HALOE v2.0 UPPER TROPOSPHERIC WATER VAPOR CLIMATOLOGY

Claudette Ojo
Hampton University

Abstract

The Halogen Occultation Experiment (HALOE) has been operating essentially without flaw on the Upper Atmosphere Research Satellite since it was first turned on in orbit October 11, 1991. HALOE measures temperature and atmospheric vertical profiles including O3, HCl, HF, CH4, H2O, NO, NO2 and aerosols at four wavelengths. This research will focus on the HALOE H2O vertical profile data in the mid-to-upper troposphere. Some analysis techniques include performing simple regression techniques to characterize the seasonal cycles. In addition, this HALOE record is of special use for global change investigations. Although tropospheric water vapor is highly variable, accurate and precise water vapor measurements are vital for the scientific community because it will contribute immensely to the study of climate change, in developing better weather prediction models, and will increase present knowledge about global warming. Goals of this research are to develop a simple upper tropospheric climatology for H2.O and to conduct studies to assess long-term changes in this parameter. Aerospace application of the research will involve the analyzation of satellite-based HALOE v2.0 upper tropospheric data.

Introduction

What is Water Vapor?

Water vapor, water vapour, also aqueous vapor, is the gas phase of water. There is no difference between the terms gas and vapor, but gas is used commonly to describe a substance that appears in the gaseous state under standard conditions of pressure and temperature, and vapor to describe the gaseous state of a substance that appears ordinarily as a liquid or solid. Because water by definition is a liquid, when used in a direct context, the gas phase of water is referred to as water vapor.

Water vapor is not visible, therefore clouds, fog and most other formations within the atmosphere that can be seen by the naked eye are not water vapor. Water vapor, however, can be sensed. If enough of it is in the air it is felt as humidity. Water vapor is one state of the water cycle within the hydrosphere. Water vapor can be produced from the evaporation of liquid water or from the sublimation of ice. Under normal atmospheric conditions, water vapor is continuously generated by evaporation and removed by condensation.

Water vapor is vital to weather and climate as clouds, rain and snow have their source in water vapor. All of the water vapor that evaporates from the surface of the Earth eventually returns as precipitation - rain or snow. Water vapor is also the Earth's most important greenhouse gas, giving us over 90% of the Earth's natural greenhouse effect, which helps keep the Earth warm enough to support life. When liquid water is evaporated to form water vapor, heat is absorbed. This helps to cool the surface of the Earth. This "latent heat of condensation" is released again when the water vapor condenses to form cloud water. This source of heat helps drive the updrafts in clouds and precipitation systems. In order to understand water vapor, some insight must be given into water.

Water and its Properties

Water is one of the main sources of the energy needed to run the Earth's weather machine. All substances, including water exist in three phases: Solid, liquid, and gas. No matter what phase it's in, a water molecule is the same - an atom of oxygen with two atoms of hydrogen attached. Their energy, as exhibited by the speed of their movement, is the only thing that makes millions of water molecules act differently when they get together in water's different phases. Water's phase changes help drive the weather as each change either releases or takes up energy in the form of latent heat. The energy of the molecules known as the average speed of molecular motion, determines the phase of a substance. Temperature, in turn, is a measure of the average speed of molecular motion. Water is special because it's the only substance that can exist in all three phases at Earth's ordinary temperatures, and it's common to have all three phases together at the same time. To understand the weather, you need to understand what happens when water changes its state. These changes are:

- **Evaporation:** From liquid to gas (water vapor).
- **Condensation:** From gas (water vapor) to liquid.
- **Freezing:** From liquid to solid (ice).
- **Melting:** From solid to liquid.
- **Deposition:** From gas directly to solid without becoming liquid.
- **Sublimation:** From solid directly to gas.

The conversation of energy is one of the very basic laws of nature. It says that energy cannot be created or destroyed, but it can change form. This means that when water molecules slow down enough to change from vapor to liquid or ice, the kinetic energy of their movement changes into another form of energy, heat. When water evaporates from a pond to become water vapor, heat energy becomes the kinetic energy of the added motion.

Latent Heat

When heat is added or extracted from a system the temperature changes. However, there are certain situations when the addition or subtraction of heat from a system does not result in a temperature change. In these situations, the heat that is added or extracted is being converted into energy to cause a phase change from one physical state to another.

