

A Study of the Nocturnal Boundary Layer Inversion in the Yampa Valley in the Central Rocky Mountains

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Abstract

Nocturnal temperature inversions form in mountain ranges all over the world. These inversions form on relatively cool, calm nights. The processes by which these inversions dissipate vary depending on the size and shape of the valley and the weather conditions in the area. The results of previous studies of temperature inversions can be applied to the Yampa Valley, which contains the city of Steamboat Springs, in northern Colorado, and can be integrated with data collected for this area. Timescales of the inversion destruction vary greatly in this study. Full mountain inversions seem to disappear sometime shortly after sunrise. Lower level inversions were observed to persist as late as nearly 1pm in one particular case, and were gone by 8am in other cases. These inversions appear to form and strengthen when wind speeds are less than 4 miles per hour. Any wind speeds above that begin to destroy the inversion quickly, or prohibit the inversion from initially forming.

Introduction

Typically in the atmosphere, temperature decreases with height. In rare cases where temperature increases with height, this is known as a temperature inversion. These inversions occur year round, but tend to form under certain conditions. Inversions are much more likely to form on clear, calm mornings, and can be enhanced by weather processes such as fresh snowfall. The processes of how these structures form and then dissipate can be very complicated. The processes by which these inversions occur and dissipate change in form and length depending on the conditions.

The study of these nocturnal and morning temperature inversions is an interesting and necessary undertaking. Information about how these inversions form and dissipate can help in forecasting these events. This information is invaluable in areas such as Steamboat Springs, where the entire state of the city, and especially the economy, can rest on what weather conditions exist. Knowing about these events can help the ski area in better determining the time to open the slopes, as well as how to prepare people for the weather conditions they may face while visiting the area.

There are two ways that these temperature inversions can be destroyed during the morning hours, and this depends on the scale and size of the valley. The first of these ways is by the formation of a convective boundary layer at the surface (Whiteman et. al. 2004). This occurs when radiation heats the surface of the valley or sinkhole. The air in immediate contact with the ground warms due to the sun's radiation, and convection begins to slowly warm the surface layer due to warm air rising. This convection leads to

mixing with the cooler air right above the ground, and slowly mixes the warmer air upwards away from the surface.

The other way that the dissipation of this inversion occurs is by subsidence, which is large scale sinking air from above. As air at the surface begins to warm, an upslope flow is created and air is removed from the surface. In order for conservation of mass to apply, the air above the surface must sink to take its place. Since this air is warmer than the air that was at the surface, the surface air temperature increases and the inversion is destroyed (Whiteman et. al. 2004).

The data collected in this study will be compared and contrasted to the information listed above. This will include the timescales of dissipation, as well as a comparison of mean wind speeds that dissolve the inversion, or prevent the inversion from forming in the first place.

Methodology

The basic plan of data collection seemed rather simple, however the collection of this data proved to be more difficult than was expected. The data had to be collected between March 12th and March 17th, no matter what the weather conditions were. During this entire time period, data was collected from eight Mesonets, which are remote weather stations that were placed around the Steamboat ski area. Each weather station measures temperature and relative humidity, and a select few take wind speed and direction measurements. These mesonets take measurements at 15 minute intervals throughout the day.

These eight mesonet locations are placed strategically around the ski area in order to provide good measurements throughout the ski area. The lowest site, from now on referred to as W0, is at the base of the ski area at 6930 feet. The highest site, from now on W6, is at the highest point in the area at 10420 feet. The other mesonets, which will be W1, W2, W3, W4, W5 and W7 from this point on, are placed all over the mountain, generally between 8000 and 9200 feet, with one exception of W4, which is at 9840 feet.

Due to the specific needs of the weather conditions for this phenomenon to occur, data collection to supplement this mesonet data was only completed on March 17th. This data collection began at 8am and continued until 10:30am. Measurements of temperature, dew point, and elevation were taken just to name a few. This collection was done while skiing down the slopes from one of the peaks of the mountain to the base of the ski area, which is slightly above the level of the town itself. Vertical temperature profiles were then taken by riding 3 separate ski lifts back to the top of the mountain. All of this data collection was completed using the Kestrel 4000, which is a handheld device that records and stores all of this data.

Results

Data from two days will be used to analyze the temperature inversion. Primary data will be used from March 16th and 17th. Again, data from the mesonets will be used for all 3 days, and supplemental data will be integrated into the mesonet data from the 17th.

