes et al., 1997; Washington et al., 2003). Such changes in aridity driven by sea surface temperatures in the tropical Atlantic have been identified with large-scale changes in African vegetation and episodes of desertification (Schefuss et al., 2003). Therefore, relative changes in sea surface temperatures as a result of future climate change or variability may affect arid regions controlled by such teleconnection mechanisms, and result in changes to vegetation cover and aridity for agricultural systems.

(b) Northern China: From the point of view of desertification in the arid and semi-arid regions of northern China, population pressure, intensive agriculture and industrialization, combined with natural processes of wind and water erosion, have affected spatial distributions of desertification (Yuxiang and Yihua, 1993; Zhenda and Wang, 1993). Research by Zhenda and Wang (1993) indicates that since the mid-1980s annual spread rates of desertified land have varied between 2 and 10 per cent of the total area of dry farmland areas and grasslands in northern China. Agropastoral regions, desert steppes and marginal zones (such as oases and inland rivers) have experienced expanding desert conditions with up to 40.5 per cent of the land area classified as desertified. In particular, open coal mining has aided extreme and rapid desertification of the Shenfu region, with the total area of desertified land in the Shenfu coalfield estimated at 62 per cent.

Further examples of the distribution of desertification and the relative importance of its causes can be seen in salinization in the Middle East (for example, Sombroek and Sayegh, 1992) and in the anthropogenic and natural effects in the Sahel region of Africa (for example, DECARP, 1976; Kassas, 1991; Hulme, 2001).

14.3 DRYLAND SURFACE CLIMATE AND AGROMETEOROLOGICAL PRACTICE

14.3.1 Understanding the dryland surface climate

Desertification involves actions that occur at the Earth's surface. The surface climate is an integral component of the surface environment that both shapes and is shaped by land degradation (Williams and Balling, 1996; WMO, 2005). Surface climates are largely characterized by exchanges of moisture or water, energy and momentum (for instance, wind) occurring at or near the Earth's surface. These events play key roles in the physical processes of desertification.

14.3.1.1 Water in the surface environment

Water movement within the near-surface dryland environment can be described by the terms of the water balance equation (see 14.2.3) (WMO and UNEP, 1983; Mather, 1984; WMO, 1992; Thompson, 1999). Rainfall is the chief form of precipitation in drylands, although moisture from fog (Seely, 1978) and dew (Evernari, 1985) can be a significant source in some areas. Precipitation variability is high in many dry environments and episodes of drought alternate with periods of normal and above-normal precipitation. Some drylands are even subject to seasonal flooding. The result of these factors is that vegetation and the accompanying erosion-thwarting leaf litter tend to be sparse. With little organic matter added to the soil, humus is largely unavailable to maximize soil moisture retention or to promote binding of individual soil particles into aggregates that more fully resist erosion. In addition, low levels of soil aggregation reduce the proportion of large pores in soil that aid water infiltration and prevent erosive overland flow. Thus, the erosion potential of drylands is high. Any actions by humans that reduce the vegetation cover or compact the soil decrease water infiltration and increase overland flow, thus raising the susceptibility to land degradation.

Rainfall, especially the high-intensity rainfall that may occur in drylands during severe thunderstorms, is the most important contributor to erosion (WMO, 2005). Heavy rainfall has a greater impact at the start of the growing season, when less protective vegetation is present. The force of heavy rainfall may act to dislodge soil particles, which then may be carried away in overland flow. Small, light soil particles are more easily moved, and when transported in sufficient quantities in storm events, may later act to seal the soil surface. In this process, fine-grained clay and silt particles clog the surface. A surface crust then develops as the soil dries (Farres, 1978; WMO, 2003*b*). This process further reduces infiltration of water into the soil. High rates of erosion reduce the soil profile depth, in turn reducing the total amount of soil moisture that can be stored. This means that the land becomes more prone to drought and floods.

Land degradation can occur either during drought or wet periods. Drought may result in increased wind and water erosion as a result of vegetation loss, even as agricultural and other economic demands on the land remain. Pressure on better-watered land may increase during drought, causing land degradation that may become highly apparent when drier times return. During wetter periods, high rainfall can erode poorly vegetated or damaged soils. The tendency is to increase agricultural production during wetter periods, again with consequences that manifest themselves when rainfall declines (Gonzalez Loyarte, 1996).

Surface evaporation from dryland soils may result in soil salinization – the accumulation of salts at the soil surface and in the root zone. Dryland soils are naturally high in salt content due to low amounts of percolating soil water available to leach the salts out of the soil layer. Human-caused salinization may occur due to (Szabolcs, 1976):

(a) Introduction of additional salts to the soil layer through irrigation water;

(b) An increase in the height of groundwater, which then permits transport of salts from deeper soil layers to the root zone through the upward motion of groundwater under capillary suction;

(c) Ineffective drainage of irrigated soils, which impedes loss of soil salts through leaching.

The consequence of salt build-up is the loss of protective vegetation and agricultural production. Salinization of water supplies and soils along coastal areas, particularly for small islands, may become problematic with a potential climate warming and sea-level rise.

14.3.1.2 Energy in the surface environment

Energy interactions in the surface environment can best be summarized through the energy balance equation for the Earth's surface,

$$(Q + q)\,(1 - \alpha) - (I_u - I_d) - H - LE - G = 0 \quad (14.1)$$

where Q and q are the direct and diffuse portions, respectively, of short-wave radiation reaching the Earth's surface; α is the surface albedo (fraction of incoming short-wave energy reflected from the surface); I_u is long-wave radiation emitted by the Earth's surface towards the overlying atmosphere; and I_d represents long-wave radiation emitted from the overlying atmosphere towards the Earth's surface. The balance of these radiative terms (net radiation) determines the amount of energy available at the surface for heating and evapotranspiration. Thus, H represents the sensible heat flow between surface and atmosphere, LE represents latent heat flow (incorporating the energy involved in evapotranspiration and condensation) between surface and atmosphere, and G is the ground heat flow. Positive terms represent energy directed towards the Earth's surface. Photosynthesis is assumed to be negligible.

Direct and diffuse radiation together are typically high in most drylands due to the low cloudiness of such environments. Net radiation is also high, even though albedos for desert soils are higher than for most other vegetated surfaces (Oke, 1988). The high dryland albedo is partially attributed to the lack of a well-developed vegetation canopy, the structure of which contributes to particularly effective interception of incident short-wave radiation.

High net radiation values mean more energy for work at the surface, such as heating and evapotranspiration. Evapotranspiration rates are usually low, however, owing to the limited environmental moisture. What little water exists is rapidly evaporated, leaving less stored soil moisture for plant use. Due to limited water availability, most energy is partitioned into heating of air and soil. High surface soil temperatures may result in cracking of clayey soils, leaving both soil surface and subsurface open to erosive forces.

