1.5 Applied Climatology In The Upgraded Minimum Temperature Prediction Tool For The Cape Canaveral Air Force Station and Kennedy Space Center

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1. INTRODUCTION

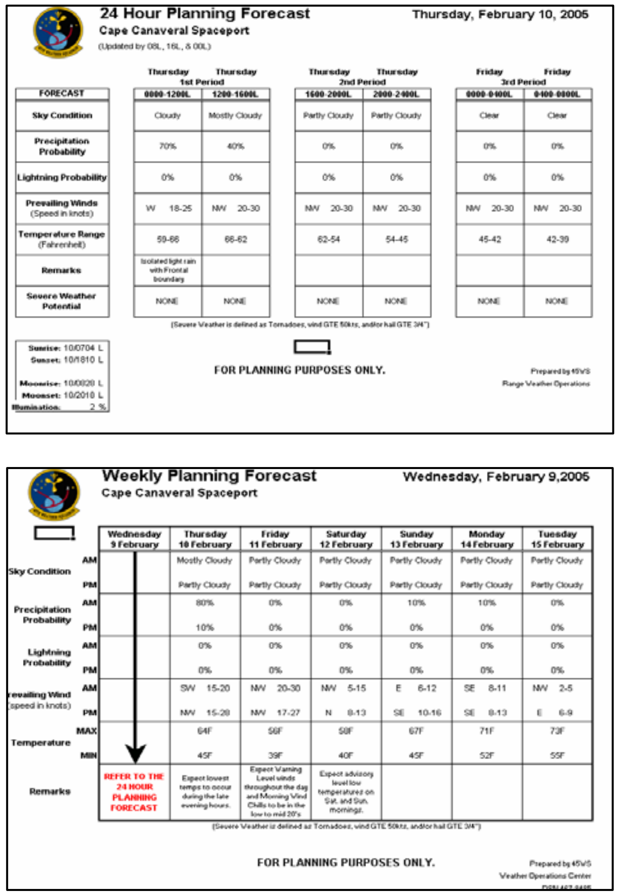
The 45th Weather Squadron (45 WS) provides comprehensive weather services to America's space program at Cape Canaveral Air Force Station (CCAFS) and NASA Kennedy Space Center (KSC) (Harms et al., 1999). During the winter, the most frequently issued warning/watch/ advisory products are low temperature advisories. The CCAFS/KSC managers must take actions to prevent icing damage to exposed refrigerated surfaces when the temperature falls below established thresholds beginning as high as 15.6°C (60°F). The 45 WS issues four low temperature advisories (Table-1). Some weather rules to protect space launch vehicles include low temperatures. The 45 WS also issues low temperature forecasts on their daily 24-Hour and Weekly Planning Forecasts (figure 1). This paper reports on recent efforts to improve the 45 WS low temperature forecast process.

Table 1.
Low temperature advisories issued by 45 WS

TEMPERATURE	DURATION	DESIRED LEAD-TIME
≤ 15.6 °C (60 °F)	Any	3 Days
≤ 7.2 °C (45 °F)	≥ 4 Hours	4 Hours
≤ 4.4 °C (40 °F)	Any	4 Hours
≤ 0.0 °C (32 °F)	≥ 4 Hours	16 Hours

2. LOW TEMPERATURE FORECAST CHALLENGES

Forecasting low temperatures at 45 WS with the required precision and lead-times can be quite challenging. The local area is a complex mix of land and water (figure 2). The surface type changes six times over only a 20 mile east-west distance: 1) Atlantic Ocean, 2) Cape Canaveral barrier island, 3) Banana River or Mosquito Lagoon, 4) Merritt Island barrier island, 5) Indian River, and 6) the mainland of Florida. The land surface types are also a wide mix of sandy soils and wetlands. A trajectory over warmer water or colder land is well known to influence low temperatures. This definitely applies in the CCAFS/KSC area, as shown by climatology of the local weather tower network, where an over-water or over-land trajectory was the most important factor in explaining the minimum temperatures (Case and Baumann, 2004). The well drained sandy soils and wetlands also contribute to the formation of local cool and warm microclimates, respectively. Forecasting the lower temperatures in the 45 WS advisories is also difficult since they occur fairly infrequently. For example, the ≤ 0.0°C (32°F) advisory occurs only twice per year on average (AFCCC, 2004a). The annual frequency of the daily minimum temperatures meeting each temperature advisory threshold is shown in Table-2.



