5.11 RADIATION FOG: UPS AIRLINES CONCEPTUAL MODELS AND FORECAST METHODS

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1. INTRODUCTION

Fog continues to be an important forecast challenge for aviation. Airlines specializing in express package delivery, like United Parcel Service (UPS) Airlines, are especially vulnerable to the impacts of fog due to the high number of arrivals scheduled close to sunrise, when fog frequency peaks. While nearly all forecasters are familiar with the fundamental forecasting concepts, skill scores for predicting fog continue to lag those of most other terminal forecast variables.

The requirement to provide fog forecasts for over 80 airports has motivated the meteorologists at UPS Airlines to develop a fog forecasting process involving useful conceptual models and practical, quantitative forecast tools. The development and operational application of these concepts and methods over a five-year period has led to improved skill in assessing elevated risks for the majority of fog events, defined as ceiling/visibility less than 200 feet/½ mile.

The purpose of this paper is to share these conceptual models and forecast methods. These ideas and techniques are not strictly limited to pure radiation fog; they apply to any fog situation involving radiative heat loss as an important component of boundary layer cooling.

2. CONCEPTUAL OVERVIEW – A More Vertical View of Radiation Fog Forecasting

The basic requirements for radiation fog are well-known—clear skies, light winds and high humidity. The usual technique for forecasting fog involves predicting surface saturation and surface winds. If the surface temperature is expected to cool to or a few degrees below the dew point and the winds are expected to be light, fog is generally expected.

The main idea behind the UPS Airlines approach is that effective fog forecasting requires a *more vertical* view of processes in the potential fog layer. Surface-based approaches to fog forecasting fail to account for key information *above* and *below* the conventionally observed and forecast data, including:

a. The vertical distribution of humidity in the potential fog layer (surface-500 feet).
b. The turbulent mixing potential of the lower boundary layer.
c. The ground temperature of the surface beneath the potential fog layer.

Furthermore, standard forecasting practice calls for clear skies as a requirement for the development of radiation fog, failing to explicitly recognize that pre-existing stratus clouds can "build down" (thicken and lower) into a fog in a radiatively cooling boundary layer. This paper will introduce how each of these concepts is applied in the UPS Airlines fog forecasting process — Section 3 will cover the vertical distribution of humidity; section 4, boundary layer turbulence; section 5, ground temperature; and section 6, stratus "build-down" fog. Some additional remarks and a summary are provided in section 7.

3. CROSSOVER TEMPERATURE – A More Vertically Sensitive Measure of Boundary Layer Humidity

Surface saturation often does not lead to fog. On some calm, clear nights the surface temperature and dew point are observed to fall in tandem for many degrees with continued excellent visibility. "Insufficient mixing" is sometimes proposed as an explanation for this; however, this fails to account for cases where fog does form in calm air. A more useful explanation for the lack of fog development with saturated surface conditions can be found by examining the vertical profile of humidity.

The importance of the vertical profile of humidity, or hydrolapse, in fog formation has long been known but largely ignored. In his 1940 classic <u>Weather Analysis and Forecasting,</u> Sverre Petterssen states, "As long as the specific humidity decreases along the vertical, fog usually does not form except in still air, and even then the cooling may result only in dew or rime on the ground." It is known that dew deposition acts as a humidity sink for the lower atmosphere, delaying the onset of fog by several hours (Lala, et al., 1974); likewise, the eddy transport of water vapor is an upward-directed humidity sink if humidity decreases along the vertical. A decreasing vertical humidity profile likely explains many of the situations involving surface saturation with no fog development.

The commonly applied fog forecasting techniques ignore the vertical humidity profile; shelter-height dew

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point is the only humidity indicator normally used, and this is for a very practical reason—it is usually the only humidity observation available. The hydrolapse is nowhere to be found in routine meteorological observations for the vast majority of airports. RAOBs do observe the humidity along the vertical, but they are not available for most airports and, even where they are, the vertical resolution in the lowest 500 feet (where fog usually forms) is poor. ACARS (Airline Communications Addressing and Reporting System) humidity soundings show some promise in this direction (Fleming, 1996; Mamrosh et al. 2002), but as of this writing they are still experimental and not routinely available. Understanding the importance of the hydrolapse, but faced with the fact that it is not directly observed, UPS Airlines forecasters employ a method of indirect observation to infer information about the vertical humidity profile.

