The generation and dissipation of a nocturnal inversion in the Yampa Valley: The comparison of wind flow between field observations and UW-NMS

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Abstract

The generation and dissipation of the nocturnal valley inversion has been studied over the last few decades via rawinsonde observation and early numerical modeling techniques. From these studies, three types of inversion dissipation mechanisms were used to characterize the destruction of these diurnal phenomena. Since the destruction of a valley inversion most commonly occurs due to type 2 dissipation discussed by Whiteman (1982), the goal of this study was to put this theory to the test via observational and modeling investigation. During the week of 28 March 2010 at the Storm Peak Laboratory in Steamboat Springs, CO, field observations and mesonet data were used to collect physical observations regarding nocturnal valley inversions. Along with this, the UW-NMS model was used to simulate a valley inversion, using a 3-grid model run. While both observation and computer modeling showed the existence of a nocturnal valley inversion in situations where inversions were expected, only the model successfully showed type 2 inversion destruction. Observations showed inversion dissipation via both the type 1 and type 3 dissipation mechanisms. Reasons for this are presented at the end of this study.

1. Introduction

The presence of an inversion and its dissipation within the morning hours has been studied for several decades. Whiteman (1982) showed that three different inversion destruction mechanisms existed within the Yampa Valley using rawinsonde data and local observations. Method 1 dissolved the inversion via the raising of the convective boundary layer via the convergence of turbulent sensible heat flux and mass entrainment at the top of the inversion via convective plumes. The second destruction method involved inversion subsidence, where warming of the valley due to morning incoming solar radiation generates thermally driven upslope flow, allowing for mass to evacuate out of the valley and lower the inversion until its destruction (Whiteman, 1982 & Whiteman et. al., 2004). The third destruction method is a combination of the first two, and is the most commonly observed type of nocturnal valley inversion destruction (Whiteman, 1982 & Whiteman and McKee, 1982).

Whiteman and McKee (1982) accurately modeled the dissipation of a nocturnal valley inversion, showing that an energy partitioning parameter “k” can be used to correctly distribute energy needed to either raise the CBL or lower the inversion via subsidence to induce its destruction. Assuming a horizontally homogeneous cross valley temperature structure, constant potential temperature (as height increases) within the inversion, arbitrary height and width values for the valley along with the rate of energy input (solar energy flux across the upper inversion surface) a type II inversion was successfully simulated within the Yampa Valley. Only the effects of shading with respect to timing of complete inversion destruction played a significant role between observational and modeling inversion destruction. Zoumakis and Efstathiou (2005) further explored the model discussed in this section, showing that the inversion destruction
height is influenced by inversion destruction types I, II and III along with the partitioning parameter k and various topographic characteristics of the valley.

Interestingly, the use of a mesoscale model not specifically designed for studying nocturnal inversions (as one was created for this special case in Whiteman and McKee (1982)) has not been studied in detail. Therefore, the goal of this project is to investigate changes in various variables as a valley inversion dissipates, along with the comparison of observations to a high resolution mesoscale model (UW-NMS). It is hypothesized that type II inversion dissipation will occur on days where a nocturnal inversion developed overnight. The NMS model will be able to show both the inversion and its dissipation through the analysis of smoke plumes throughout the morning and early afternoon hours.

2. Methods:

Observations were collected during the week of 28 March 2010 using a combination of station data and human inspection at the Storm Peak Laboratory site in Steamboat Springs, CO. Data was collected via field observations using both a handheld anemometer and thermometer. Time of observations was 1400-1800 UTC on 28 and 29 March 2010. A single observer was sent from the Storm Peak Laboratory site down to the base of the Gondola at the bottom of the valley, taking measurements at 8-11 sites (figure 1).

Along with field observation, various pre-existing mesonet stations within the mountain and valley region were also used (Table 1, see last page). Observations of dry bulb temperature (°C) and relative humidity (%) were collected from all stations from 28-30 March 2010. Wind speed (mph) and direction (°) were collected during the same time frame, but only from the Bottom of Ego and Vagabond Saddle stations, as the other stations did not list such observations.

