7. The Hydrologic Cycle

The hydrologic cycle comprises all manifestations of water molecules in the earth system. Global change issues related to the water cycle include melting ice, droughts, floods, desertification, river diversion, and coral bleaching. The ocean holds about 97% of the water that exists above the earth's crust, and is the source of about 85% of all evaporated water. The array of global changes affecting the ocean include increased heat storage, reduced vertical mixing, acidification, de-oxygenation, and fertilizer-induced anoxic dead zones.

7.1. Geophysical box model: water over the globe

A geophysical budget of water for the annually-averaged hydrologic cycle is shown in Fig. 7.1, partitioned between land and ocean. Fluxes between the atmosphere and the surface are given in units of 1000 cubic kilometers per year (10^3 km^3 yr^{-1}). Given the surface area of the earth, these numbers correspond to an average rainfall amount of 1 meter per year. Precipitation corresponds to downward fluxes, while upward fluxes are due to evaporation from wet surfaces plus transpiration from plants, together called *evapotranspiration*. Plants play an important role in the hydrologic cycle by extracting water from the ground, aided by extensive *mycorrhizae*, transporting essential minerals into the plants, which then escape into the atmosphere through their *stomata*. This occurs in concert with taking in CO_2 and giving off O_2 through the open stomata.

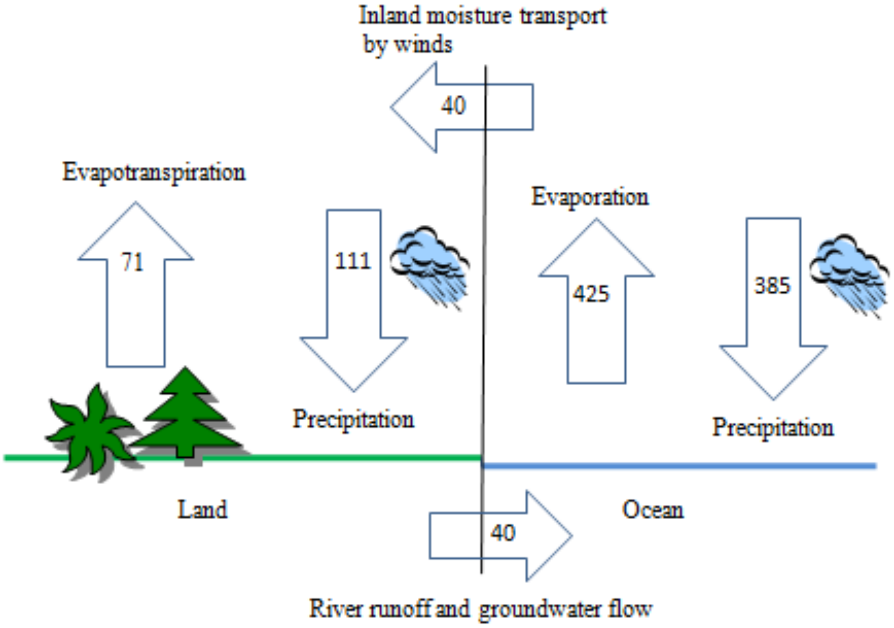


Figure 7.1. Geophysical box model for global water, showing fluxes (10^3 km^3 yr^{-1}) into the surface (precipitation) and from the surface (evapotranspiration), partitioned by land and ocean. Since there is more evaporation than rainfall over the ocean, there must be a flux from land to ocean in the form of river runoff and groundwater flow. Since there is more precipitation than evapotranspiration over the land, there must be a flux from ocean to land in the form of importing moisture by atmospheric motions.

Vegetation provides an essential global climate service through evapotranspiration. It provides for regional recycling of water molecules before flowing to the sea. A water molecule, once it evaporates, has a typical atmospheric residence time of a few days to a week. It has been estimated that the Amazon basin recycles a given water molecule about 10 times before it again reaches the sea, while water is recycled only a few times over North America before returning to the ocean. If you consider chopping down all of the trees on the land, then evapotranspiration on the land would decrease considerably. This would make less water available for precipitation, so it would get drier. With less water available to evaporate, solar radiation would instead lead to an increase in ground temperature. With less water to evaporate there would be fewer clouds to reflect sunlight and keep the planet cool. During the period ~ 1975 - 1995, the Amazon basin experienced ~ 20% deforestation, a reduction of precipitation by ~10%, and an increase in ground temperature by ~2 K (Foley et al. 2007). Complete deforestation in the tropics would likely affect midlatitude climate patterns significantly by modulating long-wave teleconnection patterns emanating from regions of tropical convection (Snyder et al. 2004, Snyder 2010).

The self-protective quality of a tropical forest ecosystem can work on scales as small as Caribbean Islands. The island of Dominica has 47% of its land reserved as parkland, protecting the forest. Due to recycled water, it rains nearly every day, replenishing the creeks with fresh water and keeping the plants moist for evapotranspiration the next day. In contrast, many of the nearby islands, which were largely deforested, receive much less rainfall.

It is interesting to note that decreased precipitation due to the lack of vegetation and evapotranspiration makes it harder for vegetation to re-grow. The existence of other trees helps keep each other warmer in the winter, cooler in the summer, moister when it's hot, and less likely to be blown down. This is why trees that were cut down hundreds of years ago in Scotland and Iceland are unable to grow back.

7.2. Human influence on the hydrologic cycle

Another key factor in determining the availability of water in a given region is export or import by rivers. Diversion of north-flowing Russian rivers can moisten subarctic climates and significantly alter the properties of the Arctic Ocean. Diversion of river water away from lakes can have devastating effects on local ecosystems. Beginning in 1958, the Amu Darya and Syr Darya rivers were diverted for the purpose of growing cotton and rice (Fig. 7.2a). Since then the Aral Sea has lost more than 60% of its water (Fig. 7.2b) and its salinity has increased from 10% to 23%. Commercial fishing on the Aral Sea ceased in 1982. The reduced lake led to a locally drier climate, with salinization, blowing salt, pesticide, and fertilizer residues causing increased mortalilty.

