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Climatology as an Alternative to Standard Meteorology for Temperature

by Brian P Reen

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14. ABSTRACT
Meteorological profiles referred to as standard meteorology are often used when better sources of meteorology (e.g., observations or numerical weather prediction forecasts) are not available. However, with easily obtainable information it may be possible to better estimate the vertical temperature profile than that provided by standard meteorology. Since surface temperature is easy to measure or even estimate, three profile estimation methodologies leveraging surface temperature are tested against numerical weather prediction profiles to evaluate their ability to estimate the temperature profile over one country. The method that performs best applies the climatological season-specific average temperature profile for that country for the surface temperature bin corresponding to the surface temperature. This technique improves over standard meteorology by 2.1 K when averaged over 0–40 km above ground level (AGL). Transitioning from height AGL to height above mean sea level climatological profiles well above the surface may provide minimal additional improvement for this country but will likely be more important for countries with higher average terrain heights. The addition of a surface pressure measurement may provide additional benefit by improving on the standard atmosphere estimates of pressure and density.

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standard meteorology, climatology, temperature, profile estimation, surface temperature, Military Information Sciences

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1. Introduction

While the most accurate estimate of the current vertical profile of meteorological fields is likely to be derived from either current observations of the profile or numerical weather prediction (NWP) forecasts incorporating recent observations, there are cases wherein neither of these sources can be used. In these cases, "standard" meteorological conditions based on the International Civil Aviation Authority (ICAO) standard atmosphere (ICAO 1993) are sometimes leveraged (henceforth referred to as Std_Atm). This may be the best choice in cases where no information is available to provide a more situation-specific estimate of meteorological conditions. However, if additional information is available about the situation (e.g., location, or season) a more accurate estimate of meteorological conditions might be obtained.

In some cases, it may not be feasible to obtain observations or NWP predictions of the vertical profile of the atmosphere and then ingest this data into an application requiring such data. Taking observations of the variation of atmospheric fields with height through thousands of meters of atmosphere requires equipment and personnel that may not be available. Obtaining up-to-date NWP predictions requires sufficient communications bandwidth to obtain. Even if meteorological data is obtained from one of these sources, there must also be a mechanism to ingest meteorological profiles from these sources.

Although observations or NWP predictions may not be feasible for some applications, there may be other information that can be leveraged to obtain better estimates of atmospheric profiles than Std_Atm. The current time of year (e.g., season) and location may allow a climatological profile to be obtained that better matches reality than Std_Atm. Additionally, while observations through thousands of meters of atmosphere can be challenging to obtain and ingest, observations at the surface are much easier to obtain. For temperature, a human observer is likely to be able to roughly estimate the temperature even without a separate sensor.

By leveraging season, location, and an estimate of the surface temperature, this study explores whether estimates of the vertical profile of temperature can be obtained that are better than Std_Atm. The location being investigated is Ukraine. Section 2 describes the methodology used, Section 3 documents the results of applying this methodology, and Section 4 provides a summary and conclusions.

2. Methodology

2.1 Overview

NWP forecasts from the Global Forecast System (GFS) are used to evaluate the ability of various techniques to predict the vertical profile of temperature over Ukraine. GFS is the operational civilian global weather prediction model in the United States and is created by the National Centers for Environmental Prediction (NCEP), which is part of the National Oceanic and Atmospheric Administration. The use of NWP forecasts rather than radiosondes allows for a much larger sample size, and thus allows a much larger range of conditions to be accounted for in the evaluation.

A very rough estimate of the border of Ukraine was used to exclude most GFS gridpoints outside Ukraine. Since it is anticipated that climatologically the meteorological conditions will be very similar just outside Ukraine to those inside Ukraine, the inclusion of points that are outside the borders of Ukraine and yet near Ukraine in the analysis should not be problematic. Additionally, all GFS grid points at which GFS considered the land surface to be water are excluded from the analysis since vertical temperature profiles near the surface over water are likely to differ from those over land, and land areas are the focus of this investigation. The result of applying these two criteria is shown in Fig. 1, which marks the GFS gridpoints included in the analysis. A total of 1551 or 1552 GFS gridpoints are used in the analysis. GFS changed the classification of one gridpoint in the area of interest from water to land sometime in the year 2021, thus making an additional gridpoint available to the analysis. The GFS terrain height among the gridpoints varies between approximately 0 and 1202 m.