Latent heat is the energy that is required to change a substance from one form to another. It is the enthalpy change that accompanies a phase change at constant temperature and pressure. It is called latent because it is somewhat hidden from detection except for the physical change in a substance's form. The value of latent heat is dependent upon the exact nature of the phase change as well as on the specific properties of the substance. Latent heat is usually expressed in terms of calories per gram. The latent heat of water is 79.7cal/g

There are various forms of latent heat, depending on what transformation is occurring when it is taken up or released. These kinds are listed below with the amounts of energy involved in each. The figures below are those normally found in meteorology texts and are for temperatures found in the atmosphere, such as 0 Celsius (32 F). **Latent heat of condensation** (Lc): Refers to the heat gained by the air when water vapor changes into a liquid. Lc=2500 Joules per gram (J/g) of water or 600 calories per gram (cal/g) of water. **Latent heat of fusion** (Lf): Refers to the heat lost or gained by the air when liquid water changes to ice or vice versa. Lf=333 Joules per gram (J/g) of water or 80 calories per gram (cal/g) of water. **Latent heat of sublimation** (Ls): Refers to the heat lost or gained by the air when ice changes to vapor or vice versa.

Ls=2833 Joules per gram (J/g) of water or 680 calories per gram (cal/g) of water.
Latent heat of vaporization (Lv): Refers to the heat lost by the air when liquid water changes into vapor. This is also commonly known as the latent heat of evaporation. Lv= -2500 Joules per gram (J/g) of water or -600 calories per gram (cal/g) of water.

Latent Heat of Vaporization

The latent heat of a physical transformation from one phase to another can also be thought of as the amount of energy required to rearrange the molecules of a substance. When a solid is transformed into a liquid, the magnitude of the vibrations of the atoms about their equilibrium positions becomes large, large enough to overcome the attractive forces that bind the atoms together into a solid form. The latent heat is the energy required to break these bonds and transform the material from the ordered solid state to the disordered liquid state. Just as energy is required to break the bonds binding the atoms of a solid together, energy is also required to weaken the attractive forces between the molecules in a liquid in order for it to become a vapor. In a liquid the molecules are closer together than in a vapor phase and so the forces between them are stronger than in a gas. In order to separate the molecules the attractive forces must be broken. Since the average distance between molecules in a vapor are larger than either the liquid or the solid states, it is obvious that more work is required to separate the molecules to form a vapor. This explains why the latent heat of vaporization is much higher than the latent heat of fusion for a given substance.

The latent heat of evaporation or, vaporization is the energy process directly involved in the formation of water vapor. When heat is added to a liquid at its boiling point , with the pressure kept constant, the molecules of the liquid acquire enough energy to overcome the intermolecular forces that bind them together in the liquid state, and they escape as individual molecules of vapor until the vaporization is complete. Vaporization at the boiling point is known simply as boiling. The temperature of a boiling liquid remains constant until all of the liquid has been converted to a gas.

For each substance a certain specific amount of heat must be supplied to vaporize a given quantity of the substance. The quantity of heat applied for each gram (or each molecule) undergoing the change in state depends on the substance itself. For example, the amount of heat necessary to change one gram of water to steam at its boiling point at one atmosphere of pressure, i.e., the heat of vaporization of water, is approximately 540 calories

Evaporation

Liquids can also change to gases at temperatures below their boiling points. Vaporization of a liquid below its boiling point is called evaporation , which occurs at any temperature when the surface of a liquid is exposed in an unconfined space. When, however, the surface is exposed in a confined space and the liquid is in excess of that needed to saturate the space with vapor, an equilibrium is quickly reached between the number of molecules of the substance going off from the surface and those returning to it. A change in temperature upsets this equilibrium; a rise in temperature, for example, increases the activity of the molecules at the surface and consequently increases the rate at which they fly off. When the temperature is maintained at the new point for a short time, a new equilibrium is soon established.

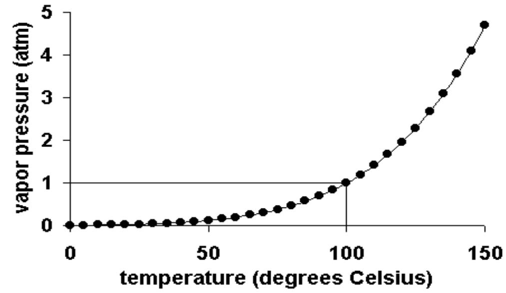
Vapor Pressure

All liquids and solids have a tendency to evaporate to a gaseous form, and all gases have a tendency to condense back into their original form (either liquid or solid). At any given temperature, for a particular substance, there is a pressure at which the gas of that substance is in dynamic equilibrium with its liquid or solid forms. This is the vapor pressure of that substance at that temperature. The vapor pressure of a liquid is the pressure exerted by its vapor when the liquid and vapor are in dynamic equilibrium.

