
Water Vapor: Distribution and Trends

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*Water in the gaseous phase, water vapor, is the most significant atmospheric trace constituent vis-à-vis climate, weather, hydrology, and atmospheric chemistry. Water vapor is the most abundant atmospheric greenhouse gas, and without it the planet's surface temperature would be well below freezing. Phase changes involving water vapor – the condensation and evaporation processes – involve exchanges of latent heat energy that affect the vertical stability of the atmosphere, the structure and evolution of storm systems, and the energy balance of the global climate system (Chahine, M T (1992) *The Hydrological Cycle and its Influence on Climate*, Nature, 359, 373–380). Water vapor is also the prime source of the atmospheric hydroxyl radical, an oxidizing agent that cleanses the atmosphere of many air pollutants.*

The total amount of water vapor in the atmosphere is about 13×10^{15} kg. For reference, oceans hold about 100 000 times as much water, and the total amount of water on land (as ice, snow, surface and ground water, and in living organisms) is about 4000 times as much as in the atmosphere. Nevertheless, changes in the amount and distribution of atmospheric water vapor, which can happen relatively quickly, both cause and provide evidence of other global environmental changes. For example, temperature and water vapor changes often go hand in hand, so that increases in water vapor can be indirect evidence of warming. As changes in climate are accompanied by changes in atmospheric circulation and the transport of water vapor, the patterns of precipitation will also change. The extent of such changes could be similar in magnitude to the shifts associated with the El Niño–Southern Oscillation phenomenon, which leads to droughts and flooding in various locations around the world.

The weight of the atmosphere's water vapor contributes to only about one-quarter of 1% of the total sea level pressure of all gases. If all the water vapor in the air were to condense and fall as rain, it would cover the Earth with a layer about 25 mm (or 1 inch) deep on average. This is called precipitable water. Since water vapor is not evenly distributed over the globe, there would be about 50 mm near the equator and less than one-tenth as much near the poles, as shown in Figure 1 (Randel *et al.*, 1996). The general decrease of precipitable water from equator to poles is a reflection of the global distribution of temperature, because warm air is capable of holding more moisture than cold air. There are exceptions in the major desert regions, where the air is very dry despite its high temperature. The most humid region is in the western equatorial Pacific, above the

so-called oceanic warm pool, where the highest sea surface temperatures are found.

The average precipitation over the globe is about 1 m annually, so there must be swift transfer of atmospheric water vapor to the surface via precipitation and back again to the atmosphere via evaporation; the average water molecule spends about 9 days in the air before returning to the surface. This rapid turnover, combined with the variation of temperature with height and geography, causes water vapor to be distributed unevenly in the atmosphere, both horizontally and vertically. The map in Figure 1 is a 10-year average depiction that is smoothly varying. On any given day, water vapor exhibits much more complex patterns associated with storm systems and wind patterns.

The uneven distribution of water vapor is even more pronounced in the vertical dimension. Water vapor concentrations (expressed as the ratio of the volume occupied by water vapor to the total volume of air, most of which is nitrogen and oxygen) decrease rapidly with height, varying over four orders of magnitude, from a few percent near the surface to a few parts per million in the lower stratosphere. Nearly half the total water in the air resides below an altitude of about 1.5 km. Less than 5% is in the upper troposphere (above 5 km), and less than 1% is in the stratosphere, nominally above 12 km. This wide range of concentrations presents challenges in designing instruments for atmospheric water vapor measurements. Therefore, a plethora of technologies exist, from low-cost, expendable balloon-borne sensors designed for daily weather observations, to research-quality aircraft- and satellite-borne instruments.

Variations in atmospheric water vapor occur on time-scales from milliseconds to decades. The fastest fluctuations are due to turbulence, and near the surface they are associated with changes in the vertical component of the wind and in evaporation. At higher altitudes, air currents generated by atmospheric instability redistribute water vapor and influence cloud formation over periods of minutes or hours. Land and sea breezes cause water vapor concentrations in coastal regions to vary considerably over the course of a day. The distribution of water vapor changes with seasonal changes in temperature and atmospheric circulation patterns. As with temperature, seasonal changes in water vapor appear to be stronger in the northern hemisphere than in the southern hemisphere. Since the Northern Hemisphere has more land, with lower heat capacity than the ocean, it shows faster temperature, and water vapor, changes.