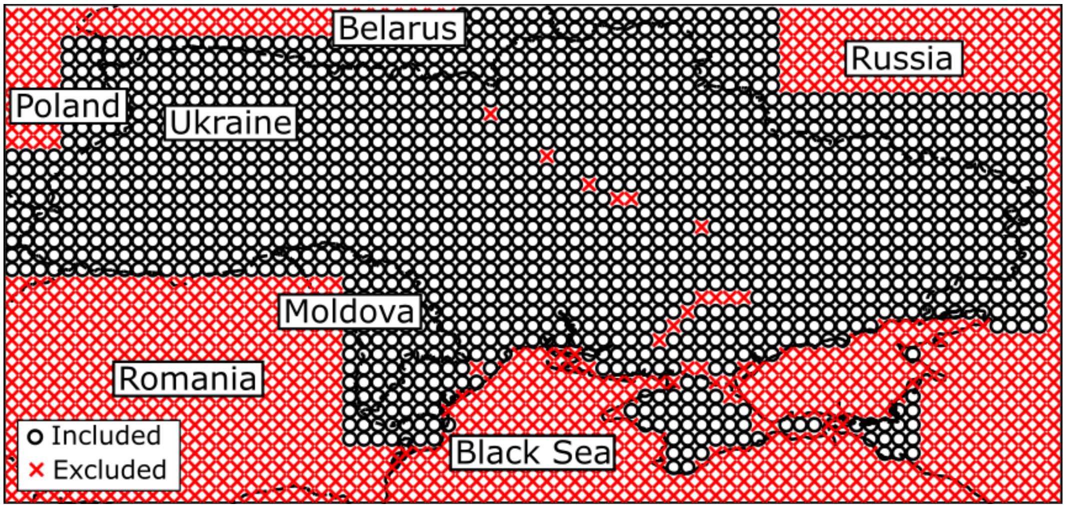


Fig. 1 Map of GFS points included in analysis (black circle) and GFS points excluded from the analysis (red X). The plot is for the period of time in which GFS indicates 1551 non-water gridpoints are available in the area of interest.

For all GFS gridpoints in Fig. 1, GFS profiles from various times of year and times of day were used to evaluate the ability of the various techniques to predict the vertical meteorological profile. For the years 2020 and 2022, data from GFS cycles starting on the 1st, 5th, 10th, 15th, 20th, and 25th of each month were included in the evaluation. For each of these days, the 3-h forecast of the 00 UTC cycle (valid at 03 UTC) and the 0-h forecast of the 12 UTC cycle (valid at 12 UTC) were used. Since local standard time (LST) in Ukraine is UTC+2, the two times investigated here are 05 and 14 LST. This allows the evaluation to include a time when the atmospheric boundary layer (ABL) will often be stable (05 LST) and a time when the ABL will often be convective (14 LST) to more fully evaluate the performance of the techniques across the range of ABL temperature profiles in Ukraine. Accounting for the number of horizontal gridpoints in GFS that are included, and the number of times evaluated at each of these locations, results in 446,832 samples at each vertical level.

GFS data on pressure levels and height levels were used to form a combined profile. The height levels are defined in terms of height above ground level (AGL) and thus are referred to as AGL levels. Temperature is available in the GFS data at 0, 2, 80, and 100 m AGL, and pressure is available at 0 and 80 m AGL. Since pressure is not available in the GFS data at 2 and 100 m AGL, pressure at those levels was calculated based on the height and pressure at adjacent levels after the combined profile was created. Temperature and height are available in the GFS data at the following pressure levels (pressure levels in italics are available for the 0-h forecast but not the 3-h forecast): *0.01, 0.02, 0.04, 0.07, 0.1, 0.2*, 0.4, *0.7*, 1, 2, 3, 5, 7, 10, 15, 20, 30, 40, 50, 70, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 925, 950, 975, and 1000 hPa. Since the height of pressure levels varies spatially and temporally, each of the combined profiles are on slightly different heights.

In some of the combined profiles there is an inconsistency in the height–pressure relationship for levels that are close to one another. For example, consider the case where the 1000-hPa pressure level is at 81-m AGL for a specific profile and thus when the pressure and AGL levels are combined, the profile contains levels 1 m apart (80- and 81-m AGL). In this case, the pressure at 81-m AGL might be larger than the pressure at 80-m AGL, presumably due to issues such as precision limitations in the calculations NCEP uses to create the 80-m AGL and 1000-hPa pressure level data from GFS data on the native levels it uses when carrying out forecasts. To overcome this issue, any pair of levels within 9.9 m of one another are modified so that 1) the heights are slightly below and slightly above the midpoint of the two levels, 2) the pressures are based on the average of the two levels' pressures and then adjusted using standard atmosphere gradients and the height difference between the midpoint height and the height of the new level, and 3) the temperature is set to the average of the two temperatures.

The combined profiles are then interpolated to a set of shared AGL levels and a set of shared levels defined in terms of height above mean sea level (MSL) (Table 1); these are used to evaluate candidate profile-generation techniques. While GFS output may have data on pressure levels that are below ground at a given point, we do not calculate data on MSL levels that are below ground, and thus some profiles will be missing data at certain MSL levels. The comparison of the profiles calculated from various candidate techniques to the GFS output is carried out on these AGL and MSL levels. For one technique the evaluation on the MSL levels is not carried out as the technique calculates solely based on height AGL. The levels at which the evaluation is carried out are those shown in Table 1. The same set of heights in meters are used for both the height AGL and height MSL levels, except that 2 m is not used as a height MSL level since it is often below the surface. While height AGL is the focus of this study, the MSL levels were included to investigate whether profiles are more closely related to height MSL than height AGL well above the ABL.