Vapor pressures differ for different substances at any given temperature, but each substance has a specific vapor pressure for each given temperature. At its boiling point the vapor pressure of a liquid is equal to atmospheric pressure. For example, the vapor pressure of water, measured in terms of the height of mercury in a barometer, is 4.58 mm at 0°C and 760 mm at 100°C (its boiling point).

Vapor pressures increase with temperature. The vapor pressure of any substance increases non-linearly with temperature according to the Clausius-Clapeyron relation : $\ln(P_2/P_1) = -DH_{vap}/R * (1/T_2 - 1/T_1)$. The most common unit for vapor pressure is the torr. 1 torr = 1 mm Hg (one millimeter of mercury).

Most materials have very low vapor pressures. Water has a vapor pressure of approximately 15 torr at room temperature. But because vapor pressures increase with temperature; water will have a vapor pressure of 760 torr = 1 atm at its boiling point of 100 ^{o}C (212 ^{o}F). Conversely, vapor pressure decreases as the temperature decreases.



The equilibrium vapor pressure is an indication of a liquid's evaporation rate. It relates to the tendency of molecules and atoms to escape from a liquid or a solid. A substance with a high vapor pressure at normal temperatures is often referred to as volatile.

Water Vapor in the Earth’s Atmosphere

The troposphere contains 75 percent of the atmosphere's mass—on an average day the weight of the molecules in air is 1.03 kg/sq cm (14.7 lb/sq in)—and most of the atmosphere's water vapor. Water vapor varies by volume in the atmosphere from a trace, or 0% to about 4%. Therefore, on average, only about 2 to 3% of the molecules in the air are water vapor molecules. The amount of water vapor in the air is small in extremely arid areas and in location where the temperatures are very low (i.e. polar regions, very cold weather). The volume of water vapor is about 4% in very warm and humid tropical air.

The amount of water vapor in the air cannot exceed 4% because temperature sets a limit to how much water vapor can be in the air. Even in tropical air, once the volume of water vapor in the atmosphere approaches 4% it will begin to condense out of the air. The condensing of water vapor prevents the percentage of water vapor in the air from increasing. If temperatures were much warmer, there would be a potential to have more than 4% water vapor in the atmosphere.

The concentration of water vapor in the atmosphere reflects the number of molecules of water compared with the total number of air molecules (mainly nitrogen and oxygen). Humidity is a measure of the amount of water vapor in the air. One way to represent humidity is the mixing ratio, defined as the mass of water vapor "mixed with" each unit mass of air. The mixing ratio is usually expressed as the number of grams of water vapor in each kilogram of air. In the atmosphere, the mixing ratio can vary from nearly zero (in deserts and polar regions and at high altitudes) to as much as 30 grams per kilogram (in warm, moist tropical regions). Other measurements of humidity include the relative humidity, which reflects the ratio of the actual pressure of water vapor in a sample of air to the pressure necessary to saturate that air at a given temperature and dew point temperature, the temperature to which the air must be cooled for water vapor to reach saturation.

Water Vapor and The Greenhouse Effect

In a very rough approximation the following trace gases contribute to the greenhouse effect: 60% water vapor, 20% carbon dioxide (CO_2). The rest (~20%) is caused by ozone (O_3), nitrous oxide (N_2O), methane (CH_4), and several other species. Water vapor amplifies the anthropogenic contribution to greenhouse warming through a positive feedback. This amplification is counteracted by the increased reflection off clouds. Water vapor is known to be Earth's most abundant greenhouse gas, but the extent of its contribution to global warming has been debated. Using recent NASA satellite data, researchers have estimated more precisely than ever the heat-trapping effect of water in the air, validating the role of the gas as a critical component of climate change. Andrew Dessler and other scientists at Texas A and M University in College Station confirmed that the heat-amplifying effect of water vapor is potent enough to double the climate warming caused by increased levels of carbon dioxide in the atmosphere.