24 Hour Planning Forecast — Thursday, February 10, 2005
Cape Canaveral Spaceport
(Updated by 08L, 16L, & 00L)

FORECAST	Thursday (1st Period) 0000-1200L	Thursday (1st Period) 1200-1600L	Thursday (2nd Period) 1600-2000L	Thursday (2nd Period) 2000-2400L	Friday (3rd Period) 0000-0400L	Friday (3rd Period) 0400-0800L
Sky Condition	Cloudy	Mostly Cloudy	Partly Cloudy	Partly Cloudy	Clear	Clear
Precipitation Probability	70%	40%	0%	0%	0%	0%
Lightning Probability	0%	0%	0%	0%	0%	0%
Prevailing Winds (Speed in knots)	W 18-25	NW 20-30	NW 20-30	NW 20-30	NW 20-30	NW 20-30
Temperature Range (Fahrenheit)	59-66	66-62	62-54	54-45	45-42	42-39
Remarks	Isolated light rain with Frontal boundary					
Severe Weather Potential	NONE	NONE	NONE	NONE	NONE	NONE

(Severe Weather is defined as Tornadoes, wind GTE 50kts, and/or hail GTE 3/4")

Sunrise: 10/0704 L
Sunset: 10/1810 L
Moonrise: 10/0820 L
Moonset: 10/2010 L
Illumination: 2 %

FOR PLANNING PURPOSES ONLY.

Prepared by 45WS
Range Weather Operations

Weekly Planning Forecast — Wednesday, February 9,2005
Cape Canaveral Spaceport

		Wednesday 9 February	Thursday 10 February	Friday 11 February	Saturday 12 February	Sunday 13 February	Monday 14 February	Tuesday 15 February
Sky Condition	AM		Mostly Cloudy	Partly Cloudy	Partly Cloudy	Partly Cloudy	Partly Cloudy	Partly Cloudy
	PM		Partly Cloudy	Partly Cloudy	Partly Cloudy	Partly Cloudy	Partly Cloudy	Partly Cloudy
Precipitation Probability	AM		80%	0%	0%	10%	10%	0%
	PM		10%	0%	0%	0%	0%	0%
Lightning Probability	AM		0%	0%	0%	0%	0%	0%
	PM		0%	0%	0%	0%	0%	0%
Prevailing Wind (speed in knots)	AM		SW 15-20	NW 20-30	NW 5-15	E 6-12	SE 8-11	NW 2-5
	PM		NW 15-28	NW 17-27	N 8-13	SE 10-16	SE 8-13	E 6-9
Temperature	MAX		64F	56F	58F	67F	71F	73F
	MIN		45F	39F	40F	45F	52F	55F
Remarks		REFER TO THE 24 HOUR PLANNING FORECAST	Expect lowest temps to occur during the late evening hours.	Expect Warning Level winds throughout the day and Morning Wind Chills to be in the low to mid 20's	Expect advisory level low temperatures on Sat. and Sun. mornings.			

(Severe Weather is defined as Tornadoes, wind GTE 50kts, and/or hail GTE 3/4")

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Prepared by 45WS
Weather Operations Center

Figure 1. Examples of 45 WS daily 24-Hour and Weekly Planning Forecasts.

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Figure 2. Map of CCAFS/KSC area. Note the numerous land-water boundaries.

Table 2.
Annual frequency of daily minimum temperatures meeting the temperature advisories at the Shuttle Landing Facility (Mar 78-Apr 03) (AFCCC, 2004b)

TEMPERATURE ADVISORY	ANNUAL FREQUENCY
≤ 15.6 °C (60 °F)	30.2%
≤ 7.2 °C (45 °F)	6.1%
≤ 4.4 °C (40 °F)	2.6%
≤ 0.0 °C (32 °F)	0.4%