Since 1800 most of the world's rivers have become regulated by hydraulic engineering. Notable examples include the Aswan dam on the Nile River, which caused river discharge to be reduced from ~10x10^3 m^3 s^{-1} before 1968 to ~2 x10^3 m^3 s^{-1} afterward, the decline of the Syr Darya flow from 1 x10^3 m^3 s^{-1} to 0.1 x10^3 m^3 s^{-1}, and the rerouting of water which increased the flow of the Burntwood River into Hudson Bay from 0.2 x10^3 m^3 s^{-1} to 1 x10^3 m^3 s^{-1} after 1975. Globally, engineered impoundments store ~ 25% of the world's runoff (Vorosmarty et al., 2003). During the past century, a vast infrastructure has been imposed on the San Francisco Bay delta, the rivers that flow into it, and connections to Southern California, creating 1000 miles of levees and reducing wetlands by 500,000 acres.

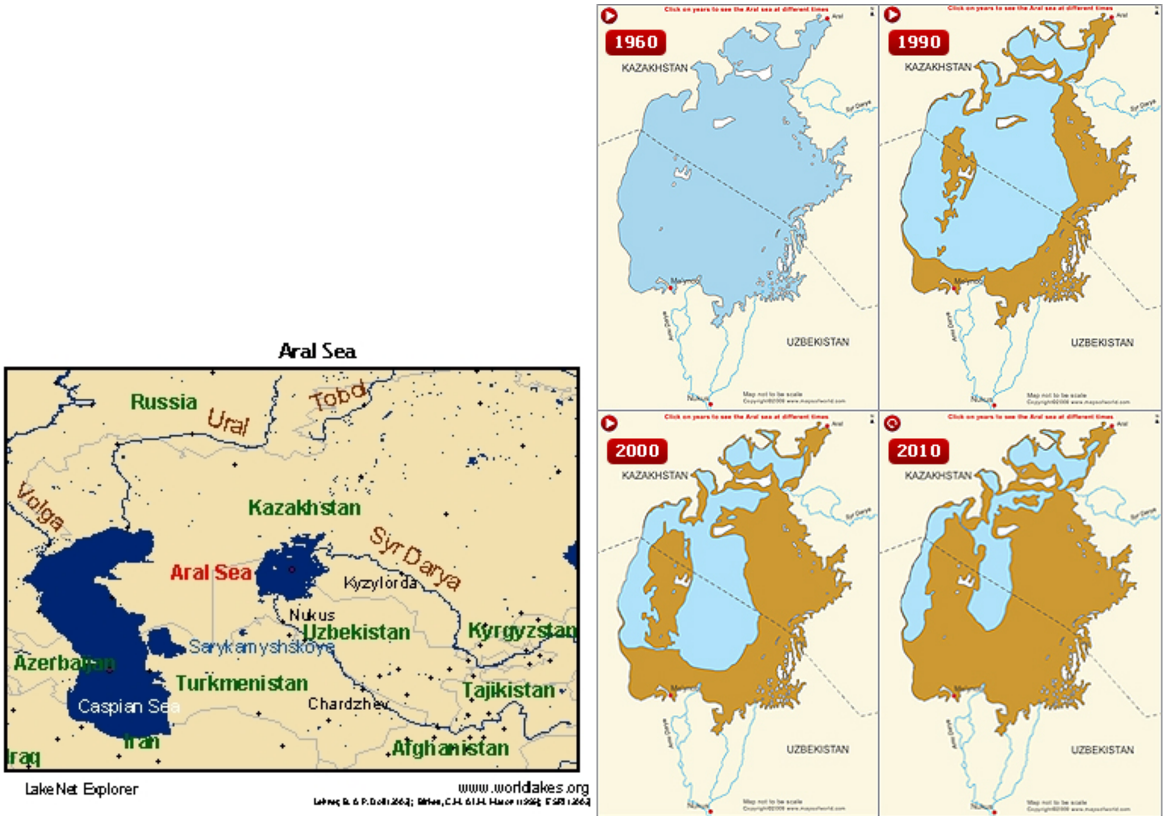


Figure 7.2. Map of region surrounding the Aral Sea, including the Amu Darya and Syr Darya rivers, together with snapshots of its areal extent in 1960, 1990, 2000, and 2010.

Humans withdraw about $5x10^3$ km^3 of water per year from the natural hydrologic cycle. This is about 1/8 of river runoff to the ocean (Fig. 7.1). Per capita water usage varies widely from country to country, with per capita water usage in the U.S.A. of ~ 2000 m^3 per year, compared to ~500 m^3 per year in Switzerland, 200 m^3 per year in Jordan, and ~ 100 m^3 per year in Ghana.

It may be surprising to find out what we use it for. In the U.S.A., we use less than 0.1% for drinking water, about 10% for domestic and city use, and about 10% for mining and manufacturing. About 38% is used to cool power plants, rendering water bodies such as Cascade Lake in Wisconsin ice free all year long. Fully 43% of water is used to irrigate crops, which are largely fed to animals that we consume. As an example of the volume used by a typical city, assuming that each person uses 5 m^3 of water per day, the 300,000 people of Madison, WI use the volume of Lake Mendota every year.

An extraordinary example of water usage for mining is the open slurry line that the Peabody Energy Company uses to pump 3 million gallons of pure spring water from the Black Mesa aquifer on the Hopi reservation in Arizona. It is used to make coal slurry, which is transported several hundred miles through the desert to a power generating plant. This uses about 25% of the natural discharge from the aquifer, so the levels in wells have gone down considerably. The 1966 lease, which originally paid only $1.67 per acre foot, was amended 35 years later with the intention that Peabody begin drawing water from the brackish Coconino Aquifer (Folger 2004). However, the Navajo Aquifer shows signs of material damage and continuing decline (Grabiel 2006).

