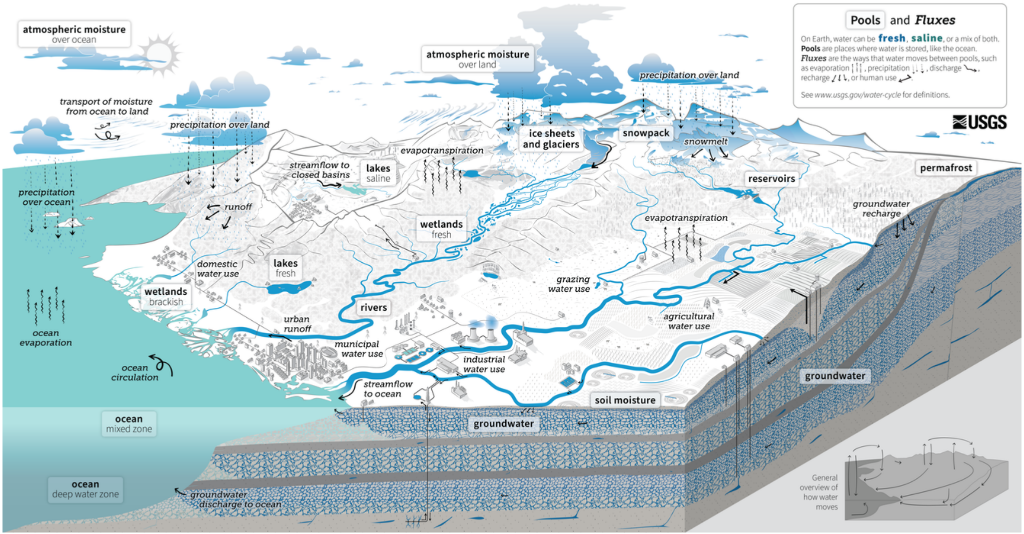
Precipitation

Katie Markovich, EPS 522/ ENVS 423L (Fall 2025)

Water Cycle



atmospheric moisture
over ocean
transport of moisture
from ocean to land
precipitation over land
atmospheric moisture
over land
precipitation over land
ice sheets
and glaciers
snowpack
snowmelt
Pools and Fluxes
On Earth, water can be fresh, saline, or a mix of both.
Pools are places where water is stored, like the ocean.
Fluxes are the ways that water moves between pools, such as evaporation, precipitation, discharge, recharge, or human use.
See www.usgs.gov/water-cycle for definitions.
USGS
evapotranspiration
streamflow to
closed basins
lakes
saline
reservoirs
permafrost
precipitation
over ocean
runoff
wetlands
fresh
evapotranspiration
groundwater
recharge
domestic
water use
lakes
fresh
wetlands
brackish
grazing
water use
ocean
evaporation
rivers
urban
runoff
agricultural
water use
municipal
water use
industrial
water use
ocean
circulation
streamflow
to ocean
groundwater
soil moisture
ocean
mixed zone
groundwater
ocean
deep water zone
groundwater
discharge to ocean
General
overview of
how water
moves

Requirements for Precipitation

1. cooling of air to the dew point temperature
2. condensation on nuclei to form cloud droplets or ice crystals
3. growth of droplets/crystals to raindrops/snowflakes/hailstones
4. importation of water vapor to sustain the process

Dew Point Temperature

Dew point (T_d): temperature to which an air parcel must be cooled to reach saturation.

$$T_d = \frac{ln(e) + 0.4926}{0.0708 - 0.00421 \cdot ln(e)}$$

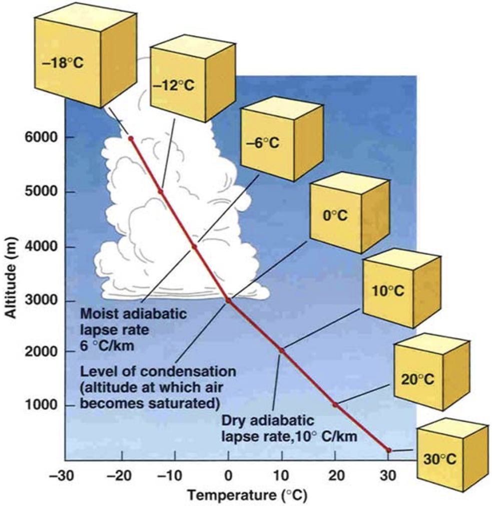
where e is vapor pressure (kPa).

