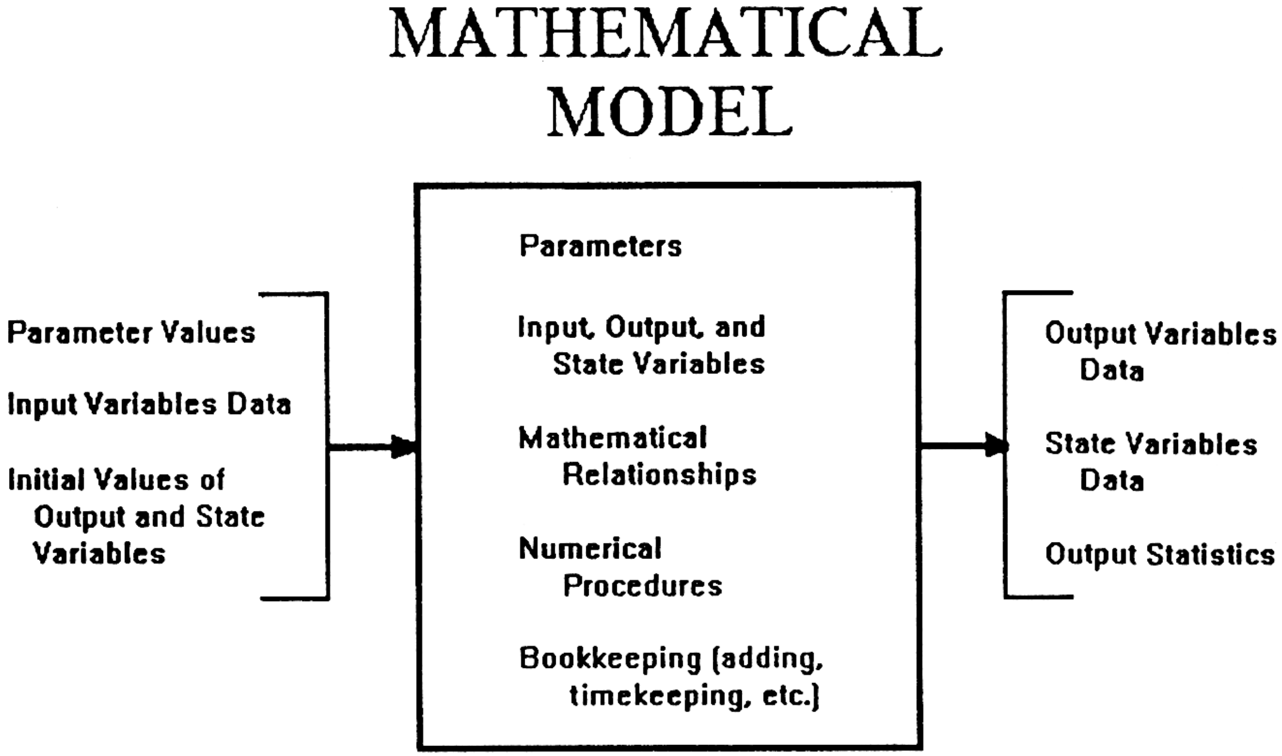
Components of a Model



Nix, S.J. 1994. *Urban Stormwater Modeling and Simulation.* Lewis Publishers, U.S.A., p. 23.

Mathematical models have three basic components: The **input data**, the **algorithmic portion** that does the modeling, and **outputs** that describe the results

Lumped vs. Distributed Models

- We can distinguish between two types of models:
- **Lumped Models** – These are the sorts of models you likely would have focused on a hydrology course
  - They represent inputs and responses in terms of the **dimensions of time and whatever is being modeled** (issues of location and associated dimensions of length, area and volume are often absent)
  - **No account is taken of variation** within the entity being modeled: It is **assumed to be homogenous and well-mixed**, i.e. Suppose we were running an evaporation model for a particular forest stand. Even though there are likely various types of trees, canopy heights and densities, variations in soil etc. we model that forest stand using a single LAI and K, and with uniform soil characteristics etc.

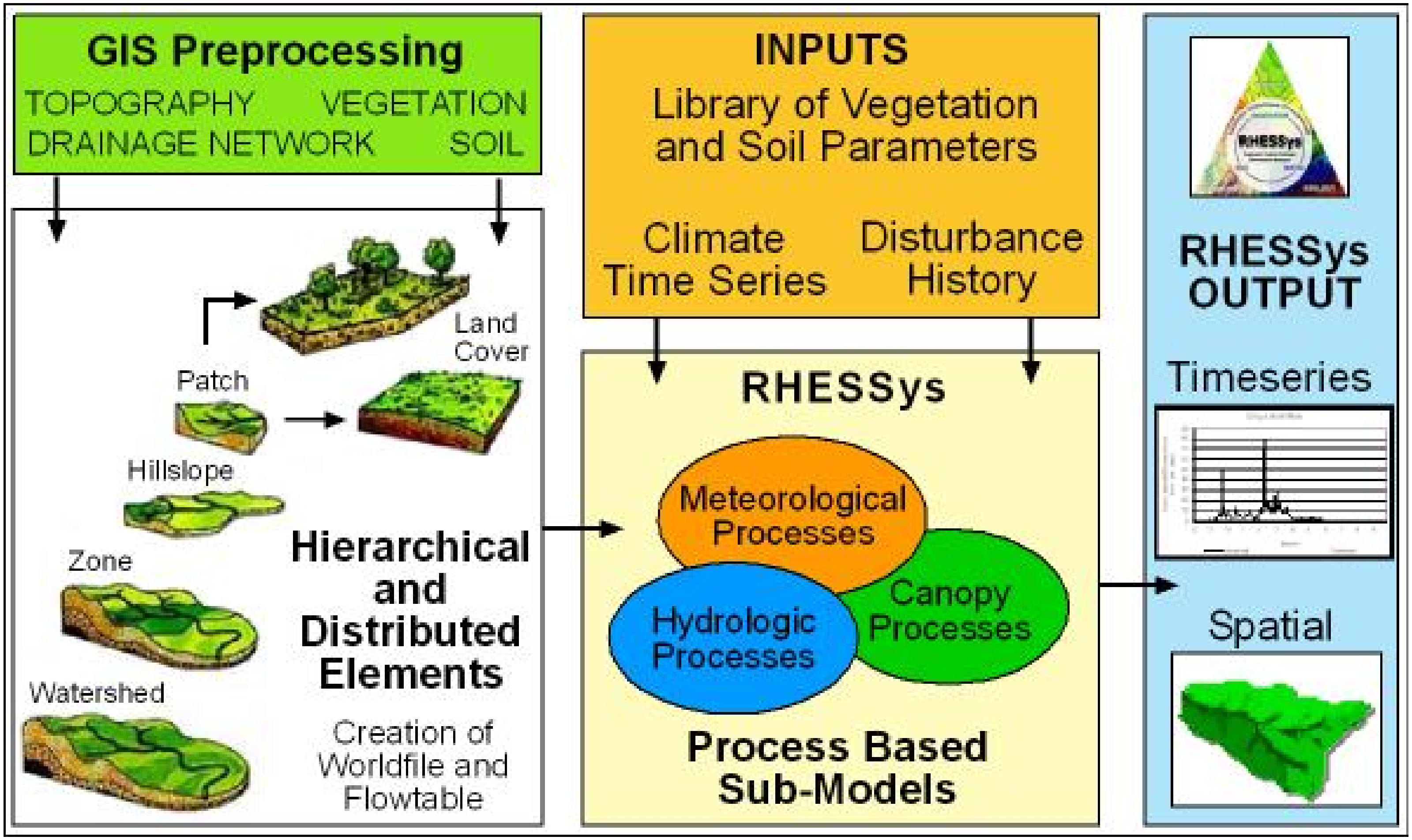
Lumped vs. Distributed Models

- **Distributed Models** – These sorts of models take the variation of phenomena in space into account in their model structure
  - Both **inputs and responses have a spatial aspect** to them, i.e. **mapped information is required** as part of the input, and the output includes **spatial pattern** information
  - Distributed models are thus very useful when it comes to **representing and studying variation**. While the modeled sub-units still usually use the assumptions of homogeneity and being well-mixed, the units' size and shape are adjusted to make these **assumptions as reasonable as possible**, i.e. Perhaps the forest stand we are modeling consists of 2 or 3 distinctly different sub-units, each with distinct species, and canopy and soil characteristics. We could then model each of these **sub-units with its own parameters**.

Catchment Representation in Distributed Models

- There are a tremendous number of **strategies** that can be used in **breaking up the world into sub-units**
- We can generalize that the goal is usually to **minimize variation with a sub-unit and maximize the variation between units**, but beyond that the possibilities are endless:
  - Tessellations can use **regular** (repeating) or **irregular** shapes
  - **Raster or vector** spatial data models can be used
  - The set of **model elements can be fixed** throughout a simulation, or **they can change as well** …
- The representation chosen usually reflects the particular **catchment and processes** being studied, and the **assumptions** made about their variation

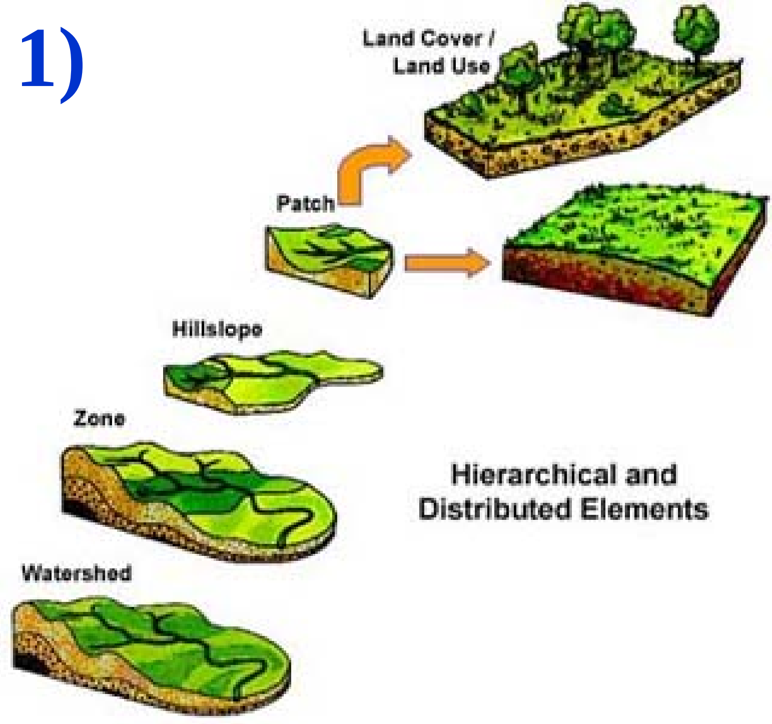
Regional HydroEcological Simulation System (RHESSys)



Landscape Representation through Object Partitioning

- RHESSys **divides** the landscape into a series of successively **contained** partitions:

1)



2) The **method** for creating a partition is **determined** by the processes it will represent

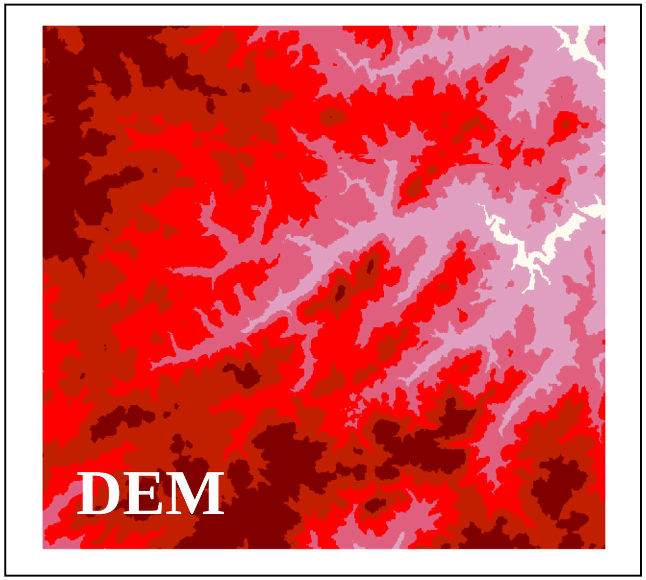
3) Once landscape objects in a partition are defined, **parameters** at that level are determined

