World Geomorphological Landscapes

Paolo Billi *Editor*

Landscapes and Landforms of the Horn of Africa

Eritrea, Djibouti, Somalia

Springer

World Geomorphological Landscapes

Series Editor

Piotr Migoń, Institute of Geography and Regional Development, University of Wrocław, Wrocław, Poland

Geomorphology – 'the Science of Scenery' – is a part of Earth Sciences that focuses on the scientific study of landforms, their assemblages, and surface and subsurface processes that moulded them in the past and that change them today. Shapes of landforms and regularities of their spatial distribution, their origin, evolution, and ages are the subject of geomorphology. Geomorphology is also a science of considerable practical importance since many geomorphic processes occur so suddenly and unexpectedly, and with such a force, that they pose significant hazards to human populations. Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, Nature often surprises us creating shapes which look improbable. Many geomorphological landscapes are so immensely beautiful that they received the highest possible recognition – they hold the status of World Heritage properties. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for millions of years and include unique events. This international book series will be a scientific library of monographs that present and explain physical landscapes across the globe, focusing on both representative and uniquely spectacular examples. Each book contains details on geomorphology of a particular country (i.e. The Geomorphological Landscapes of France, The Geomorphological Landscapes of Italy, The Geomorphological Landscapes of India) or a geographically coherent region. The content is divided into two parts. Part one contains the necessary background about geology and tectonic framework, past and present climate, geographical regions, and long-term geomorphological history. The core of each book is however succinct presentation of key geomorphological localities (landscapes) and it is envisaged that the number of such studies will generally vary from 20 to 30. There is additional scope for discussing issues of geomorphological heritage and suggesting itineraries to visit the most important sites. The series provides a unique reference source not only for geomorphologists, but all Earth scientists, geographers, and conservationists. It complements the existing reference books in geomorphology which focus on specific themes rather than regions or localities and fills a growing gap between poorly accessible regional studies, often in national languages, and papers in international journals which put major emphasis on understanding processes rather than particular landscapes. The World Geomorphological Landscapes series is a peer-reviewed series which contains single and multi-authored books as well as edited volumes.

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ISSN 2213-2090 ISSN 2213-2104 (electronic)
World Geomorphological Landscapes
ISBN 978-3-031-05486-0 ISBN 978-3-031-05487-7 (eBook)
https://doi.org/10.1007/978-3-031-05487-7

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Series Editor Preface

Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, nature often surprises us creating shapes which look improbable. Many physical landscapes are so immensely beautiful that they received the highest possible recognition—they hold the status of World Heritage Sites. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for tens of million years and include unique geological events such as meteorite impacts. In addition, many landscapes owe their appearance and harmony not solely to the natural forces. For centuries, and even millennia, they have been shaped by humans who have modified hillslopes, river courses and coastlines, and erected structures which often blend with the natural landforms to form inseparable entities.

These landscapes are studied by geomorphology—'the science of scenery'—a part of Earth Sciences that focuses on landforms, their assemblages, surface and subsurface processes that molded them in the past and that change them today. To show the importance of geomorphology in understanding the landscape and to present the beauty and diversity of the geomorphological sceneries across the world, we have launched a book series *World Geomorphological Landscapes*. It aims to be a scientific library of monographs that present and explain physical landscapes, focusing on both representative and uniquely spectacular examples. Each book will contain details on geomorphology of a particular country or a geographically coherent region. This volume covers Horn of Africa—an area, which is one of the least known and nowadays very difficult to access parts of the continent. And yet, it contains very diverse and fascinating geomorphology that includes the towering faulted escarpment of the Eritrean Highland, parts of the Afar Triangle with its active volcanoes and salt lakes, fascinating dryland rivers throughout the region and inselberg-dotted plains of Somalia. It is also home to some important archeological discoveries connected with the hominin history. But this book not only shows the geomorphological legacy of long-term landscape evolution and climate change, but also indicates relevance of geomorphology to successful environmental management of today. Several chapters examine issues of soil erosion, water resources and geomorphological hazards, all vital to the populations living in this unsettled part of the world.

The World Geomorphological Landscapes series is produced under the scientific patronage of the International Association of Geomorphologists (IAG)—a society that brings together geomorphologists from all around the world. IAG was established in 1989 and is an independent scientific association affiliated with the International Geographical Union (IGU) and the International Union of Geological Sciences (IUGS). Among its main aims are to promote geomorphology and to foster dissemination of geomorphological knowledge. I believe that this lavishly illustrated series, which keeps to the scientific rigor, is the most appropriate means to fulfill these aims and to serve the geoscientific community. To this end, my great thanks go to Prof. Paolo Billi, a person long involved in geomorphological research in the Horn of Africa, for agreeing to coordinate this unique volume in the series, which in a way complements the previous volume about Ethiopia. I am also very grateful to all individual authors who accepted invitations to contribute and shared their research experience from these remote areas.

In contrast to many other countries, the Horn of Africa is far less known regarding its geomorphology at the local scale and many of its regions are still *terra incognita*. Moreover, persistent political unrest makes the region very difficult to visit nowadays and large parts of Somalia, in particular, are essentially off-limits. Therefore, it was not feasible to strictly follow the format of previous volumes in the series and offer a wide range of site-specific stories. However, I am sure the readers will warmly welcome this unique presentation of the geomorphic environment of the Horn of Africa—perhaps the only comprehensive source of reference about this vast part of Africa.

Wrocław, Poland Piotr Migoń

Preface

The Horn of Africa shows a wide diversity of landscapes and landforms. Eritrea, Djibouti and Somalia owe their large-scale geomorphological features mainly to the complex crustal dynamics, characterized by large-scale uplifting, rifting and faulting, to the alternation of cycles of peneplanation, sea transgression and regression, marine and continental sedimentation. Quaternary faulting propelled intense volcanic activity and, in combination with erosion and hydrological processes, influenced alluvial, colluvial, lacustrine and coastal sedimentation. All these events affected Eritrea, Djibouti and Somalia in different ways and at different rates in space and time providing them with markedly contrasting, and often spectacular, physiographic and geomorphological features.

The Oligo-Miocene doming of the Arabian-Ethiopian region is, however, the most important geological event in the whole Horn of Africa. This remarkable uplifting was also associated with a three-lateral rifting and spreading converging toward the Afar depression and resulting in the Red Sea and Danakil troughs, the Gulf of Aden trough and the Ethiopian rift valley. The uplifting created high plateaus in Eritrea and northern Somalia. In Eritrea, the relief contrast between the plateau and the coastal lowlands is striking, with a jump of 2400 m in about 90 km from Asmara to Massawa on the Red Sea coast. The rift faults fragmented the Eritrean plateau and largely controlled the drainage network development and pattern.

Unlike Ethiopia, where the rifting is characterized by the emplacement of huge trap basalt amounts, basalts are present only in northern Somalia and in relatively small areas south of Asmara in Eritrea.

The geological evolution of the Horn of Africa also records long intervals of tectonic quiescence during which the whole landmass underwent vast denudation and the formation of peneplains. Outstanding examples of the Triassic peneplanation of the Precambrian crystalline basement are evident in Eritrea, whereas the Early Cretaceous to Oligocene marine regression made Somalia a very extensive table land that still today characterizes the largest part of this country. By contrast, Djibouti landscape is mainly the result of recent (Miocene to Quaternary) volcanic activity which has provided the country with most of its present landscape.

A complementary, and not secondary, factor in shaping the landforms we can observe today in Eritrea, Djibouti and Somalia is certainly the climate which varies from subhumid in southern Somalia to hyper-arid in Djibouti, the Danakil depression and along the Eritrean and northern Somalia coastal belt.

From this very short summary of the main geological events and climate diversity that characterize the eastern countries of the Horn of Africa, it is easy to prefigure the richness of their geological and geomorphological features.

Unfortunately, in the last two decades, critical conditions of social and political instability made impossible to carry out protracted and extensive field investigations in the region. Though also this book reflects such a difficult situation, ultimately, the efforts made by the authors resulted in a motivating collection of studies on different aspects of landscape and on the main factors influencing its development, including climate and man activity.

Moreover, most of the book chapters reports about remote areas that seldom have been visited by earth science scholars and whose peculiar landforms were before only succinctly described. The scientific and informative value of this book stands, therefore, not only in the variety of the research topics investigated, but also in the scarcity and dispersion of scientific publications on landscape and landforms of this part of the world.

Tottori, Japan Paolo Billi

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About the Editor

Prof. Paolo Billi has been working in the University of Florence and the University of Ferrara in Italy and closed his academic career at the International Platform for Dryland Research and Education of the University of Tottori in Japan. His main research topics include fluvial geomorphology, sediment transport and sediment yield. He carried out his research activities on rivers in Italy and in the Horn of Africa. He is also editor of Springer volume on *Landscape and Landforms of Ethiopia*.

Climate Variability in the Horn of Africa Eastern Countries: Eritrea, Djibouti, Somalia

1

Paolo Billi

Abstract

Eritrea, Djibouti and Somalia have peculiar physiographic characteristics and, though their climate is mainly controlled by the north–south–north movement of the Intertropical Convergence Zone (ITCZ), the large difference in elevation (3000 m from sea level to the highest peak) and the variable distance from the ocean also play an important role, accounting for considerable spatial variability in climate characteristics. Gridded and ground instrumental data of mean monthly temperature and precipitation were the main platform to describe the climate of Eritrea, Djibouti and Somalia. The basic precipitation and temperature data were used to obtain other parameters such as rainfall erosivity and aridity indices. Data of other basic parameters such as wind or humidity are available only for a very small number of meteo-stations, and their time series are very short. The gridded data time series span a century-long interval (1901–2015) and were used to investigate mean annual temperature and precipitation trends. A complementary analysis of climate variations was carried out using old (early twentieth century) data reported by Fantoli (Elementi preliminari del clima dell'Etiopia. Sansoni, Firenze, 1940; Contributo alla climatologia della Somalia: riassunto dei risultati e tabelle meteorologiche e pluviometriche. Ministero degli Affari Esteri, Cooperazione Scientifica e Tecnica, Roma, 1965) and modern data. The gridded data time series show a marked increase in temperature in the three countries. A decreasing trend of precipitation is evident for Eritrea, whereas an increasing trend is observed for Somalia. Rainfall erosivity is relatively low, despite the presence of vast degraded areas. The aridity indices indicate that the region is already under desertification conditions and the situation is expected to get worse with a decrease in water resources and severe threats to agricultural productivity.