Human use of drylands may result in a modification of the surface energy balance. A significant change of albedo may occur due to changes in land use, removal of vegetation, or degradation of soil. Irrigation is used to enhance soil moisture for agriculture, resulting in increased evapotranspiration and lower surface temperatures. Agriculture, soil degradation, loss of vegetation cover and burning of various fuels release carbon dioxide and other trace gases into the atmosphere, which may intensify incoming long-wave radiation from the atmosphere. Various activities that promote wind erosion can result in a substantial load of wind-blown dust, with implications for stability of the lower atmosphere (Williams and Balling, 1996; WMO, 2005). Remotely sensed imagery has revealed that Saharan dust is sometimes blown across the Atlantic Ocean to the Caribbean Islands, where it has been linked to human illnesses, algal blooms and the decline of the coral reefs. Thus, impacts of desertification may extend beyond the source region with important global ramifications.

14.3.1.3 Momentum in the surface environment

The mean wind speed at the near surface can be described as

$$U(z) = (u_*/k)\ln(z/z_0) \quad (14.2)$$

where $U(z)$ is the mean wind speed at height z, k is von Kármán's constant (about 0.4), and z_0 is the roughness parameter, a measure of the aerodynamic roughness of the surface. The value u_* represents the friction velocity, which is equal to the square root of the sheering stress divided by the air density.

Surface winds may act as a surface erosive force or modifier of the terms of the energy balance. With vegetation removal, changes to the surface roughness may result in enhanced wind speeds or mechanical turbulence, each of which could act to increase transport of sensible and latent heat into the overlying atmosphere. In addition, advection (horizontal transport) of hot air over irrigated fields in drylands may create an oasis effect in which downward transport of energy can result in a considerable evaporation of irrigation water from fields. Finally, wind can act as an erosive force, carrying soil and dust into the overlying atmosphere. Wind-generated duststorms can significantly block incoming solar radiation to the surface, resulting in a significant drop-off of net radiation available for heating and evapotranspiration. The lighter soil fractions (such as clay and silt) are preferentially eroded, leaving behind a course-textured soil (high in sands and pebbles) that has a smaller soil moisture-holding capacity.

14.3.2 Application of agrometeorological practices to the surface environment

Combating the root causes of desertification often requires addressing interrelationships among climate and economic, political and social drivers of land degradation. While amelioration of problems of a socio-political or socio-economic nature may require long-term efforts, a variety of readily available agrometeorological methods to address the biophysical concerns of desertification at the farm and local levels are possible and are discussed in the present publication. Other strategies that are implemented on regional to international scales, including drought preparedness, early warning and agroclimatic mapping, are covered in 14.4, 14.6.5 and 14.6.6.

The aim of agrometeorological practice as applied to the surface environment is to maintain the surface climate within a range of conditions to promote:

(a) Protection of the soil surface through maintenance of good soil structure and resistance to erosion;
(b) Efficient use of available rainwater and snowmelt, with consideration given to the advisability of surplus water storage;
(c) The success of natural plant and crop productivity;
(d) High carbon and nutrient maintenance within the plant biomass, leaf litter and soil matrix;
(e) Ecosystem stability and biodiversity.

As implied in these objectives, prevention of land deterioration is preferable to reversal of already-degraded land. Desertified land may be resistant to treatment measures. Furthermore, the costs of desertification are high, considering the expense of rehabilitation efforts and loss of ecosystem services and economic productivity (Millennium Ecosystem Assessment, 2005). A variety of agrometeorological techniques may be applied to prevent and treat soil erosion, improve water use efficiency and make appropriate land-use choices (Table 14.4). Optimal interventions for particular places must take into account local needs, traditions and environmental knowledge, and involve recipient communities in the decision-making process. In such an approach, the agrometeorologist is seen as more of a facilitator than a prescriber of solutions (Scoones, 1997).

Table 14.4. Examples of mitigation strategies employed over various scales

Macroscale (2 000–10 000 km) International strategies	*Mesoscale (2–2 000 km) National/ regional strategies*	*Microscale (<2 km) Practices of communities or individual farmers*
United Nations Convention to Combat Desertification (UNCCD): International cooperation in research, education and combating desertification Inter-Agency Task Force on Disaster Reduction: Statement on short-term climate variability/ climate extremes European Commission Thematic Strategy for Soil Protection: Measures for combating soil erosion and policy options for prevention and remediation	National action programmes: National long-term strategies and practical measures to support UNCCD Vegetation policies: Laws prohibiting the cutting of vegetation in northern Burkina Faso Windbreak schemes: Shelter belts of scattered trees and grasses over a large area to settle wind-blown sand in central Sudan (Stigter et al., 2005*b*) Reforestation schemes: Development of forest reservations and roadside avenues in Israel on degraded lands Crop/livestock policies: Prohibition in Syria of barley production where rainfall is less than 200 mm; restriction of numbers of grazing livestock	No-till farming Crop rotation Cover crops/legume fallows Agroforestry schemes: In Kenya's Laikipia District, *Grevillea robusta* trees and *Coleus* hedges, providing shade, wind protection and increased water infiltration, were grown with maize and beans (Stigter et al., 2005*b*) Local water resource projects: When removal of gravel from Malir River, Pakistan, resulted in decreased groundwater recharge and crop productivity, public awareness was promoted and a traditional water reserve expanded

Soil conservation techniques can substantially reduce water erosion. Details of the procedures can be found in WMO (1992), Toy et al. (2002), Troeh et al. (2003) and Morgan (2005). Water harvesting, contour farming, terracing and strip cropping act to reduce the speed of surface runoff and thus erosional forces on slopes, while increasing soil moisture infiltration and storage. A variation of these techniques using local knowledge by farmers in western Africa involves placing branches and stones on fields to slow runoff and increase infiltration. In South-East Asia, hedges of tall, deep-rooted perennial grasses are planted to create a living wall on slopes. Erosional forces and raindrop impact can be reduced through the accumulation of crop residues on the soil surface, and this is one aim of reduced or no-till agriculture. In South America, the dibble stick is used to punch holes into the ground for planting seeds, leaving the rest of the surface cover undisturbed. Organic matter on the surface means increased soil humus content, fertility, and soil moisture infiltration and holding capacity.

Maintenance of soil fertility is important in providing an ample vegetation cover to protect the soil surface. While organic fertilizers have the benefit of providing both nutrition and organic matter for good soil structure, they are sometimes difficult to obtain in drylands. Integrated soil fertility management supports combined use of organic and inorganic fertilization, as well as policies that promote successful economic environments and conservation incentives for the farmer (Breman and van Reuler, 2000). Mixed farming based on both crop and livestock production promotes soil fertility through easy application of livestock manure to nearby cropland. Crop rotation prevents depletion of key soil nutrients and may even replace some lost soil nutrients.

Farmlands in windy regions may be protected from wind erosion by tree shelterbelts or other windbreaks made from grasses and other natural materials. Wind speed reductions to the lee of the structure are established over larger areas when the windbreak is taller and porous. Soil moisture is conserved as a result of reduced surface evapotranspiration (Rosenberg et al., 1983; Oke, 1988). Even scattered trees may arrest erosional processes contributing to desertification (Stigter et al., 2003, 2005*a*). Design rules for success of protective shelterbelts have been determined by Al-Amin et al. (2005). Windbreaks of various forms can also stabilize moving sand dunes, as have boulders, sand fences made from crop residues, and straw grids. Where irrigation water is available, shrubs can be planted on the dune's lower windward side, reducing wind speeds and blowing sand. Higher wind speeds at the dune top will produce a flat surface on which trees can be planted for stabilization (Walker, 1996). Stigter et al. (2002) have reported on the use of vegetation in local solutions to a variety of problems caused by wind. Careful consideration should be given to the selection of tree, shrub and grass species that can withstand drifting sand in deserts; a comparison of the performance of various types is provided in Al-Amin et al. (2006). Elephant grass (*Pennisetum purpureum*) has been planted on hillsides of East Africa, providing both forage and protection of soils.

