The Art and Science of Forecasting Morning Temperature Inversions

by Anthony J. Sadar

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The author provides an overview of the key resources and variables used to produce morning surface air inversion forecasts in Pittsburgh, PA. Although the focus is southwestern Pennsylvania, the forecasting approach can be applied to similar locations across the globe.

Air quality in southwestern Pennsylvania, as in most other areas of the world, is very much influenced by surface-based temperature inversions. An atmospheric temperature inversion occurs when air temperature increases with increasing height. In the layer of air nearest the earth's surface—the troposphere—this situation is the inverse of the "normal" condition where a warm ground keeps low-lying air warmer than air higher up. Normally then, the warm surface air can rise and the cool air aloft can descend, causing the atmosphere to mix.

A surface-based (or ground-level) temperature inversion forms when air close to the ground cools faster than air at a higher altitude. So, surface inversions frequently form overnight and last into the morning when the ground is coolest. With a cool ground chilling the surface air, warmer, lighter air is found above cooler, heavier air. In such a situation, air is stable and mixing within the surface air layer will be suppressed.

The dispersion of atmospheric contaminants is affected by the stability of the atmosphere. Typically, some of the worst-case conditions for the buildup of pollution concentrations occur under stable situations when surface-based temperature inversions are present and mixing of the air is limited.

Accurate forecasting of the onset of an inversion would benefit areas prone to strong and/or persistent inversions. Advanced notice of impending stagnant air conditions would give government regulators, industry operators, and the public time to mitigate emissions, and hence, pollutant concentrations, as well as reduce exposure to elevated pollution levels.

Detecting Inversions

To collect temperature, wind, and other data with height, the National Weather Service (NWS) releases a balloon-borne measurement transmitter called a radiosonde (see Figures 1 and 2). Radiosondes are sent into the atmosphere at least twice a day—once in the morning starting shortly after 1100 UTC (6:00 a.m. EST) and once in the evening starting shortly after 2300 UTC (6:00 p.m. EST)—from approximately 70 locations across the contiguous United States (see Figure 3). There are similar simultaneous launches at about 800 locations outside the conterminous United States. These daily radiosonde observations are reported at 1200 UTC (7:00 a.m. EST) and 0000 UTC (7:00 p.m. EST) and are used throughout much of the world to help interpret weather conditions in the upper atmosphere. In air pollution meteorology, such observations are critical to characterizing dispersion potential in the lower portion of the atmospheric boundary layer—a variable layer of air extending from the Earth's surface up to a few kilometers, depending on atmospheric conditions.

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Figures 1 (left) and 2 (right). Radiosonde with Balloon and Parachute.
Photos courtesy of U.S. National Weather Service, Denver/Boulder Forecast Office.

When radiosonde data indicate that temperature from the surface to some level above the surface is increasing with ascent, then a surface-based temperature inversion exists. The strength of that inversion is commonly indicated by the magnitude of temperature increase from the ground to the top of the inversion layer (a level above which temperature starts to decrease with height).

Example Inversion Data for Pittsburgh

Because the author prepares inversion forecasts to inform air pollutant dispersion assessments in Allegheny County, PA (Pittsburgh area), inversion statistics for that region are presented here for the purpose of illustration. Table 1 shows the strength and frequency of substantial surface-based temperature inversions estimated from NWS balloon launches near Pittsburgh, PA, from 2008 through 2017. In this 10-year period, the strength of the morning (1200 UTC, or 7:00 a.m. EST) inversions was 3.8 °C on average. The depth of the inversion layer topped out at an average height of 240 meters above the ground. Following sunrise and solar heating of the ground surface, the inversions tended to dissipate by 9:30 am EST. (Understandably, stronger, deeper inversions typically take longer to dissipate.) The frequency of inversion occurrence during this period averaged 44 percent of all days annually (about 158 days per year), a substantial amount.

