Land-Atmosphere Interactions and Parameter Relevance

PREFER – Feb. 11 2022

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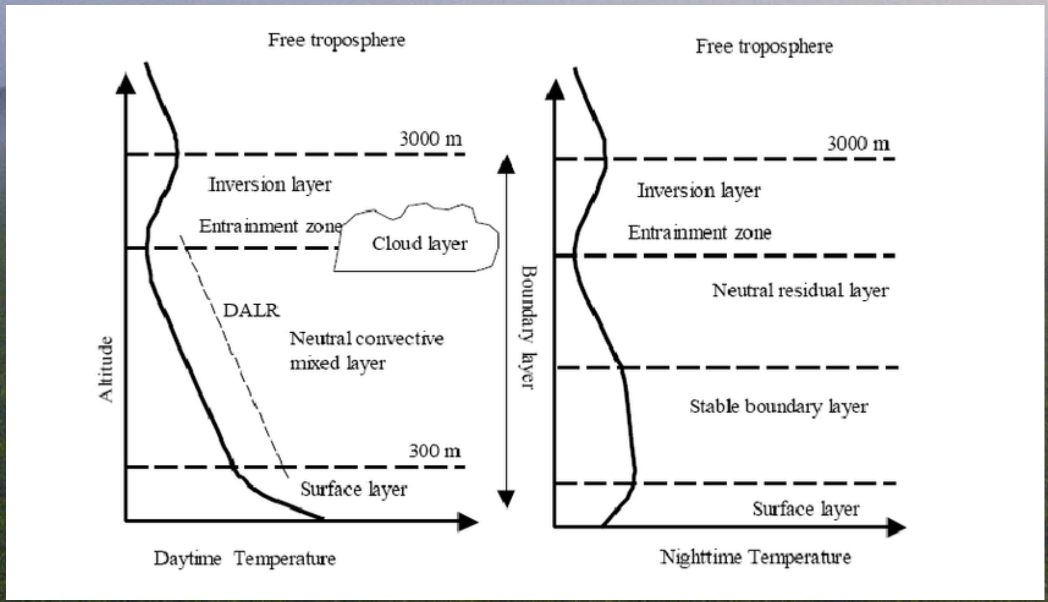
What are Nocturnal Inversions

- Nocturnal thermal inversions occur after sunset when the land surface cools the lowest layer of the atmosphere (~0-100 meters) more rapidly than the air above it.
- As a result, the densest air lies near the surface and is very stable. Air is unable to mix vertically.



Why Nocturnal Inversions are Important

Farming/Ag.

- Drift
- Frost
- Animal Emissions

Transportation

- Aviation
- Road/Water Safety

Public Health

- Respiratory Health
- Severe Weather

Turbulence

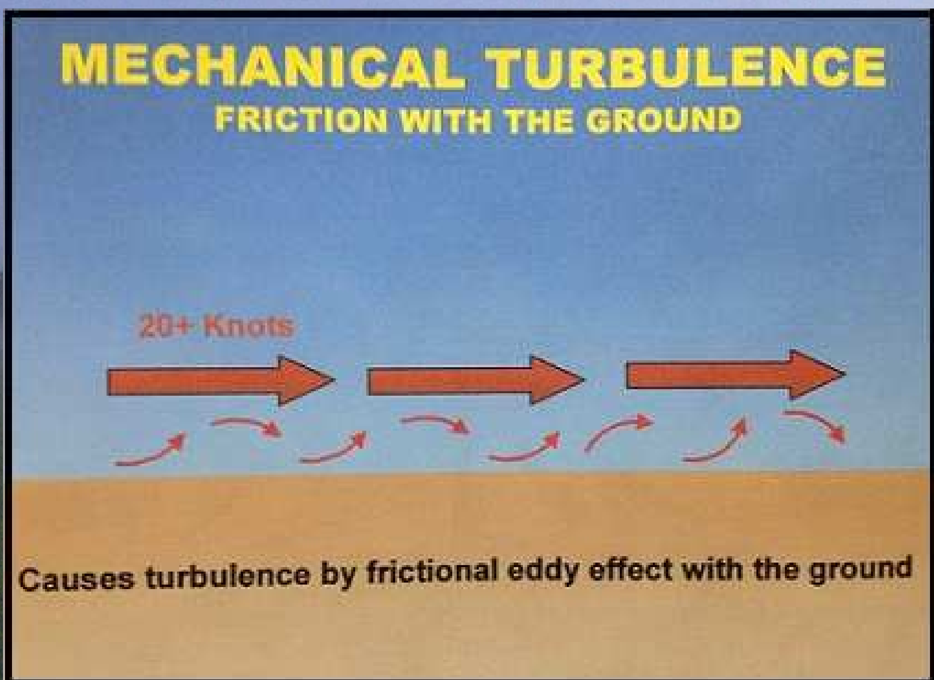
- The collapse of turbulent kinetic energy, $\frac{1}{2}(\overline{u'u'} + \overline{v'v'} + \overline{w'w'})$, is a sure sign of a transition from a mixed to a stable boundary layer that occurs during inversion onset.

- Two major contributors to the TKE budget are buoyancy and shear production/destruction

$$Shear = -\overline{u'w'}\frac{d\bar{u}}{dz} - \overline{v'w'}\frac{d\bar{v}}{dz}$$

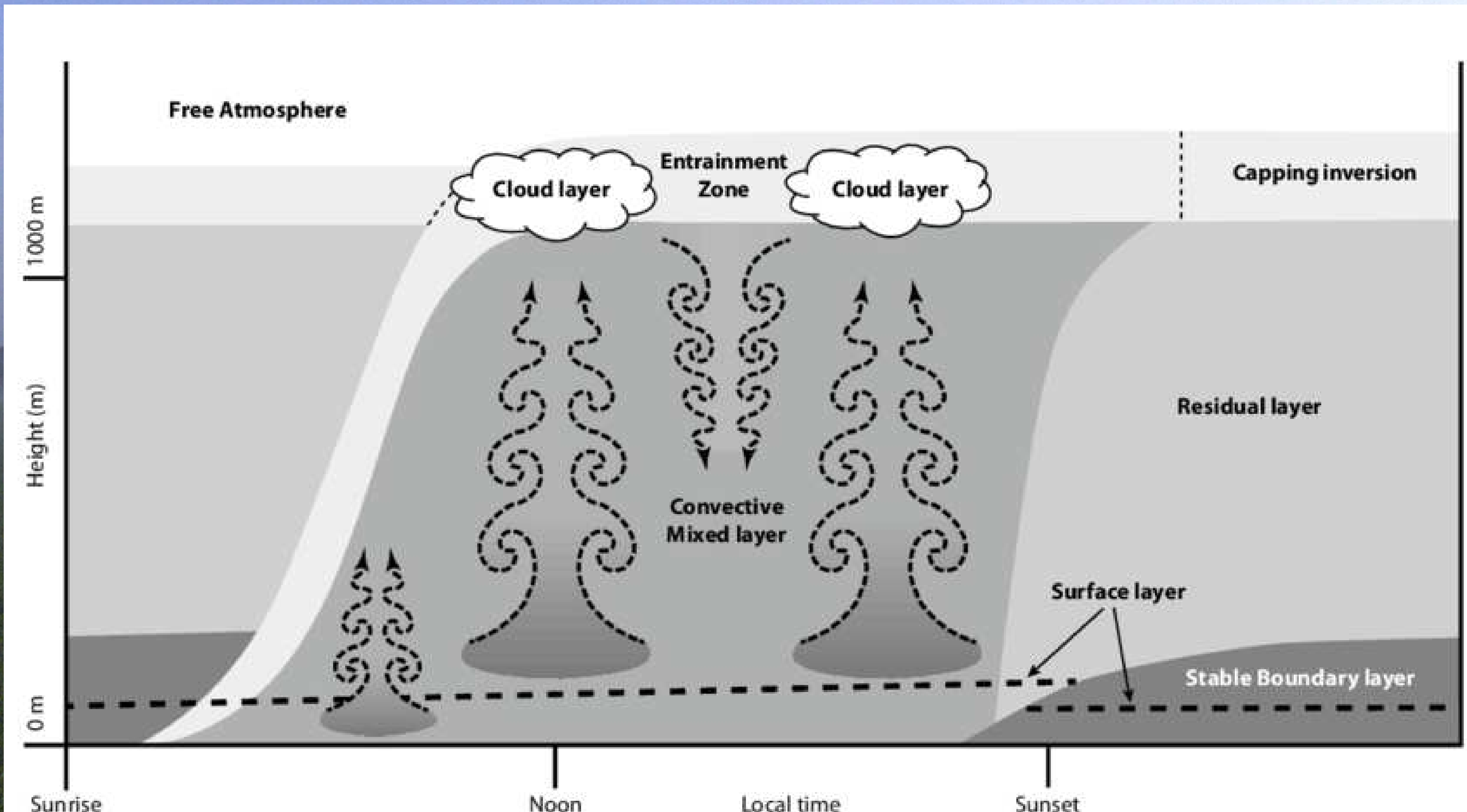
$$Buoyancy = g\left(\frac{\overline{w'T'}}{\bar{T}} + 0.61\overline{w'q_v}\right)$$

