Chapter 2
Climate Conditions and Classification

2.1 The Climate Elements

The climatic elements to be considered for open-air and protected cultivation of plants are (von Zabeltitz and Baudoin 1999):

- Solar radiation
- Temperature
- Precipitation
- Humidity
- Evaporation and evapotranspiration
- Wind velocity

The relationship between precipitation and evapotranspiration plays an important role for open-field cultivation. Crops under protected cultivation receive all their water by irrigation systems. If rainwater storage for irrigation is planned, the relationship precipitation to evapotranspiration inside the greenhouse has to be taken into consideration.

2.1.1 Solar Radiation

The solar radiation at the edge of the earth's atmosphere, called solar constant, is 1,349 kW/m^2. Solar radiation is reduced in the earth's atmosphere by reflection, absorption and scattering, so that only part of it reaches the earth's surface. The solar radiation on the earth's surface changes with latitude, season, and time of day, as well as by the various radiation losses in the earth's atmosphere, e.g., clouds and haze.

Figure 2.1 shows the *annual mean of daily solar radiation* energy (kWh/m^2 day) at the earth's surface in relation to the latitude (von Zabeltitz and Baudoin 1999). Average solar radiation increases from very low mean values at the poles up to 20°

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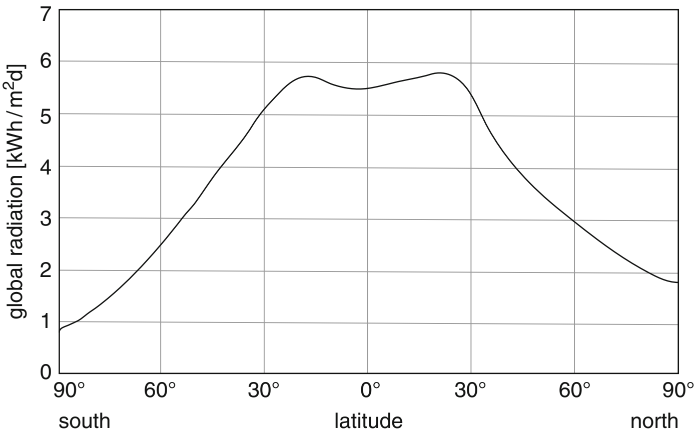
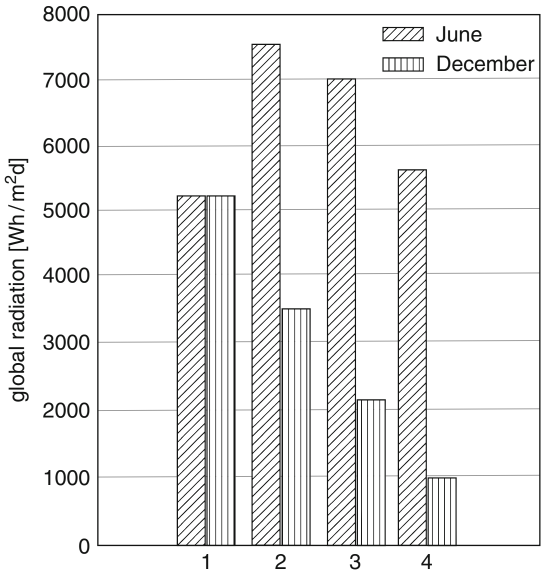


Fig. 2.1 Annual means of global radiation depending on the latitude

Fig. 2.2 Mean daily sum of global radiation for different latitudes. (*1*) Equator zone, (*2*) 25°–30° north, (*3*) 35°–40° north, (*4*) 45°–55° north (von Zabeltitz and Baudoin 1999)



latitude. In the equatorial zone, the mean solar radiation remains almost constant. A high amount of vapor in the atmosphere results here in extremely high radiation losses.

For the production of plants, it is important to know the *monthly mean* of daily solar radiation energy. Figure 2.2 shows the mean daily sum of solar radiation for different latitudes of the northern hemisphere in the months of June and December. The daily solar radiation in the equatorial zone (1) is the same in summer and in winter, while the other zones show considerable differences between summer and winter. Daily solar radiation decreases in summer and winter evenly with growing latitudes. The same is true for the southern hemisphere.

Figure 2.3 indicates the annual course of the daily solar radiation for different locations. Variations are small in the equatorial zone in the course of the year. Some locations show maxima in March/April and in September/October (Mogadishu, Bongabo). Higher latitudes show strong annual amplitude. Solar radiation sums for Mediterranean countries in summer, i.e., in latitudes between 30° and 40°, are often higher than at the equator. This also depends on the different day lengths and on the mean sum of daily hours of sunshine (Fig. 2.4).

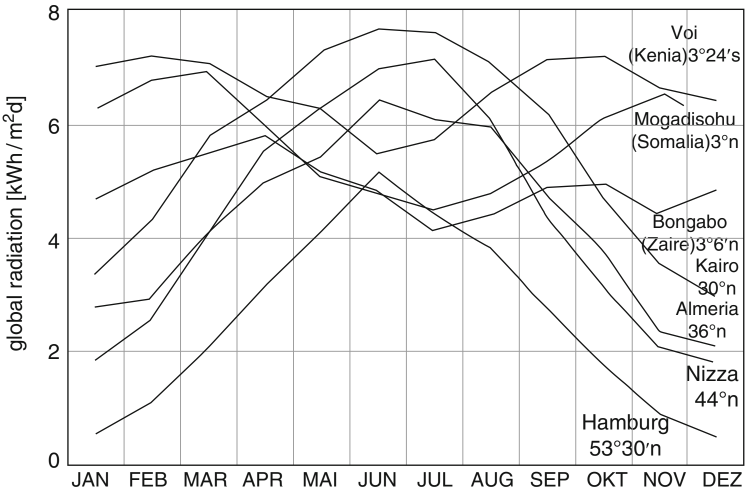


Fig. 2.3 Mean daily sum of global radiation in different months for different locations (von Zabeltitz and Baudoin 1999)

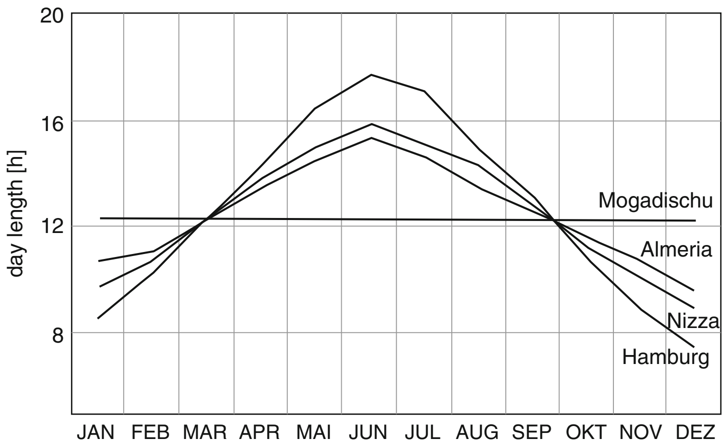


Fig. 2.4 Day lengths of different locations

The production of plant dry matter decreases almost linearly with the radiation at low solar radiation values. The growth comes to a halt at the compensation point, which is at 14–30 W/m^2 light power for plants (0.1 kWh/m^2 day) (Krug et al. 2002). An efficient production of dry matter cannot be expected in higher northern and southern latitudes during winter without artificial lighting.