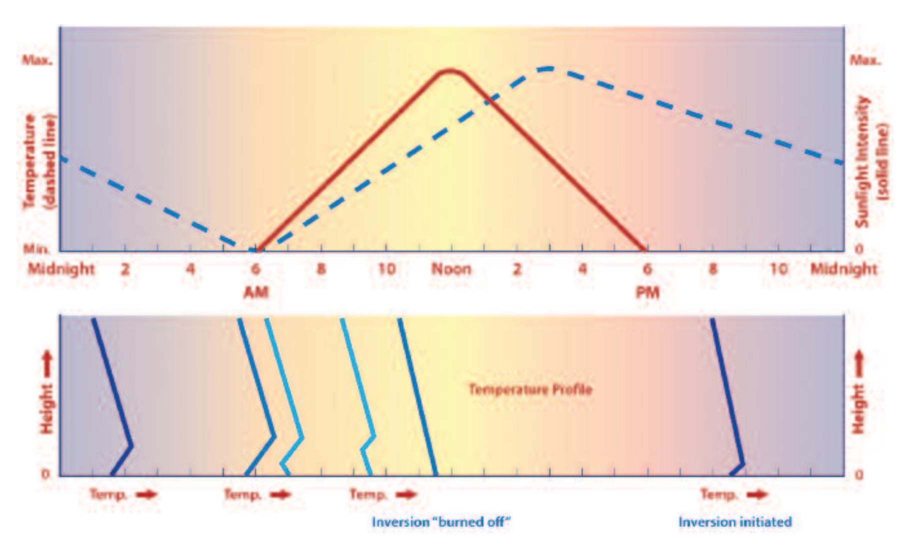
In the many valleys and low-lying areas of southwestern Pennsylvania, inversions can form first and/or be more intense and persistent than at elevated locations. Since, Allegheny County is the area of public health interest for forecasting air-dispersion conditions chosen by the author, the surface inversion minimum of 1.0 °C was chosen to make sure that an inversion observed at the Pittsburgh NWS station in western Allegheny County at a relatively high elevation was also indicative of conditions throughout most of the rest of the county where elevations can be lower. In addition, surface inversions were required to be typically at least 15-m deep to be considered significant.

Besides the annual inversion data for Allegheny County illustrated above, the author has also analyzed the county's inversion frequency and strength on a seasonal basis. Although those data are not presented here, they do provide very useful information regarding the seasonal variation of inversion severity. The season with the overall worst-case morning inversions is fall (September, October, and November). Fall has the strongest inversions and those inversions are statistically deep, frequently-occurring, and persistent. By contrast, the season with the overall most-favorable dispersion conditions (as measured by morning surface inversions) is summer (June, July, and August). Although inversions occur the most frequently in summer, those inversions are also the weakest, the most-shallow, and dissipate sooner than for any other season.

Figure 3. Radiosonde Launch Sites in the Contiguous United States.
Note: GCOS = Global Climate Observing System; Location of PIT NWS launch site circled.
Source: U.S. National Weather Service upper-air network.

Understanding Inversions and Their Formation

As described earlier, a temperature inversion happens when air temperature increases with increasing altitude. Inversions beginning at the earth's surface can form under various conditions that cause warm air to reside above cool air. One situation commonly producing a surface inversion occurs during the overnight hours when the ground cools as it radiates its thermal energy to space under clear night skies. As the ground cools, it then cools the layer of air just above it, leaving that air colder than the air layer above it. As the air temperature then increases with height above ground, a temperature inversion has formed, specifically, a radiation-type inversion.



6:00 a.m. (Sunrise) – Sunlight intensity weak, surface temperature begins to increase from overnight minimum, ground inversion strongest.

7:00 a.m. – Sunlight intensity increases as sun rises and ground is warmed, which in turn, warms the air. Thus, inversion “burns off” from ground up.

11:00 a.m. – Inversion completely burned off (i.e., isothermal or typical daytime profile developed).

Noon – Sunlight intensity maximum.

3:00 p.m. – Approximate time of maximum temperature (because of time lag between ground heating and subsequent air heating).

6:00 p.m. (Sunset) – Sunlight intensity negligible, temperature decreasing, ground inversion soon to begin. At night, temperature decreases, ground inversion strengthens.

Figure 4. Daily Lifecycle of Temperature Inversions.
Note: Stylized diurnal variation of temperature, sunlight intensity, and vertical temperature profile in continental mid-latitudes.

Figure 4 is a stylized, rough depiction of the usual sequence of events leading to the formation and destruction of a ground-level radiation-type inversion. The assumption is that few or no clouds exist during the sequence of events shown and that wind speeds remain light.