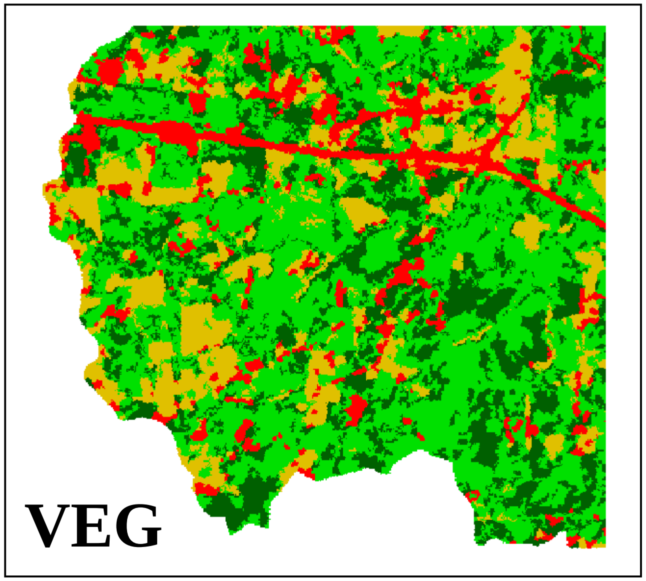
RHESSys GIS Preprocessing

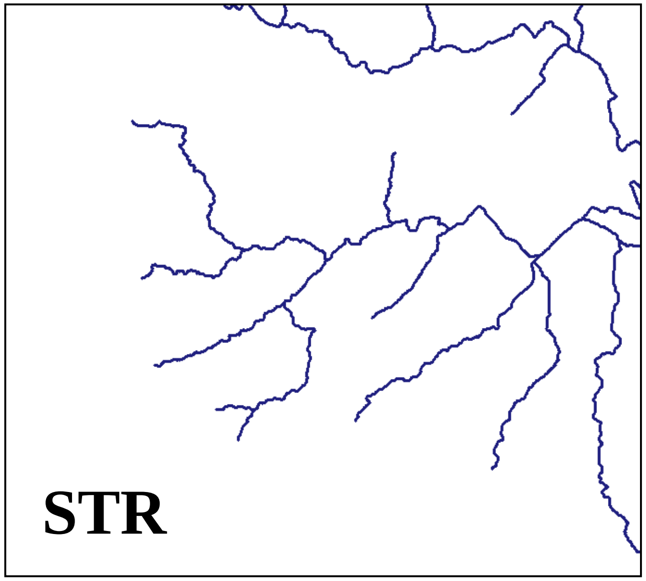
GIS Preprocessing

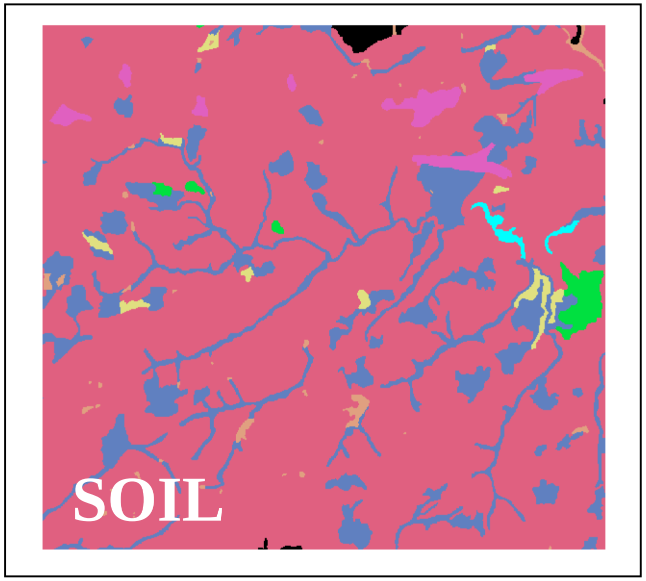
TOPOGRAPHY VEGETATION

DRAINAGE NETWORK SOIL

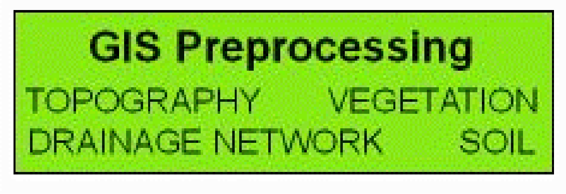








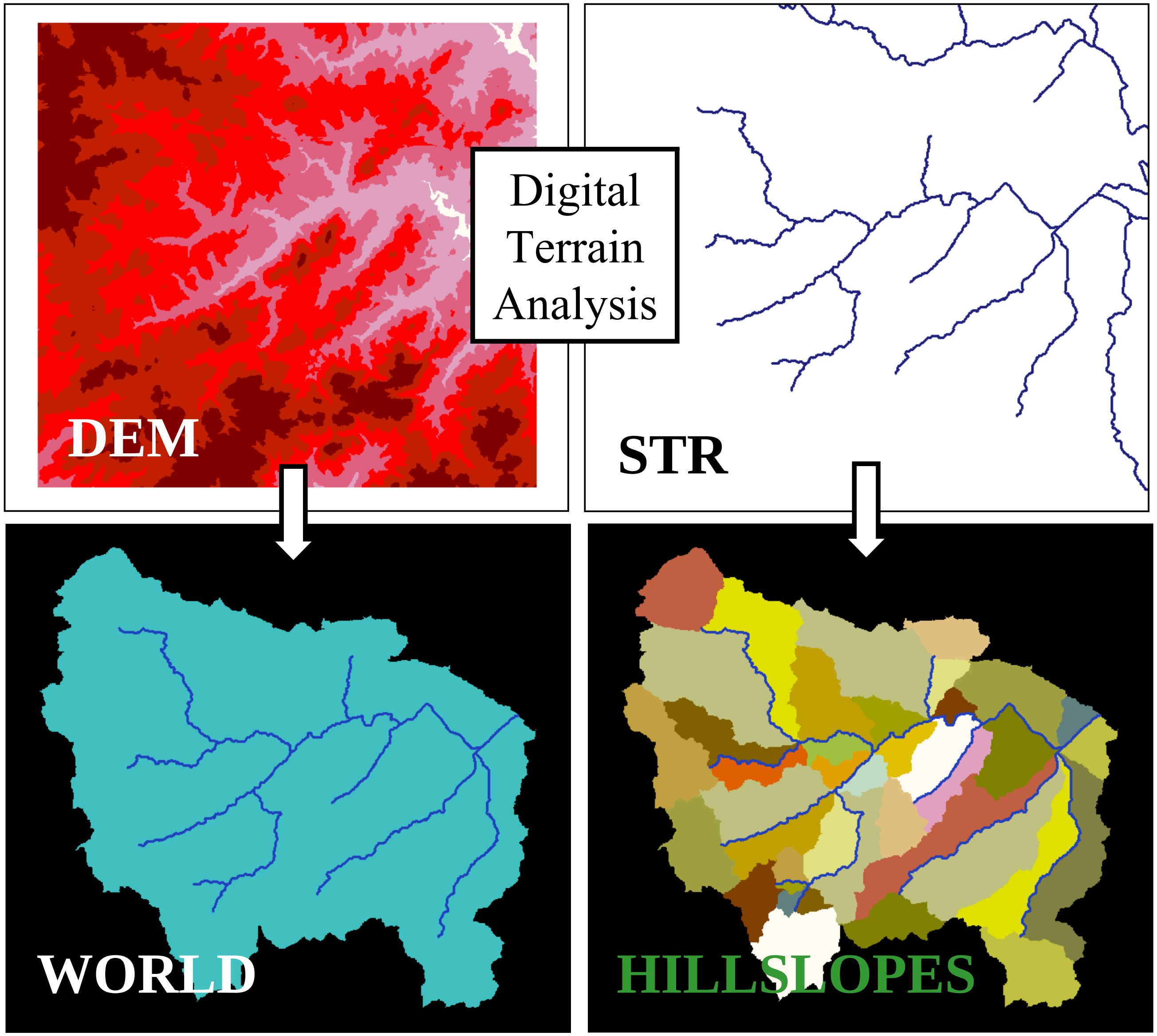
RHESSys GIS Preprocessing



GIS Preprocessing

TOPOGRAPHY VEGETATION

DRAINAGE NETWORK SOIL



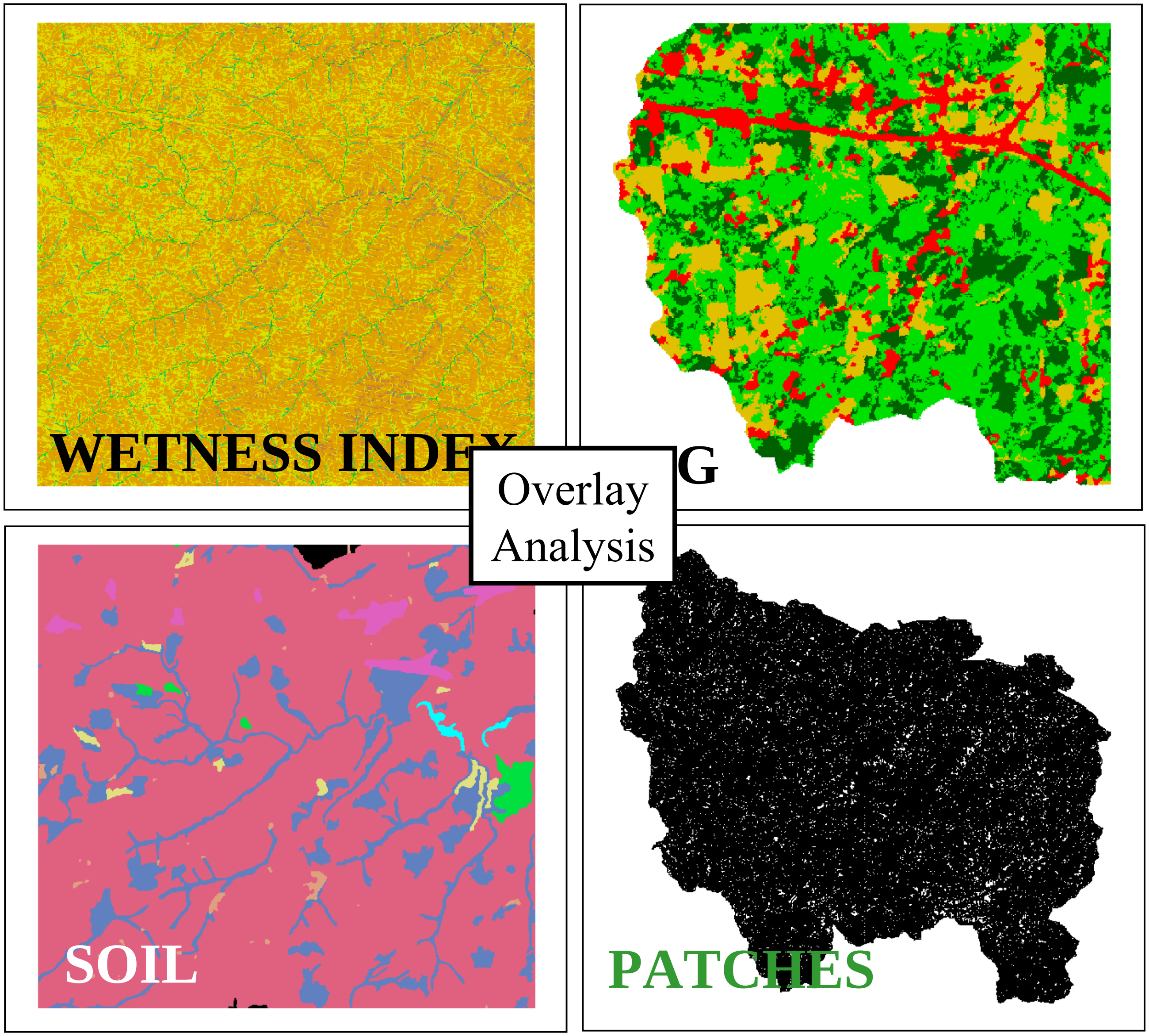
Digital Terrain Analysis

RHESSys GIS Preprocessing

GIS Preprocessing

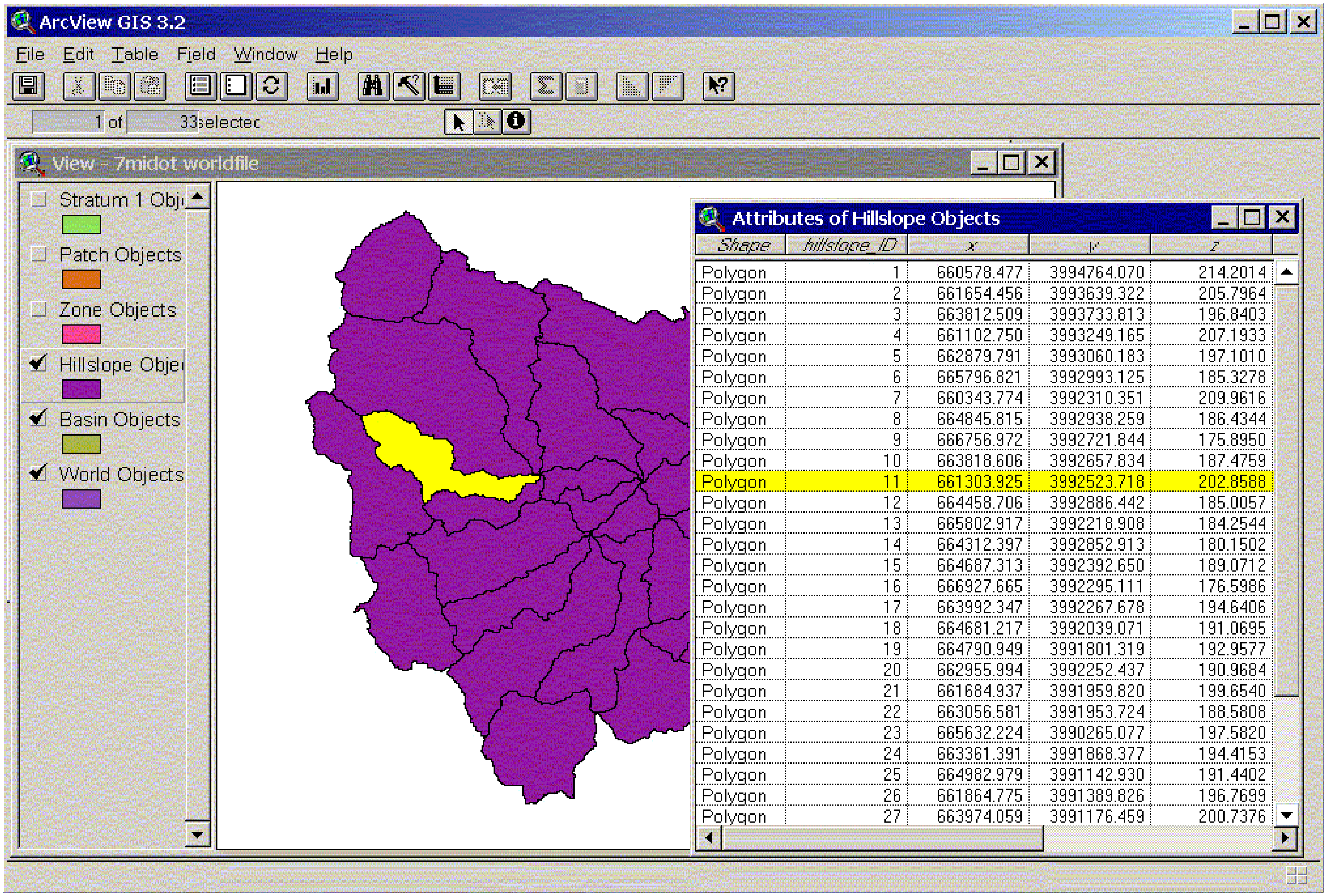
TOPOGRAPHY VEGETATION

DRAINAGE NETWORK SOIL



Overlay Analysis

RHESSys GIS Preprocessing



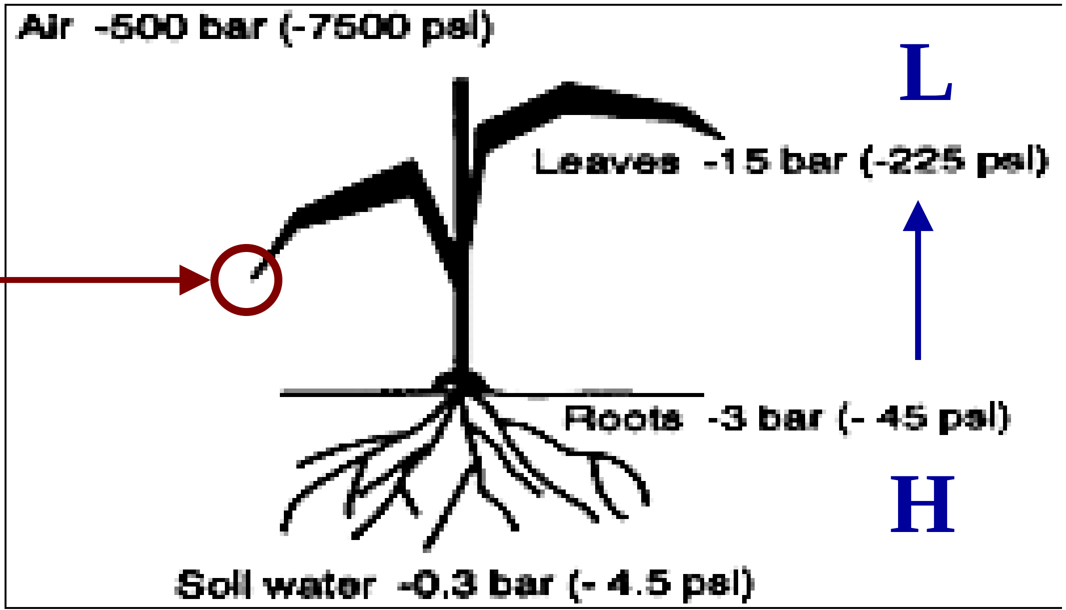
Shape	hillslope_ID	x	y	z
Polygon	1	660578.477	3994764.070	214.2014
Polygon	2	661654.456	3993639.322	205.7964
Polygon	3	663812.509	3993733.813	196.8403
Polygon	4	661102.750	3993249.165	207.1933
Polygon	5	662879.791	3993060.183	197.1010
Polygon	6	665796.821	3992993.125	185.3278
Polygon	7	660343.774	3992310.351	209.9616
Polygon	8	664845.815	3992938.259	186.4344
Polygon	9	666756.972	3992721.844	175.8950
Polygon	10	663818.606	3992657.834	187.4759
Polygon	11	661303.925	3992523.718	202.8588
Polygon	12	664458.706	3992886.442	185.0057
Polygon	13	665802.917	3992218.908	184.2544
Polygon	14	664312.397	3992852.913	180.1502
Polygon	15	664687.313	3992392.650	189.0712
Polygon	16	666927.665	3992295.111	176.5986
Polygon	17	663992.347	3992267.678	194.6406
Polygon	18	664681.217	3992039.071	191.0695
Polygon	19	664790.949	3991801.319	192.9577
Polygon	20	662955.994	3992252.437	190.9684
Polygon	21	661684.937	3991959.820	199.6540
Polygon	22	663056.581	3991953.724	188.5808
Polygon	23	665632.224	3990265.077	197.5820
Polygon	24	663361.391	3991868.377	194.4153
Polygon	25	664982.979	3991142.930	191.4402
Polygon	26	661864.775	3991389.826	196.7699
Polygon	27	663974.059	3991176.459	200.7376

Water movement through the soil-plant-atmosphere continuum

- Soil water that can be freed from the soil can proceed to the atmosphere in **two ways**:
- **Evaporation** - Water in the soil evaporates **directly** into the atmosphere. Evaporation only affects the **thin surface layer** of soils, as the resistance to liquid water movement in soils is high
- **Transpiration** - Plants provide an ideal conduit for the movement of water between soils and the atmosphere. Roots grow deep into the soil and can tap into **water reserves far from the surface**, providing a pathway between the deeper soil and the atmosphere

Transpiration loss

- a **major component** of vapor exchange at soil – atmosphere interface…



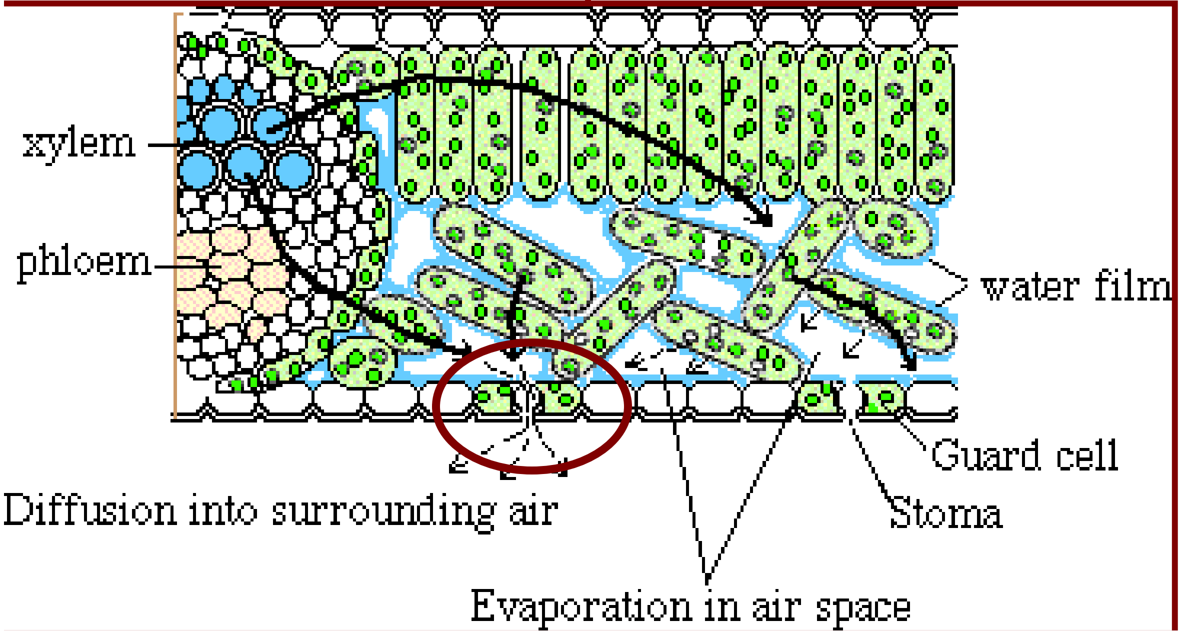


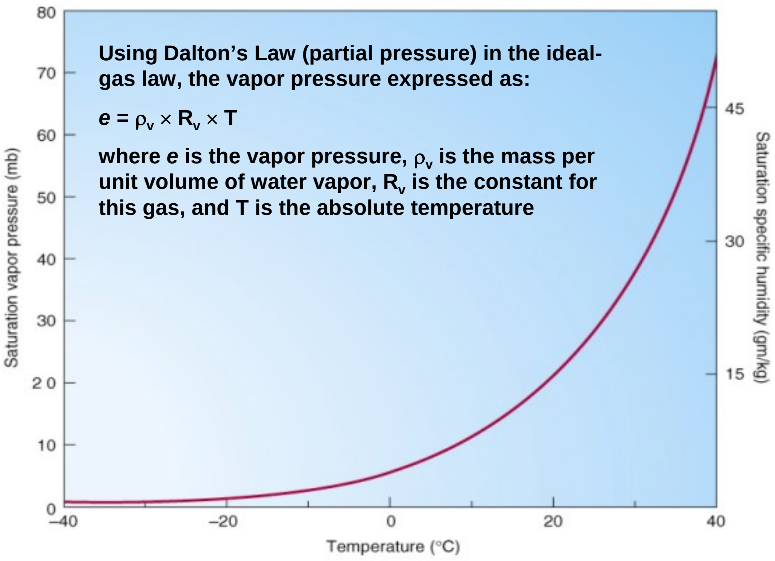
Fig. 1: vapor pressure (e_a) at soil – plant – atmosphere interface

Controlling factors for ET

1. **Water**:
   - open bodies, intercepted, soil, plants

2. **Energy**:
   - major source is short-wave solar radiation
   - long-wave (sensible heats surfaces) &
   - latent heat (exchanged within air masses)

3. **Vapor pressure (humidity)**:
   - Difference between atmosphere & water source
   - pressure gradient controls rates of movement of H_2O molecules from moist surfaces to atm.
   - recall, $e_a \leq e^*$ or $e_a \leq e_s$
   - cannot exceed RH =100%



Using Dalton's Law (partial pressure) in the ideal-gas law, the vapor pressure expressed as:

$e = \rho_v \times R_v \times T$

where *e* is the vapor pressure, ρ_v is the mass per unit volume of water vapor, R_v is the constant for this gas, and T is the absolute temperature

Controlling factors for ET

4. **wind**:
   - turbulent airflow above moist surfaces removes saturated air replacing it with unsaturated air ($\downarrow e_a$)

5. **vegetation**:
   - transpiration is a product of photosynthesis
     - uses soil moisture
   - rates controlled by e_a
   - also includes E_i losses from plant canopies
   - E from bare soil may actually » T from veg… why?

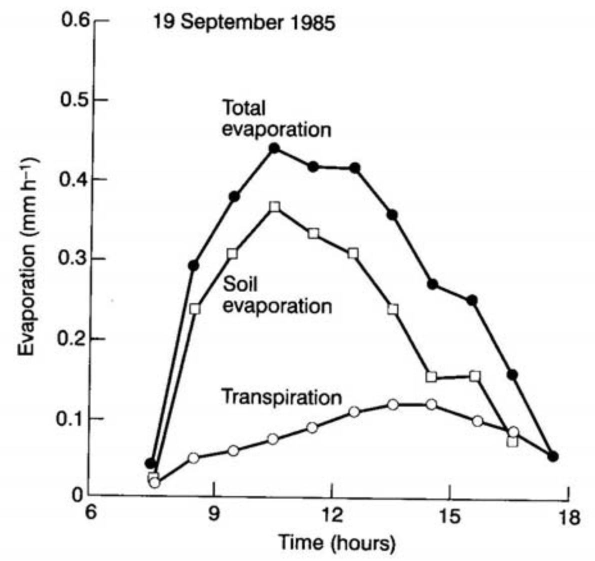


Figure 4.11 Direct soil evaporation may, after rainfall, account for twice the water loss resulting from transpiration (from Wallace *et al.*, 1989).

Latent heat exchange (LE)

- LE is ‘lost’ during **vaporization** (λ_v) & causes a **reduction in T_s** (i.e., cooling of surface) …. Example?
  - if we measure ΔLE, we know amount of energy avail. for evaporation

- LE = $\rho_w \cdot \lambda_v \cdot E \quad = \rho_w \cdot \lambda_v \cdot K_e \cdot v_a (e_s - e_a)$

  - λ_v **latent heat of vaporization** [$E\ M^{-1}$] or MJ kg^{-1}
  - as **T_s increases, λ_v decreases**: $\lambda_v = 2.5 - 2.36 \times 10^{-3}\ T_s$
  - about **2.45 million joules** are required to evaporate 1 kg of water at 20°C

Sensible heat exchange (H_S)

- upward **sensible heat transfer**, H_S via turbulence:

$$H_S = K_h \cdot v_a (T_s - T_a)$$

$$K_h \equiv C_a \cdot \rho_a \left[6.25 \left(\ln\left[\frac{z_m - z_d}{z_0} \right] \right)^2 \right]^{-1}$$

  - K_h coefficient describing **upward transfer** of H_S by wind
  - C_a is **heat capacity** of vapour-bearing air

Bowen Ratio

- **Bowen Ratio** (β) used to describe ratio of H_S:LE

$$\beta \equiv \frac{H_S}{LE} = \frac{C_a \cdot \rho_a \cdot (T_s - T_a)}{0.622 \cdot \lambda_v \cdot (e_s - e_a)} = \gamma \cdot \frac{(T_s - T_a)}{(e_s - e_a)}$$

γ= **psychrometric constant**

- describes the heat capacity, air density and latent heat of vapourization properties of the air mass

Measuring & modeling ET

Five commonly used approaches:

1. **Direct measurement** of moisture loss
2. **Radiation balance-based**
3. **Aerodynamic based** (mass transfer)
4. **Combined radiation-aerodynamic**
5. **Temperature-based**

Direct measurement

- <u>evaporation pan</u>: E of exposed water from budget of W inputs & Δ storage volume (V)
  - $E_{pan} = P - [V_2 - V_1]$
  - more appropriate for short vegetation & ground cover
  - spatially limited, design biases, does not measure transpiration

Evaporation station at private laboratory of Robert Horton. In: <u>Monthly Weather Review</u>: 1919, Sept.: 608.