The desert southwest has experienced, and will experience significant periods of drought. The drought of 2000-2007 was about the fifth worst in the past millennium, with that of 1130-1180 AD being the worst (Woodhouse et al. 2010). With increasing deforestation in the west and the subtropical drying expected with global warming (Feng and Fu 2013), one might expect increasing challenges with droughts in the southwest. The autumn dry Santa Ana winds of Southern California are likely to lead to more burned houses in the future. What will desert cities do for their water supply?

The Las Vegas metropolitan area has grown from 127,000 in 1964 to 2,300,000 in 2022. Las Vegas uses three times the average amount of water per capita as other arid cities such as Los Angeles and Tucson, due to the extensive construction of artificial lakes, lawns, swimming pools, and attractions such as a replica of the Nile River and a faux Grand Canyon (New York Times, 1994). Their plans for obtaining more water include 1) negotiating an increase in the city's allocation from the Colorado River, 2) build a 1,200-mile network of pipes to suck water from 20,000 square miles of wilderness, ranch, and national parks, and 3) use the Virgin River which flows through Zion Park. A map of the Colorado River compact of 1922 is shown in Fig. 7.3.

Figure 7.3. Map of the Colorado River compact among the states of Colorado (3.9 million acre-feet), Wyoming (1.0), Utah (1.0), Arizona (2.8), New Mexico (0.9), Nevada (0.3), and California (4.4). It is based on an assumed river flow of 18 million acre-feet.

California and other states are extremely reluctant to give up any of their water rights. Fig. 7.4 shows that there has been a modest decrease in water supply over the past 90 years and that water use has equaled supply for more than a decade. Note that Mexico is supposed to receive 1.5 million acre-feet, but now usually gets next to nothing. With the southeast likely becoming more and more arid, competition for diminishing Colorado River water will be an increasing challenge (Hoerling et al. 2019, Lucas and Peyton 2020). It remains to see what cities like Las Vegas will do for more water.

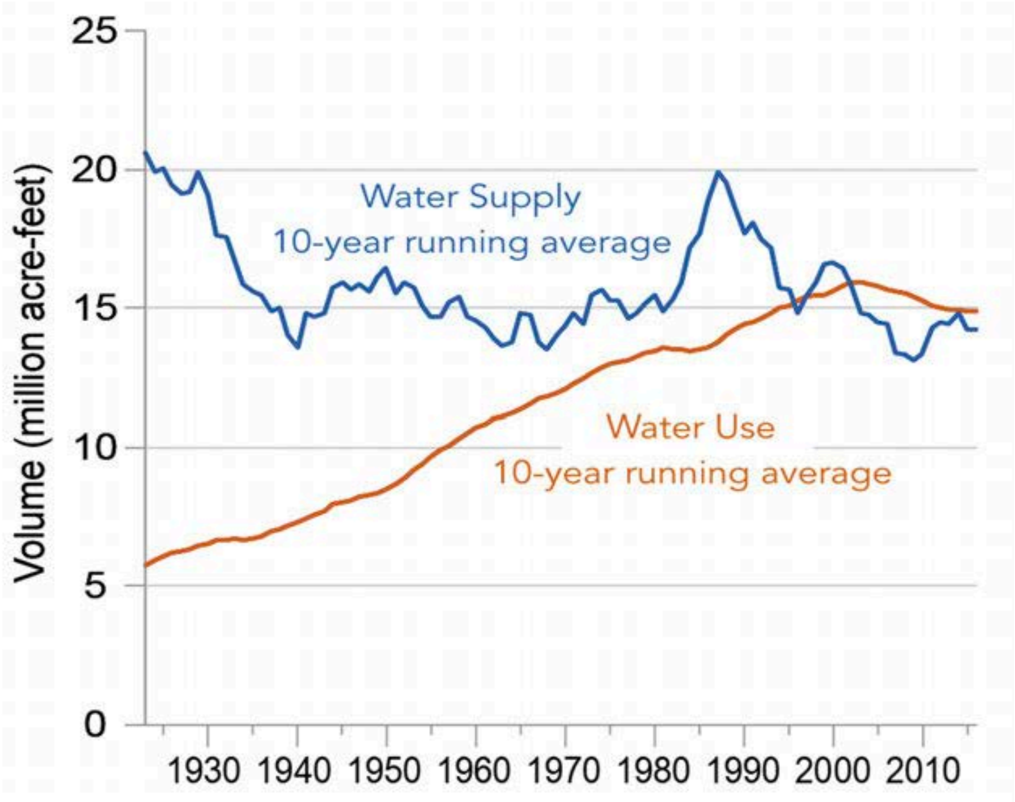
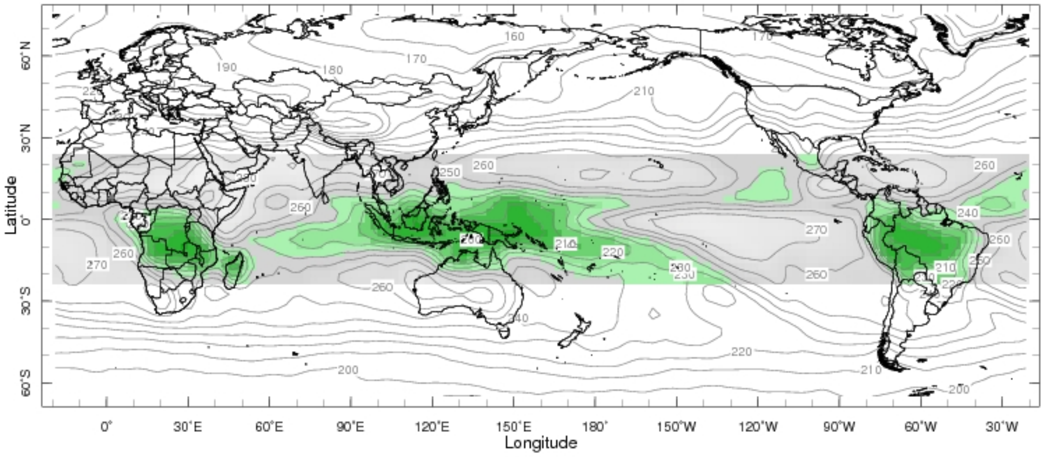