Keywords

Temperature • Rainfall • Rainfall erosivity • Aridity

1.1 Introduction

Eritrea, Djibouti and Somalia take up a wide belt around Ethiopia, making the transition from the ocean to the inner highlands. Altitudinal differences are pronounced and find their maximum expression in Eritrea, where the largest range of elevations is from −75 m at Lake Kulul, in the Eritrean portion of the Danakil depression, to 3018 m asl at Emba Soira, the highest mountain peak of Eritrea. Also in Djibouti and Somalia, there are large differences in elevation between sea level and the highest mountains such as Mt. Shimbiris (2460 m) and Mt. Mousa Ali (2063 m) in Somalia and Djibouti, respectively. These mountain tops are near the sea, 42, 33 and 82 km, respectively, which makes the local physiography and landscape even more impressive. Eritrea and Djibouti are mainly mountainous countries. In Eritrea, lowlands are found only in the western part of the country, crossed by the Barka River, and along the coastal belt. Djibouti has no significant flat land, whereas flat lowlands make up the largest proportion of Somalia, which has high mountain ranges only along the northern coast. Such a highly variable physiography, the influence of the ocean, the presence of fairly large mountain ranges and the effects of the global atmospheric circulation result in a wide variability of the average climate characteristics across the region. Eritrea, Djibouti and Somalia are also subjected to marked seasonality, interannual and longer-term variability of rainfall and other climatic parameters that stand as clear symptoms of ongoing climate change (Schreck and Semazzi 2004), with negative implications on natural systems and the

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P. Billi (ed.), *Landscapes and Landforms of the Horn of Africa*, World Geomorphological Landscapes,
https://doi.org/10.1007/978-3-031-05487-7_1

appearance of stronger constrains to sustainable development. The countries in concern include both drylands and flood-prone areas. According to international organisations (e.g. UNEP 1992; EU 2007; IPCC 2019) and several studies (e.g. Middleton and Thomas 1997; Huq et al. 2006; Sivakumar and Stefanski 2007), in developing countries climate change will lead to an increased susceptibility to soil erosion, flood hazard, droughts and shortage of cultivable land and will widen social inequalities, which in turn will increase human pressure on land and will speed up land degradation. Though in the countries considered here the available data series show large gaps, discontinuities and different lengths and even if the density of meteo-stations is low and not uniform, an attempt is made in this chapter to address the variability of the main climatic parameters and their long-term trends, with implications for soil erosion and land degradation.

1.2 Study Area, Data and Methods

Somalia is the largest country, with a surface of 637,657 km^2, Djibouti is the smallest with 23,200 km^2 (almost the size of Sardinia island in Italy) and the area of Eritrea is 125,700 km^2. With the exception of a very small portion in southern Somalia, all three countries are included within the equator and the Tropic of Cancer (Fig. 1.1).

Eritrea shows the largest physiographic variability, with lowlands in the west and along the coast, the central highlands and the Asmara plateau, at elevations ranging from 2000 to 2400 m asl, with the western slope and the steep eastern escarpment connecting the highlands to the western and eastern lowlands, respectively, and the Danakil depression, where the lowest elevation is −75 m below sea level (Fig. 1.2). Such variability of physiography and elevation over short distances is a crucial factor in determining different climatic regimes of this country.

Djibouti is mainly a mountainous country, though with the exception of a couple of peaked mountain ranges (Mt. Mousa Ali in the north and Goda mountains in the centre) with elevations close to 2000 m asl and other few mountains, especially in the portion north of the Tadjoura Gulf, with elevations around 1700 m asl, the majority of the country is below 1000 m asl. The overall landscape of the country consists of low mountains and hills with a few flat-bottomed depressions interposed (Fig. 1.1).

Somalia is mainly a flat land. Mountain ranges are present only in the northern portion facing the Gulf of Aden. Mt. Shimbiris is the highest peak (2460 m asl), located close to the sharp edge of the Gulf of Aden. An escarpment connects the uplifted land with the ocean across a horizontal distance of only 32 km. The central and southern portion of Somalia is a gently inclined plain, with the highest elevations <500 m asl, bounded eastward by the Indian Ocean (Fig. 1.1). The more uniform physiography of Somalia is reflected by less pronounced variation of the main climate characteristics.

The three countries are bound eastward by the sea (the length of coastline is 1083 km in Eritrea, 314 km in Djibouti and 3333 km in Somalia). The vicinity to the sea and coastline orientation also have substantial influence on the climate of coastal towns and settlements.

1.2.1 Data Type and Sources

Though the study area is vast (786,557 km^2 in total), the density of meteo-stations is rather low. Climatic data are very heterogeneous (Fessehaye et al. 2019). Only very few stations have long records spanning over three decades; otherwise, the data records are punctuated by many gaps of different size, the total length and the beginning and end of the time series are highly variable and asynchronous, with some stations having been moved to a different, though near, location. Attempts to fill the data gaps with standard correlation methods proved to be acceptable only in a few cases and were in general poorly successful. This results in a certain degree of approximation in data analysis. Notwithstanding such limitations, it is possible to depict spatial variability of the main climatic factors and of some derived parameters across the countries. The investigation of trends is affected by the same limitations and though gridded data at country scale level are available, the most reliable information is still provided by the few meteo-stations with longer data records.

The data used in this study were obtained from different sources. They include original data of the National Meteorology Agency of Ethiopia for some meteo-stations of Eritrea as recently as the year 2000, i.e. shortly after the separation of this country from the Ethiopian Federation. Since then, unfortunately, ground data of Eritrea are very scanty (Fessehaye et al. 2019) due to economic resource shortage. A similar, or even worse situation, is present in Somalia, where several years of civil war have hindered the collection of meteo-data. Since 2002, the SWALIM project of FAO re-established some meteo-stations and provided the conditions for their maintenance (Muchiri 2007). Other average climate data were obtained from Internet sources, e.g. climate-data.org. All data of this organisations derive from a climate model with a resolution of 30 arc seconds. The model uses weather data from thousands of weather stations from all over the world. The data refer to the 1982–2012 interval but are also refreshed from time to time. Other monthly data were obtained from the Global Historical Climatology Network (GHCN) (Menne et al. 2012). For long-term analysis of precipitation and temperature trends at country level, data covering the 1901–2015 interval were

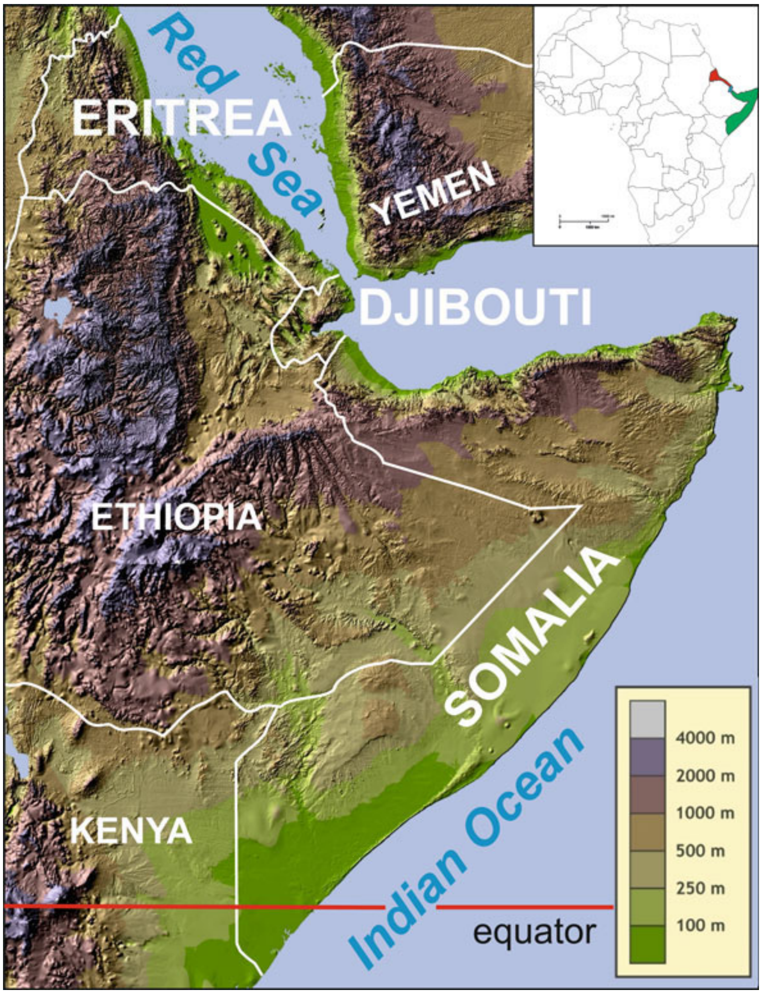


Fig. 1.1 Location map of the study countries: Eritrea, Djibouti, Somalia

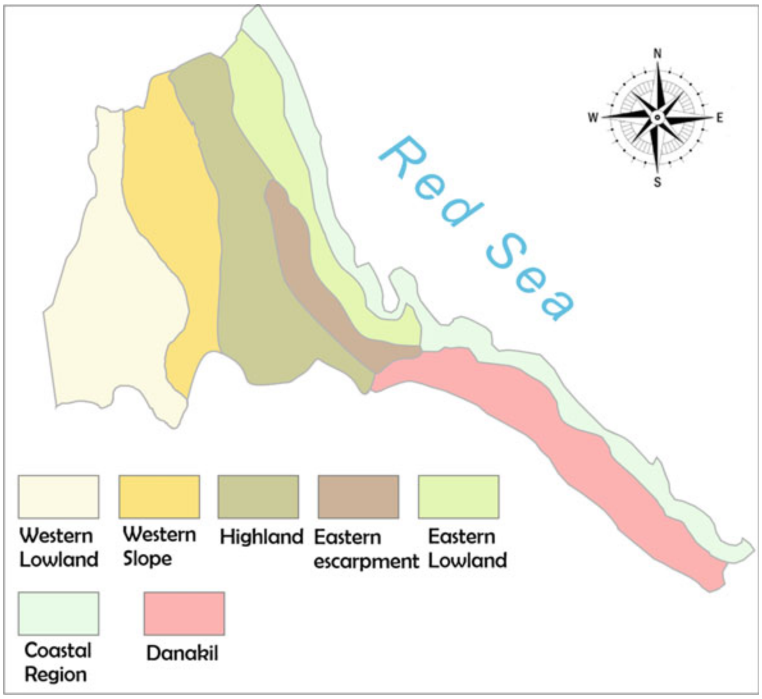


Fig. 1.2 Main physiographic areas of Eritrea

downloaded from the Climate Change Knowledge Portal of the World Bank (2019). These time series are based on gridded data interpolated into 0.5° latitude/longitude grid cells and derived from observational, quality-controlled data by the Climatic Research Unit (CRU) of University of East Anglia (UEA) in UK (Harris et al. 2014). Aggregated data were also obtained from Stat World (2019), and these are based on Berkeley Earth flat data (2019). The Berkeley Earth averaging process generates a variety of output, bias-corrected and quality-controlled data. Data sources include GHCN (Global Historical Climatology Network) and NCAR (National Centre for Atmospheric Research).

To investigate climate change, of particular interest are the data collected by Fantoli for Eritrea and Somalia (Fantoli 1940, 1965). This author collected several data sets ranging from 1912 to 1958 for some Somali stations and even older records for a few Eritrean stations. Most of the data were measured by Italian colonial authorities during the occupation, but this author also presents some older data, collected by other authors and British institutions, that he used to construct the time series and average data reported in his publications.