3. THE NEW LOW TEMPERATURE FORECAST PROCEDURE

The 45 WS previous method to forecast temperatures below 15.6°C (60°F) was a flowchart (figure 3). This flowchart used a 'first guess' minimum temperature based on the 1000-500 HPa (1000-500 Mb) thickness. A series of correction factors were then applied to the 'first guess' for the final minimum temperature forecast. The correction factors included cloud cover, wind speed, wind direction, and radiation inversion. This flowchart was based on subjective professional judgment from many years of local experience. This technique was selected for improvement since low temperature advisories are the most frequent advisory/watch/warning product issued by 45 WS in the winter (figure 4). It is also the winter product with the most room for improvement (figure 5), as estimated by the Advanced Range Technology Working Group (ARTWG, 2004). Combining frequency with likely improvement (figure 6), the low temperature advisories are the 45 WS winter product that offered the most operational benefit for the improvement effort.

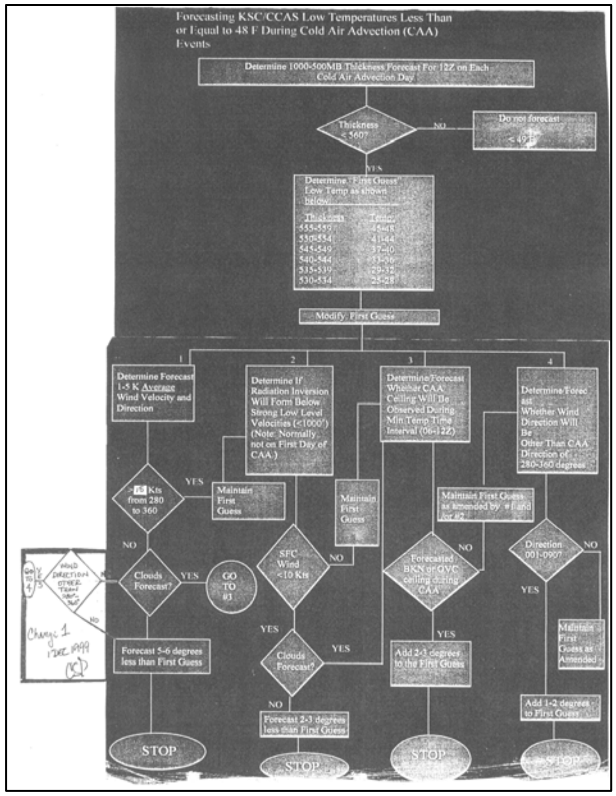

Figure 3. Previous 45 WS manual flowchart for forecasting low temperatures.

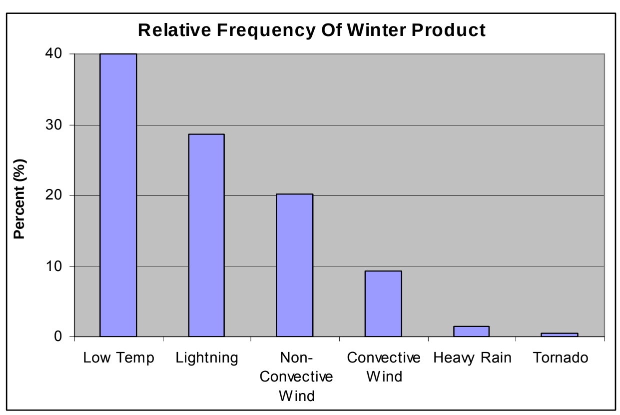

Figure 4. Relative frequency of 45 WS advisory/watch/warning products in winter (Jan 2000-Mar 2005).

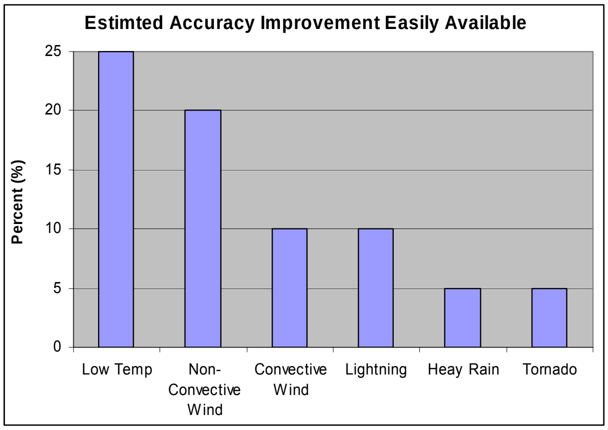

Figure 5. Estimated accuracy improvement easily achievable in 45 WS winter products.

