

Microscale Temperature Fluctuations in the Boulder Valley

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ABSTRACT

It is well known that there are often drastic temperature variations within very short distances. Although the locations of these fluctuations can generally be predicted by analyzing

factors such as topography and wind velocity, there are some cases where there are exceptional changes in temperature without an obvious reason. Understanding the causes behind these extreme temperature variations will help improve weather predictions that may ultimately influence important components of society such as agriculture and transportation. The Boulder Valley is an ideal location for the study of microscale temperature fluctuations due to its unique topography and spatial variation in terrain. This research will examine the several possible factors that influence large temperature variations over short distances. This will be tested by using a weather station that is mounted on a bike to record temperature variation within the Boulder Valley.

THE PROBLEM

Temperature and other meteorological factors affect many of our daily activities including health, transportation, and agriculture. Most of our information on temperature is based on limited measurements at specific locations. We know that these measurements do not represent the large variability that exists on the microscale. The microscale involves meteorological features that occur on a scale of less than two kilometers. This research will therefore evaluate temperature variability within the Boulder Valley and will assess the impacts of terrain characteristics, wind, and cloud-cover on temperature variation. More specifically, my research will address gaps in our understanding of microscale temperature variability with the following specific objectives:

1. To measure the temperature along two specific routes

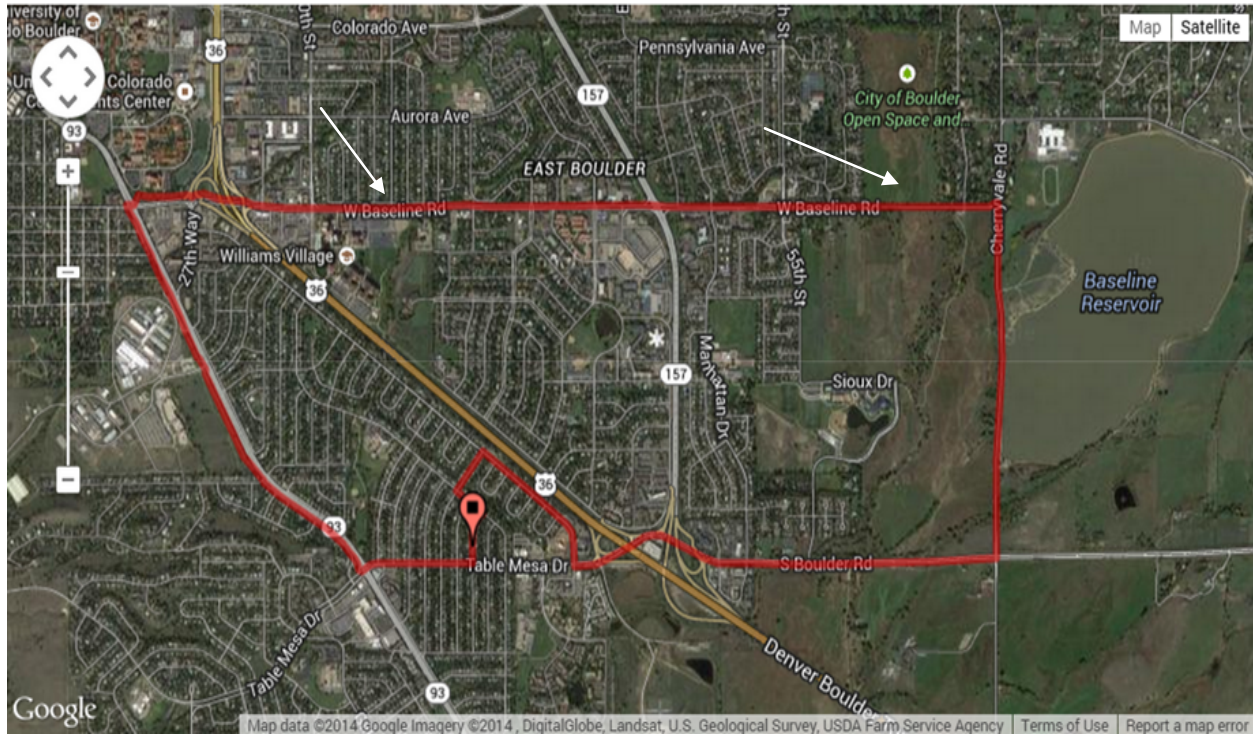
2. To compare the measures of temperature variation over space with the reference measurements collected at fixed-location ATOC (Department of Atmospheric and Oceanic Science) weather stations in order to account for temperature trends
3. To evaluate the role of wind velocity, terrain, and cloud-cover on the spatial variation of temperature determined from the collected temperature data

HYPOTHESIS

To develop hypotheses regarding factors influencing temperature variation within the Boulder Valley, I considered static factors that greatly influence temperature, such as topography, surface material (i.e. asphalt, grasslands), surrounding structures and bodies of water. I also considered the dynamic, or changing factors that have an impact on temperatures such as wind and cloud cover. With this information in relation to the specific bike routes where I planned to make measurements, I developed the following specific hypotheses:

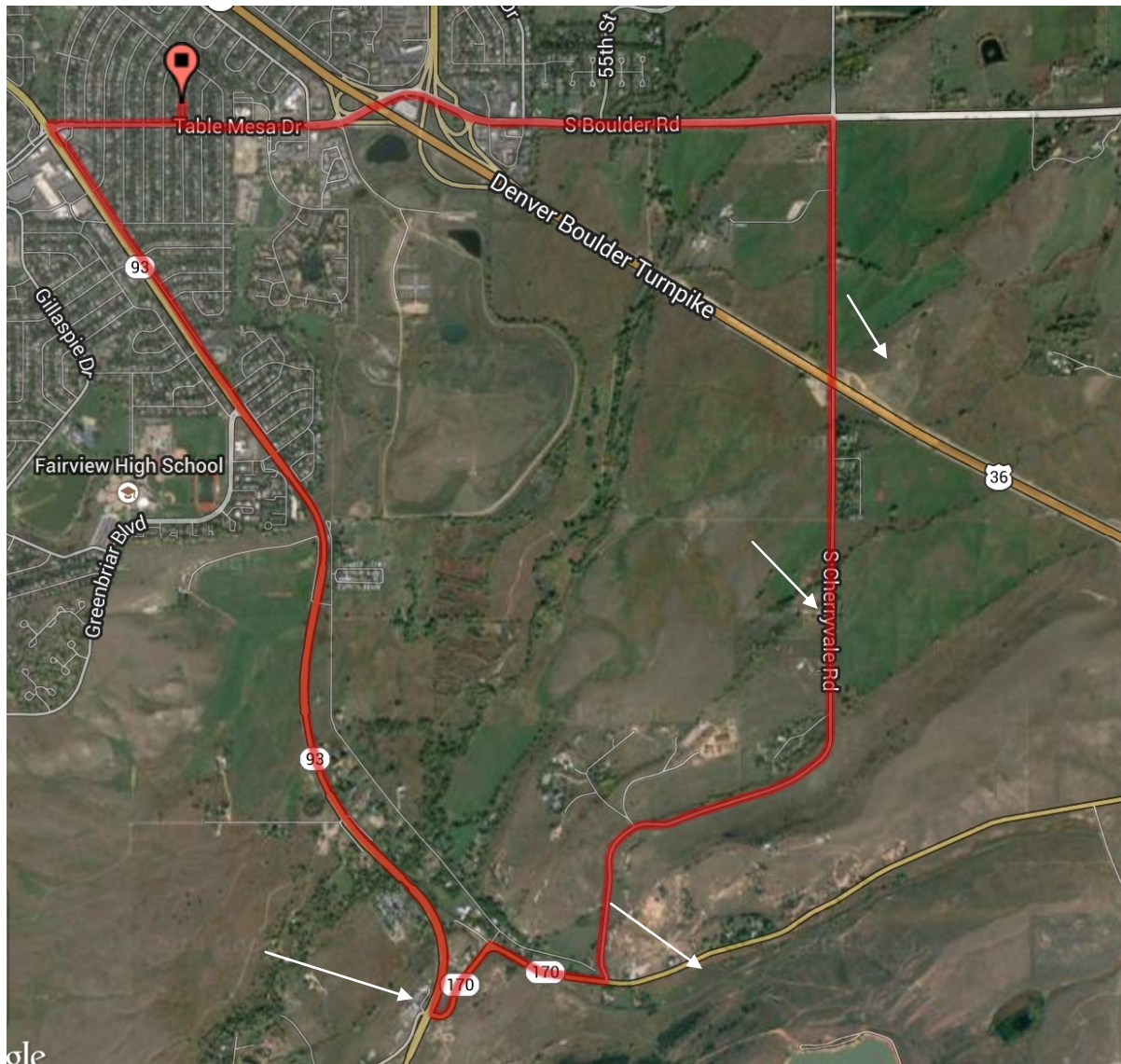
1. There is greater temperature variation during periods of clear skies and calm winds, compared to a more uniform temperature distribution on days with cloudy skies and breezy conditions.
2. Higher relative temperatures will be present in urban areas and lower relative temperatures will be observed in rural areas with lots of vegetation and fewer paved surfaces.
3. Lower temperatures will be measured in areas of lower compared to higher elevations.