1.2.2 Data Processing Methods

Basic data processing was carried out to provide general information on spatial variability of climate across the countries and to have an insight into climatic trends. Unfortunately, very few long time series are available for the study area. In this regard, an invaluable help came from the data of Fantoli (1940, 1965) by which it was possible to depict the climate of a century ago on the basis of a few stations that provided instrumental data. The gridded data of the World Bank (2019) cover a very wide time interval (1901–2015), but they are reported as whole country-averaged values of precipitation and temperature. These data, though based on existing ground measurements at several meteo-stations, were generated by model interpolation and can be used in a general approach to climate change analysis in the three countries. Yet, the support of even very few instrumental data sets is important to substantiate the trends obtained from gridded data.

The basic data of temperature and precipitation were used to derive other parameters and to describe climate variability among the meteo-stations considered and their variation through time. The Precipitation Concentration Index (PCI) (Oliver 1980) is a measure of seasonal concentration of rainfall. It is defined as:

$$\mathrm{PCI} = 100\left\{\sum p_i^2 / \left(\sum p_i\right)^2\right\} \tag{1.1}$$

in which p_i is the mean monthly precipitation of each month.

When the rainfall amount is the same in every month, the PCI takes its minimum value of 8.3. By contrast, in the hypothetical situation of the whole annual precipitation falling in one month, the PCI assumes the value of 100. According to Oliver (1980), a PCI less than 10 indicates uniform distribution; a value from 10 to 15 denotes moderately seasonal distribution; a value from 15 to 20 indicates seasonal distribution, whereas an index above 20 reflects strong seasonal effects, with increasing values indicating increasing monthly rainfall concentration.

Very similar to the PCI in its structure, but defined for soil erosion investigation purposes, is the Modified Fournier Index (MFI) (Arnoldus 1980):

$$\mathrm{MFI} = \sum p_i^2 / P \tag{1.2}$$

in which p_i is the amount of rain in the ith month (mm) and P is the annual precipitation (mm).

Though these two indexes are very similar and related by a factor $1/P$, no significant correlation was found by Gabriels (2006). The MFI has been developed and used as a surrogate of rainfall erosivity index (e.g. CORINE 1992; Lee and Heo 2011). It is classified into five classes (Table 1.1). One limitation of the MFI is that it does not take into account the aridity of climate, in which short intense storms may be very effective in terms of soil erosion (Gabriels 2006). Therefore, this index should be used with caution and for areas with similar climatic conditions (Gabriels 2006).

Another rainfall erosivity index, developed for a simpler calculation of the R-factor in the USLE (and, for this reason, very often used in the literature), is the erosivity R-factor proposed by Renard and Freimund (1994):

$$R = 0.0483P^{1.61} \tag{1.3}$$

in which P is annual precipitation (in mm) and R has the units of MJ mm ha^{-1} h^{-1} yr^{-1} for annual precipitation less than 850 mm, which is the case of the three countries.

Desertification is big threat for many sub-Saharan countries, and the study area is not an exception. A very commonly used parameter to measure the tendency to desertification is the aridity index expressed by the UNEP (1992) as P/PET, that is the ratio between annual precipitation and the potential evapotranspiration calculated with the Thornthwaite (1948) method. An area is considered under desertification conditions when $P/\mathrm{PET} < 0.6$.

In this study, the De Martonne (1925) Aridity Index was also used:

$$\mathrm{AI} = P/(T + 10) \tag{1.4}$$

in which P is annual precipitation in mm and T is mean annual air temperature in °C.

Table 1.1 Classification of MFI (from Gabriels 2006)

MFI	Description	Class
<60	Very low	1
60–90	Low	2
90–120	Moderate	3
120–160	High	4
>160	Very high	5

Table 1.2 Relationship between the De Martonne (1925) aridity index and irrigation requirement (Baltas 2008; ARPAV 2019)

AI	Condition	Irrigation
<5	Arid	Indispensable
5–10	Semi-arid	Indispensable
10–20	Dry sub-humid	Very useful
20–30	Sub-humid	Often useful
30–50	Humid	Not required

Though it is rather old, this aridity index was selected because its values can be associated with irrigation requirements (Baltas 2008; ARPAV 2019) (Table 1.2) and, therefore, it can be used to investigate current and future conditions of cultivation stress and water demand.

1.3 General Climate and Atmospheric Circulation

Climate is highly variable within the study area, but also within each of the countries. Such variability is mainly expressed by monthly distribution of rain, which is strongly controlled by the general atmospheric circulation, including factors such as the position of the Intertropical Convergence Zone (ITCZ) (Muchiri 2007), the Indian ocean temperature (Goddard and Graham 1999) or the strength of El Nino Southern Oscillation (ENSO) (Indeje et al. 2000). The vicinity to the ocean, the occurrence of highly elevated mountain ranges and plateaus, and marked relief contrasts contribute to the high variability of climate characteristics of Eritrea, Djibouti and Somalia.

The interannual movement of the ITCZ is the main engine of the study area climate, propelling distinct changes in wind direction throughout the year. In its oscillation across the equator, the ITCZ passes over the study area twice a year. This migration causes the onset of winds from the north-east, when the ITCZ is located in the south, and from the south-west, when it is in a northern position. This pattern results in two rainy seasons (typically there is a small and a main rainy season), that occur in March–June in southern portion of the study area, when the ICTZ moves northward, in July–September in the north and then in October–November in the south, as the ITCZ moves to the south. Some regional variations lead to different timing of rainy seasons or to the occurrence of only one rainy season (e.g. in the Eritrean highlands and western lowlands, or in the southernmost tip of Somalia–Kismayo). In spring (April–June), the ITCZ lies across the southern border between Ethiopia and Somalia. At this time, pressure is high in the subtropical latitudes of the Sahara and southern Africa, whereas a strong cyclonic cell develops over the equatorial region. Here, south-easterly and north-easterly winds converge causing the vertical upward motion of air, the formation of clouds and precipitation, especially in Somalia. The moist, south-easterly winds bring rain also to the central highlands of Ethiopia, producing the small rainy season (*belg* in the local language) (Fazzini et al. 2015).

In summer (June–September), the ITCZ reaches its northernmost position. Northern Ethiopia and Eritrea are under the influence of south-west equatorial westerlies and monsoon-type southern winds from the Indian Ocean. These winds are rich in moisture, and when they ascend over the highlands of Ethiopia and Eritrea, they produce heavy rains giving rise to the main rainy season (responsible for 50–80% of the annual precipitation) in this area. The Eritrean north-eastern escarpment and lowlands, being rain shadow areas, are dry, though in the Eritrean escarpment the condensation of humidity coming from the very near Red Sea, also in the dry season, results in the landscape greener than expected and in favourable condition for cultivation.

In the same period, in Somalia, the south-west monsoon and the southerly winds converge in a narrow belt along the coast producing some rain, whereas the south-westerly winds are pushed up by high-elevation areas of northern Somalia and inland Djibouti, leading to local precipitation (Muchiri 2007) and resulting in a bimodal distribution of rain similar to that of inland Ethiopia. In October, the ITCZ moves back southwards, producing over Somalia the same conditions as in the spring months. The transit of the ITCZ over Somalia gives way to two distinct rainy seasons, locally named as *Gu* (March–May), the main wet season, and *Deyr* (October–November), the secondary rainy season.

In winter, the ITCZ is to the south of the study area, which goes under the influence of continental air currents originated from high-pressure centres over north Africa and Arabia deserts and experiences dry and cloudless conditions and high temperatures. Exceptions to this general climatic situation are the Eritrean escarpment and the coastal plains of Eritrea and Djibouti, where the influence of the Red Sea and the development of local eddies produce moderate winter rains, though in some places such as Filfil, located about 30 km NNE of Asmara at the base of the escarpment, mean annual rainfall may exceeds 1000 mm (EMA 1988; Sati 2008).

Previous work demonstrated that other factors such as El Niño Southern Oscillation (ENSO) and warm than usual sea surface temperature (SST) in the western equatorial Indian Ocean may have an important effect in the interannual variations of precipitation amounts (Liebman et al. 2014). During El Niño Southern Oscillation (ENSO) conditions, a short rainy season with precipitation above the average is recorded in the eastern Horn of Africa (Liebman et al. 2014). Using data from 31 meteo-stations in Somalia, Hutchinson (1992) found that rainfalls are only moderately predicted by changes in the Southern Oscillation Index (SOI), i.e. the atmospheric component of ENSO, but rainfall was low in association with high values of the SOI, that is La Niña conditions. Mason and Goddard (2001), however, suggested caution in stressing climate response to strong ENSO events and pointed out that the areas affected by ENSO may change from season to season and that not necessarily less than average precipitation is to be expected during La Niña events and vice versa. This conclusion is also supported by Indeje et al. (2000), though they confirm that some relationships exist between seasonal rainfall in East Africa and phases of ENSO. Behera et al. (2005) highlighted an even more important role of the Indian Ocean sea surface temperature (SST) in affecting the amount of short rains in East Africa. The east–west dipole of SST anomalies, commonly indicated as the Indian Ocean Dipole (IOD), has been shown to be significantly correlated with rainfall variability in East Africa and Indonesia (Saji et al. 1999), with above average rainfall in the former during a positive event and the opposite in the latter. During El Niño years, the Indian Ocean becomes warmer and moist convergent currents flow over East Africa (Goddard and Graham 1999). In this regard, there is some obvious link between ENSO and IOD. Nevertheless, IOD and ENSO events, though sometimes may co-occur, are independently evolving phenomena and, according to the statistical model of Behera et al. (2005), 79% of extreme short rains occur during IOD years.

The complexity, overlapping and counteracting of such atmospheric forcings and the strength and frequency of their teleconnections over the eastern Horn of Africa are reflected by the variability of the average climatic conditions depicted essentially in terms of monthly patterns of temperature and precipitation. In 1997, the FAO produced an agro-ecological map of Eritrea that, though focussed on agro-ecological zones, in practice can be also considered a good climatic map (Fig. 1.3), as it will be shown in the next sections. A similar eco-climate map was produced by the FAO-SWALIM project in 2007 (Muchiri 2007) for Somalia (Fig. 1.4). These two maps show that in both Eritrea and Somalia arid and semi-arid conditions predominate, whereas humid and sub-humid climates are restricted to small and very small proportion of the territory of Eritrea and Somalia, respectively. In Djibouti, warm desert climate (BWh of Koeppen classification) prevails over warm semi-arid climate (BSh of Koeppen classification).

1.4 Temperature

As anticipated in Sect. 1.2.1, the temperature data used in this study are heterogeneous. They come from different sources and were measured by ground instrumentation or obtained from gridding estimates. In all three countries, long time series of climate data are very uncommon and unevenly distributed, so the combined use of different data was a necessary compromise, which Ledesma and Futter (2017) consider as acceptable.