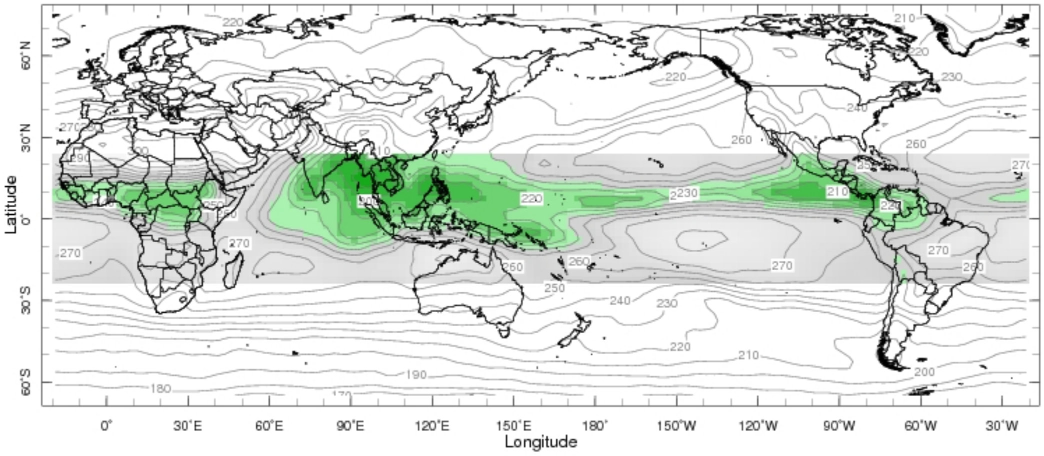
Figure 7.4. Comparison of the 10-year running average of water supply (blue) and water use (red) for the Colorado River basin during 1923-2009 (Harrison and Bales, 2015).

7.3. Desertification

The seasonal cycle in the migration of deep tropical convection is shown in Fig. 7.5. Emission of outgoing longwave radiation is smallest from the cold cloud tops near the tropical tropopause and is largest from the exposed ocean in cloud free areas. In DJF, NH winter, maxima in deep convection (green) can be seen over the Amazon, Africa, and Indonesia. The convective center over Indonesia is the largest and most energetic and owes its properties to the many islands in the vicinity which heat more quickly than water, giving it the name "*Maritime Continent*". During JJA, NH summer, centers of deep convection migrate north and west to the Gulf of Panama, sub-Saharan Africa, and Southeast Asia.



Dec 2014 - Feb 2015



Jun-Aug 2014

Figure 7.5. Outgoing longwave radiation (OLR) averaged for (top) December 2014 – February 2015 and (bottom) June - August 2014, contour interval 10 W m^{-2}. Green areas are for tropical OLR values less than 240 W m^{-2}, indicating the prevalence of deep convection. These seasonal OLR maps were made by the NOAA NCEP Climate Prediction Center.

These convective centers are connected by a thin band of deep convection, which corresponds to where the easterly trade winds from the NH and SH converge in the *Intertropical Convergence Zone* (ITCZ). As the sun makes its way northward toward the equator during boreal springtime, the ITCZ and region of maximum convection shift northward toward the Sahel. The Sahel is a zonally elongated band about 3-5^{o} wide in latitude, centered near 15^{o}N, characterized by scattered xerophytic plants, separating the desert to the north from the grasslands and jungle to the south (Fig. 7.6). Despite the relative lack of water, the Sahel region supports hundreds of millions of people. In years when the convective region doesn't make it as far north, the Sahel suffers from drought.

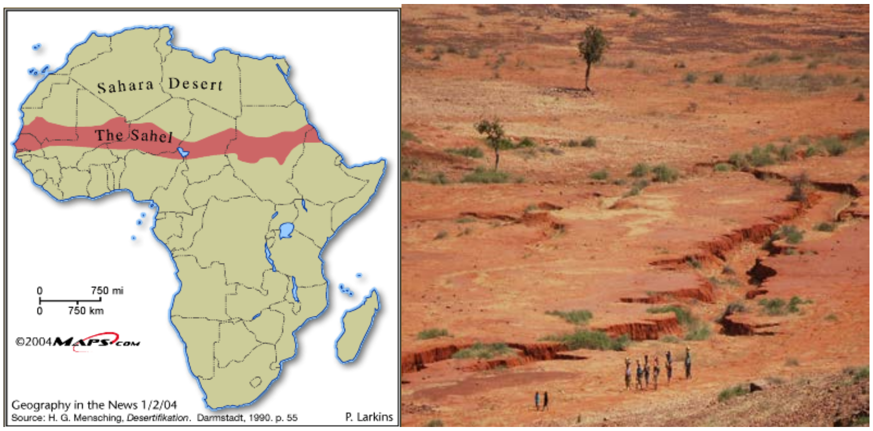


Figure 7.6. Geographical location of the Sahel region of Africa, showing Lake Chad in its midst, together with a picture of the typical landscape.

The population of Africa is expected to grow at a tremendous rate during this century, including in the Sahel. A significant concern is that an increasing population will lead to desertification, as shown in Fig. 7.7. In this scenario, an increase in population leads to more extensive grazing and usage of raw plant material, which leads to fewer plants and reduced evapotranspiration. With less moisture in the air it will be harder to form convective clouds, so the northward progress of the ITCZ will be hindered. Reduced precipitation makes for fewer plants in the Sahel, requiring grazing farther and farther from villages, exacerbating the problem.