Mechanical Turbulence

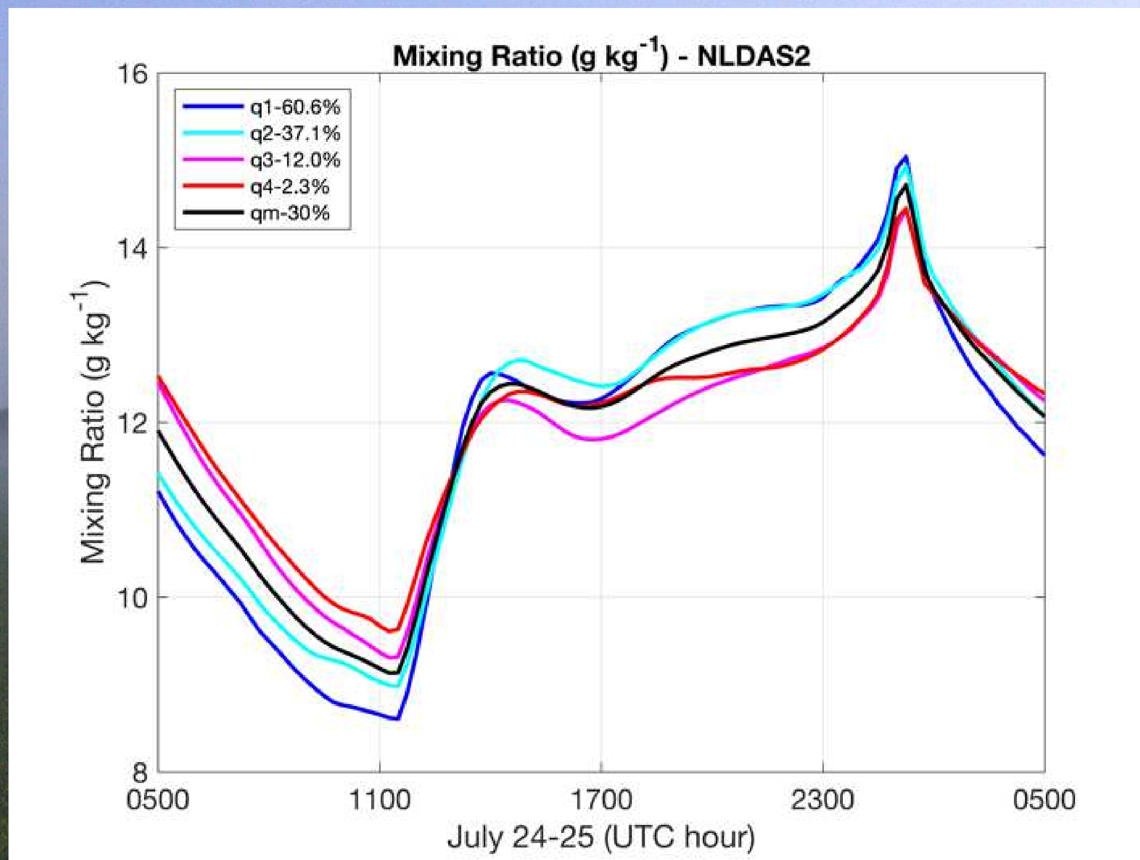


Buoyancy

The Atmospheric Boundary Layer



Thermal Coupling: Convective Initiation



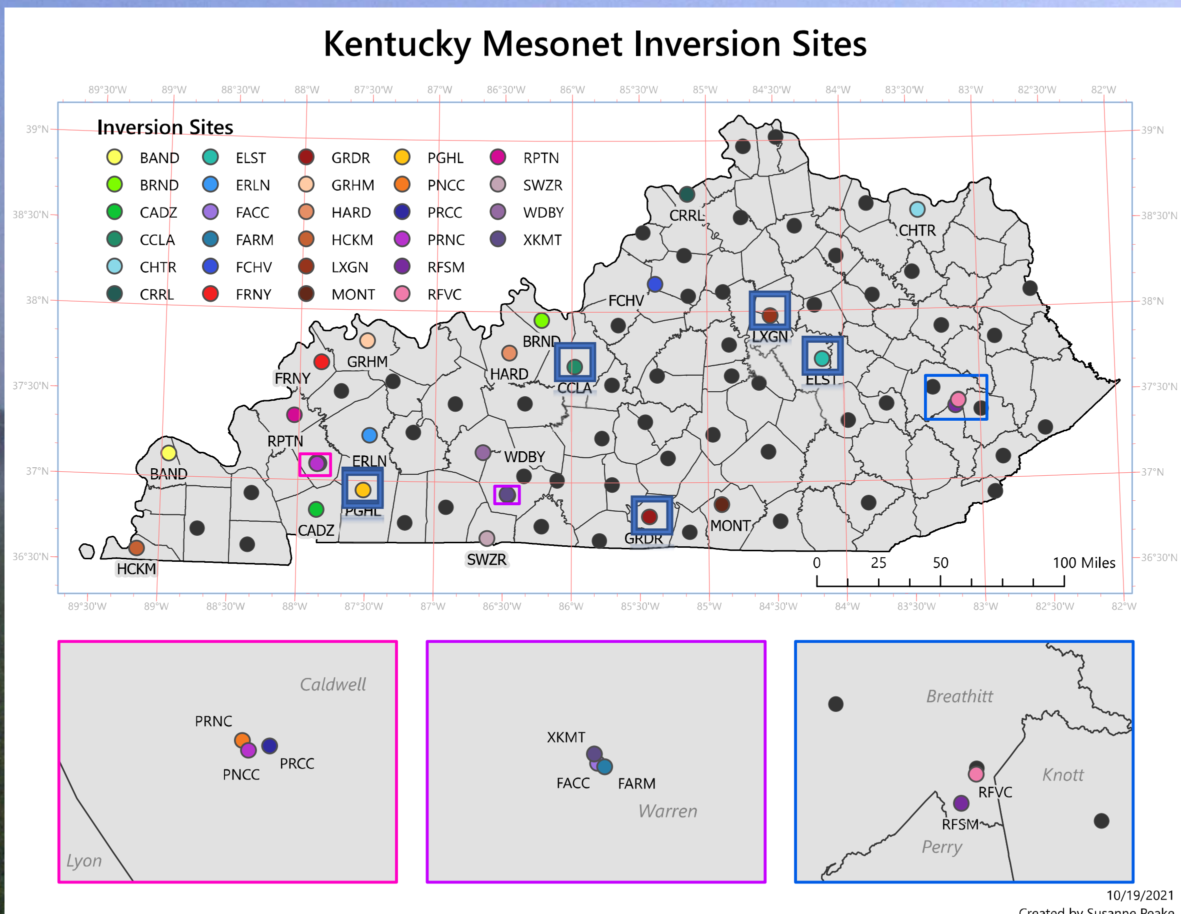
Nocturnal Inversion Formation

- Inversion formation is a micrometeorological phenomenon
- Micrometeorological in the sense that turbulent fluxes dictate many aspects of the inversion behavior:
  - Development: flip in the sign of the turbulent heat flux
  - Deepening and Maintenance: Surface radiative flux divergence in the absence of turbulent mixing.
  - Decay: Surface latent and sensible heat flux ability to warm and moisten the surface layer and grow to the remnant residual layer. *Inversion depth and free tropospheric stability are keys*

- The above factors are dependent on the local heterogeneity:
  - Land use / land cover (e.g. roughness length, albedo, evapotranspiration)
  - Terrain / relative elevation (e.g. basin, valley, ridge, etc.)

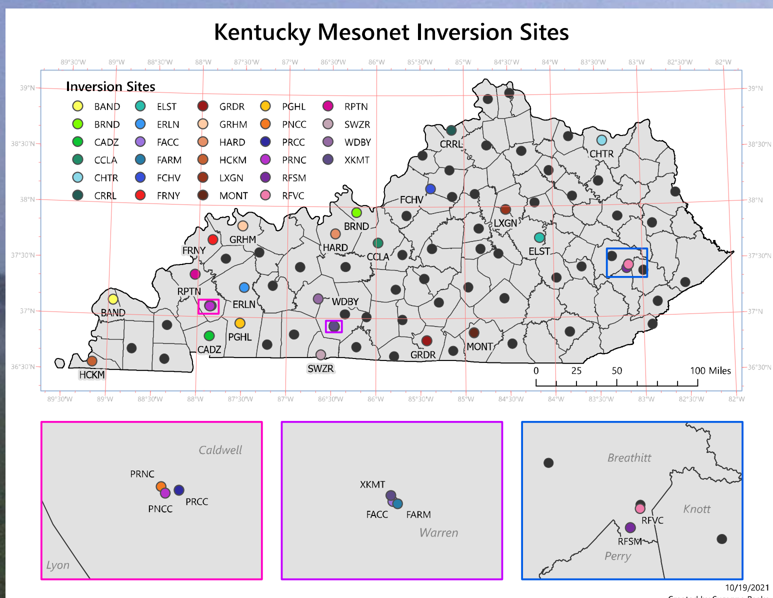
- Local in that the footprint is localized to the observation site. The footprint does not extend upwind or downwind significantly due to the weak winds and low moisture content in fair weather conditions frequent in inversion formation.

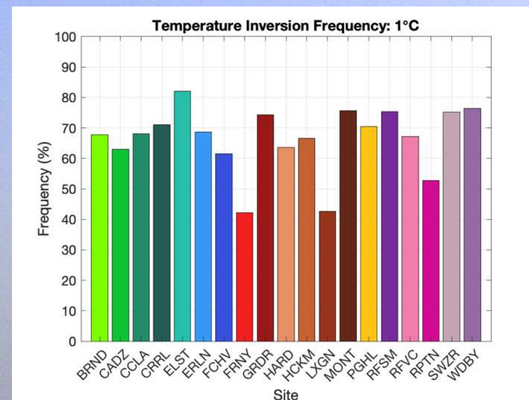
Kentucky Mesonet Sites

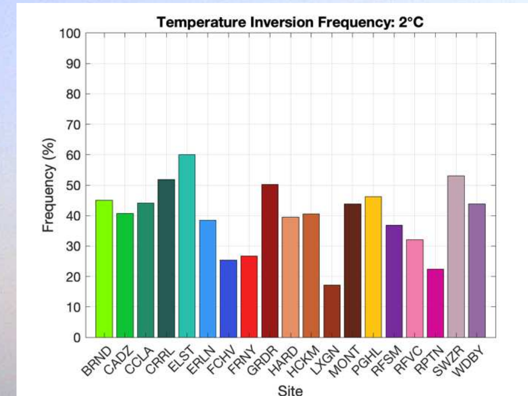


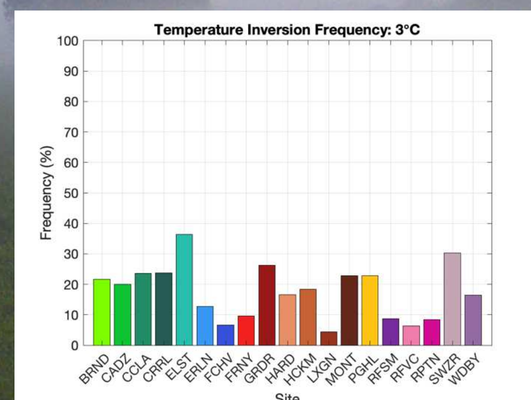
- An inversion is defined when the following conditions are met:
  - INV_f - Inversion formation: $T_9 > T_2$
  - INV_d - Inversion duration: $INV_f >= 1$ hour
  - INV_t - Inversion threshold: $T_9 > T_2$ by a set temperature threshold at any time from sunset to sunrise

Kentucky Mesonet Inversion Observations



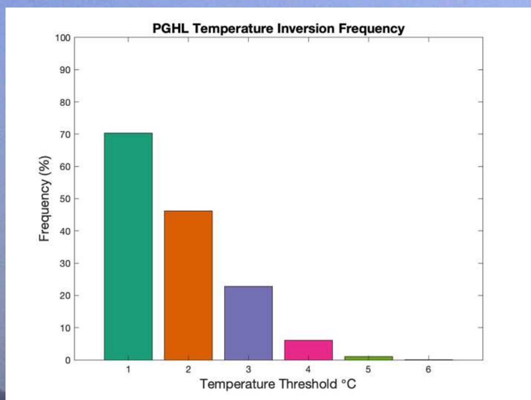




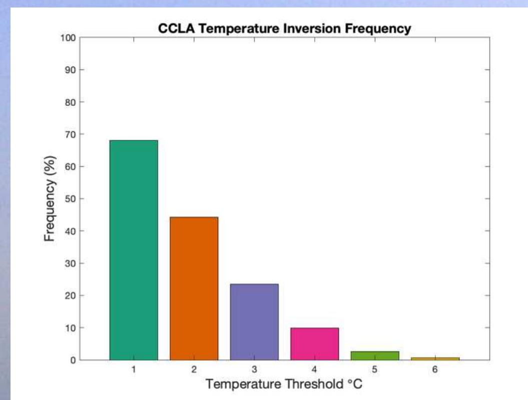


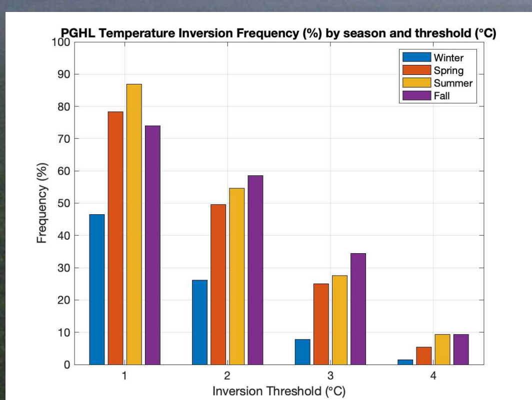
PGHL vs. CCLA

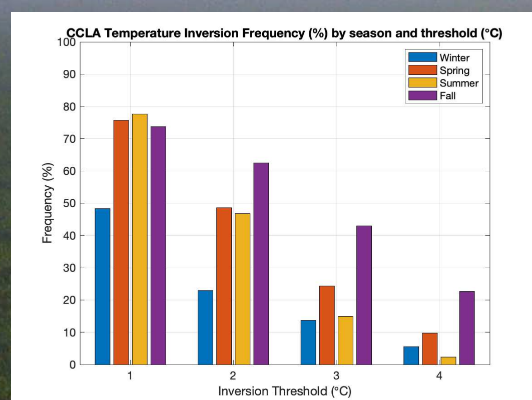
PGHL



CCLA



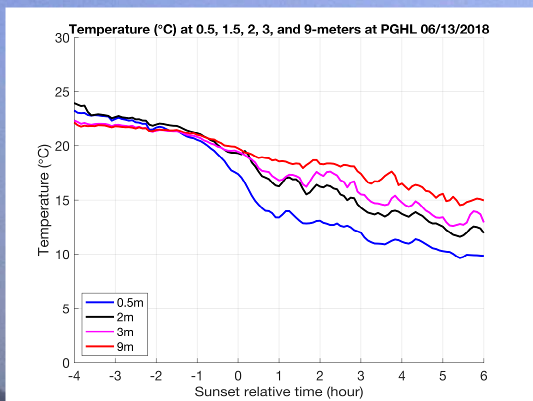


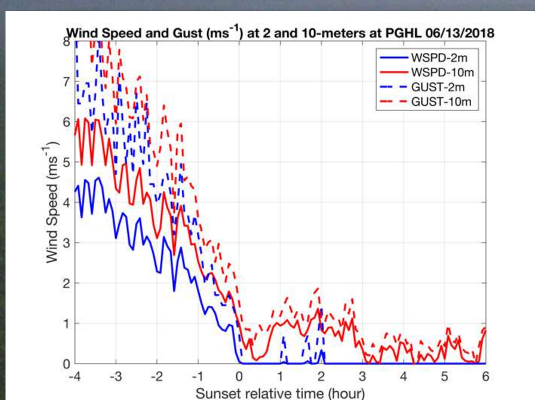


- While the NTI frequencies as a function of the threshold temperature are similar, the seasonal variations show slight differences. While the winter, spring, and summer show similar frequencies, the fall shows significant differences, This may be a result of CCLA having a higher latitude and longer nights this time of year, but it is an ongoing avenue of research

