Hygrometry

The art or science of humidity observation
Humidity

• Under normal atmospheric conditions, the amount of water vapor any sample of air can hold depends primarily on its temperature.

• Various terms can be used to express the amount of water vapor in the atmosphere – knowing just one and the temperature allows the derivation of the others.
Humidity Measurements

• Main objective – study the amount of water vapor present in the atmosphere

• Can be determined by
  – Weight
  – Volume
  – Partial pressure
  – Fraction of the saturation vapor pressure
Water Vapor Pressure

• Pure water vapor in equilibrium with a plane surface of pure water exerts a pressure
• Pressure is a function of temperature of the vapor and liquid phases
Water Vapor as a Gas

• Consider a thermally isolated container of fixed volume (V), partly filled with water at temperature (T).
Water Vapor as a Gas

• Pressure due to water vapor can be used to characterize the humidity
  – The more vapor in the air, the heavy the vapor, the higher the pressure

• If there is a mass \( m \) of water vapor present in the container of volume \( V \) at a temperature \( T \), how can you find the pressure exerted by the vapor?
Vapor Pressure

• Express the equation in terms of the mass of the water vapor:
Saturation Vapor Pressure

• When the exchange of water molecules from liquid to vapor and vapor to liquid is equal, the vapor is saturated with respect to the water.
• The vapor pressure in this saturated condition can be calculated using the vapor pressure equation using the saturated mass of water vapor present \( (m_s) \) to find the saturation vapor pressure \( (e_s) \).
Saturation Vapor Pressure

• $e_s$ varies with which parameter, $T$ or $T_d$?

• The variation of $e_s$ with respect to Temperature is described by the Clausius-Clapeyron equation, which considers the equilibrium between two phases of the same substance (water in this case)
Clausius-Clapeyron

• The equation states that:
Simplified Equation

• Temperature variation can be found by integration of the Clausius-Clapeyron equation, but allowance is also needed for variation of $\lambda$ with temperature

• Simpler parameterization used is:
Coefficients for Calculating $e_s$ over water and ice

<table>
<thead>
<tr>
<th>Water (Bolton’s coefficients)</th>
<th>Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (hPa)</td>
<td>6.112</td>
</tr>
<tr>
<td>B</td>
<td>17.67</td>
</tr>
<tr>
<td>$C$ (°C)</td>
<td>243.5</td>
</tr>
<tr>
<td>Range</td>
<td>–35°C to 30°C</td>
</tr>
</tbody>
</table>
Absolute Humidity ($\chi$)

- ratio of the mass of water vapor ($m_v$) to the total volume of moist air ($V$)
- This mass per unit volume can also be expressed as a concentration of water vapor in the volume of air
Specific Humidity \( (q) \)

• Also known as mass concentration – ratio of the mass of water vapor \( (m_v) \) to the mass of moist air \( (m_v + m_d) \)

• Need to account for air pressure \( (p) \) with vapor pressure \( (e) \)
Specific Humidity (q)

• Accounting for $p$ and $e$ (which is good to about 1%):

• Can also be expressed in terms of the humidity mixing ratio ($r_v$):
Relative Humidity (%)

- Ratio (%) of the actual vapor pressure ($e$) to the saturation vapor pressure ($e_s$) at the air temperature ($T$):

- **Relative humidity is NOT** $= 100 \times \frac{T}{T_d}$
Temperature (T)

- Also known as Dry-bulb temperature
Dewpoint Temperature \( (T_d) \)

• Temperature at which ambient water vapor condenses and air becomes saturated with respect to a plane surface of pure water

• Two methods for calculating it
  – Invert eqn from slide 11
Dewpoint Temperature \((T_d)\)

- Second method uses relationship of RH to \(T_d\) to find \(T_d\)
Frost Point Temperature ($T_f$)

- Temperature at which ambient water vapor freezes (sublimates)
- Related to a similar equation as $T_d$, but using the coefficients for ice instead of water from slide 12.
Wet-Bulb Temperature ($T_w$)

- Temperature indicated by the wet-bulb thermometer of a psychrometer.
  - Temperature a parcel of air would have if it were cooled to saturation by the evaporation of water into it.
  - How is this different from Dewpoint?
Wet Bulb, Dry Bulb and Dewpoint