With new observations, the scientists confirmed experimentally what existing climate models had anticipated theoretically. The research team used novel data from the Atmospheric Infrared Sounder (AIRS) on NASA's Aqua satellite to measure precisely the humidity throughout the lowest 10 miles of the atmosphere.

That information was combined with global observations of shifts in temperature, allowing researchers to build a comprehensive picture of the interplay between water vapor, carbon dioxide, and other atmosphere-warming gases. Most agree that if you add carbon dioxide to the atmosphere, warming will result. The amount of warming that occurs can be found by estimating the magnitude of water vapor feedback. Increasing water vapor leads to warmer temperatures, which causes more water vapor to be absorbed into the air. Warming and water absorption increase in a spiraling cycle.

Water vapor feedback can also amplify the warming effect of other greenhouse gases, such that the warming brought about by increased carbon dioxide allows more water vapor to enter the atmosphere. More water vapor in the air also gives rise to an increase in the formation of clouds in the troposphere. Clouds do consist of small water droplets, though, and, hence, they do absorb radiation. But they also have a moderating effect on the process of earth's warming because clouds reflect a significant portion of solar isolation. Thus, this portion does not reach the surface of the earth and thus surface is less heated.

Climate models have estimated the strength of water vapor feedback, but until now the record of water vapor data was not sophisticated enough to provide a comprehensive view of at how water vapor responds to changes in Earth's surface temperature. Past ground instruments and previous space-based could not measure water vapor at all altitudes in Earth's troposphere -- the layer of the atmosphere that extends from Earth's surface to about 10 miles in altitude.

AIRS is the first instrument to distinguish differences in the amount of water vapor at all altitudes within the troposphere. Using data from AIRS, the team observed how atmospheric water vapor reacted to shifts in surface temperatures between 2003 and 2008. By determining how humidity changed with surface temperature, the team could compute the average global strength of the water vapor feedback.

"This new data set shows that as surface temperature increases, so does atmospheric humidity," Dessler said. "Dumping greenhouse gases into the atmosphere makes the atmosphere more humid. And since water vapor is itself a greenhouse gas, the increase in humidity amplifies the warming from carbon dioxide."

Specifically, the team found that if Earth warms 1.8 degrees Fahrenheit, the associated increase in water vapor will trap an extra 2 Watts of energy per square meter (about 11 square feet)."That number may not sound like much, but add up all of that energy over the entire Earth surface and you find that water vapor is trapping a lot of energy," Dessler said. "We now think the water vapor feedback is extraordinarily strong, capable of doubling the warming due to carbon dioxide alone."

Because the new precise observations agree with existing assessments of water vapor's impact, researchers are more confident than ever in model predictions that Earth's leading greenhouse gas will contribute to a temperature rise of a few degrees by the end of the century. "This study confirms that what was predicted by the models is really happening in the atmosphere," said Eric Fetzer, an atmospheric scientist who works with AIRS data at NASA's Jet Propulsion Laboratory in Pasadena, Calif. "Water vapor is the big player in the atmosphere as far as climate is concerned. (Hansen.K. Water Vapor Confirmed As Major Player In Climate Change)

Detecting Water Vapor in the Atmosphere

Water plays a crucial role in weather and climate, and identifying the amount of water vapor in the atmosphere will help scientists understand clouds, severe weather, precipitation, hydrology, and global climate change. There has been a general lack of information on the way water moves around in Earth's atmosphere - where it comes from and where it ends up. The details of this journey are critical for understanding clouds and climate, as well as changes in precipitation patterns and water resources. Because of water vapor’s great mobility and brief residence time, water vapor is a central component of the global hydrological cycle. How this cycle may change globally and regionally in the future is a major issue for climate science and society. Water vapor is vital for Earth’s energy and water cycles, it must be monitored in time and space if we are to explain and predict behavior of the climate system.

Measuring water vapor sufficiently well to properly understand the processes responsible for its variability has proven disappointingly elusive. This situation results in part because water vapor is not dynamically constrained, and its high special variability makes adequate sampling difficult. Problems associated with the various water vapor measurement technologies also have hindered progress. Standard humidity sensors carried out by radiosondes have complex error statistics up through the mid troposphere and their performance is severely diminished at higher levels. The network of radiosonde stations works best on ground locations and the number of these has diminished over the past decades. Satellite images provide global coverage, but their vertical resolution in the lower troposphere, where water vapor is most abundant, is poor compared with that of ground-based radiosondes systems. Long term water vapor coverage can also be problematic due to several factors such as gradual changes in instrument sensitivity and local crossing time, abrupt changes resulting from satellite replacements, and short or intermittent system lifetimes.