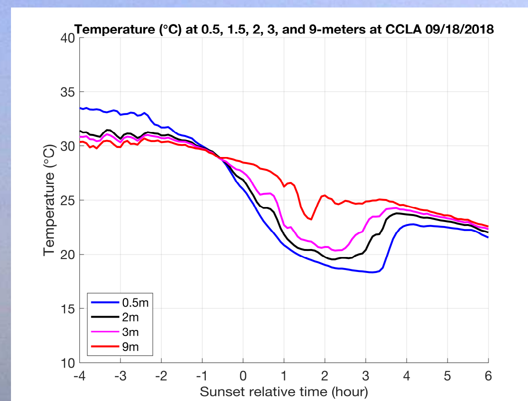
PGHL vs. CCLA

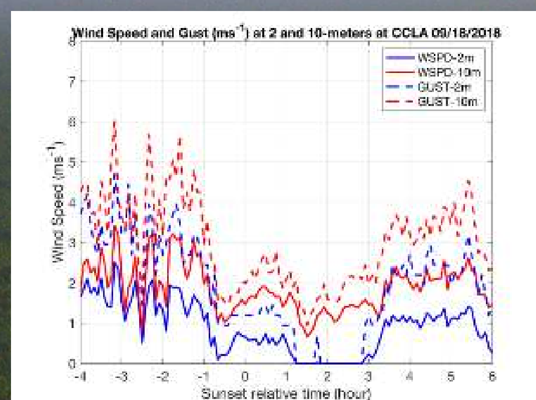
PGHL





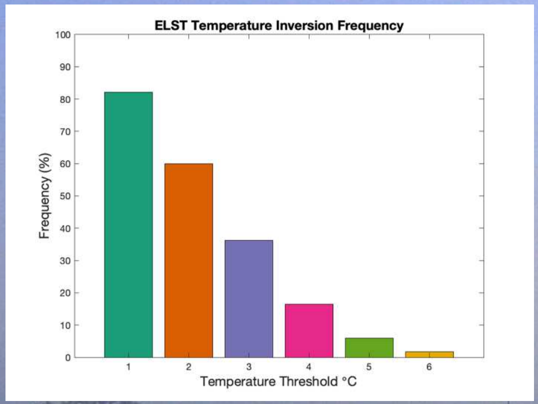
CCLA

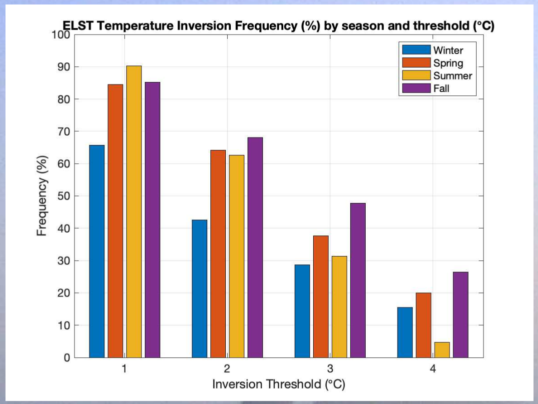


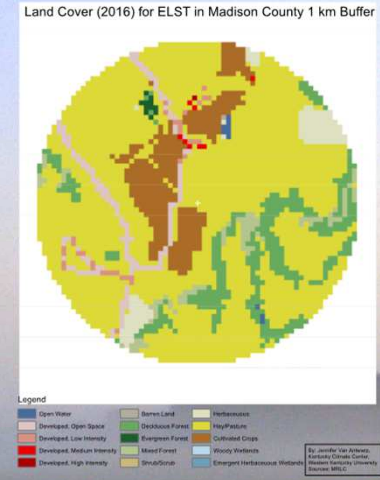


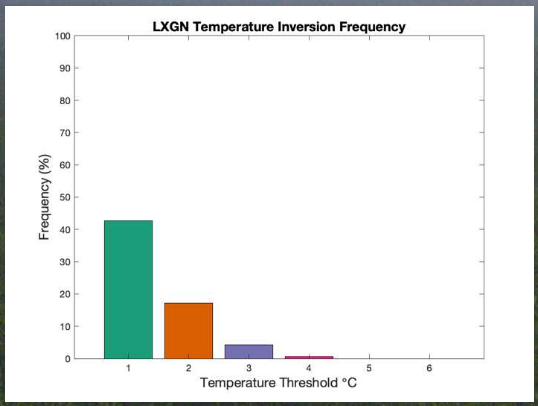
- Both sites show classic NTI development with two slow cooling phases sandwiched between a rapid cooling phase that last from roughly an hour before to an hour after sunset.
- Both sites show a 5-7 °C temperature difference between 0.5 m and 9 m and a strong deceleration of the winds during rapid cooling.
- While drainage flow could be part of the contribution to the cooling at PGHL, the NW winds suggest fair weather associated with high pressure is a leading contributor to NTI formation.
- CCLA, an event that occurred in the middle of a flash drought (dry soil) displays a very strong NTI with a 10 °C temperature drop in the rapid cooling phase!
- With winds out of the NE, the flow passes through the patch of trees which may act to generate turbulence and yield the wind increase and decay of the NTI 3 hours after sunset. This is unclear as it could be a transitory atmospheric phenomenon that weakens the NTI.

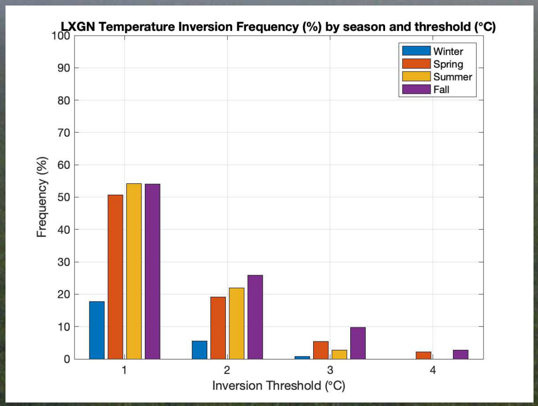
ELST vs. LXGN

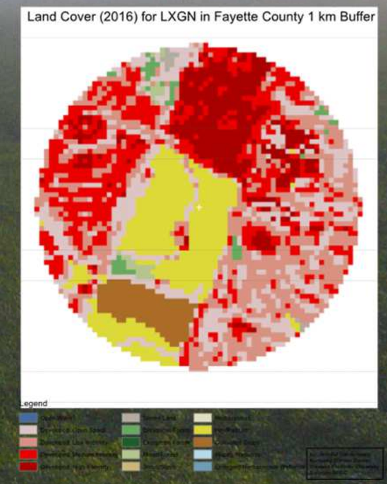

ELST Temperature Inversion Frequency
Frequency (%)
Temperature Threshold °C


ELST Temperature Inversion Frequency (%) by season and threshold (°C)
Winter
Spring
Summer
Fall
Frequency (%)
Inversion Threshold (°C)


Land Cover (2016) for ELST in Madison County 1 km Buffer
Legend
Open Water
Developed, Open Space
Developed, Low Intensity
Developed, Medium Intensity
Developed, High Intensity
Barren Land
Deciduous Forest
Evergreen Forest
Mixed Forest
Shrub/Scrub
Herbaceuous
Hay/Pasture
Cultivated Crops
Woody Wetlands
Emergent Herbaceuous Wetlands

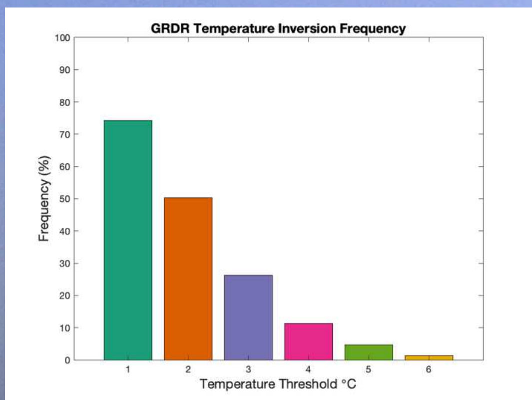

LXGN Temperature Inversion Frequency
Frequency (%)
Temperature Threshold °C

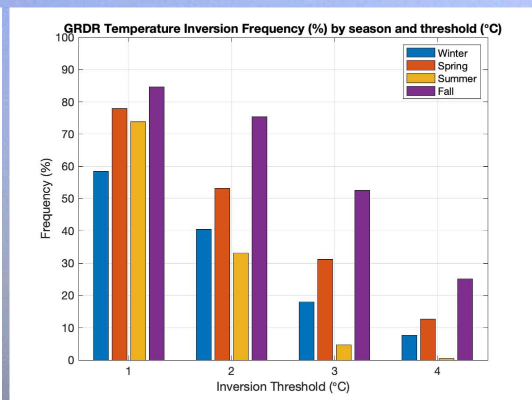

LXGN Temperature Inversion Frequency (%) by season and threshold (°C)
Winter
Spring
Summer
Fall
Frequency (%)
Inversion Threshold (°C)