The minimum amount of irradiation necessary to ensure sufficient growth and flowering corresponds to a daily global radiation of 2.0–2.3 kWh/m^2 day (Nisen et al. 1984). The solar radiation values in the equatorial zone do not drop below the minimum during the year, and do not fall below the minimum even in winter in higher latitudes up to 40°. Vegetable varieties are adapted to the day length. For tropical regions, appropriate varieties must be chosen with regard to the shorter day length during summer. The light loss in greenhouses should be considered.

Most important for photosynthesis, i.e., the growth of plants, is solar radiation power (W/m^2). Figure 2.5 shows the mean solar radiation (W/m^2) in relation to time of day at various locations. The maximum solar radiation at lower latitudes at noon can be very high (Voi, Kenya) because of the relatively short day length in summer. Shading may be necessary if the radiation power becomes too high.

Cloud conditions and altitude above sea level produce significant deviations from the mean radiation distribution.

- Due to *heavy cloud and high precipitation*, radiation in equatorial zones is constantly reduced. In regions with distinct rainy seasons, the decrease in radiation is limited to these seasons.
- With *increasing altitude*, radiation is intensified. Corresponding climatic conditions can be found, e.g., in the tropic plateaus of Ecuador, Colombia and Kenya near the equator.

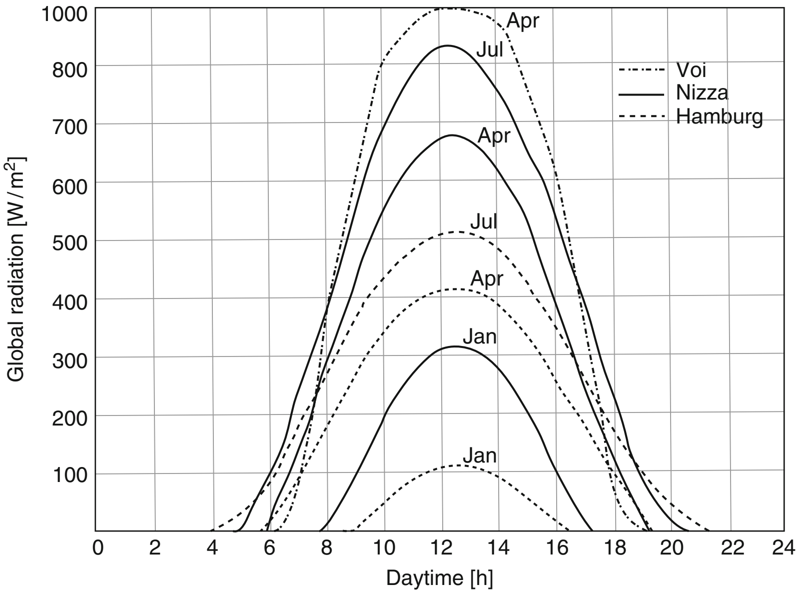


Fig. 2.5 Mean hourly global radiation at different locations (von Zabeltitz and Baudoin 1999)

The mean daily sum of global radiation in the months of the year can be found for many stations all over the world in Müller (1996) and from FAO, Rome (http://www.fao.org/ag/AGLN/climwat.stne).

2.1.2 Temperature

The course of temperature for a location depends on radiation, season and altitude above sea level, distance to seas, wind conditions and cloud conditions. Therefore, it is difficult to make general statements.

The conditions shown in Figs. 2.6 and 2.7 result from considering only mean temperatures up to an altitude of 500 m above sea level (von Zabeltitz and Baudoin 1999). Figure 2.6 shows the mean daily maximum temperatures for the warmest (t_{maxw}) and the coldest (t_{maxc}) month in relation to latitudes of the northern hemisphere. The same is true for southern latitudes.

The mean of maximum temperatures in the warmest months is 33°C at the equator. It rises to 37°C at the 27th latitude. Then it drops to 23°C at the 50th latitude. Scattering around the mean value increases from the equator to the 39th latitude and then decreases. The mean of the maximum temperatures in the coldest month hardly differs from the warmest month at the equator. It only starts sinking considerably from the 18th latitude on. Scattering around the mean grows with increasing latitudes.

Correspondingly, Fig. 2.7 shows the mean daily minimum temperatures in the warmest (t_{minw}) and in the coldest (t_{minc}) month. The course of the minimum

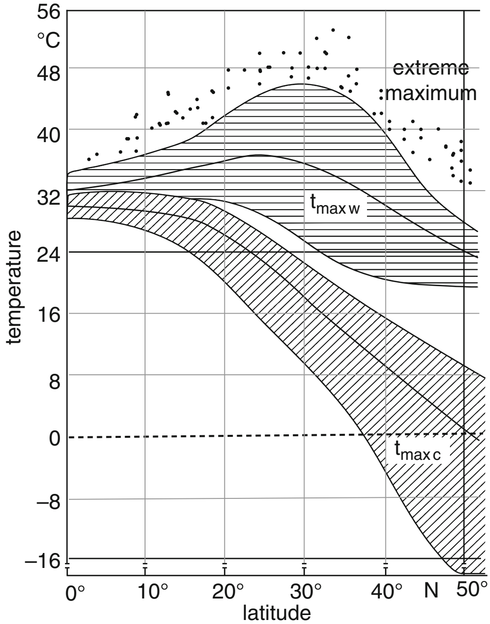


Fig. 2.6 Mean daily maximum temperatures for the warmest (t_{maxw}) and coldest (t_{maxc}) month of the year and extreme maximum temperatures depending on northern latitudes

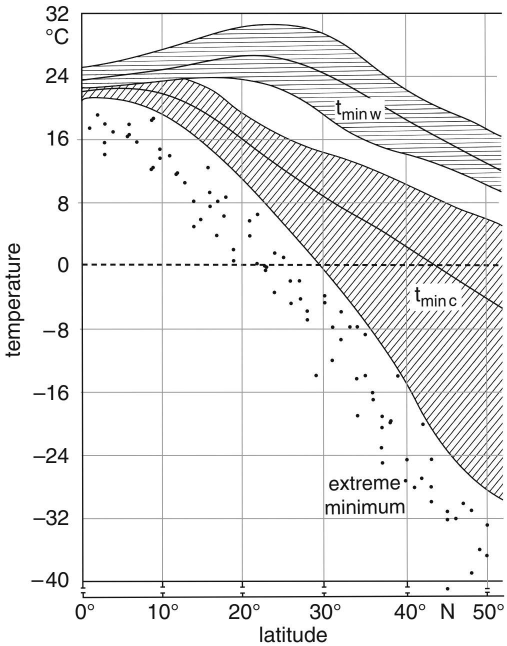


Fig. 2.7 Mean daily minimum temperatures for the warmest (t_{minw}) and coldest (t_{minc}) month of the year and extreme minimum temperatures depending on northern latitudes

temperatures is similar to that for the maximum temperatures; only the temperature scales are shifted.

A survey of the mean temperature variation between the warmest and coldest months is given in Fig. 2.8. The differences of the means of Figs. 2.6 and 2.7 are as follows:

- Latitudes 0°–10°:

The mean temperature differences between the warmest and coldest months are smaller than 5°C.

- Latitudes 0°–23°:

The mean temperature differences are smaller than 13°C.

- Latitudes 23°–48°:

The mean maximum temperature differences between the warmest and coldest months rise continuously up to 24°C at the 48th latitude. The mean minimum temperature differences rise up to ~17°C and then stagnate. The temperature differences between the extreme values are much bigger.

At temperatures between 0°C and 8°C, the growth rate of vegetables is small, and fruit may even be destroyed. Absolute minimum temperatures should be above 0°C. Optimal growth rates are guaranteed at temperatures between 20°C and 30°C.

Compared to those temperature values for vegetable growth, good conditions for vegetable cultivation are given up to the 23th latitude. Open-air cultivation throughout the year is possible.