Instrumentation

Since its launch on September 12, 1991 from the Space Shuttle Discovery, the Halogen Occultation Experiment (HALOE) has been collecting profiles of middle atmosphere composition and temperature on board the Upper Atmosphere Research Satellite (UARS). HALOE uses solar occultation to measure simultaneous vertical profiles of Ozone (O_3), Hydrogen Chloride (HCl), Hydrogen Fluoride (HF), Methane (CH_4), Water Vapor (H_2O), Nitric Oxide (NO), Nitrogen Dioxide (NO_2), Temperature, Aerosol Extinction at 4 infrared wavelengths, Aerosol composition and size distribution versus atmospheric pressure with a 1.6 km instantaneous field of view at the Earth's limb.

Aimed at better understanding the coupled chemistry, dynamics, and energetics of the Earth's middle and upper atmosphere, HALOE was selected to fly on UARS supported by the NASA Mission to Planet Earth program. HALOE is a collaboration among the Langley Research Center; Max Planck Institute for Chemistry; University of Chicago; University of Michigan; University of California, Irvine; NOAA/Environmental Research Laboratory; and Imperial College, U. K. Fabricated and calibrated in-house by engineers at NASA Langley Research Center, the over 14 years of flawless operation of HALOE is an icon of their dedication and commitment to quality.

Dr. James M. Russell III from Hampton University in Hampton, Virginia is the HALOE Principal Investigator. The HALOE Project Scientist is Dr. Ellis E. Remsberg located at the NASA Langley Research Center in Hampton, Virginia.

Science Goals

- Improve understanding of stratospheric ozone depletion due to ClOy, NOy, and HOy by collecting and analyzing global data on key chemical species, including: O_3, HCl, CH_4, H_2O, NO, NO_2, and CO_2 (T,P)

- Study the CFC impact on ozone by conducting simultaneous measurements of: HCl and HF

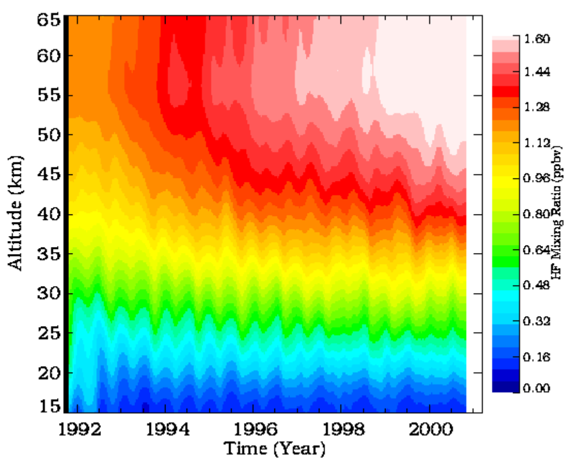
- Analyze the global distribution and temporal behavior of vertical aerosol extinction coefficient profiles at eight infrared wavelengths

Science Objectives

- Study dynamics of polar and other atmospheric regions using HALOE tracers CH_4, HF, and H_2O

- Use trends in HCl and HF to study the relative importance of anthropogenic versus natural chlorine sources

- Develop and prepare a climatology of HALOE measured stratospheric gases and aerosols
- Carry out stratospheric chemistry studies (especially ClOy and NOx) including effects of heterogeneous chemistry
- Analyze the H2O and total hydrogen budget using HALOE H2O and CH4 data in the stratosphere and mesosphere
- Conduct studies to identify and assess stratosphere/troposphere exchange
- Test diurnal photochemistry using HALOE NO and NO2 results
- Analyze in detail the development and recovery of the Antarctic ozone hole
- Describe the changing Pinatubo aerosol morphology for several years after the eruption (June 12, 1991)



Observations of water vapor isotopes from HALOE V.2.0

<u>Summary</u>

Overall these figures demonstrate a substantial degree of interannual variability in the HALOE data in the lower stratosphere. While the climatological features in HALOE data are in good overall agreement with seasonality in aircraft and balloon measurements, the utility of HALOE for quantifying interannual variability is a subject of ongoing research.

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