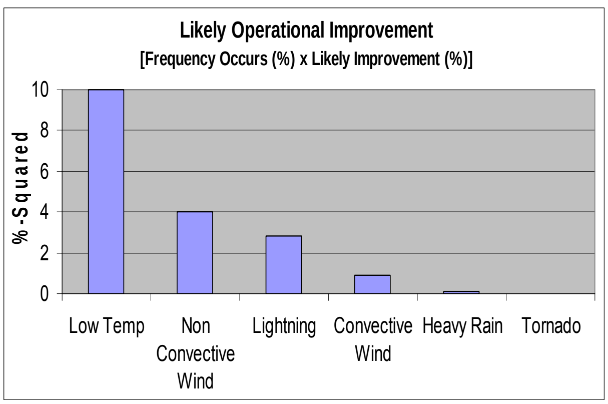

Figure 6. Operational benefit of improving 45 WS winter products calculated from the product of relative frequency (%) and estimated likely improvement (%).

The 45 WS made several refinements and additions to improve the low temperature forecast flowchart, especially in replacing the subjective professional with climatology. An analysis of error contribution from each factor in the previous tool identified the order to upgrade and amount of effort to apply to each factor (figure 7). The subjective first guess model, which uses the 1000-500 Mb thickness to estimate the low temperature, was the largest source of error and was upgraded first. A climatological analysis of the thicknesses from local weather balloons and associated low temperatures replaced the previous subjective opinion. Several of the correction factors were also improved in the order indicated in figure 7: wind speed, cloud cover, and fog. The correction factors for wind direction and radiation inversion were left unmodified. New correction factors for humidity and dew point were added. The correction factors were optimized using five years of local surface observations from 2000-2004. Finally, a Graphical Users Interface (GUI) was developed to increase easy usability of the new tool by the 45 WS forecasters.

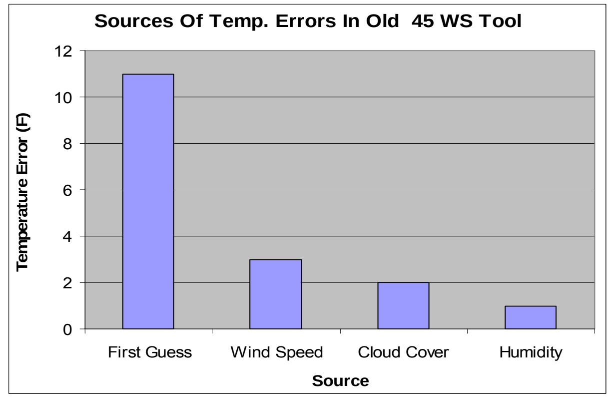

Figure 7. Sources of errors in old 45 WS low temperature tool.

3.1 Improved First Guess: 1000-850 HPa Thickness Regression

The most important upgrade to low temperature flowchart was a new 'first guess' based on climatological analysis of local weather balloon and temperature observations. The new 'first guess' uses the 1000-850 HPa (1000-850 Mb) thickness, which is more representative of the surface and boundary layer than the previously used 1000-500 HPa thickness. Most importantly, the 'first guess' now uses linear regression to predict the minimum temperature, rather than the previous subjective estimates. These linear regressions are based on 2,217 CCAFS RAOBs over a 27-year period (1978-2004).