Typically, the dew point reaches its diurnal minimum during the warmest hours of the day. This afternoon drop in dew point is related to the fact that "under normal atmospheric conditions, specific humidity decreases upward" (Petterssen, 1940; Munn, 1966). During the warmest daytime hours, the well-mixed planetary boundary layer is established and the upward transfer of water vapor is maximized, lowering the surface dew point. UPS Airlines forecasters note the behavior of the dew point during the hours of daytime heating to infer information about the hydrolapse. If the dew point decreases during the afternoon hours, a moisture decrease with height is assumed, reducing the fog risk. If the dew point remains constant or increases during the well-mixed PBL hours, moisture does not decrease with height, and the fog risk is heightened.

This information is applied to the forecast process by defining **the "crossover temperature," (T_{Xover}) which is equal to the minimum dew point observed during the warmest daytime hours.** Fog is forecast when the shelter temperature is expected to cool to a few degrees below the *crossover* temperature, rather than a few degrees below *the dew point*. In effect this method forecasts saturation aloft, 100-200 feet above the ground, where fog condensation typically initiates (Pilie, et al., 1975). The crossover temperature establishes a cooling threshold *at shelter height* for the purpose of indicating when saturation will occur *aloft*.

At UPS Airlines the crossover temperature[1] is applied as follows[2]:

> If $\mathbf{T = T_{Xover}}$, generally forecast 1-3 miles visibilities in mist, with a *risk* for lower visibilities, especially along coasts)
>
> If $\mathbf{T} <= (\mathbf{T_{Xover} - 3^{o}F})$, generally forecast 1/2 mile visibility or lower, unless turbulent mixing will prevent fog (see section 4)

Where **T** = shelter-height temperature forecast and $\mathbf{T_{Xover}}$ = crossover temperature

To illustrate the crossover method in a fog development situation, Figure 1 shows a time series of temperature and dew point. The dew point temperatures rose during the daytime, which likely indicates moisture increasing with height and an elevated fog risk.

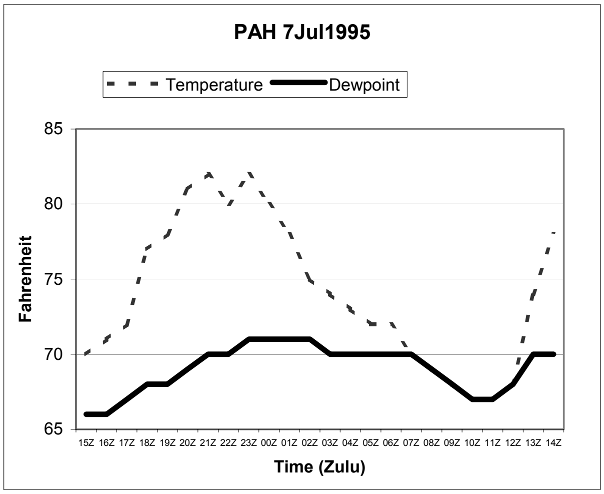

Figure 1

In this case, the crossover would be 70°F. Some of the raw observations are listed below, showing that dense fog developed at 1–2°F below the crossover.

```
SA 1850 M25 BKN 35 BKN 10 200/78/68/2608/013
SA 1950 25 SCT M35 BKN 10 197/81/69/2508/012
SA 2050 25 SCT M35 BKN 10 190/82/70/2307/010
SA 2150 25 SCT M35 BKN 10 190/80/70/2007/010
SA 2250 23 SCT 100 SCT 10 183/82/71/2307/008
SA 2350 23 SCT 10 183/80/71/2009/008
SA 0050 20 SCT 250 -SCT 10 183/78/71/1906/008
SA 0150 250 -SCT 10 184/75/71/2106/008
SA 0250 60 SCT 10 187/74/70/2105/009
SA 0350 60 SCT 10 187/73/70/2106/009
SA 0450 60 SCT 10 191/72/70/2206/010
SA 0550 55 SCT 7 195/72/70/2304/012
SA 0650 CLR 5F 195/70/70/2404/012
RS 0750 CLR 2F 195/69/69/2303/011
SP 0807 W1 X 1/2F 0000/012
SA 0850 W1 X 1/8F 195/68/68/0000/012
```