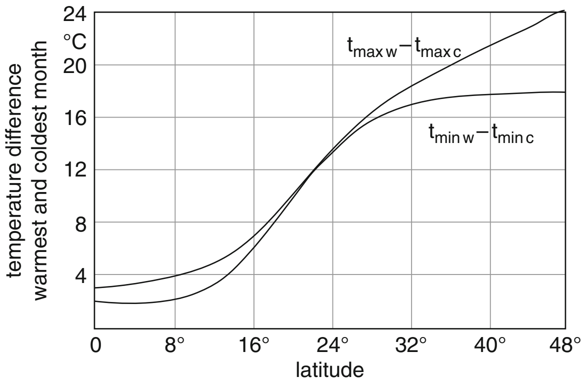


Fig. 2.8 Temperature differences between warmest and coldest month depending on latitude

In the climatic zones between the 23th and 40th latitudes, problems resulting from extreme excess temperatures and the danger of frost have to be considered. A year-round plant production in greenhouses without cooling and heating encounters difficulties.

For more detailed information, the local microclimate of the country or location in question has to be examined, as temperatures also depend on altitude above sea level, distance to the seas, wind, and cloud conditions. Data can be found in Müller (1996) and FAO (http://www.fao.org/ag/AGLN/climwat.stne). More examples and figures for crop growth requirements are given in Chap. 3.

Some main conclusions are:

- Temperatures sink with increasing altitude above sea level. In tropic plateaus and mountains, temperature extremes do not change between summer and winter (Fig. 2.9), but every 12 h between day and night. In spite of high day temperatures, near-zero temperatures can be reached at night in highlands. This cannot be seen from the monthly means.
- The temperature amplitude grows with increasing distance to the seas (continental climate).
- The effects of cold air can advance further down than to the 30th latitude.
- The cloud conditions influence the sun radiation and the long-wave radiation of the earth. During the rainy seasons, temperatures change because of clouds. Lower radiation during the day reduces the warming up; reduced long-wave radiation during the night reduces the cooling. The course of temperatures is more even.

Figure 2.9 shows the extreme maximum and minimum temperatures for the Seychelles at sea level and for Bogota, Colombia, at an elevation of 2,556 m. Even temperatures suitable for vegetable production throughout the year are given at regions near sea level. Extreme minimum temperatures can range below the biological optimum in highlands.

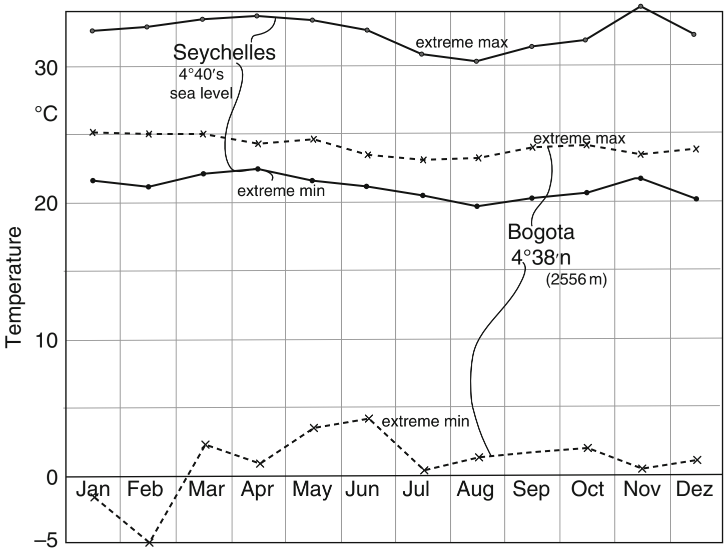


Fig. 2.9 Extreme maximum and minimum temperatures for the Seychelles (sea level) and Bogotá (highland), Colombia

2.1.3 Precipitation

Water is a vital element for plant growth. In order to evaluate protected cultivation in a region, it is necessary to have information about the most important characteristics of rainfall, e.g., total quantity, seasonal distribution, intensity, and frequency. Variability from year to year is also an important factor.

Greenhouses must have gutters in regions with heavy rainfall to drain off the water and to avoid penetration into the greenhouse.

Together with precipitation, evapotranspiration is an important element, especially for the water supply (water balance) in open-air cultivation. Under protected cultivation, the total water consumption of the plants is covered by irrigation systems, but rainwater can be collected for irrigation if enough rainfall is available for economical design of storage facilities (see Chaps.13 and 14). Evapotranspiration in the greenhouse is important in order to estimate water consumption and necessary water quantity for irrigation. A comparison of the crop water requirement and the possible amount of storable rainwater makes it possible to calculate the volume of rainwater storage.

Figures 2.10–2.12 (von Zabeltitz and Baudoin 1999) show the mean annual precipitation in different countries of the earth (Trewartha et al. 1980) and the coefficients of variation as standard deviation in percent of the average (Duckham and Hasefield 1971). Variation in precipitation may change over the years due to global climate change, but the given coefficients give an idea of the possible rainfall.

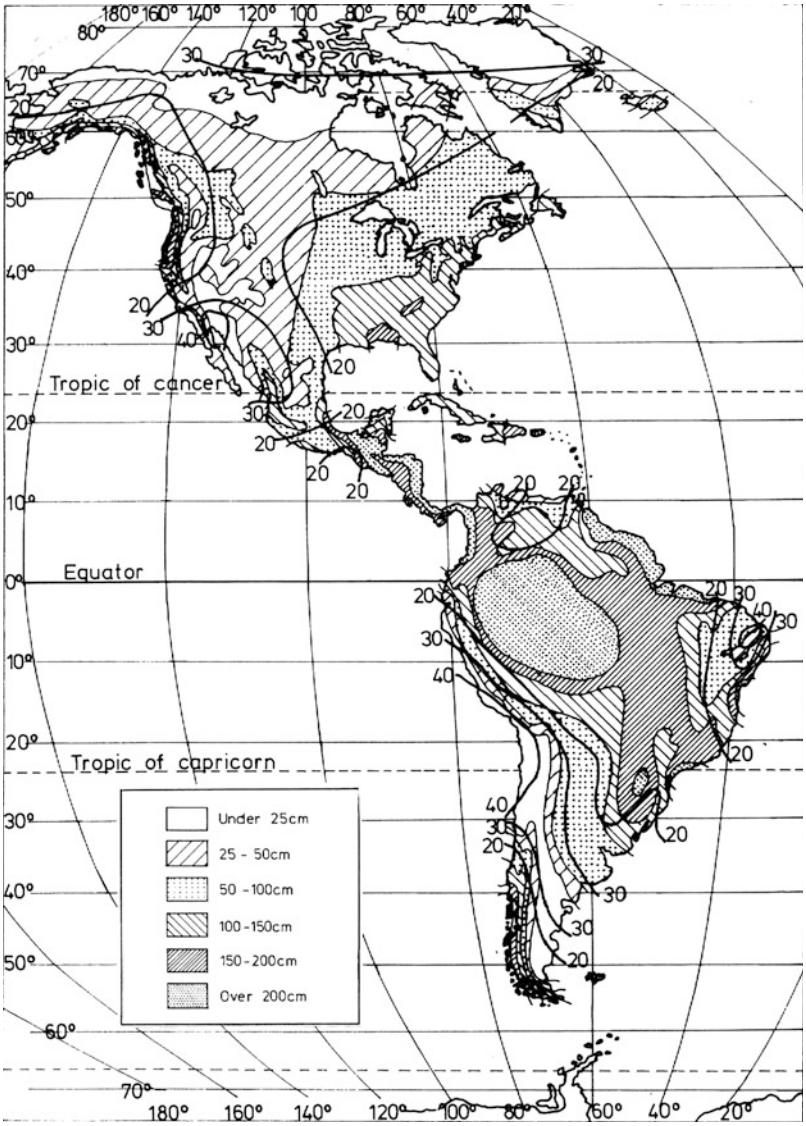


Fig. 2.10 Mean annual precipitation and coefficient of precipitation variation (%) for America

Regions of precipitation are determined by:

- Belts of ascending air at the equator and at polar fronts.
- The direction and kind of moisture-bearing winds, and their relation to ocean currents.
- The distance to the main source of water.