Direct measurement

- **Lysimeter**: Δ in weight of a control volume of soil proportionate to Δ in volume of moisture lost by surface evaporation & plant transpiration

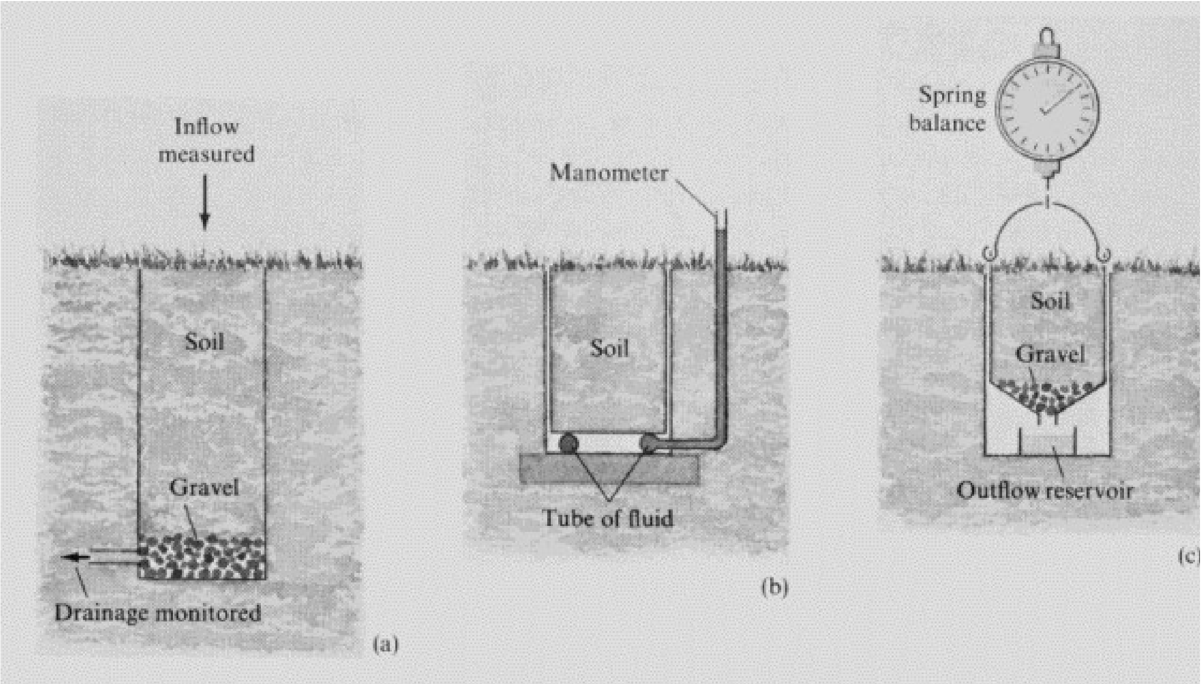


Figure 5-2 Schematic diagrams of types of lysimeters: (a) Drainage type. (b) Weighing float type. (c) Spring-balance weighing type.

(b) A giant 'floating' lysimeter containing a mature Douglas fir tree at Cedar River, Washington. The observer (centre left) is reading the manometer which monitors mass changes by the soil-tree monolith. Tensiometers are installed both inside and outside the lysimeter to ensure that similarity of moisture content is maintained. The brace in the foreground prevents rotation, and the tree is lightly 'guyed' to surrounding trees to prevent it falling over in high winds.

Radiation balance-based

- After the Earth's surface receives R_n radiative energy, the energy is **used in the following ways**:
- A portion of it will be used to **evaporate or transpirate** water from the liquid state to the gaseous state. This is called **latent heat (LE)** as the energy will be released when the gaseous water changes back to liquid state
- A portion of it will be used to **heat the atmosphere**, which is called **sensible heat (H_S)**
- A portion of it will **pass through the Earth's surface** to **heat the soil** below (Q)
- A **small fraction** of the energy is used by leaves for **photosynthesis** and this **energy is stored** in the chemical bonds of carbohydrate produced by photosynthesis (A)

Radiation balance-based

- We can describe the way the **net radiation** received by the Earth's surface is partitioned using the **Energy Balance Equation**:

$$R_n = LE + H_S + H_G + A$$

Where:
LE: Latent heat
H_S: Sensible heat
H_G : Energy stored in the soil
A: Energy stored in photosynthate

- How R_n is distributed among the items on the right hand side is determined by the **ecosystem biophysical characteristics** and has major consequences for ecosystem development and functions

Radiation balance-based

- You can calculate the ratio between sensible and latent heat fluxes, and this is known as the **Bowen Ratio (β)**:

$$\beta = H / LE$$

- The sensible heat flux is often **difficult to measure**, but if you can estimate the Bowen Ratio, you can rewrite the **net radiation balance equation** in terms of latent heat:

$$R_n = H + LE + H_G$$

$$R_n = (\beta * LE) + LE + H_G$$

$$LE = (R_n - H_G) / (1 + \beta)$$

Radiation balance-based

- Evaporation calculated via **Bowen ratio energy balance** method

$$LE = R_N - H_S - H_G$$

$$LE = \frac{(R_N - H_G)}{(1+\beta)}$$

$$E = \frac{(R_N - H_G)}{\rho_W \cdot \lambda_V \cdot (1+\beta)}$$

- Method seeks to apportion available energy between sensible and latent heat flux by considering their ratio

$$\beta = \frac{H_S}{LE} = \gamma \cdot \frac{\Delta T}{\Delta e}$$

- assumes neutral stability (buoyancy effects are absent) and steady state (no marked shifts in radiation)

Radiation balance-based

- Semi-empirical approach requires measurements on one level above surface

Priestly & Taylor (1972):

$$\mathrm{PET} = \alpha \cdot \frac{s}{s+\gamma} \cdot \frac{(R_N - \mathrm{H_G})}{\rho_w \cdot \lambda_v}$$

where:

PET is **potential evapotranspiration** (mm per time)

$s = (e^*_s - e^*_a)/(T_s - T_a)$... describes **gradient** of e* vs. T at a given air temperature

α is an empirically derived **evaporability factor** (usually 1.26)

Combined approaches

- **Penman** (1948) developed a method considering the factors of **both energy supply and turbulent transport of water vapor** from an evaporating surface

- Requires meteorological measurements at **only 1 level**

- in the combination method LE is **calculated as the residual** in the energy balance equation with sensible heat flux estimated by means of **an aerodynamic equation**

- **widely used** for estimating potential evapotranspiration

- original method designed to estimate evaporation from **open-water or well-watered surfaces**
  - e.g., lake, pond, and wetlands

Combined approaches

Penman (1948):

$$\mathrm{PET} = \frac{s \cdot (\mathrm{R_N} - \mathrm{H_G}) + \dfrac{\mathrm{C_a} \cdot (\mathrm{e_s} - \mathrm{e_a})}{\mathrm{r_a}}}{\rho_\mathrm{W} \cdot \lambda_\mathrm{V} \cdot (s + \gamma)}$$

$$\mathrm{r_a} = \frac{[\ln(\mathrm{z} - \mathrm{d})/\mathrm{z_O}]^2}{\kappa^2 \cdot \mathrm{u_z}}$$

Aerodynamic resistance, r_a, describes the resistance from the water or vegetation upward and involves friction of air flowing over water or vegetative surface

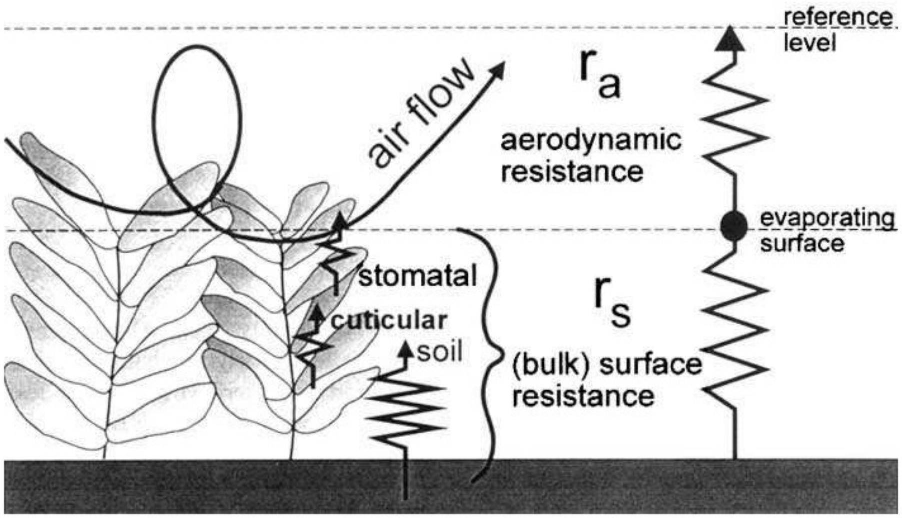
r_a = aerodynamic resistance (s m^{-1})

u_z = is wind speed (m s^{-1}) at elevation z (m)

κ= van Karman's constant (0.4)

κz_o = roughness length (m)

κd = zero plane of displacement



Combined approaches

- **Penman-Monteith equation** common for ET from a vegetated land surface

$$PET = \frac{s \cdot (\mathrm{R}_N - \mathrm{G}) + \dfrac{\rho_a c_a \cdot (e_s - e_\mathrm{a})}{r_a}}{\rho_w \cdot \lambda_v \cdot [s + \gamma \cdot (1 + r_c / r_a)]}$$

$$r_c = \frac{\mathrm{r}_\mathrm{i}}{LAI_{active}}$$

where:

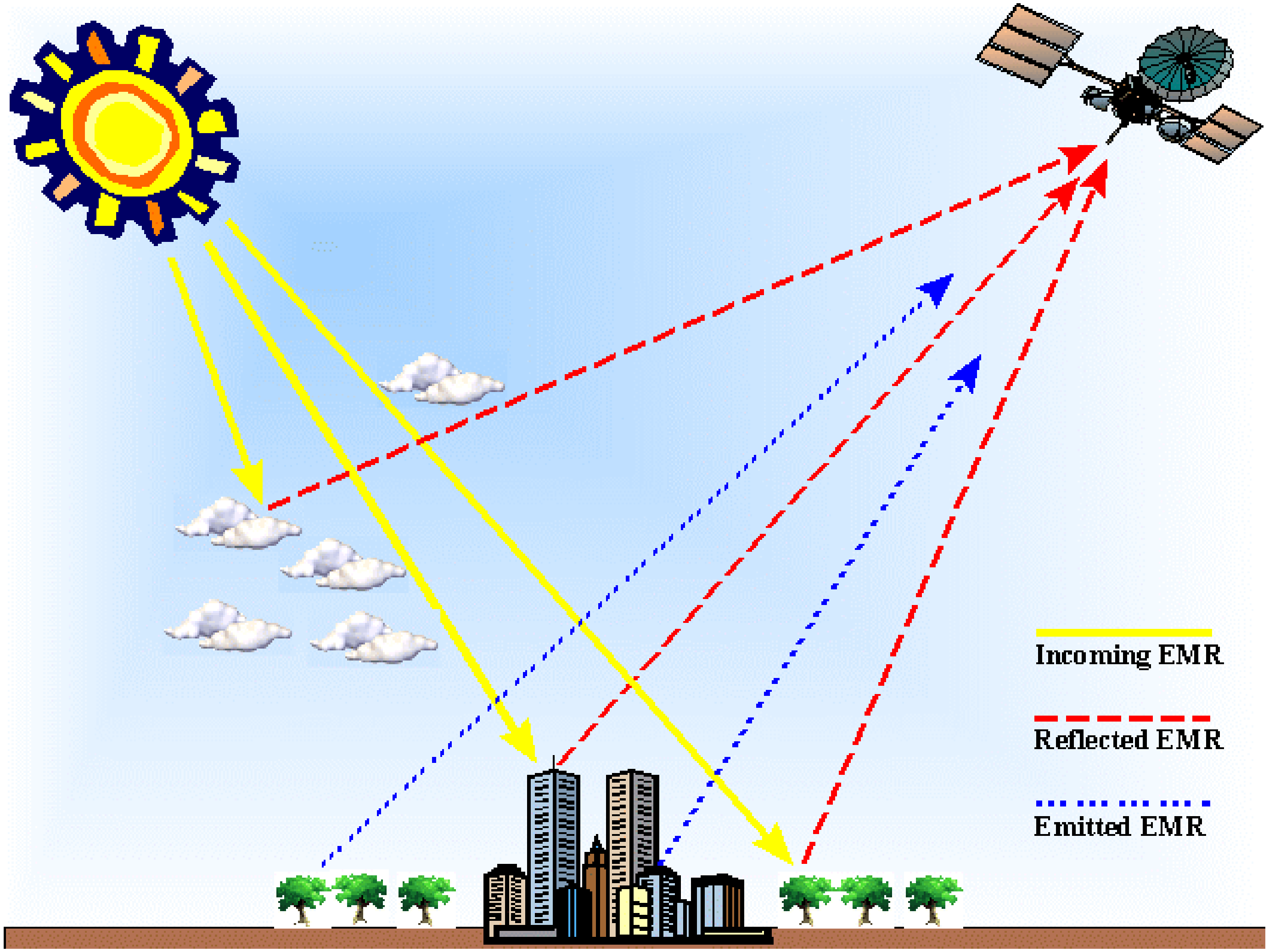
r_c = canopy resistance (s m^{-1})

r_i = bulk stomatal resistance of the well-illuminated leaf (s m^{-1})

$\mathrm{LAI}_\mathrm{active}$ = active (sunlit) leaf area index (m^2 leaf area per m^2 soil surface)

Satellite Imagery - Sensing EMR

- Digital data obtained by sensors on satellite platforms

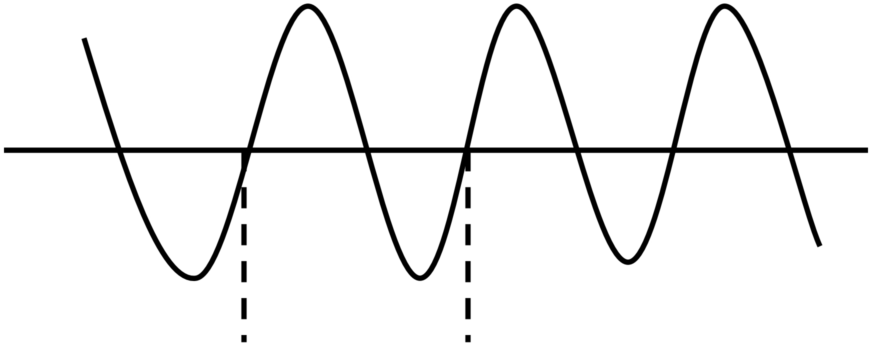


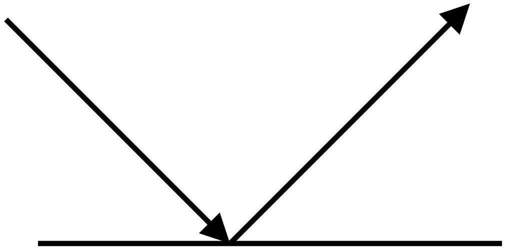
Two Types of Remote Sensing

- In remote sensing, the medium that usually carries the information is **electromagnetic radiation**. Using various sensors, we can collect the electromagnetic radiation in **any portion of the spectrum**. Based on the source of the energy, remote sensing can be broken into two categories:
- **Passive remote sensing**: The source of energy collected by sensors is either **reflected solar radiation** (e.g. cameras) or **emitted by the targets** (thermal imaging).
- **Active remote sensing**: The source of energy collected by sensors is actively **generated by a man-made device**. Examples include radar (which uses microwave energy) and LIDAR (LIght Detection Imagery And Ranging, which uses a laser).

Solar Radiation

Electromagnetic radiation energy: **Wave-particle duality**

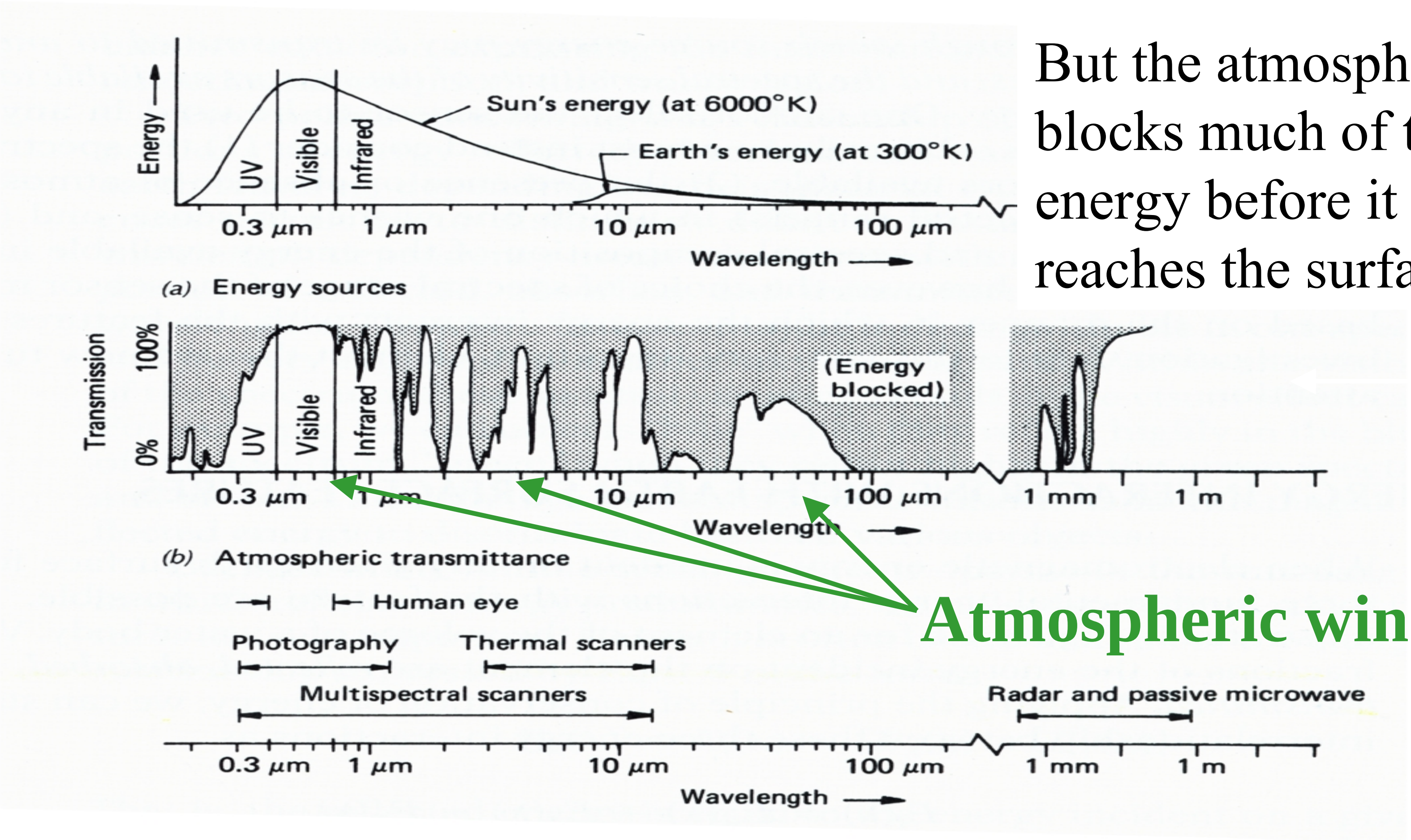




- EMR energy moves at the **speed of light (c)**: $c = f \lambda$
- ***f* = frequency**: The number of waves passing through a point within a unit time (usually expressed per second)
- **Energy** carried by a photon: $\varepsilon = h f$ [h=Planck constant (6.626×10^{-34} Js)]
- The shorter the wavelength, the higher the frequency, and the **more energy** a photon carries. Therefore, short wave ultraviolet solar radiation is very destructive (sunburns)