Table 1 Heights at which candidate profile-generation techniques are evaluated. The 2-m level is included as a height AGL level but not as a height MSL level since it is frequently below the ground.

AGL (m) and MSL (m) of levels
39,000
37,000
35,000
33,000
31,000
29,000
27,000
25,000
23,000
21,000
19,500
18,500
17,500
16,500
15,500
14,500
13,500
12,500
11,500
10,500
9500
8500
7500
6500
5500
4750
4250
3750
3250
2750
2250
1750
1250
750
350
100
2

The metric used to evaluate the profile-generation techniques is mean absolute difference (MAD). The temperature generated by each profile-generation technique is compared to the GFS temperature for that location, time, and height, and then the absolute value of that difference is calculated. The absolute difference is then averaged over all locations and times to generate the MAD for that level. Profiles of temperature MAD are shown to compare the performance of the profile-generation techniques.

2.2 Methods to Predict Profiles

The following subsections describe the methods that will be used in this study to predict the temperature profile given knowledge of the surface temperature.

2.2.1 Standard Atmosphere

The ICAO standard atmosphere described in ICAO (1993) specifies profiles of atmospheric quantities from –5 to 80 km MSL. The ICAO standard atmosphere is identical to the standard atmosphere in ISO 2533 (ISO 1975). The Std_Atm specifies that the variation of temperature with height is different within different height layers. Table 2 describes the Std_Atm temperature specification. The Std_Atm temperature profile up to 41-km MSL is shown in Fig. 2. Since the highest GFS terrain height among the gridpoints processed is approximately 1202-m MSL, translating the highest AGL level in Table 1 into MSL yields 40,202-m MSL and hence plotting the Std_Atm temperature profile up to 41-km MSL is sufficient for the current investigation. Note that the Std_Atm temperature profile is not dependent on the surface temperature, and thus the Std_Atm method will predict the same temperature profile regardless of the observed surface temperature.

Table 2 Std_Atm temperatures at the edge of layers and the vertical temperature gradients (dT/dz) within each layer (adapted from Table D in ICAO [1993] and used by permission of the ICAO)

Geopotential height (km)	Temperature (K)	dT/dz (K/km)
–5	320.65	
		–6.5
0	288.15	
		–6.5
11	216.65	
		0.0
20	216.65	
		1.0
32	228.65	
		2.8
47	270.65	
		0.0
51	270.65	
		–2.8
71	214.65	
		–2.0
80	196.65	