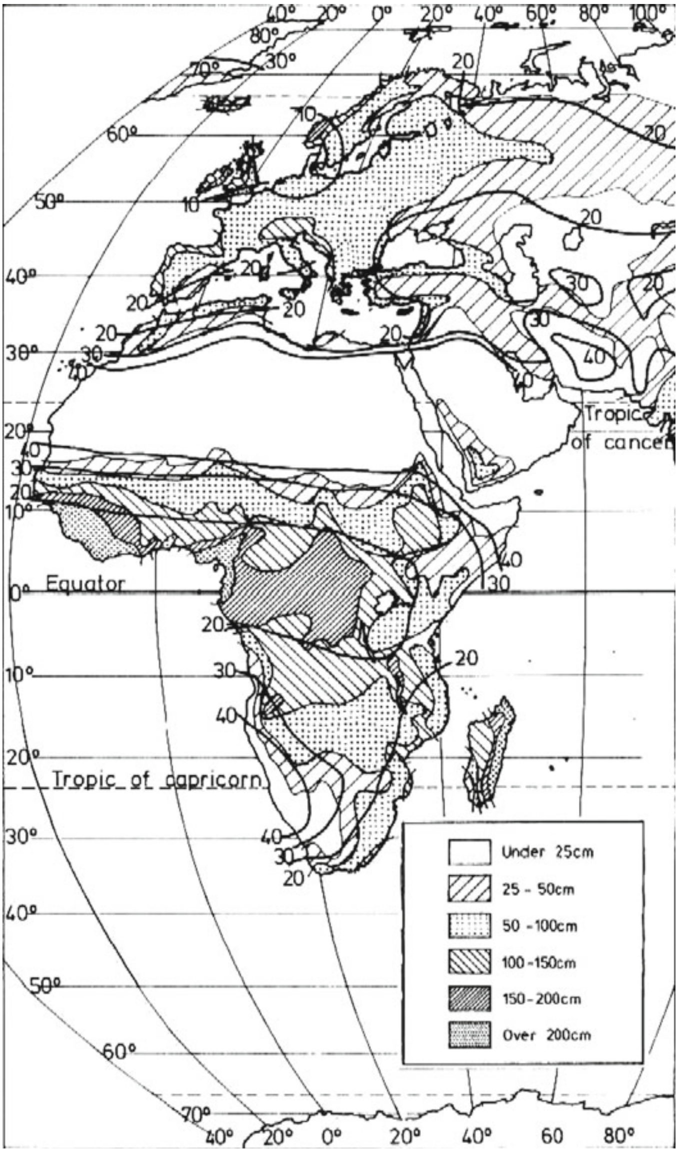


Fig. 2.11 Mean annual precipitation and coefficient of precipitation variation (%) for Europe and Africa

Rainfall in tropical regions tends to occur in high intensities together with storms. Excess rainfall, which the soil can not absorb, flows away as surface run=off. It is not available to the plants, and causes strong soil erosion. Generally speaking, rain intensities larger than 10 mm/h are dangerous with regard to erosion. These intensities, however, occur frequently in tropical regions. Therefore,

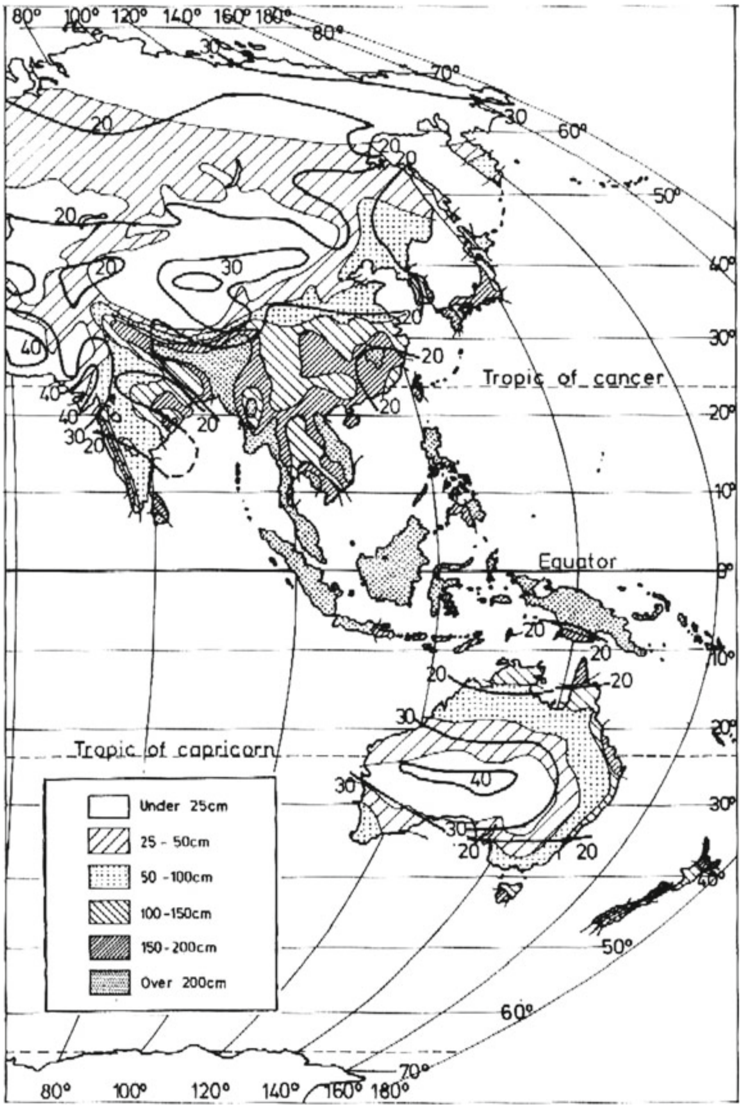


Fig. 2.12 Mean annual precipitation and coefficient of precipitation variation (%) for Asia and Australia

protected cultivation is advantageous even in the tropics, because crop and soil are protected from high rain intensities. The rain can be collected for irrigation in seasons with little rainfall.

Tropical humid climates suffer from intensive rainfall, whereas subtropical climates have large areas with only very little rainfall. Usually, rainfall shows the biggest variation where the total quantity of rain is smallest.