On longer time scales, water vapor changes are thought to contribute to an important positive feedback mechanism for climate change, as follows. Warming of the surface, particularly the sea surface, leads to enhanced evaporation. Since warmer air requires more moisture to reach saturation, atmospheric temperature increases allow for increases in atmospheric water vapor. Due to the fact that water vapor is a greenhouse gas, enhanced water vapor in the lower

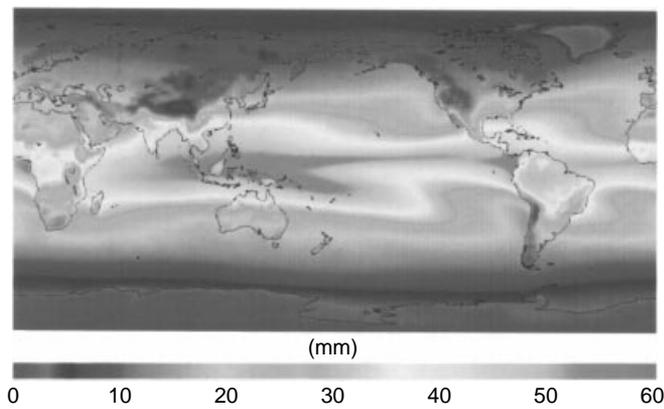


Figure 1 The global distribution of total atmospheric water vapor (precipitable water) above the Earth's surface. This depiction includes data from both satellite and weather balloon observations and represents an average for the period 1988–1997

troposphere results in further warming, allowing a higher water vapor concentration, thereby creating a positive feedback. This mechanism is well represented in global climate models, and observations of year to year variations in temperature and water vapor show high correlations (Wentz and Schabel, 2000). However, it is less clear whether this mechanism operates in the upper troposphere, where, despite its relatively low concentrations, water vapor has a more powerful greenhouse effect (Harries, 1996). The variability of upper-tropospheric water vapor with surface temperature is not well documented, mainly because of the lack of long-term measurements in this region (Rind, 1998). Mechanisms have been proposed by which upper-tropospheric water vapor changes, particularly in the tropics, may lead to negative feedbacks on surface temperature (Lindzen, 1990), but overall water vapor changes are thought to contribute to a positive feedback to global warming (Stocker, 2001).

With global warming, an increase in the rate of evaporation must be matched by an increase in the rate of precipitation, because the atmosphere holds so little water. This acceleration of the global hydrological cycle seems likely to lead to an increase in the frequency of extreme precipitation events, and an increase in the proportion of precipitation falling in extreme events (Trenberth, 1998, 1999), which has been observed in some regions (Folland and Karl, 2001). Such changes would have important consequences for agriculture, flood control, and other aspects of human society. Water vapor feedback may also be amplifying atmospheric temperature changes, suspected to be the primary driver of the observed rapid retreat, and in some cases the disappearance, of ice caps and glaciers at high elevations in the tropics and subtropics (Thompson, 2000). Evidence for long-term changes in atmospheric water vapor is limited by the availability and quality of measurements. However, data for the last three or four decades of the

twentieth century indicate an increase in water vapor in the lower troposphere over parts of the Northern Hemisphere (Ross and Elliott, 2000).

Measurements are so limited in the stratosphere that detecting changes in stratospheric water vapor is very difficult. Although the spatial representativeness of the observations remains a question, observations made over Boulder, Colorado, in the 1980s and 1990s show an upward trend in water vapor concentration (Oltmans *et al.* 1995). Unlike the troposphere, the stratosphere is not well mixed, and stratospheric water vapor is not controlled by the same processes operating in the troposphere. The observed stratospheric water vapor increases are larger than can be attributed to increases in methane, which is a chemical source of stratospheric water vapor, and do not appear compatible with the current understanding of changes in the temperature of the tropical tropopause, where tropospheric water vapor enters the stratosphere. Circulation changes are hypothesized to be a contributing factor. Changes in stratospheric water vapor, and related changes in stratospheric clouds, could alter the chemistry of the stratospheric ozone layer and contribute to a cooling of the stratosphere.

Thus, water vapor, a natural and familiar atmospheric constituent, plays many important roles in the global environment. In the greenhouse effect, the global water cycle, and global air chemistry, water vapor both brings about, and is a manifestation of, global environmental change.

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