Eritrea is the country in which temperature is spatially more variable (Fig. 1.5). This is due to its higher relief

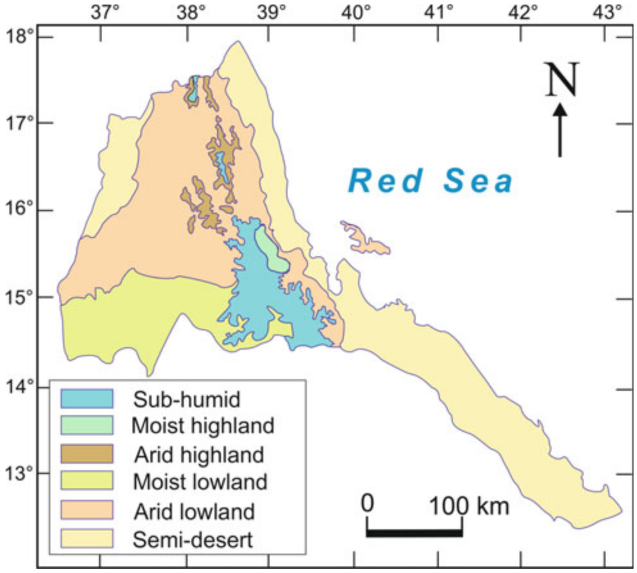


Fig. 1.3 Agro-ecological map of Eritrea

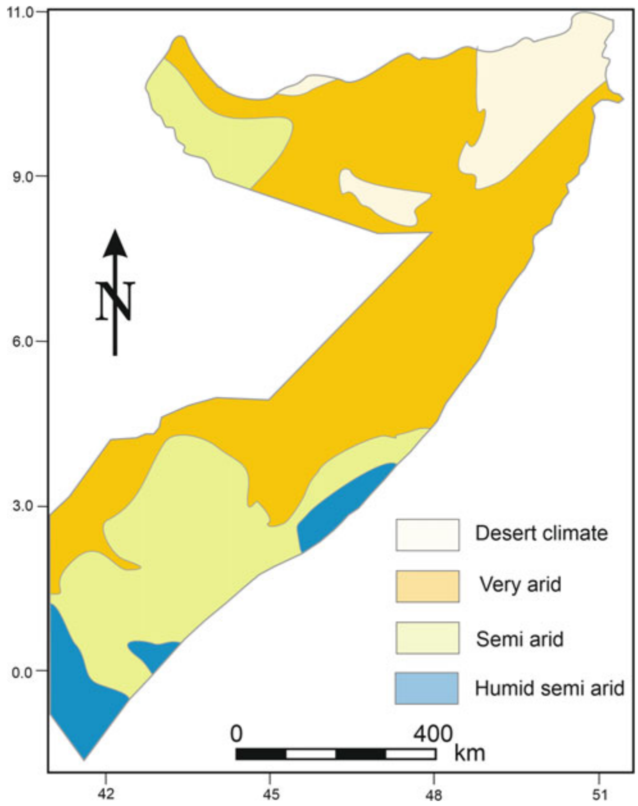


Fig. 1.4 Eco-climate map of Eritrea (modified from Muchiri 2007)

contrast. In Djibouti, the spatial viability of temperature is reduced (Fig. 1.6) because of the small size of this country and smaller relief contrast, whereas the rather uniform physiography of Somalia (with the exception of northern highlands) results in a rather uniform distribution of temperature (Fig. 1.7). Djibouti and Somalia are hottest countries. Their mean temperature, obtained by averaging the mean annual temperature of all the meteo-stations in a country, is 26.6 and 26.1 °C, respectively. Eritrea is the coolest with 22.9 °C. Actually, for the Eritrean Danakil, a very hot part of this country, climate data are not recorded on a regular basis and, for this reason, also the gridded data are not reliable. According to WMO data, reported by the Norwegian Meteorological Institute (NMI 2020) for the plain of Badda lake (about 100 m below sea level) in the centre of Eritrean Danakil depression, in the 1961–1990 interval the mean annual temperature was 29 °C, with the mean monthly maximum temperatures of 40–41 °C from June to August. In the Samoti plain (see Chap. 7 of this book for more information about this area), located about 18 km north-east of Badda, in November, the author of this paper commonly measured daytime temperatures of 42–44 °C and night-time temperatures of 28–30 °C. Travellers of the past and very sporadic earlier studies (Pedgley 1967) reported peak temperatures as high as 50 °C for the Dallol area in Ethiopia, only 16 km and 50 km south of the border with Eritrea and Badda lake, respectively. High temperatures, close to those in Danakil, are also reported for Djibouti where, in summer, the monthly mean maximum temperatures range from 37 to 41 °C, i.e. show values very similar to those recorded at Assab and Massawa (Figs. 1.5 and 1.6).

The hottest towns in the study area are Luuq and Berbera in Somalia (mean annual temperature Ta = 30.9 and 30.2 °C, respectively), followed by Beylul (30.6 °C) on the southern Red Sea coast of Eritrea, 45 km north-west of Assab, and Djibouti City (29.9 °C). The highest monthly temperatures are recorded at Luuq (42.2 °C in March) in Somalia, at Djibouti City (41.3 °C in July) and at Tennessee (40.9 °C in May) in Eritrea, close to the Sudan border.

The coolest town is Saladero (Ta = 15.6 °C; 2325 m asl) in the Eritrean highlands, about 16 km south-west of Asmara, whereas the coolest town in Somalia is Warmaddow (Ta = 16.8 °C; 2100 m asl), in the coastal range about 60 km east of Bosaso and Diyara (Ta = 20.9 °C; 1546 m asl) in the mountains of the Day Forest National Park of Djibouti. The lowest minimum monthly temperatures are recorded in January in Asmara (6.3 °C) (Fig. 1.5), Ceerigaabo (6.7 °C) (Fig. 1.7) and Day (10.9 °C) (Fig. 1.6) in Eritrea, Somalia and Djibouti, respectively.

The smallest value of the annual temperature range (Tr) is measured at Ceeldheer (Tr = 2.6 °C; Ta = 27.3 °C) on the Somali coast about 286 km north-east of Mogadishu. In Eritrea, the smallest value of Tr is recorded at Algena (Tr = 4.1 °C; Ta = 18.3) (Fig. 1.5), whereas it is 8.3 °C at Ali Sabieh (Ta = 25.6 °C) in Djibouti (Fig. 1.6). The largest annual temperature excursion is recorded at Xamass (Tr = 14.4 °C; Ta = 26.2 °C; 588 m asl) on the Gulf of Aden rift escarpment (Fig. 1.8), a few kilometres to the north-west of Burco/Burao; the second largest value of Tr is found in Djibouti City (Tr = 11.3; Ta = 29.9; 19 m asl) and the third one at Massawa on the Eritrean coast (Tr = 10.3 °C; Ta = 29.4 °C; 10 m asl).

In Eritrea, the annual temperature range tends to decrease with elevation ($R^2 = 0.61$) (Fig. 1.9) and to increase with mean annual temperature ($R^2 = 0.57$) (Fig. 1.10). Instead, no correlation was found for Somalia and Djibouti. This latter country has the largest proportion (44%) of stations with the mean annual temperatures Ta > 28 °C. In Eritrea, 27% of the stations record annual temperatures higher than 28 °C, but the proportion of stations with an annual temperature range less than 5 °C is 34% (Tr > 5 °C in all the meteo-stations of Djibouti). In Somalia, the mean annual temperatures are a bit milder (only in 20% of stations Ta > 28 °C) but hot temperatures are persistent as 36% of stations record a Tr < 5 °C and 69% of stations record a Ta > 26 °C. The World Climate Research Programme (WCRP-WMO 2011) reported daily peaks of 47–49 °C, recorded at Massawa and Assab, and extreme low values of −6.5 and −5.4 °C measured in December–January in

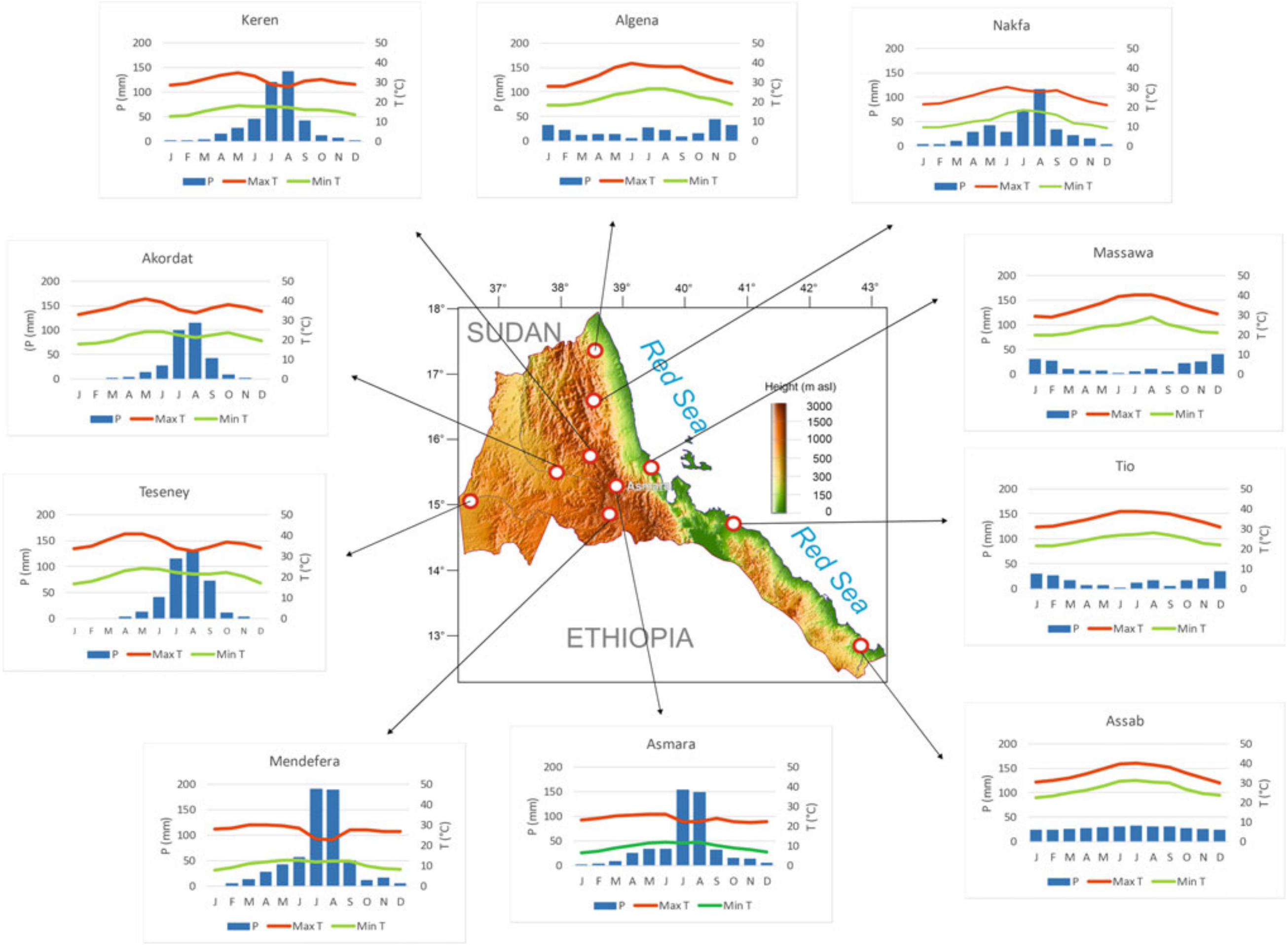


Fig. 1.5 Representative climograms of the main physiographic and climatic areas of Eritrea

Asmara. Northern Somalia experiences extreme daily temperatures, with peaks of 45 °C in July along the coastal plains of the Gulf of Aden, and December lows below zero in the highlands (Hadden 2007). The highest diurnal temperature of 52 °C, however, was measured near Lake Assal in Djibouti (Nicholson 2011).