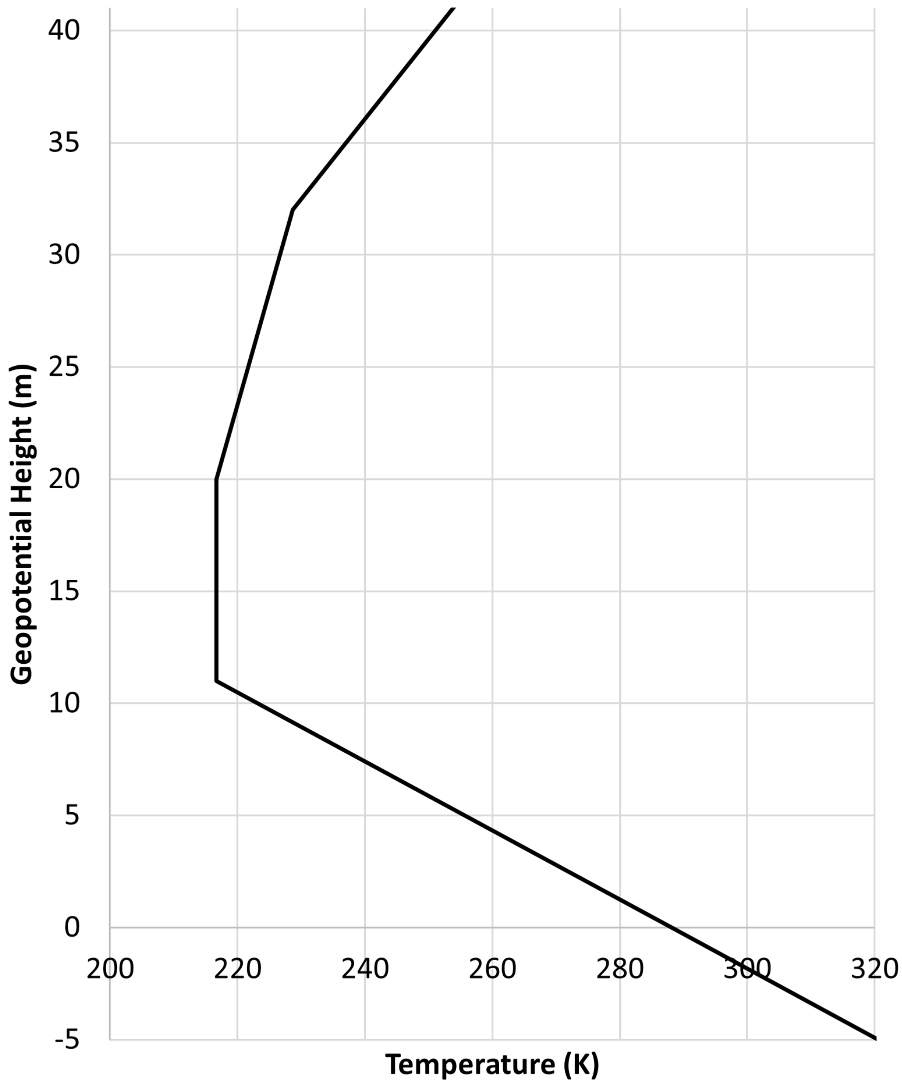


Fig. 2 ICAO standard atmosphere temperature profile (K)

2.2.2 Laser Environmental Effects Definition and Reference (LEEDR)

The LEEDR software characterizes the atmosphere and carries out radiative transfer calculations (Fiorino et al. 2014). Some of the methodologies used in LEEDR V4.00.034 to calculate atmospheric temperature profiles are adapted here to calculate profiles that will be referred to as LEEDR profiles. The LEEDR technique used here applies the observed surface temperature at the surface, assumes a dry adiabatic lapse rate through the ABL, and then applies a region- and season-specific temperature profile above the ABL. Note that LEEDR has various options for specifying an atmospheric profile and thus the LEEDR technique adapted here is not the only technique available in LEEDR.

LEEDR applies the dry adiabatic lapse rate (–9.8 K km^{-1}) starting at the surface up until the height at which a parcel lifted from the surface saturates, and then applies the moist adiabatic lapse rate. However, in this study the dry adiabatic lapse rate is applied throughout the ABL. This investigation examines improving the temperature profile provided by the ICAO standard atmosphere (in cases where the surface temperature, region of interest, etc., is known). The ICAO standard atmosphere assumes there is no water vapor, and since investigating potential improvements of the water vapor field is outside the scope of this study, we retain the assumption of no water vapor. Given that there is no water vapor, a parcel lifted from the surface will never saturate and thus the dry adiabatic lapse rate is applied throughout the ABL.

The depth of the ABL can be specified in LEEDR as a function of the local time and the season (Table 3). To determine local time in this study, a rough approximation of local solar time is calculated using solely longitude and UTC time. While it appears that LEEDR assigns all times of year to either summer or winter, here a weighted average of the summer and winter ABL depths is used. Specifically, for the Northern Hemisphere in July the summer ABL depth is used, in January the winter ABL depth is used, and for all other months the ABL depth is a linear combination between the summer and winter values based on proximity to January and July. For the Southern Hemisphere, the weightings are assigned similarly but with January being the month to which the summer ABL depth is solely applied and similarly July for the winter ABL depth.

Table 3 ABL depth (m) specified based on surface type, local time, and season, as can be used in LEEDR and is applied in the LEEDR method here. The LEEDR method applied here does not vary ABL depth over water based on time and so the time columns are marked with ellipses.

Surface	Local time		ABL depth (m)	
	≥	<	Summer	Winter
Non-water	0000	0300	500	500
	0300	0600	500	500
	0600	0900	1000	500
	0900	1200	1524	1000
	1200	1500	1524	1524
	1500	1800	1524	1524
	1800	2100	1524	1000
	2100	0000	1000	500
Water	. . .	. . .	500	500

Above the ABL, a regional climatological atmospheric profile used in LEEDR is applied. LEEDR leverages winter and summer temperature profiles by MSL height for six regions: polar north, polar south, midlatitude north, midlatitude south, tropical, and desert. For the LEEDR profiles in this study, the winter and summer temperature profiles are weighted using the same methodology as described previously for ABL depth. This study is limited to Ukraine and its immediate surroundings, and so the midlatitude north upper-air temperature profiles were the only ones used here. The regional upper-air atmospheric profiles appear to have been derived from the Global Upper-Air Climatic Atlas, which includes monthly mean values at the surface and on 14 pressure levels at 2.5° latitude/longitude spacing based on European Centre for Medium Range Weather Forecasts from 1980 to 1991.

Since the LEEDR techniques adopted here use a different technique near the surface (i.e., 0-m AGL) than well above the surface (to allow it to represent the ABL), the technique is not amenable to applying it in terms of height MSL. Thus, the LEEDR technique is only applied in terms of height AGL.

Two samples of profiles generated using this methodology are plotted in Fig. 3 and described in Table 4. Both profiles were generated for the same location, but one was for 15 January 2021 at 0300 UTC and assumes a surface temperature of 271.5 K, whereas the other is for 15 July 2021 at 1200 UTC and assumes a surface temperature of 308.8 K (the surface temperatures are those provided by GFS). For this longitude, a rough estimate of solar time for the two cases is 0457 for the January profile and 1357 for the July profile. Given that this is a land point, and given the times and seasons of these profiles, Table 3 indicates that the ABL depth should be 500 m for the January case and 1524 m for the July case.