After the completion of field observations, a numerical model simulation was run using the University of Wisconsin Non-Hydrostatic Mesoscale System (UW-NMS) (Tripoli, 1992) with respect to 31 March 2010 inversion. A 3-grid (nested) system was used such that the highest resolving grid was placed over the Steamboat Springs, CO region. Using Vis5d display, plots of cloud cover and the path of a smoke plume tracer within the Yampa Valley was used to show the existence and dissipation of a valley inversion.

Figure 1: Map of Steamboat Springs region, with bold solid lines denoting routes skied by human observers for data collection. Regions marked with a circled “x” indicate approximate location of an observation region. Route 1 is denoted as a red, solid line, while route 2 is denoted as a black, solid line. Route 3 was located on the backside of this map along the Morningside Slope (not shown).
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Table 1: Mesonet Station Information listed in ascending order (based on height) from the Yampa Valley to the top of Storm Peak. Observations from the Mesonet sites were taken daily in 15 minute increments. Information retrieved from Gannet Hallar.

3. Synoptic Setup:

In order for an ideal nocturnal inversion to develop and dissipate successfully, clear skies are required overnight and during the morning hours, along with light winds in the valley (Whiteman, 1982). These conditions were observed on 28-30 March 2010. Over the Colorado region, an upstream ridge (supergeostrophic flow) along with a downstream trough (subgeostrophic flow) at 300 hPa indicates convergence aloft and downward vertical motion. This allows for high pressure in the Yampa Valley to develop, along with the lack of significant cloud and precipitation development during this time. Northwesterly flow occurs over Colorado (figures 2a, 2b, 3a and 3b) until 30 March 2010, where flow shifts to a more westerly flow throughout the troposphere (figures 2c and 3c).

On 30 March 2010, a strong jetstream feature moves over the west-central United States. The right jet-exit region approaches western Colorado, favoring downward vertical motion in the region (figure 2c). Due to this, clouds and precipitation are not significant, allowing for clear skies to develop during the evening and morning hours. Therefore, all 3 days analyzed are favorable for the generation and dissipation of a nocturnal inversion.

4. Conceptual Model:

Figure 4 outlines a conceptual model describing the genesis of a nocturnal inversion along with its dissipation via type 2 dissipation discussed by Whiteman (1982). Figure 4a (top-left) shows the genesis of the inversion. Clear skies and light winds within the valley allow for radiational cooling to occur, generating a lower valley cold pool. Strong winds aloft (at the top of the valley) can still exist during inversion development. Katabatic (downslope) winds flow into the valley, adding cool, dense air into the valley system. From this, air in the cold pool can rise due to mass continuity, as mass must go up due to the piling of mass in the valley. Due to the radiational cooling, a temperature inversion is created. The temperature profile is shown to the left of the valley in the conceptual model, with temperature increasing to the right along the abscissa (height increases upwards along the ordinate).

During sunrise (figure 4b), the slope receiving the most sunlight (not shaded) heats rapidly, generating thermally driven upslope winds. Over time, the shaded slope begins to develop upslope winds also as the sun moves position throughout the day. The upslope winds take mass out of the valley, and by mass continuity, the inversion will begin to sink due to this lower-level mass divergence. Up-valley winds occur in the cold pool region below the inversion top, with down-valley winds near the top of the inversion. Winds increase in magnitude within the boundary layer and lower valley, with strong winds still present aloft.
As incoming solar radiation continues to heat the valley slopes throughout the day (figure 4c), the inversion continues to sink.

Figure 2: 3-panel plot of 300 hPa geopotential height (solid white contour every 30 m), wind speed (fill, knots) and wind vectors (larger vector indicates stronger magnitude). Plot times are all 1200 UTC at a) 28 March 2010, b) 29 March 2010, and c) 30 March 2010. All plots obtained from Unisys Map Archive website.