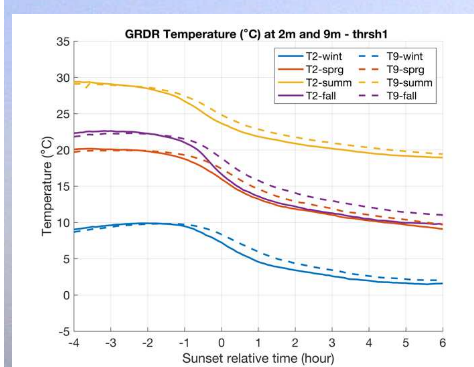

Land Cover (2016) for LXGN in Fayette County 1 km Buffer
Legend

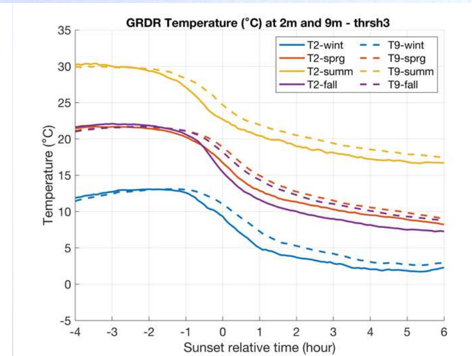
GRDR

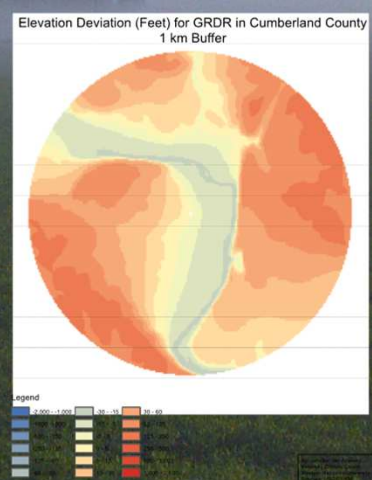
Composites

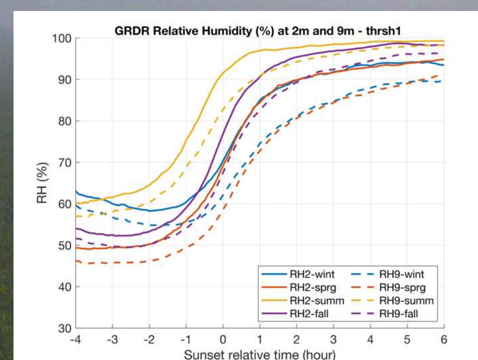


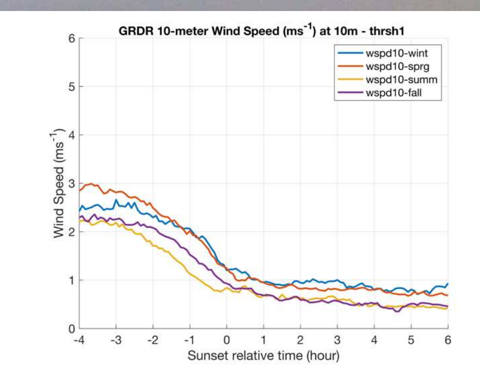




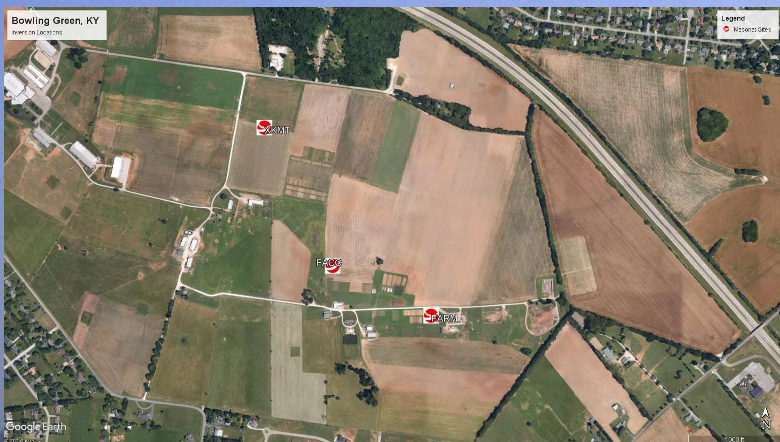


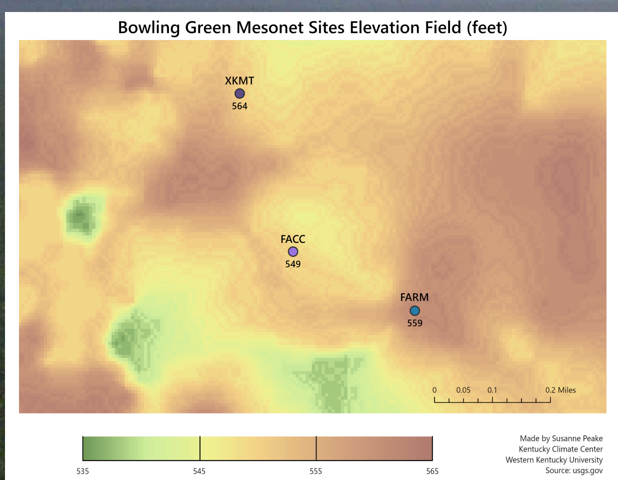


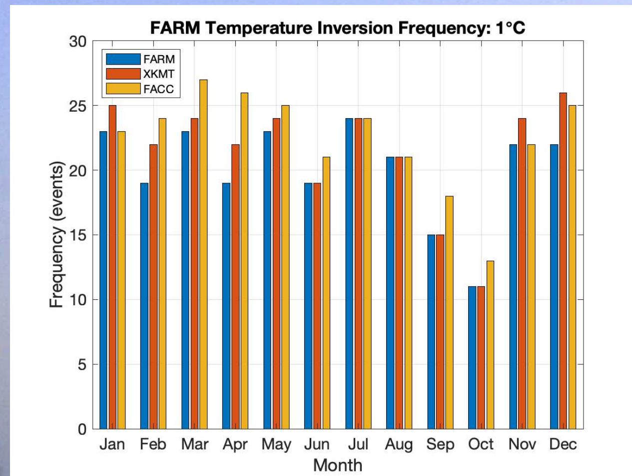


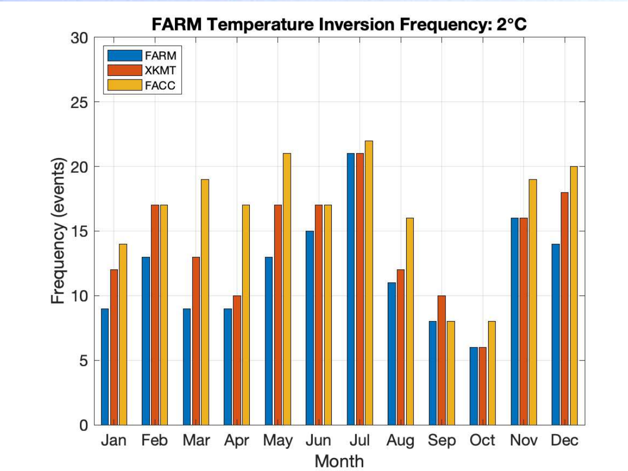


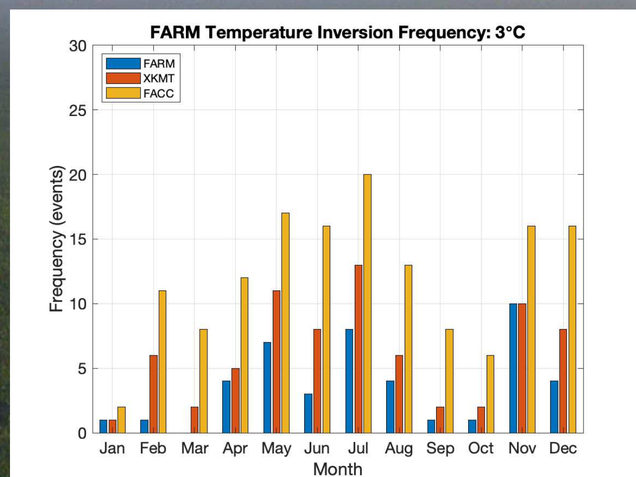
WKU Farm – Microscale Nature of Inversions

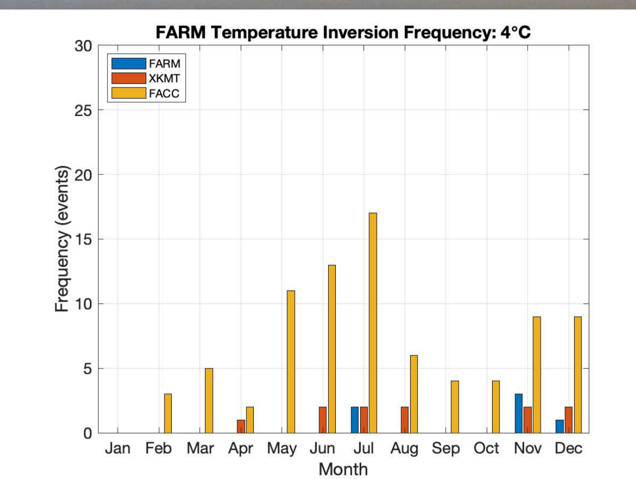






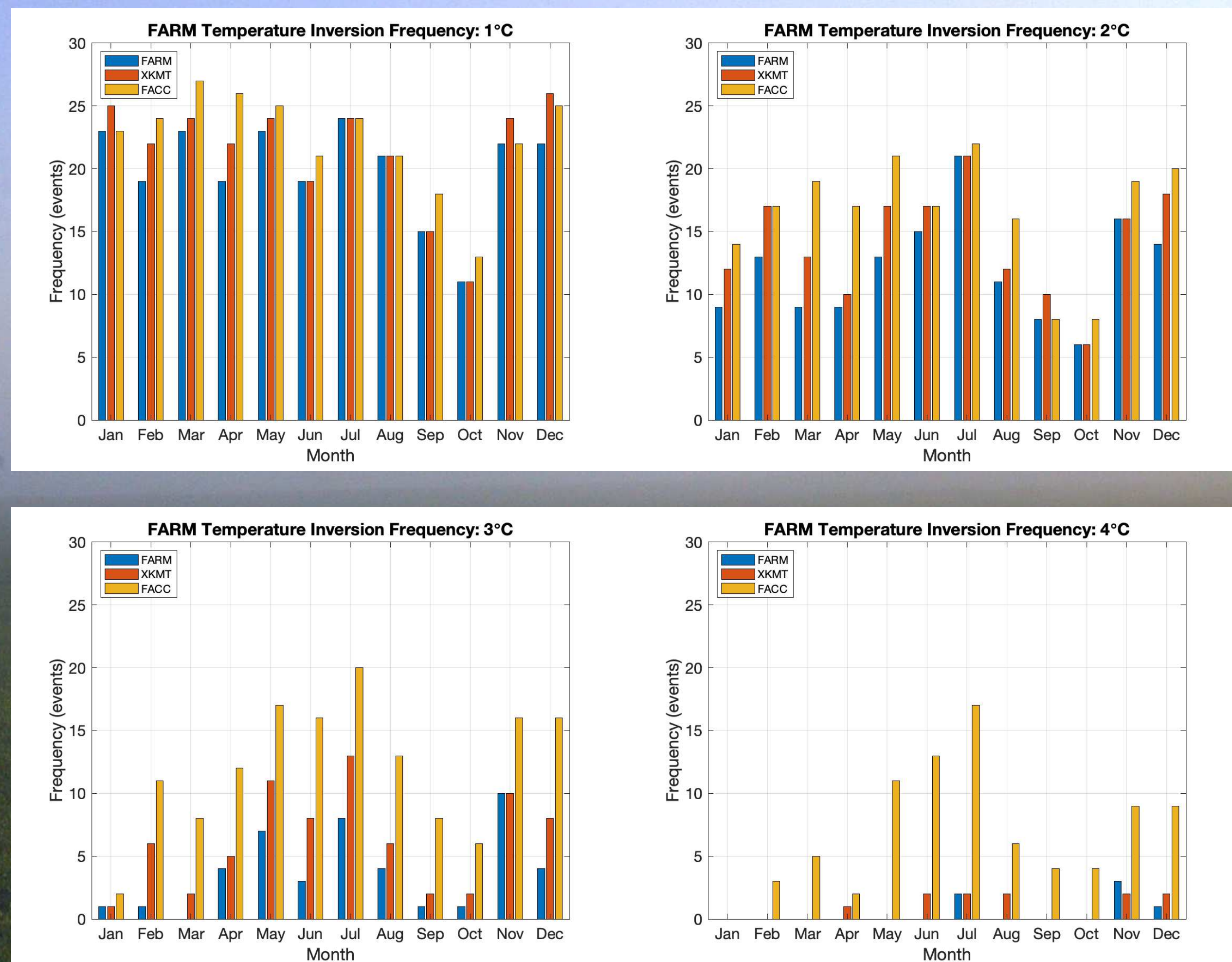




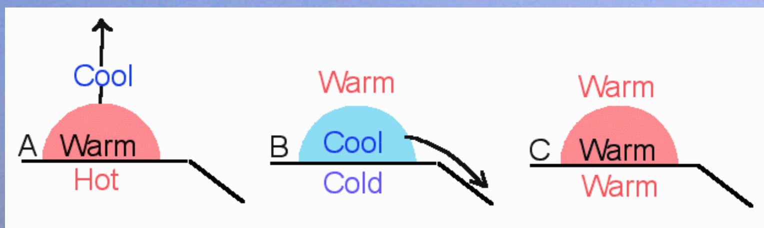


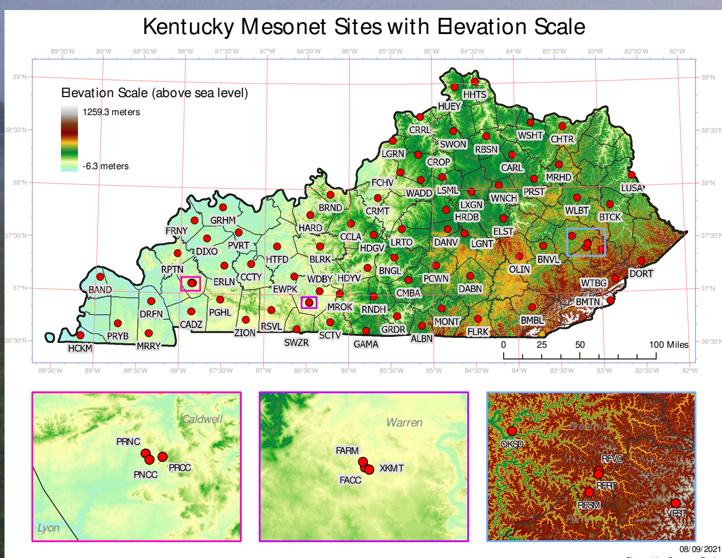
WKU Farm – Microscale Nature of Inversions