Solar Electromagnetic Radiation

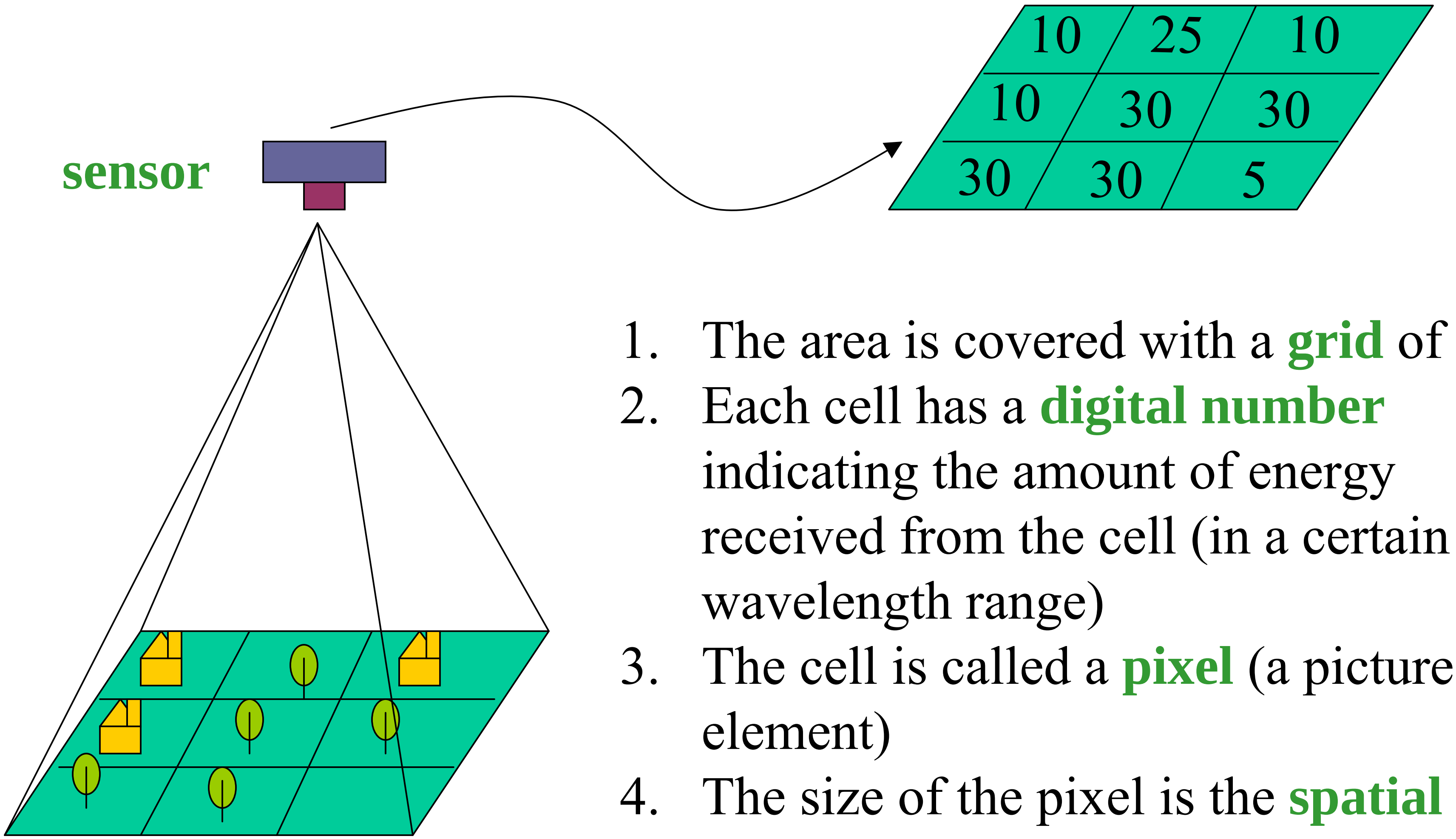
- The sun emits EMR across a **broad spectrum** of wavelengths:



But the atmosphere blocks much of the energy before it reaches the surface

Atmospheric windows

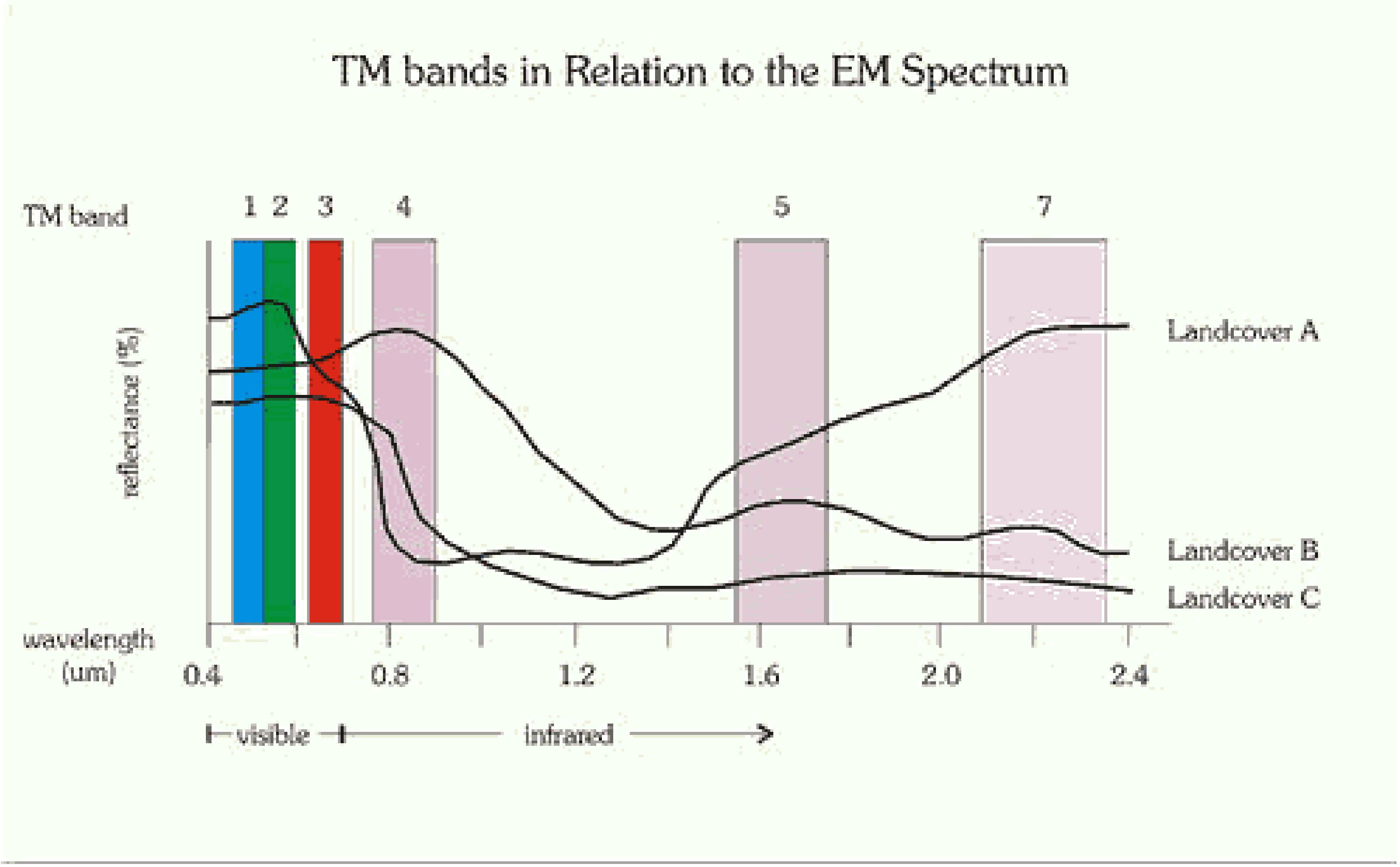
Digital Images



10	25	10
10	30	30
30	30	5

1. The area is covered with a **grid** of cells
2. Each cell has a **digital number** indicating the amount of energy received from the cell (in a certain wavelength range)
3. The cell is called a **pixel** (a picture element)
4. The size of the pixel is the **spatial resolution**

Multispectral Remote Sensing



Spectral Bands of Landsat Thematic Mapper Sensors
http://www.satelliteimpressions.com/landsat.html

Satellite Imagery - 4 Resolutions

- Satellite imagery can be described by four resolutions:
  - **Spatial resolution**: area on ground represented by each pixel, e.g.
    - Landsat Thematic Mapper - 30m
    - Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolutions Imaging Spectrometer (MODIS) - 1km
    - SPOT - 10m panchromatic /20m multispectral
    - IKONOS - 1m panchromatic /4m multispectral
  - **Temporal resolution**: how often a satellite obtains imagery of a particular area
  - **Spectral resolution**: specific wavelength intervals in the electromagnetic spectrum captured by each sensor (bands)
  - **Radiometric Resolution**: number of possible data values reportable by each sensor (how many bits)

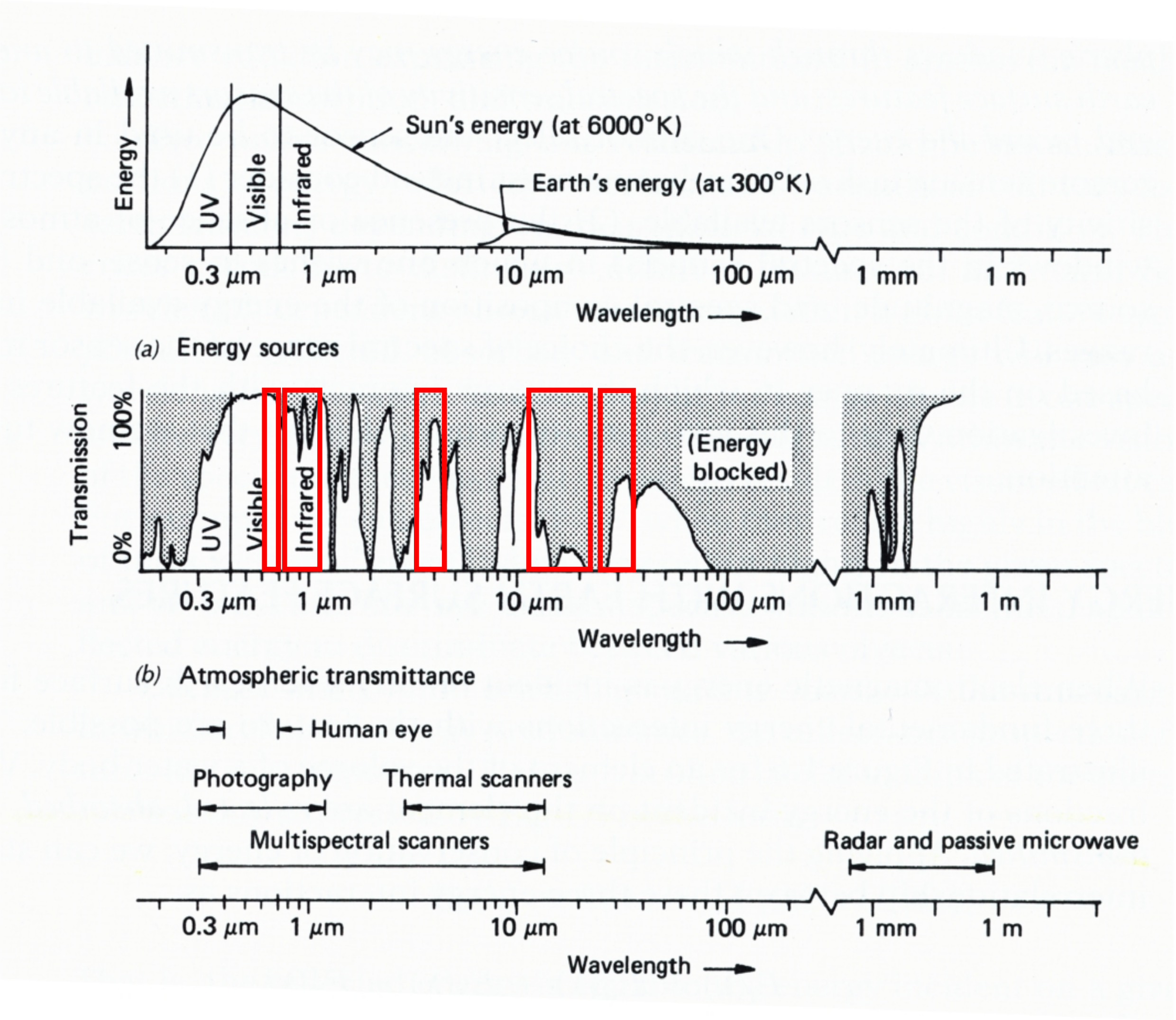
Spectral Enhancements

- Can take ratios or other **combinations of multiple input bands** to produce indices, e.g.:
- **Normalized Difference Vegetation Index (NDVI)**
  - Designed to contrast heavily-vegetated areas with areas containing little vegetation, by taking advantage of vegetation's strong absorption of red and reflection of near infrared:
  - NDVI = (NIR-R) / (NIR + R)
- **Surface temperature (T_s)** from IR bands using Price (1984):
  - $T_S = TIR1 + 3.33 (TIR1 - TIR2)$
    - Wavelengths: TIR1 = 10.8 µm, TIR2 = 11.9 µm

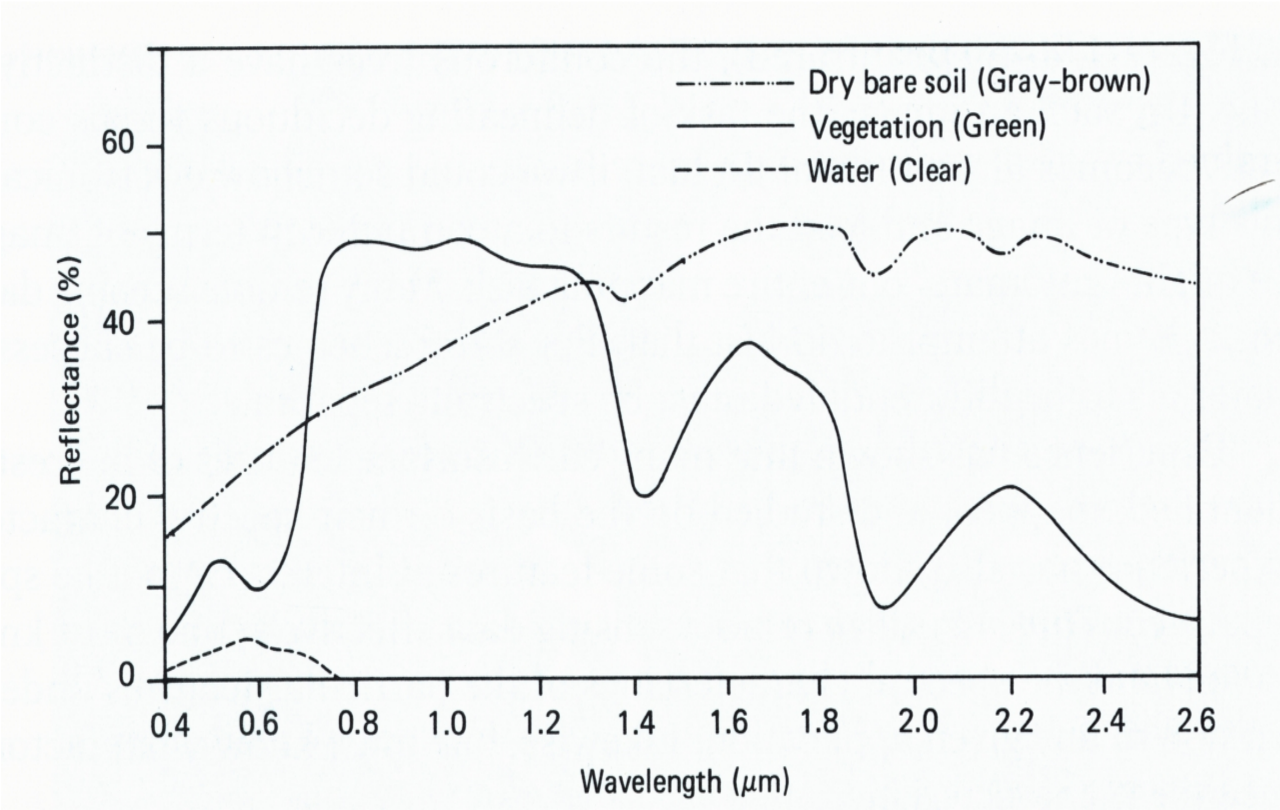
AVHRR

- **AVHRR (Advanced Very High Resolution Radio-meter)** is also a joint venture between NASA and NOAA, and this sensor has been present on many platforms
- AVHRR images **water vapor** in the atmosphere and **surface temperatures**, and does so at a spatial resolution of 1.1 km pixels at nadir, and uses a sun-synchronous orbit that has these satellites image the entire surface of the Earth every 12 hours
- Because AVHRR has **red and near infrared bands**, along with short-wave infrared and thermal infrared bands, it can be used for **vegetation studies** in addition to the applications described above

AVHRR Bands


Energy
UV
Visible
Infrared
Sun's energy (at 6000°K)
Earth's energy (at 300°K)
0.3 μm
1 μm
10 μm
100 μm
1 mm
1 m
Wavelength
(a) Energy sources
Transmission
100%
0%
UV
Visible
Infrared
(Energy blocked)
0.3 μm
1 μm
10 μm
100 μm
1 mm
1 m
Wavelength
(b) Atmospheric transmittance
Human eye
Photography
Thermal scanners
Multispectral scanners
Radar and passive microwave
0.3 μm
1 μm
10 μm
100 μm
1 mm
1 m
Wavelength

Normalized Difference Vegetation Index

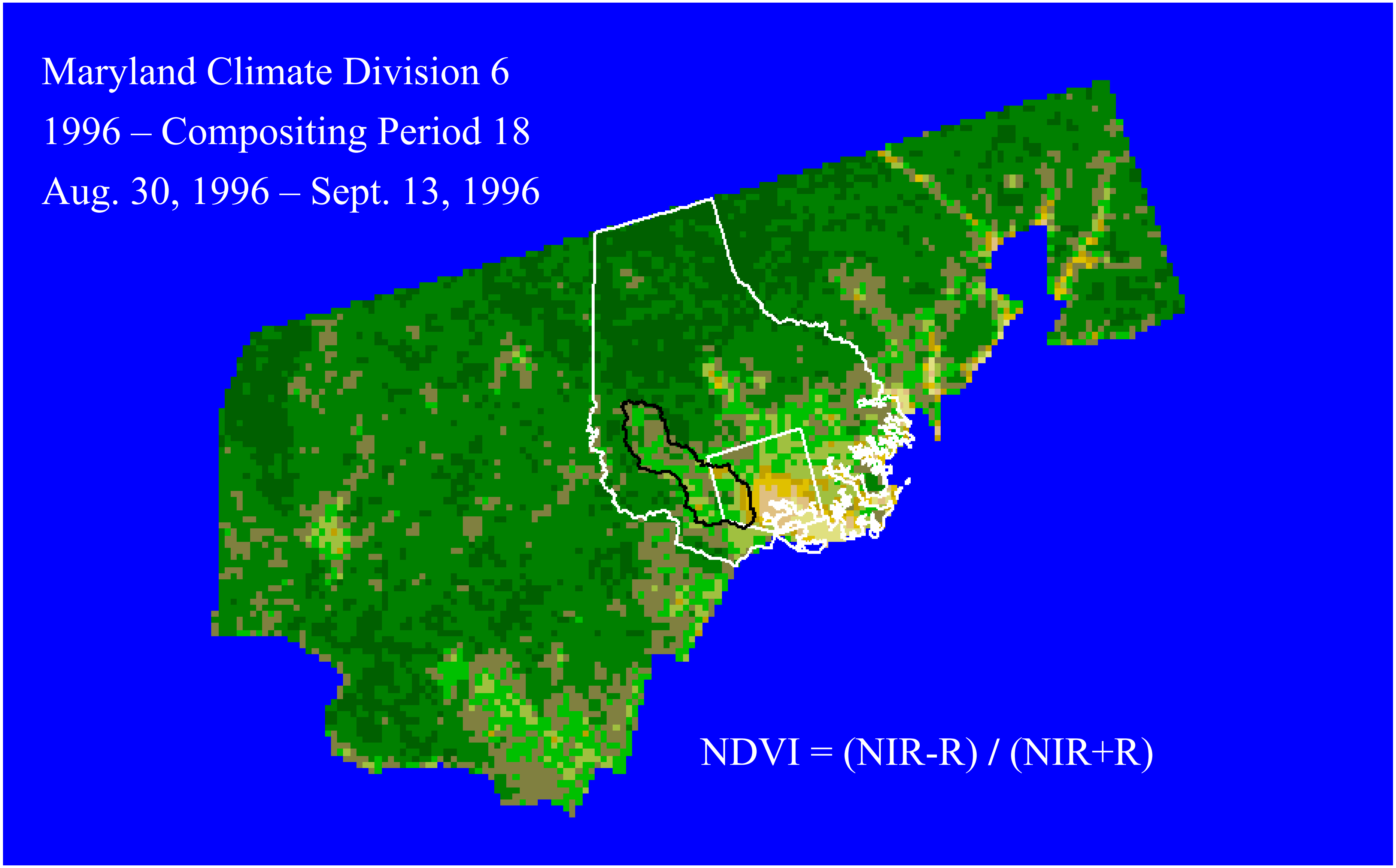


$$\text{NDVI} = \frac{(\text{NIR} - \text{R})}{(\text{NIR} + \text{R})}$$

NDVI [-1,1]