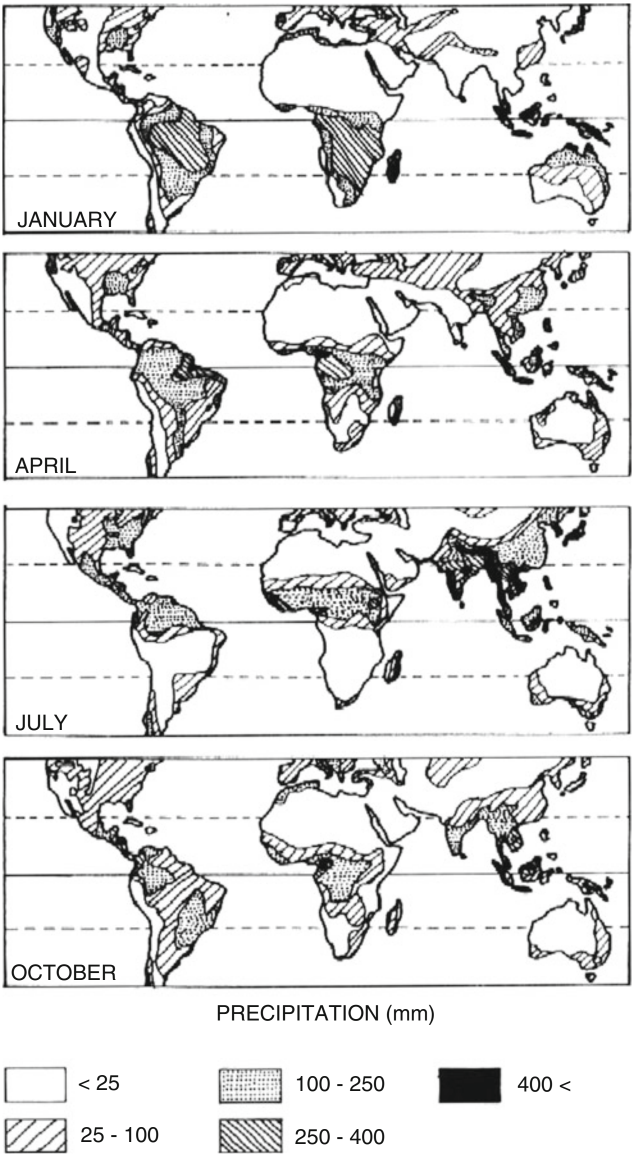


Fig. 2.13 Mean monthly precipitation on the continents

Figure 2.13 shows mean precipitation in January, April, July, and October (Jackson 1977).

- In January, a zone of heavier rain can be found south of the equator in South America and Africa. In Asia including northern Australia, these zones can be found on both sides of the equator.
- In April, the rain zones shift north, especially in Southeast Asia.

- These shift northward progresses in the month of July. In Southeast Asia, the association with the monsoon is noticeable.
- In October, the rain zones move back south.

The seasonal distribution of rainfall differs considerably within the global regions at different locations.

Mean monthly rainfall as well as maximum and minimum precipitation for many stations in the world can be found in Müller (1996) and FAO http://www.fao.org/AGLN/climwat.stne

2.2 Classification of Climates

The climatic conditions of the different regions are very important for the protected cultivation of vegetables and ornamental plants in greenhouses or shading halls. A classification of climate has therefore to be considered. The most important factors of influence are temperature, precipitation, and global radiation. In addition, evapotranspiration is an important factor for crop growth in open field and greenhouses.

This study is based on the classification of Trewartha et al. (1980), which is based on the classification of Köppen. Temperature and precipitation are the main factors of influence in most of the classifications.

Climate classification is divided into six main climatic groups; five of them are based on the five great thermic zones, and the sixth group is the dry group which overlaps with four of the thermic groups.

Figures 2.14–2.16 show climatic maps of the earth with the climatic zones (von Zabeltitz and Baudoin 1999). The five thermic zones A, C, D, E, and F have a zonal orientation, and are based on temperature boundaries. Group B is based on precipitation criteria. The definitions of the climatic symbols and boundaries are (according to Trewartha et al. 1980):

2.2.1 A. Tropical Humid Zones

Killing frost is absent; in marine areas, temperature of the coolest month is above 18°C.

- r (rainy) = 10–12 months wet; 0–2 months dry
- w = winter (low-sun period) dry; more than 2 months dry.
- S = summer (high-sun period) dry

2.2.2 B. Dry Zones

Potential evaporation exceeds precipitation.

- W = desert or arid
- S = steppe or semiarid

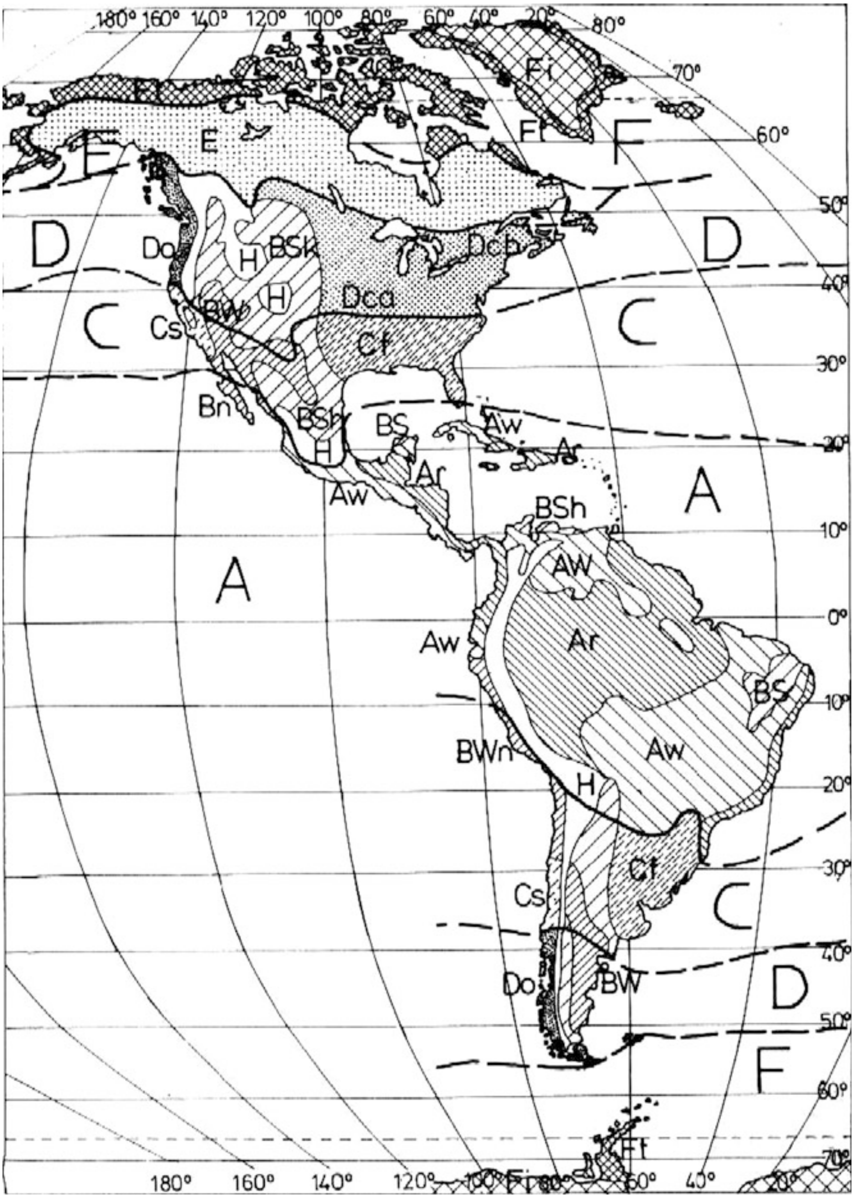


Fig. 2.14 Climatic map of America

- h = hot; 8 months or more with mean temperature above 10°C
- k = cold; less than 8 months with mean temperature above 10°C
- s = summer dry
- w = winter dry
- n = frequent fog