4. Measured temperatures will be dependent on the physical characteristics of the areas upstream of the measurement location.



Lowest-Lying Area

Fig. 1. Illustration showing the first bike route within the Boulder Valley (in red) that was followed for each temperature data collection time. The route passes adjacent to Baseline reservoir, rides through rural and urban areas, and covers topographically diverse terrain. The map is from maps.google.com.



Marshall/170

Fig.2. An illustration showing the second bike route within the Boulder Valley. Significant locations are labeled on this image.

METHODS

All measurements were collected in the topographically diverse landscape of the Boulder Valley using the Weather Bike instrumentation described by Cassano (2014). I designed two specific routes along which I expected to encounter both urban and rural areas of varying elevation which would allow me to collect measurements to test the above hypotheses.

Route 1: With the exception of the data that was collected on November 10, 2014, temperature measurements were collected along Route 1 in the evening hours. Generally speaking, regardless of the wind speed, direction, or amount of cloud-cover, I expect the temperatures to remain higher in areas where concrete structures exist in comparison to the grasslands to the east of Boulder. This is because concrete and asphalt surfaces have a higher heat capacity and a lower albedo than most natural surfaces. As the earth receives incoming shortwave radiation from the sun, the concrete ground has a greater potential to absorb this energy, which in turn warms the air located directly above the surface. Surfaces such as grassland are faster in releasing this energy and therefore cool off at a faster rate than asphalt surfaces, causing a decrease in the surrounding air temperature. In addition, the rural areas that surround Boulder have a higher density of vegetation. These plants decrease the temperature of the surrounding air through a process called evapotranspiration, which is essentially evaporational cooling caused by plants emitting water vapor (EPA). The Urban Heat Island effect is more pronounced on days where skies are clear and the winds are light due to the lack of turbulent mixing within the boundary layer. However, its effects can be seen on cloudy and windy days as well.

As I begin my course through the Martin Acres neighborhood, I predict that the temperature will remain relatively cool in comparison to the other built-up areas of Boulder that I will pass through. I expect to see temperatures in this area differ from other urban areas the most when the skies are clear and the winds are light. This is because Martin Acres lies at one of the lowest elevations along my ride. With calm winds, there will be little turbulent mixing taking place which will force the cooler, denser air to sink into topographic depressions. Additionally, with relatively few concrete structures upstream of this area, colder air that manages to form over the grasslands to the west of Boulder may flow downhill, again, due to the denser air being forced to sink downwards.

While passing the Table Mesa Park and Ride and into the grasslands located east of Foothills Parkway, I expect the temperature to drop due to the characteristics of the surrounding surface material, which has a lower heat capacity than concrete. As South Boulder Road ascends a hill as it approaches Cherryvale Road, I am anticipating a slight increase in temperature due to cold pooling at the lower elevation located at the bottom of the hill. In some cases, the temperature might not vary if cold pools have not formed if winds are strong. This warming caused by the slight gain in elevation may be counterbalanced by the increased distance from the Boulder Urban Heat Island, causing no significant variation in temperature.

As I head north on Cherryvale road, I expect the temperature to decrease slightly as the elevation decreases roughly forty feet. This temperature drop is once again likely to be caused by cold pooling in topographic depressions. I will then parallel Baseline Reservoir, which is located to the east of Cherryvale Road. This water body's effect on temperature surrounding the lake depends highly on the wind speed and direction. For example, a wind with any

easterly component is likely to take on the characteristics of the water and advect this air over Cherryvale Road. On a cold day, the water is likely to be warmer than the surrounding land due to the greater heat capacity of water. The cold air that is located close to the surface is then warmed as it passes over the water, caused by the heat exchange between the two systems. As a result, I am expecting microscale warm air advection to take place as I ride adjacent to the reservoir when easterly winds are present during the late-fall and winter months. This warm air advection will result in an increase in temperature as I pass by Baseline Reservoir. However, the reservoir is located at a lower elevation than the surrounding terrain, therefore the magnitude of the temperature change is highly dependent on the magnitude of the wind speed and the differential heating of the land and the water.

Turning west onto Baseline Road, the terrain flattens out and the surroundings remain open with trees and grassland prairie. On a night with clear skies and light winds, I expect this area to be one of the coolest spots along the first route. This is because this stretch of Baseline Road from Cherryvale Road west towards 55th Street is the lowest topographic portion of my bike route. Cold pools will develop, and additional cooling from the vegetation and lack of urban structures will enhance the temperature change relative to the surrounding areas.

Once I pass west of 55th Street, there is a slight increase in elevation as I continue heading west towards Broadway. There are also more concrete structures as I pass the intersection of 55th Street and Baseline Road, which I expect will increase the temperature slightly due to the Urban Heat Island Effect. I am then anticipating a steady temperature until I reach the US 36 overpass, where I expect temperatures to climb dramatically. This is because longwave radiation is radiating off the concrete surfaces that shelter the bike path, resulting in a feature

that resembles a heat tunnel. Once I pass underneath the overpass, the temperature should decrease to its initial value before riding underneath US 36. As I ride adjacent to Wolf Law, sprinklers are occasionally turned on which I predict will have an evaporational cooling effect on the surrounding air, causing a decrease in temperature.

While heading southeast on Broadway, the terrain remains quite flat with relatively few structures upstream. For this reason, I expect the temperature to cool off slightly before seeing a more significant drop in temperature as I lose 25 feet in elevation. Grasslands also surround this topographic depression which serves to decrease the temperature even further through longwave radiation escaping from the surface.

After passing Dartmouth Road, there is a steep 35 foot altitude increase along with an increase in the number of houses. These two factors should produce a gradual increase in temperature before seeing a greater spike in temperature once I reach Table Mesa Drive. The asphalt that composes Table Mesa Drive is completely black, which radiates longwave radiation at a slower rate in comparison to grey asphalt and concrete surfaces. The result is a warming of the air directly above the black surface, given that there is relatively little turbulent mixing.

A second route was chosen in order to explore another portion of the Boulder Valley. This route does not pass through an urban landscape. However, the terrain is diverse and there are extreme topographic changes over short distances, which is expected to have an impact on microscale temperature trends.