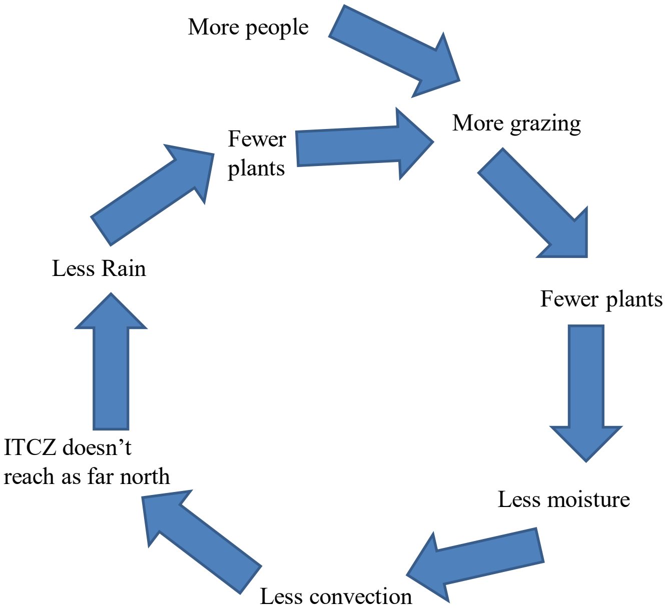


Figure 7.7. Anthropogenic desertification can occur as indicated in this positive feedback process leading to increasing dryness.

There are natural long-term variations in rainfall in the Sahel and it has been challenging to prove whether or not anthropogenic desertification is making a crucial difference. Fig. 7.7 shows the results of a modeling study for discharge of water into Lake Chad (Coe and Foley, 1996). Since 1953 Lake Chad has shrunk to less than 10% of its former size. The solid line shows that observed stream flow into Lake Chad has diminished from ~1300 m^3/s to ~500 m^3/s in the 1990s. They estimate that about 40% of this loss is due to diversion for irrigation since 1980.

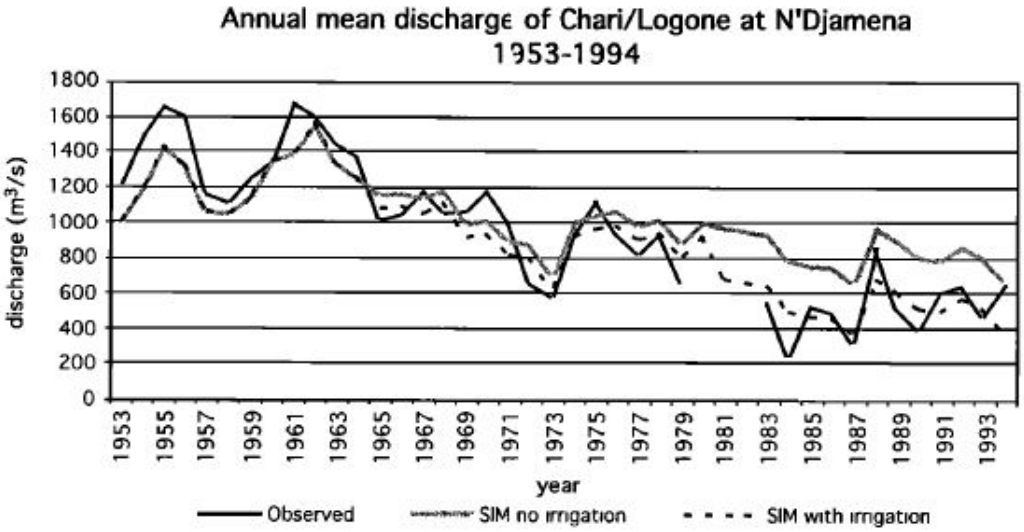


Figure 7.8. Annual mean discharge at N'Djamena (12°N; 15°E) from 1953 to 1994 for observations (black curve), the iBIS/HYDRA simulation without irrigation (grey curve), and the IBIS/HYDRA simulation with estimated irrigation losses (dashed curve) (Coe and Foley 1996).

Anthropogenic global warming is anticipated to cause aridification of the subtropical regions, as shown in Fig. 7.9. Note the widespread drying and desertification anticipated in the NH subtropics for western North America, the Mediterranean, Russian steppe, and western Sahel. The subtropical SH is also anticipated to become more dessicated, especially near 20°S in South America, South Africa, and Australia. It is occurring in conjunction with widening of

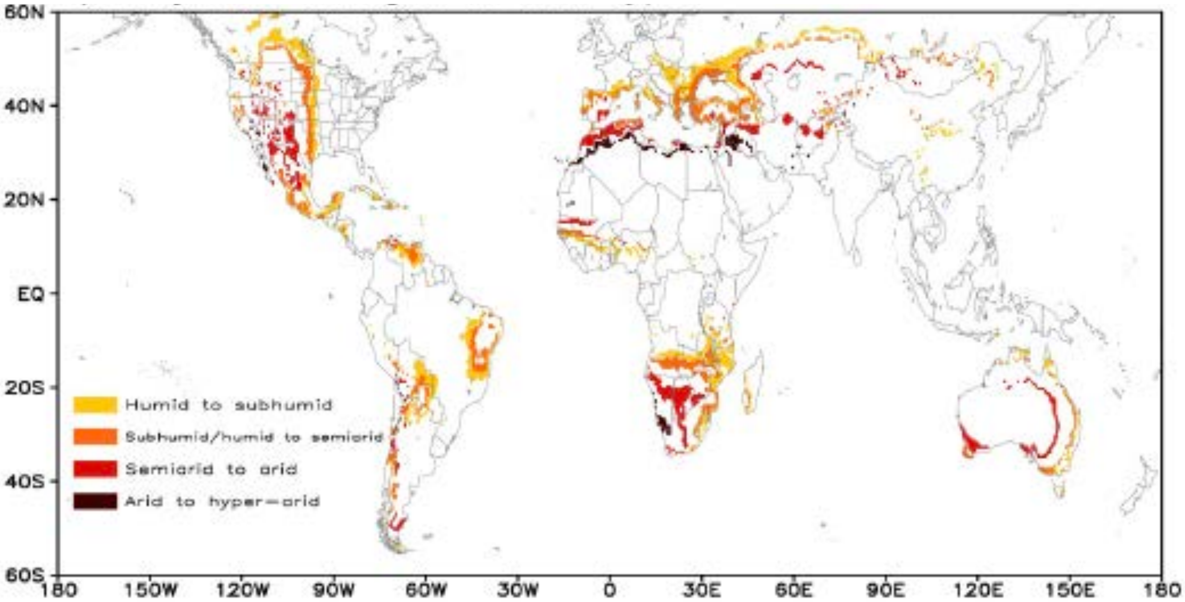


Figure 7.9. Projected changes in dryland coverage to drier types for 2071-2100 relative to 1961-1990 under scenario RCP8.5 (Feng and Fu, 2013).

the tropics. If this widespread subtropical drying does occur, it will be one of the foremost challenges to our food supply. The hot spots won't just be overseas. The entire American West is anticipated to be under increasing water stress later in this century.