Relation between e^* and T_a

#1 Cooling

While many processes can lead to cooling, vertical uplift is the only process that achieves it at sufficient rates for precipitation.

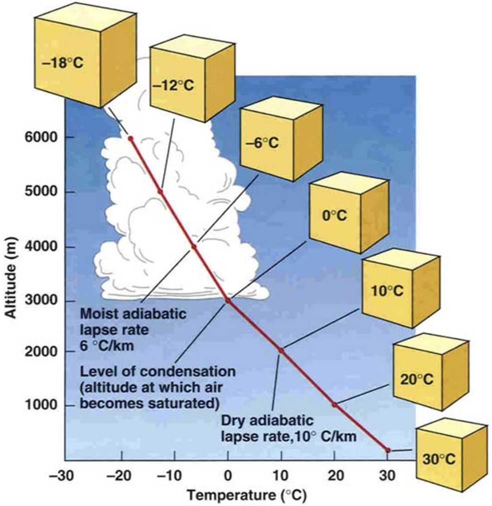
A rising parcel of dry air cools **adiabatically**, that is without transfer of energy, at a rate of 1°C/100 m. The change in a state variable with altitude is a **lapse rate**, hence this is called the **dry adiabatic lapse rate**.



#1 Cooling

Once the parcel has cooled to its dew point temperature, condensation occurs and the air becomes saturated. It then follows the **moist adiabatic lapse rate**, which is roughly half the dry rate (0.5°C/100 m).

The average lapse rate in the troposphere is roughly 0.65°C/100 m, a weighted average of the moist and dry rates.

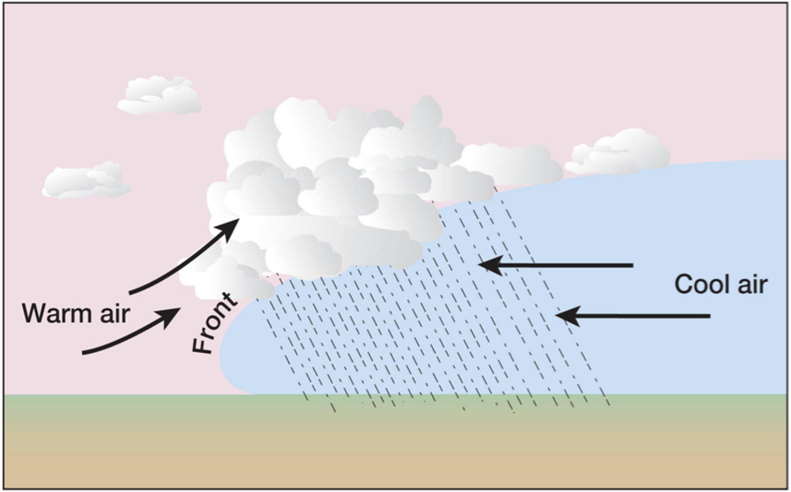


Uplift Mechanisms

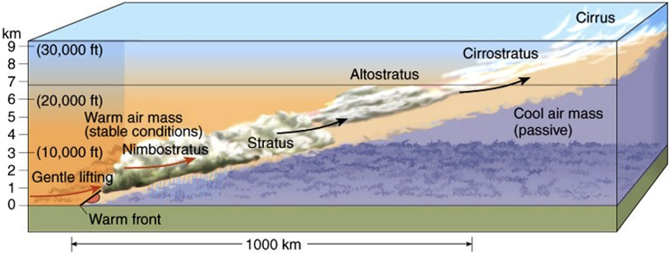
1. Uplift Due to Convergence
2. Uplift Due to Orography
3. Uplift Due to Convection