New and traditional programmes of establishing vegetation to support soil quality, ecosystem services, raw material availability and diverse livelihoods have been employed, especially in Africa. Renewed interest in agroforestry means that trees are increasingly left or planted in fields where they are managed along with crops and livestock for their various resources. One tree species that is particularly valuable is the *Acacia albida*, which returns nitrogen to the soil and provides shading, moisture, browse and fruit. The shea butter tree (*Vitellaria paradoxa* ssp. *nilotica*) protects soils, while the seeds are used in making oil for cooking, cosmetics and chocolate (McIntosh, 2004). The Eden Foundation promotes the cultivation of perennial drought-tolerant, edible plants in Niger through a voluntary seeding programme (Eden Foundation, 1999). A Global Environment Facility–United Nations Development Programme project advances community-based integrated ecosystem management (IEM), incorporating community co-management of protected areas and community nature reserves in Senegal (Global Environment Facility, 2002). Salt- and drought-resistant crops and native vegetation with wide genetic variation provide good soil cover under numerous environmental conditions. Legumes restore soil nitrogen. Agroclimatic mapping assures that planted crops are likely to withstand prevailing climatic conditions. Loss of existing vegetation can be prevented through the promotion of careful land-use management and the use of alternative fuels, construction materials and livelihoods.

Careful management of water resources in drylands goes hand in hand with protection of soil and vegetation. Drip irrigation systems may reduce erosion from the spread of irrigation water, while reducing evaporative losses. Rainwater harvesting (Mather, 1984; Hatibu and Mahoo, 2000; Lancaster, 2006, 2007), surface and subsurface water storage

(Ludwig, 2005), floodwater spreading and fog collection maximize available water supplies. Revegetated upstream areas promote groundwater storage and streamflow during drier times. Irrigation applications should be carefully planned to avoid salinization and waterlogging. Water budgeting techniques that track soil moisture content may be useful for determining the need for and appropriate amounts of irrigation applications (Mather, 1978; CIMIS, 2009). Planting of deep-rooted trees may arrest salinization associated with rising water tables caused by excessive irrigation or vegetation removal. Subsurface drainage of waterlogged soils may be appropriate in other situations.

Agricultural techniques aimed at effective energy management through manipulation of the surface energy balance are sometimes applied to desertifying lands. Such methods as albedo control and mulching can reduce energy income and surface evapotranspiration. More detailed discussion is available in Rosenberg et al. (1983) and Lowry (1988).

Conservation agriculture (CA) is another approach to long-term protection of agricultural yields that is not focused on particular technologies per se, but on a series of conservation objectives. CA seeks to optimize, rather than maximize, yields and profits in order to "achieve a balance of agricultural, economic and environmental benefits" (Dumanski et al., 2006). This approach to sustainable agriculture combines modern technology that maintains or enhances the ecological integrity of the soil with traditional knowledge to enable adjustment to local areas and changing conditions. In general, CA promotes zero tillage, careful management of farm residues and wastes, integrated pest management, crop rotations, cover crops, balanced and precision applications of farm chemicals, legume fallows and agroforestry. Benefits include a reduction in water/soil pollution, external inputs, fossil fuel costs and soil erosion, with an enhanced soil water economy and soil biological health. Such an approach works effectively against forces of desertification.

14.4 RANGELAND MANAGEMENT

The material in this section has been drawn largely from the work of Sombroek and Sene (1993) and FAO (2004). Based on the classification of farming systems in developing regions specified by FAO/World Bank (2001), most of the farming systems in drylands fall into the category of rainfed farming systems in dry, low-potential areas. These may be characterized by mixed crop–livestock and pastoral systems that merge into sparse and often dispersed systems with low productivity or potential because of extreme aridity. Rangelands are predominantly pastoral systems, of which the main types in drylands are:

(a) Nomadic/transhumance pastoral systems: Nomadic systems involve more or less the continuous movement of livestock with no set pattern. Herding is with drought-hardy livestock, such as camels, goats and sheep, and in some cases a few cattle. Transhumance is typified by the movement of livestock along more predetermined routes leading from wet-season grazing in arid zones to fallow lands in semi-arid areas in the dry season.

(b) Sedentary livestock systems: Farmers who are mainly concerned with rainfed sedentary cropping in semi-arid areas practice this system of agriculture. Livestock are grazed on fallow or communal land close to the village and these areas can be intensively grazed.

(c) Ranching: Ranching is typical of highly commercial, market-based pastoral systems in the drylands of developed nations, such as the United States and Australia, though not exclusively. The development of lucrative markets in countries such as Argentina, Brazil and Nigeria has encouraged full-scale ranching systems and trails to established ranches in the savanna zone.

In the last 50 years, traditional agricultural practices in rangelands have been either overwhelmed or discouraged in favour of non-traditional, large-scale, capital-intensive agricultural systems (such as ranching) originally developed for more humid or temperate climates. In addition to their exposure to the effects of rapid population growth, rangelands have come under increased pressure from new systems of agricultural practice, leading to rangeland degradation and desertification. An assessment undertaken by UNEP in 1990/1991 indicated that the largest area of degraded rangelands lay in Asia and Africa. Overall, estimates indicate that 3.333 million hectares, or about 73 per cent of the total area of rangelands in the world's drylands, are affected by degradation, mainly through vegetation removal accompanied by soil erosion processes. The continuing and accelerating course of degradation in rangelands shows many common features, including:

(a) Deterioration in quantity, quality and persistence of native pasture (for example, diminution of plant cover, invasion of shrubs of low pastoral value and reduced germination rates);

(b) Structural changes in plant cover (for example, the loss of shrubs and trees through collection of fuelwood and agricultural deforestation);

(c) Changes in soil surface conditions (such as soil compaction, reduced organic matter, deterioration of soil–plant–water relationships);
(d) Additional processes of sand drift (such as dune migration and deflation, leading to further destruction of vegetation).

The two main causes of rangeland degradation in drylands are overgrazing and encroachment of rainfed sedentary agriculture or ranching, aggravated by climate factors (rainfall and temperature). Other factors such as government policies and new technology are important, too, usually heightening the impact of overgrazing and increasing sedentary agriculture on rangelands. For example, overgrazing occurs when livestock density becomes excessive and too many animals are allowed to graze on the same area of rangeland. As plant cover is degraded, soil erosion becomes increasingly serious. Livestock density can increase in a number of ways. First, herd sizes grow too large during wet years to be sustained during drier periods, or they may expand as a result of improved veterinary care or heavily subsidized feed prices. Second, the area available for grazing decreases as nomads are displaced by sedentary farmers owing to pressures such as expanding rural populations or government policy, which can include resettlement schemes that result in the concentration of livestock around certain features such as villages, or the sinking of permanent boreholes. Finally, traditional controls on grazing break down due to growing urban populations, economic development and market-oriented agriculture. Furthermore, many of these social, economic and political pressures contributing to rangeland degradation may be exacerbated through natural factors such as frequent drought, periods of prolonged desiccation and climate change.

