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MOUNTAIN CLIMATES

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Mountain climates

Climate variables undergo systematic changes with elevation, most notably a decrease in temperature. It is often argued that the altitudinal belts parallel latitudinal climate variations, but this applies only as a first approximation, as changing slope, aspect and other effects can largely compensate or exacerbate the effect of altitude alone.

Altogether, mountain climates are characterised by a rather distinctive combination of temperature, radiation, wind and rainfall patterns, as well as a larger variability of climate, both spatial and temporal (at scales from days to seasons) compared with lowlands at the same latitude. In addition to the aforementioned parameters, which will be covered in some detail, atmospheric pressure and carbon dioxide (CO2) should also be mentioned.

Atmospheric pressure decreases with altitude in a very regular fashion. Although the values may be affected by moisture content and temperature, the "standard" atmosphere yield the following pressure values, in % of the atmospheric pressure at sea level: 89 % at 1000 m, 78 % at 2000 m, 60% at 3000 m and 53 % at 5000 m. In addition, due to its molecular weight being larger than that of oxygen (O_2), the abundance of CO_2 relative to O_2 (concentration of CO_2 / concentration of O2) tends to decrease with elevation. Other things being equal, the decreased availability of CO_2 both in absolute and relative terms poses some problems to the photosynthesis of plants and constitutes one of the factors of the relatively low productivity of mountain climates.

Temperature and winds

Temperature normally decreases with elevation, mainly because the source of heat is the solar energy absorbed by the soil and re-radiated into the atmosphere as thermal radiation. The lower temperatures are thus a direct consequence of the decreasing atmospheric pressure.
The change in temperature as a function of elevation is normally about 0.6 ºC per 100 m, but it may vary significantly as a function of moisture, temperature, etc. It is relatively low (0.5ºC per 100m) for wet air (i.e. air saturated with water, as in clouds) and 1º C for "dry" air (below 100%moisture).

When atmospheric conditions are stable (usually high atmospheric pressure and little wind), it occurs frequently that cold air accumulates in low-lying areas (valleys and other depressions), so that we observe an inversion of the "normal" temperature pattern. Such temperature inversions are often characterised by fog (the name given to clouds when they touch the surface of the earth) and risk of frost. Above the inversion the normal decrease with altitude starts again, so that the area just above the inversion is often referred to as a "warm belt", usually well-known to local farmers.

Mountains have predictable wind patterns, which interfere with the thermal stratification in a typical way. Similar to the sea and land breeze in coastal areas, winds tends to blow from the highland into the valley at night (contributing to the above-mentioned inversions), and from valley to mountain during the day, when high elevations undergo a relatively faster heating than the lowlands.

At the regional scale, one of the best known winds are the Foehn "family". They come under a variety of names (e.g. Chinook in North America) and occurs when a wet air mass is blown against a mountain; it cools quickly as it rises, reaches water vapour saturation, which results in rainfall, a phenomenon, which releases heat . As the relatively warmer air mass then flows down the mountain on the leeward side of the mountain, it is further heated by compression, resulting in warm winds, which typically increase avalanche risk during winter and fire risk during summer.

Similar effects are frequently observed at a more local scale when wind follows valleys. As valleys get narrower, wind accelerates and, conversely, slows down as valleys open. It is the effect of topography, which is largely responsible for wind turbulence in mountains.

Solar Radiation

Due to high elevation, low aerosol load and low moisture, solar energy undergoes significantly less absorption by the atmosphere than in the lowlands. In addition, shade, slope, aspect and cloudiness play a dominant part in the spatial distribution of solar energy at a given elevation, to the extent that solar energy input can easily vary by a factor of 100 from a permanently shaded valley bottom to a well exposed slope.

Figure 1 below illustrates the effect of slope and aspect on the radiation climate. Note that the figure refers to the Northern Hemisphere; in the Southern Hemisphere, the N and S sky directions are inverted, i.e. the curve standing for North becomes South, South-East and South-West becomes North-Eeast and North-West, etc.. Also note that the curves go through a maximum at the slope that corresponds to the latitude, i.e. the closer the station is to the equator, the "flatter" the curves get: near the equator, steep slopes receive relatively less energy than gentle slopes.