Route 2: Data was collected along Route 2 within an hour after sunrise. The route starts at the intersection of 44th Street and Table Mesa Drive, and follows a path similar to that

of the first route, leading up to the intersection of South Boulder Road and Cherryvale Road. From here I head south on Cherryvale Road, where there is a gradual incline up until the overpass that crosses US 36. I expect the temperature to be relatively constant along this stretch of the route, mainly because there is no sharp increase in elevation, and no large area of vegetation. Assuming calm and clear conditions, I expect the temperature to drop significantly as I ride onto the Cherryvale Road overpass that intersects US 36. This is because this portion of Cherryvale Road is highly exposed to the surrounding air, with no structures blocking or reflecting outgoing longwave radiation. Quickly, Cherryvale Road decreases in elevation, with a patch of vegetation situated east of the road. There is also a notable decrease in elevation to the west of Cherryvale road, with a significant increase in elevation to the east. I expect cold pools to form within this topographic depression if skies are clear and winds are light.

Next, the route gains elevation gradually once again, with Marshall Mesa located to the east of Cherryvale Road and Boulder Valley located to the west. I expect the wind speed to increase along this portion of the route due to a funneling effect. Cherryvale Road then makes a sharp turn towards the west and is accompanied by a slight decrease in elevation. I anticipate the temperature to remain constant along this segment of the route. Once again, the route veers south and experiences a quick, 65 foot decrease in elevation until the intersection of Cherryvale Road and Marshall Road. I expect this point to be the coldest point along the route, due to it having the lowest point in elevation throughout my ride. This intersection also lies in a topographically unique area, with Marshall Mesa surrounding this point to the east and to the south. In cases where the winds are strong, I expect this area to be one of the warmer spots on my route due to funneling of the wind in between both mesas. Once I turn southwest onto

Highway 170, I expect the temperature to increase slightly as I gain elevation until the road intersects with Highway 93. As I head northwest onto Highway 93, there is a large decrease in elevation over a short distance. In this area, I expect the temperature to drop dramatically due to cold pooling at the base of both mesas. Highway 93, or Broadway, then cuts up another large hill, where I anticipate the temperature to rise substantially again.

INSTRUMENTATION

I collected temperature and wind measurements on a bicycle mounted platform (Fig. 3). This approach allowed for an efficient collection of data along my route in a relatively short amount of time. I used a standard route which covers a variation in elevation, land use, and surface characteristics. Measurements of temperature were collected on a Kestrel 4000 weather monitor.

The Kestrel 4000 is an extremely useful tool when it comes to analyzing microscale temperature fluctuations. This is partly because the Kestrel has the capability of recording and logging temperature as frequently as every two seconds, which allows for measurement of temperature differences over very short distances when mounted on a bike. I set the Kestrel 4000 to take measurements in 10 second increments in order to account for the spatial uncertainty involved in determining the causes for these temperature variations. While taking measurements in two second intervals would ultimately give a more detailed temperature spread, it would be extremely difficult to identify the factors that influence such temperature fluctuations at such a small scale. It is for this reason that I collected meteorological data points

over a spatial interval of roughly 50 meters, assuming an average biking speed of 12 miles per hour.



Fig. 3. The Kestrel 4000 Weather Station on a bicycle-mounted platform.

One atmospheric variable that the Kestrel is unable to measure is the wind direction. Since it is difficult and inaccurate to estimate the wind direction while biking, the wind speed and direction at the ATOC weather stations in Boulder, Louisville, and the National Weather Service station at Boulder Municipal Airport were recorded prior to and following the bike ride. The wind direction can play a key role in determining the temperature trend along each route while also having an effect on the magnitude of temperature variations within the Boulder Valley.

One further advantage of using the Kestrel is that it can provide wind speed data with measurements at a precision of one tenth of a mile per hour. However, the wind speeds that

are measured by the Kestrel are also affected by the speed at which the bike is moving, therefore these recorded wind speeds are not relative and not accurate measurements of the actual wind speed.

It is also worth mentioning that the Kestrel's ability to record elevation is directly correlated to the instrument's capability of measuring barometric pressure. Using the relationship between altitude and pressure given by the hydrostatic equation, atmospheric pressure can be defined as the weight of air above a fixed point at the surface. It is for this reason that at a fixed point in time, pressure decreases as elevation increases since there is less air overlying the surface at a higher altitude. Conversely, pressure increases as one descends in altitude.

ANALYSIS

I tested my hypotheses by riding along the first route and taking temperature measurements during the afternoon and evening. I analyzed three different scenarios:

1. Conditions with calm winds and clear skies (Fig.4.)
2. Windy conditions under cloudy skies (Fig.5.)
3. Cloudy conditions with an easterly wind after the passage of a cold front (Fig.6. and Fig.7.)

I will first describe the clear skies and calm winds scenario (Figure 4), where I observed temperature variation of as much as ten degrees Fahrenheit along my route. The first notable

drop in temperature occurred after passing the intersection of South Boulder Road and Cherryvale Road, which is located at the top of a hill. Once I headed north on Cherryvale Road, the temperature plummeted nearly six degrees within a few hundred meters as I lowered in elevation. This was likely caused by colder air settling in low-lying areas due to a negative sensible heat flux, causing this cool and dense air to sink simply because it is heavier than the surrounding air. As I expected, the adjacent reservoir had little influence on the temperature in this scenario simply because winds were not blowing off the body of water.

The next notable drop in temperature occurred just west of the intersection of Baseline Road and Cherryvale Road, after seeing the temperature gradually increase as I approached this intersection. This decrease in temperature was likely caused by this area being one of the lowest points in elevation along my route, along with being highly vegetated with few concrete structures in the vicinity. The vegetation in this area transpires water vapor, through a process called evapotranspiration, which results in a cooling of the surrounding air causing a decrease in temperature. In addition, the soil in this area has a lower heat capacity than concrete, which allows for the surface to cool off at a faster rate, again causing a decline in temperature.

The temperature then quickly increased as the amount of vegetation decreased and concrete structures and surfaces became more prominent as I passed 55th Street into a mixed residential and commercial district. This spike in temperature was likely caused by the Urban Heat Island Effect, due to concrete having a higher heat capacity along with lower moisture content than other surfaces such as grass. As I continued to head west on Baseline Road, the temperature spiked at intersections with an abundance of concrete structures, particularly next

to commercial districts such as the area surrounding Baseline Road and 30th Street.