The three countries are characterised by a significant ($0.86 < R^2 < 0.95$) temperature gradient. The decrease of mean annual temperature with elevation (commonly referred to as “lapse rate”) is 5.6, 5.9 and 5.3 °C every 1000 m in Eritrea, Djibouti and Somalia, respectively (Fig. 1.11).

1.5 Precipitation

1.5.1 General Considerations

As schematically presented in Sect. 1.3, the influence of a few main climate drivers at planetary scale, combined with the local topography and the distance from the ocean, results in different monthly rainfall patterns across the eastern countries of the Horn of Africa.

The precipitation spatial variability of Eritrea is mainly controlled by elevation, the proximity to the Red Sea and the influence of the Saharan high on the western lowlands. The eastern escarpment is, therefore, dominated by winter rains, hot temperatures and greater cloud cover, whereas the highlands have a bimodal distribution of monthly precipitation with the main, larger rainy reason in summer (July and August) and a small rainy season in spring (March–May). The summer rains result from the migration of the Intertropical Convergence Zone (ITCZ) to the north of Eritrea, and the convergence associated with it releases generalised rains in the area. The big rains run out when the ITCZ regresses southward in September. The spring rains result from high, cold westerlies encountering warm moist air flowing from the south propelled by the Arabian high pressure, weakening as it moves southward to the Indian Ocean. In the western lowlands, the majority of rain falls from July to September, when the ITCZ is in a northern position. In the eastern, coastal belt,

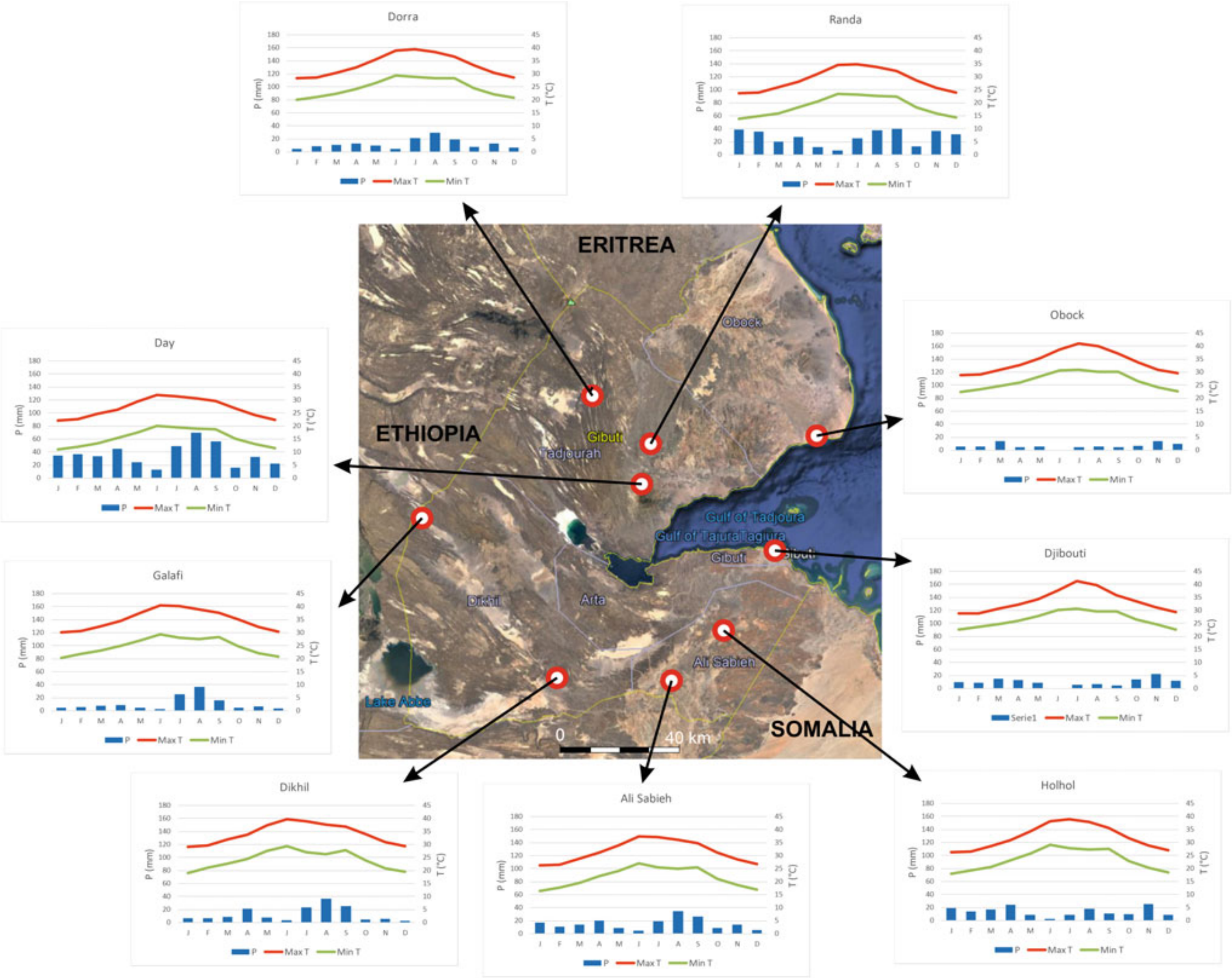


Fig. 1.6 Representative climograms of the main physiographic and climatic areas of Djibouti

precipitation is scarce and it is mainly concentrated in winter, when the Indian Ocean easterlies and the Atlantic westerlies converge (Ethiopian Mapping Authority 1988; Van Buskirk and Amare 1994) (Fig. 1.5).

In Somalia, rains are highly variable in space and time (Fig. 1.7). They are mainly controlled by the northward and southward movement of the ITCZ, giving way to two distinct rainfall seasons: the spring main rainy season (April–June) (*Gu* in the local language) and the small rains (October–November) (*Deyr* in the local language). The position of the ITCZ and the pressure characteristics of the air masses over Arabia and India influence also the prevailing winds over Somalia. In January, the north-easterly winds prevail. They originate over Arabia; hence, they are dry, hot and cloudless (Fig. 1.12). In April and October, the ITCZ is passing over Somalia in its northward and southward movement, respectively, and south-easterly and north-easterly winds meet in a convergence zone resulting in the upward movement of air which, on its turn, causes condensation, cloud formation and rainfall (Fig. 1.12). In July, moist winds flow from the Indian Ocean and, as they cross the equator, become the south-west monsoon. A narrow belt of convergence is then formed, especially along the southern Somali coast, which receives substantial amounts of rain (Fig. 1.12) (Muchiri 2007).

The precipitation pattern of Djibouti shares the climatic characteristics recorded by the coastal meteo-stations in southern Eritrea and northern Somalia. In the inland areas of Djibouti, the monthly rainfall pattern may be both unimodal or bimodal, but the main rainy season is always in July–August. In the coastal areas, rain is very small and falls mainly in winter (Fig. 1.6).

It is worth recalling here that the same considerations about the general quality of temperature data are valid for precipitation as regards the source of data (ground instrumental measurement and gridded data), length of observations and rain gauges distribution over the territory.