On the evening of the 15th, winds of up to 40 miles per hour were persistent at the top of the mountain. These winds were still strong, so supplemental observations were not going to be taken on the morning of the 16th, as an inversion was not expected. Looking at the mesonet data for the 16th, however, an inversion did form. The winds diminished

over night and clouds cleared out early in the evening. This date will be analyzed completely using mesonet data. The inversion first appeared at 3am in the mesonet data the morning of the 16th. The inversion then strengthened very slowly to a difference of over 9 degrees Fahrenheit at 7:30am from the top of the mountain to the bottom. The inversion then disappeared very quickly, as it was gone by 8:15am.

Figure 1 above shows the temperature difference from the top of the mountain (Mesonet W6) to the bottom of the mountain (Mesonet W0). This chart begins at

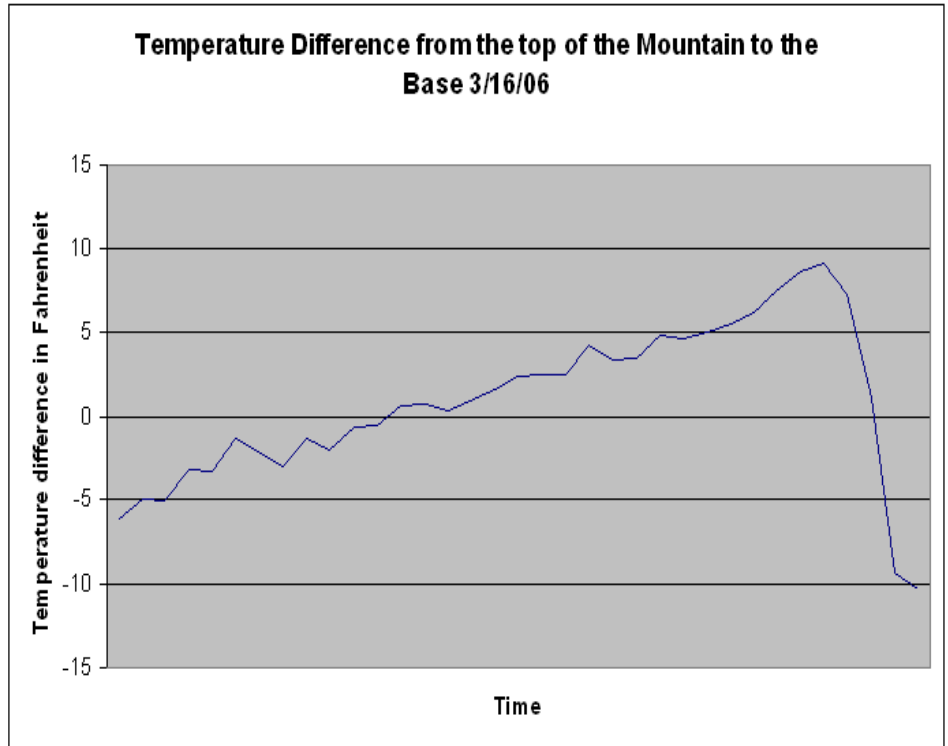


Fig 1) This is a chart of the temperature difference from the top of the mountain to the bottom. Positive values indicate warmer temperatures at the top than the bottom. The chart begins at 12am and ends at 8:30am on the 16th.