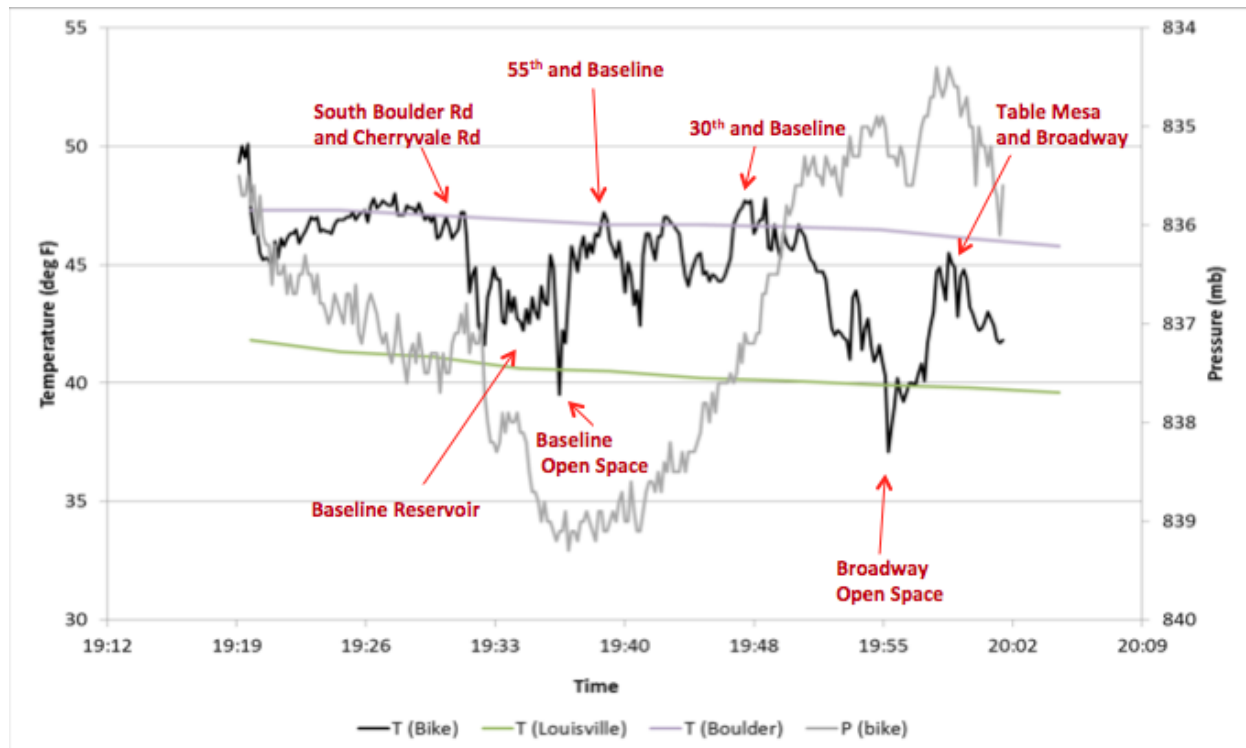


Fig.4. Temperature data taken during the evening of October 27, 2014 under clear skies and calm winds. The pressure axis is inverted, with high pressure values towards the bottom of the graph. The grey curve represents pressure, the black curve is temperature, the green curve denotes temperature at the Louisville ATOC weather station, and the blue curve represents temperature at the Boulder ATOC weather station. The temperature recorded at these fixed points are taken on five minute intervals whereas the bike-mounted Kestrel weather station was set to take measurements every 10 seconds. All instruments made temperature measurements that were precise to one tenth of a degree Fahrenheit.

The most notable drop in temperature along this route occurred along Broadway between Rayleigh Road and Dartmouth Avenue. This area has no concrete structures upstream, which likely correlates to colder temperatures over the higher terrain to the west of my location. This colder air then flowed downhill towards lower elevations, which dramatically

decreased the temperature at my location, causing the lowest temperature reading along my ride.

As I passed Dartmouth Avenue, the temperature increased once again as I gained elevation and more concrete structures were located upstream of my location as I began passing through the Table Mesa residential neighborhood. Along this segment of the route, I saw a maximum temperature at the intersection of Table Mesa and Broadway where there is a large commercial district. While the temperature fluctuated significantly throughout my route under clear skies and calm conditions, cloudy and breezy conditions lead to fewer temperature variations.

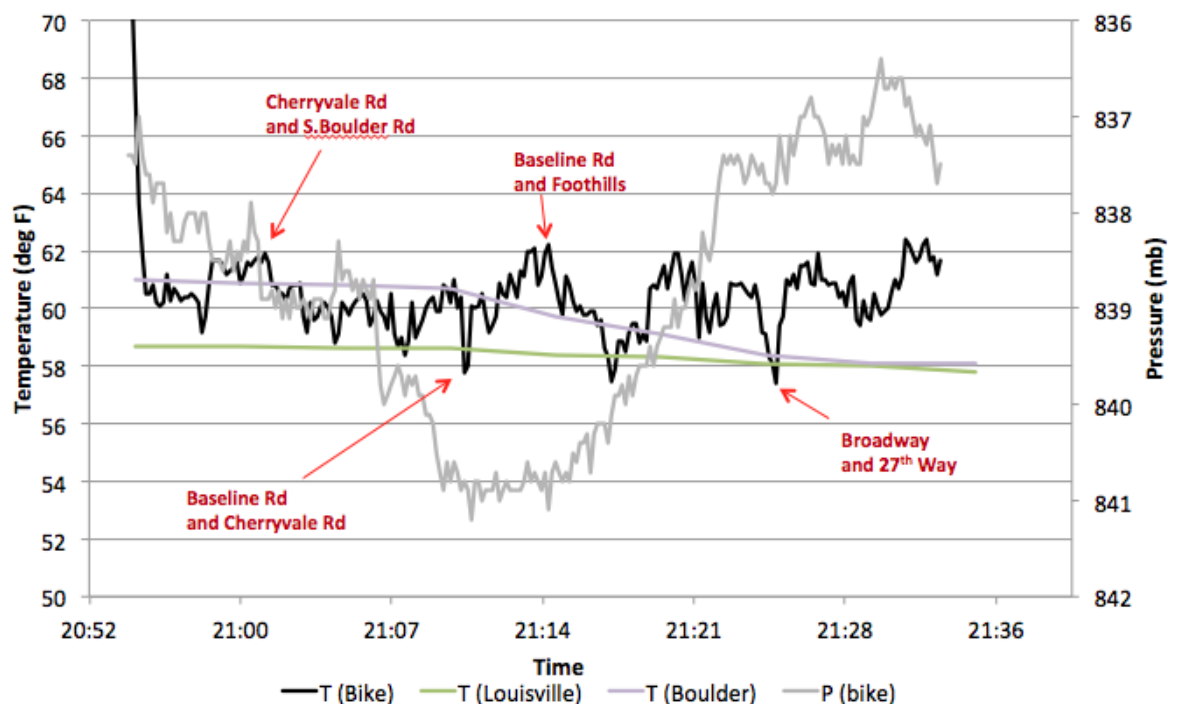


Fig.5. Temperature data taken during the evening of October 22, 2014 with cloudy skies and breezy conditions. The dramatic decrease in temperature that occurred early in the ride was a result of the Kestrel 4000 adjusting to the ambient outdoor temperature.

Figure 5 shows how the temperature varied along this same route under overcast skies and gusty winds. As expected, the temperature did not vary as much in comparison to calm conditions. This is because gusty winds tend to homogenize the temperature profile of the boundary layer, meaning that there is little horizontal and vertical temperature variation due to turbulent mixing. The slight temperature variations that I did measure appeared to be more random, except for when I passed through areas with a large number of concrete structures such as the intersection of Baseline Road and Foothills Parkway. These slight increases in temperature are likely due to a greater sensible heat flux over concrete surfaces than over grassland prairie. Although these were windy conditions, winds were blowing from the southwest which did not have a large impact on the temperature as I rode adjacent to Baseline Reservoir. A more interesting case arises when easterly winds do blow off the reservoir and evidently influence the temperature as I ride along Cherryvale Road.