The 45 WS requested the linear regressions from the Air Force Combat Climatology Center (AFCCC) in October 2004 using the minimum temperatures from the KSC Shuttle Landing Facility and from the nine weather towers across CCAFS and KSC used to verify the low temperature advisories: towers 211, 311, 313, 39 A, 39 B, 412, 509, 512, and 709 (figure 8). The tower regressions were for the mean and lowest minimum temperatures. The regression for the KSC Shuttle Landing Facility was done first so that 45 WS could start using the new improved 'first guess' as soon as possible in the 2004-2005 cool season (October-April), which had just started. The AFCCC could provide the Shuttle Landing Facility regression quickly, since surface observations are immediately available for analysis in a database. The 45 WS weather towers are not immediately available and AFCCC takes more time to put this non-standard data into a database. The initial regressions used temperatures in Kelvin to test if 'regression through the origin' increased the goodness of fit. However, 'regression through the origin' actually had a marginally worse fit, though not statistically significant, and so was not selected for the final tool. The regressions for the weather towers were done for the mean minimum temperature of the nine verification towers and the lowest minimum among these towers. However, the difference between the predicted mean minimum and lowest minimum temperatures was at most only 2°C. Therefore, the 45 WS implemented only the first guess for the lowest minimum temperatures at the towers, for a conservative safety factor and for operational simplicity in the new tool.

The final regression equation using the 1000-850 HPa thickness for lowest minimum temperature at the verification weather towers explains 74.9% of the observed variance and provides an up to 6.1°C (11°F) improvement over the original first guess. The 1000-500 HPa thickness regression explains 68.5% of the observed variance. As expected, the 1000-850 HPa thickness regression performed slightly better than the 1000-500 HPa thickness and was selected as the primary first guess (figure 9). The 45 WS also implemented the 1000-500 HPa regression, as a backup 'first guess', in case the 1000-850 HPa thickness was ever not available. The primary and back-up regression equations are shown below.

$$\text{Min Temp}(°\text{C}) = 0.1927(\text{TH}_{1000\text{-}850\text{HPa}}(\text{m})) - 251.28, \quad R^2 = 0.749$$

$$\text{Min Temp}(°\text{C}) = 0.0633(\text{TH}_{1000\text{-}500\text{HPa}}(\text{m})) - 342.58, \quad R^2 = 0.685$$

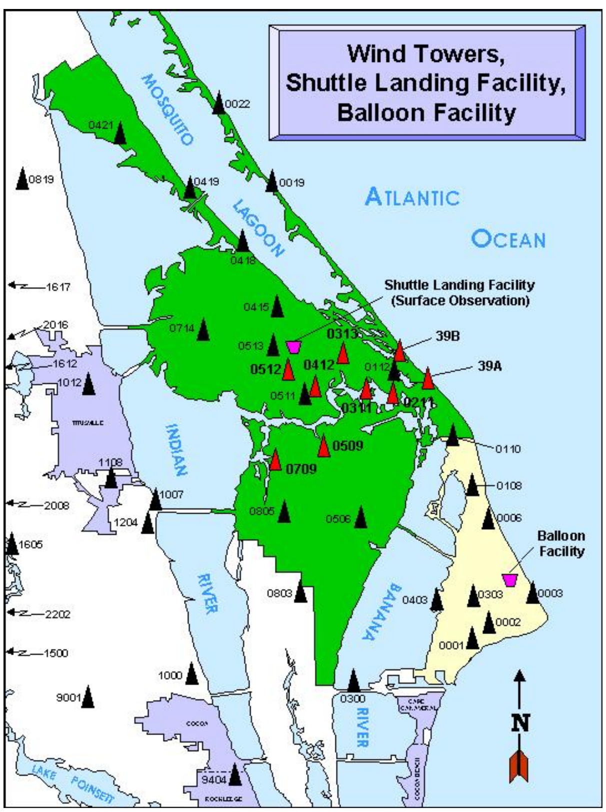

Figure 8. Location of the radiosonde facility, Shuttle Landing Facility surface observation, and verification weather towers (highlighted in red).