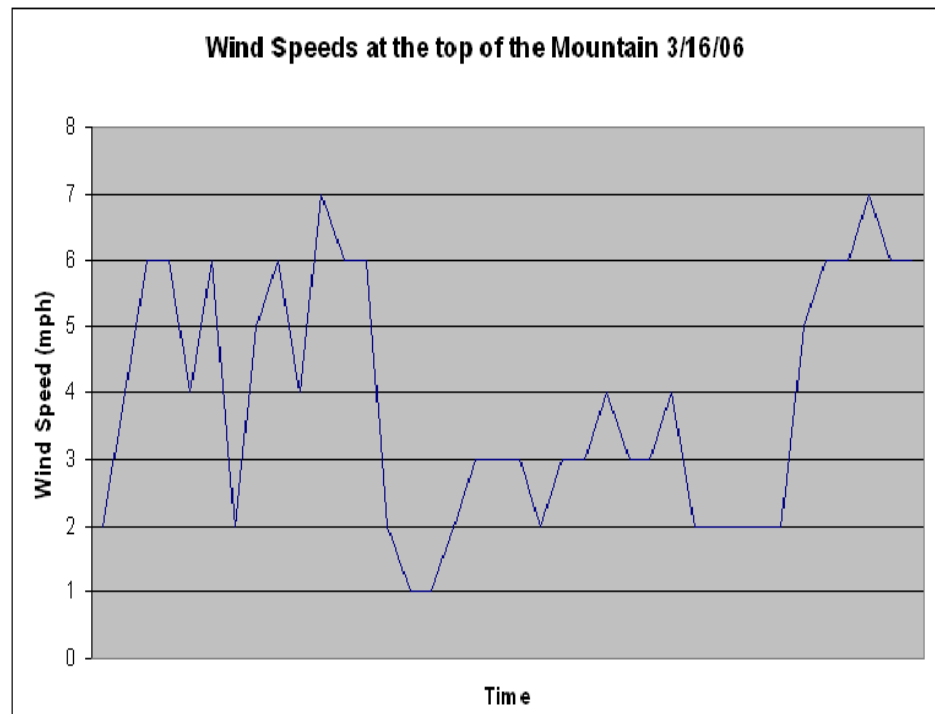


Fig 2) This is the chart of wind speeds at the top of the mountain that corresponds to the same time as the temperature difference seen in figure 2 above. Measurements are taken every 15 minutes.

midnight, and runs until 8:30am, which is after the inversion dissipated. Positive values indicate when temperatures were warmer at the top than at the bottom.

The wind speeds overnight began to drop, and between 3am and 3:15am, the wind speed dropped from 6 miles per hour to 2 miles per hour. Wind speeds then stayed light, between 2 and 4 miles per hour, until 8:15am, when speeds picked up to 7 miles per hour. This time of increased wind speed corresponds exactly to the time when the inversion quickly disappeared.

Figure 2 shows mean wind values at the top of the mountain (Mesonet W6). This graph also begins at 12am and runs until 8:30am. Wind speeds are above 4 miles per hour until 3am, which is the time when the inversion began to form, as can be seen again by looking at Figure 1. Winds then begin to increase at 8am, which is right after the inversion has reached its maximum strength, and right before the inversion disappears.

The first partially clear night of the trip without howling winds occurred on the night of the 16th, into the morning of the 17th. An inversion did form on this day as well, and this will be analyzed using the mesonet data, as well as the data collected as discussed in the methodology section. The strength of the inversion from the top of the mountain to the bottom was much weaker on this day than on the previous day. Clouds were more persistent the night of the 16th into the 17th. The wind speeds, however, were much weaker on the night of the 16th than on the night of the 15th.

The inversion took a different form on the 17th, however. The inversion mixed out of the top of the mountain area very quickly, such as in the previous day. All evidence of a bottom to top inversion was gone by 7:30am. After this time, however, a nearly isothermal layer, or layer where temperature is constant with height, appears above