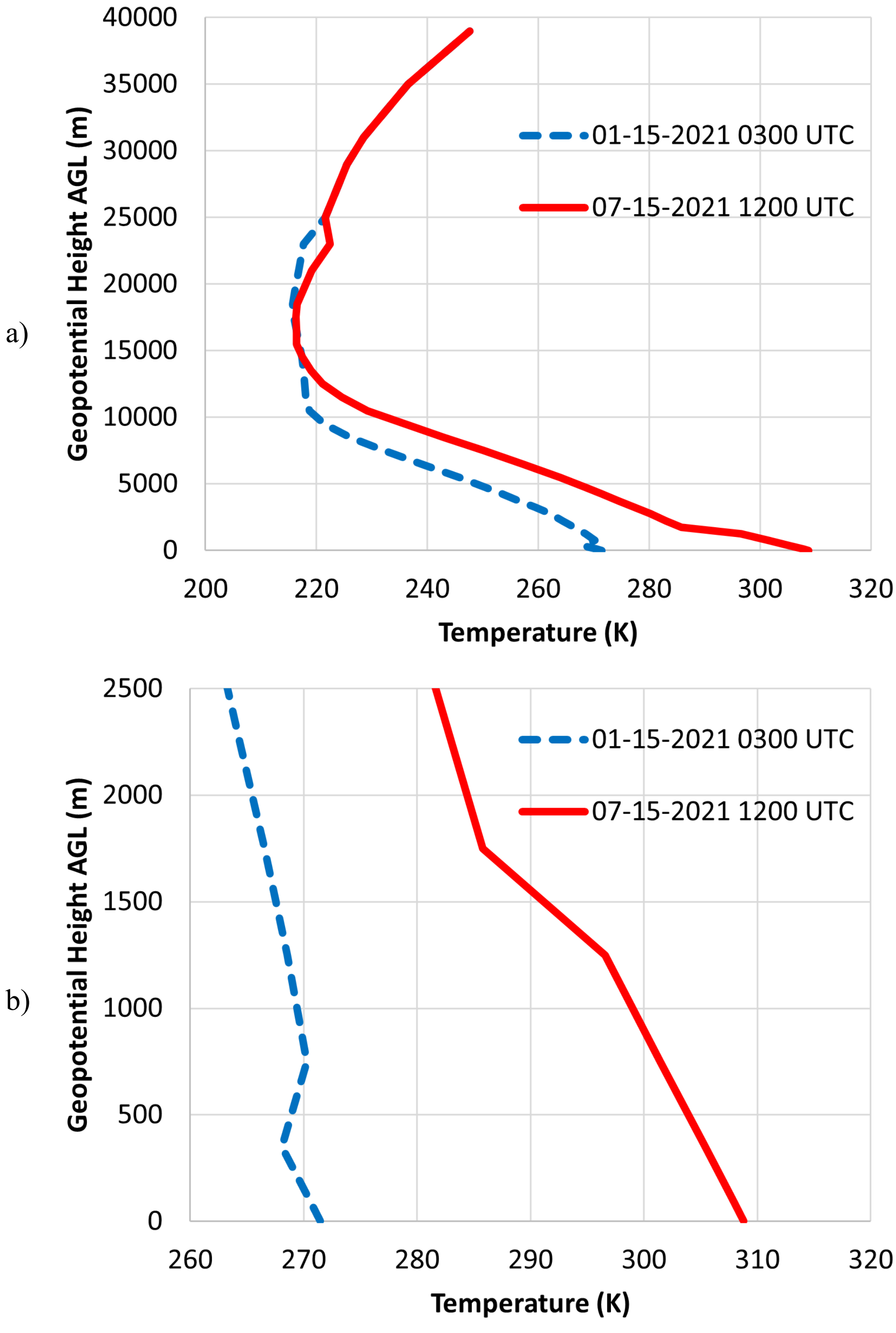


Fig. 3 Sample LEEDR temperature profiles for a) 0–39 km AGL and b) the same profiles but only showing 0–2.5 km AGL. Further details regarding the profiles are in Table 4.

Table 4 Details regarding the sample LEEDR temperature profiles in Fig. 3

Profile characteristic	Profile 1 (blue-dashed line)	Profile 2 (red line)
Surface temperature (K)	271.5	308.8
Date	15 January 2021	15 July 2021
UTC time	0300	1200
≈ Local solar time	0457	1357
Latitude	45.00°	45.00°
Longitude	29.25°	29.25°
ABL depth (m)	500	1524
Land/sea	Land	Land

In Fig. 3b, the January sample profile indicates two heights where the vertical temperature gradient changes: 350- and 750-m AGL. The LEEDR technique used here involves applying a temperature gradient throughout the ABL (in this case 0–500 m AGL) and then applying a regional climatological temperature profile above this. The changes in gradient at 350- and 750-m AGL, even though the ABL top is at 500 m, are because the AGL levels at which the profile is being evaluated do not include a level at 500 m and the nearest levels are 350- and 750-m AGL. This is also seen in the July profile, where the ABL depth is set to 1524 m, but the vertical temperature gradient assigned to the ABL only occurs up through the nearest level below 1524 m—namely, 1250 m.