UPS meteorologists have found the crossover technique helpful in reducing both false alarms and missed detections of fog events. In order to accurately assign the crossover temperature it is wise to "buddy check" afternoon dew points with those of neighboring

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[1] UPS Airlines meteorologists compute crossover temperatures using Fahrenheit temperatures for increased precision over whole degree Celsius temperatures.

[2] An identical technique for use in moist ground situations was previously developed by United Kingdom forecasters under the name "British Quick Fog Point" (Reymann, et al., 1998)

reporting stations, especially for automated sites which are more prone to dew point errors.

The strict application of this technique is limited to situations involving no significant moisture advection, and no significant addition of moisture from precipitation. When moisture advection is present, forecasters must judiciously replace the crossover temperature with a suitable replacement (often an upwind dew point) that better reflects the expected humidity profile of the nocturnal stable layer.

3.1 Example of Common Crossover Pattern

Figure 2 shows an example of a more typical crossover pattern, where the dew point drops during the warmest part of the day. The crossover temperature would be 46°F. At 0756Z, the visibility was 5 miles with a temperature of 48°F, dew point 47°F. At 0824Z the temperature was 45°F, dew point 45°F, with visibility ¼ mile.

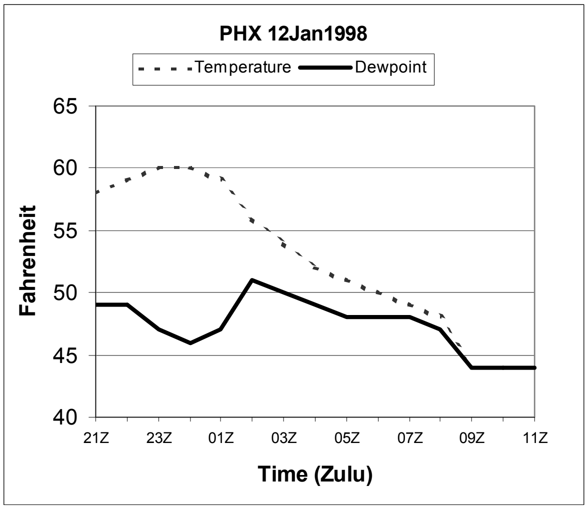


Figure 2

4. MODIFIED RICHARDSON NUMBER – Forecasting Boundary Layer Turbulence

Having determined whether a station will radiatively cool enough for saturation ("crossover"), the forecaster must assess whether boundary layer turbulence will support fog formation.

It is commonly known that strong winds prevent the development of radiation fog. Strong winds indicate turbulent mixing in the boundary layer which inhibits surface cooling and the establishment of a nocturnal inversion. Even if saturation occurs in a turbulently mixed boundary layer, condensation will normally take place in the upper portion of the mixed layer resulting in stratus clouds rather than fog. Furthermore, in the presence of the typical moisture decrease with height, turbulent mixing from wind flow will serve to ventilate humidity upward through the boundary layer, thereby reducing the fog risk.

The problem for fog forecasters is that "light winds" or "winds that are not too strong" are almost never defined quantitatively. Fog training resources are rightfully reluctant to set gradient or 850mb wind speed thresholds for fog since the wind speed at the surface is strongly dependent upon the strength of the nocturnal inversion. The real requirement for radiation fog is not lack of *wind*, per se, but lack of *turbulence*, which can result from various combinations of stability and boundary layer wind speeds.