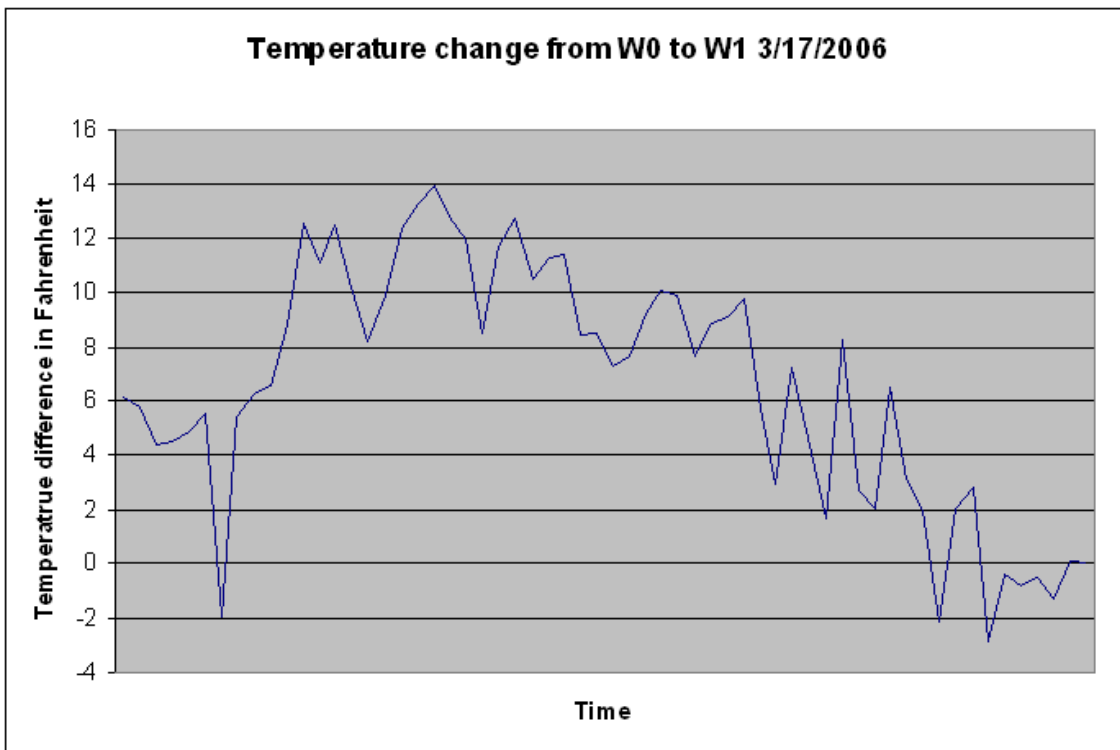


Fig 3) This figure shows the temperature difference between the base at 6930 feet and a point on the mountain at 8070 feet. This chart begins at 12am and runs until 2pm on the 17th. Positive values indicate warmer temperatures at the higher altitudes.

approximately 8000 feet.

The upper level isothermal layer may be a result of large scale synoptic forcing due to a large weather system. Sinking air from above that was already relatively warm, warms even more as it sinks. As this air sinks down the mountain, the temperature increases. Upper air analysis maps from Unisys weather indicates a high pressure system centered right over northern Colorado at 6am on the 16th. This would lead to a large scale sinking motion in the atmosphere and warming air as it descends.

This warming is counteracted by the cooling effect that would normally form a mountain inversion. The air at lower levels efficiently radiates heat to the upper atmosphere without the synoptic scale warming, allowing the lower level inversion to form below it.

The lower level inversion appears to be a typical nocturnal mountain inversion. Clear skies allow for efficient radiation of heat to the free atmosphere. The cold air then pools at the bottom of the valley with the warmer air sitting above it.

This lower level inversion was much stronger in magnitude than the early morning upper level inversion. From all the data taken, this inversion appears to only go up to approximately 8100 feet, so the inversion depth is about 1200 feet. This inversion reached its maximum strength at 4:45am when there was a temperature increase of 14 degrees Fahrenheit from 6900 feet to 8100 feet. This inversion stayed approximately the same strength, between 9 and 14 degrees Fahrenheit until 9:30am. Up to this point, the katabatic flow of cold air down the mountain had been counteracting the heating due to radiation on the sunny morning.

At this point, the inversion began to inconsistently decrease until it disappeared around 12:30pm. Looking at the wind values at the top of the mountain, 9:30 is approximately the time when the average wind values went from 1-2 miles per hour and