Figure 3: 3-panel plot of 700 hPa geopotential height (solid black contour every 30 m) over the CONUS. Plot times are all 1200 UTC at a) 28 March 2010, b) 29 March 2010, and c) 30 March 2010. All plots obtained from Plymouth State University Archived Data website.
Up-valley winds begin to decrease in magnitude as the cold pool dissipates due to mass evacuation. Towards the early to middle afternoon hours, the cold pool below the inversion dissipates, and the inversion eventually dissipates. Upslope winds start to weaken, and become katabatic winds during the evening and overnight hours. Winds within the valley are similar in magnitude to winds aloft in the afternoon.

It should be noted that snow cover increases the longevity of inversion existence. Since snow cover increases surface albedo, more incoming solar radiation is reflected, preventing an increase in the magnitude of thermally driven upslope winds. Since the Yampa Valley is snow covered during this time of the year, snow cover is an important factor to consider.

Figure 4: Conceptual Model of the creation and dissipation of a nocturnal inversion. See text for detailed description.

5. Results:

a) Field Observation Results:

An inversion was observed during both the 8:15 am and 10:55 am LST ski runs (figure 5a and 5b) on 28 March 2010. The magnitude of the inversion (defined as the greatest temperature difference between the surface and top of the inversion) was ~8 °C near 775 hPa. Another inversion appears to be present at ~740 hPa, but is not considered the true nocturnal inversion, since this feature does not reach the surface. While dew point temperatures increase with height within the inversion range, a small dew point inversion correlates with the lower level inversion at 775 hPa. Wind speeds remained light and variable between the valley surface and the top of the inversion, as expected from Whiteman (1982) (figure 5c). Wind speeds do increase aloft (near Storm Peak Laboratory) to ~14 knots.

During the 10:55 am run, the inversion appears to increase in height, as the inversion top is ~745 hPa. The magnitude of the inversion increases to ~10 °C. A weak inversion is present below the largest inversion, with smaller inversions above the main inversion. These inversions are neglected, as plots represent a best fit curve for the collected data. Nevertheless, the valley inversion is rising with height, which was not expected initially.
Field observations from 29 March 2010 were only collected during one time (~10:00 am LST), but data was collected from three different ski runs, mapped out in Figure 1. Regardless, an inversion was measured in all three cases (figures 6a and 6b). The run 1 inversion occurs at ~746 hPa, with a magnitude of only ~2°C (figure 6a). The inversion in runs 2 and 3 occur at ~755 hPa and ~692 hPa, respectively. A magnitude of ~5°C was observed with both inversions in runs 2 and 3. Similar to the 28 March 2010 observations, runs 1 and 2 show dew point inversions around the same pressure level as temperature inversions. On the other hand, run 3 does not exhibit such a correlation.

An analysis of vertical wind speed profiles for each run (figure 7) is consistent with the wind profile from 28 March 2010. Runs 2 and 3 (figures 7b and 7c) show the best profiles, with wind speeds remaining light and variable below and just above the inversion. Aloft (towards the lowest pressure levels observed), wind speeds are over 10 knots. In the first run (figure 7a), winds remain under or near 5 knots throughout the profile. Hence, while winds within the inversion region are light as expected, the lack of stronger winds aloft was an unexpected result.

b) Mesonet Results:

Due to the risk of significant error from field observations (explained in the discussion section), mesonet data from 28-30 March 2010 was used to confirm any inversions observed. Fortunately, nocturnal inversions did develop and dissipate during this timeframe. Inversions from all 3 days began to strengthen around 6:00 am LST (figure 8a), with the inversion on 30 March 2010 exhibiting the strongest magnitude (~9°C). Magnitudes of the other inversions are ~4°C. Throughout the morning, solar heating along the valley slope increases the magnitude of the inversions on 28 and 29 March, while the 30 March inversion slightly weakens (all inversions ~8°C in magnitude) (figure 8b). The height of the inversions decrease in the 28-29 March cases, while the 30 March case does not exhibit a significant height change.
Figure 6: Plot of temperature (dark grey line, °C) and dew point temperature (light grey line, °C) created from field observations on 30 March 2010. All runs performed ~10:00 am LDT. See figure 1 for routes taken for runs 1, 2 and 3. For all plots, temperature is plotted on the abscissa, with pressure (hPa) along the ordinate.