The UPS Airlines fog forecasting process involves the use of a quantitative index of boundary layer turbulent mixing called the "modified Richardson number" (**MRi**) taking the following form:

$$\mathbf{MRi} = (T_b - T_{sfc})/u^2 \qquad (1)$$

Where: T_b = boundary layer temperature forecast (**T1** or **T3**, whichever is warmer, from FOUS60/ETA or FOUS60/NGM(°C))

T_{sfc} = shelter temperature forecast (°C)

u = boundary layer wind speed (FF from ETA/NGM (knots))

This index, actually a stability ratio, is a simple, convenient modification of the well-known Richardson number. It approximately quantifies the balance between the *turbulence producing* force of wind shear and the *turbulence suppressing* force of buoyancy in a stable atmosphere. This particular form of **MRi** was chosen because the input parameters are familiar and readily available to forecasters. Over five years of operational use have resulted in the following forecast thresholds at UPS Airlines:

MRi <= **0.025** is **"mixy".** Turbulently mixed boundary layer suppresses cooling in the lowest 200 feet and favors stratus rather than fog if saturation occurs.

MRi between 0.025 and 0.040 is **"marginal".**

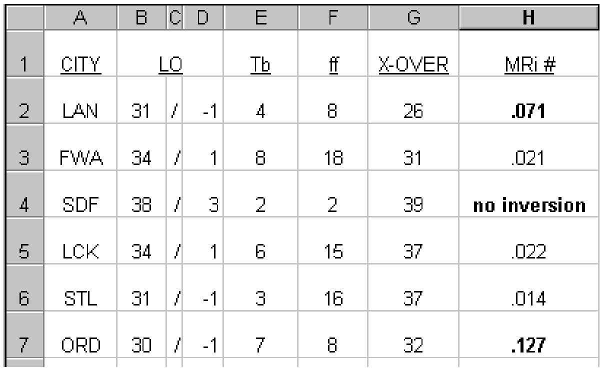
MRi >= **0.040** is **"decoupled".** Low-level winds decoupled from winds aloft. Unmixed boundary layer supports strong cooling in the lowest 200 feet and favors fog rather than stratus, if saturation occurs.

The thresholds given above apply only to the *development* of radiation fog. For the turbulent *dispersal* of an *existing* fog, **MRi** must decrease to 0.008 or lower. In addition, UPS meteorologists use the following modifications and exceptions to **MRi**:

- **MRi** thresholds must be adjusted downward for situations where significant surface airflow is *needed* to force boundary layer cooling (advection and upslope fogs). For the relatively common radiation/advection hybrid fog near coastlines with onshore flow, 0.015 is the threshold for “mixy”.

- Advection fog situations involving air with dew points in excess of 10°F higher than the underlying surface temperature can produce fog in “mixy” boundary layers; for these extreme situations **MRi** is irrelevant.

MRi contours can be graphically depicted on a workstation for general overview purposes, while more station and time-specific **MRi**s are better computed by hand. Figure 3 shows an example of a spreadsheet that UPS meteorologists use to facilitate fog risk assessment for a long list of locations. The user enters temperature and wind data and the spreadsheet performs **MRi** calculations.



	A	B	C	D	E	F	G	H
1	CITY	LO			Tb	ff	X-OVER	MRi #
2	LAN	31	/	-1	4	8	26	**.071**
3	FWA	34	/	1	8	18	31	.021
4	SDF	38	/	3	2	2	39	**no inversion**
5	LCK	34	/	1	6	15	37	.022
6	STL	31	/	-1	3	16	37	.014
7	ORD	30	/	-1	7	8	32	**.127**

Figure 3. Column A lists the airport identifiers; B and D the forecast low temperatures (°F and °C, respectively); E the boundary layer temperatures (°C); F the boundary layer winds (knots); G the crossover temperatures (°F); and H the calculated **MRi**s using equation (1).