Control of desertification by means of proper rangeland management is a priority. Both management of rangelands and rehabilitation of degraded rangelands should rely on sound ecological and integrated management of natural resources, using both indigenous knowledge of the ecosystem and sensitive scientific applications. Adapted technology, economic planning, and legal and financial measures should also support management of degraded rangelands, underpinned with improved institutional policy and planning. Agrometeorology applications for rangeland management play an important role through the provision of localized and international expertise, with an emphasis on local practices using favourable microclimates, which can be created by simple and inexpensive devices. Conservation agriculture (such as that advocated by the European Conservation Agriculture Federation, for instance) can play an important role in protecting rangelands.

At the local level, practical advice for management of rangelands parallels that provided in 14.3.2. Techniques addressing domestic and stock water supplies, runoff use (ponding, berms), flood irrigation schemes (syphoning), wind erosion reduction (afforestation, mulching), and grassland and savanna management (seed collection, sowing, planting, protection) should be provided in conjunction with local knowledge. For example, in parts of Niger, soil fertility is viewed much more holistically by farmers than by agronomists, who disaggregate influences on crop productivity into factors such as water supply, water intake, wind stress, individual nutrients and soil structure (Osbahr and Allen, 2002). Local farmers are aware that productivity of different soils is determined by a combination of factors, but do not rationalize it in the same way as an agronomist. Hence, in a wet year, clay-rich soils in depressions may be waterlogged and unproductive, while sandy soils, where managed adequately, yield acceptable crop returns. Clay-rich soils at better-drained sites may be very productive and responsive to inputs of manure or fertilizer. The maintenance of appropriate livestock densities and rotational grazing systems also prevent overgrazing and consequent soil erosion.

At an international level, agrometeorology can provide support for evaluating, forecasting and predicting current, near-future and future changes in natural conditions, and this helps furnish information that is used to target rangeland degradation through a number of different management techniques. From a meteorological point of view, drylands have long been undergoing continual transformation in response to environmental changes (for example, Washington et al., 2003), and traditional forms of agriculture have responded. Dryland environments are now widely recognized and accepted as having a complex history of change, based on event-driven non-equilibrium dynamics rather than gradual, linear change (Scoones 2001; Sorbo, 2003). Therefore, such scientific evaluations and information should provide for event-driven policies (Reenberg, 2001), as planning in such an environment will be challenging. Instead of simplified, standardized approaches and predefined technical solutions, rangeland management will need to offer an array of technological and management options from which farmers can choose according to their needs.

Specific agrometeorological techniques are available for the management of dryland livestock rangelands. Many agrometeorological applications for sustainable management of rangeland farming systems are contained in a recent WMO publication (WMO, 2004). Many of the applications remain simple indicators for assessing and monitoring the current status of rangelands, but these simple techniques for evaluation become more powerful when combined with quantitative mathematical models and Geographical Information Systems (GIS).

Evaluation of the water and wind erosion hazard in rangelands can be undertaken using simple soil erosion relationships that incorporate major soil loss factors. The application of the Revised Universal Soil Loss Equation (RUSLE) model (Renard et al., 1994) may be undertaken in order to understand soil erosion for agricultural application using the following equation:

$$A = R\ K\ L\ S\ C\ P \qquad (14.3)$$

where A is the soil loss per year (t/ha/yr), R represents the rainfall-runoff erosivity factor, K is the soil erodibility factor, L represents the slope length, S is the slope steepness, C is the cover management and P denotes the supporting practices factor.

14.5 MEASURES OF DESERTIFICATION AND RELATED TECHNIQUES

In 1977, the United Nations Conference on Desertification (UNCOD) gave legitimacy to the term desertification as a synonym for dryland degradation. Since then, four attempts to assess the global extent and severity of desertification have been made (Dregne, 2002). The first World Map of Desertification was prepared for UNCOD by FAO, the United Nations Educational, Scientific and Cultural Organization (UNESCO), and WMO. This map was basically a vulnerability map and did not show severity of actual land degradation. This initial desertification map was improved upon three times in succession. The fourth attempt by UNEP was an analysis of human-induced soil degradation (but not vegetation degradation) for arid and humid regions (Oldeman et al., 1990). It was based on expert knowledge from soil scientists around the world, and not on actual data of soil degradation status. This Global Assessment of Soil Degradation map has been much criticized, but it is by far the best representation of global soil degradation (Dregne, 2002). It also provided the basic data for the UNEP World Atlas of Desertification (UNEP, 1992). The second edition of this atlas (UNEP, 1997) was improved by shifting the attention from soil degradation alone to include vegetation degradation as well.

A general problem with these assessment studies is the lack of high-quality data and a poor definition of desertification indicators. Many dryland areas are (and have always been) subject to degradation processes such as wind and water erosion. Hence, an observation of wind erosion in a certain area is not sufficient to conclude that the area is experiencing desertification. Only when the frequency of duststorms rises and the magnitude of the storms increases is there a clear indication of ongoing land degradation. Obviously, such analysis requires detailed data on the frequency and size of duststorms, but these data are rarely available. A different indicator that has been used to identify land degradation is crop yield data. In the Sahel, for instance, shrinking yields of pearl millet have been used to indicate soil degradation. But the data encompassed a decline in rainfall during more or less the same period and were perhaps more reflective of moisture shortages than soil degradation status. Also, decreasing yields could have been caused by a lack of fertilizer use, and thus the yield data did not necessarily indicate desertification.

The best possible indicator for desertification is probably the vegetation cover in an area. When persistent changes in vegetation cover are observed and more and more areas become barren, there is an indication of desertification. This indicator should be treated cautiously, however. The seasonality and variability of rainfall in drylands will also cause variability in vegetation cover. Timing of the vegetation observations is of crucial importance and should be done during the growth period, when vegetation cover is at its maximum. Observations should be related to the annual rainfall, as a drought year may have less vegetation cover than other, more normal years. Finally, it is important to compare the observed vegetation cover in a certain area with historic vegetation cover, which cannot always be done due to a lack of information.

Before the introduction of remote-sensing satellites, the assessment of land use, land cover, landscape features, soil characteristics and land degradation features was performed with the help of aerial photographs for the most part. These studies were usually complemented by detailed field observations to verify the different classes and their distribution as derived from the photographs. Multiple sets of aerial photographs always were and in fact still are very useful to monitor land degradation problems in a given area, because of the generally high resolution of the photographs. Land degradation features such as gullies and barren, crusted patches are easily distinguished. The disadvantage of aerial photographs is the relatively small spatial extent the photographs cover, and the relatively high cost of ordering sets of good-quality photographs. Usually, people rely on whatever sets of photographs are available for an area, irrespective of the times at which the photographs were taken.