Above the ABL, the two sample profiles indicate differences at many heights below 25-km AGL. The January sample profile is based solely on the winter LEEDR regional climatological profile, and the July sample profile is based solely on the summer LEEDR regional climatological profile.

2.2.3 Climatology

Climatological temperature profiles were created using output from the GFS NWP model. While the evaluation of the three profile-generation methods is carried out using GFS data from the years 2020 and 2022, the climatological temperature profiles are generated using GFS data from the years 2021 and 2023. Evaluating the climatological profiles with different data than are used to create the climatological profiles means that the evaluation is not merely measuring how well the climatological profiles fit the data on which they are created, but instead how well they can be used to predict profiles not in the dataset used to create them. While different years are used for creating than are used for evaluating, the climatological profiles are based on the same days of the year and GFS cycle—forecast length combinations used in the evaluation dataset. This means that the climatological profiles were created using GFS data for the years 2021 and 2023 from GFS cycles starting on the 1st, 5th, 10th, 15th, 20th, and 25th of each month.

For each of these days, the 3-h forecast of the 00 UTC cycle (valid at 03 UTC) and the 0-h forecast of the 12 UTC cycle (valid at 12 UTC) were used.

The same GFS gridpoints as are used in the evaluation of generated profiles are used in creating the climatological temperature profiles. Specifically, the climatological temperature profiles are based on the GFS gridpoints marked in Fig. 1 as being used (as noted in the discussion of that figure, one gridpoint is only used for a portion of the study period since GFS changed that gridpoint's classification from water to land). Thus, the climatological profiles are based on GFS output in or near Ukraine.

To create the climatological profiles, the 446,942 GFS profiles from 2021 and 2023 are binned according to the surface temperature. The bins are 5 K in width and range from 237.5 to 317.5 K, but with the coldest and warmest bins including any profiles whose surface temperature falls outside that range. The temperature bins are shown in Table 5. At each height, the temperature from each profile in the bin is averaged to calculate a bin-average temperature.

Table 5 Temperature range for each climatological bin. The first bin includes all surface temperatures ≤242.5 K and thus there is no lower temperature bound as signified by the ellipses; the specification of the last bin has ellipses as it has no upper temperature bound.

Temperature range included in each bin (K)	
>	≤
. . .	242.5
242.5	247.5
247.5	252.5
252.5	257.5
257.5	262.5
262.5	267.5
267.5	272.5
272.5	277.5
277.5	282.5
282.5	287.5
287.5	292.5
292.5	297.5
297.5	302.5
302.5	307.5
307.5	312.5
312.5	. . .

In addition to the bin-average temperature profiles created using all the case days, season-specific bin-average temperature profiles were also created. Since the entire area of interest is in the Northern Hemisphere, seasons are defined here as: winter: December–February, spring: March–May, summer: June–August, and fall:

September–November. Season-specific bin-average temperature profiles were investigated because it is anticipated that temperature profiles well above the ABL are likely to vary by season.

The all-season climatological temperature profiles for each bin in terms of height AGL are plotted in Fig. 4. Near the surface, the vertical temperature gradient varies from positive for the lowest surface temperature to negative for the highest surface temperatures. This is consistent with the expectation that the lowest surface temperature will occur in concert with a surface inversion and the expectation that the highest surface temperature will be accompanied by a large decrease with temperature just above the surface. While the range in temperatures among the bins is highest at the surface, the range of temperatures remains nonzero throughout the profile. No profiles were found in these cases for the coldest two bins. The coldest and warmest bins that contain data have profiles differing somewhat in shape from the other bins. This is likely due to fewer samples being available in these bins. The number of profiles in the coldest bin with data is approximately 12% of the number of profiles in the next warmest bin. Similarly, the number of profiles in the warmest bin with data is also approximately 12% of the number of profiles in the next coldest bin. Both the coldest and warmest bins with data are based on less than 1% of the number of profiles (79,932) used to create the profile for the bin based on the highest number of profiles.