4.1 Phoenix (PHX) Fog Example using MRi

On the afternoon of 10 January 1998, PHX received several hours of rain and thunderstorms between 1800-2400Z. During the precipitation, the dew points rose to 10.6°C (51°F), then settled in at 10.0°C (50°F) under a 3000-6000 foot ceiling between 0300-0500Z of the 11th.

```
KPHX 2356Z 09003KT 9SM BKN030 OVC060
11/11 A3001 RMK A02 RAE14 SLP157 P0001
60029 T01110106 10117 20100 53004
```

Nested Grid Model (NGM) Model Output Statistics (MOS) guidance showed clearing skies with a forecast minimum temperature of 45°F (7.2°C). Here is the raw NGM model output for PHX:

```
OUTPUT FROM NGM 12Z JAN 11 98
TTPTTR1R2R3 VVVLI PSDDFF HHT1T3T5
PHX//755013 –0603 180206 50100497
06000563935 –1007 180105 53110499
12000433561 01206 172606 54130600
18000492447 –0506 173211 54120501
24000545545 –1006 173404 54110601
30000556035 –1606 192905 54120600
36000436043 01104 162513 56150701
42000548494 –0202 182818 54130701
48000884874 00900 183013 52090600
```

T3 temperatures indicated an absence of cold air advection between 0600 and 1200Z (forecast hours 18, and 24), along with weak downward motion and generally low humidities at R2 and R3. This, combined with a forecast minimum temperature 5°F below the crossover suggests a serious fog potential. But is it decoupled enough?

To compute the **MRi**, take the higher of T1 or T3 and compare it with the forecast surface temperatures to see if there is any temperature inversion. Notice that the observed surface temperature at 0000z is 11°C, with a forecast T1 of 13°C and a wind of only 6 knots. To calculate **MRi,** using equation (1):

0000Z **MRi** = (13-11)/ 6^2 = 0.055 (decoupled).

Based on forecast clearing and radiational cooling, surface temperatures were forecast to drop to 8°C by 0600Z and 7 C at 1200Z. Computing the MRi for 0600Z and 1200Z:

0600Z **MRi** = (12-08)/ 11^2 = 0.033 (marginal).

1200Z **MRi** = (11-07)/ 4^2 = 0.250 (very decoupled).

In this case, clearing occurred at 0748Z at which time the visibility dropped to 3 miles, and on down to ¼ mile at 0756Z at 47°F. The visibility was less than ¼ mile from 0956Z to 1322Z, and again from 1537Z to 1704Z.

This example shows that an objective, process-oriented approach to fog forecasting based on the meteorological situation can be effective, even at locations like Phoenix where fog is very rare. The use of crossover temperature and modified Richardson number helps overcome fog forecasting biases based on climatology or diurnal persistence[3].

5. GROUND TEMPERATURE – Its Importance as a Fog Forecasting Adjustment Factor

The importance of the underlying surface temperature (water, snow or ground) for the development of advection fog is well known. However, it is not widely recognized that ground temperature can

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[3] The tendency to forecast fog (or its absence) based on the previous night’s observations.

be a significant factor in supporting or inhibiting radiation fog development.

The cooling rate of the lower nocturnal boundary layer can be significantly affected by the temperature of the underlying ground. The heat exchange from warm ground partially offsets surface radiational heat loss, thereby slowing the cooling rate of the lower atmosphere and delaying or preventing saturation. Conversely, cold ground provides less compensating heat exchange to the surface, allowing rapid radiative cooling and subsequent saturation. Ideally forecasters should adjust shelter temperature predictions for the effect of unusually warm or cold ground *prior* to computing crossover timing and MRi.

Ground temperature is often not routinely considered in radiation fog forecasting, in part because it is not included in conventional observation and forecast data sets. However, numerical weather models explicitly calculate soil physics, and 4" soil temperatures can be provided as gridded output if they are not already available. Some climate and agricultural reports contain soil temperatures for a limited number of specific sites. In addition experimental numerical weather model output on the Internet contain forecasts of 4" soil temperature contours for most of the United States.

Forecasters at UPS Airlines compare the soil temperature with the crossover temperature, and then adjust the fog forecast accordingly. For situations where the ground temperature is at least 5^{o}F *warmer* than the crossover temperature, fog risk is *reduced*, especially with marginal **MRi**. Even with eventual saturation these situations tend to produce low stratus or patchy fog with variable visibility rather than persistent, dense fog.