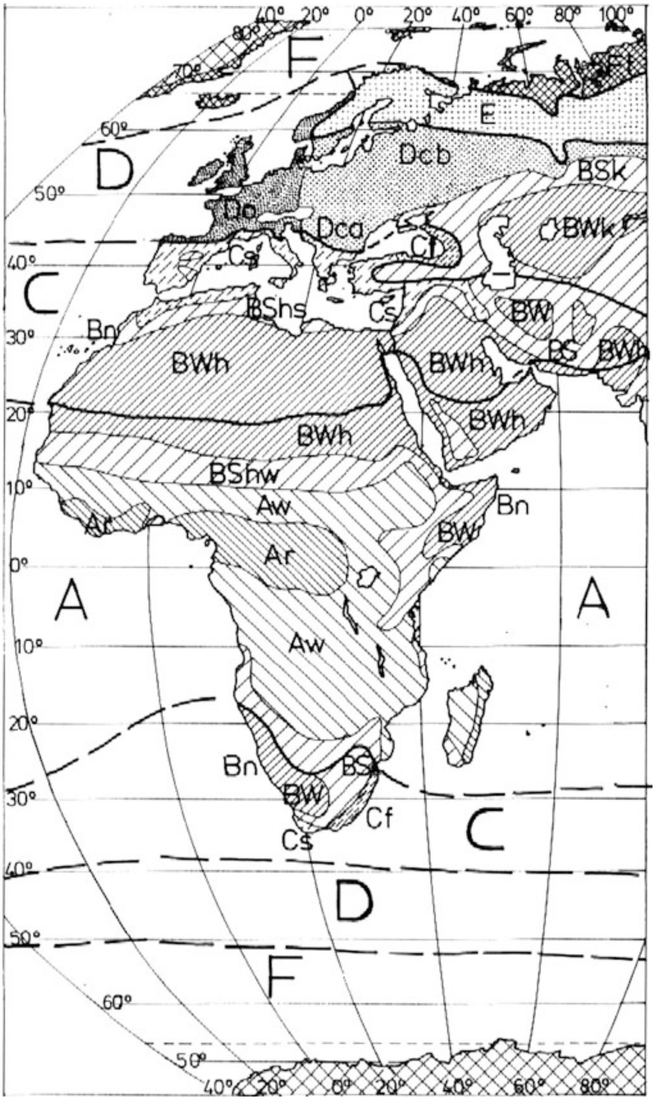


Fig. 2.15 Climatic map of Africa and Europe

2.2.3 C. Subtropical Zones

For 8–12 months temperatures are above 10°C; coolest month below 18°C.

- a = hot summer; warmest month above 22°C
- b = cool summer; warmest month below 22°C
- f = no dry season; difference between driest and wettest months less than required for s and w; driest month of summer more than 3 cm rainfall

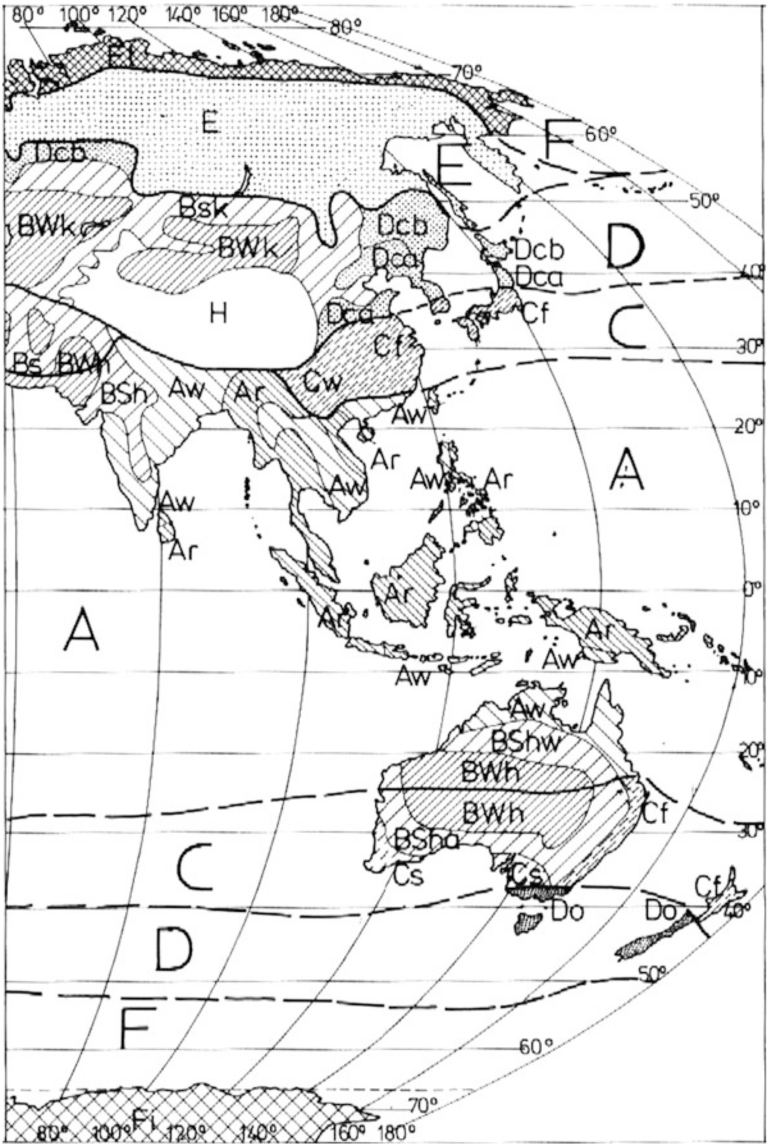


Fig. 2.16 Climatic map of Asia and Australia

- s = summer dry; at least three times as much rain in winter half of year than in summer half of year; driest summer month less than 3 cm; annual total under 89 cm rainfall
- w = winter dry; at least ten times as much rain in summer half of year as in winter half of year

2.2.4 D. Temperate Zones

4–7 months over 10°C

- o = oceanic or marine; cold month over 0°C
- c = continental; cold month under 0°C
- a, b, f, s, w: same definition as for C.

2.2.5 E. Boreal

- 1–3 months over 10°C

2.2.6 F. Polar

All months below 10°C

- t = tundra; warmest month between 0°C and 10°C
- i = ice cap; all months below 0°C

The Boundaries in Figs. 2.14–2.16:

- A/C boundary = equatorial limits of freeze. In marine locations, the isotherm of 18°C for the coolest month
- C/D boundary = 8 months 10°C
- D/E boundary = 4 months 10°C
- E/F boundary = 10°C for warmest month
- BA, B/C, B/D, B/E boundary = potential evaporation equals precipitation.

The following climatic areas in particular have to be distinguished for the construction of greenhouses and shading halls, without taking into consideration regionally limited microclimatic conditions. The details for greenhouse construction are described in Chap. 5.

2.2.7 Tropical and Equatorial Zone

- A_r = tropical wet, not more than 2 dry months,
- A_w = tropical wet and dry, high sun wet, low sun dry,
- BW and BS = arid and semiarid, mostly dry and short rainy season.

Within latitudes 30° North and 30° South, also (Cf) subtropical humid.

The following characteristics of tropical climates are important for protected cultivation.

A climate: tropical humid

- The humid regions have a constantly warm climate. It is frost-free. In many locations, the temperature differences between day and night are larger than the temperature difference of the mean values between the warmest and coldest days.
- Usually, the climatic conditions reach up to an altitude of about 600 m.
- The amount of rain is high and usually occurs in large quantities, together with storms and thunderstorms. The annual and seasonal distribution of rainfall differs considerably.

Ar climate – tropical wet

- Characteristics for those climatic zones are even monthly temperatures with mean values from 25–27°C, with very small monthly temperature variations only; the daily temperature variations are higher and reach 6–14°C.
- There is heavy rainfall throughout the year, and there are no dry seasons, or only 2 dry months at most. The annual rain quantities are 1,800–2,500 mm.
- Solar radiation and humidity are high.
- The typical course of temperature and precipitation in a tropical-wet Ar climate is shown for Singapore in Fig. 2.17.