Since the early 1970s a great number of remote-sensing satellites have been launched with many different sensors and resolutions. The sensors can be divided into two classes. Optical systems measure the reflection of sunlight in the visible and infrared parts of the electromagnetic spectrum, as well as thermal infrared radiance. Radar imaging systems actively transmit microwave pulses and record the received signal (backscatter) (Vrieling, 2006). Optical remote-sensing systems have most frequently been applied in studies of land degradation. Depending on the type of study and the spatial scale, a choice has to be made from the many optical satellite systems. Some systems, like IKONOS and QUICKBIRD, have very high spatial resolutions (on the order of 1 m), but cover relatively small areas, albeit with much detail. Other systems, such as the LANDSAT 7 Enhanced Thematic Mapper (ETM) and SPOT 4, have lower spatial resolutions (on the order of 10–30 m), but cover much larger areas. Vrieling (2006) provides a thorough review of the available satellite remote-sensing sensors and how these different sensors have been used for water erosion assessment.

Satellite data can be used to directly detect land degradation features, such as duststorms (Figure 14.3), or the consequences of land degradation, such as polluted surface waters resulting from high sediment contents. Other features that can be detected from satellite images are (Lantieri, 2006):

(a) Salinization patterns in irrigation schemes (salt appears as white patches);
(b) Overgrazing features, such as low-cover grasslands around animal paths, for example;
(c) Water erosion patterns of great size and over large areas (primarily gully erosion);
(d) Burned areas or areas subject to bush fires.

In addition, it is possible to detect bare surfaces and land-use changes (through multitemporal analysis) that may help to assess land degradation problems in a particular area.

Satellite remote-sensing imagery is especially useful for classification of vegetation cover. The most common index used for vegetation cover is the normalized difference vegetation index (NDVI), which is defined as the near-infrared reflection minus red reflection divided by the sum of the two (Tucker, 1979). When vegetation cover maps are created for different years, it is possible to determine the changes in land cover, which may indicate desertification. It is important that the maps be created for more or less the same time of the year, however, preferably in the late growing season, when vegetation cover is at its maximum. Also, it should be verified that moisture conditions at the times the various satellite images were taken were not widely divergent. A comparison of vegetation cover between a wet year and a dry year may lead to wrong conclusions about vegetation changes and possible desertification. This straightforward method of using vegetation cover maps to assess desertification is robust and rather accurate, but remains restricted to a physical state assessment of desertification. It does not look at driving forces, and therefore it identifies the problem, and may

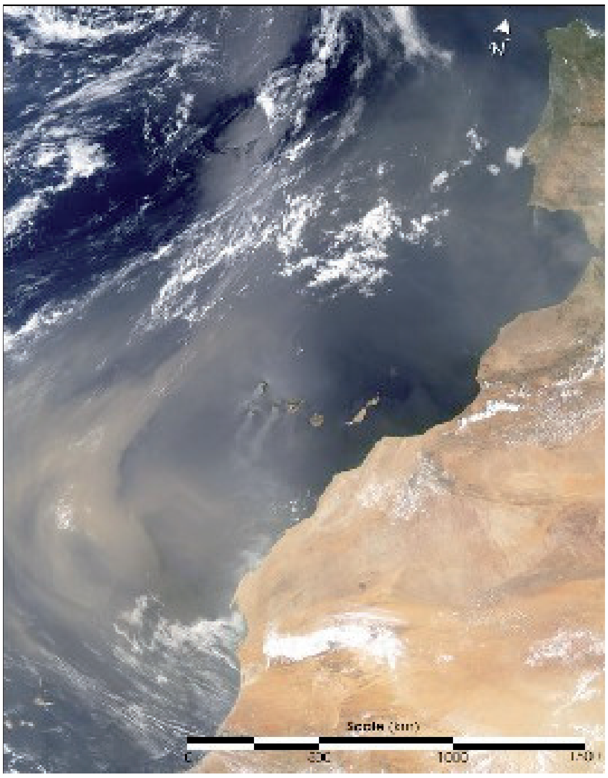

Figure 14.3. Dust cloud moving over the Atlantic Ocean off the coast of Morocco (NASA Earth Observatory; image taken from the Terra–MODIS satellite on 25 July 2004)

assess its intensity, but does not provide guidance as to its solution (Lantieri, 2006).

Usually studies of land degradation combine satellite remote-sensing information with other spatial data, such as topography, soils and land use, into a Geographical Information System. A GIS enables analysis of combinations of different data layers, which may result in a better understanding of land degradation problems, causes and consequences. Also, within a GIS, modelling with relatively simple empirical and semi-empirical models can be done to determine the risk of land degradation in an area. For instance, Okoth (2003) used a simple logit regression equation that combines the parameters of slope and ground cover to determine water erosion risk in Kiambu District of Kenya. The ground cover and slope data were derived from remote-sensing imagery, while the erosion data for the regression analysis came from field studies. In the GIS, the regression model was used to determine the erosion risk in the entire area. A similar approach was used by Vrieling et al. (2002) to determine water erosion risk in the Colombian Eastern Plains. Instead of a simple erosion model, they used a decision tree for erosion classification. The decision tree combined relevant information on soils, slopes and vegetation cover, and was derived from expert knowledge.

14.6 ACTIVITIES RELATING TO DROUGHT AND DESERTIFICATION

14.6.1 International activities: the role of WMO in the UNCCD and the United Nations International Strategy for Disaster Reduction

Widespread international concern over the consequences of desertification came to the forefront in the late 1960s and early 1970s with the spread of the Sahelian drought. By the 1980s a significant area of sub-Saharan Africa had suffered enormous environmental, economic and social impacts. As a result, a United Nations Conference on Desertification was held in Nairobi in 1977. Products of the conference included the gathering and synthesis of the state of knowledge related to desertification, resulting in the paper “Desertification: An Overview” (UNCOD, 1977), and global and regional desertification maps of varying quality. A Plan of Action to Combat Desertification was adopted to “prevent and to arrest the advance of desertification and, where possible, to reclaim desertified land for productive use” (UNCOD, 1978). The approach was one of “adaptation and application of existing knowledge”, using education in mitigation techniques and training programmes to address desertification. UNCOD was beset by funding and political issues, however (MacDonald, 1986). In 1991 the United Nations Environment Programme found that complications from desertification had increased since the implementation of the UNCOD Plan of Action.

The United Nations Conference on Environment and Development (UNCED), which took place in Rio de Janeiro in 1992, promoted a new holistic, integrated approach to the prevention of land degradation in susceptible drylands by encouraging sustainable development. As a result of the efforts initiated at this conference, an intergovernmental committee was established to create a legally binding treaty to address desertification. The United Nations Convention to Combat Desertification was adopted in Paris in 1994 and went into effect in 1996 with the signature of the fiftieth country. The heart of the UNCCD (http://www.unccd.int/main.php) is the development and implementation of National Action Programmes (NAPs). NAPs specify long-term strategies and practical measures to engage governments and local communities in combating desertification, to promote sustainable development and to reduce poverty in drylands.

Today, WMO supports the UNCCD through the application of the meteorological and hydrological sciences to agriculture and other human activities related to desertification. As such, WMO facilitates the “systematic observation, collection, analysis and exchange of meteorological, climatological and hydrological data and information; drought planning, preparedness and management; research on climatic variations and climate predictions; and capacity-building and transfer of knowledge and technology” (WMO, 2005). WMO’s Agricultural Meteorology Programme (AGMP) (http://www.wmo.int/pages/prog/wcp/agm/agmp_en.html) and Hydrology and Water Resources Programme (HWRP) (http://www.wmo.int/pages/prog/hwrp/index_en.html) have been particularly involved in these efforts.