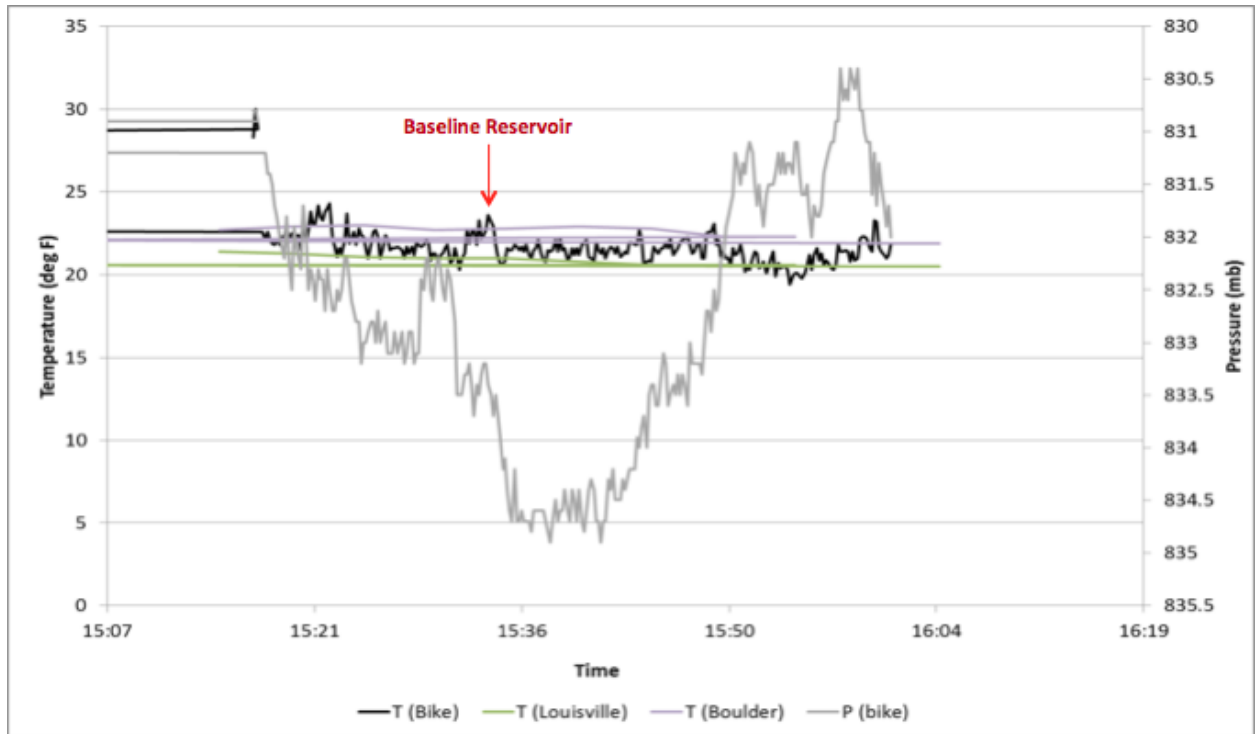


Fig.6. Temperature data that was taken prior to the passage of a strong cold front that dropped the temperature nearly 40 degrees Fahrenheit on November 10, 2014. Easterly winds were observed at the time of this observation.

While the overall temperature trend does not vary much in Figure 6, there is an interesting phenomenon that is taking place. These temperature measurements were taken in the afternoon after the passage of a strong cold front, with temperatures around 60 degrees Fahrenheit that morning, and then falling to around 20 degrees by mid-day. As a result of differential cooling, ground temperatures were significantly colder than the water temperature. As cold, easterly winds blew over the warmer, moist water surface, the air became saturated and condensation took place, resulting in steam fog. These easterly winds then pushed the air that was warmed and humidified by the reservoir over Cherryvale Road where I saw an increase

in temperature and dewpoint temperature (Fig.7.). Along the entire route the temperature did not vary more than four degrees simply due to turbulent mixing within the boundary layer.

Figure 8 shows a similar scenario to Figure 5 and Figure 6. The temperature trend remains fairly constant throughout the route due to overcast skies and breezy conditions. Along Baseline Road between Foothills Parkway and 30th Street, sprinklers were turned on, which may be the reason for the spontaneous drop in temperature (Figure 8). The mist that is emitted by the sprinklers cools the surrounding air through evaporation, which could explain the cause of the decrease in temperature. Right after passing these sprinklers, the temperature increased 4 degrees Fahrenheit, likely due to the increase in concrete structures that surrounds the intersection of Baseline Road and 30th Street.

When comparing Figures 4, 5, 6, and 8, we can clearly see that there is a greater temperature variation under clear skies with calm winds, whereas the temperature distribution is rather uniform in the cloudy skies and gusty wind scenario. The temperature may vary by as much as ten degrees Fahrenheit (Figure 4) under clear skies, while the temperature tends to vary only a few degrees given overcast conditions (Figures 5, 6, and 8). Supporting my fourth hypothesis, Figures 6, 7, and 8 demonstrate clearly that the temperature and moisture trend can depend on the physical characteristics of a feature upstream, or adjacent to my location. In support of my third hypothesis, Figures 4 and 5 show that the lowest temperature was found in low-lying areas such as the intersection of Baseline Road and Cherryvale Road.

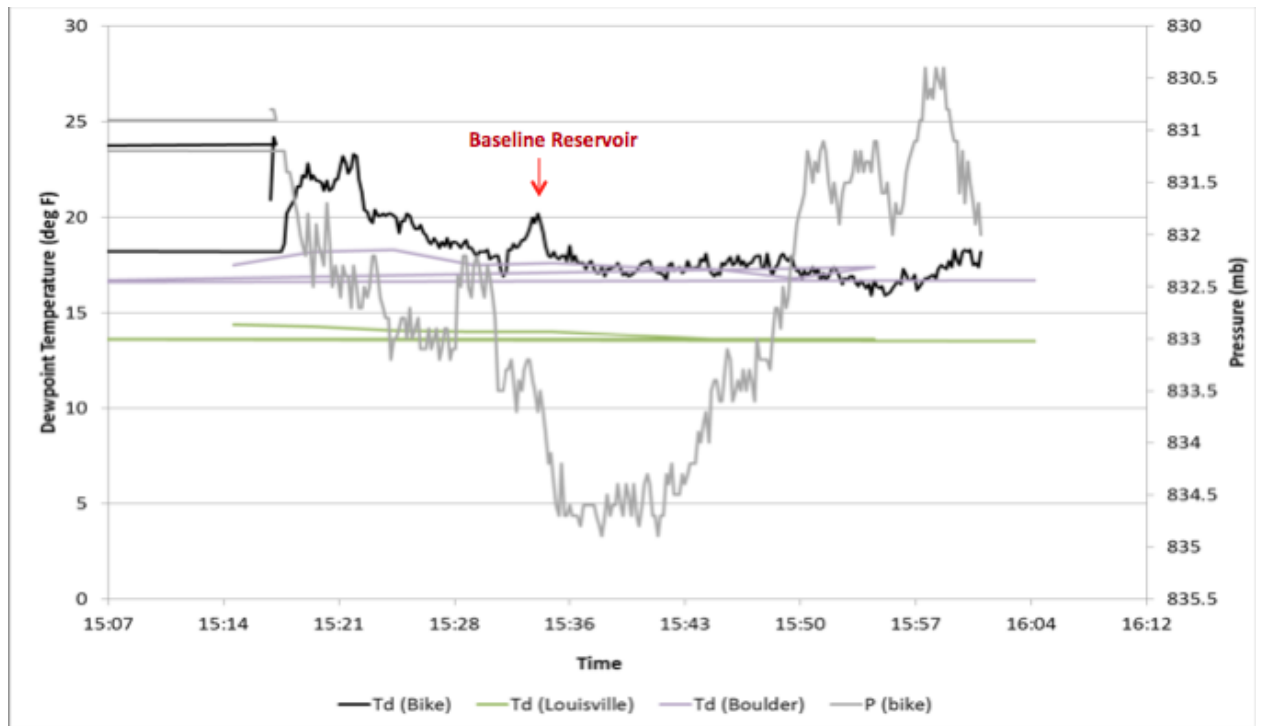


Fig.7. Dewpoint temperature data that was recorded over the same time interval as Fig.5. Higher dewpoint temperatures indicate that more moisture is present in the air. When the temperature is the same as the dewpoint temperature, the air is saturated.