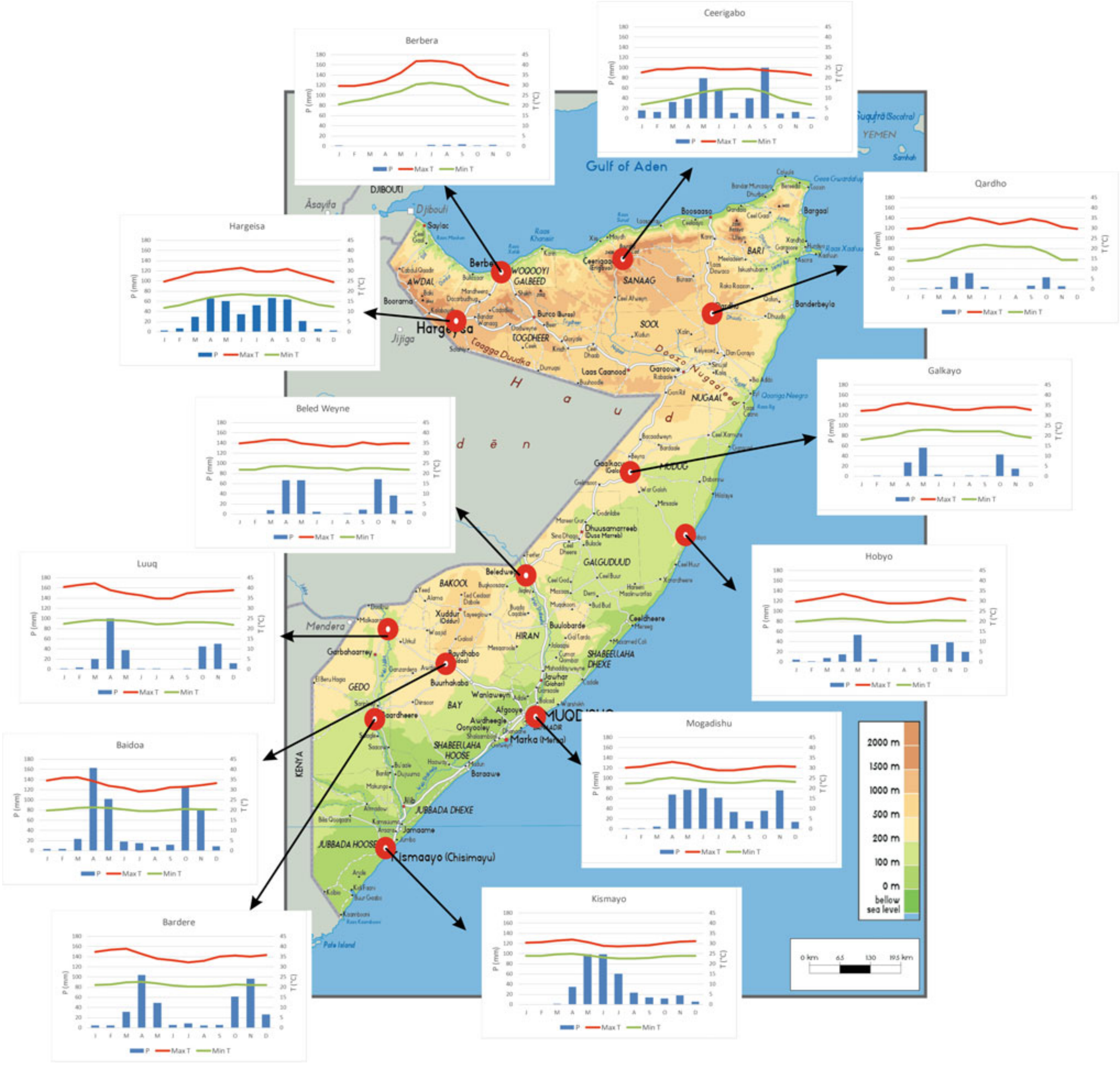


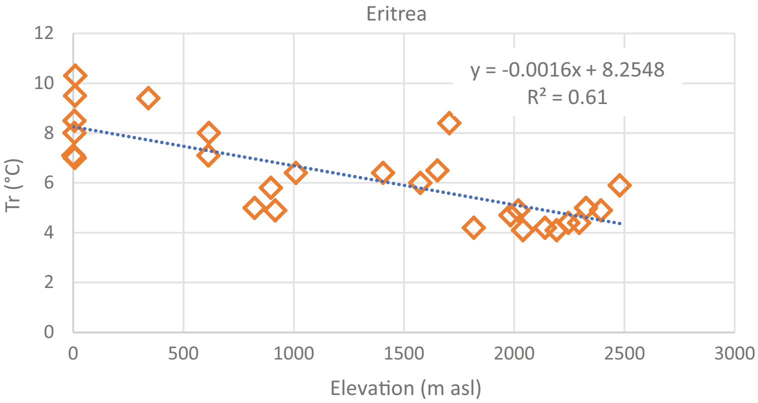
Fig. 1.7 Representative climograms of the main physiographic and climatic areas of Somalia

The Precipitation Concentration Index (PCI) (Oliver 1980) varies from 10.2 to 26 across Eritrea and indicates a wide range of rain seasonality (from moderate to strongly seasonal distribution). A slightly smaller PCI range (9.5–24.5) is calculated for Somalia, which implies a rain seasonality grade similar to that of Eritrea. In Djibouti, the PCI range is smaller (9.5–13.3) indicating a moderate seasonality of rain. These results reflect the complex interactions of factors controlling precipitation over the eastern Horn of Africa.

The first synthetic result, obtained from averaging the annual precipitation (P) of all the meteo-station used in this study, indicates Eritrea as the country that receives the largest amount of rain, 421.9 mm, followed by Somalia, 308.7 mm, and Djibouti, 240.3 mm. These differences are also confirmed by the spatial distribution of rain in the three countries. In Eritrea, in fact, 76% of the rain gauges considered record an annual precipitation higher than 250 mm, whereas in Somalia and Djibouti the percentages decrease to 57 and 37%, respectively. The higher percentage in Eritrea is probably due to the lack of data in the driest zones of this country, i.e. the Danakil and the western lowlands (Fig. 1.3), and to a larger number of meteo-stations located at higher elevations than in the other two countries (Fig. 1.11).

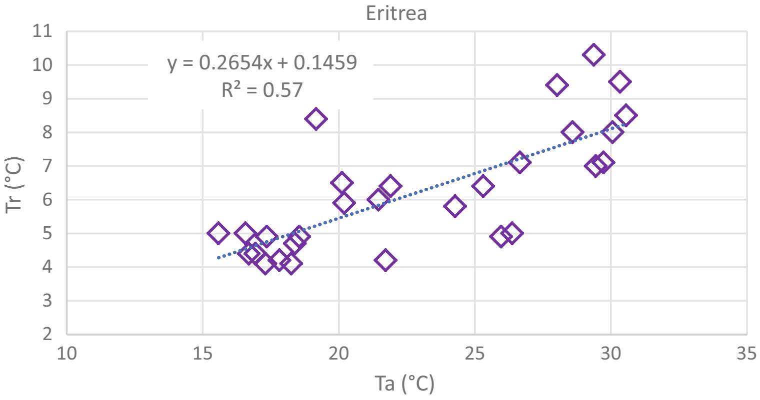
Fig. 1.8 Northern Somalia escarpment facing the Gulf of Aden near Sheikh

Fig. 1.9 Change of annual temperature range (Tr) with elevation in Eritrea



Among the meteo-stations considered, the wettest one is Nefasit (766 mm), in the main escarpment, about 14 km east of Asmara. Nefasit is not located at 1652 m asl, i.e. an intermediate elevation for Eritrea, but its higher than average precipitation is due to an additional rainfall contribution from the condensation of the moist winds coming from the Red Sea in winter. The highest annual precipitation of Djibouti is recorded at Diyara (439 mm) in the Day Forest National Park, whereas the wettest meteo-station of Somalia is Buur Gaabo (595.5 mm), on the southern coast of Somalia, about 56 km from the border with Kenya. The meteo-station with the lowest rainfall of Eritrea is Beylul (69 mm), located on the Red Sea coast, about 46 km north-west of Assab. As already reported, the lack of data from the Eritrean Danakil does not allow to make any consideration about rainfall in this area, but presumably there are sites which may receive less than 50 mm of rain in a year (Fig. 1.13). The same argument could be brought about for central Somalia, where we find the lowest precipitation for this country at Abudwak (35 mm), or the

Fig. 1.10 Change of annual temperature range (Tr) with mean annual temperature (Ta) in Eritrea



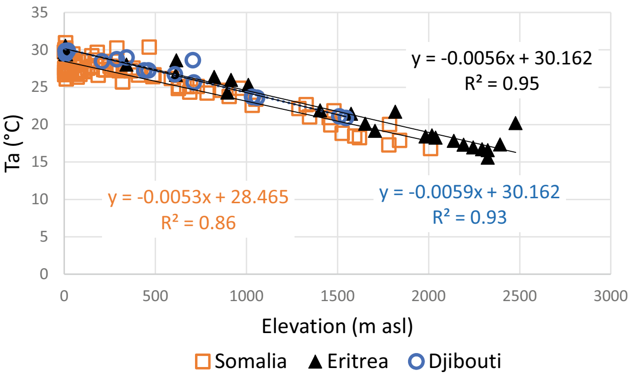


Fig. 1.11 Lapse rate in Eritrea, Djibouti and Somalia

northern coastal areas (Fig. 1.14). The lowest precipitation of Djibouti is recorded at Obock (91.1 mm) on the northern coast, opposite to Djibouti City.

In the areas of Eritrea with a unimodal monthly precipitation pattern, the summer (July–September) main rainy season accounts from 60 to 80% of the annual precipitation. In Somalia, the main rainy season (*Gu*, April–June) and the minor one (*Deyr*, October–November) on average amount to 46% (range 18–62%) and 25.5% (range 5–46%) of the annual precipitation, whereas in Djibouti no specific main rainy season can be clearly identified since precipitation is rather uniformly distributed in every month, as confirmed by the average PCI = 10.6.

Unfortunately, hourly rainfall intensity data are not available and also daily data are scarce. According to the WCRP-WMO (2011) report, extreme intensities of 143 and 124 mm in 3:30 and 3:50 h, respectively, have been recorded in Asmara. Extreme daily intensities were measured in Massawa (113–130 mm/24 h and 364 mm/48 h), Akordat (113 mm/24 h) and Teseney (109 mm/24 h) (WCRP-WMO 2011). For this study, daily rainfall data of Somalia were available only for Galkayo, Garowe, Hargeisa and Mandera (a small town in Kenya near the triple border junction with Somalia and Ethiopia, on the Dawa River, the largest tributary of the Juba River). The highest precipitation in 24 h (89.7 mm/24 h) was measured in Garowe (*P* = 121.2 mm yr^{-1}), a small town in the Nogal valley, about 155 km from the Indian Ocean coast. Other meteo-stations recorded slightly lower intensities, e.g. 82.9 mm/24 h in Hargeisa (*P* = 327 mm yr^{-1}), 64.3 mm/24 h in Mandera (*P* = 584 mm yr^{-1}) and 60.7 mm/24 h in Galkayo (*P* = 183 mm yr^{-1}), located about 200 km south of Garowe and about 190 km far from the Indian Ocean (Fig. 1.7). It is worth noticing that the highest daily intensity was measured in an arid area (Garowe), where the annual precipitation is the least. No daily rainfall data were instead available for Djibouti. The town of Gode is located in Ethiopia, but it is only 122 km from the border with Somalia and subjected to an arid climate (annual precipitation is only 237 mm), similar to that of the Somali territories beyond the border. In Gode, the maximum daily intensity ever recorded by the local meteo-station was 174 mm/24 h; one can therefore expect similar values for inland areas of central Somalia.

Drought is a recurrent event in the three countries, with hundreds of thousands of affected people (Fig. 1.15). According to Nicholson (2014), droughts in the Horn of Africa are a consequence of years with annual rainfall 30–75% below normal. Other authors (e.g. Marthews et al. 2015) attribute an important role in the failure of the long rains to human influence: higher temperatures caused by human activities have been resulting in an increased net incoming radiation at the surface. Lott et al. (2013) framed the reduced precipitation during the main rainy season in the Horn of Africa within the global warming rather than invoked the effects of a local anthropogenic change.

Djibouti shows a distinctive (R^2 = 0.88) control of elevation on annual precipitation gradient (Fig. 1.16), whereas the change of annual precipitation is poorly correlated with elevation in Eritrea (R^2 = 0.49). In Somalia, a weak, inverse precipitation gradient exists only if the data of the dry and hot coastal stations and those of the Bur Region are neglected and only meteo-stations at elevation <500 m asl are considered (Fig. 1.17). This very unusual result may

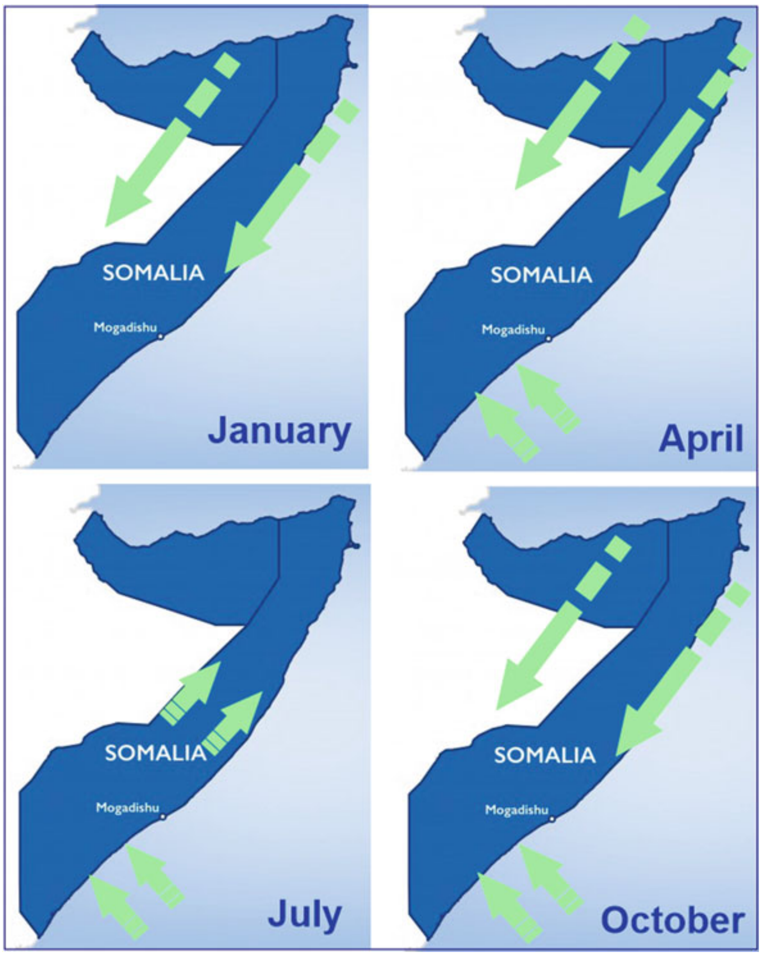


Fig. 1.12 Prevailing winds over Somalia in different seasons (modified from Muchiri 2007)

depend on the high spatial variability of precipitation across Somalia, associated with the distance from the ocean. A large portion of Somalia is a uniform tableland, gently inclined towards the ocean, and the elevation of inner meteo-stations is typically lower than 500 m asl. The influence of the moist winds coming from the ocean tends to progressively decrease as they move to the hotter inland and lose humidity all the way long.