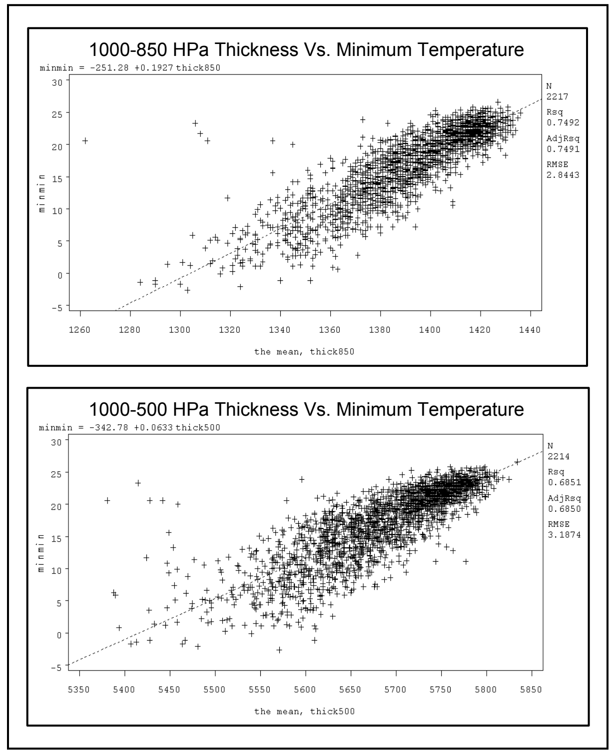

Figure 9. Scatter diagrams for the 1000-850 and 1000-500 HPa thicknesses versus the lowest minimum temperatures at the 45 WS verification towers. Analysis and figures provided by AFCCC at 45 WS request.

3.2 New Correction Factor: Wind Speed

The original correction factor for wind speed only allowed for extra cooling at low wind speeds in two categories: < 15 Kt and < 10 Kt, which later were determined to be too high for extra cooling. In addition, a logic error in the flowchart sometimes did not apply the correction factor when required.

The new wind speed correction factor recognizes that a thickness-based 'first guess' forecasts the minimum temperature under average conditions. Thus, correction factors should have zero effect at their average conditions. For wind speed, this means extra cooling should be applied for wind speeds less than average and extra warming should be applied for wind speeds above average. The climatological average wind speed for CCAFS/KSC area between local midnight and sunrise during the cool season is around 5 Kt (AFCCC, 2004b). The up to 3°C of extra cooling at low wind speed from the original flowchart was accepted for calm conditions in the new tool. Two data points for suppressed cooling at higher wind speeds (extra warming relative to average wind speed) were taken from the Air Force Weather Meteorological Techniques-Revised Technical Note 98/002 (AFWA, 2005): 2 and 5°C of suppressed cooling at 15 and 35 Kt, respectively.

Curve fitting was applied to these four data to provide a continuous wind speed correction factor that allows both extra cooling and warming relative to average. Several candidate curves were explored using the trend-lines function in the Microsoft EXCEL spreadsheet. The log-linear and power law curves could not be tested on the original data, since predictor and predictand values of zero were used. However, these curves were desired for testing, so the original data were transformed with simple translation, with the offsets to be removed after the curve fitting. The two best candidate curves were the second order polynomial and power law, with r^2 values of 0.997 and 0.979, respectively. The 45 WS selected the power law (even though the quadratic fit performed marginally better statistically) because the power law matched meteorological expectations when extrapolated to higher speeds. The power law predicts extra warming as turbulent mixing extends through the entire depth of the planetary boundary layer, though with decreasing amount at higher speeds. However, the quadratic curve reaches a maximum value of extra warming and then decreases at higher speeds, which is physically unreasonable. This crosscheck against expected meteorological behavior should always be done when developing statistical applications, especially with limited data. The power law for the wind speed correction factor is provided below with the curve shown in figure 10.

$$\text{Wind Speed (°F) Correction Factor} = 2.29(\text{Speed (Kt)} + 0.1)^{0.3681} - 4 \text{ Kt}, \quad R^2 = 0.979$$

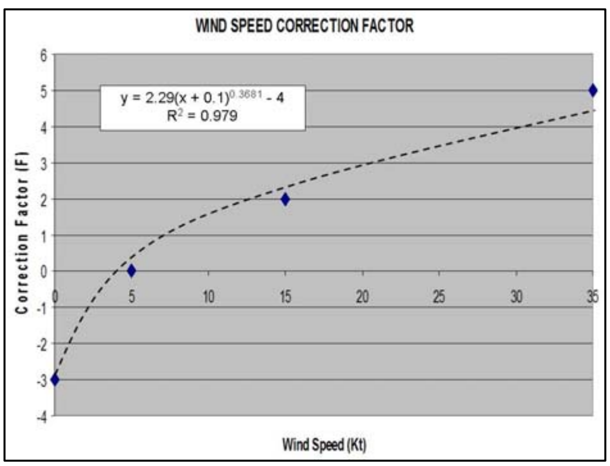

Figure 10. Best fit power law for wind speed correction factor. Equation includes transformations to avoid power law best-fit difficulties with zero values, but the data points and curve are untransformed.