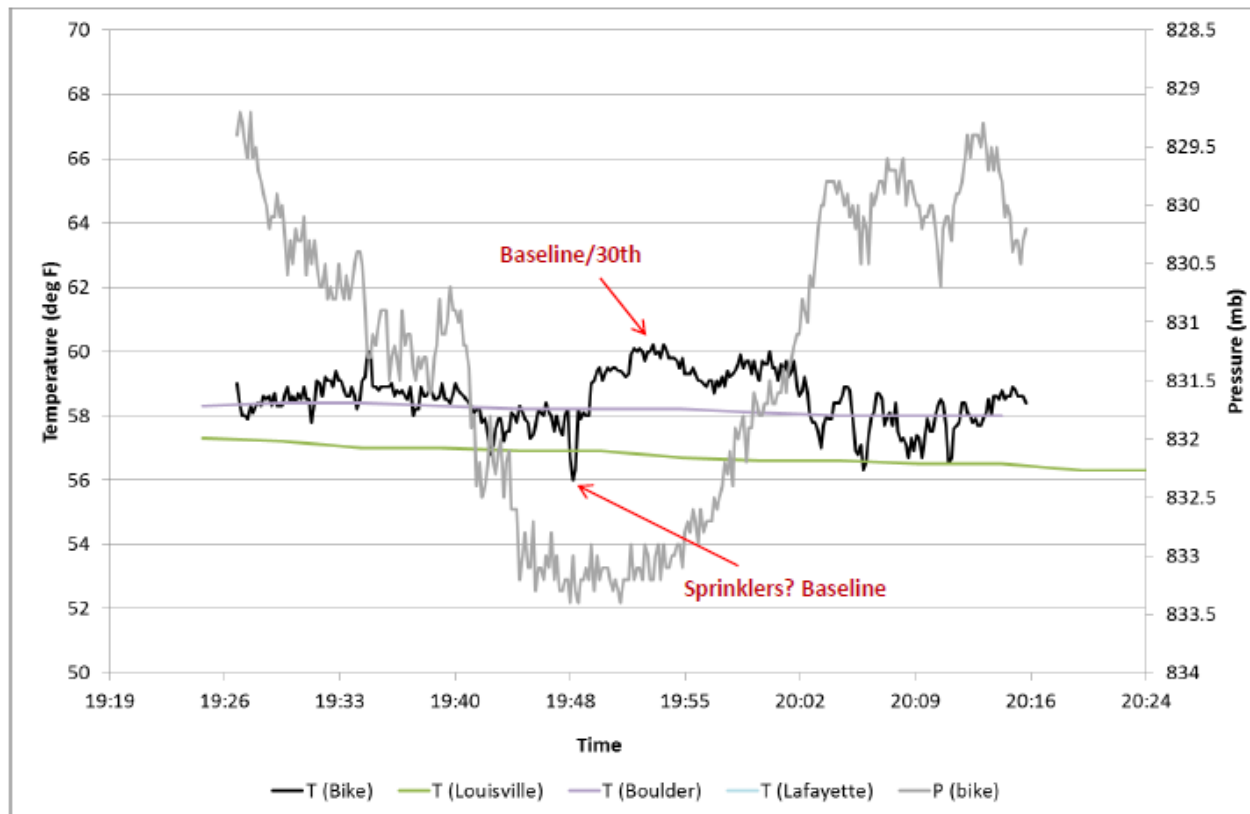


Fig.8. Temperature data collected on the evening of September 30, 2014 under cloudy skies and breezy conditions.

Route 2

I further tested my hypotheses by riding along a second route and taking temperature measurements during the morning. I analyzed three different scenarios:

1. Clear skies and calm winds (Fig.9.)
2. Cloudy skies and calm winds (Fig.10, Fig.11, Fig.12)

3. Cloudy skies and breezy conditions (Fig.13)

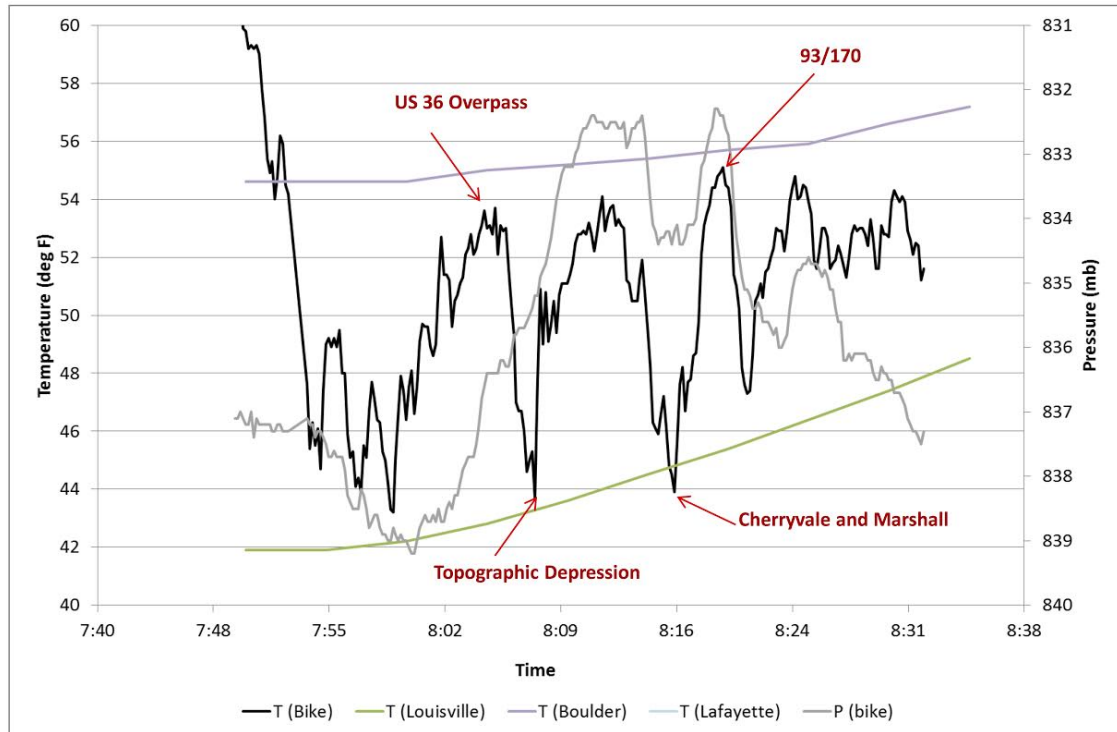


Fig.9. Temperature data that was recorded along the second route during the morning of January 27, 2015 under clear skies and calm conditions.

Figure 9 shows the temperature trend along the second route under clear skies and calm conditions on January 27, 2015. Similar to the other temperature plots, the large decrease in temperature at the beginning of the ride is due to the Kestrel adjusting to the outdoor temperature. Here we can see a number of noteworthy temperature fluctuations along this route: There is a temperature maximum while riding over US 36, a temperature minimum just south of the overpass, another temperature minimum at the base of Marshall

and Davidson Mesas, and a large increase in temperature as the route increases in elevation towards the intersection of Highway 170 and Highway 93.

The temperature spike that is occurring over US 36 is likely due to a combination of factors. First, the large amount of concrete that composes the highway and the overpass has a greater heat capacity than the surrounding soil and vegetation. This implies that these surfaces cool off at a slower rate than the surrounding vegetated surfaces. In other words, there is less escaping outgoing longwave radiation occurring over concrete, which results in higher surface temperatures. Additionally, the flowing traffic on US 36 below the Cherryvale overpass acts to mix the warmer air that is over the concrete surface in a turbulent manner. This may result in a mechanical transport of the warmer air to the surrounding areas. Finally, the lack of vegetation in this area serves to reduce the amount of evaporational cooling of the air through the process of evapotranspiration.

After passing over US 36, there is a quick decrease in elevation, which is where the temperature dropped over 10 degrees Fahrenheit in just a few hundred meters. The decrease in elevation helps cold air pool in these localized topographic depressions. The colder air in this valley is denser than the warmer air over US 36, which causes it to sink due to a gravitational force. Also, there is substantially more vegetation surrounding this drop in elevation in comparison to the Cherryvale-US 36 overpass, which enhances the cooling of this air.

The next notable drop in temperature occurs at the intersection of Marshall Road and Cherryvale Road. This point lies between Marshall Mesa and Davidson Mesa, where there is a 60 foot drop in elevation as the route continues south along Cherryvale Road. It is no surprise

that this location is one of the coolest spots, due to cold air sinking downwards into this topographic depression. In this case, the temperature dropped 10 degrees Fahrenheit from the top of the hill, to the base of both mesas at the intersection of these two roads.