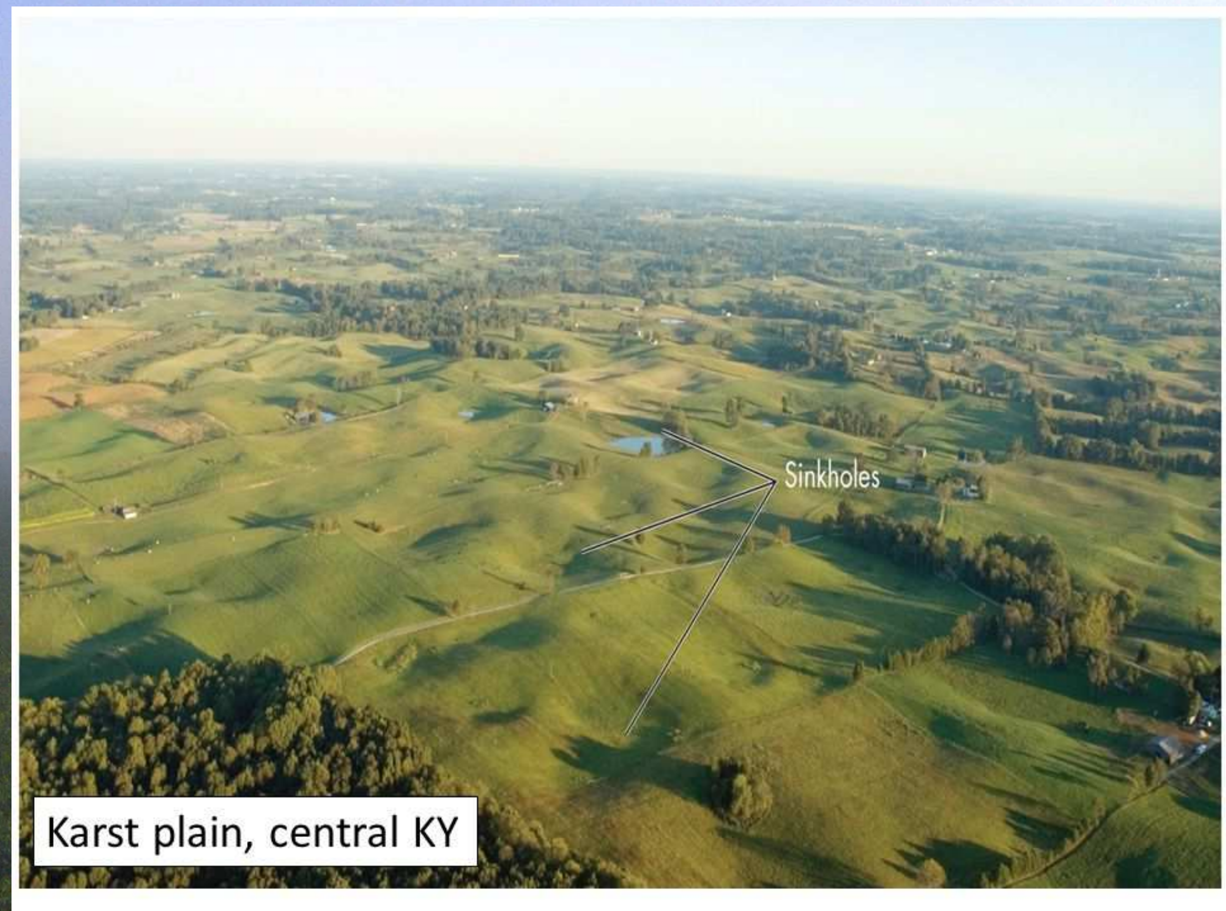
	FARM (170.4m)	XKRT (171.0m)	FACC (167.3m)
1°C	66%	71%	74%
2°C	40%	46%	54%
3°C	12%	20%	40%
4°C	2%	3%	23%