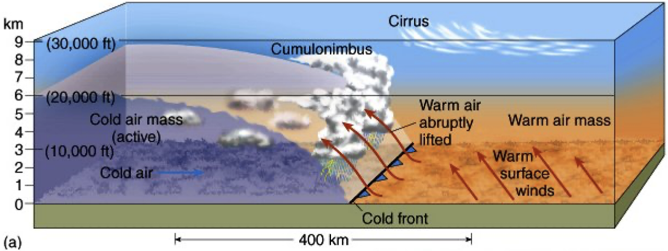
Uplift Due to Convergence

Frontal Convergence



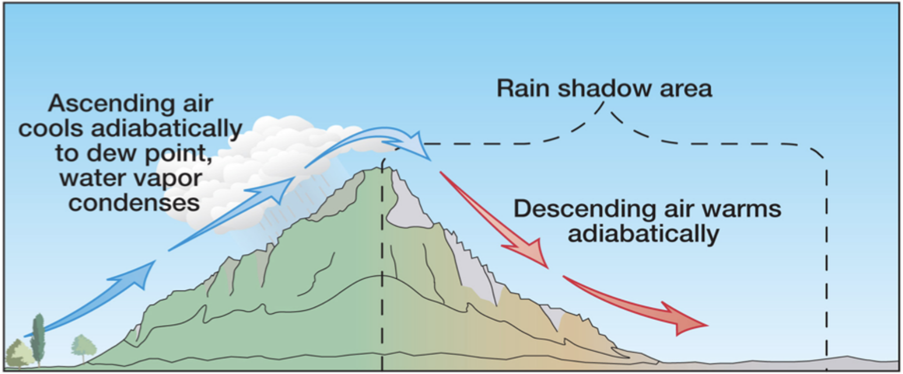
Uplift Due to Convergence



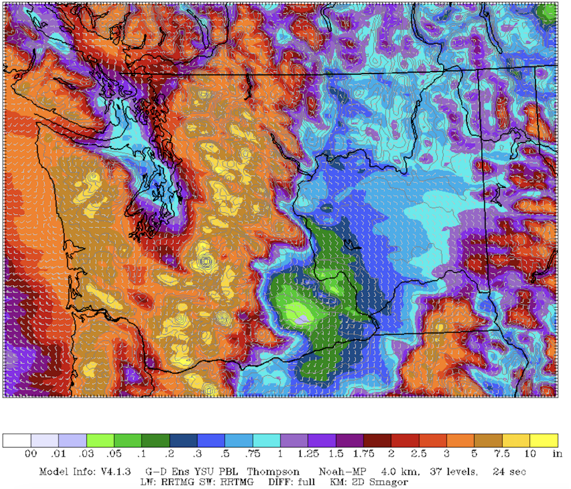


(a)

Uplift Due to Orography

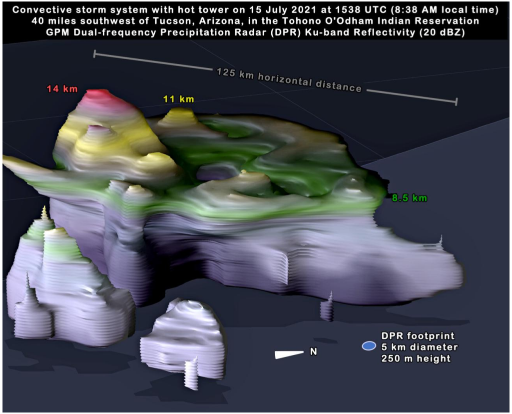


Uplift Due to Orography



Uplift Due to Convection

Convective precip arises from a parcel of air that heats, rises, and cools adiabatically. The heating is due to conduction from the land surface (heated by intense solar radiation throughout the day).



This storm produced precip rates of 1 in/hr !