- Vegetation has a **strong contrast in reflectance** between red and near infrared EMR, and NDVI takes advantage of this to **sense the presence/density of vegetation**

AVHRR Satellite Imagery - NDVI



Maryland Climate Division 6

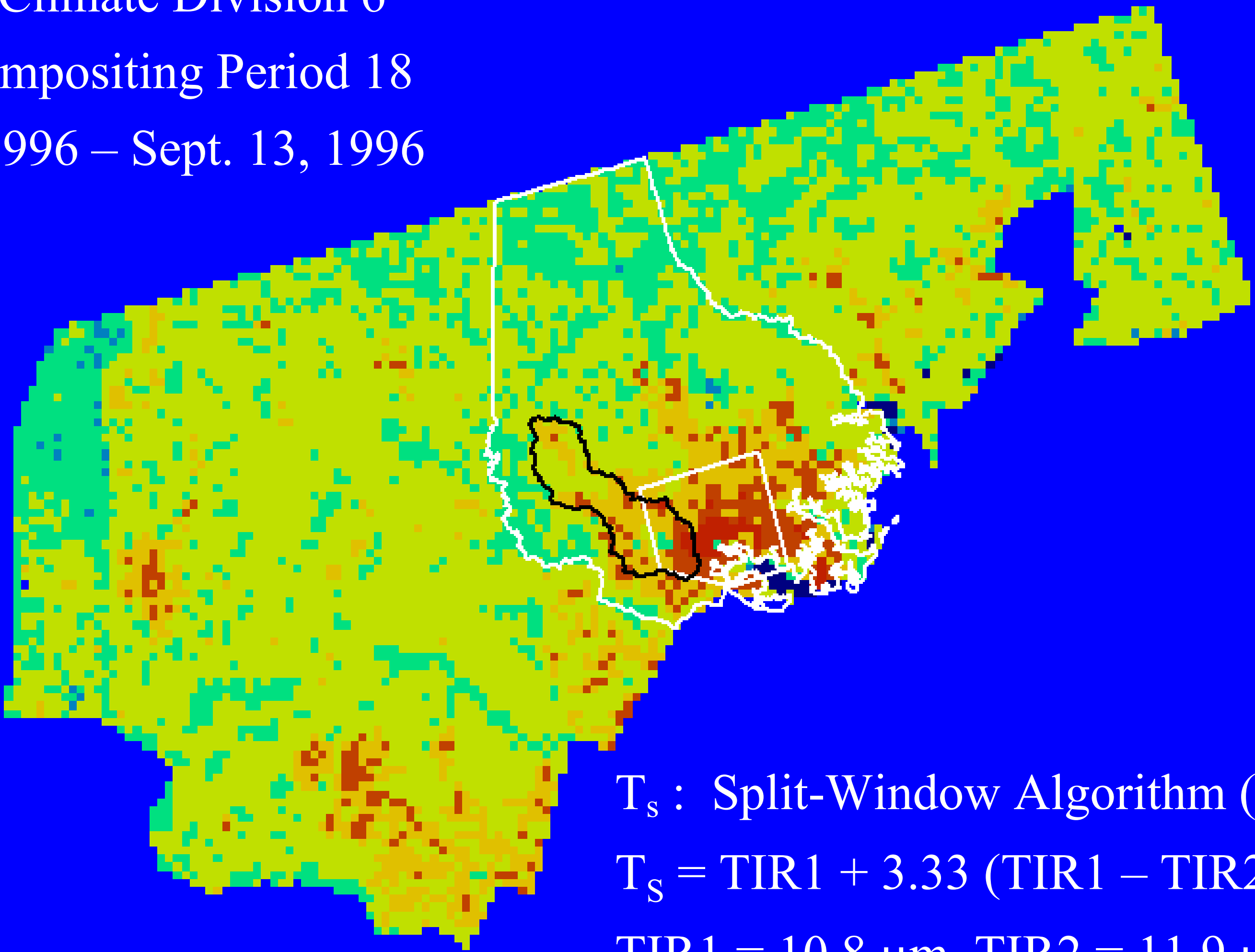
1996 – Compositing Period 18

Aug. 30, 1996 – Sept. 13, 1996

$\text{NDVI} = (\text{NIR-R}) / (\text{NIR+R})$

AVHRR Satellite Imagery - T_s

Maryland Climate Division 6
1996 – Compositing Period 18
Aug. 30, 1996 – Sept. 13, 1996

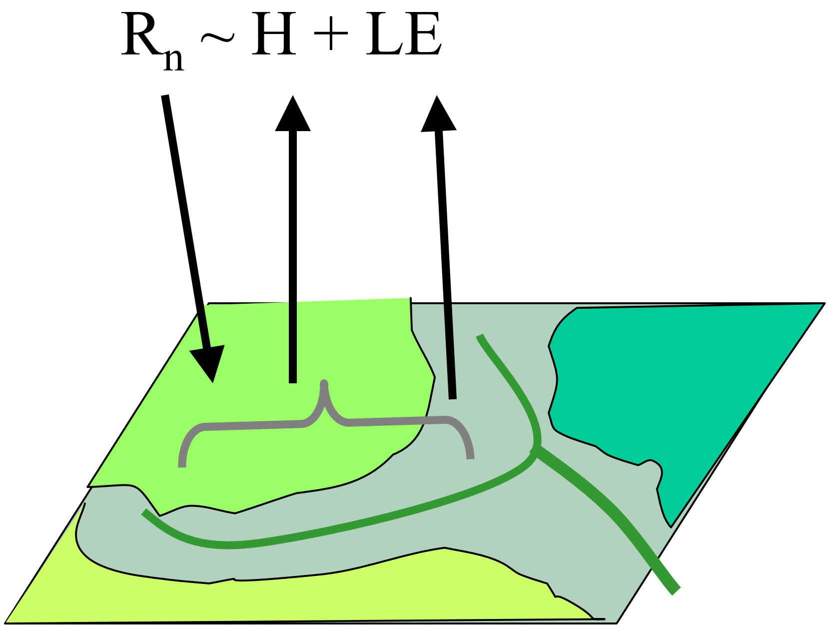


T_s : Split-Window Algorithm (Price 1984)

$$T_S = \mathrm{TIR1} + 3.33\,(\mathrm{TIR1} - \mathrm{TIR2})$$

TIR1 = 10.8 µm, TIR2 = 11.9 µm

Surface water/energy budget coupling over heterogeneous terrain



$LE = f_{veg}\, LE_{veg} + (1 - f_{veg})\, LE_{soil}$

$LE = f(R_n, T, g_c, g_a, g_{soil}, VPD)$

$g_a = f(\text{canopy structure, wind, ...})$

$g_c = f(\text{soil water, VPD, PAR, T, LAI})$

$g_{soil} = f(\text{soil water, ...})$

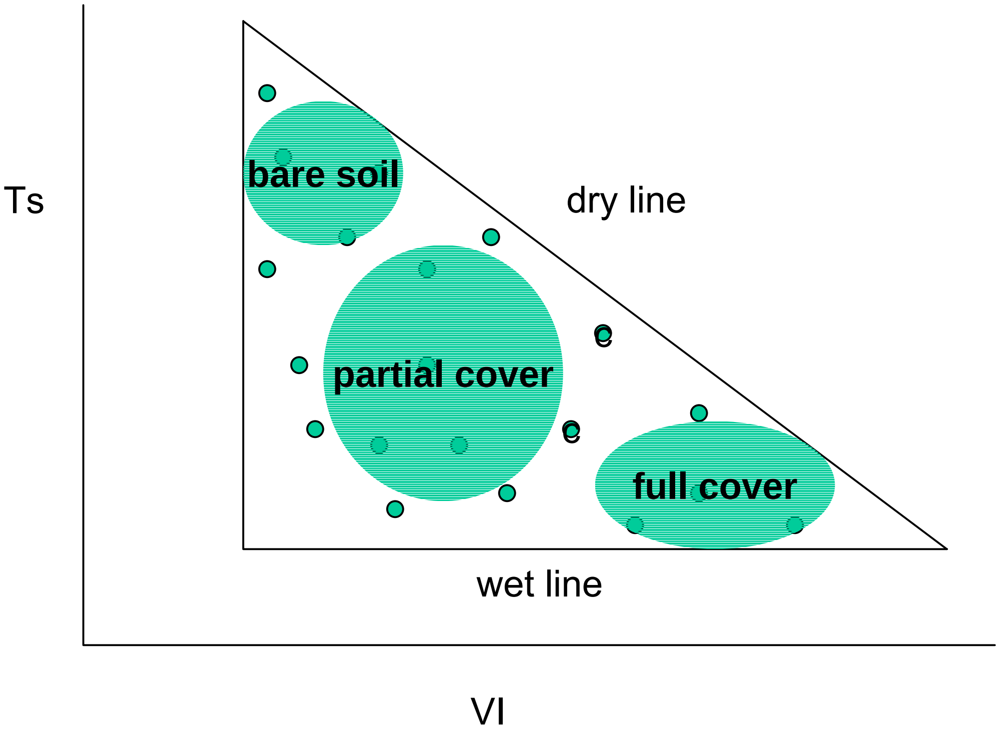
T_s lower with greater LE (evaporative cooling) as a function of soil water (other factors), greater canopy cover (higher NDVI)

T_s and NDVI estimated by a set of operational remote sensors

Sensing Vegetation and Temperature

- Can take ratios or other **combinations of multiple input bands** to produce indices, e.g.:
- **Normalized Difference Vegetation Index (NDVI)**
  - Designed to contrast heavily-vegetated areas with areas containing little vegetation, by taking advantage of vegetation's strong absorption of red and reflection of near infrared:
  - NDVI = (NIR-R) / (NIR + R)
- **Surface temperature (T_s)** from IR bands using Price (1984):
  - $T_S = \text{TIR1} + 3.33\ (\text{TIR1} – \text{TIR2})$
    - Wavelengths: TIR1 = 10.8 µm, TIR2 = 11.9 µm

Interpretation of the VI-T_s Space

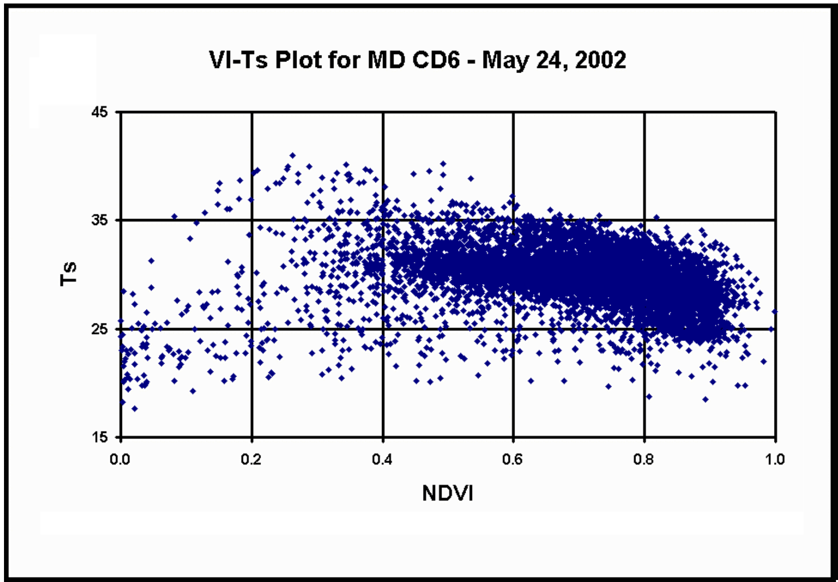


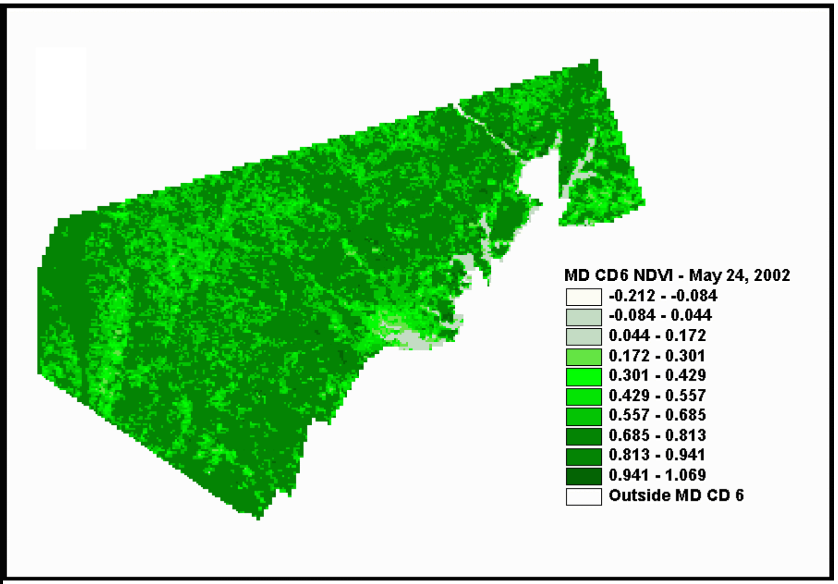
Adapted from Sandholt et al. 2002

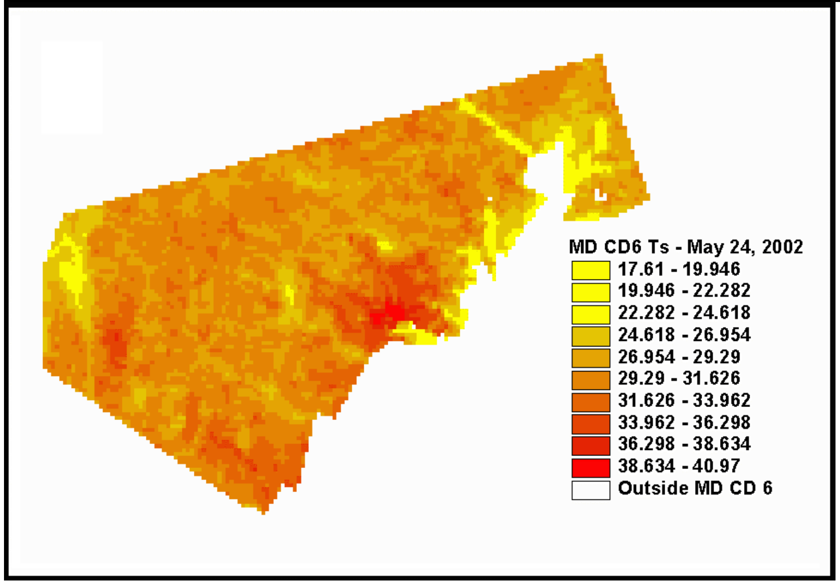
Dry Line Slope – Sigma (σ)

- Nemani and Running (1989) suggested, and later Nemani, Pierce, Running, and Goward (1993) demonstrated, that **the slope of the dry line** (symbolized using σ) is a good overall indicator of the **surface moisture condition** of a region (where the T_s and VI pixels that are drawn from to form the 2-D T_s-VI distribution) on the occasion when the imagery was collected
    - **Steeper, more negative** slopes represent **drier conditions** (where T_s disparities are greater)
- So **how** do we form the 2-D T_s-VI distribution and find the slope of the dry line?

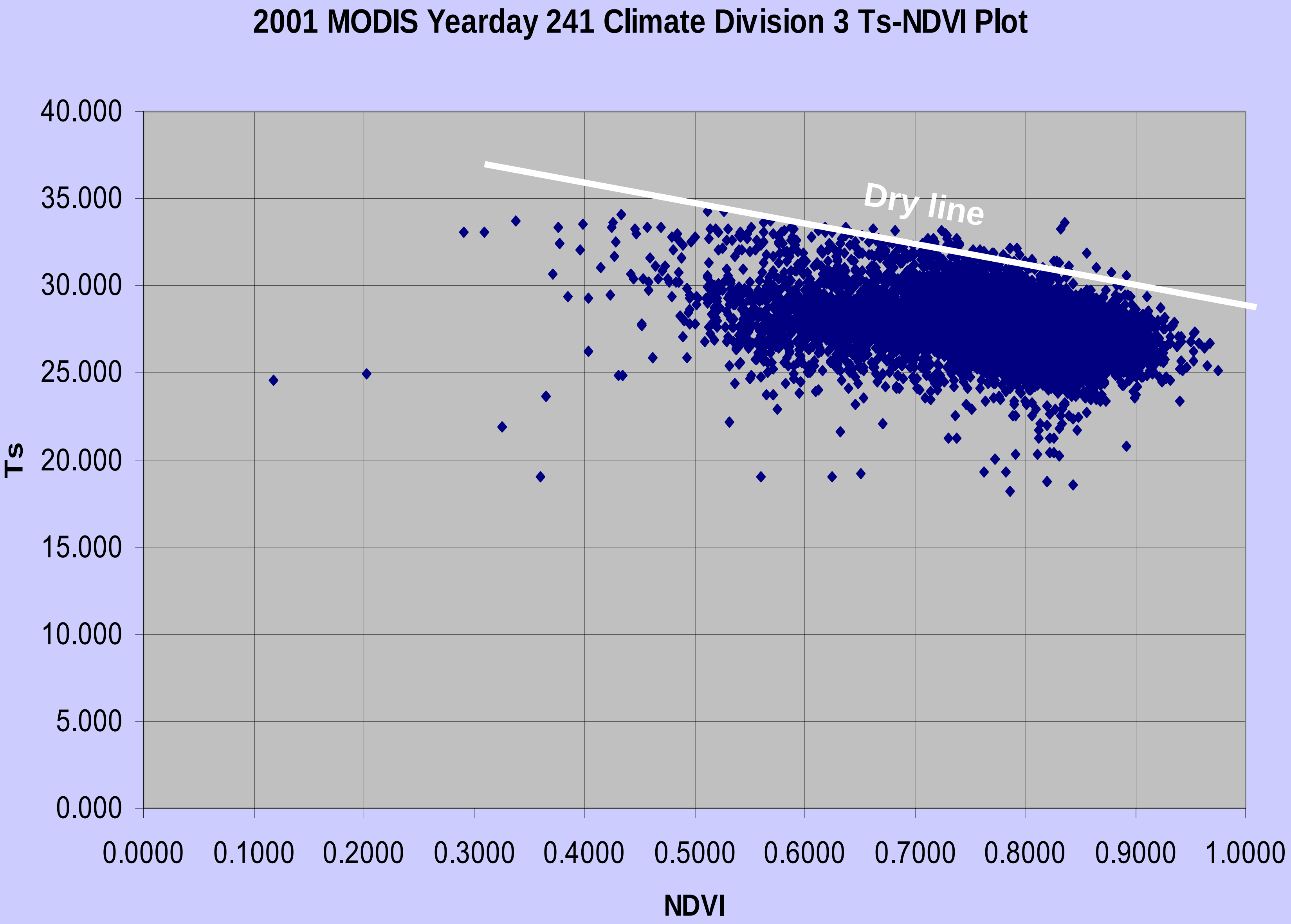
Finding the Dry Line (σ) Slope







- We begin with **T_s and VI data**, ideally collected using the **same sensor at the same time** (e.g. from AVHRR bands 1, 2, 4, & 5)
- We then translate the values for each pixel into a **2-D parameter space**, the VI on the x-axis and the T_s on the y-axis