For cold ground where the ground temperature is at least 5^{o}F *colder* than the crossover, fog risk is *increased*, especially with marginal **MRi**. Cold ground is frequently associated with unexpectedly early fog formation, in many cases prior to midnight, and the resulting fog tends to be dense and persistent. Cold ground also supports the development of fog from the thickening and lowering of stratus clouds.

6. THE STRATUS "BUILD-DOWN" CONCEPT – Fog Developing From Stratus Cloud Situations

Forecasters generally interpret the existence of stratus clouds as a sign of reduced fog risk. This is understandable—the development of stratus often indicates a turbulently mixed boundary layer, and the cloud layer reduces surface radiative heat loss.

In many cases, however, the base of the cloud layer is observed to build downward toward the surface, developing into fog (Petterssen, 1940). While it is true that in the presence of stratus clouds surface radiative cooling is *reduced*, it is generally not *eliminated*, especially when the cloud layer is thin. Furthermore, the top of the stratus itself becomes a radiatively cooling surface in the absence of clouds aloft. Mixing redistributes this heat loss downward, cooling the air below the cloud layer and lowering the condensation level. Cloud top cooling also promotes droplet growth and settling, which further promotes cloud base lowering. Since any upward transfer of heat from the ground counteracts this "build-down" process, the most rapid "build-downs" are associated with a cold underlying surface.

UPS Airlines forecasters evaluate the "build-down" potential of any area of stratus cloud with bases 2,500 feet or lower. If the ground temperature is significantly (5^{o}F or more) *warmer* than the crossover temperature, fog is generally *not* expected unless the base of the stratus is very low and radiation fog conditions are otherwise ideal. With the ground temperature significantly (5^{o}F or more) *colder* than the crossover temperature, the *fog risk if high* with stratus bases lowering at rates of 300-400 feet/hour.

Typical "build-down" rates of 100-200 feet/hour are usually observed when the ground temperature is within a few degrees of the crossover; faster "build-downs" tend to occur with fewer clouds aloft and colder ground below. Snow-covered regions are especially vulnerable to stratus "build-downs" (and fog development in general) due to the excellent longwave radiative emissivity and poor thermal conductivity of snow. This leads to rapid boundary layer cooling since the surface radiative heat loss is uncompensated by the transfer of heat from the warmer soil below.

To help identify areas of low stratus, UPS employs an automated hourly graphic that contours ceiling and visibility from every reporting station in the United States. This tool helps focus attention on the areas of concern, often highlighting deteriorating conditions before they materialize at a nearby UPS airport.

The stratus "build-down" concept effectively transcends the boundaries of traditional fog type classifications. UPS Airlines forecasters apply the stratus "build-down" technique to advection, radiation, upslope, frontal, inversion and steam fog situations, making appropriate allowances for the effects of upslope flow or moisture addition.

7. REMARKS AND SUMMARY

Although space limitation prevents a more complete exposition of the various factors relating to radiation fog, the importance of accurate cloud cover forecasts, though certainly not one of the neglected fundamentals, deserves special emphasis. Radiation fog develops in the presence of a clear radiative atmospheric channel aloft, and hour-by-hour visibility variations can often be directly related to the passages of cloudy and cloud-free patches.

Airports reporting clouds or rain during the day with clearing near sunset are particularly vulnerable to rapid and early fog development in the absence of immediate and sure cold, dry advection. In particular, weak cold fronts are often followed by a “clearing-out” zone that radiatively cools and decouples for several hours until the trailing low-level cold air advection begins. In some cases, the radiative cooling leads to the development of an inversion strong enough to prevent turbulent mixing even with weak to moderate cold advection above the stable nocturnal layer.

The conceptual models and forecast methods of the UPS Airlines Meteorology Department eschew the traditional classification-based view of fog forecasting in favor of a more process-oriented approach. The fundamental ideas behind these methods are not new—they were all published in a 1940 textbook (Petterssen, 1940)—but they have been neglected to varying degrees. Operational necessity guided the forecasters of UPS Airlines back to these effective fundamentals, and the purpose of this paper is to share these ideas with the aim of promoting their more general use.

Acknowledgements

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