WMO is also a member of the Inter-Agency Task Force on Disaster Reduction (IATF/DR) for the International Strategy for Disaster Reduction (http://www.unisdr.org/isdrindex.htm). Composed of 25 United Nations, international, regional and other organizations, IARF/DR is the lead body responsible for creation of disaster reduction policy. Working Group 1 on Climate and Disasters is chaired by WMO, and has chosen drought as a focus to promote working group interactions.

14.6.2 Meteorological observing networks and monitoring of drought and desertification

WMO is a specialized agency of the United Nations whose main role is to promote international cooperation in the provision and rapid exchange of information on weather, water and climate. WMO engages National Meteorological and Hydrological Services (NMHSs) in the development of long-term strategies for systematic weather, climate, hydrological and water resource observation; the exchange and analysis of data; and enhanced drought monitoring. These activities support Article 16 of the UNCCD, which stresses the importance of collection and coordination of relevant, timely data to further the monitoring, assessment and understanding of drought and desertification.

WMO coordinates a global network of meteorological observing platforms under the Global Observing System (GOS) of the World Weather Watch Programme. The network integrates some 10 000 land-based stations, 1 000 stations performing upper-level observations, 3 000 aircraft, 7 000 sea vessels and about 1 200 buoys and fixed marine platforms. The resulting 150 000 daily observations are enhanced with the addition of observations of 16 meteorological and environmental satellites. The newly formed WMO Space Programme has already improved satellite data access, utilization and products across WMO and its supported programmes. In parallel with the objectives of GOS, the World Hydrological Cycle Observing System (WHYCOS) (http://www.whycos.org/rubrique.php3?id_rubrique=2) focuses on measurement and collection of hydrological parameters through existing national/regional meteorological and hydrological stations. Additional specialized observations are made for atmospheric chemical constituents and various ocean and circulation measures through other specialized programmes. The Global Climate Observing System (GCOS) (http://www.wmo.int/pages/prog/gcos/), sponsored in part by WMO, seeks to provide the comprehensive observations required for monitoring, research and assessment of the climate system.

14.6.3 Research

WMO supports research by universities and international and national organizations related to causes of climatic variations, interactions between climate and land degradation, and advances in climate prediction. Since the 1970s, Sahelian droughts have been studied to determine the possible causes, such as the impact of human modifications of the land surface and atmosphere on the energy balance of local and regional climates. Numerical model simulations of these interactions have been carried out for a large number of drylands across the globe. Many of these same objectives are being carried out at present under the Global Energy and Water Cycle Experiment (GEWEX) (http://www.gewex.org) of the WMO World Climate Research Programme (WCRP) (http://wcrp.wmo.int/wcrp-index.html; Sivakumar, 2005).

Drought conditions often appear in relation to variations in strength or displacements in the location of a number of large-scale features of the general circulation of the atmosphere. Accordingly, a number of WMO programmes advance the understanding and prediction of climate variability over seasonal to interannual timescales. Adequate representation in models of the processes that guide climate permits better decision-making by NMHSs across the globe in regard to the prevention of, response to, and recovery from drought and desertification impacts. Better understanding of El Niño–Southern Oscillation events is beginning to enable advance warning of drought on the order of seasons to over one year.

Two WMO activities in particular address climate variability and prediction. Climate Variability and Predictability (CLIVAR) (http://www.clivar.org) within WCRP hosts a number of projects related to drought, including evaluation of temporal and spatial precipitation patterns from general circulation models, causes of droughts and floods, and climatic feedback processes (Sivakumar, 2005). The Working Group on Tropical Meteorology Research of the WMO World Weather Research Programme (http://www.wmo.int/pages/prog/arep/wwrp/new/tropical_meteorology.html) seeks better understanding and prediction of tropical monsoons and droughts, and of the meteorology of semi-arid regions and rain-bearing tropical systems, as well as enhanced use of model tropical forecasts.

The Intergovernmental Panel on Climate Change (IPCC) (http://www.ipcc.ch/), established jointly by WMO and UNEP, evaluates peer-reviewed, published literature in assessing the risk of human-induced climatic change, and potential impacts and adaptation/mitigation strategies. According to the IPCC

Fourth Assessment Report (IPCC, 2007*a*, 2007*b*), the warming of the climate system is unequivocal. Eleven of the last 12 years (1995–2006) rank among the 12 warmest years in the instrumental record of global surface temperature. The 100-year trend (1906–2005) is 0.74°C. The linear warming trend over the last 50 years (0.13°C per decade) is nearly twice that for the last 100 years. At continental, regional and ocean-basin scales, numerous long-term changes in climate have been observed. These include changes in Arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heatwaves and the intensity of tropical cyclones. More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics.

Projected warming in the twenty-first century is expected to be greatest over land and at the highest northern latitudes. For the next two decades a warming of about 0.2°C per decade is projected. Increases in the amount of precipitation are very likely in high latitudes, while decreases are likely in most subtropical land regions. Drought-affected areas will likely increase in extent. It is very likely that hot extremes, heatwaves and heavy precipitation events will continue to become more frequent. Given these projections of future climate change, there will be increased land degradation owing to droughts and increased soil erosion owing to heavy rainfall events.

Carbon dioxide-induced climate change and desertification remain inextricably linked because of feedbacks between land degradation and precipitation. Water resources are bound inseparably to climate. Annual average river runoff and water availability are projected to increase by 10–40 per cent at high latitudes and in some wet tropical areas, and to decrease by 10–30 per cent over some dry regions at mid-latitudes and in the dry tropics. Soils exposed to degradation as a result of poor land management could become infertile as a result of climate change.

Climate change may exacerbate desertification through alteration of spatial and temporal patterns in temperature, rainfall, solar radiation and winds. The impacts can be described as follows:

(a) Soil properties and processes, including organic matter decomposition, leaching and soil water regimes, will be influenced by temperature increase.

(b) At lower latitudes, especially seasonally dry and tropical regions, crop productivity is projected to decrease with even small local temperature increases (1°C–2°C).

(c) Agricultural production in many African regions is projected to be severely compromised by climate variability and change. The area suitable for agriculture, the length of growing seasons and yield potential, particularly along the margins of semi-arid and arid areas, are expected to decrease.

(d) In the drier areas of Latin America, climate change is expected to lead to salinization and desertification of agricultural land.

(e) In Southern Europe, higher temperatures and more frequent drought are expected to reduce water availability, hydropower potential and crop productivity in general,.