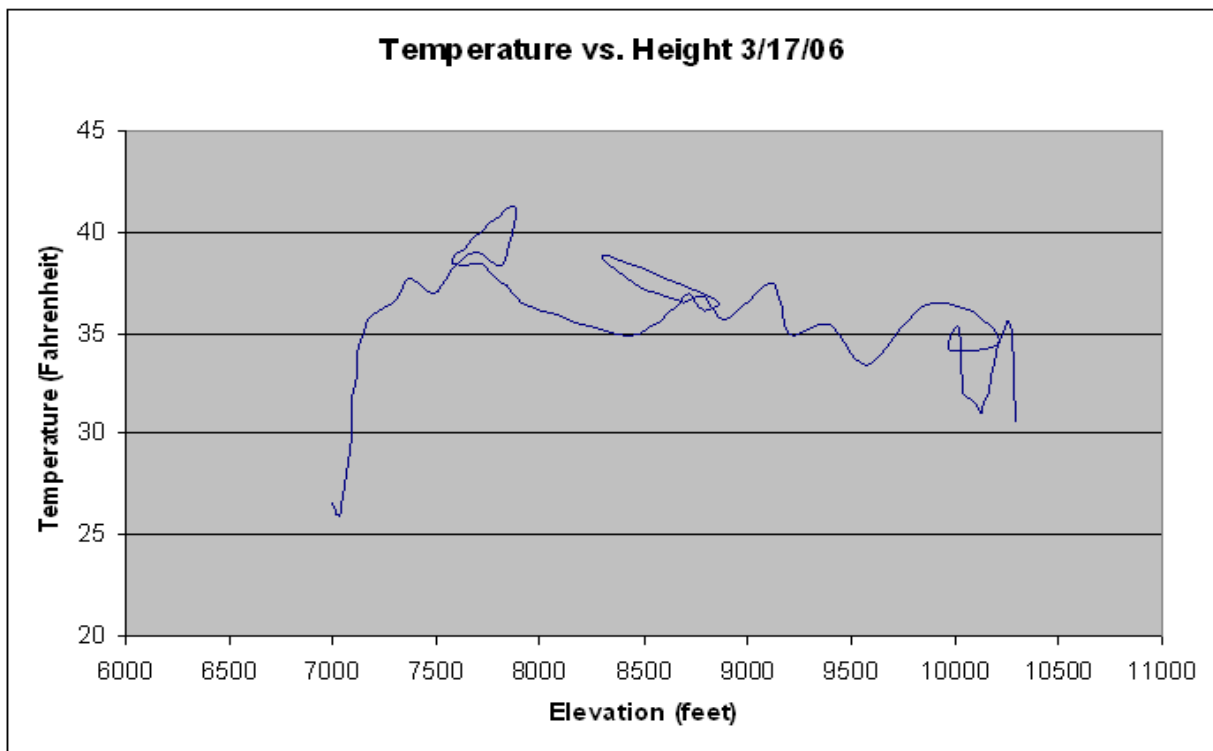


Fig 4) This is a vertical temperature profile from the base of the mountain (6994 feet) to the Storm Peak (10420 feet). A nearly isothermal layer is observed above 8100 feet where the inversion ends.

began to increase to up to 11 miles per hour. These winds were consistent with wind values over the entire mountain, where wind values picked up around 9:30am. After 12:30, normal temperature profiles were observed, as temperature was either constant or decreased with height.

Figure 3 shows the temperature difference from the base of the mountain (Mesonet W0) to a point higher on the mountain at 8070 feet (Mesonet W1). This plot begins at 12am on the 17th and ends at 2pm on the 17th. Figure 3 shows that the temperature inversion persists until 12:30pm.

A vertical temperature profile of the entire mountain can then be looked at to get an idea of the structure of the inversion. The vertical temperature profile was discovered by using the Kestrel 4000 as described in the methodology for collecting supplemental data. The data used to create this vertical profile was collected between 9:13am and 10:08am on the 17th. Although the inversion can change in intensity and level in this amount of time, this is the only way that a vertical temperature profile could be acquired without the ability to launch radiosonde balloons, which would measure temperature throughout the depth of the atmosphere.

Figure 4 shows this vertical profile. The coldest temperatures in the profile were at the bottom of the mountain at 6994 feet. The temperature then increases rapidly until approximately 8100 feet. The temperature difference between the base and the top of the inversion is 15.4 degrees Fahrenheit. This inversion strength is slightly stronger than that observed in the mesonet data in Figure 3. This may be because of the small scale of the top layer of the inversion. Mesonets are not placed frequently enough to accurately depict the exact height and temperature difference of the inversion. Above approximately 8100 feet, the temperature stays quite consistent, and actually decreases with height slightly to the top of the mountain. The lower height of the inversion verifies the idea of a large scale subsidence event making the inversion layer relatively shallow as the height of the inversion decreases with time.

Discussion

These results from the Yampa Valley study will now be compared to the conclusions of previous studies of mountain valley inversions.