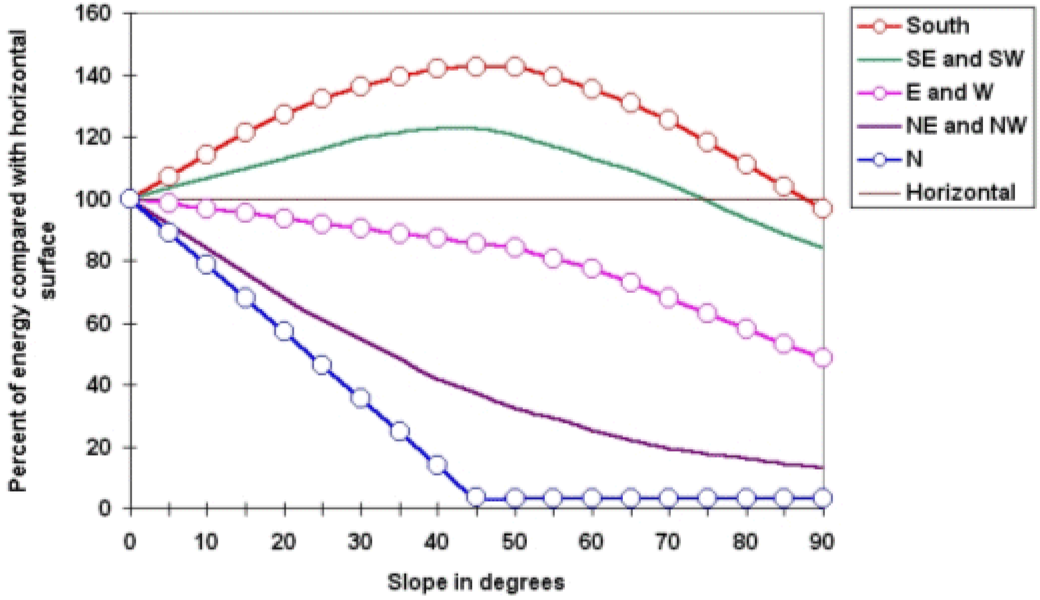
Figure 1: Amount of energy received by a sloping surface compared with a horizontal surface (Northern Hemisphere, 45º latitude). The abscissa indicates the slope in degrees, varying from 0º (horizontal) to 90º (vertical), while the different curves show the effect of aspect, i.e. the direction in which a perpendicular to the surface points, e.g. East and West indicates the energy received by surfaces that face the East and those that face the West (modified from Guyot, 1999, Climatologie de l'Environnement, Dunod, Paris, 525 pages.)

Rainfall and water balance

Because of the mechanism explained above, atmospheric water tends to precipitate when an air mass is lifted and cooled when it reaches a mountain range. Windward slopes typically received significantly more rains than the leeward slopes. This is particularly spectacular in monsoon climates when some stations at the foothills of the Himalayas are among the wettest locations on Earth (Cherrapunji, India, 10600mm per year). The same phenomenon occurs as well in other continents, albeit in a less spectacular fashion: la Vuelta, Colombia, records 9050 mm per year and Douala, Cameroon, 3800 mm.

Figure 1: **Amount of energy received by a sloping surface compared with a horizontal surface (Northern Hemisphere, 45º latitude). The abscissa indicates the slope in degrees, varying from 0º (horizontal) to 90º (vertical), while the different curves show the effect of aspect, i.e. the direction in which a perpendicular to the surface points, e.g. East and West indicates the energy received by surfaces that face the East and those that face the West (modified from Guyot, 1999, Climatologie de l'Environnement, Dunod, Paris, 525**

pages.)