7.4. Coral bleaching

Coral reefs are the most significant ecosystems of biodiversity in the ocean. One square meter of Great Barrier Reef can contain 200 species of crab and shrimp. Including all macroscopic phyla, it is estimated that reefs are home to 1-10 million different species. Estimates of the annual value in terms of goods and services that coral reefs provide in the form of food, protection of shoreline, and income exceed $300 billion. An example of the physical complexity of barrier reefs is shown in Fig. 7.10, the section of the Great Barrier Reef in Australia where Captain Cook ran aground and managed to careen his ship and sail out of the reef. Examples of the abundant wildlife are shown in Fig. 7.11.

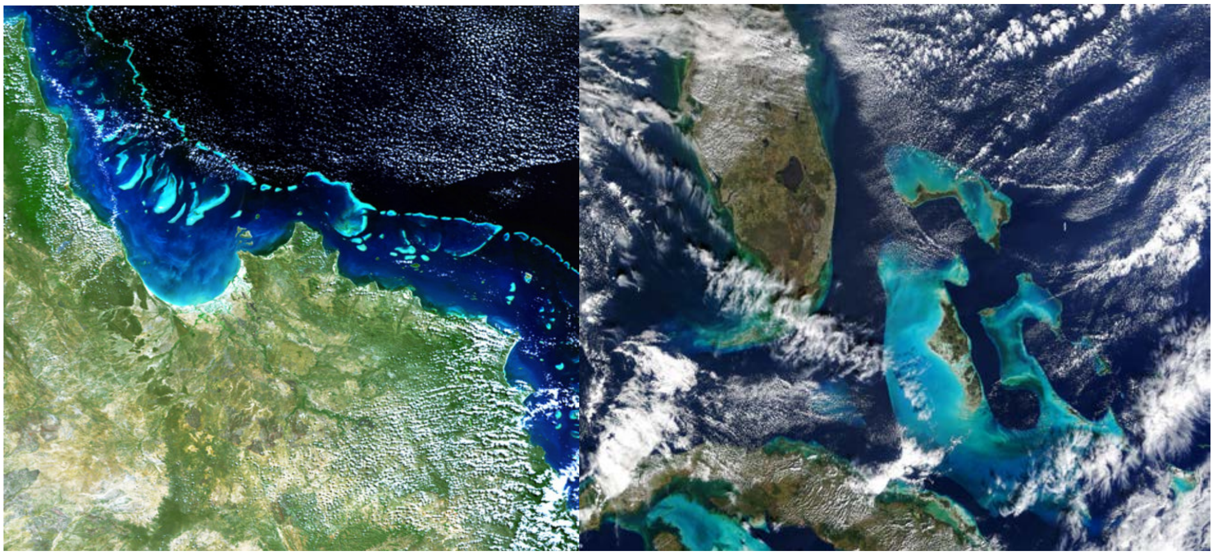


Figure 7.10. A section of Australia's Great Barrier reef (left), and coral reefs near the Bahamas (right), as seen from space (MODIS images courtesy Space Science and Engineering Center).

Figure 7.11. Examples of coral reef inhabitants.

Corals are animals which host symbiotic algae in their tentacles called *zooxanthellae*. The coral animal builds its house out of calcium carbonate fixed from sea water, a process which is inhibited if the water is too acidic. The tentacles pull in food from the sea water. Arrayed in multiples of six around the mouth, the tentacles contain cells which host the algae. The zooxanthellae undergo photosynthesis and thereby supply the coral with oxygen and an auxiliary supply of food. The algae also help the coral grow its calcium carbonate skeleton and provide color to the reef. In turn, the coral provides a stable platform for photosynthesis and makes essential nutrients available to the zooxanthellae. Despite the scarcity of nutrients in the ocean, coral reef organisms collectively are so efficient at recycling nutrients that they trap and maintain locally high amounts of organic building blocks: the byproducts of each organism are used by another. It may be a useful analogy to note that the symbiotic relationship between coral reefs and algae is somewhat similar to the relationship between forests and mycorrhizae.