The geography of the valley is the first thing to consider because that can have an effect on the structure of the inversion beyond weather conditions. The base of the valley is at 6930 feet, which is approximately 2112 meters. The total depth of the valley is approximately 3600 feet, or 1100 meters (www.steamboat.com, Steamboat Rec. Area). The base elevation of the valley is similar to that of the research by C.D. Whiteman, but the vertical depth is much greater. The Yampa Valley is also very broad when compared to valleys studied by Whiteman and others. According to the research done by Whiteman, in larger valleys, the inversions typically reach a depth of one half the depth of the valley. In the case of the 17th, the inversion reached approximately 8100 feet, which is almost exactly 1/3 the depth of the valley. This number is relatively smaller than the depth observed in other studies. This could be due to the result of the larger

scale weather conditions, or the fact that people live in the Yampa valley, which cannot be said of the other valleys studied. Warming from commerce below may help reduce inversion strength. This may also be a direct result of the increased broadness of the Yampa Valley when compared to the other valleys studied in previous research.

These inversions observed in the Yampa Valley were generally much weaker than the inversions observed by C.D. Whiteman and others. The maximum strength of the inversion in the Yampa Valley was 15.4 degrees Fahrenheit, or a little less than 9 degrees Celsius. This is much weaker than the average strength of the inversions observed by Whiteman and others. With such a small survey in the Yampa Valley case, it is difficult to tell if these are typical values of inversion strength or not. The conditions may not have been favorable to form strong inversions. Winds were also not as calm as they could have been which may have helped disrupt formation. Also, as mentioned above, a residential population living in the Yampa Valley may have an impact on the temperature structure. There was also a previous study by Whiteman and McKee (1981) in the Yampa Valley where winter temperature inversions averaged -10 degrees Celsius from bottom to top.

The effects of wind speed at the top of the mountain are very well defined for the Yampa Valley. Looking at the data from the entire week, 4 miles per hour seemed to be the key value. When winds were greater than 4 miles per hour, an inversion did not form, or destruction of the inversion began. When winds were 4 miles per hour or less, the inversion could form, or continue to intensify.

The timescales of dissipation of the inversion in the Yampa Valley varied greatly over the course of the study. The very weak inversion observed from the bottom to the top of the mountain dissipated within approximately 1.2 hours of sunrise on both mornings that it formed. The strong lower level inversion, however, lasted approximately 6.1 hours. The lower level inversion is cut off from the main flow of the wind, making it much easier for that inversion to last longer. The timescale of the inversions discussed in the introduction land in between these two values. Again, with such a small sample, it is difficult to know if this is typical or not.

The destruction of these inversions appears to fit the "Pattern 3" dissipation as described by Whiteman (2004), especially on the morning of the 17th, where subsidence appears to be lowering the inversion, and strong sunshine creates a convective boundary layer and helps destroy the inversion.

The height of the inversion on the 17th of 8100 feet, or approximately 750mb also varies from the study done by Whiteman and McKee (1981). In this 1981 study, Whiteman et. al. revealed an average boundary layer inversion height of 780mb, which would put it lower on the mountain than observed in this research. These values are close enough to validate previous studies with the Yampa Valley case. Again, it is difficult to assess this value with the small sample taken here, but this could be due to different synoptic conditions on this day.

A number of useful observations can be taken from this study, even though the sample data is limited. The first is that if the wind is over 4 miles per hour, inversions will not form, or dissipate quickly from the mountain top down. This value is only valid for the Yampa Valley. A second conclusion, which was not noted in other research, was that even though conditions do not have to be perfect to form an inversion, clouds seem to have a greater impact on stopping inversion development than higher wind speeds.

This is noted based on the fact that there were a few clouds on the evening of the 16th, and the top to bottom inversion was much weaker than on the previous night when winds were slightly stronger. A final conclusion is that the destruction of nocturnal boundary layer inversions in the Yampa Valley is due to the combination of the development of a convective boundary layer, as well as subsidence aloft, which makes it a “Pattern 3” destruction, according to Whiteman.

Conclusions

Boundary layers and their destruction is a phenomenon that is only beginning to be better understood. Much of the research that has been done on this topic has occurred in the last 10 years. One possible reason for the lack of research is the great cost of sending radiosonde balloons into the atmosphere at the frequency that is required to accurately depict the transformation that occurs in the short time period in the boundary layer (Whiteman et. al. 2004).

Having inversion destruction information could be very useful in determining when these inversions are going to occur and how long they will last. Forecasting these inversions will be useful for a diverse group of people, and can help with anything from predicting harmful health conditions to predicting conditions that will be favorable for different precipitation types based on the surface inversion.

Acknowledgements

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