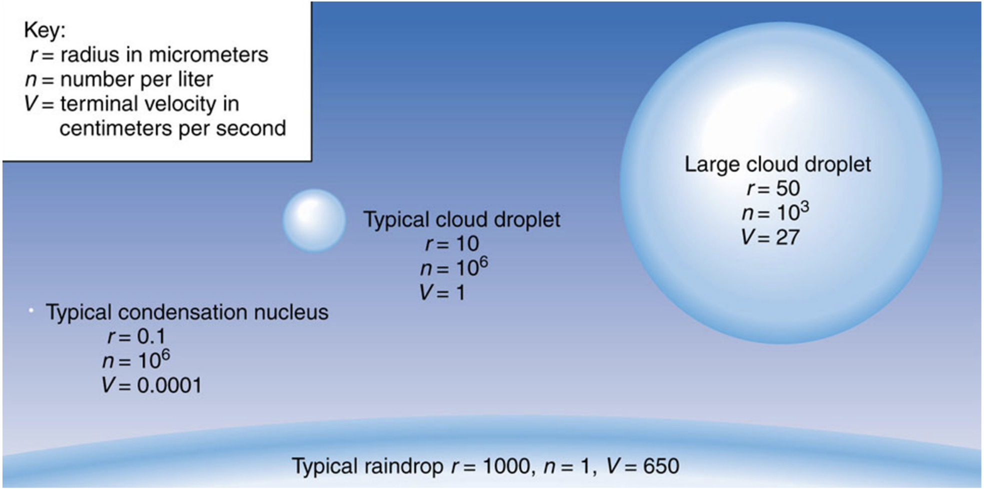
#2 Condensation on Nuclei

For condensation to occur near the dew point, particles larger than 10^{-4} mm to which water molecules are attracted must be present to provide a substrate. These are called **cloud condensation nuclei** (CCN).

CCN are naturally present as meteoric dust, windborne clay and silt, volcanic material, smoke from forest fires, and sea salt.

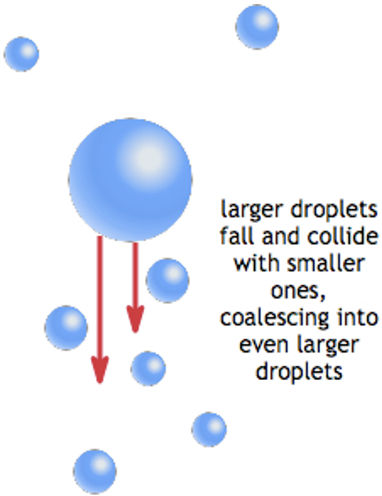
#3 Droplet Growth

In order for precip to fall, the cloud droplets must grow to a size such that their fall velocity is > uplift and such that they withstand evaporation.



Droplet Collision

Because cloud droplets range in size (0.4 to 4 mm), the larger droplets have faster fall velocities and collide with the smaller droplets, resulting in coalescence and gradual growth.



Ice Crystal Growth

At temperatures below freezing, clouds often consist of a mix of ice crystals and super cooled water droplets.

The saturation vapor pressure of an ice surface at a given temperature is less than that of a liquid-water surface at the same temperature. Thus, H_2O molecules tend to evaporation from the liquid droplets and condense on the ice crystals, leading to growth and eventually aqcuiring a high enough fall velocity.

#4 Importation of Water Vapor

Concentration of liquid or ice in clouds ranges from 0.1 to 1 g/m^3.

So, even if a cloud was very thick (10,000 m) such that the total volume of cloud per 1 m^2 of Earth surface was 10,000 m^3, a density of water of 0.5 g/m^3. would result in only 0.5 cm of rainfall (roughly a quarter inch).

Therefore, substantial amounts of precipitation require a continual supply of water vapor, provided by winds converging on the wind-producing clouds.

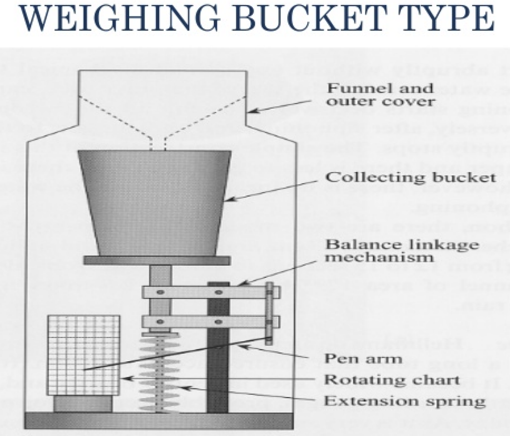
Measurement at a Point

Precipitation is the input to the land phase of the hydrologic cycle, and hydrologists are often interested in quantifying the amount or rate of precipitation over a watershed. Issues with accuracy can be summed up in two questions:

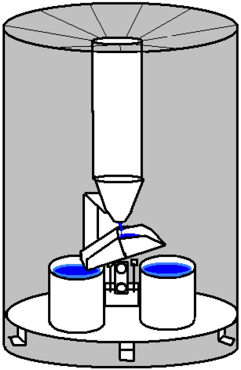
1. How accurate are point measurements of precipitation?
2. How accurately can point measurements be converted into measurements over an area?