2001 MODIS Yearday 241 Climate Division 3 Ts-NDVI Plot
Dry line
Ts
NDVI
40.000
35.000
30.000
25.000
20.000
15.000
10.000
5.000
0.000
0.0000
0.1000
0.2000
0.3000
0.4000
0.5000
0.6000
0.7000
0.8000
0.9000
1.0000

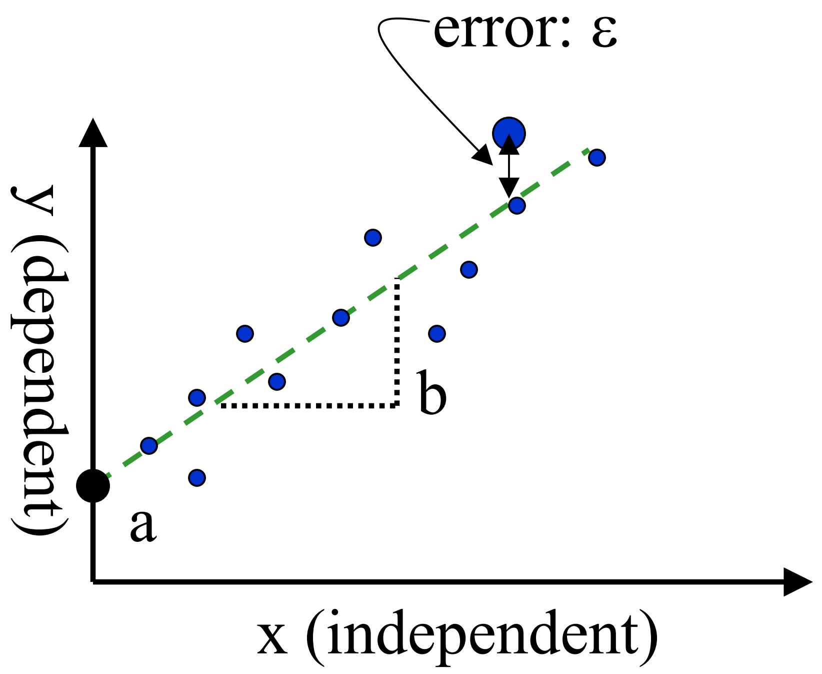
Finding the Dry Line (σ) Slope

- With a **real** T_s-VI distribution, **fitting a line** to the upper envelope of the distribution is **a little bit tricky**!
- We can break it down into a **two-part process**:
  - 1st, we must **identify a subset of all pixels** in the distribution that represent **the upper envelope**, that is those pixels with **the highest T_s for a given VI** → We can accomplish this through some sort of **classification/filtering method**
  - 2nd, once we have **identified the upper envelope** pixels, we must **fit a line through them** → We can accomplish this through fitting a **simple linear regression model**

Simple Linear Regression

- **Simple linear regression** models the relationship between an independent variable (x) and a dependent variable (y) using an equation that expresses y as a linear function of x, plus an error term:

$$y = a + bx + e$$



x is the **independent** variable

y is the **dependent** variable

b is the **slope** of the fitted line

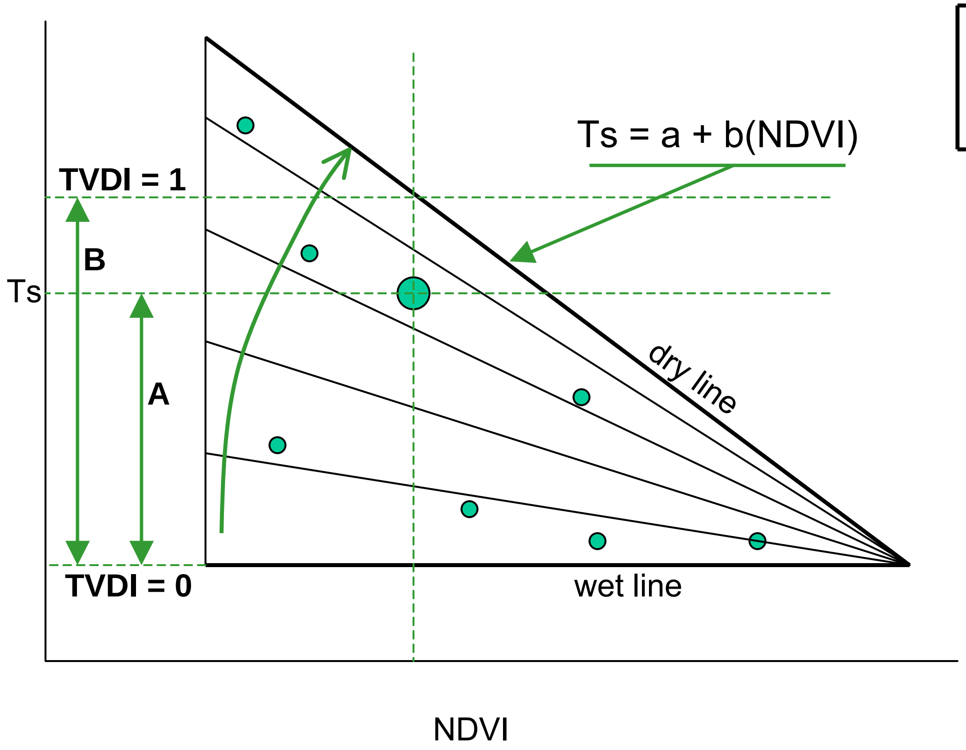
a is the **intercept** of the fitted line

e is the **error** term

Obtaining Per Pixel Dryness Info

- **The slope of the dry line** (symbolized using σ) is a good overall indicator of the **surface moisture condition of a region** (where the T_s and VI pixels that are drawn from to form the 2-D T_s-VI distribution)
  - But it is just that, **a single number** that is a **regional descriptor** of the **surface moisture condition** of the **overall aggregate set of pixels**
- What if we want to know something about the **surface moisture condition of individual pixels**? How can we do this?
  - One way is to take an approach that **describes each pixel's position** in the distribution

Temperature Vegetation Dryness Index

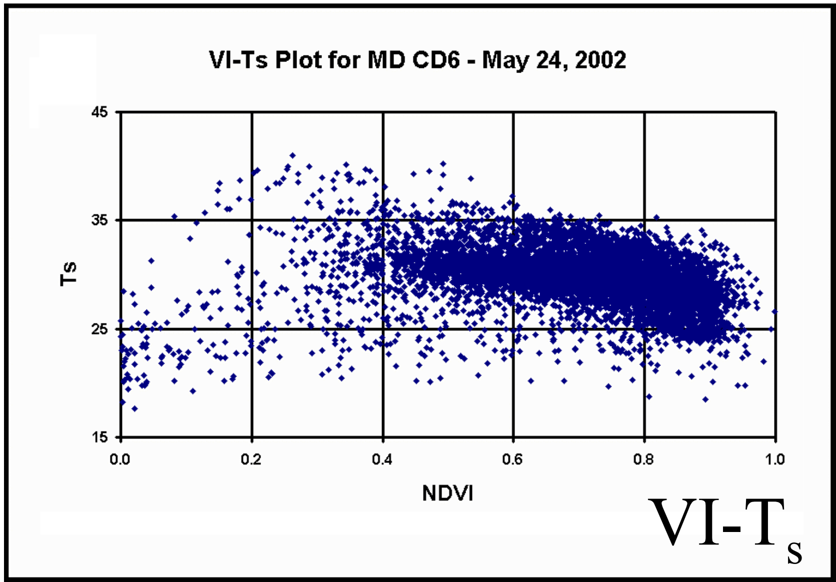


Sigma = b

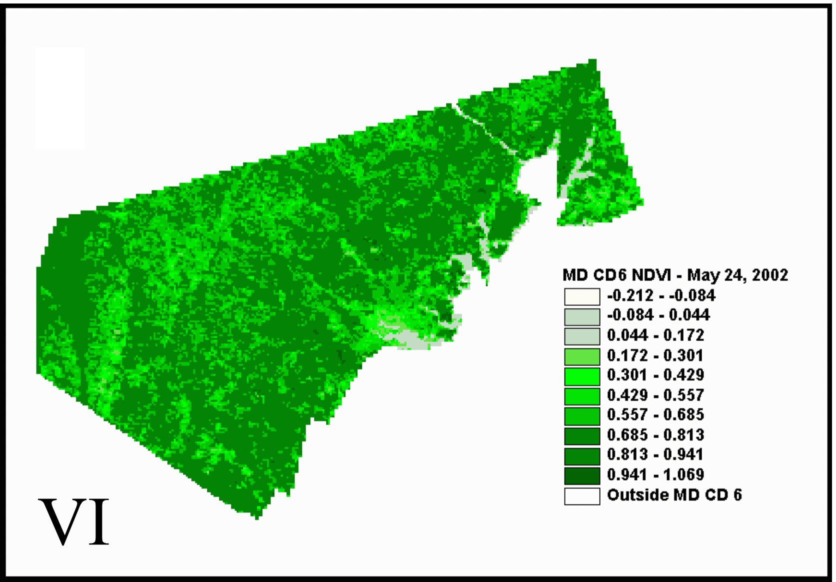
TVDI = A/B

Adapted from Sandholt et al. 2002

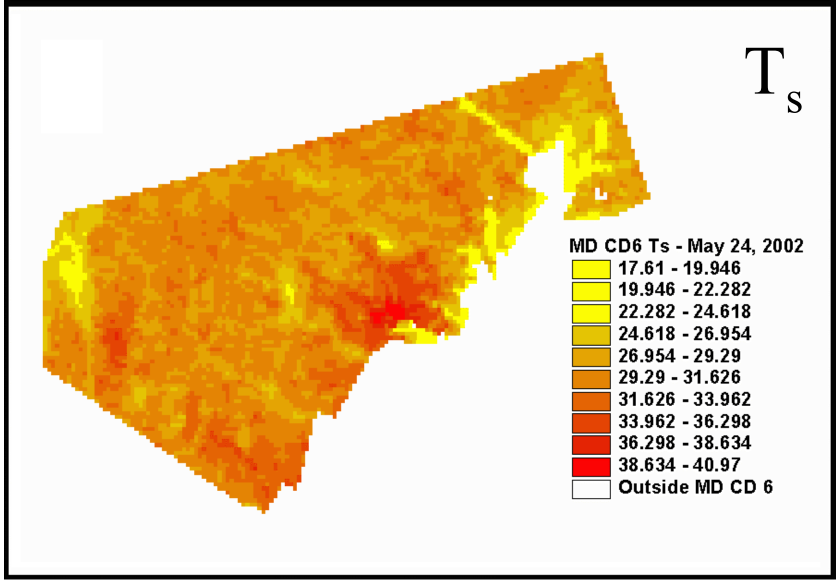
Generating TVDI Values



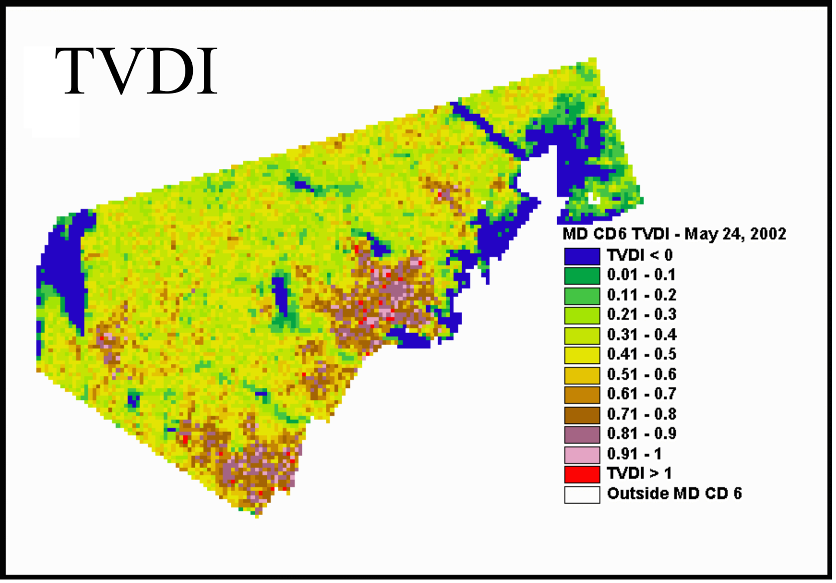
VI-T_s



VI



T_s



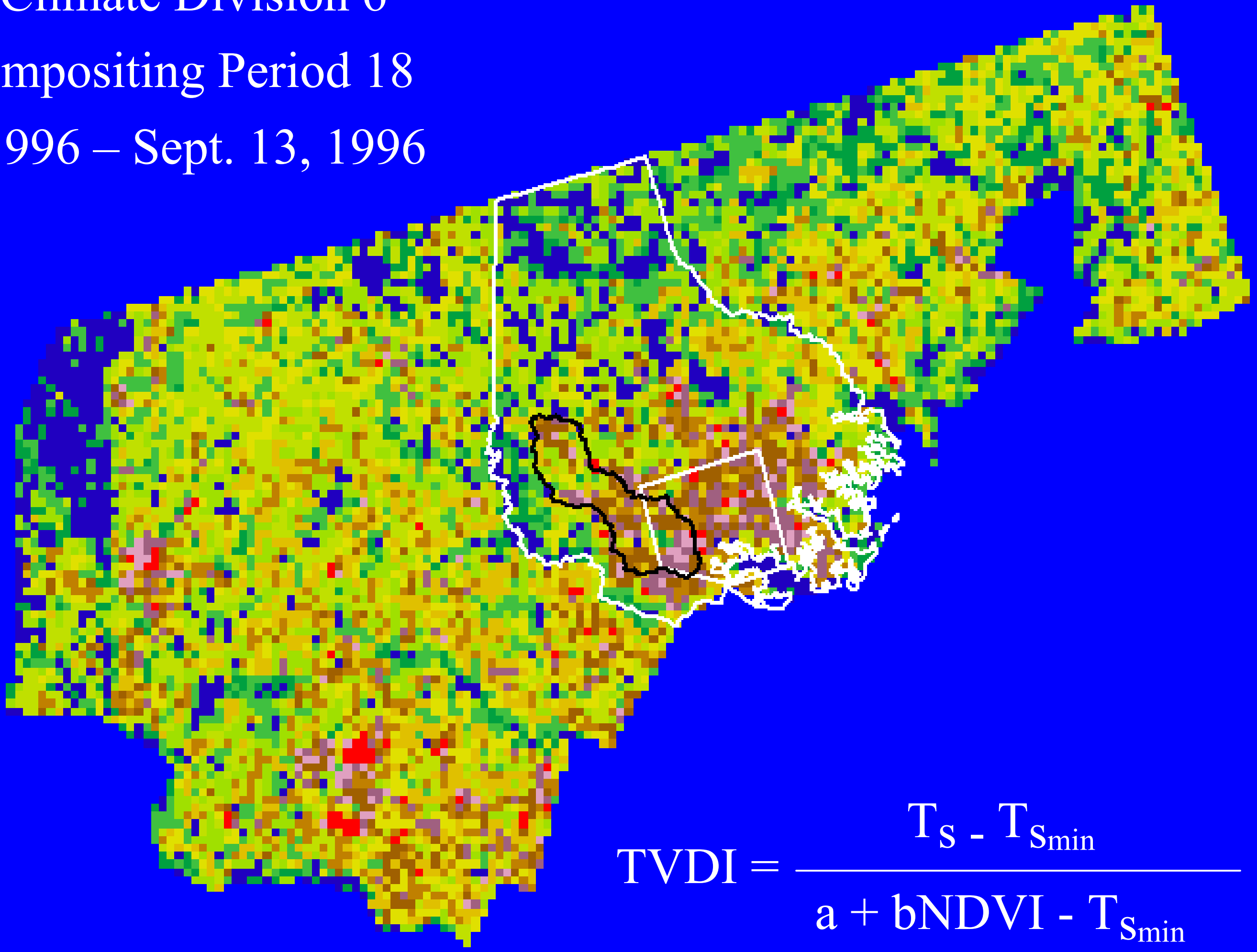
TVDI

AVHRR Satellite Imagery - TVDI

Maryland Climate Division 6

1996 – Compositing Period 18

Aug. 30, 1996 – Sept. 13, 1996



$$TVDI = \frac{T_S - T_{S_{min}}}{a + bNDVI - T_{S_{min}}}$$

Temperature Vegetation Dryness Index

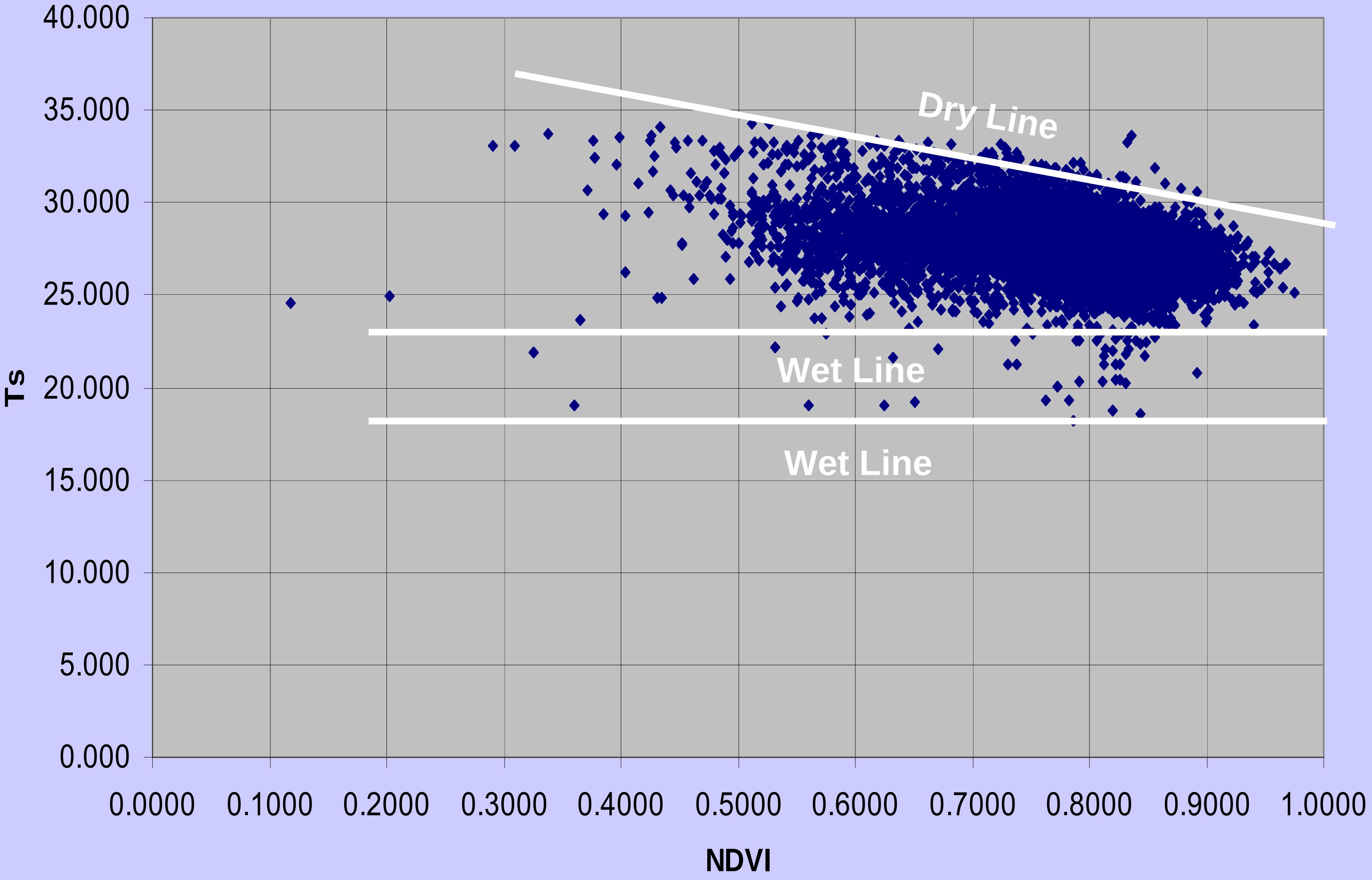
- The **procedure for creating TVDI** initially requires all the steps required to obtain σ :

  1. Form the 2-D T_s – VI distribution
  2. Calculate/find σ

  followed by **a few further steps**:

  3. Define the wet line along the bottom the triangle (which can usually be safely done in a fairly unsophisticated fashion)
  4. Calculate TVDI as described (where is the point/pixel of interest positioned between the dry and wet lines at the given NDVI)
  5. Take the resulting values and map them back to their respective pixels