3.3 Refined Correction Factor – Cloud Cover & Fog

The original correction factor for cloud cover only allowed for suppressed cooling for broken to overcast conditions and did not consider cloud height, nor was fog considered. The new cloud cover correction factor again recognizes that a thickness based first guess predicts minimum temperatures under average conditions and thus correction factors should have zero impact at their average conditions. More or lower cloud cover than average yields suppressed cooling, while less or higher cloud cover yields extra cooling. For the CCAFS/KSC area during the cool season, from midnight to sunrise, the average sky condition is scattered middle altitude clouds (AFCCC, 2004b). The correction factors in table-3 were created quasi-subjectively. Fog was considered to have the same impact as overcast low clouds. Calibration points for setting the correction factors were taken from the previous correction factor, the idea that overcast low clouds should suppress most of the diurnal cooling, taken from AFCCC (2004b), and that the correction factor for clouds should be stronger than for humidity, as discussed in section 2.4.

Table 3.
Cloud cover correction factor (°F).

	CLOUD HEIGHT		
CLOUD AMOUNT	LOW	MID	HIGH
CLEAR	-2		
SCATTERED	+2	0	-1
BROKEN	+5	+2	0
OVERCAST/FOG	+8	+5	+2

3.4 New Correction Factor -- Humidity

The previous flowchart did not account for suppressed cooling from atmospheric humidity under little to no cloudiness. Table-4 was implemented, adapted from AFWA (2005) for the humidity in the lowest 5,000 Feet of the atmosphere and personal experience for the mid-level humidity from satellite vapor imagery when the boundary layer is relatively dry.

Table 4.
Atmospheric humidity correction factor (°F).

IF CLOUD CORRECTION ≤ 0 °F, THEN	
Mean Relative Humidity In Lowest 5,000 Ft	**Humidity Correction Factor**
> 80%	+5 °F
50 to 80%	+2 °F
< 50% and MetSat Vapor = High	+2 °F

3.5 New Correction Factor – Dew Point

The temperature cannot fall below the dew point temperature. This has long been a standard technique to set a lower limit on the expected minimum temperature (AFWA, 2005). The dew point at the time of minimum temperature can be quickly estimated as the same as the dew point at the time of maximum temperature the previous afternoon (AFWA, 2005). A better method is to use the Modified Diurnal Curves (ModCurv) tool, which considers the current dew point, climatological diurnal variation, and expected winds and cloud cover (ModCurv, 20004). An example of the ModCurv output for CCAFS/KSC is at figure 11.

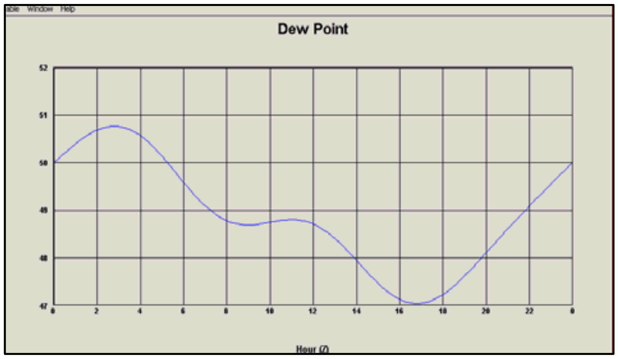

Figure 11. Example of the ModCurv (AFCCC, 2004c) dew point temperature curve for KSC with initial conditions of T_d = 50°F for 00 UTC in February with northerly wind and clear skies.

3.6 Unmodified Correction Factors – Wind Direction And Nocturnal Radiation Inversion

The correction factors from the previous flowchart for wind direction and nocturnal radiational inversion were deemed appropriate and were duplicated in the new tool. As seen in figure 1, easterly winds advect warmer temperatures from over the Atlantic Ocean. Therefore, wind directions from 001 to 180° yield a correction factor of +1.1°C (+2°F). The presence of a nocturnal radiation inversion yields a correction factor of +1.7°C (+3°F).