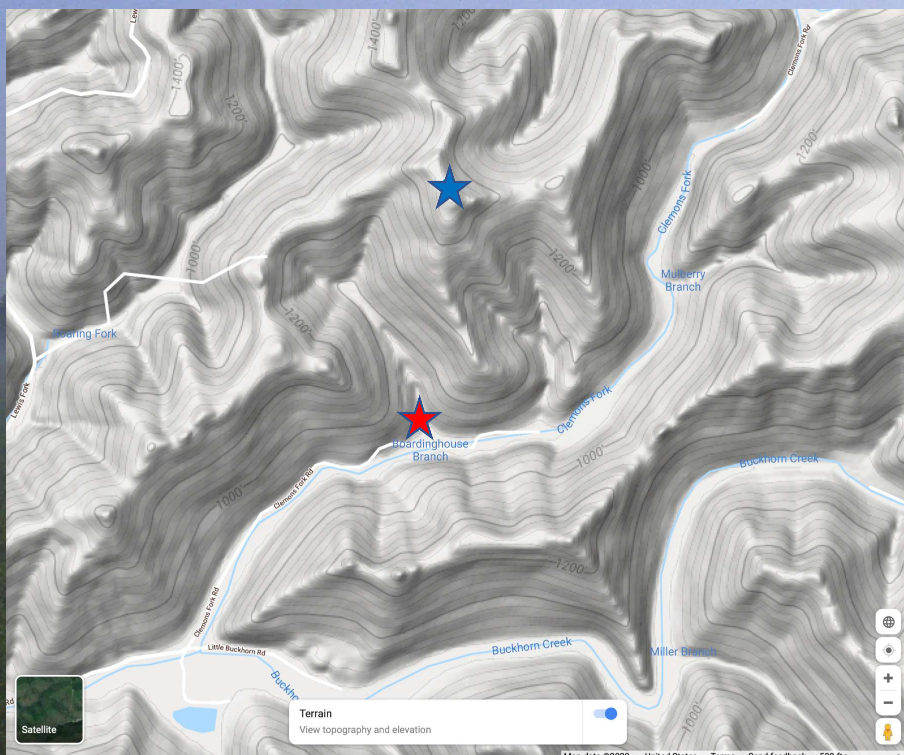
Cold Pool Development

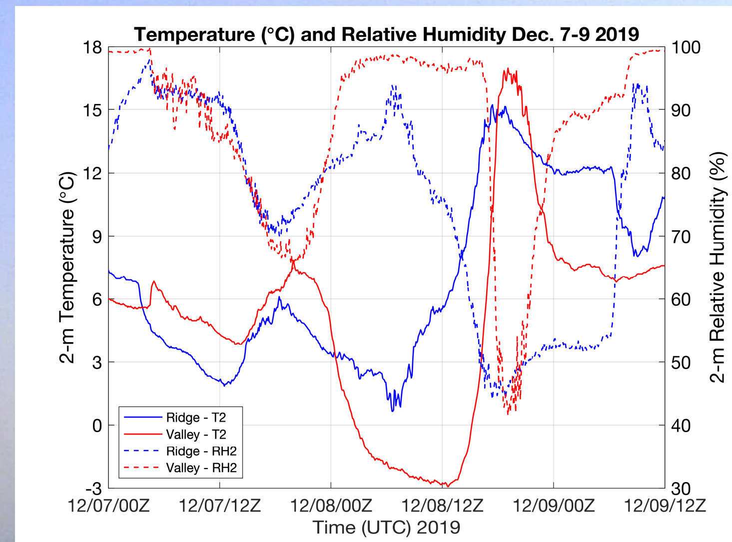


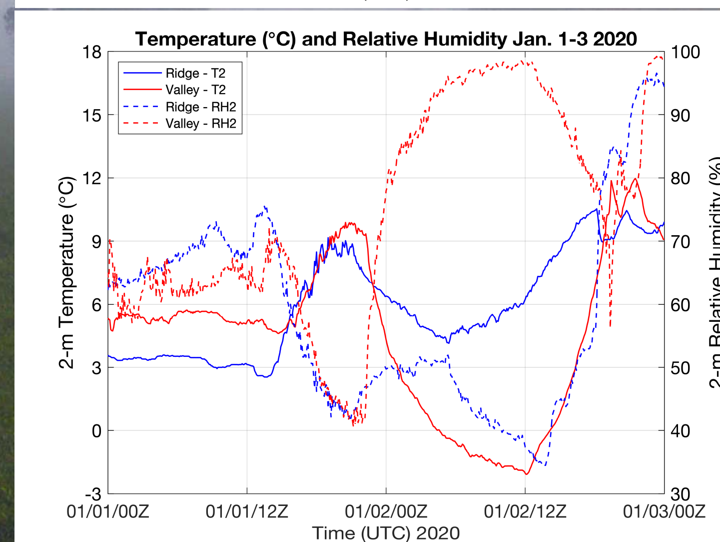




Cold Air Drainage

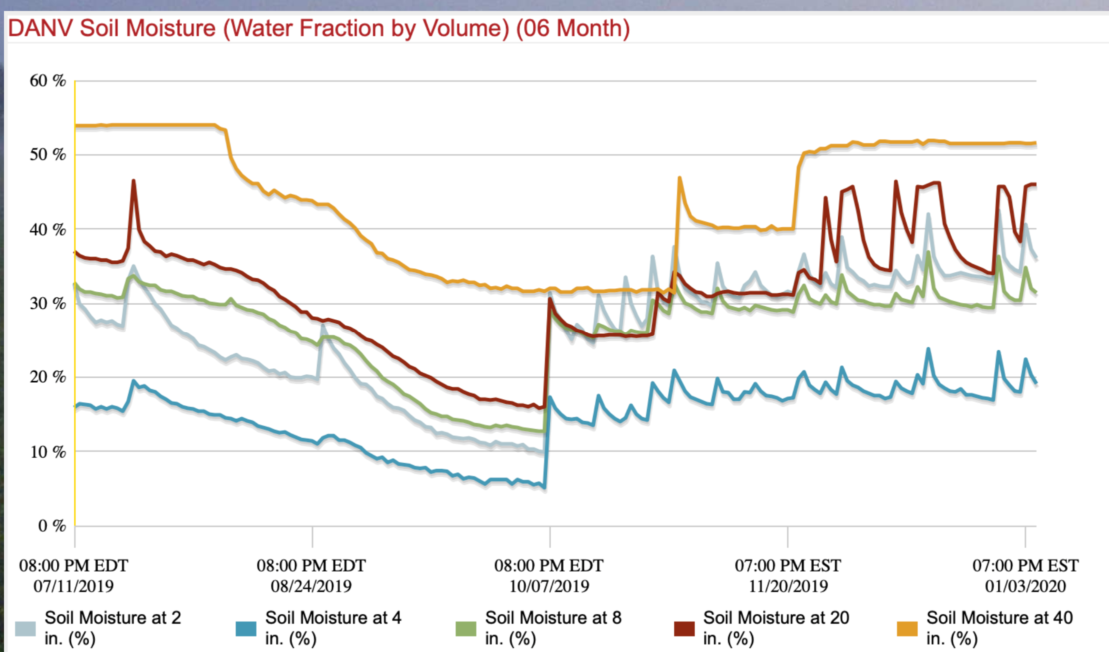


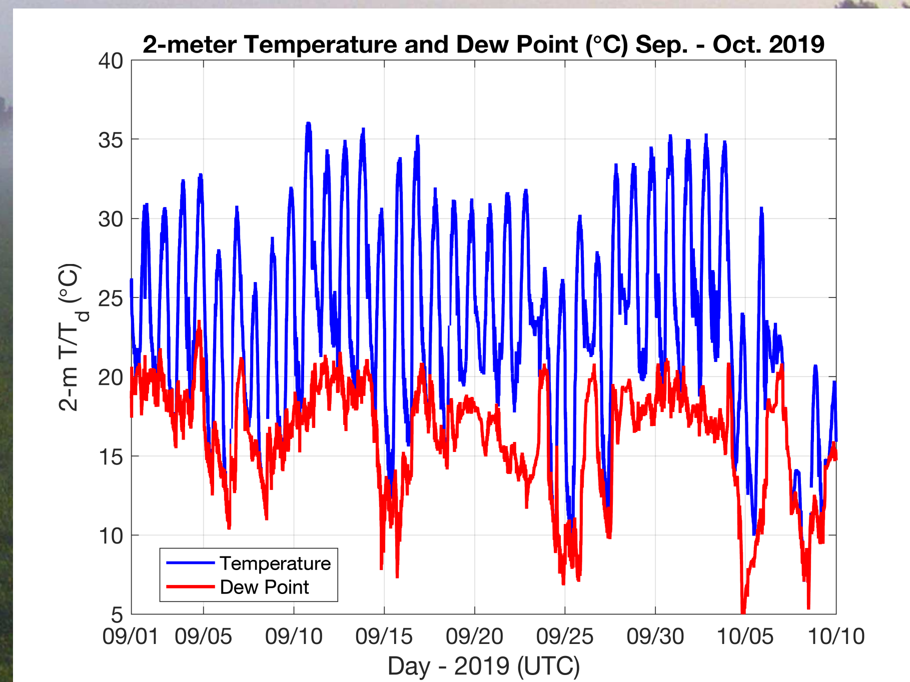




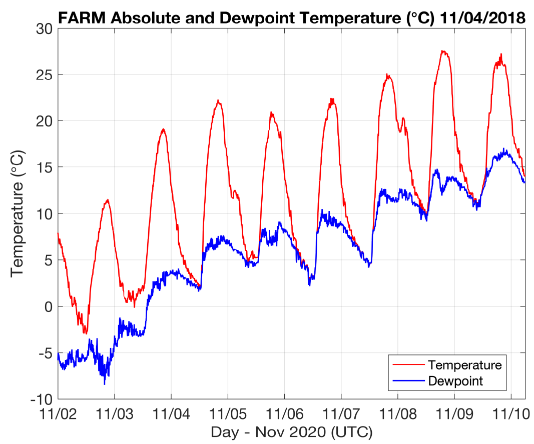
Land-Atmosphere Coupling: Drought

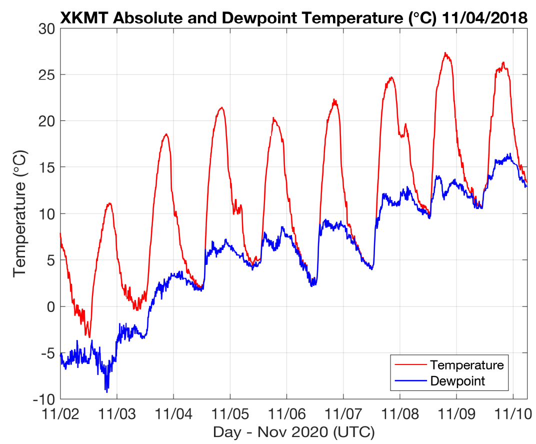
- ***Drought:*** Decreases in soil moisture => increase in potential evapotranspiration => increase in actual evapotranspiration => further soil moisture depletion; plant wilting => decrease in actual evapotranspiration => limited moisture for cloud development in the absence of large-scale advection

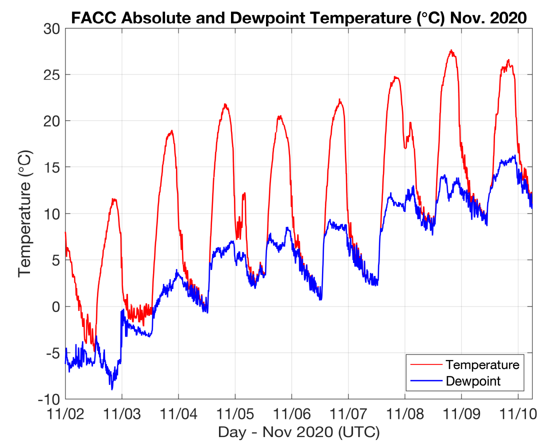


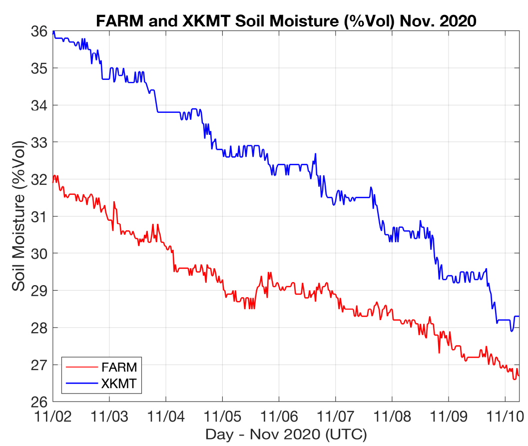


Land-Atmosphere Coupling (Cool things Mesonets can observe)



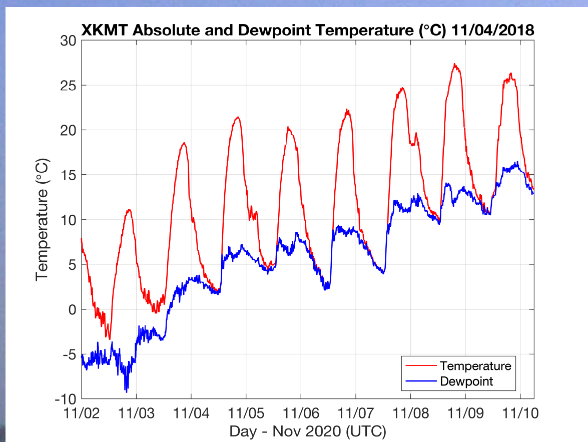


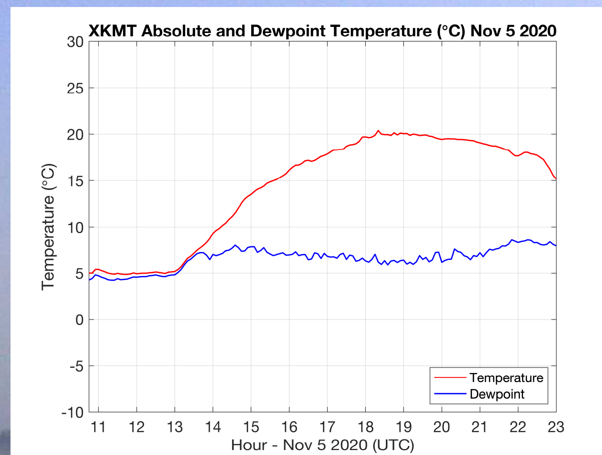




- A week of fair weather brought on strong L-A coupling
- The Bermuda high extended west of the Mississippi leading to southerly flow at the surface.
- Flat geopotential at 250 hPa
- **Perfect setup for warm days and cold stable nights! (note FACC) And…….**
- **DROUGHT**
- This is a good example of the early onset of meteorological drought. Rapid increases in dewpoint depression would soon follow

Three-Dimensional Evolution (Cool things Mesonets can do)

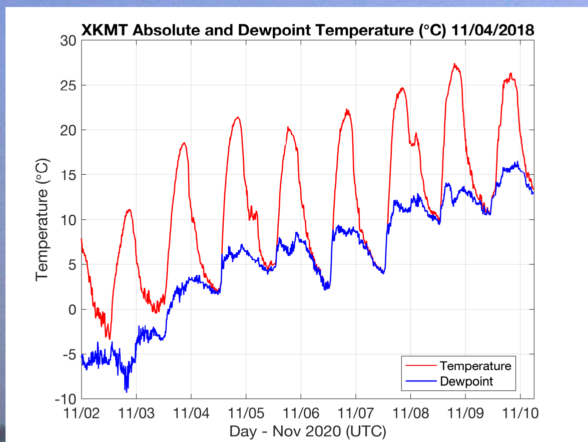


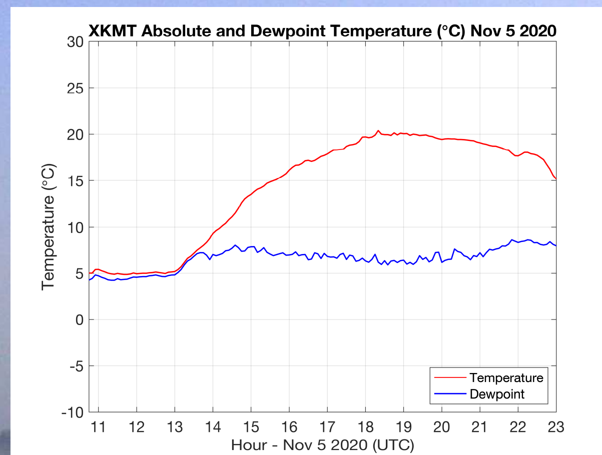


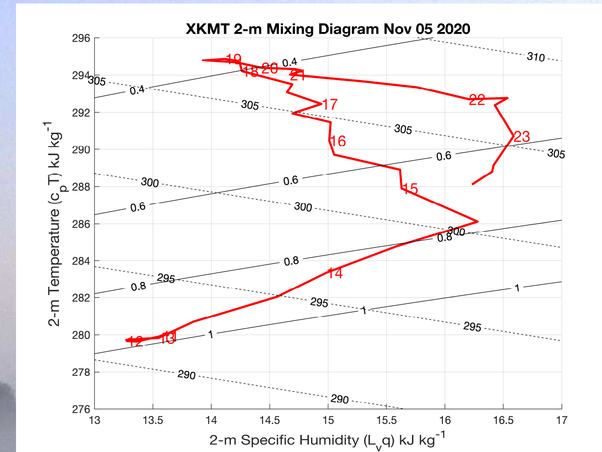
- Note the dual dewpoint peaks during the well-mixed phase of boundary layer diurnal cycle:
  - Peak 1: Rapid moistening after sunrise prior to explosive PBL growth
  - Peak 2: Moisture flux convergence due to continued latent heating during the transition to a stable PBL

- Behavior between the two peaks dependent on the land surface state, particularly the soil moisture
  - Slow decline in midday dewpoint if moisture fluxes cannot compensate entrainment heating/drying
  - Slow increase if soil moisture sufficiently large to maintain a large Bowen Ratio to reduce sensible heating, PBL growth and subsequent dry air entrainment and mixing

Three-Dimensional Evolution (Cool things Mesonets can do)



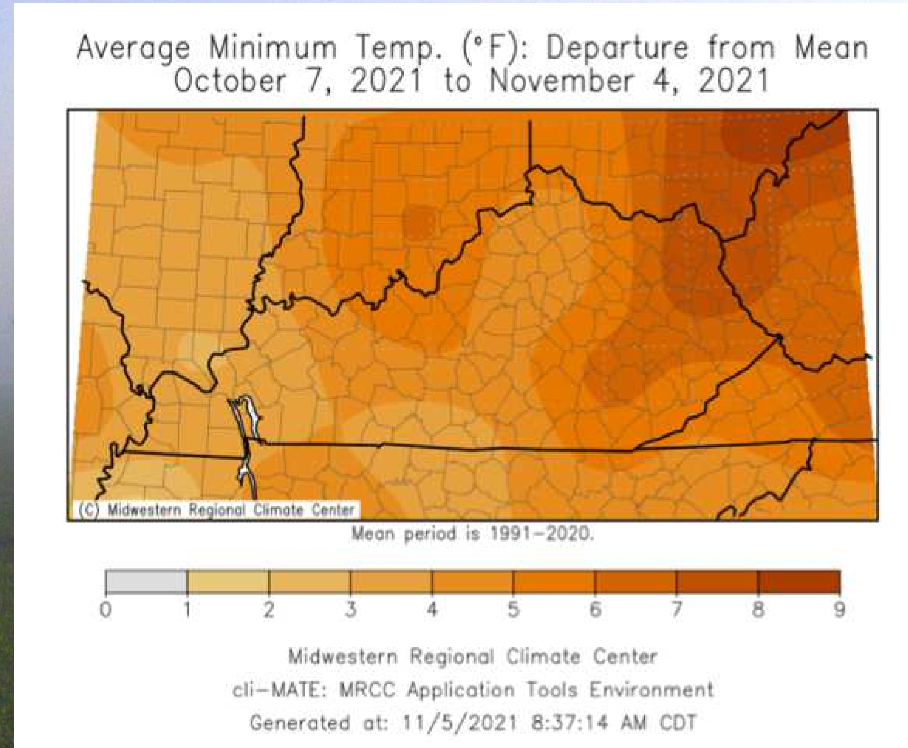




- Mixing Diagrams, or phase space diagrams of the conserved variable moist static energy, allows us to visualize the three-dimensional evolution without knowledge of surface or entrainment fluxes:

Climate Indices and Micro-Macro: Tropical Nights Example

- On the northern edge of the North American energy constrained sub-tropical climate, increases in the number of tropical nights are an important impact of climate change.
- Different in Gulf Coastal regions?