• In a saturated parcel, all three are the same
• In an unsaturated parcel
  – the dry bulb temperature will be warmest
  – the dewpoint temperature will be the coldest
  – the wet bulb temperature will fall somewhere in-between
Wet Bulb, Dry Bulb and Dewpoint

- If you cool the unsaturated air without adding or removing any water vapor
  - Dry bulb temperature falls
  - Dewpoint remains constant
  - Wet bulb temperature falls
Wet Bulb, Dry Bulb and Dewpoint

• If you add water vapor (but not by evaporation)
  – Dry bulb temperature would remain the same
  – Dewpoint temperature would increase
  – Wet bulb temperature would increase
Wet Bulb, Dry Bulb and Dewpoint

• If you add water vapor by evaporation to increase RH to 100%
  – Dry bulb temperature would decrease
  – Dewpoint temperature would increase
  – Wet bulb temperature would remain the same
Mixing Ratio \((w)\)

- ratio of the mass of water vapor \((m_v)\) to the mass of dry air \((m_d)\):
Partial Pressure

- Pressure a gas would exert if it alone occupied the volume
Virtual Temperature ($T_v$)

- (density temperature) – temperature that dry air would have if it had the same density as moist air at the same pressure ($T_v \geq T$)
Vapor Pressure vs Temperature
Methods for Measuring Humidity

• Six classes of hygrometric methods
  – Removal of water vapor from moist air
  – Addition of water vapor to moist air
  – Equilibrium sorption of water vapor
  – Attainment of vapor-liquid or vapor-solid equilibrium
  – Measurement of physical properties of moist air
  – Chemical reactions
Removal of Water Vapor from Moist Air

• Accomplished using a desiccant, freezing out or separation of moist air constituents using a semi-permeable membrane

• After removal of water vapor, mass of vapor and remaining air are determined and humidity calculated
Addition of Water Vapor to Air

• Humidity can be determined by measuring the amount of water vapor that must be added to a sample of moist air to achieve complete saturation
Psychrometry

• Method of adding water vapor to moist air where complete saturation is not achieved

• Humidity is determined from the cooling of a wet bulb relative to the ambient air temperature
Psychrometer

- First Psychrometer invented by Adolph Richard Aßmann in 19th century
- Composed of two thermometers exposed to the ambient air flow
- One sensor measures dry-bulb temperature
- The other sensor has a wick moistened with water that measures a lower temperature
- Forced ventilation gives optimum performance
Psychrometer Sources of Error

- Sensitivity, accuracy and matching of temperature sensors
- Ventilation rate – ideally should be 3 m/s
- Radiation incident on thermometers
- Size, shape, material, wetting of wick
- Relative positions of wet and dry bulb sensors
- Purity of water used to moisten the wick
Psychrometer Formula

• Used to convert wet- and dry-bulb temperatures to ambient vapor pressure
Equilibrium Sorption of Water Vapor

• Water vapor interacts with almost every substance through the process of sorption (absorption and/or adsorption)
• Absorption is a process in which a substance diffuses into a liquid or solid to form a solution
• Adsorption is a process that occurs when a gas or liquid solute accumulates on the surface of a solid or a liquid (adsorbent), forming a film of molecules or atoms (the adsorbate)
Equilibrium Sorption of Water Vapor

• The process of sorption causes the material to expand or contract, or alters electrical resistance or capacitance

• When a material exhibits a change that is sufficiently reversible, reproducible, and detectable, it can be used as a humidity sensor
Characteristics of Sorption Sensors

• Sensor input cannot be relative humidity; sensor input can be e or T, but $e_s$ must be calculated

• Mass of a sorption sensor is proportional to ambient relative humidity
  – Nicholas De Cusa invented the first hygrometer using wood
  – Hygrometers take up water substance in liquid or solid form
Characteristics of Sorption Sensors

- Water substance in the sensor is in liquid form for temperatures down to -50 Celsius. Forms a thin film (few molecules thick) on the sensor surface or on the surface of pores in the sensor.
- A sorption sensor must be hygroscopic.
Electric Hygrometers

• Form of sorption sensors where water causes a change in an electrical parameter (resistance or capacitance)