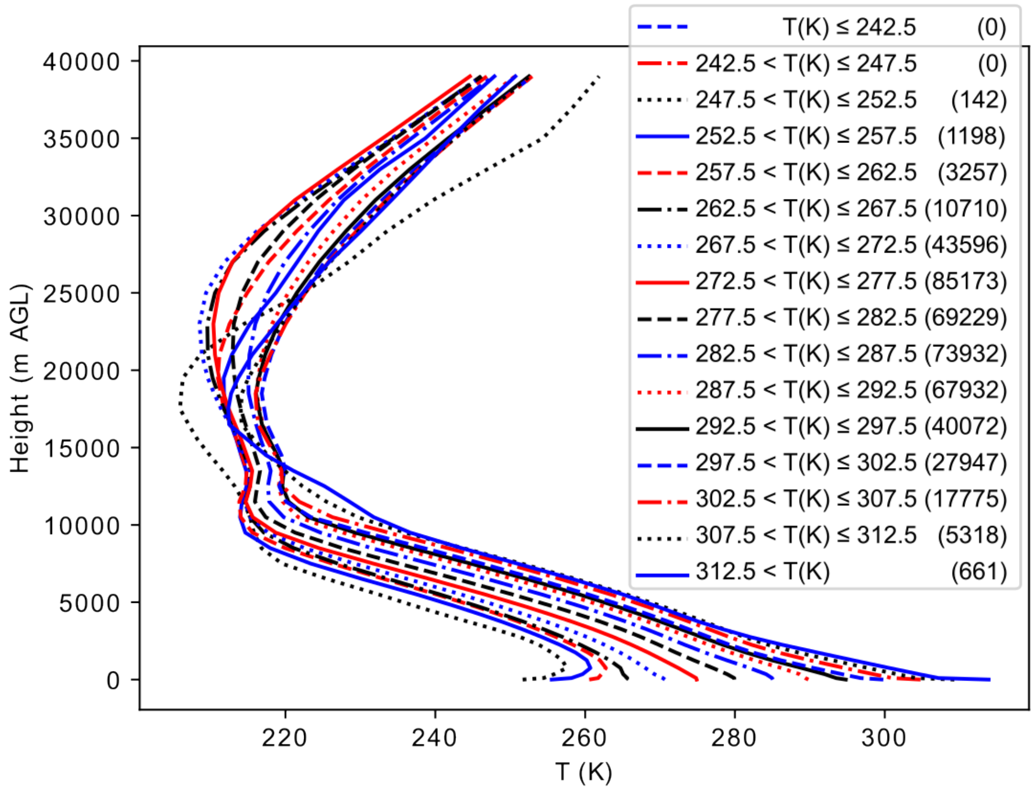


Fig. 4 **All-season climatological temperature profiles in terms of height AGL for 5 K bins of surface air temperature calculated using GFS profiles from the years 2021 and 2023. The number of profiles used to create each profile is noted in parentheses.**

The season-specific climatological temperature profiles in terms of height AGL are shown in Fig. 5. Above 30-km AGL, the variation of temperature among bins varies notably among the seasons. The smallest variation is seen during summer, with variation somewhat larger in winter, spring is next largest, and fall the largest. In general, the profiles for the individual seasons appear similar to the all-season profiles, except that the bins for which there are data varies by season (e.g., the winter season unsurprisingly lacks profiles for the warmest bins). While in Fig. 5 each season-specific bin-averaged profile includes in its legend the number of profiles used to create it, Fig. 6 combines this data to provide a comparison among the seasons as well as with the all-season bin-averaged profile.

When using the climatological temperature profiles to construct a profile based on a surface temperature, the surface temperature may be in a bin that did not have any profiles in the dataset used to create the climatological temperature profiles. For example, none of the case days in 2021 or 2023 had a GFS profile with a surface temperature in the 242.5–247.5 K bin. If a surface temperature of 245.0 K were encountered in the GFS data in one of the case days from 2020 or 2022 used to evaluate the value of the climatological temperature profiles, there would be no climatological temperature profile available for that bin. In such cases, the climatological temperature profile from the bin nearest to the desired bin that has a climatological temperature profile will be used.