2001 MODIS Yearday 241 Climate Division 3 Ts-NDVI Plot



MODIS

- AVHRR has been superceded by **MODIS (Moderate Resolution Imaging Spectrometer)** which is a project being run by NASA, in partnership with the USGS (US Geological Survey)

- The MODIS sensors are the ‘centerpiece’ sensors on two new satellites that have been called Earth Observing Systems (EOS-AM and EOS-PM), codenamed **Terra and Aqua**

- **Terra** was designed to focus on land-based applications and has an equatorial **overpass time of about 10:30 AM**, while **Aqua** was designed for more sea-oriented applications and has an equatorial **overpass time of about 2:30 PM**, and the MODIS sensors on them are known as MODIS-AM and MODIS-PM

MODIS Characteristics

Orbit: 705 km,

Time to cross equator: 10:30 a.m. descending node (Terra),
2:30 pm descending node (Aqua)

sun-synchronous, near-polar, circular

Sensor Systems: Across Track Scanning (‘Wiskbroom’)

Radiometric resolution: 12 bits

Temporal resolution: 1-2 days

Spatial Resolution:

250 m (bands 1-2)

500 m (bands 3-7)

1000 m (bands 8-36)

Design Life: 6 years

MODIS Bands

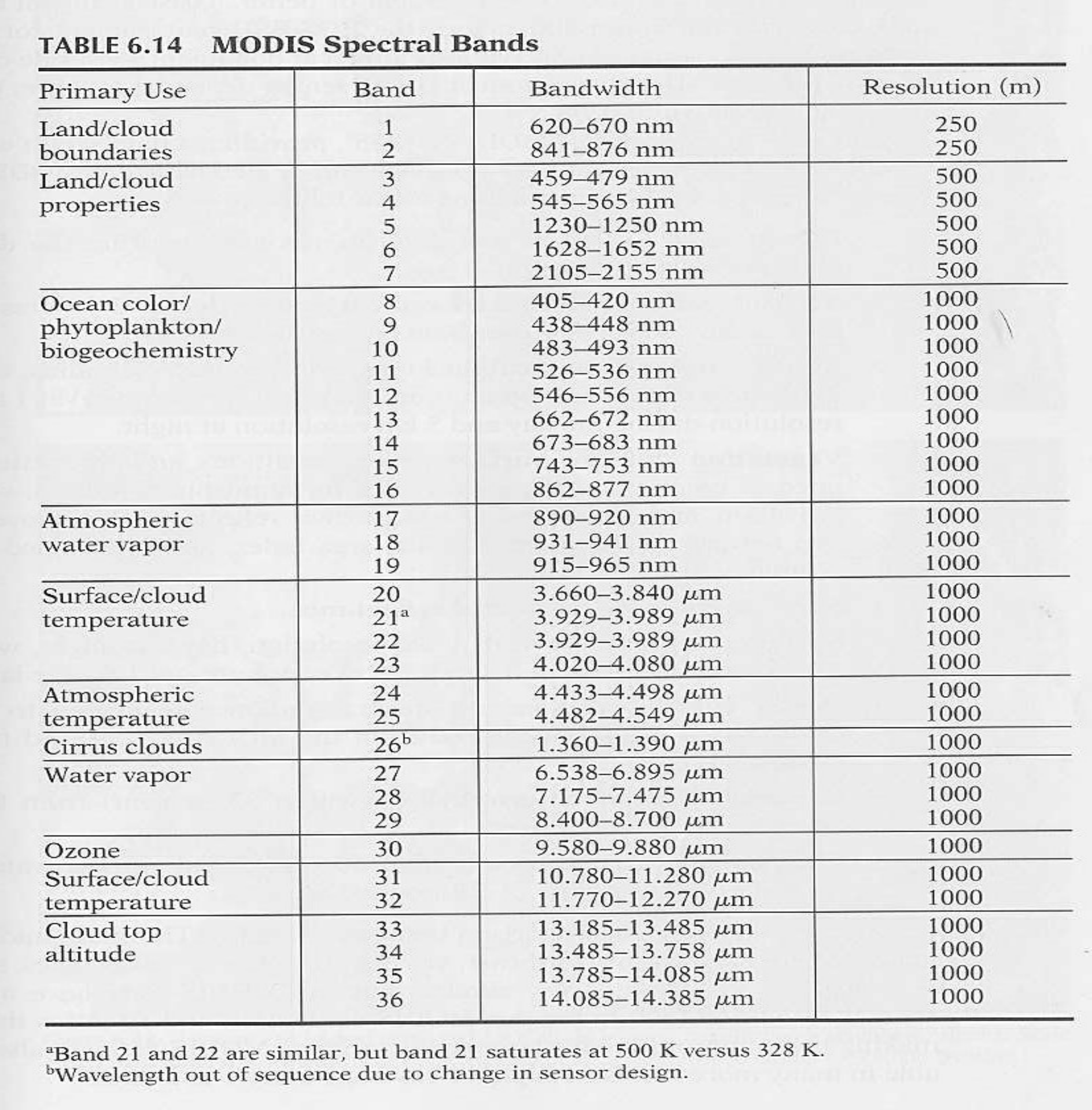


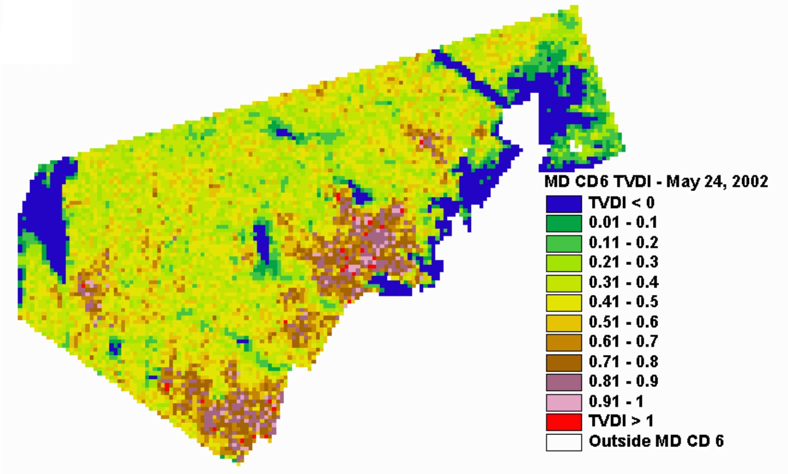
TABLE 6.14 **MODIS Spectral Bands**

Primary Use	Band	Bandwidth	Resolution (m)
Land/cloud boundaries	1	620–670 nm	250
	2	841–876 nm	250
Land/cloud properties	3	459–479 nm	500
	4	545–565 nm	500
	5	1230–1250 nm	500
	6	1628–1652 nm	500
	7	2105–2155 nm	500
Ocean color/ phytoplankton/ biogeochemistry	8	405–420 nm	1000
	9	438–448 nm	1000
	10	483–493 nm	1000
	11	526–536 nm	1000
	12	546–556 nm	1000
	13	662–672 nm	1000
	14	673–683 nm	1000
	15	743–753 nm	1000
	16	862–877 nm	1000
Atmospheric water vapor	17	890–920 nm	1000
	18	931–941 nm	1000
	19	915–965 nm	1000
Surface/cloud temperature	20	3.660–3.840 µm	1000
	21[a]	3.929–3.989 µm	1000
	22	3.929–3.989 µm	1000
	23	4.020–4.080 µm	1000
Atmospheric temperature	24	4.433–4.498 µm	1000
	25	4.482–4.549 µm	1000
Cirrus clouds	26[b]	1.360–1.390 µm	1000
Water vapor	27	6.538–6.895 µm	1000
	28	7.175–7.475 µm	1000
	29	8.400–8.700 µm	1000
Ozone	30	9.580–9.880 µm	1000
Surface/cloud temperature	31	10.780–11.280 µm	1000
	32	11.770–12.270 µm	1000
Cloud top altitude	33	13.185–13.485 µm	1000
	34	13.485–13.758 µm	1000
	35	13.785–14.085 µm	1000
	36	14.085–14.385 µm	1000

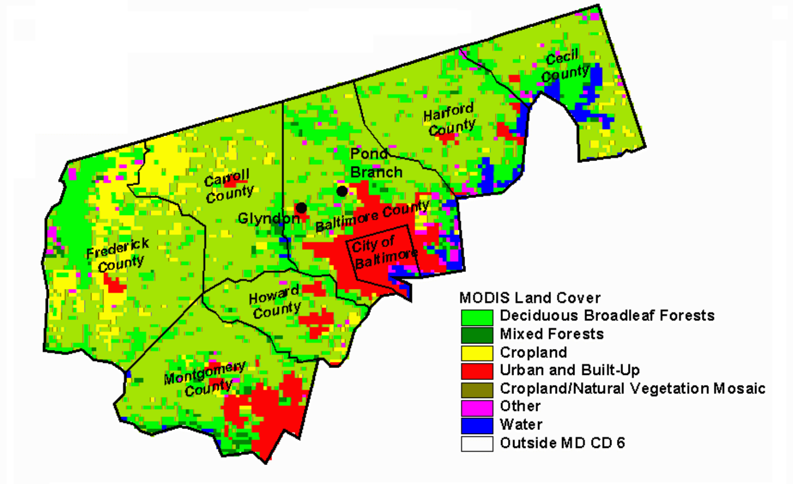
[a] Band 21 and 22 are similar, but band 21 saturates at 500 K versus 328 K.

[b] Wavelength out of sequence due to change in sensor design.

Modeling TVDI



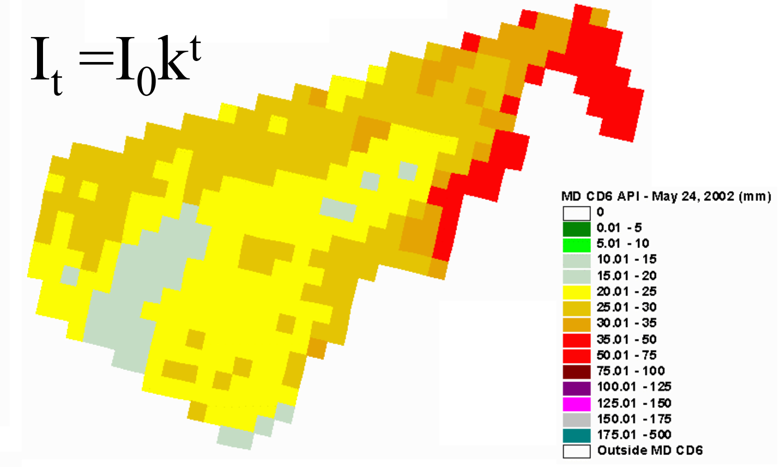
TVDI



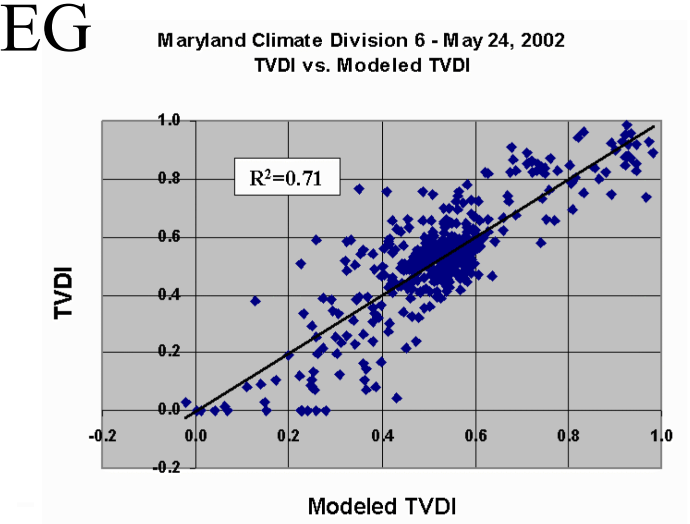
LULC

API

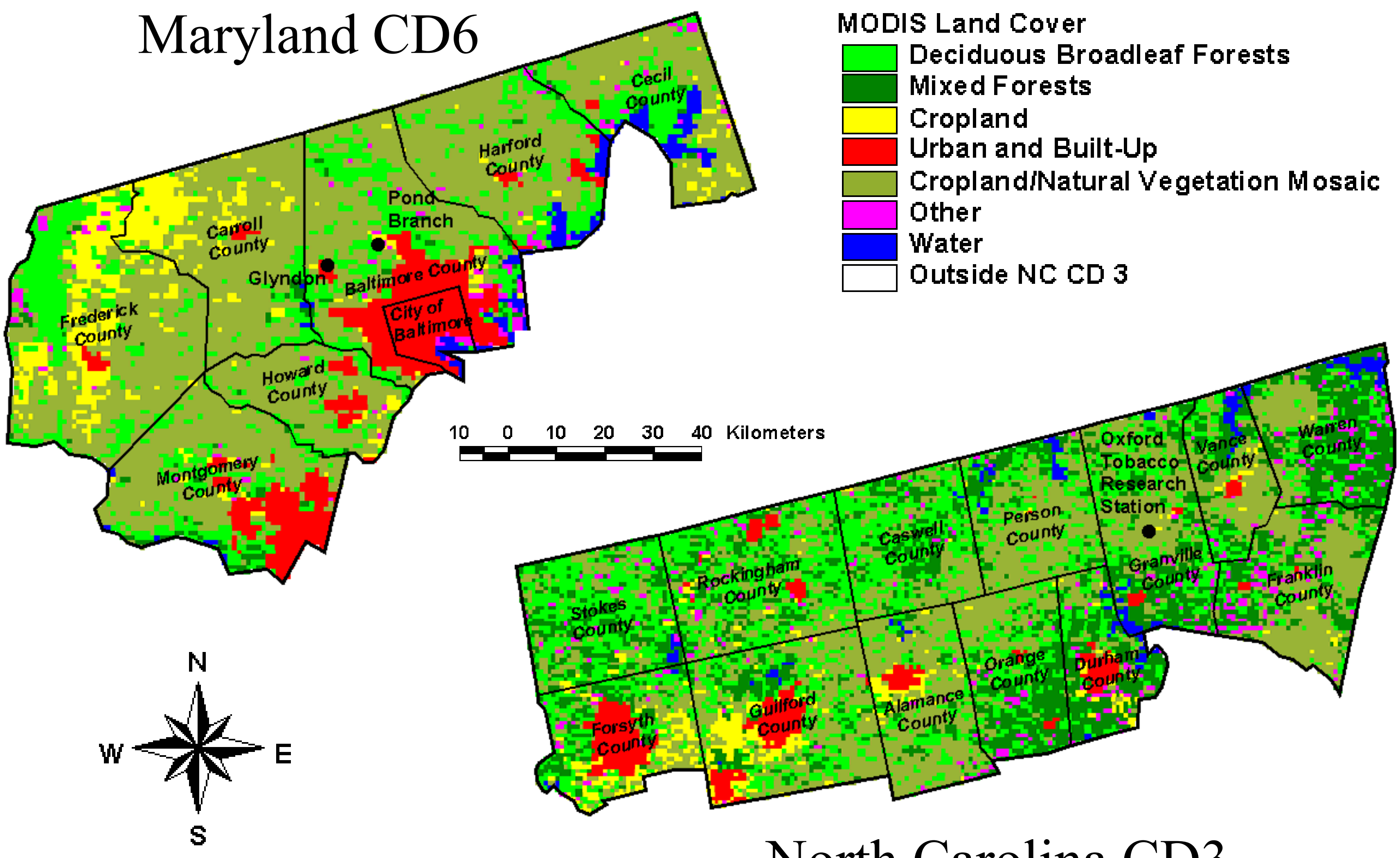
$$I_t = I_0 k^t$$



REG



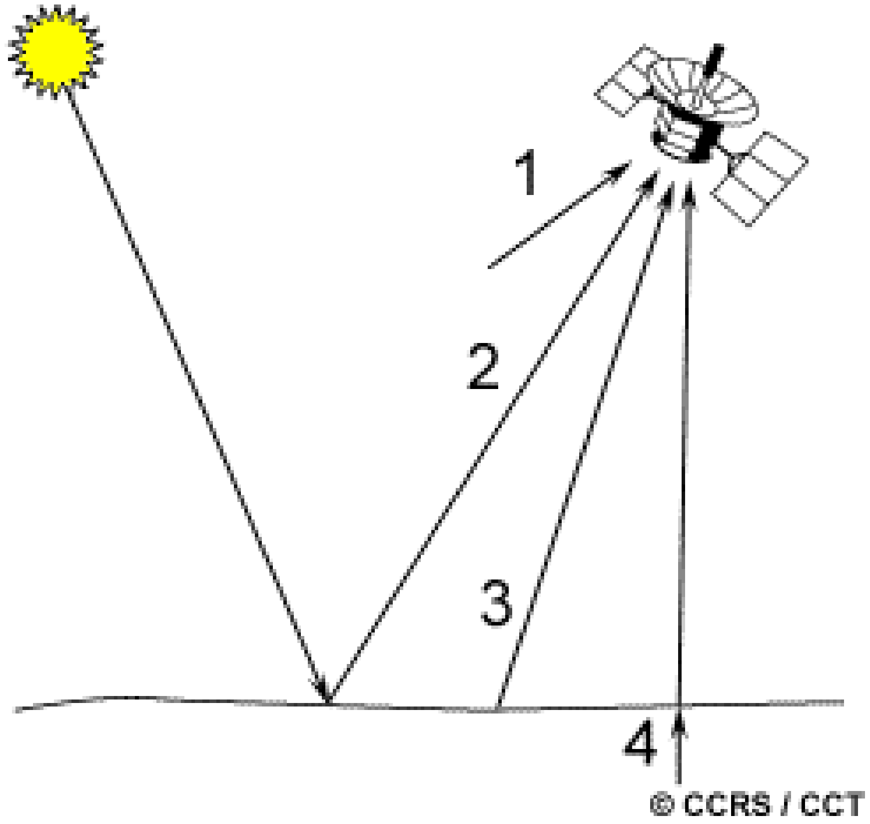
MODIS LULC In Climate Divisions

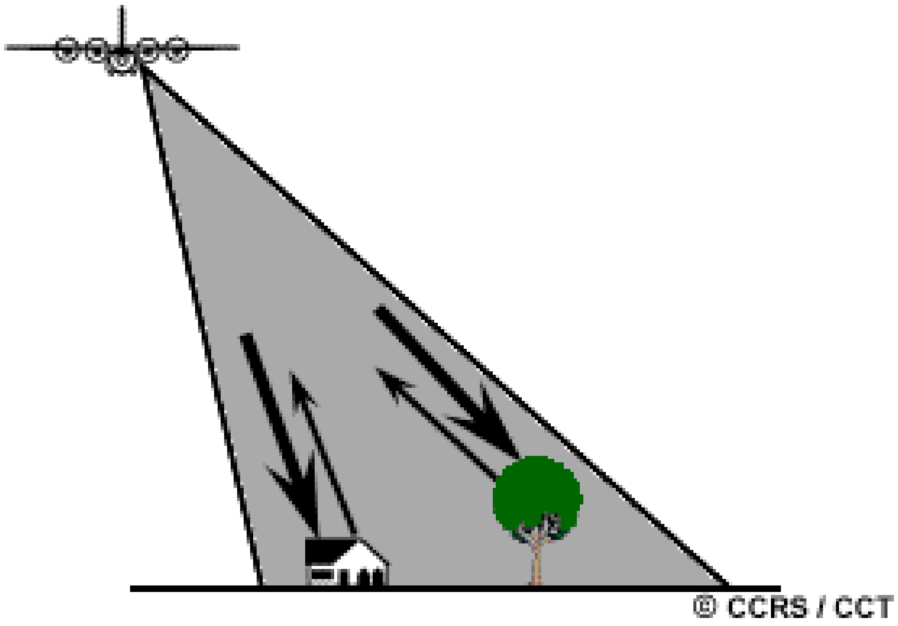


Maryland CD6

North Carolina CD3

Passive vs. Active Remote Sensing





http://www.ccrs.nrcan.gc.ca/ccrs/learn/tutorials/fundam/chapter3/chapter3_1_e.html

Passive sensors receive **solar energy reflected** by the Earth's surface (2), along with energy emitted by the atmosphere (1), surface (3) and sub-surface (4)

Active sensors receive energy reflected from the Earth's surface that originally came from an **emitter other than the Sun**