Types of Rain Gages

Storage, weighing, and tipping bucket gages



The tipping bucket rain gauge measures rainfall electronically using a bucket with known volume and counting the number of times it fills.



Factors Affecting Measurement Accuracy

Gage catch is the fraction of true precip that enters the gage.

- Size of orifice
- Orientation
- Height
- Wind effects
- Distance to obstructions
- Gage losses

Orifice size and orientation

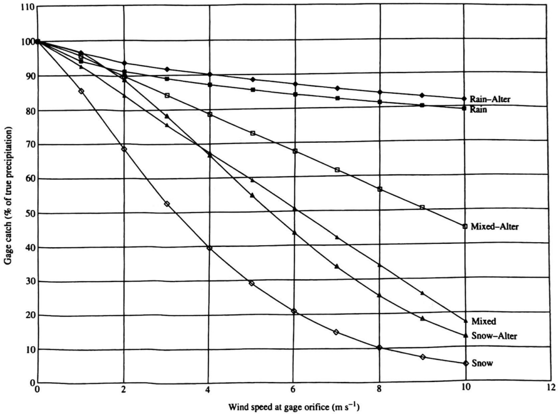
- For rain, diameter should be no less than 30 mm. Beyond this, size has little effect on gage catch.
- For snow or mixed precipitation, a larger orifice is recommended, with the standard being 8 in (200 mm).
- For virtually all situations, the gage orientation should be level (as opposed to parallel to ground surface).

Height and wind effects

Rain gages that project above the surface cause wind eddies that reduce the catch of snowflakes and smaller raindrops.

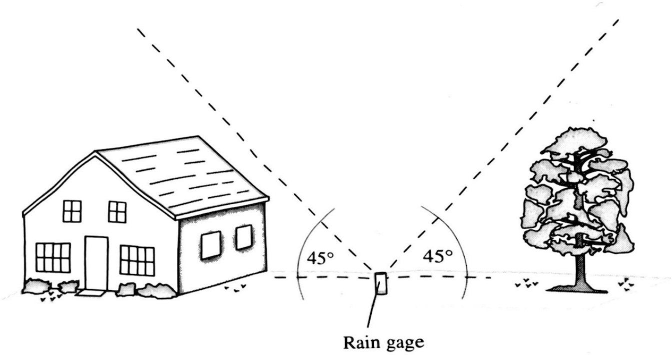
Using a wind shield can help protect against this, with more efficacy for rain than snow.

Empirical equations have been derived (that are a function of wind speed) are applied to correct daily precipitation data for these effects.



Obstructions

Best location to site a gage is in an open space with a fairly uniform enclosure of trees, shrubs, fences, etc. to reduce the potential for wind effects. Rule of thumb: an isolated obstruction should not be closer than twice its height above the gage.



Gage Losses

- If surface of water within gage is too close to orifice, in-falling drops can cause splash out of water. Using a deeper gage, collecting freuqently, or routing water to an enclosed vessel can help.

- If the gage is left to record for multiple days, evaporation from surface or the gage walls can lead to inaccurate measurements. Routing water to a closed vessel or using an immiscible oil to prevent evaporation can help with this. Evaporative losses are mostly an issue for regions that receive frequent, low-intensity precip.

Estimating Missing Data

- Station Average Method (only works when nearby stations differ by less than 10%)

$$\hat{p}_0 = \frac{1}{G} \cdot \sum_{g=1}^{G} p_g$$

- Normal-Rain Method (estimate based on annual averages)

$$\hat{p}_0 = \frac{1}{G} \cdot \sum_{g=1}^{G} \frac{P_0}{P_g} p_g$$

where $\hat{p}_0$ is missing data, g is nearby gage, G is the total number of nearby gages, P_0 is annual average at the gage with missing values, and P_g is annual average at the nearby gage.

Estimating Missing Data

- Inverse-Distance Weighting (only considers distance)

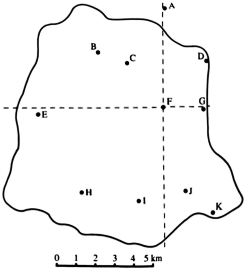
$$D = \sum_{g=1}^{G} d_g^{-b}$$

$$\hat{p}_0 = \frac{1}{D} \cdot \sum_{g=1}^{G} d_g^{-b} p_g$$

where d is distance from the gage g to the gage with missing data and b is either 1 (inversely proportional to distance) or 2 (inversely proportional to distance squared).