Once the route veers west onto Marshall Road, there was a gradual increase in elevation and correspondingly an increase in temperature. The warming may be due to a combination of an increase in elevation along with a “funneling” effect which is caused by the surrounding terrain. Marshall Road is situated in a topographic depression at the mouth of Eldorado Canyon which is located to the west. The unique location of this road sits between Davidson Mesa to the east, Marshall Mesa to the south, and a small hill to the north. When the prevailing westerly winds are forced downwards by the foothills to the west, the air is compressed and warmed adiabatically. These winds are being forced in between topographic barriers which acts to accelerate the flow. Since westerly winds would be flowing downhill along this segment of the route, the adiabatic warming could possibly be enhanced. It is difficult to pinpoint the exact cause of the drastic warming, mainly because the winds were calm throughout this time period. However, a similar trend can be shown under breezy conditions.

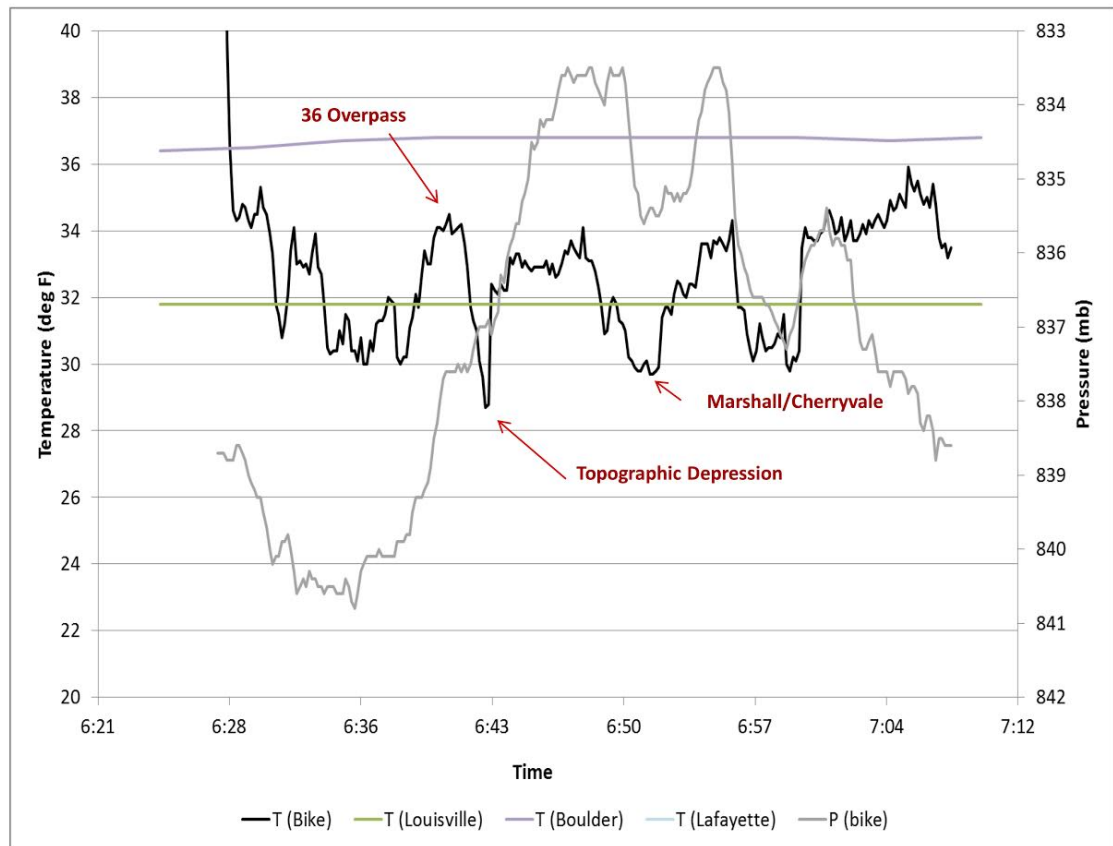


Fig.10. Temperature data collected along the second route during the morning of January 30, 2015. Mid and high-level clouds were observed during the data collection period, along with calm winds.

Figures 10, 11, and 12 show cases with cloudy skies and calm winds. In general, temperatures did not vary as much under cloudy skies as they did under clear skies. As mentioned earlier, clouds trap outgoing longwave radiation from escaping the boundary layer, which moderates temperatures and limits radiational cooling. The cloud type must also be considered. Low-lying, thick stratus clouds are more effective at trapping outgoing longwave radiation than mid or high-level clouds such as altocumulus and cirrus.

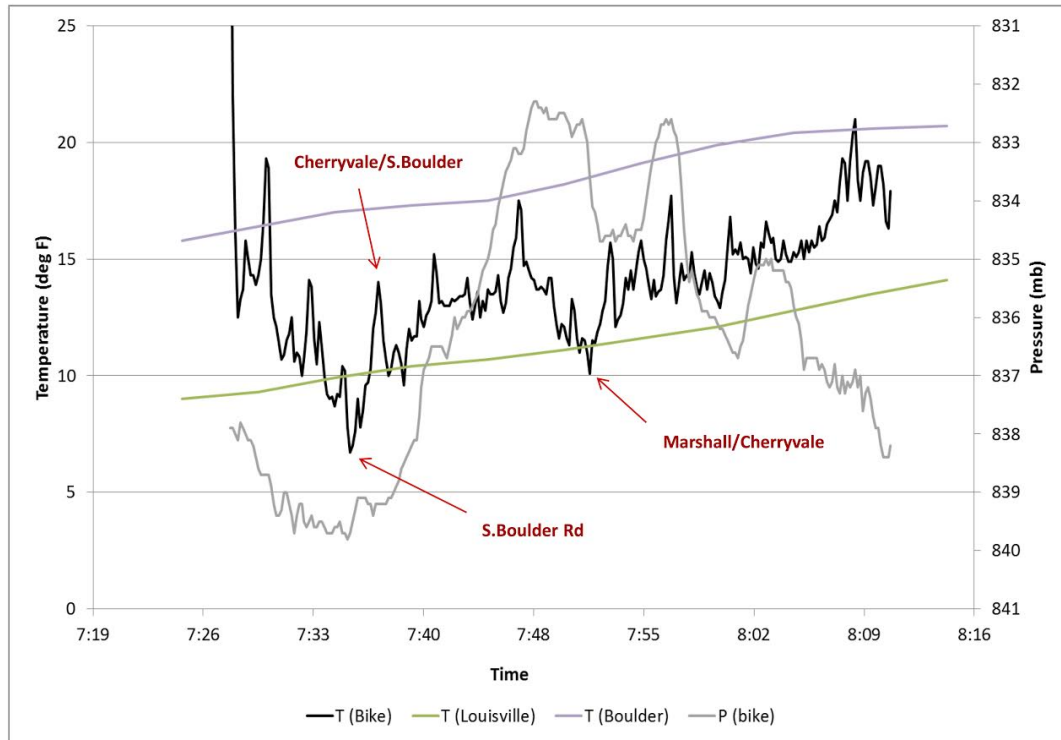


Fig.11. Temperature data collected during the morning of March 5, 2015. At the time, there were mid-level clouds and calm winds.