RADAR Remote Sensing

- Remote sensing using RADAR can be active or passive:
  - Some earth materials do emit radiation in the **microwave range of wavelengths** (anywhere from a millimeter to a meter), and these can be sensed by a detector that operates just as many that we have already looked at does, sensing the energy passively
  - However today we’re primarily going to look at active RADAR remote sensing, where the **source of the microwave energy** which returns to the sensor is a man-made source or emitter, and the characteristics of the emitter and sensor are both selected for the particular application (i.e. choose the wavelength and other factors based on what you want to capture in the imagery)

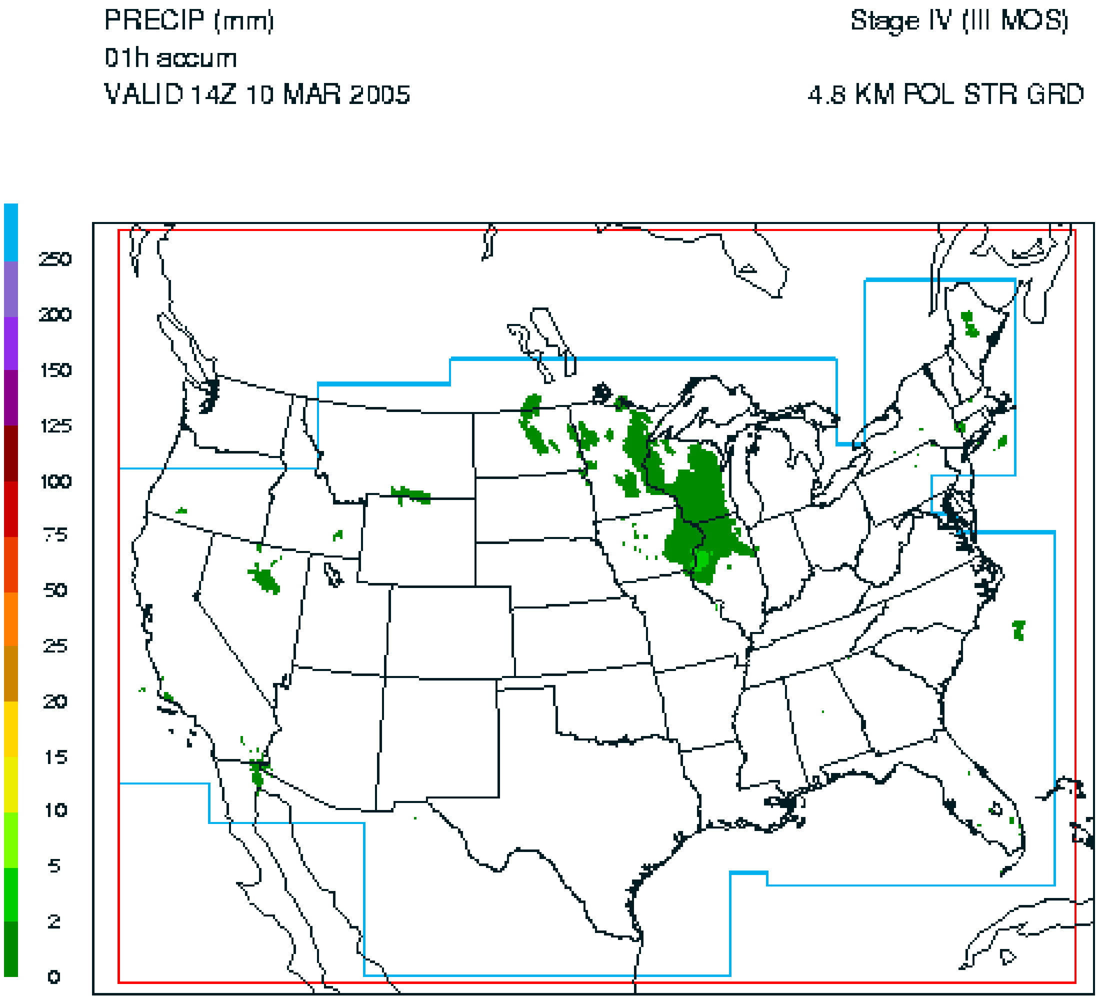
Nexrad Doppler Weather RADAR

- The **Nexrad** network of weather RADAR sensors consists of 158 radars that each have a maximum range of 250 miles that together provide excellent coverage of the continental United States

http://www.roc.noaa.gov/

The sensors are known by the designation **WSR-88D** (Weather Surveillance Radar 88 Doppler), and the station in this area is located at RDU airport is #64 - KRAX

CONUS Hourly Nexrad Rainfall



- Here is Nexrad gauge-corrected for **six one-hourly periods** for the afternoon and evening of March 10, 2005

- Note the changes in shape of the **blue bounding box**, which show that some RADARs were offline where no overlapping coverage was present, thus no information was available

http://wwwt.emc.ncep.noaa.gov/mmb/ylin/pcpanl/stage4/images/st4.6hrloop.gif

Antecedent Precipitation Index (API) from Stage IV Nexrad Data

- Successive **daily Stage IV Nexrad rainfall data** were accumulated into an antecedent precipitation index (API) for the study climate divisions for the study period

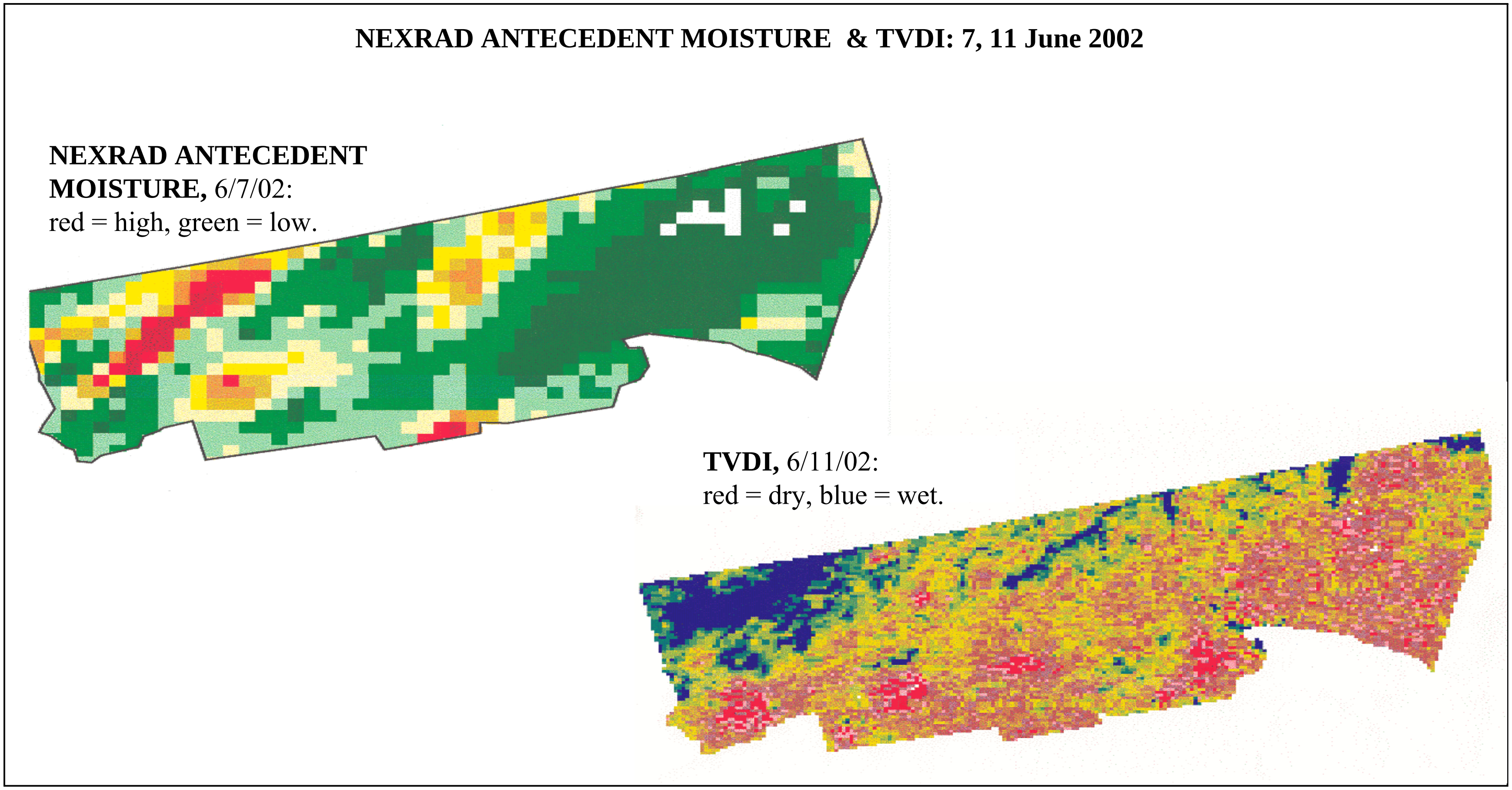
- The **API** is of the form $I_t = I_0 k^t$ where I_0 is an initialization value, and k is a decay constant (0.9 is a typical value from Dunne & Leopold)

  - For example, assume I_0 = 5 mm and k = 0.9
  - On t = 0, I_t = 5 mm * (0.9^0) = 5 mm
  - On t = 1 it rains 1.5 mm, I_t = 5 mm * (0.9^1) + 1.5 mm

    = (5 mm * 0.9) + 1.5 mm

    = 4.5 mm + 1.5 mm = 6 mm
  - On t = 2 it does not rain, I_t = 6 mm * (0.9^1) = 5.4 mm

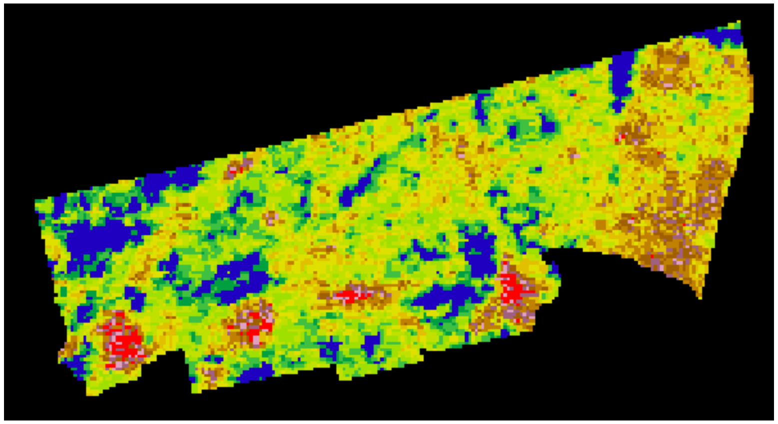
Antecedent Moisture from NEXRAD



NEXRAD ANTECEDENT MOISTURE & TVDI: 7, 11 June 2002

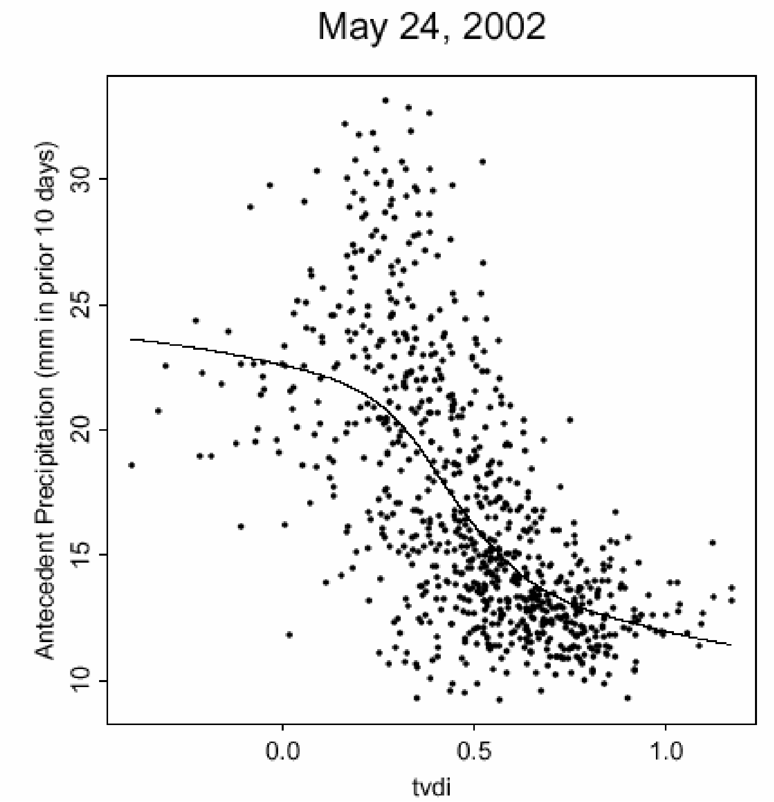
NEXRAD ANTECEDENT MOISTURE, 6/7/02:
red = high, green = low.

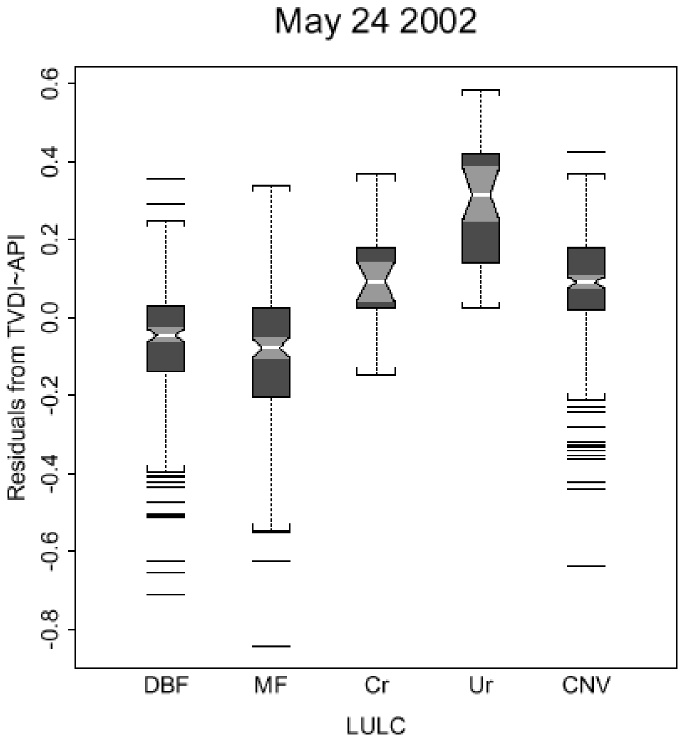
TVDI, 6/11/02:
red = dry, blue = wet.



Significant explanation of residuals of plot based on land use/land cover

TVDI variation with API

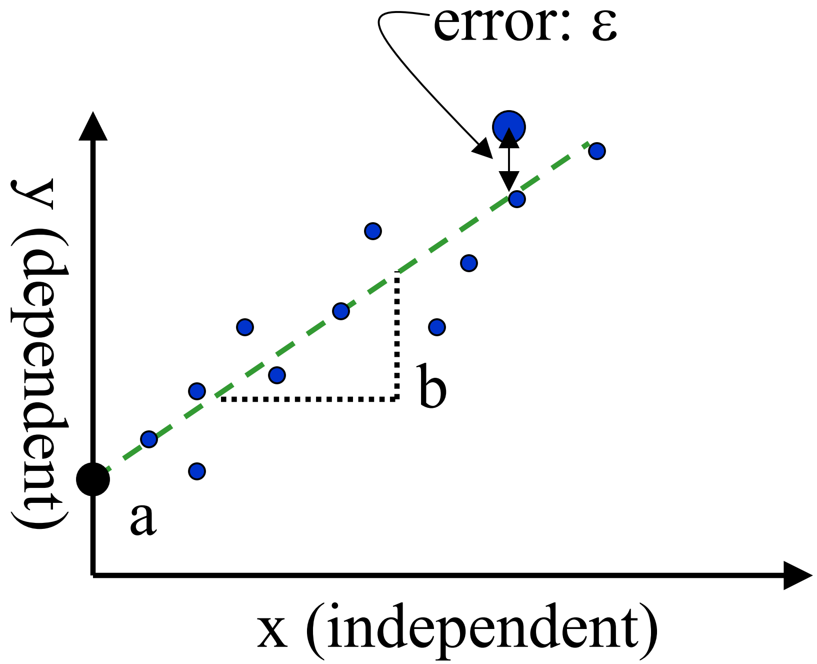




Simple Linear Regression

- **Simple linear regression** models the relationship between an independent variable (x) and a dependent variable (y) using an equation that expresses y as a linear function of x, plus an error term:

$$y = a + bx + e$$



x is the **independent** variable

y is the **dependent** variable

b is the **slope** of the fitted line

a is the **intercept** of the fitted line

e is the **error** term

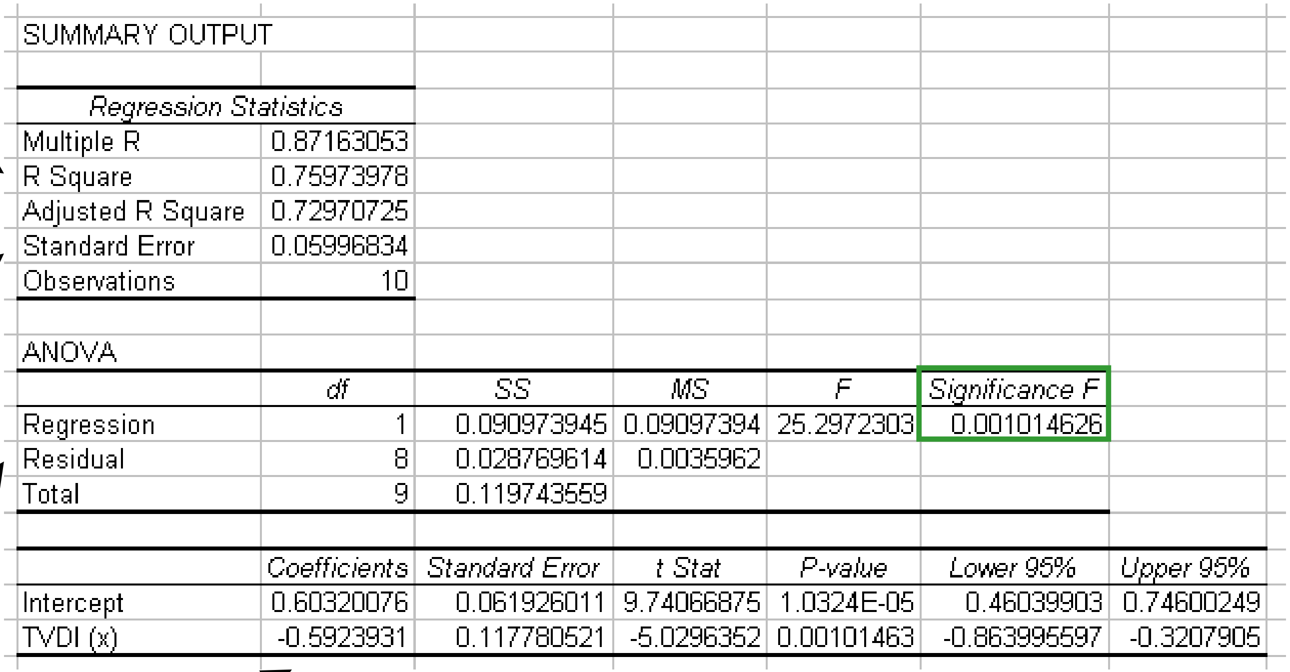
Regression Analysis Tool

- The **basic output** the tool produces includes:

The coefficient of determination (r^2)

The standard error of the estimate (e.g. the standard deviation of the residuals), s_e

An ANOVA table, including the minimum α where F would be **significant**



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.87163053
R Square	0.75973978
Adjusted R Square	0.72970725
Standard Error	0.05996834
Observations	10

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.090973945	0.09097394	25.2972303	0.001014626
Residual	8	0.028769614	0.0035962		
Total	9	0.119743559			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.60320076	0.061926011	9.74066875	1.0324E-05	0.46039903	0.74600249
TVDI (x)	-0.5923931	0.117780521	-5.0296352	0.00101463	-0.863995597	-0.3207905

The regression coefficients produced by the least squares optimization (in the simple case, like this one, the intercept and the slope)

The standard error associated with each parameter (e.g. for the regression slope parameter, this is s_b, the standard deviation of the slope)

The t-statistic and the minimum α where each parameter would be significant