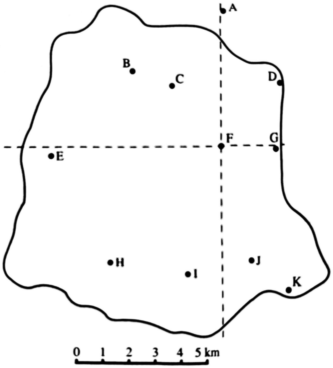
Exercise

Estimate the value of storm precipitation at gage F using the station average, normal-ratio, and inverse-distance methods.



Gage	Distance from Gage F (km)	Average Annual Precip. (mm)	Measured Storm Precip. (mm)
A	5.13	1373	14.4
B	4.43	1452	12.2
C	2.93	1404	11.6
D	3.36	1433	14.8
E	6.63	1665	13.3
F	0.00	1137	—
G	2.13	1235	12.3
H	6.10	1114	11.5
I	4.95	1101	11.6
J	4.40	1086	11.2
K	5.93	1010	9.7

Areal Estimation



$$P = \frac{1}{A} \cdot \int \int p(x, y) \cdot dx \cdot dy$$

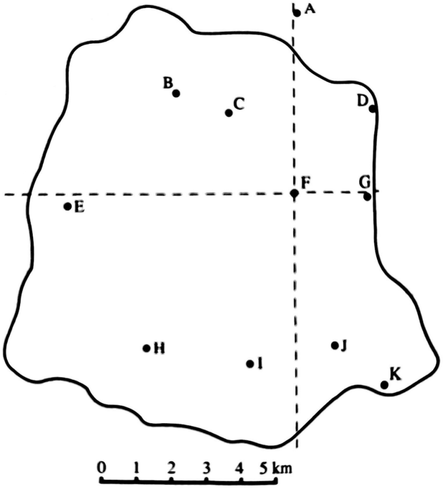
where P is the average precipitation over a region, A is the area of the region, x,y are the coordinates of point measurements, and p(x,y) is the precipitation at those points.

estimates of P ($\hat{P}$) are calculated as either a weighted average of the measured values or using surface-fitting methods.

Weighted Averages

The simplest is an **arithmetic average**, which assumes equal weight for all gages equal to $\frac{1}{G}$:

$$\hat{P} = \frac{1}{G}\sum_{g=1}^{G} p_g$$



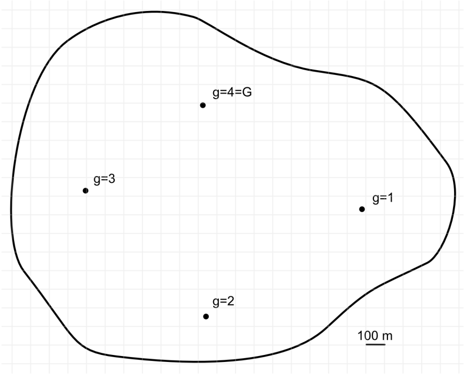
Weighted Averages

Slightly more sophisticated is an area-based weighting approach called **Thiessen Polygons**:

$$\hat{P} = \frac{1}{A} \sum_{g=1}^{G} a_q \cdot p_g$$

Thiessen Polygons demo

1. Draw straight line connecting adjacent gages, forming a network of triangles.
2. Perpendicular bisectors are drawn on each line until they connect, forming polygons around the gages.
3. The area of these polygons can be estimated by overlaying the network and region on a grid and counting up the number of squares (or using GIS).