Surface-level inversions can form in other ways, such as when warm air moves over cooler surface air as a warm front is advancing into an area, or when cool maritime air undercuts warm continental air, as is the case in the Los Angeles basin, or when cool hilltop air drains into a valley, undercutting the warmer valley air in areas of complex terrain, including Pittsburgh.

Forecasting Inversions: The Good, the Bad, and the Not-So-Good Looking

There is an art to the science of weather forecasting. Years of studying synoptic (continental-scale) weather patterns and weather prognostic products, along with observing the atmosphere itself yields an intuition that can be applied to the analysis and forecasting of meteorological events such as temperature inversions. That's the good news. The bad news is that, as with all predictions that involve exact times and locations, the amount and mix of variables producing the actual event are numerous and their interactions complex. So, the clarity when looking ahead at weather conditions can turn out to be not-so-good.

Table 1. Inversion Statistics for Pittsburgh, PA (2008-2017).*

Year	Avg. Inversion Strength (°C)	Avg. Inversion Top Height (m)	Inversion Break-Up Time (EST)	Total Annual Days of Inversion (%)
2008	4.1	263	10:00	160 (44)
2009	3.8	244	9:30	154 (44)
2010	4.1	226	9:30	171 (47)
2011	3.7	246	9:30	134 (37)
2012	3.9	229	9:30	158 (43)
2013	3.4	244	9:30	127 (35)
2014	3.4	233	9:30	141 (39)
2015	3.9	250	10:00	166 (45)
2016	4.1	262	10:00	167 (46)
2017	3.8	214	9:30	203 (56)
2008–2017 Average	**3.8**	**240**	**9:30**	**158 (44)**

**Note:* Inversion statistics are based on morning (12:00 UTC, 7:00 a.m. EST) inversion data observed by the U.S. National Weather Service (NWS) office serving Pittsburgh, located near the International Airport in Allegheny County, PA. A minimum surface inversion strength of 1.0 °C was chosen to ensure that an inversion observed at the NWS office at a relatively high elevation was indicative of conditions throughout most of the rest of the county. The estimated time until break-up of the morning inversion was calculated using a method developed by the author.

How can the accuracy of inversion forecasts be improved? To start, it is certainly helpful to have a thorough understanding of the conditions that lead to substantial surface inversions, well beyond the simplified explanations presented above.

Surface temperature inversions are ultimately about losing energy at the ground and/or gaining energy aloft. In Table 2, conditions are summarized that commonly favor the formation of surface inversions in continental Northern Hemisphere locations that have hilly/mountainous terrain (like southwestern Pennsylvania). These conditions generally assume that wind speeds are light.

Morning surface inversions of various strength levels and the conditions that are expected to produce them in southwestern Pennsylvania are summarized in Table 3. These associations are

Table 2. General Conditions Favoring Surface Inversion Formation.

Losing Energy Below	Gaining Energy Above
Cold surface cover (e.g., snow and ice); Clear sky overnight (radiational cooling); Cold air advection into the local area at the surface.	Warm air advection overhead (e.g., approaching warm front); Strong and/or persistent southerly winds.

generally reliable, but are subject to alteration/refinement when additional meteorological observations are available.

Forecasting Resources

Key resources available for use in forecasting morning surface inversions include the following:

NWS surface observation and synoptic products. The U.S. National Weather Service (NWS) issues a wide array of materials helpful to forecasting inversions, such as maps and charts, showing surface-level and higher-altitude temperature, moisture, and winds. These materials can portray historic data, real-time current data, or forecasted data. As an illustration of how the data from these particular materials can be used to forecast inversions, consider surface moisture data. Forecasters know that inversions typically occur with relatively dry air near the surface.

Upstream upper-air wind measurements. General airflow across much of the northern hemisphere is from west to east; hence, the parade of weather systems across the hemisphere is also generally from west to east. Therefore, for the Allegheny County area for example, cognizance of weather conditions to the west of the county helps in predicting what weather conditions are imminent for the county, in turn, enabling subsequent assessment of whether those forecast conditions favor formation of inversions.