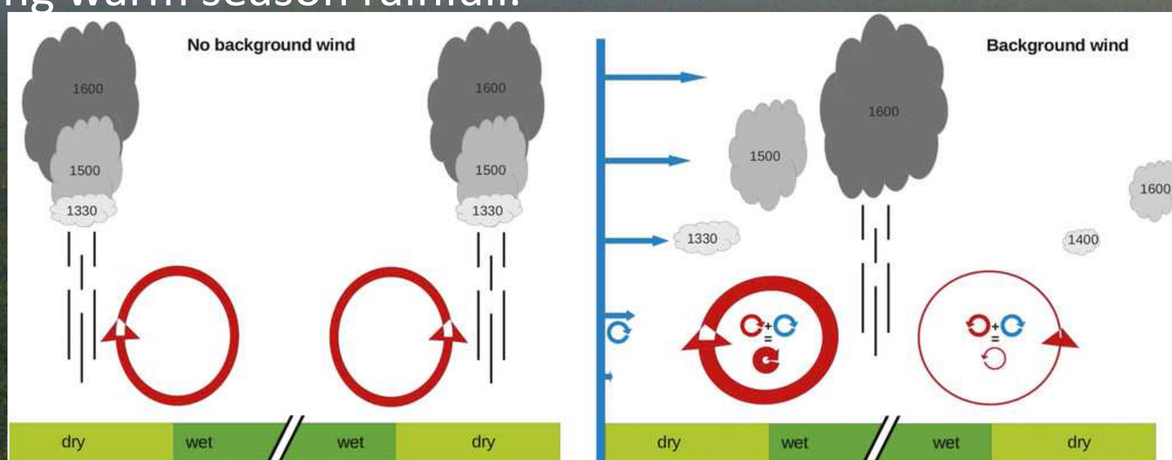
- Underlying Methodology of PREFER (e.g. machine learning with mesonet training data sets) lends itself naturally to find important correlations in the understanding of climate change

Climate Indices: Aggregate on daily, weekly, monthly, seasonal, and annual timescales

- Temperature, Pressure, Humidity Indices (e.g. Mean, Min., Max values)
- Cold Wave Indices (Growing Degree Days, Frost Days, etc.)
- Heat Wave Indices (15 different definitions of a heat wave)
- Precipitation Indices (e.g. Precipitation sums: see below)
- Wind Indices (e.g. Days with a given wind direction)
- Heat/Drought Indices (Drought Measures, Reference Evapotranspiration, etc.)
- Compound Indices (e.g. Soil Moisture – Precipitation)

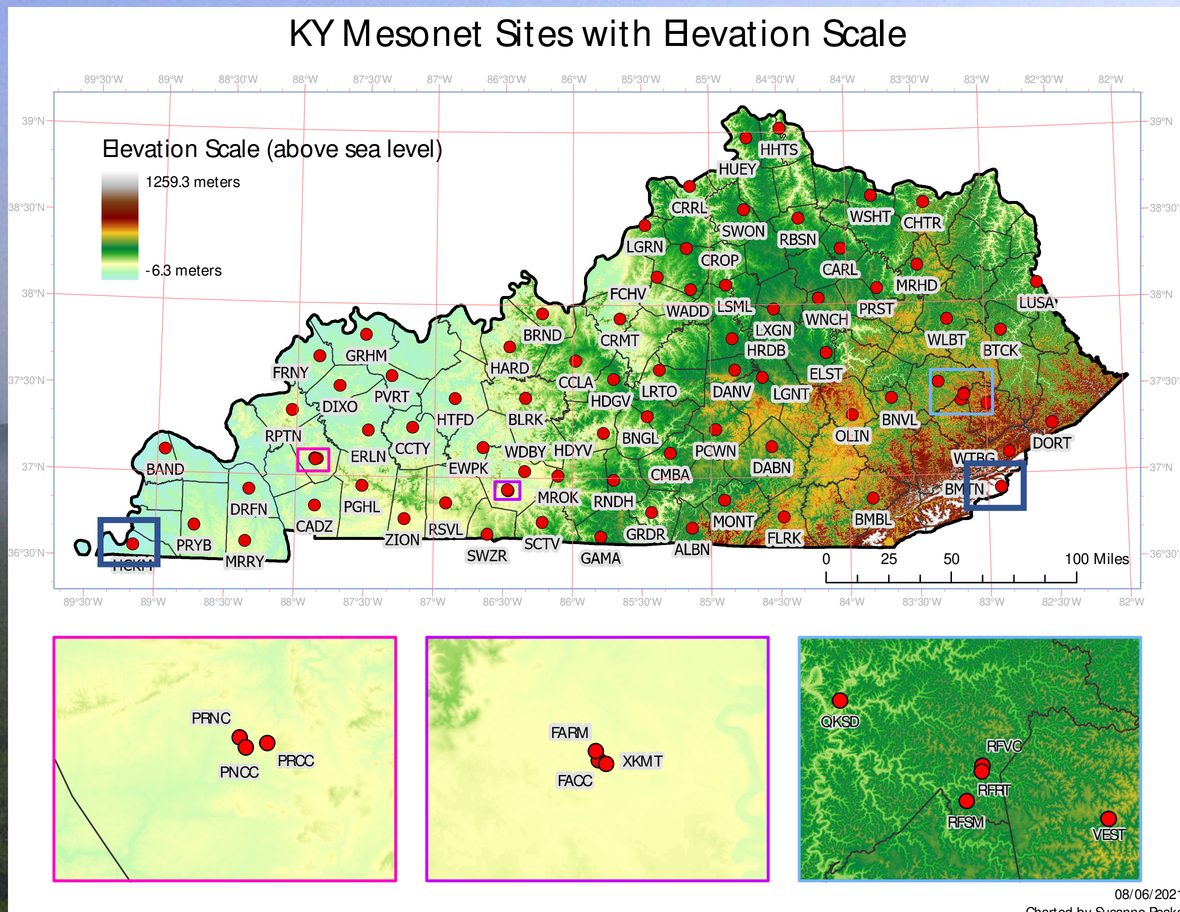
Soil Moisture – Precipitation Feedbacks

- A problem that has vexed meteorologists for decades is the relationship between soil moisture and precipitation
- Transitions between wet and dry soil patches may produce thermal circulations like a land/sea breeze that produce clouds/rain
- Do wet soils promote heavy rain locally or regional/downstream. Does a soil moisture gradient impact the precipitation gradient? Inversion formation?
- With a decade plus of soil and precipitation data, the PREFER project can explore a vast treasure of soil moisture-precipitation data and utilize the results for forecasting warm season rainfall.

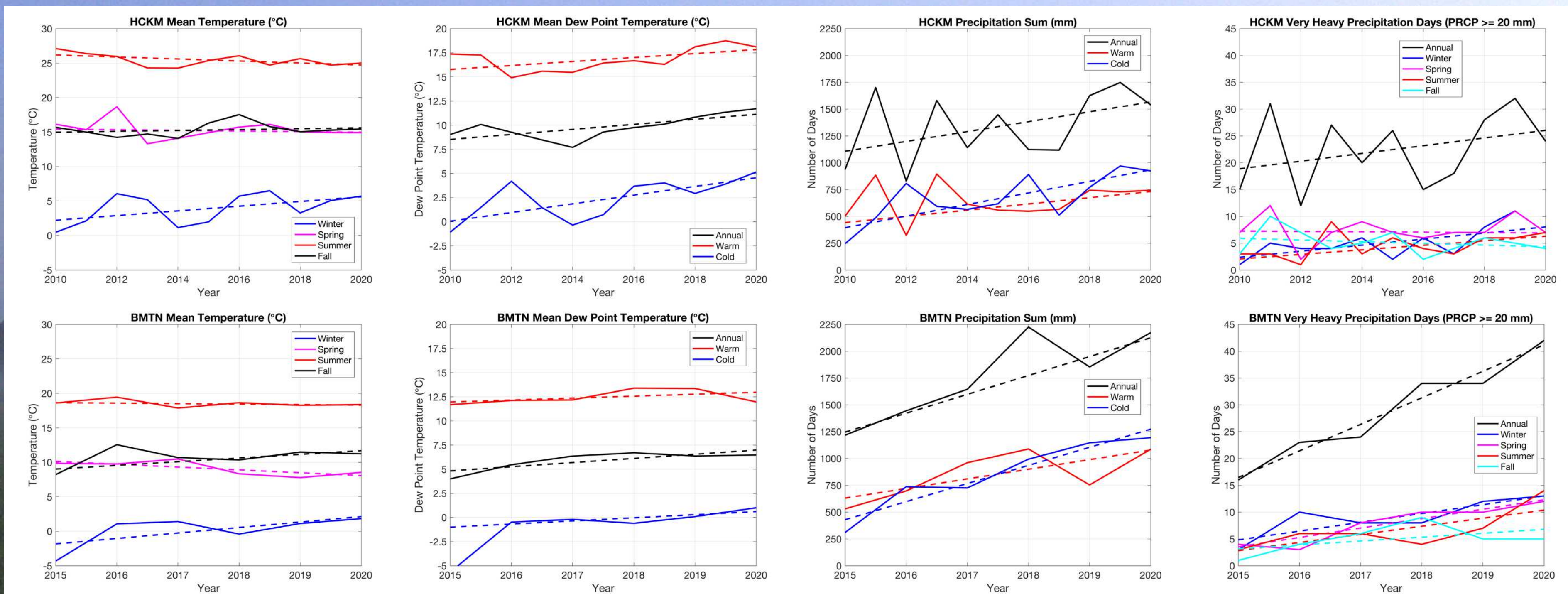


Froidevaux, P., Schlemmer, L., Schmidli, J., Langhans, W., & Schär, C. (2014). Influence of the background wind on the local soil moisture–precipitation feedback. *Journal of the atmospheric sciences*, *71*(2), 782-799.