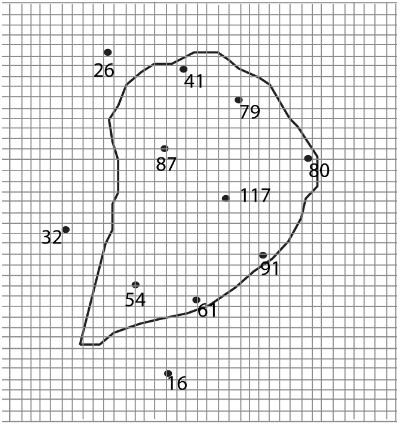
Surface-Fitting Methods

Measured values are used to identify a surface that represents precipitation at all data points in a region of interest. With **smoothing**, the surface doesn't have to exactly honor the point data, where **interpolation** honors the point data. We will cover:

- Isohyetal method
- Hypsometric methods
- Kriging method

"Eyeball" Isohyetal Method

The simplest approach is the **eyeball isohyetal** method. Isohyet is a contour line connecting areas of equal precipitation (analogous to elevation contour)



Hypsometric Method

The precip surface over a region is assumed to be a function of elevation. It is therefore, only appropriate for regions with significant orographic effects.
First, a relationship is determined between precip (p) and elevation (z), often using a linear regression:

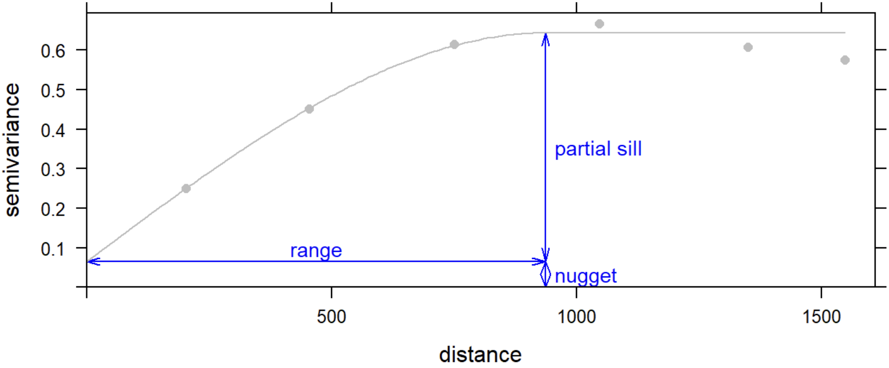
$$p(z) = a + b \cdot z$$

This approach is enabled by the availability of high resolution DEMs.

PRISM is an example of an algorithmic hypsometric method–it primarily relies on the regression with elevation, but also takes into account aspect, coastal proximity, and topographic index.

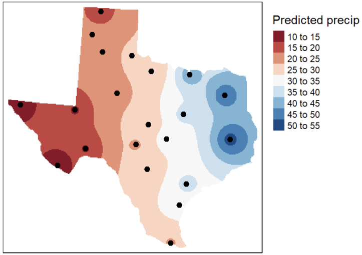
Kriging Method

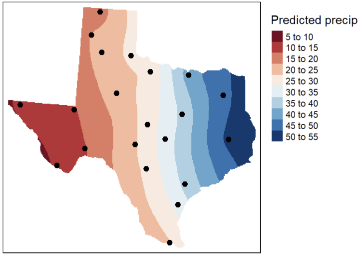
Kriging is a statistical interpolation method which uses spatial auto-correlation (empirically derived from the data, called a **variogram**) to calculate the weights of point data and interpolate values for the region of interest. It also provides an estimate of interpolation uncertainty for the entire field.