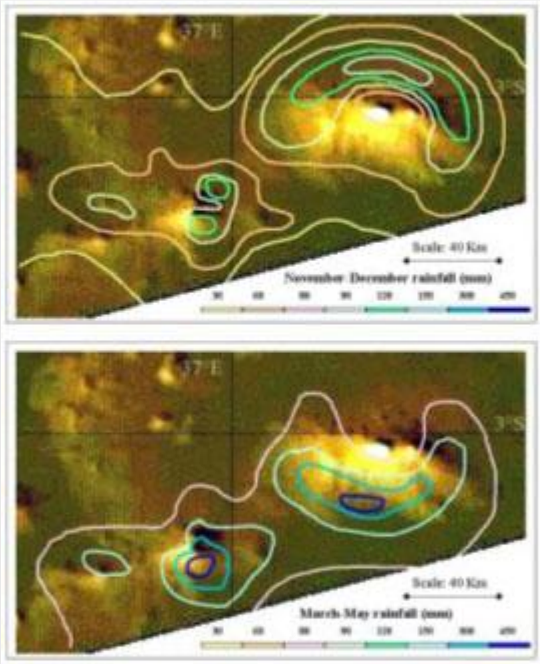
Mount Kilimanjaro, situated at 3 degrees Southern latitude, is exposed successively to the SE monsoon and to the NE monsoon, resulting in the East facing-slopes being significantly wetter than the Western ones, some of which are actually semi-arid. Kilimanjaro illustrates another well known features of rainfall in mountains: once all the precipitable water has been removed from the atmosphere, rainfall decreases again, so that, similar to the "warm belt" just above temperature inversions, many mountains also display a "wet belt", usually at elevations significantly higher than the "warm belt" (figures 2a and 2b).

Figure 2: A superimposition of a satellite image of Mt. Kilimanjaro (5895 m, East) and Mt. Meru (4585 m, West) in Tanzania with normal isohyets (mm/season).

During the "short rains", (about Oct-Jan; 2a shows the period from November to December), Kilimanjaro gets the NE monsoon, the S and W of the mountains record relatively little rain, and the maximum rain (about 150 mm during November and December) is recorded on the N slope, while the top of the cone gets only 60 mm or so. During the "long rains" (about March-June: March to May illustrated in 2b), the rain is coming from the South-East. This time, is the N slope that gets little rain. The top gets about 80 mm, while some areas on the Southern slope record more than 450 mm in March to May. Needless to say, this pattern is reflected in the vegetation and in the distribution of agriculture, mostly concentrated to the S and W

(Source of isohyets: I.J. Jackson, 1977, Climate, water and agriculture in the tropics, Longman, London and New York, 248 pp.)

Figure 2a (top) and 2b (bottom)



When mountains are not very high, like most mountains on the African continent - except Kilimanjaro, figure 2 -, the temperature drop with elevation is not sufficient to remove all precipitable water from the atmosphere, with the consequence that on average rainfall increases with elevation (annually, about 100 mm every 1000 m). In Asia and South America, in spite of the wet belts, the general tendency is a decrease of rainfall with elevation, of the order of 300 mm every 1000 m in Asia and 100 mm per 1000 m in Latin America.

Depending on elevation and latitude, a sizeable fraction of precipitation can be in the form of snow. In Europe, for instance, elevations above 3600-3800 receive only snow.

As with radiation, the effects described above result in the precipitation climate of mountains to be characterised by a very marked spatial and temporal variability, including dry valleys and dry plateaux at high elevations that would normally be expected to receive fair amounts of rainfall.

Snow constitutes a sizeable storage of water during the cold season. The water will be released more or less gradually when snowmelt sets in. In addition, potential evapotranspiration (the atmospheric water demand) also undergoes altitudinal changes. In spite of usually dryer air, the effect of temperature results in ETP decreasing by 100 to 200 mm (annually) per 1000 m of elevation. The result is that relatively little water will be evaporated at high elevations: soils will often be wet, accumulate organic matter and provide a regular supply of water to the surrounding lowlands. This can be used for irrigation, but also for many rainfed crops.

Because of low temperatures, growing seasons are usually much shorter at high elevation than in the surrounding lowlands, but plant growth can be intense during the growing season because of a favourable radiation climate and a marked contrast between day-time and night-time temperature (reduced respiratory loss during night-time).

Endnotes

1. The evaporation of water absorbs heat, which is released again as the water condenses in the form of dew or rainfall.

2. It is also worth mentioning UV-B radiation, which is typically 2 to 4 times more intense at high elevations than in the lowlands. Nanism of some plants is often quoted as one of the consequences.