Aw climate – tropical wet and dry

- The annual rainfall is distributed less evenly over the year than for Ar climate. The wet season is shorter, the dry season at low-sun time longer and there are also severe droughts.

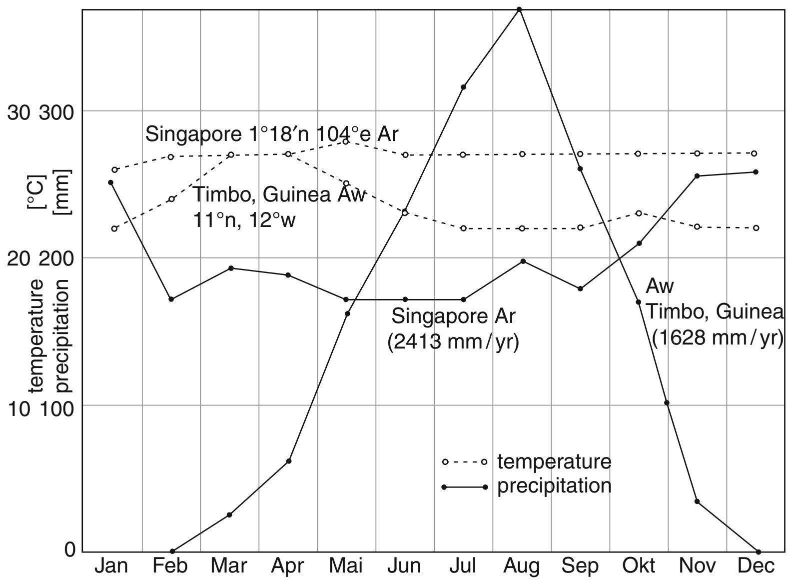


Fig. 2.17 Typical tropical wet, A_r and tropical wet and dry climate, A_w

- Temperature courses are similar to those in Ar climates. With almost vertical position of the sun and same day and night length throughout the year, the monthly variations of mean temperatures are small and range from 3 to 8°C.

  Figure 2.17 shows a typical tropical wet and dry climate for Timbo, Guinea.

2.2.8 Subtropical Climate: C

The subtropical climates stand out due to strong seasonal rhythms of temperature between summer and winter (Fig. 2.18).

Cs climate: Subtropical dry summer (Mediterranean)

The Cs climates are on the west side of the continents between the latitudes 30° and 40°. In simplified terms, they show three features:

1. Most of the rain falls during the winter. Summers are very dry
2. Summers are very hot, winters mild
3. Solar radiation is very intensive, especially in summer; only little clouding

- The mean temperatures in winter are between 4° and 13°C, and in summer between 21° and 28°C. The annual variations of the monthly mean temperatures range from 11° to 17°C. During 3 months in winter, there are occasional frost nights.
- The annual rainfall of 380–760 mm is usually not enough for plant production.

  A typical example is shown for Haifa, Israel, in Fig. 2.18.

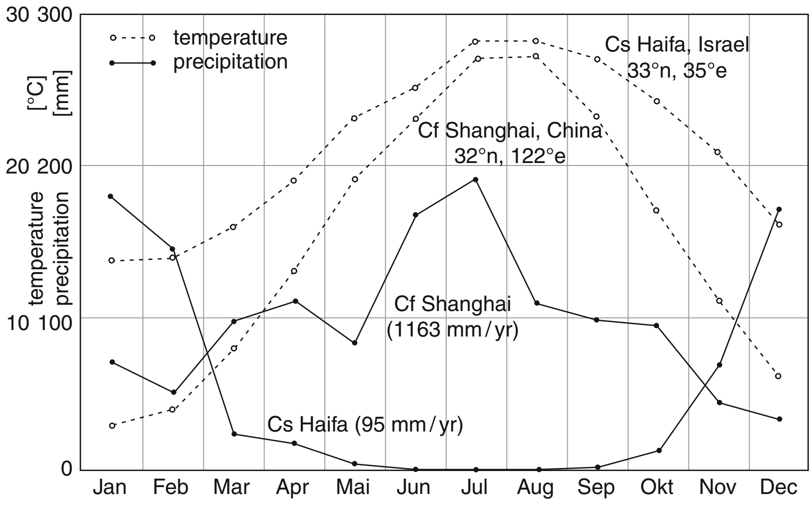


Fig. 2.18 Typical subtropical climates for Haifa (Cs) and Shanghai (Cf)

Cf climate: subtropical humid

Subtropical humid climates are found between latitudes 25° and 40° and differ from subtropical dry-summer Cs climates in three points, Fig. 2.18:

1. They are on the east side of the continents.
2. The annual rainfall is higher.
3. The distribution of rainfall is extended over the whole year, with a maximum in the warm months. There is no summer drought.

- The summer months are very hot along with a high humidity. Winters are relatively mild with mean temperatures of 4°–13°C. Frost can occur occasionally in some winter months during the night.
- The total annual quantity of rain comes to 760–1,700 mm.

2.2.9 Dry Climates: B

Dry climates are not only defined by temperature boundaries but also by the quantity of rain.

- In dry climates, the annual potential evapotranspiration is larger than the precipitation. The boundaries of the dry climates are determined by the fact that the annual potential evapotranspiration equals the precipitation.
- Daily temperature variations are very high, especially in winter. With a mostly cloudless sky, there is a high solar radiation that makes temperatures rise during the day. The relative humidity during the day is low at 12–30%. With a (usually) cloudless sky, thermal radiation from the ground is very high during the night; consequently, temperatures drop correspondingly.

2.2.10 Highlands: H

The climate in highlands varies considerably, and is determined by many local influences. A description is therefore difficult.

- With growing altitude, irradiation increases and temperature drops.
- Rainfall can vary considerably according to location.
- In equatorial highlands, such as in Kenya, Colombia and Malawi, very good conditions for the production of plants are given

Figure 2.19 shows a section of Colombia in the area of 4°N.

Figure 2.20 illustrates the climatic conditions of the highlands of Bogotá, at an altitude of ~2,600 m. There are about 1,500 ha of greenhouses for ornamental plants in this highland around Bogotá. In comparison to Bogotá, the climate of Medellin (Colombia) is shown at an altitude of 1,550 m. Here, average temperatures and rain quantities are higher.

The mean maximum and minimum temperatures, as well as solar radiation, are important for the evaluation of climate conditions for plant growth.