14.6.4 Capacity-building and transfer of knowledge and technology

WMO believes that advances in scientific understanding of the atmosphere should be in support of sustainable development and social and economic decision-making of communities around the world. Enhancing understanding and capabilities in accessing, adapting and applying advances in climate science and prediction, remote-sensing and Geographical Information Systems can substantially improve the fight against drought and desertification. To these ends, WMO has sponsored a number of programmes aimed at the dissemination and successful use of research achievements. The Climate Information and Prediction Services project (CLIPS) (http://www.wmo.int/pages/prog/wcp/wcasp/CLIPSIntroduction.html) was created by the Twelfth World Meteorological Congress for this purpose. Efforts are made to ensure that NMHSs have access to global and regional monitoring products and that the staff are sufficiently trained to provide climate-based decision-making to local communities. Other programme activities have included demonstration/pilot projects, various training opportunities and liaisons between research programmes. For example, to promote capacity-building associated with the UNCCD National Action Plans, WMO sponsored Roving Seminars on the Application of Climatic Data for Desertification Control, Drought Preparedness and Management of Sustainable Agriculture in Beijing, China, in May 2001 and in Antigua and Barbuda in April 2004.

Regional Climate Outlook Forums were organized by WMO to assist advanced climate prediction centres around the world in developing consensus forecasts and other climate prediction products, along with appropriate users' guides. The resulting interaction among the agencies was effective in the transfer and discussion of the current knowledge and limitations of climate prediction, which ultimately led to an improved consensus forecast product.

WMO has sponsored the preparation and distribution of publications relating to climate and desertification, including *Interactions of Desertification and Climate* (Williams and Balling, 1996) and *Agrometeorology Related to Extreme Events* (WMO, 2003*b*). *Climate and Land Degradation* (WMO, 2005) was prepared for the seventh session of the Conference of the Parties (COP–7) of the UNCCD in October 2005, and a corresponding International Workshop on Climate and Land Degradation was held in Arusha, Tanzania, in December 2006 (http://www.wmo.int/pages/prog/wcp/agm/meetings/wocald06/wocald06_en.html).

14.6.5 Application of agrometeorological science and methods

The WMO Agricultural Meteorology Programme has played a leading role in the application of meteorological and hydrological sciences to agriculture through the delivery of various agrometeorological services and through the provision of assistance to farmers in the application of agrometeorological methods. The scope of such applications includes practices relating to the manipulation of the microclimate to favour the growth of crops and other vegetation (see 14.3.2). Afforestation programmes and land-use planning practices can combat desertification both on and off farm fields. The Commission for Agricultural Meteorology (CAgM) (http://www.wmo.ch/pages/prog/wcp/agm/cagm/cagm_en.html) has been active since the 1970s in recommending agrometeorological approaches to drought. The commission has promoted development of indices for drought assessment, drought probability maps, national and regional drought management plans, assessments of the economic impacts of drought, and improvements in agrometeorological bulletins and methodologies for advising farmers. The commission collaborates with the International Society for Agricultural Meteorology (INSAM) (http://www.agrometeorology.org/) to promote networking among agrometeorologists all over the world in support of better agrometeorological practice. The WMO WHYCOS Programme (http://www.whycos.org/rubrique.php3?id_rubrique=2) promotes detailed monitoring, assessment and management of water resources in support of drought mitigation and other goals.

Successful drought and desertification intervention requires not only mitigation, response and remedial action, but also preparedness. As such, WMO promotes the use and establishment of partnerships in drought-preparedness strategies, risk management applications and hazard vulnerability assessment. Temporal comparisons of 10-year mean isohyet maps enable easy detection of areas undergoing continued desiccation and in which rainfed agricultural operations should be avoided. Proper agroclimatic zoning is an important element in minimizing climatic risks to agriculture by identifying appropriate crops for an area using an array of relevant climatic elements. Similarly, the mapping of climatic hazards permits integration of numerous biophysical variables for spatial assessments of hazard likelihood and magnitude for land-use and preparedness planning. Remote-sensing products have multiplied the quantity of information available for such analyses, while Geographical Information Systems have enabled the rapid manipulation and evaluation of the many data layer components. Hazard and agroclimatic mapping products may play an integral role in government and resource management decision support systems. The continuing efforts by WMO in encouraging the quality and quantity of systematic observation across meteorological networks are imperative for such projects.

14.6.6 Drought preparedness and early warning systems

Drought is a normal part of the climate system and occurs virtually in all regions of the world (Wilhite, 1992). Drought may be classified broadly into several main types – meteorological, hydrological, socio-economic and agricultural – though a precise and universally accepted definition of drought is largely absent (Wilhite and Glantz, 1985). Meteorological drought occurs when there is a prolonged absence or marked deficiency of precipitation. Hydrological drought occurs when there is sustained and extensive occurrence of below-average natural water availability, in the form of rainfall, river runoff or groundwater. Agricultural drought is defined as a deficit of rainfall in respect to the long-term mean, affecting a large area for one or several seasons or years, which drastically reduces primary production in natural ecosystems and rainfed agriculture (WMO, 1975). Socio-economic drought occurs when water supply is insufficient to meet water consumption for human activities such as agricultural production, industrial output, urban water supply, and so forth (Heathcote, 1974; WMO, 1975).

While these definitions of drought may be meaningful for scientists, however, in most cases a lack of consideration as to how other disciplines or policymakers will eventually need to apply the definition to actual drought situations is problematic. Other types of drought definitions may be more specific. For example, an agricultural drought describes a situation in which rainfall amounts and distribution over a wide region combine with evaporation losses, soil water reserves and surface or subsurface water resources to markedly diminish crop or livestock yields. Therefore, a strict meteorological definition of drought conditions may be insufficient for agricultural purposes. A working definition is needed in order to facilitate drought-preparedness planning through the linking of environmental considerations involving drought (that is, meteorological, hydrological and ecological factors) to specific impacts in key socio-economic sectors (agriculture, tourism, poverty, nutrition, and so on).

Overall, drought plans and the use of early warning systems (EWSs) have become widely accepted tools for governments at all levels to apply in order to reduce the exposure of agricultural activities to risks of future drought events. Effective drought EWSs play an integral part in efforts to improve drought preparedness, with timely and reliable data and information the cornerstone of effective drought policies and plans for rainfed agriculture and pastoral systems of farming. Notable examples include the United States monitoring tool – Drought Monitor – developed in 1999, and the inception of the Australian National Drought Policy in 1992. Without a doubt, the core principle of "self-reliance" moved Australia's drought policy away from a crisis-driven approach to one that treated drought as a normal part of the Australian farming environment (WMO, 2000*a*). Most progress in the preparation and development of drought plans, however, is in developed countries (for instance, Australia and United States), and while many developing countries have some type of drought plan and early warning system, these systems are not always comprehensive and have limited use.

14.6.6.1 Role of WMO and drought preparedness

In addition to providing meteorological data services, WMO promotes preparedness for drought through the establishment of national drought plans, drought risk assessments and data input to EWSs. Based on a clear definition, drought preparedness should contain three basic components (after WMO, 2000*b*), which include:
(a) Monitoring and early warning;
(b) Risk assessment;
(c) Mitigation and response.

WMO activities in the field of drought are focused primarily on these components and encompass four phases: mitigation/prevention; preparedness; response; and recovery. These phases are primarily organized through the various scientific and technical programmes of WMO and include:
(a) World Weather Watch (http://www.wmo.int/pages/prog/www/index_en.html);
(b) World Climate Programme (http://www.wmo.int/pages/prog/wcp/index_en.html);
(c) World Weather Information Service (http://www.worldweather.org);
(d) Severe Weather Information Service (http://severe.worldweather.wmo.int/);
(e) Hydrology and Water Resources Programme (http://www.wmo.int/pages/prog/hwrp/index_en.html).