3.7 Improved Performance Of The New Tool

The 45 WS compared the performance of their low temperature advisories between the 2003-2004 and the 2004-2005 cool season (October-April). The previous flowchart was the main low temperature tool used in the former season, while the new tool was implemented incrementally during the latter season. The false alarm rates changed from 67% to 38%--a 29% improvement. The number of advisories meeting the desired lead-time changed from 33% to 75%--a 42% improvement. These improvements represent a lower limit, since the new tool was implemented incrementally during the 2004-2005 cool season. A comparison of the two techniques on the same time period would have been best, but wasn't done due to personnel shortages.

3.8 New GUI

A new GUI was developed in EXCEL and implemented on the internal website along with the other web-based tools used by 45 WS (figure 12). This GUI does all the calculations and logic, and requires only the following inputs from the forecaster: expected thickness, wind speed, cloud cover, humidity, wind direction, and radiation inversion. The required inputs are highlighted in yellow, with the new expected minimum temperature displayed in the adjacent cell. If the expected minimum temperature would meet one of the 45 WS low temperature advisories, it is highlighted in one of four shades of blue—the lower the temperature threshold being met, the deeper the shade of blue. The GUI significantly eases the use of the new minimum temperature tool by the operational forecasters while increasing the accuracy and speed of the product, all of which increases the likelihood that the new tool will be used.

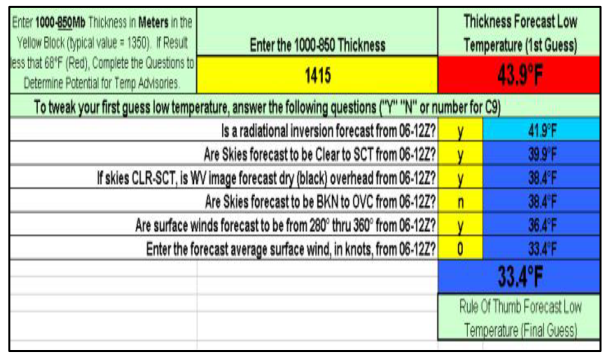

Figure 12. Example of new 45 WS minimum temperature GUI.

4. ON-GOING WORK AND FUTURE PLANS

As of May 2005, the 45 WS is currently optimizing the correction factors in this low temperature tool. All days with a daily minimum temperature of 15.6°C (60°F) or less from 2000 to 2004 have been identified. A maximum likelihood estimation technique is being used to set an initial estimate for the optimal correction factors. This technique assumes all the other correction factors, besides the one being optimized, are randomly distributed. Since this is not necessarily true, an iteration process around the maximum likelihood estimation will be used for the final optimization.

The thickness based 'first guess' should work best for forecasting the mean temperature. Applying the difference between the mean minimum and mean temperature will be investigated, i.e. half the mean diurnal range. This should introduce increased accuracy and introduce some seasonality to the first guess. The minimum/mean temperature difference would be interpolated from monthly to daily values, to avoid arbitrary discontinuities when changing months.

The 45 WS also plans to expand the comparison of the performance of their low temperature advisories before and after the new method was implemented.

5. SUMMARY

The 45 WS implemented an improved minimum temperature tool, since low temperature advisories are the most frequent warning/watch/advisory they issue during winter. Applied climatology was used extensively in this improvement. A linear regression using the 1000-850 HPa thickness for a first guess forecast of the minimum temperature was developed. The previous technique used the 1000-500 HPa thickness and subjective estimates of the first guess forecast. Applied climatology was also used to optimize most of the correction factors to the first guess forecast: wind speed, cloud cover, humidity, dew point, and wind direction. The new tool significantly improved forecasts of minimum temperature as compared to the previous method: 11°F more accurate, 29% better false alarm rate, and 42% more meeting desired lead-time. A website GUI was developed to increase the ease of use and accuracy of the new technique.

Acknowledgments: The 45 WS gratefully acknowledges the contributions of the Air Force Combat Climatology Center to this project, specifically the regression analyses of 1000-500 HPA and 850-500 HPA thicknesses versus observed minimum temperatures, and providing past surface and RAOB observations for fine tuning the correction factors.

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