Satellite images. Assessment of real-time (current) inversion conditions is aided by daily satellite imagery that captures images at about 6:15 a.m. EST, or 45 minutes before the reporting time for the radiosonde measurements. (*Note:* In order to get a radiosonde sounding completed in time for the 7:00 a.m. EST reporting, the radiosonde must be launched about 45 minutes before the official reporting hour, so the earliest measurements by the radiosonde represent the near-surface atmospheric conditions.) The satellite view that shows cloud cover at about the time of the radiosonde launch is superimposed on a map of current surface weather conditions that gives the location of pressure systems, fronts, and the like. Matching the satellite and surface conditions to the vertical readings provided by the radiosonde helps in the evaluation of the role clouds, wind, and temperature play in the formation of low-level inversions.

Table 3. Specific Conditions Favoring Surface Inversion Formation.

Strength*	Expected Nightime Conditions Favorable for Surface Inversions
Strong	Calm or light wind and clear sky entire night (especially with snow/ice cover)
Strong	Approaching warm front (especially with snow/ice cover)
Moderate to Strong	Snow or ice cover, with air temperature substantially above freezing
Moderate to Strong	Strong southerly flow
Moderate	Calm or light wind and clear sky for at least 2 hours before dawn
Moderate	Moderate wind with clear sky overnight
Weak	Calm or light wind and partly cloudy sky
Weak	Strong southerly flow with light rain in area
None to Weak	Fast approaching cold front
None	Moderate to strong northerly flow (even with clear skies)
None	Low altitude overcast sky (especially with moderate or greater wind speed)
None	Heavy precipitation not associated with a front (especially with moderate or greater wind speed)

**Note:* Morning Surface Inversion Strengths are arbitrarily categorized by the author as "Strong" at > ~5 °C; "Moderate" at ~3 to ~5 °C; "Weak" at ~1 to ~3 °C; "Slight" at ~0.4 to ~1 °C. Strengths are also somewhat dependent on surface inversion depths, with deeper inversions indicative of greater strength.

Earth System Research Laboratory High Resolution Rapid Refresh (ESRL HRRR) model output. The ESRL's HRRR is a National Oceanic and Atmospheric Administration real-time state-of-the-art model that updates hourly. The model incorporates convection activity simulation, radar images, and other inputs while simulating expected hourly radiosonde sounding results out to about 24 hours. The hourly anticipated upper-air conditions for specific locations, including Pittsburgh—although not always available for 24-hour prognostications—can be quite useful especially for fine-tuning a forecast of surface inversion strength.

In addition to the use of these tools, the season of the year must be considered in forecasting surface inversions. Sun angle, as well as sunrise and sunset times, vary with the season and are crucial factors in determining the warming of the earth's surface. The timing and intensity of solar energy help to determine the onset, duration, and strength of ground inversions. For example, in the Pittsburgh area, summer is the season during which inversions are of the shortest duration annually. This makes sense since, with Pittsburgh located at approximately 40 °N latitude and 80 °W longitude, the sun in summer would set later in the day and rise earlier in the morning than in the other seasons. This results in longer daily warming of the earth's surface, and that additional surface warmth readily dissipates the ground-level inversions that form overnight.

Conclusion

Analysis and forecasting of surface inversions, and thus poor air dispersion conditions, requires consideration of numerous variables and their interaction—including, meteorological, solar, and topographic variables. NWS radiosonde data have been key to documenting, analyzing, and predicting the onset and intensity of inversions. Besides the radiosonde data, other NWS products also aid in inversion forecasting—including, nationally-mapped meteorological data at the surface and aloft, satellite images of cloud cover, and government models that forecast expected variation of temperature and winds with height in the atmosphere.

Accurate forecasting of an inversion would benefit areas prone to strong and/or persistent inversions. Accurate inversion forecasting enables reliable advanced notice of impending stagnant air conditions that can result in excessive air pollution build-up and unhealthy air pollution exposure, and give all concerned parties time to implement immediate curbs on short-term air pollutant emissions, in order to mitigate concentrations during the inversion event and reduce the public's exposure to elevated pollution levels.

Predictive techniques, though, can be quite site-specific, especially in complex terrain, as is the case with southwestern Pennsylvania. Regardless, the overview and recommendations given here can help diagnostic and prognostic activities in similar areas across the globe. The author welcomes insight from other forecasters, to help improve understanding and forecasting of inversion conditions that are conducive to poor air quality. **em**