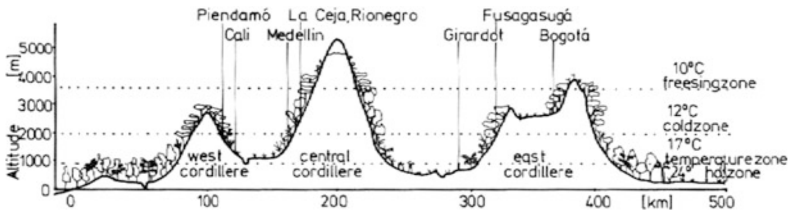


Fig. 2.19 Section of Colombia

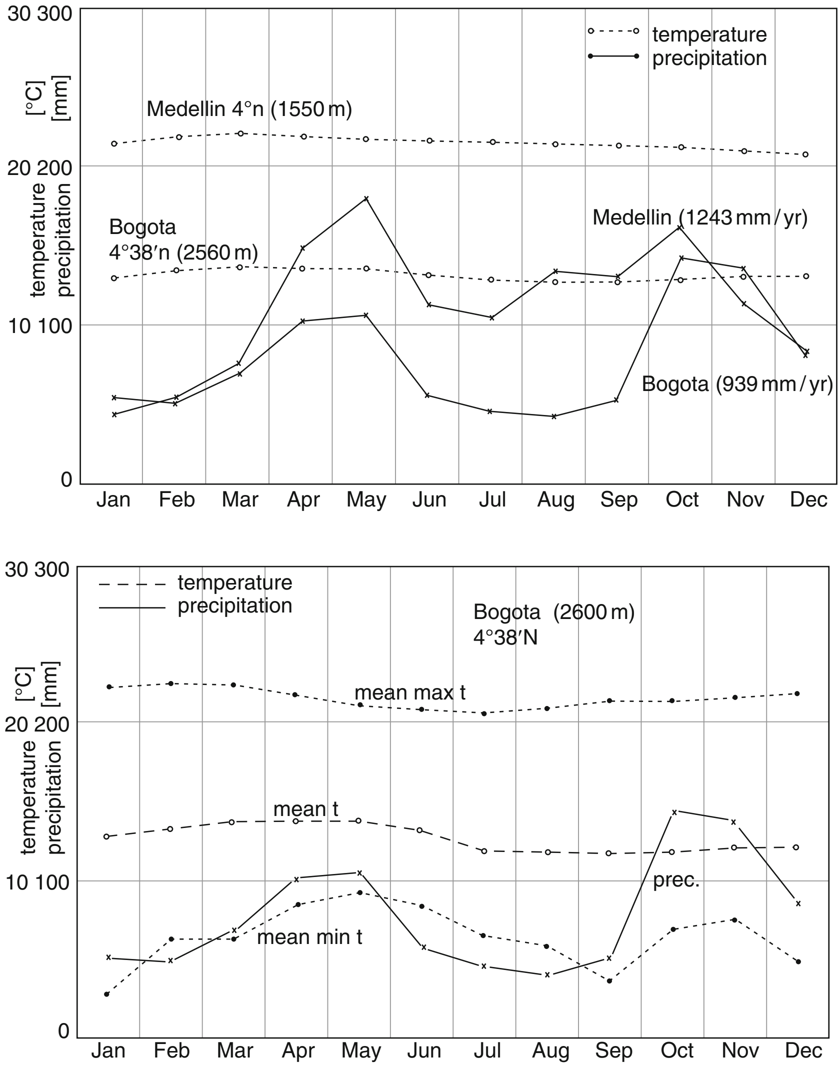


Fig. 2.20 Climates of highlands in Colombia

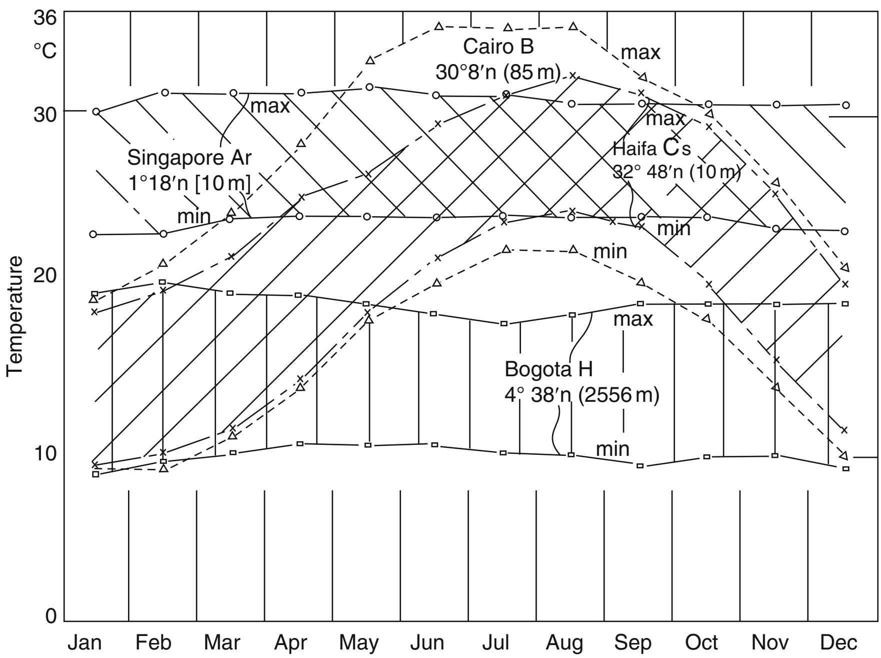


Fig. 2.21 Mean maximum and minimum temperatures for different climate regions

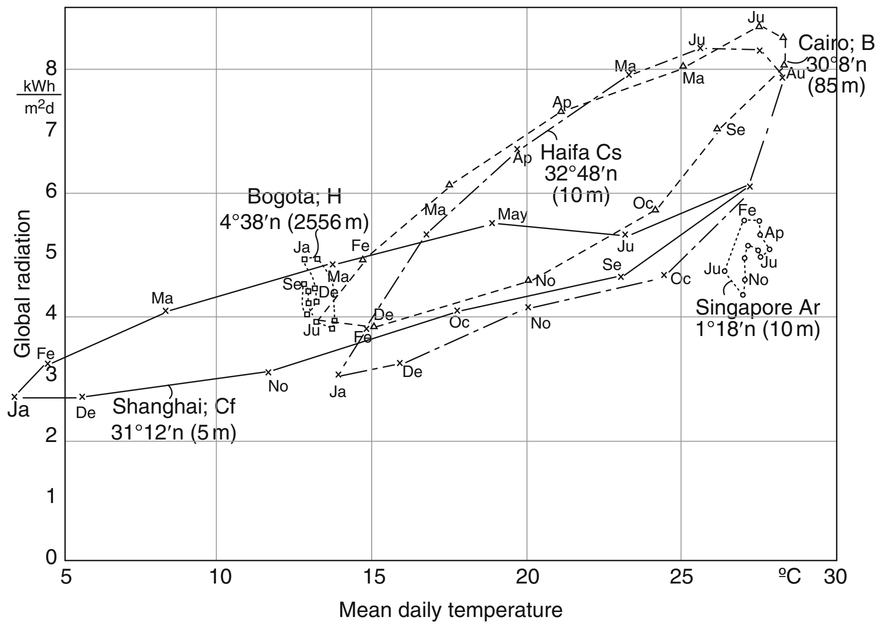


Fig. 2.22 Mean daily global radiation depending on mean daily temperature

Figure 2.21 shows the range between mean maximum and minimum temperatures for some typical climates throughout the year.

In the tropical wet climate Ar of Singapore, the mean maximum temperature does not exceed 31°C. In the dry climate B of Cairo and the subtropical dry summer climate Cs of Haifa, the mean maximum temperatures are higher than 32°C in summer. There are many days with much higher temperatures at daytime.

The mean minimum temperatures do not fall below 9°C, even in the Highland H of Bogotá at an elevation of 2,556 m.

The suitability of the climatic conditions of different regions can also be compared in Fig. 2.22, where the mean daily global radiation is plotted against the mean daily temperatures for the 12 months of the year for different climate regions. The mean temperatures are close together in a narrow range in tropical lowland (Singapore), and the mean daily global radiation does not exceed 5.5 kWh/m^2 day. The temperatures vary very much from winter to summer in dry and subtropical climatic regions, and the daily global radiation exceeds 6–8 kWh/m^2 day during summer (Cairo, Haifa). The mean daily temperatures are also close together in tropical highlands (Bogotá) but they are significantly lower than in tropical lowlands.