• Capacitive sensor is comprised of gold plating (for the capacitor) and a polymer (sorption sensor)

• Errors can produce an output indicating humidity in excess of 100%
Electric Hygrometers

• Two types of resistive sensors
  – Bulk Polymer
  – Carbon Hygristor
Bulk Polymer Resistance Sensors

- Bulk polymer has a thick polymer layer (as compared to a capacitive sensor)
- Resistance in a bulk polymer is measured through the volume of the polymer (resistance decreases as humidity increases)
- Resistance changes up to 5 orders of magnitude from 0% to 100%
- Less accurate at values of RH below 20% due to difficulty maintaining high resistance
Carbon Hygristor Sensor

- Hygristor - A resistor whose resistance varies with humidity
- Experiences a dimensional change in response to a change in RH
- Size of the carbon grains increases with RH
- Typically only used in radiosondes
Mechanical Hygrometers

• Made of dimensionally variable materials that are mechanically coupled to an indicator
• Usually composed of human hair, gold-beater’s skin, cotton, silk, nylon, paper and wood
Measurement of Physical Properties of Moist Air

• Physical properties of air such as refractive index, radiative absorption, thermal conductivity, viscosity, density, and sonic velocity vary depending on the amount of water vapor present
Spectroscopic Hygrometer

• Measures hygrometer measures the attenuation of certain bands (UV and IR) in the spectrum due to water vapor absorption

• Fraction of incident radiation transmitted through an atmospheric path, $\tau$, is given by Beer’s law

• Absorption in the atmospheric path is given by $a = 1 - \tau$
Spectroscopic Hygrometers

• Laser hygrometer - expensive, not suitable for field applications

• IR hygrometer – cheaper, more suited to field applications

• Lyman-alpha hygrometer – simpler, smaller and faster than an IR hygrometer. Suitable for research aircraft and tower measurements of turbulent fluctuation of humidity
Attainment of Vapor-Liquid or Vapor-Solid Equilibrium

- Humidity can be determined by cooling a surface until vapor-liquid or vapor-solid equilibrium is achieved
- Chilled-mirror hygrometer
Chilled-Mirror (Dew- and Frost-Point) Hygrometer

- Surface of the mirror (usually metallic) is temperature controlled
- An air-intake system provides a flow of ambient air at some uniform rate
- Filters can be installed to remove dust, but can add moisture if they get wet
- Formation of dew or frost on the mirror is detected optically with an LED and one or more photodetectors which sense the change in light scattering
Chilled-Mirror Hygrometer

• Difficult to measure the front surface of the mirror without interfering with the dew or frost formation
• Controlling mechanism must be sensitive to rate of change of ambient humidity and air temperature
• Presence of extremely small amounts of water-soluble material on the mirror can lower vapor pressure and hence dew-point
Chilled-Mirror Hygrometer

• If condensate forms as extremely small drops, the internal pressure increases due to the surface tension of the curved drop surfaces; this increases vapor pressure and dew-point

• At temperatures below freezing, initial condensate formed may be either dew or frost; dew can form down to -27 C

• Control system can fail when ambient humidity changes rapidly

• Capable of high accuracy with maintenance
Dewcel

• Mixing ratio of moist air in equilibrium with a plane surface of a saturated aqueous salt solution is a function of temperature and pressure
• Dewcel contains saturated solution of LiCl applied to a wick surrounding a thermometer
• Heater with a control circuit raises the solution to the equilibrium temperature
Dewcel

• Can operate in temperature ranges from -30 to +100 Celsius
• Must be protected from high ventilation that may cause excessive heat loss
• Loss of power may cause cooling and saturation with liquid water that may wash salt from the wick
• Speed of response depends on rate the dewcel can be heated or lose heat to surroundings
Chemical Reactions

- Used only in laboratory
- Water vapor is removed by use of a chemical reagent and the resulting water is weighed
Choosing a Humidity Sensor

• Factors
  – Cost
  – Accuracy
  – Maintenance
  – Applicability
  – Response time
  – Power consumption
Exposure

• Since humidity almost always requires the measurement of air temperature, exposure of humidity sensors is thus closely related to exposure of temperature sensors

• What must one be aware of in coastal environments?

• What is the biggest error that affects hydrometers?