Figure 7: Plot of the wind speed profile (red line, knots) during a) Run 1, b) Run 2 and c) Run 3. All field observation runs were conducted ~10:00 am LDT on 30 March 2010. Wind speed is plotted on the abscissa, with pressure (hPa) along the ordinate in all plots.

At 12:00 pm LST (figure 8c), the inversion features have nearly dissipated in all 3 cases. The 28-29 March scenarios show no significant height change from the 9:00 am LST profiles, with inversion strengths ~3.5°C.

The inversion is virtually invisible on 30 March 2010 at this time, with a ~1.5°C magnitude. This inversion increases slightly with height.

While figures 8a-8c show results expected with inversion dissipation, the temperature profiles of 28-29 March show...
unexpected results during the middle afternoon hours (~3:00 pm LST). Inversions seem to exist above the region of previously noted inversion heights during earlier hours, with two inversion peaks occurring in both situations. The peaks occur ~2400 m and ~2750 m AGL. The 28 March 2010 inversion shows inversion magnitudes of 5°C (higher inversion) and ~1.5°C (lower inversion), with the 29 March 2010 having magnitudes of ~5°C and 3.5°C for the higher and lower level inversions.

On the other hand, figure 8d shows no existence of a significant valley inversion for 30 March 2010. A nearly constant decrease in temperature is observed throughout the valley. This was expected based on past findings by Whiteman (1982) and Whiteman and McKee (1982). Only a slight increase in temperature is seen at 2500 m AGL, but this is insufficient to be considered an inversion based on time of day along with the weak magnitude of the temperature perturbation.

Figure 8: 4-panel plot of the Yampa Valley temperature profile as observed by a series of mesonet stations at a) 0600 LST, b) 0900 LST, c) 1200 LST and d) 1500 LST for 28-30 March 2010. Temperature (°C) is plotted on the abscissa, with height (m) along the ordinate.

c) Model Simulation Results:

An analysis of the 3-grid model simulation using UW-NMS simulates the creation of a nocturnal inversion on 31 March 2010, but does not model its destruction very accurately. The evolution of the inversion feature is shown in figure 9. Since cloud cover was minimal overnight (figure 10), radiative cooling allows for the development of a nocturnal inversion at ~600 hPa. Wind speeds remain calm under the inversion, with winds aloft greater than towards the surface. Over time, the inversion feature becomes stronger, as the temperature difference between the inversion and surface increases. At the same time, the inversion begins to lower throughout the morning hours (figures 9b and 9c). Subsidence of the inversion occurs, as daytime heating along the slope of the Storm Peak Mountain induces mass evacuation out of the valley in the form of daytime upslope wind. The neutral layer above the inversion appears to sink along with the inversion. The inversion is nearly destroyed by 0400 UTC 1 April 2010, as the magnitude of the inversion is ~1°C. An inversion still exists at this time, and this could indicate the formation of a second inversion.
from the setting of the sun for the following evening.

Figure 11 shows the existence of the nocturnal inversion on 31 March 2010 via the path of anthropogenic forcing within the Yampa Valley. At 0700 UTC, a smoke plume rising from the valley travels from the surface upwards, but is sheared at a 90° angle towards the northeast due to the strong winds aloft (figure 11a). Since the plume rises upwards without changing its path until reaching the upper tropospheric wind field, it is shown that winds are calm within the valley. Throughout the morning and early afternoon hours (figures 11b and 11c), the tracer spreads throughout the Yampa Valley, indicating an increase in wind speed and a wind shift allowing for this to occur. Since the inversion is lowering, mass is evacuated out of the region, allowing for slope winds to spread the tracer around. This continues all the way into the evening hours (figure 11d).