Increasingly, society is recognizing the impacts that climate has on human activities, whether from long-term climate change or climate variability. These Websites are designed to provide a single and centralized source of climate and meteorological information on the Internet for a wide range of stakeholders, such as the public, scientists, regulators, non-governmental organizations, governments, policymakers and business, so as to limit potential negative impacts to agriculture of climatic hazards and enhance agricultural planning activities through the developing capacity of climate science. Therefore, the Websites combine different functions that work closely with and aid NMHSs in the provision and exchange of climate data and services. Broadly, these functions include:
(a) Information and forecasting services (World Weather Information Service);
(b) Database and data management services (World Weather Watch);
(c) Technical support and implementation of climate services (World Climate Programme/CLIPS).

14.6.6.2 Early warning systems

As a consequence of drought and associated famine in West and East Africa during the late 1970s and early 1980s, the affected areas and international agencies were faced with the need to provide appropriate tools to facilitate preparedness for reoccurring droughts. Although they are still in the development and evolutionary stages, EWSs are being introduced as a means of integrated management to bring drought preparedness to agricultural systems, and to aid in the prevention of famine and in the prediction of drought. Table 14.5 provides a summary of current EWSs and agrometeorological models used for forecasting drought and anticipating food crises. From a meteorological perspective, more developed and extensive recording stations, coupled with deeper knowledge and dissemination of climate processes (such as teleconnections and their effects) through WMO programmes, have permitted the collection and use of data that underpin EWS schemes.

Agrometeorological monitoring for EWS schemes consists primarily of various data and information that can affect the outcome of agricultural production. It combines observational data as well as satellite data and model outputs. For seasonal forecasting, outputs of ocean–atmosphere dynamic models, coupled with outputs of national statistical models, are used to delineate zones for which forecasts are made. Seasonal forecasts for agricultural production purposes are usually made up of the probabilities of July–August–September rainfall or maximum river flow, which are combined with specific agrometeorological models (such as the ZAR, or Zones à Risque, model). Most information is based on monitoring of the cropping season and determining risk zones, however, and is addressed to policymakers at the government or international aid agency level. Several agrometeorological indicators are used throughout the rainy season to assess crop and livestock conditions. Indicators include, among others:

(a) Rainfall amounts (10-day and cumulative);
(b) Potential evaporation;
(c) Air temperature and radiation levels;
(d) Surface water level and flow;
(e) Crop and overall biomass yield estimates;
(f) Crop water requirements;
(g) Cropping season start;
(h) Natural vegetation status;
(i) Disease status.

Early warning is an art, not a science, however, and EWSs are used to make predictions based on an analysis of available information and, inevitably, an element of judgement (WMO, 2000*c*). Long-range forecasts of drought are not yet operationally possible despite improvement of best practices and methodologies of current EWS schemes (for example, the Global Information and Early Warning System, or GIEWS; Système Intégré de Suivi et Prévision, or SISP; and ZAR). Indeed, a feature of EWSs is that data are never as comprehensive and accurate as practitioners would like, and the earlier the warning, the less certain a forecast will be. This issue of long-range uncertainty in EWS forecasts sits at odds with the usually risk-adverse, quantifiable decision-making of many governments and donor agencies that usually look for evidence before responding (Thomson et al., 1998). Increasing gains are being made in developing EWSs for the forecast of droughts and their potential effect on crop and livestock production, however, by using multidisciplinary technical structures and inter-agency committees for the development of EWSs and drought plans (Martini et al., 2004). Recognition of the need to define methods to optimize the use and integration of available data and administrative structures has aided, and will further aid, the ongoing development of EWS schemes.

Table 14.5. Examples of early warning systems and agrometeorological models used for decision-making by governments and international agencies in the area of food security

Early warning system	*Organization*	*Output*
GIEWS	FAO	Monitoring of world food prices, estimates of global food production and supply
FEWS	United States Agency for International Development	Compilation of hazard information: hazard, shock factors and risk analysis
WFP–VAM	World Food Programme	Vulnerability analysis: identification of important income sources for population groups and analysis of risk related to productive activities and coping capacity to provide vulnerability conditions
SISP	Agrhymet	Seasonal monitoring, crop growth assessment, yield forecasting
ZAR	Agrhymet	Identification of successful sowing dates, areas of failed sowing, potential duration of growing season
DHC–CP	Agrhymet	Identification of first and successful sowing dates

14.6.7 WMO, desertification and the future

Since its inception, WMO has been committed to improving global meteorological and hydrological monitoring networks and strategies for systematic observation. In a new era when a potential rise in global temperature, increased climate variability and growing population pressure may place increased stresses on the land, the need for accurate and systematic climatic data observations in assessing interactions between climate and desertification is apparent. While greater information on rainfall intensity is needed in particular, strengthened systems of meteorological and land degradation monitoring allow for better spatio-temporal evaluation of the role of individual climatic elements in desertification processes. In addition, there is an enhanced ability to develop accurate seasonal climate forecasts for improved dryland decision-making.

In future efforts to combat desertification, WMO will promote:

(a) Use of appropriate instruments and statistical processing for meteorological data in support of effective drought early warning systems;

(b) Continued efforts towards effective provision and communication of drought warnings and long-term predictions from drought monitoring centres to farmers through extension agents and non-traditional methods such as rural radios, facsimile, e-mail, Internet, mobile telephones and wireless access. Local people should be involved in a collaborative process with applicable community, regional, national and international organizations and research entities for the purpose of the production, exchange and dissemination of such information;

(c) Strengthening drought prevention, preparedness, management and contingency plans across multiple geographic scales, based on coordinated efforts by the relevant government authorities, extension agents, local citizens and economic sectors;

(d) Inclusion of geographic assessment tools such as multi-indicator drought monitoring maps, agroclimatic zonation, temporal isohyet analysis, remote-sensing products, and climatic hazard and vulnerability mapping in effective decision-making related to land use;

(e) Creation of global databases on the frequency, intensity, onset, spread and duration of meteorological and hydrological drought, and the related impacts on agriculture, livestock and forestry;

(f) Full and improved application of agricultural meteorological practices and hydrologic management in combating drought and desertification, with associated capacity-building and education efforts;

(g) Continuation of research in climate variability and drought processes, including the role of large-scale global atmospheric circulation and improved seasonal forecasting.

Drought and desertification are insidious processes with manifold environmental, social and economic repercussions, but progress is being made. The past decade has seen an explosion in remote-sensing and geospatial technologies for enhanced dryland monitoring and decision-making, and expanded communication and education capacities through greatly improved access to microcomputers, the Internet, mobile phones and e-mail. Advances in the climate science in relation to El Niño–Southern Oscillation phenomena are beginning to make possible climate prediction on the order of a few seasons. Yet the challenges in addressing a potential climate change and increasing climate extremes with a global population that is expected to reach 8.2 billion by 2020 loom large. With nearly one in six people worldwide presently at risk from the impacts of land degradation, much work remains in terms of monitoring and preventing desertification, understanding causal interactions, and education. Through its outreach efforts in these areas, WMO stands to play a significant role in maintaining the sustainability of drylands and the well-being of the millions of people who are dependent on them.

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