1.5.2 Rainfall Erosivity

According to FAO (Nana-Sinkam 1995), many African countries have already lost a significant quantity of their soils, subject to various forms of degradation. Many areas in Africa are said to be losing over 50 tonnes of soil per hectare per year and the countries of Horn of Africa are not exempt from such a calamity (Figs. 1.18 and 1.19). Soil degradation caused by rainfall-induced erosion, desertification, deforestation, and poor agricultural practices is undermining the very resources on which people depend for their survival. Land degradation is typically expressed by the occurrence of deep gullies, the origin of crusts that water cannot infiltrate, and laterite that hand tools and plant roots cannot penetrate.

A complex combination of several factors determines the rate of soil erosion. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1958) and its revised forms (e.g. RUSLE) (Renard et al. 1997) were the first successful attempt to quantify the role of the main factors involved and to suggest the way to measure them. Rainfall is definitely the triggering factor in hydrological soil erosion. Rainfall erosivity is the capacity of rain to detach soil particles and to generate overland flow which, in turn, entrains soil particles. Rainfall erosivity is a function of physical characteristics of precipitation and its energy (Nyssen et al. 2005). The procedure to calculate the USLE rainfall factor (*R*-factor) proposed by Wischmeier and Smith (1958) is rather complex and surrogate or alternative factors, easier to be calculated, have been proposed in the literature. Most of them are based on the annual precipitation (e.g. Renard and Freimund 1994; Eq. 1.3) or on the concentration of monthly rain as the Modified Fournier Index (MFI) proposed by Arnoldus (1980) (Eq. 1.2). Lee and Heo (2011) tested eight alternative methods (including the MFI and the Renard and Freimund's

Fig. 1.13 Drylands in the Eritrean Danakil about 150 km south of Massawa

R-factor) to calculate rainfall erosivity against more than 20 years of actual rainfall erosivity calculated by high resolution precipitation data in South Korea. They concluded that both annual precipitation and alternative parameters could be used for Korea, but their regression models had limitations when used to predict actual rainfall erosivity in other locations and the simplified methods for estimating rainfall erosivity should be used with caution.

In Horn of Africa countries, rainfall data sets are commonly incomplete and cover short periods. Hourly data are not available, and the only reliable precipitation data are those about monthly rainfall (and daily data, but only for few meteo-station). For these reasons, though the argument of Lee and Heo (2011) is embraceable, in order to explore the geomorphological effectiveness of rainfall in the study area, Arnoldus's (1980) MFI and the *R*-factor of Renard and Freimund (1994) were used. In Eritrea, the MFI ranges between 8 and 153, with 45% of the meteo-stations recording MFI values higher than 120, i.e. from moderate to high erosivity (Gabriels 2006) (Table 1.1). The *R*-factor ranges between 44 and 2126 MJ mm ha^{-1} h^{-1} yr^{-1} and values higher than 1150 MJ mm ha^{-1} h^{-1} yr^{-1}, indicating moderate to high erosivity (Panagos et al. 2017) (Table 1.3), are calculated for 31% of the meteo-stations. It is worth noticing that while the lowest values of both parameters are calculated for the area of Beylul, where also the lowest annual precipitation is recorded, the highest value of the MFI is calculated for the meteo-station of Bet Ansian (a small village located on the southern part of the central highlands, close to the Ethiopian border), where the second largest annual precipitation is recorded, whereas the highest value of the *R*-factor is measured at the meteo-station with the highest annual precipitation, which is not surprising since this parameter is directly proportional to the annual rain (Eq. 1.3).

Djibouti is characterised by very low ($9 < \text{MFI} < 44$) (Table 1.1) and very low to moderate ($69 < R\text{-factor} < 868$) (Table 1.3) rainfall erosivity. Both the lowest and highest

Fig. 1.14 Arid coastal belt a few kilometres south of Berbera in northern Somalia

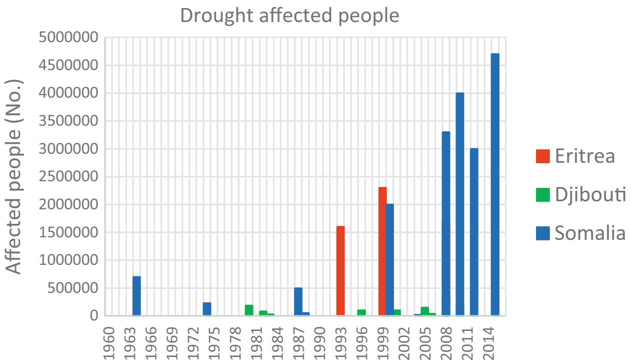


Fig. 1.15 Number of drought affected people in the study countries since 1960

erosivity of both parameters are calculated for the sites of Obock, on the northern coast, and Diyara, in the Day Forest National Park, respectively. The range extremes of both parameters coincide with the smallest and largest annual rainfall. The range of rainfall erosivity calculated for Somalia is larger than for Djibouti, but narrower than for Eritrea. The MFI, in fact, ranges from 5 to 109, i.e. from very low to moderate erosivity (Table 1.1), and the *R*-factor ranges from 15 to 1417 MJ mm ha^{-1} h^{-1} yr^{-1}, that is from moderate to high erosivity (Table 1.3). The MFI extremes do not coincide with the lowest and largest values of annual precipitation, but are very close to them. The former are recorded at Bosaso, on the northern coast and at Ischia (in the local language it means water spring) Baidoa in the Bur Region.

A rough comparison with the actual conditions of land degradation and soil erosion of the sites, where the extreme low or high rainfall erosivity was observed, seems to confirm the conclusion of Lee and Heo (2011) that these alternative methods to express rainfall erosivity are probably not very effective in addressing the real amount of energy transferred by the rain to the soil. In Horn of Africa countries, the wide variability in temperature, rainfall distribution, geographic position and elevation and, ultimately, human impact, play an important role as well. More studies in arid and semi-arid regions are however needed to investigate the effectiveness of the MFI and the *R*-factor in providing even broad reference values of rainfall erosivity.

Fig. 1.16 Variation of mean annual precipitation with elevation in Eritrea and Djibouti

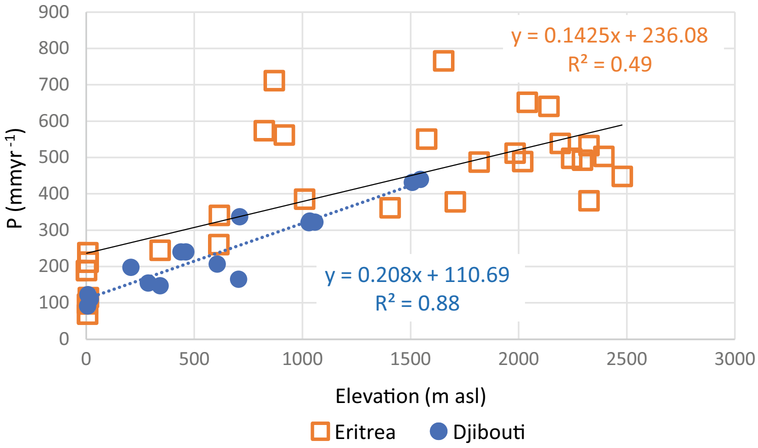
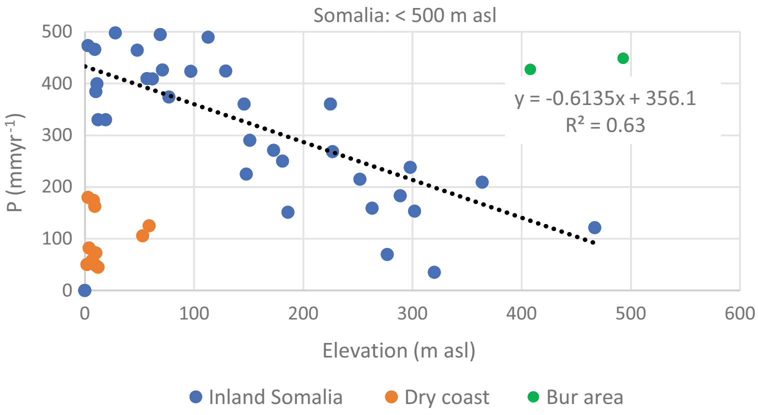


Fig. 1.17 Variation of mean annual precipitation with elevation in Somalia



1.6 Relative Humidity

Only very few data of relative humidity data are available for Eritrea and Djibouti. The higher values are recorded on the coast in February–April, with 74–77 and 69–71% at Massawa and Assab, respectively (Fig. 1.20). In Asmara, relative humidity shows a peak in August and September (73–78%), whereas in other months it ranges between 43 and 62% (Fig. 1.20). Lower values of relative humidity (29–61%) (Fig. 1.20) are recorded at Teseney, in the Eritrean western lowlands (Fig. 1.5) close to the Sudan border. In Djibouti, relative humidity is rather constant 70–75% every month, with the exception of summer months (June–September), during which relative humidity values range from 40% in July to 55% in September.

The data of relative humidity are more abundant for Somalia thanks to the data set compiled by FAO-SWALIM (Muchiri 2007). The Somali sites with higher relative humidity are found on the coast, whereas those with lower values are located inland or in areas at higher elevation, as illustrated by the analysis of selected meteo-stations reported in Fig. 1.21. Mogadishu, Hobyo and Kismayo experience high relative humidity conditions all year round ranging from 75 to 80%. Berbera and Bosaso have similar values but in summer (June–September) relative humidity falls down to 53–59% (Fig. 1.21a). By contrast, inland areas and more elevated sites in Somalia have more pleasant climate, characterised by lower values of relative humidity ranging from 47 to 64% (Fig. 1.21).