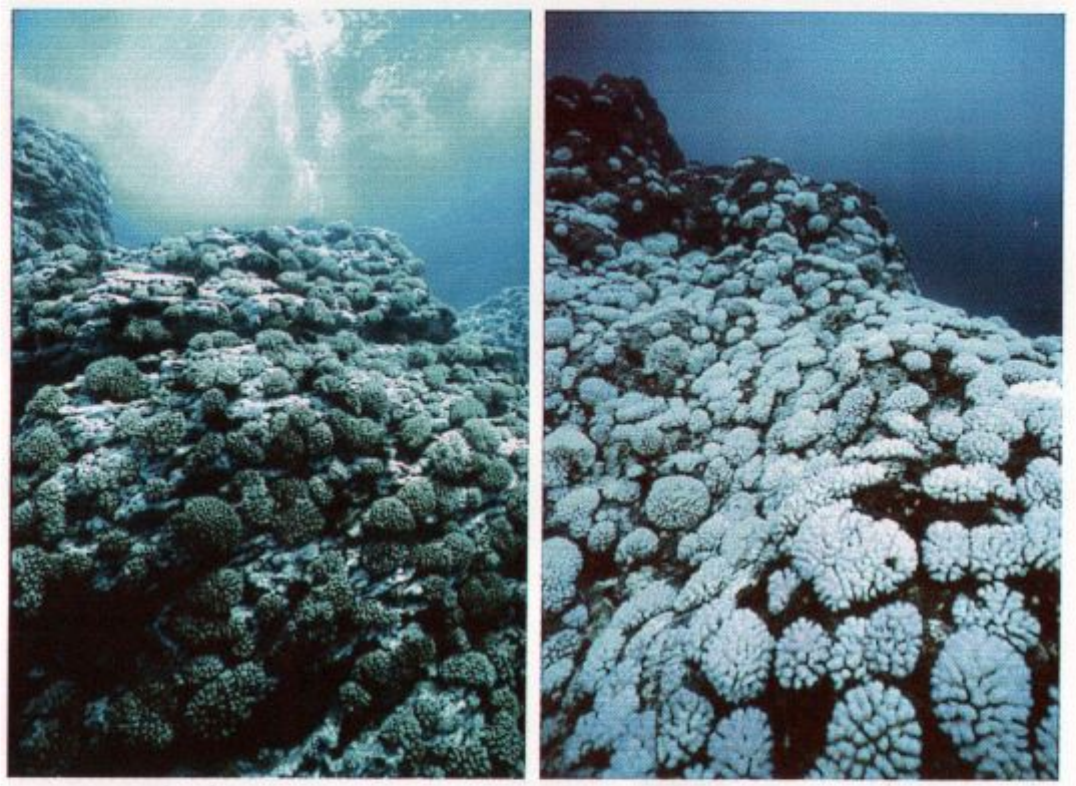


Figure 7.12. Colonies of Pocillopora verrucosa at 10-m depth near Hanga Roa, Easter Island (Rapi Nui). The photograph on the left (March 18,1999) shows healthy zooxanthellae pigmented colonies; on the right (March 14,2000), virtually all coral colonies are bleached after exposure to several weeks of exceptionally high sea surface temperatures. The whitened appearance indicates the absence of symbiotic algae in the coral tissues (Wellington et al., 2001).

Corals are able to host viable zooxanthellae in the temperature range 25-30°C. There are ~90 species of these symbiotic, photosynthetic dinoflagellates in the genus Symbiodinium which help coral and perhaps 70,000 different types of coral. When the temperature gets too high the zooxanthellae produce too much O_2, as a byproduct of increasing photosynthesis (Kolbert, 2016). When O_2 concentrations are too high it harms the coral, so they expel the zooxanthellae and wait for more favorable conditions. The exact temperature depends on the species of the algal symbiont, the species of coral, acidity, and other factors. So, when the temperature exceeds ~30°C the coral expels its algae, rendering itself white, or bleached. If the temperature stays above this level for more than 6 months, and the coral cannot find a more suitable alga, it is likely that the coral reef will die. Coral bleaching due to high water temperatures is occurring with increasing frequency and over more widespread areas in conjunction with global warming (e.g., Fig. 7.12). The 1998 El Nino event killed about 15% of corals world-wide. In 2014 and 2015 unusually warm water near the Hawaiian Islands, associated with “The Blob” warm SST anomaly, caused extensive coral bleaching.

Other causes of coral bleaching include unusually cold temperatures, salinity being too low or too high, and too much turbidity from river-borne sediment. Other factors that are deleterious to coral reefs include pollution, fish harvesting with bombs and cyanide, boat anchors, and infection by fungal spores on windborne sand from the Sahara desert. During the

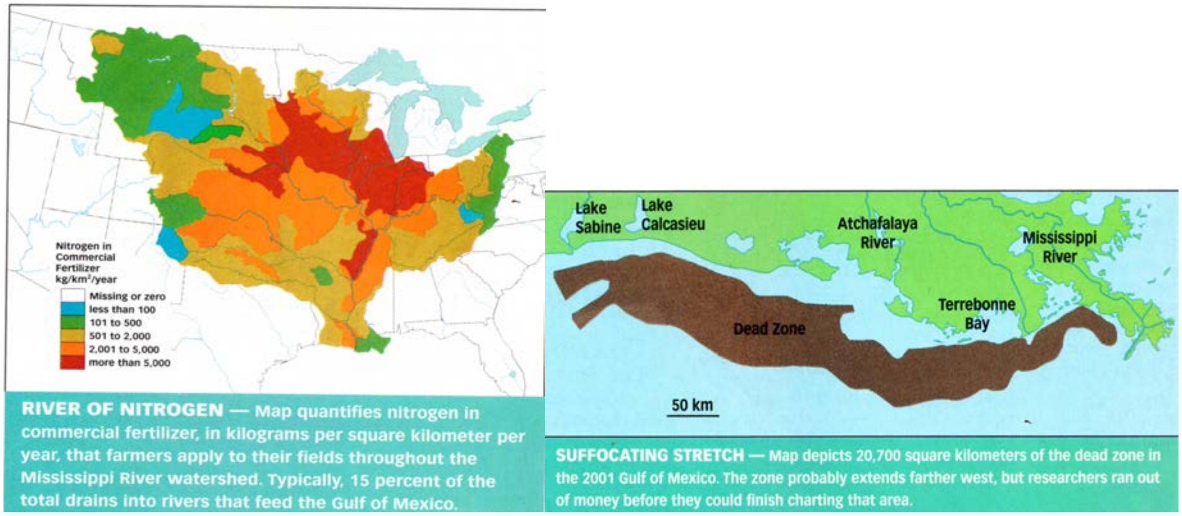
1980s about half of the coral reefs in the Caribbean succumbed to white-band disease. When coral bleaching occurs, their surface is often colonized by a thick coat of algae, which prevents recovery and recolonization.

Corals can clone themselves to create new adjacent polyps and tentacles. They also produce both egg and sperm which they release once a year in the summertime after a full moon (Kolbert 2016). Coral embryos drift around for a while before settling. Hence the time scale for natural recovery from coral bleaching through recolonization can be fairly long. Cross-breeding requires many generations.