6. Discussion and Conclusions:

While both the field observations along with the mesonet data shows the existence of an inversion each morning from 28-30 March 2010 in the Yampa Valley region, the dissipation mechanism for each inversion did not match the type 2 dissipation mechanism from Whitman (1982) as expected. For example, the 28-29 March 2010 inversion cases did not show a significant increase or decrease in height throughout the day. In fact, it is difficult to tell whether or not the inversions truly dissipated. This is due to the existence of an inversion in both cases towards the top of the valley. It is possible that this may be the same inversion as investigated in the morning hours, but the inversion increased height rather than subsided. Since the inversions increased with height before expected dissipation, this indicates that the convective boundary layer growth forcing dominated any mass evacuation due to thermally driven upslope flow induced by daytime heating.

Similarly, while nocturnal inversion dissipation was observed on 30 March 2010, no significant inversion subsidence occurred either. While the inversion did not increase height significantly, the inversion remained near the same height throughout the morning and early afternoon hours. This implies a combination of the type 1 and type 2 inversion dissipations, and therefore this inversion dissipation followed type 3 destruction. Therefore, both the increase in depth of the convective boundary layer along with the mass evacuation due to daytime heating leading to inversion subsidence must have occurred.

While not expected, the lack of a significant height change with observed inversions during the 28-29 March 2010 field observation sessions were most likely a combination of unexpected dissipation mechanism along with human and instrumental error. For example, temperature and wind speed error can easily occur based on where the observer was standing. Since the observer is on the ground along the valley slope, the blocking of wind flow due to trees, along with the local trapping of incoming solar radiation along the ski hill area can easily distort wind and temperature data.

While the observational data did not show the dominance of type 2 inversion dissipation in the Yampa Valley, the UW-NMS model simulation was able to successfully and accurately simulate this. The inversion feature developed during the overnight hours with no significant cloud cover present. The inversion grew in magnitude and, upon simulating daytime hours, began to subside as mass was evacuated from the valley. This was also represented by analyzing a smoke plume tracer in the region. During the inversion existence, the smoke plume was “trapped” in the valley, and the smoke stopped rising near the middle troposphere. Upon inversion dissipation, the smoke plume traveled throughout the valley, as air was evacuated via thermally driven upslope winds. Therefore, nocturnal inversion generation and type 2 inversion dissipation were represented successfully.

One parameter that was difficult to determine was the amount of snow cover within the Yampa Valley. While many of the
Figure 9: Soundings in the Yampa Valley region generated by UW-NMS during the 1800 UTC 30 March 2010 model run. Sounding times are a) 0700 UTC, b) 1300 UTC, c) 1700 UTC and d) 0400 UTC 31 March 2010. Temperature is plotted as a solid red line, with dew point temperature plotted as a solid green line.

Figure 10: Vis5d images of topography (yellow isosurface) and log differential of cloud droplet condensate (blue fill) from the Yampa Valley region at a) 0700 UTC 31 March 2010, b) 1300 UTC 31 March 2010, c) 1700 UTC 31 March 2010 and d) 0400 UTC 1 April 2010. View is southwest to northeast (corner into the image the farthest).
mountain peaks were observed to have snow on them, the valley floor did not have snow cover until 1 April 2010. Since only 3 grids were used to simulate the inversion, snow cover within the valley itself was difficult to resolve. Nevertheless, a type 2 inversion was still produced regardless.

To summarize, while observations and model simulation results show successful inversion generation in a clear sky situation, the dissipation mechanism is not agreed on between the two methods of investigation. Type 1 and type 3 inversion dissipation were both observed from 28-30 March 2010, with both types tough to resolve on 28 and 29 March 2010. Type 3 inversion was concluded for 30 March 2010. The main reason for the disagreement is most likely due to the time of year, as type 2 inversions are most common in the winter months with significant snow cover. Nevertheless, this finding was still a surprise since type 2 inversions are common in valleys around the world. Fortunately, smoke plume tracers, cloud cover and sounding data from the UW-NMS model simulation showed type 2 inversion dissipation, with mass being evacuated out of the valley to allow for inversion subsidence and eventually its destruction.

7. Acknowledgements:

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8. References:


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