1.7 Wind

Wind data are also scarce and, in a few cases, they are not measured with standard instrumentation and procedures (Rosen et al. 1999; Muchiri 2007). According to the Government of Eritrea (2007) report on Wind Energy Applications in Eritrea, a total of 20 wind recording stations were operating in 2007. Unfortunately, the data published in that report refer to a small number of stations and cover a very short interval of 3–4 years (2000–2004). More data are available for Somalia thanks, once again, to the FAO-SWALIM project (Muchiri 2007). All the wind data available for this study refer to average monthly wind velocities.

Fig. 1.18 Degraded land south of Mendefera in the southern highlands of Eritrea close to the border with Ethiopia

On the basis of data available for this study, higher wind velocities of Eritrea are recorded at Massawa and Asmara (Fig. 1.22), with 5.6 m s^{-1} average velocity measured at Massawa from April to July. At Asmara, wind velocity is slightly lower than in Massawa, but more constant in every month, with values around 4.6 m s^{-1}. The inland meteo-stations of Akordat and Teseney record lower but rather invariable wind velocities around 2.0 and 1.8 m s^{-1}, respectively, throughout the whole year. Intermediate velocities (around 2.8 m s^{-1}) are observed at Edd, a small village on the Red Sea coast, about 150 km north of Assab. Wind directions are not available.

Faster winds are measured in Djibouti where the meteo-stations of Obock and Djibouti City report a range of 3.1–5.1 m s^{-1} (higher velocities occurring in July and September) and 3.3–5.28 m s^{-1} (higher velocities recorded in August and September), respectively (Fig. 1.23).

In Somalia, wind velocity and direction are substantially influenced by the movement of the ITCZ and the local physiography (especially in the north) (Muchiri 2007). The strongest winds of Somalia (8.4–11.5 m s^{-1}) are recorded in summer (June–August), during the south-westerly monsoon, primarily in the northern part of the country, but also in Mogadishu, though with slower winds (5.6–7.8 m s^{-1}) (Fig. 1.24). Mogadishu experiences the highest wind velocity in winter (8.9 m s^{-1}, in February), whereas Luuq and Jowhar record similar, lower velocities (2.2–4.2 m s^{-1}). At Hobyo, higher values, close to those in Mogadishu, with a peak of 6.7 m s^{-1} are recorded in July–August and a low value of 4.2 m s^{-1} typifies November and December (Fig. 1.24).

General information about the prevailing wind direction can be obtained from the orientation of aeolian landforms. In the southern coastal strip of Eritrea, barchanoid dunes (Fig. 1.25) indicate a prevailing, strong wind from south-east. A similar orientation of sand dunes can be observed in the Samoti plain in the northern part of the Eritrean Danakil (see Chap. 7). The wind responsible for the morphology and movement of these dunes is locally known as “*khamsin*”. It is a dry, hot and rather intense wind (gusts may reach a velocity of 22 m s^{-1}) coming from south-east and blowing for a few days without interruption. Sometimes, it is also able to generate dust storms. The *khamsin* is active from late winter to late spring, and it is generated by high-pressure cells over the northern Arabian Peninsula and Mediterranean deep depressions moving eastward. In the

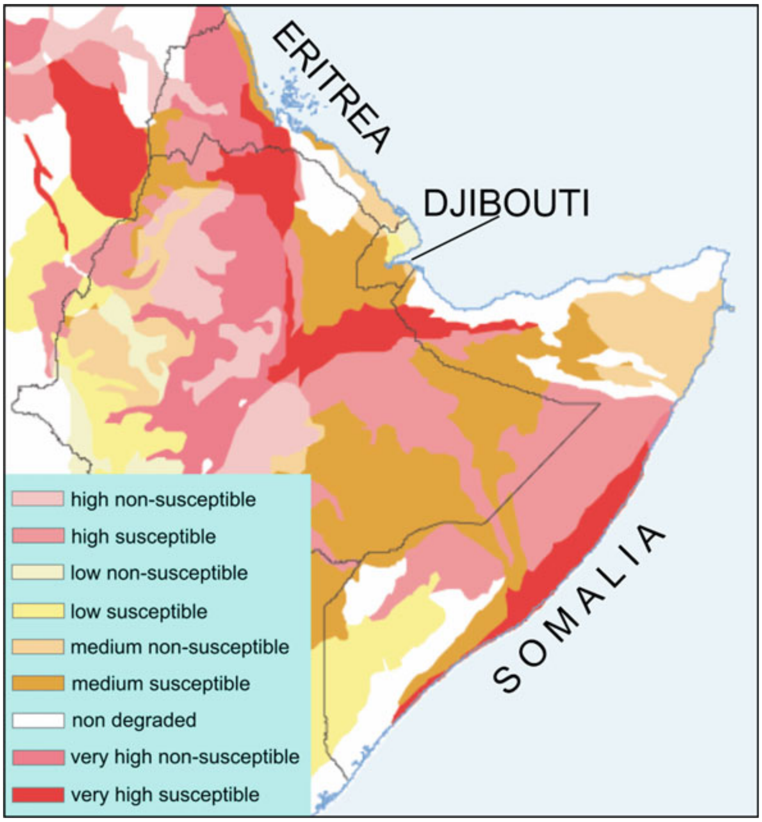


Fig. 1.19 Map of the susceptibility to erosion in the study countries (modified from UNEP 2010)

Table 1.3 Classification of erosivity *R*-factor based on Panagos et al. (2017)

R-factor	Description
<200	Very low
200–400	Low
400–1150	Moderate
1150–3100	High
>3100	Very high

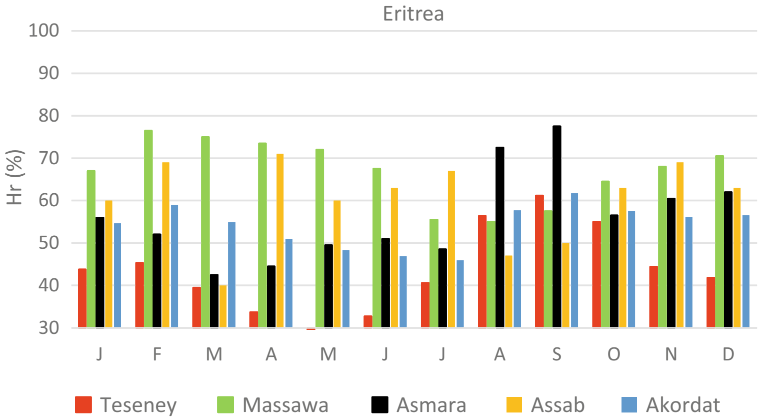
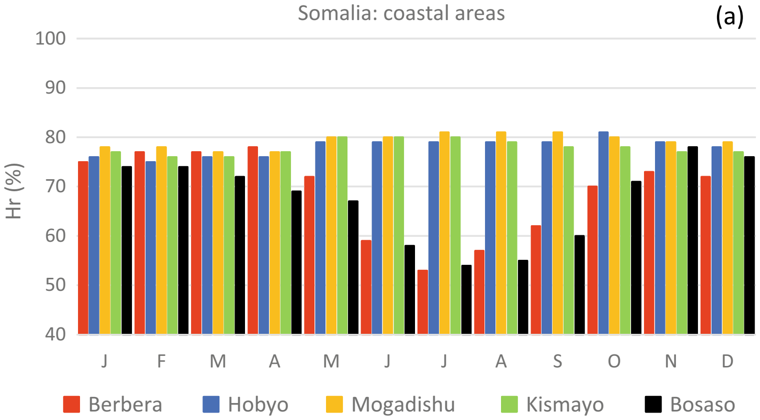


Fig. 1.20 Mean monthly relative humidity in selected meteo-stations of Eritrea

Fig. 1.21 Mean monthly relative humidity of selected meteo-stations in the coastal areas (**a**) and in the inland and highlands (**b**) of Somalia



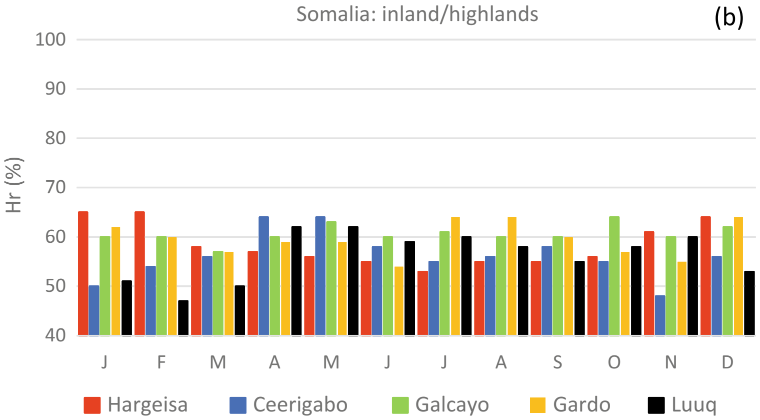
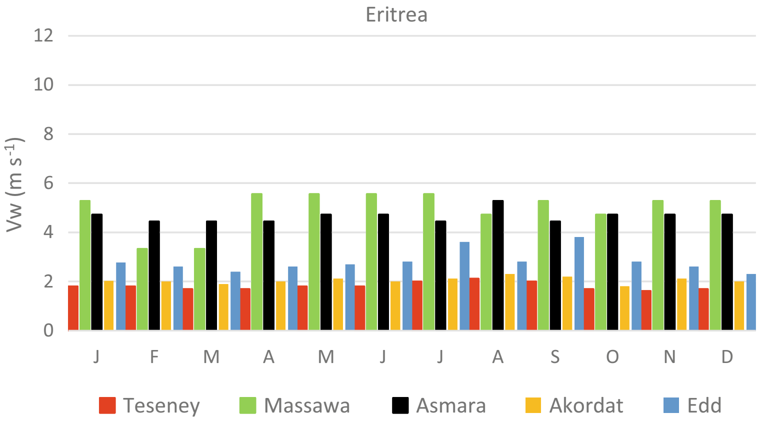


Fig. 1.22 Mean monthly wind velocity in selected meteo-stations of Eritrea



central coastal belt, instead, linear dunes (Fig. 1.26) indicate winds with a north–south direction. According to the observations of Fantoli (1940), at Massawa and on the coast, the dominant winds are from the south-east. In winter, they alternate with a mainly northerly airflow produced by the North African anticyclone and directed towards the Red Sea low pressure trough. As a result, the northern part of the Red Sea is exposed to predominantly north-west to north winds that can also reach the northern coast of Eritrea (Fantoli 1940; Edwards 1987).

This alternation may be responsible for the formation of linear dunes. According to a few authors (e.g. Tsoar 1989; Lancaster 2011), field observations indicate that linear dunes are formed under conditions of a bidirectional wind regime, with the two modes separated by 90° or more, and are parallel to the resultant wind. Recent studies, however,