During the last few years there has been widespread coral bleaching in the northern half of the Great Barrier Reef. Charts of sea surface temperatures show that temperatures are about 1°C above average, but not record high. However, ocean acidity increases northward toward the tropics near the Great Barrier Reef. Perhaps the combined influence of somewhat higher temperatures and somewhat more acidity has rendered the northern half bleached. Some scientists are trying to selectively breed and genetically engineer Super Corals, which are somehow metabolically more resistant to higher temperatures. Yet what determines the viability of a coral animal remains subtle and delicate and rather poorly understood.

7.5. Factors affecting the global oceans

The world's oceans are currently subject to an increasing array of threats. These include the observed increase in sea surface temperatures and increased heat storage. More than half of the excess energy trapped in the earth system by anthropogenic carbon dioxide loading of the atmosphere has gone into increasing upper ocean temperatures, which increases stratification and reduces nutrient upwelling (Jewett et al. 2017). The acidity of the ocean has increased by ~30% (pH reduction of -0.1) due to increasing atmospheric carbon dioxide. The ocean is also being de-oxygenated due to warming, increased stratification, and increasingly large anoxic dead zones at river mouths due to farm fertilizer and runoff (Fig. 7.13).



RIVER OF NITROGEN — Map quantifies nitrogen in commercial fertilizer, in kilograms per square kilometer per year, that farmers apply to their fields throughout the Mississippi River watershed. Typically, 15 percent of the total drains into rivers that feed the Gulf of Mexico.

SUFFOCATING STRETCH — Map depicts 20,700 square kilometers of the dead zone in the 2001 Gulf of Mexico. The zone probably extends farther west, but researchers ran out of money before they could finish charting that area.

Figure 7.13. Every spring excess nitrogen fertilizer in major food growing regions washes downstream, causing an algae bloom, which then decay via bacteria, which uses up most of the oxygen by the time the water reaches the sea, creating a large area of water where nothing can live (Science News).

Gruber (2011) estimates that by 2100 the ocean will experience 1-7% loss of oxygen, and that the ocean is "warming up, turning sour, and losing breath". Moreover, phytoplankton abundance is declining at a surprising rate of 1% per year (Boyce et al., 2010) and global fisheries have declined by 10-50%. The next chapter on the carbon cycle explores the cause of ocean acidification in more detail.

Key words

evapotranspiration – evaporation from wet surfaces plus transpiration from plants

Intertropical Convergence Zone (ITCZ) – a thin band of deep convection in the tropics which occurs where the moist trade easterly winds converge

Maritime Continent – Indonesia, most powerful tropical convective region on earth

mycorrhizae –fungal hyphae associated with plant roots which aid uptake of nutrients and water

Sahel – ecosystem on the equatorward fringe of the Sahara desert

SST – sea surface temperature

xerophytic – plants that are able to grow well in very dry climates

zooxanthellae – symbiotic photosynthetic dinoflagellates hosted by coral which provide nutrients and color

References Cited

Boyce, D. G., M. R. Lewis, and B. Worm, 2010: Global phytoplankton decline over the past century. *Nature*, 2010 Jul 29;466(7306):591-6. doi: 10.1038/nature09268.

Brasseur, G. P., J. J. Orlando, and G. S. Tyndall Eds., 1999: *Atmospheric Chemistry and Global Change*, Oxford University Press, 688 pp.

Coe, M. T., and J.A. Foley, 2001: Human and natural impacts on the water resources of the Lake Chad basin. *J. Geophys. Res. – Atmos.*, **106 (D4)**, 3349-3356.

Feng, S, and Q. Fu, 2013: Expansion of global drylands under a warming climate. *Atmos. Chem. Phys.*, **13**, 10081–10094.

Foley, J. A., et al., 2007: Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin *Front. Ecol. Environ.*, **5(1)**, 25–32.

Folger, T., 2004: A thirsty nation. *One Earth*, Fall 2004, 1-33.

Grabiel, T., 2006: Drawdown: An update on groundwater mining on Black Mesa. NRDC, March 2006.

Gruber, N., 2011: Warming up, turning sour, losing breath: Ocean biogeochemistry under global change. *Phil. Trans. A*, **369(1943)**,1980-1996.

Harrison, B., and R. Bales, 2015: Skill Assessment of Water Supply Outlooks in the Colorado River Basin. *Hydrology*, **2 (3)**, 112–131.

Hoerling, M. P., J. J. Barsugli, B. Livneh, J. Eischeid, X. Quan, and A. Badger. 2019: Causes for the Century-Long Decline in Colorado River Flow. *J. Clim.*, JCLI-D-19-0207.1.

Jewett, L. and A. Romanou, 2017: Ocean changes – warming, stratification, circulation, acidification, and deoxygenation. Publications, Agencies and Staff of the U.S. Department of Commerce, 580.

Kolbert, E., 2016: "Unnatural selection", April 8 2016 New Yorker, 22-28.

Lukas, J., and E. Payton, eds. 2020. Colorado River Basin Climate and Hydrology: State of the Science. Western Water Assessment, University of Colorado Boulder. DOI: https://doi.org/10.25810/3hcv-w477.

Snyder, P. K. , J. A. Foley , M. H. Hitchman , and C. Delire, 2004: Analyzing the effects of complete tropical forest removal on the regional climate using a detailed three-dimensional energy budget: An application to Africa. *J. Geophys. Res*., **109**, D21102. doi:10.1029/2003JD004462.

Snyder, P. K., 2010: The influence of tropical deforestation on the Northern Hemisphere climate by atmospheric teleconnections. *Earth Interactions*, **14**, 1-33.

Vorosmarty, C. J., M. Meybeck, B. Fekete, K. Sharma, P. Green, and J. Syvitski. Anthropogenic sediment retention: Major global impact from registered river impoundments. *Global and Planetary Change*, **39**, 169-190.

Wellington, G. M., et al., 2001: Crisis on coral reefs linked to climate change. *EoS Trans*, **82**, 1-5.

Woodhouse, C. A., D. M. Meko, G. M. MacDonald, and E. R. Cook, 2010: A 1,200-year perspective of 21st century drought in southwestern North America. *PNAS*, **107 (50)**, 21,283-21,288.