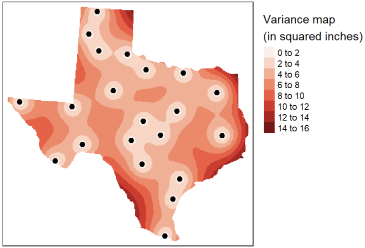


IDW versus Kriging

from https://mgimond.github.io/Spatial/spatial-interpolation.html



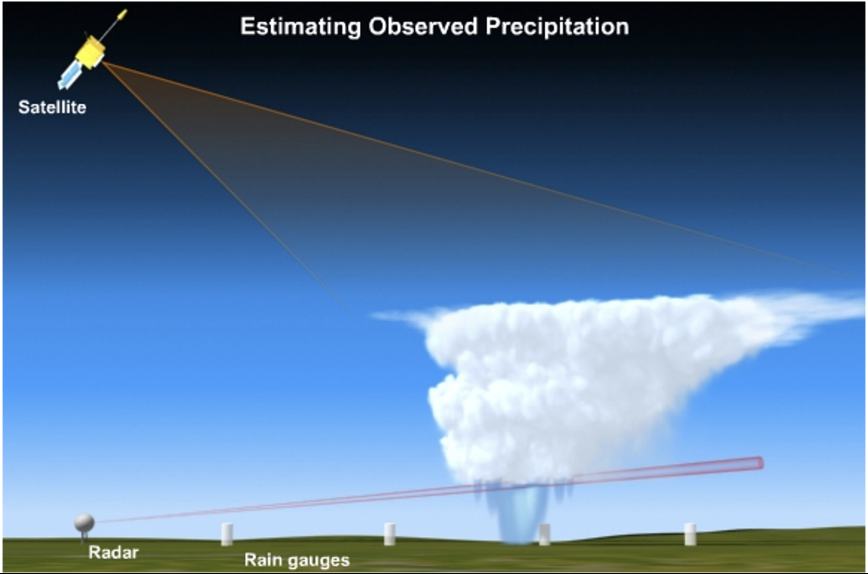




Rain "Sensing"

1. **Optical gage**: precipitation rate is proportional to the disturbance to a beam between an infrared light-emitting diode and a sensor. Avoids many of the limitations of rain gages, but relatively expensive.
2. **Doppler radar**: areal distribution and instantaneous precipitation rates are measured by microwaves reflecting off of precipitation. Can also measure horizontal movement (storm tracking). Not very accurate measurement on their own, but useful for storm tracking and accuracy can be improved when used in conjunction with point measurements.
3. **Satellite**: measure precipitation rates and distribution by direct (passive sensing of microwave energy absorbed and scattered by precipitation) and indirect (sensing infrared radiation emitted by clouds and relating that empirically to precipitation rates). Much larger scales, and carry large uncertainties, but important for global coverage.

Integrated Precipitation Measurement



Existing Gage Networks

Gridded Precipitation Datasets

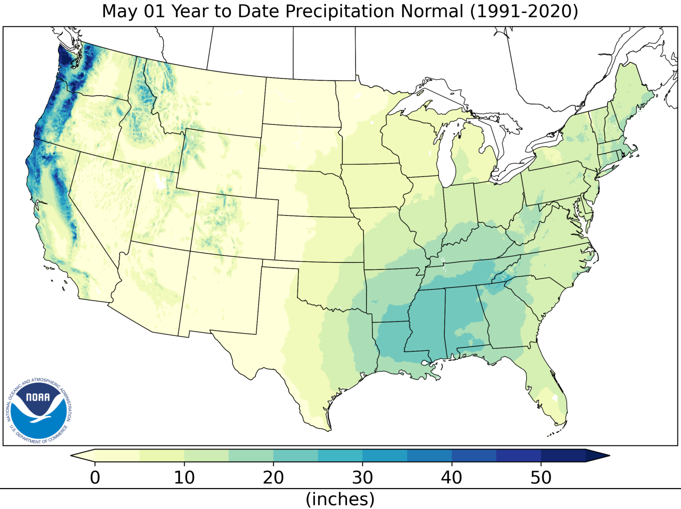
Reanalysis Data: Merging of modeled and observed measurements to produce a temporally and/or spatially comprehensive historical dataset, i.e. "maps without gaps".

Rainfall Statistics

1. Long-term average (30-year normals)
2. Probable maximum precipitation
3. Depth-duration frequency analysis

Long-term Average

National Centers for Environmental Information generate 30-year climate normals every ten years.



Probable Maximum Precipitation (PMP)

PMP is theoretically the greatest depth of precip for a given storm over a given duration in a given location at a given time of year.

Engineers use PMP to estimate the **probable maximum flood** (PMF) from which to design things like dam spillways or diversion channels.

NM-CO PMP mapper

Frequency Analysis

Most applications don't require PMP-level designs. **Frequency analysis** is more appropriate in less extreme circumstances.

The underlying assumption for frequency analysis is that there is a sufficiently long record that captures the "full" distribution and that the moments of that distribution do not change over time (i.e., the **stationarity** assumption).

Two approaches exist for rainfall:

1. depth-duration frequency (DDF) analysis
2. intensity-duration frequency (IDF) analysis

DDF and IDF

Rainfall frequency statistics for all of CONUS have been calculated and are accessible via NOAA Atlas 14.

It is currently being updated to account for the fact that climate change is violating the stationarity assumption.