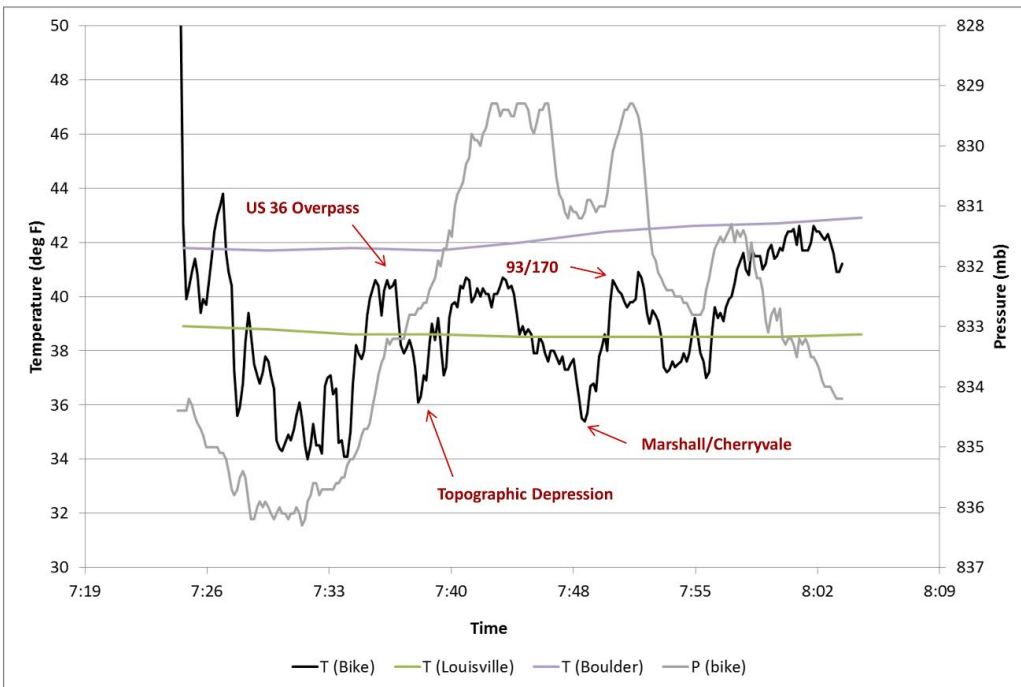


Fig.12. Temperature data collected during the morning of March 23, 2015 under mid-level clouds and calm winds.

When comparing Figures 10, 11, and 12 to Figure 9, we can see that under cloudy conditions, the temperature only varies by as much as 5 to 7 degrees Fahrenheit. Under clear skies, the temperature can vary by as much as 12 degrees Fahrenheit. It is also worth mentioning that there are many other factors that have an effect on the temperature distribution other than topography, wind speed, and cloud-cover.

Figure 12 represents a case with cloudy skies and breezy conditions. One interesting aspect of this data is the potential effect of snow cover on the temperature distribution. Right after Cherryvale Road turns to the west, the north-facing slope that is adjacent to the road was snow-covered. This is not surprising because slopes that face northward in the northern

hemisphere receive far more shade than slopes with a southerly aspect. As a result, the north-facing slopes tend to maintain their snow-cover for longer periods of time.

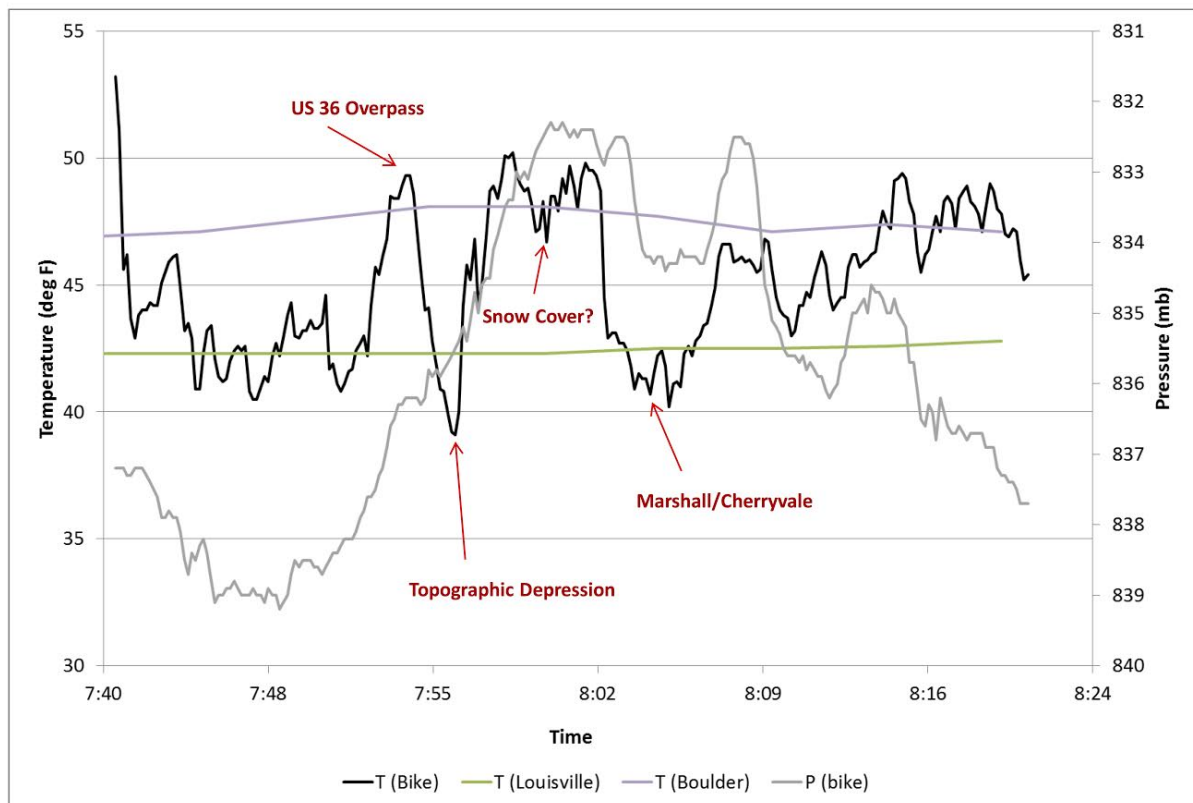


Fig.13. Observed temperature data during the morning of March 12, 2015 along the second route.

High clouds and breezy conditions were observed during the time of the data collection. An area of snow cover is indicated on the graph.

As I rode past the snow-covered region, there was a significant drop in temperature (Figure 12). Although the surrounding air temperature was above freezing, the temperature of

the melting snow over the slope was at the freezing point. This resulted in a downward sensible heat flux, since heat fluxes always flow down the temperature gradient. Since there was less of a vertical temperature gradient over the bare ground than over the snow-covered slope, there is less of a downward sensible heat flux over the bare ground than over the snow cover. This resulted in a cooler temperature over the snow-covered slope, because the vertical temperature gradient is proportional to the sensible heat flux. The larger downward sensible heat flux in this case, is providing the energy for the absorption of latent heat, which is what is melting the snow. This observation supports the fourth hypothesis.

Although the temperature trend in Figure 13 was observed during breezy conditions with some mid and high-level cloudiness, the larger temperature variation in comparison to Figures 10, 11, and 12 is likely to be partly due to this snow-cover located alongside the route throughout various spatial intervals. However, breezy conditions tend to moderate the boundary layer temperature distribution due to turbulent mixing, and therefore the exact cause of the large temperature range is unknown. Figures 9, 10, 11, 12, and 13 are supported by the third hypothesis, since low-lying areas experienced the lowest temperatures.

CONCLUSION

The data that was collected demonstrates how the temperature can fluctuate along a given route over very short distance and time intervals. As expected, the temperature did not vary as much given overcast and windy conditions in comparison to the clear sky and light wind

scenario. Topography, having few structures upstream, vegetation, and snow-cover seemed to have the highest impact on temperature given these conditions. When data was collected under windy conditions, the temperature variations were minor and seemed to occur on a random basis. An exception to this general trend occurred while passing through heavily built-up areas, where there was a slight increase in temperature, along with snow-covered areas where there was a decrease in temperature.

This research topic could be further explored by taking temperature measurements over even smaller time intervals. Additionally, the data could be collected along other different routes with similar spatial characteristics. The data collected along these different routes could then be compared to the measurements that were taken along the routes used in this research. The Kestrel 4000 Weather Station that was used in this research proved to be an extremely useful tool in determining what caused the temperature to vary over small spatial and time scales.

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