Climate Indices

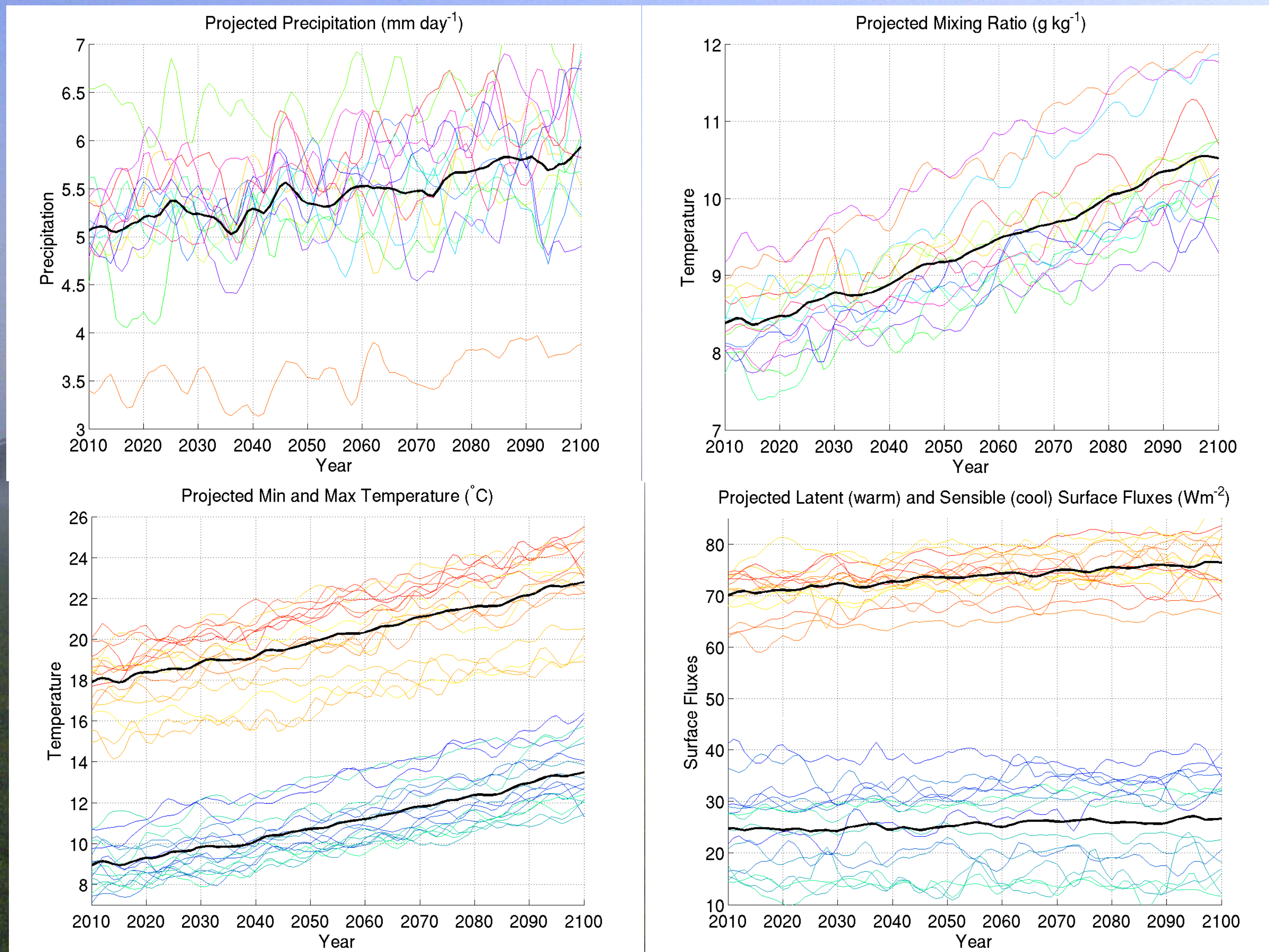


Climate Indices



Mann-Kendall Trend Test with Sen's Slope Estimator

Projecting Climate in the Ohio River Valley



HRRR Relevant Parameters: Radiation

- Only considering HRRR parameters that can be observed from mesonet sites or remote sensing (satellite obs.) or parameterized from observations

- DSWRF: Downwelling shortwave radiation
  - Directly measured at mesonet sites
- DLWRF: Downwelling longwave radiation
  - Parameterized from mesonet site moisture and temperature
- USWRF: Upwelling shortwave radiation
  - Calculated from MODIS derived albedo and mesonet site observed DSWRF
- ULWRF: Upwelling longwave radiation
  - Parameterized from mesonet site shortwave radiation and parameterized DLWRF

HRRR Relevant Parameters: Dynamics/Kinematics

- Only considering HRRR parameters that can be observed from mesonet sites or remote sensing (satellite obs.) or parameterized from observations

- SFCR: Surface Roughness (important for wind speed interpoloation)
  - Parameterized from MODIS derived NDVI (normalized difference vegetation index)
- FRICV: Friction Velocity (with observed temperature and moisture can be used to estimate atmospheric stability, Obukhov length: strong stability = inversion!)
  - Observed at mesonet sites with wind speed measurements at two mast heights under neutral stability conditions.
- UGRD: 10 m zonal wind
  - Directly measured at mesonet sites
- VGRD: 10 m meridional wind
  - Directly measured at mesonet sited
- GUST: Surface gusts?
  - Assuming this is 10 m, directly measured at mesonet sites

HRRR Relevant Parameters: Thermodynamics

- Only considering HRRR parameters that can be observed from mesonet sites or remote sensing (satellite obs.) or parameterized from observations

- LCDC and MCDC: Low and mid-level cloud cover (absorbs upwelling longwave radiation and reemits downward to warm the surface
  - Remote sensing: Use IR imagery with brightness temperature being a function of cloud height. The larger the brightness temperature value, the lower the cloud)
- TMP: 2 m temperature (1013.2 and 1000 hPa temperatures also available for vertical structure using the hydrostatic relationship given the geopotential height at 1013.2 which is a HRRR parameter. In calculating density se the average of the two pressure level temperatures)
  - Directly measured at mesonet sites
- DPT: 2 m dew point temperature
  - Directly measured at mesonet sites (dew point or rh along with pressure can be used to calculate vapor pressure and mixing ratio)
- RH: 2 m relative humidity
  - Directly measured at mesonet sites
- PWAT: precipitable water (column integrated water vapor and used to measure the greenhouse effect which negatively impacts inversion development)
  - Remote sensing: MODIS/GOES 16
- HGT: height of adiabatic condensation from surface. Extremely useful in soil moisture-precipitation feedbacks
  - Parameterized from direct observations of temperature and relative humidity (pressure can be useful too) at mesonet sites

HRRR Relevant Parameters: Land Surface

- Only considering HRRR parameters that can be observed from mesonet sites or remote sensing (satellite obs.) or parameterized from observations

- TSOIL: Soil temperature
    - Directly measured at mesonet sites
- SOILW: Soil moisture
    - Directly measured at mesonet sites and key to energy flux partitioning, and hence the surface energy budget (also impacts albedo) and therefore PBL evolution
- VGTYP: Vegetation type
    - Remotely sensed and important for surface roughness and albedo
- Terrain Roughness: Standard deviation of elevation (key for cold air drainage)
    - Remotely sensed digital elevation model

Conclusions: Inversions

- Observations
  - Nocturnal inversions are ubiquitous but formation and evolution are unique to sites due to land surface characteristics that describe land-atmosphere coupling.
  - While weak winds and lack of cloud cover are a necessary condition to limit vertical mixing for formation, land surface conditions provide the sufficient condition for formation.
  - For example, under a dome of high pressure, drier soils should lead to more frequent inversion formation. Similarly, regions susceptible to downslope cold pools would be more likely to develop a surface inversion than flat terrain.
- Modeling
  - SCM is ideal for exploring how model physics (e.g. LSM-PBL coupling) hindcast the afternoon-evening transition and inversion development.
  - Setup a LAM with high surface layer resolution to provide forecasts of inversion onset.
  - Utilize LES or LAM/LES for theoretical process studies of inversion formation and disruption.
  - Utilize perpetual offline LSM “spin-ups” to provide a more accurate lower BC

Future Work / Conclusions

- Micronet Setup: 3 portable micronet platforms to expand microscale investigation of inversion formation, intensity, evolution, and early morning decay
  - Land Between the Lakes National Recreation Area
  - Appalachia

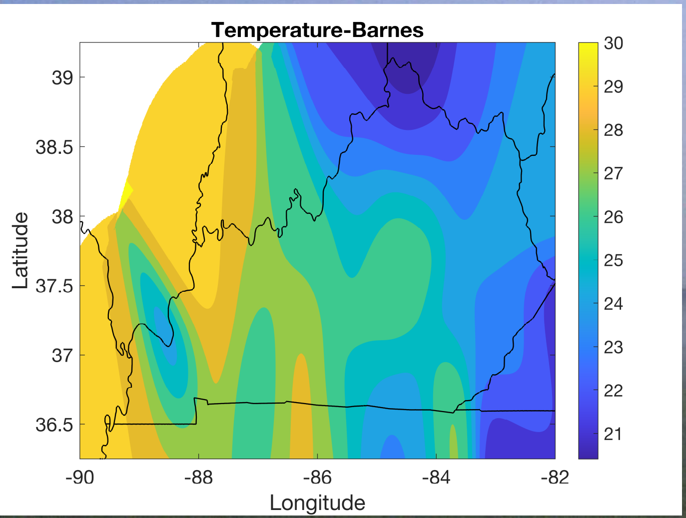
Future Work / Conclusions

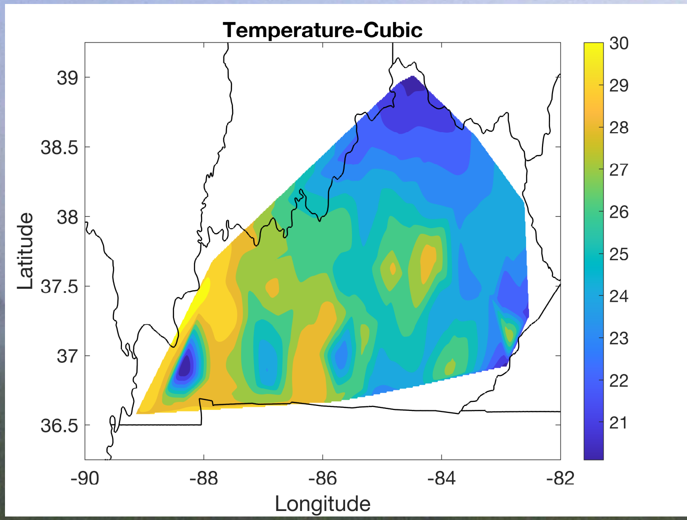
- Micronet Setup: 3 portable micronet platforms to expand micronet investigation of observations.
- Given lengthy data sets, utilize observations to train machine learning algorithms to forecast inversions.
- Two periods to Investigate
  - After-Evening Transition (Inversion Formation and Intensity).
  - Morning Transition (Inversion Duration and Decay).
  - Microscale monitoring setup yields the significance of elevation (cold air drainage and pooling), in addition to winds and moisture (clouds) in inversion development.
- Inversions can yield temperature changes of the same magnitude and time scale as a moderate cold front (~10°C in 2 hours).

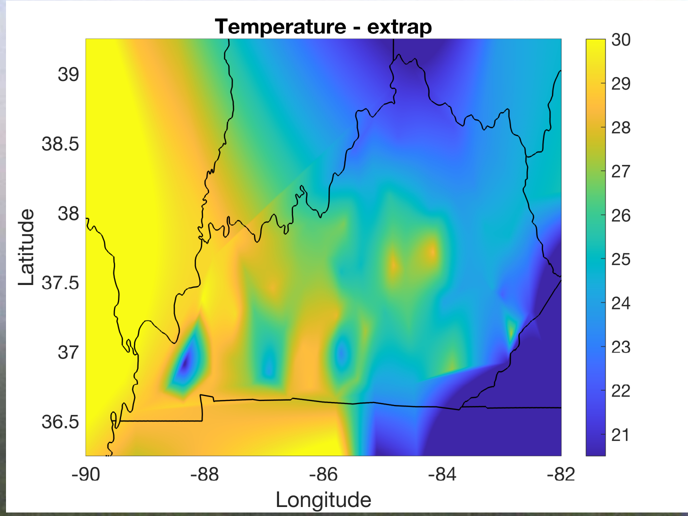
Interpolation Algorithm

- Physical-based interpolation (*Rouf et al. 2020, Journal of Hydrometeorology*):
  - Use Barnes objective analysis method (optimal or optimum interpolation) to generate cartesian grid system at 500-meter grid spacing. Complete
  - Use 1/3 arc second USGS (United States Geological Survey) DEMs (digital elevation models) to determine thermal lapse rates to account for elevation changes on temperature and humidity. Complete

Interpolation Algorithm







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  - Use the DEM and remotely-sensed NDVI (normalized difference vegetative index) to determine roughness length and slope factors to account for changes in wind speed and surface radiation
  - Precipitation is highly stochastic and therefore the most difficult… Use random forests/cluster analysis/machine learning

Conclusions: Climate Indices

- In addition to inversion prediction, certain indices are worth considering for prediction do to our wealth of data
  - Frost days (Tmin > 32F)
  - Tropical nights (Tmin> 0C)
  - Soil moisture – Precipitation Feedbacks
  - These are just a few!