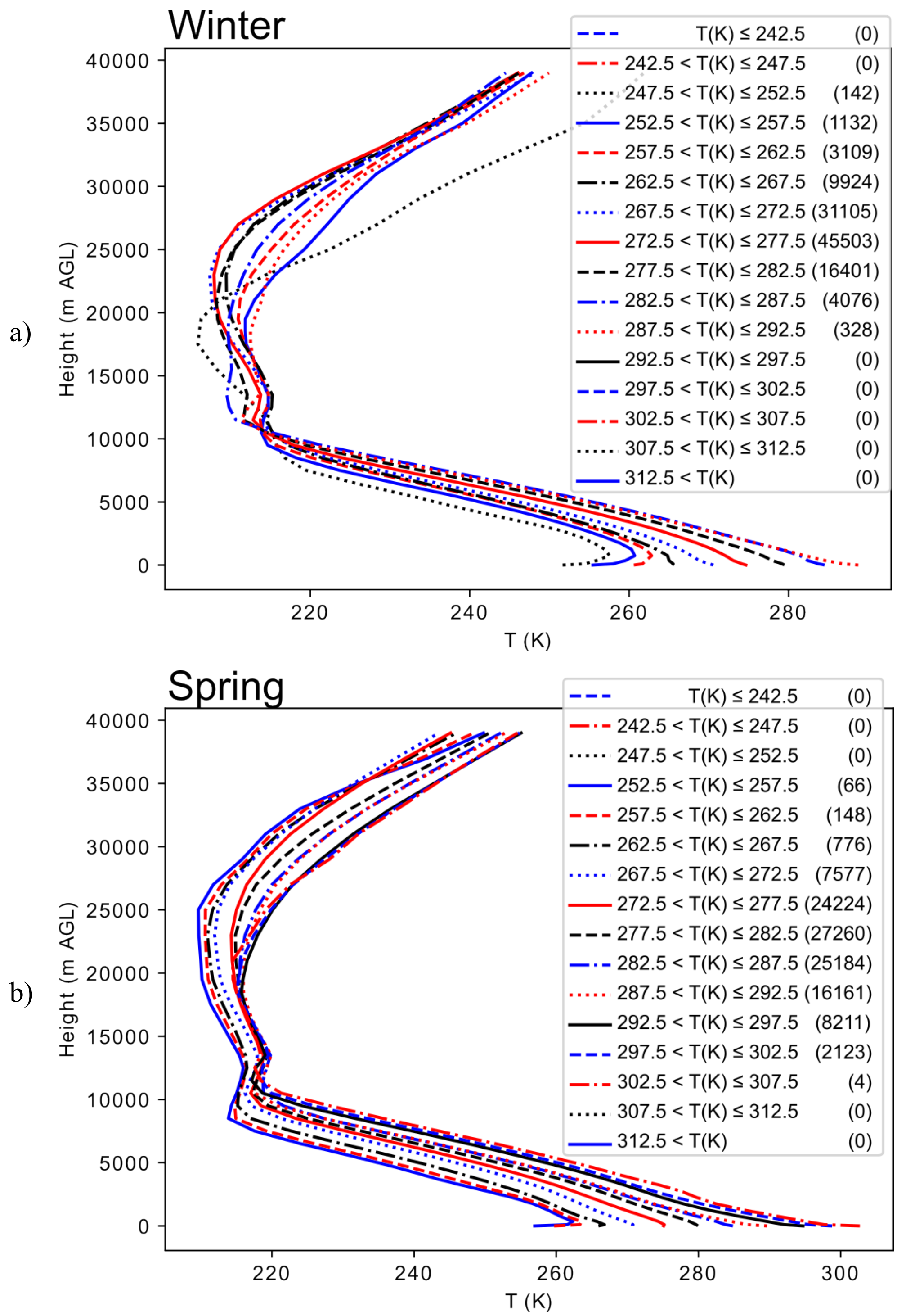
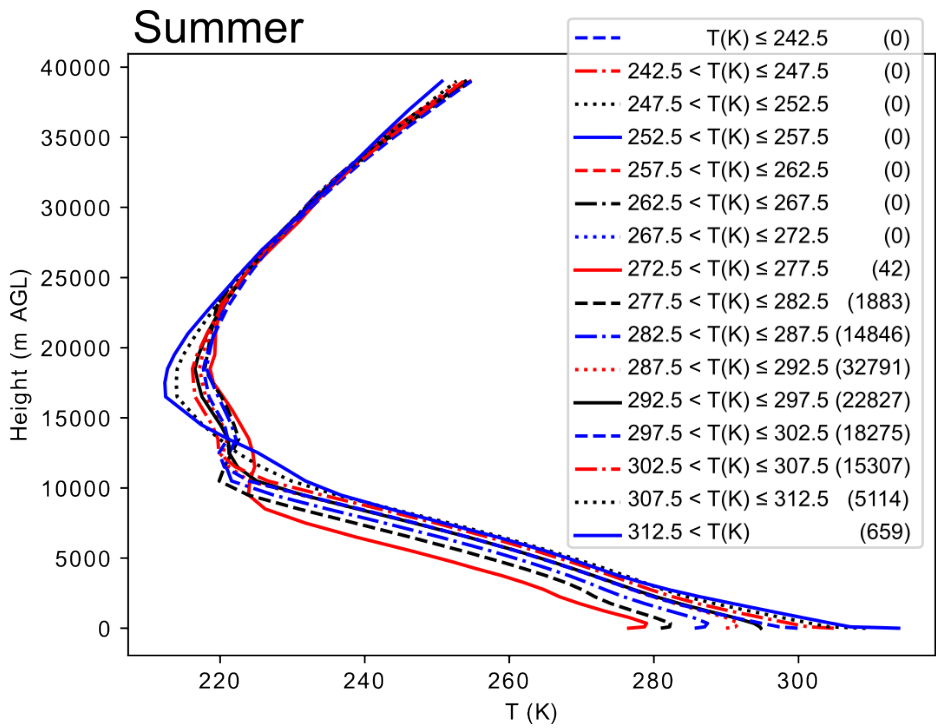


Fig. 5 Climatological temperature profiles in terms of height AGL for 5 K bins of surface air temperature calculated using GFS profiles from the years 2021 and 2023 for a) winter, b) spring, c) summer, and d) fall. The number of profiles used to create each profile is noted in parentheses.

c)



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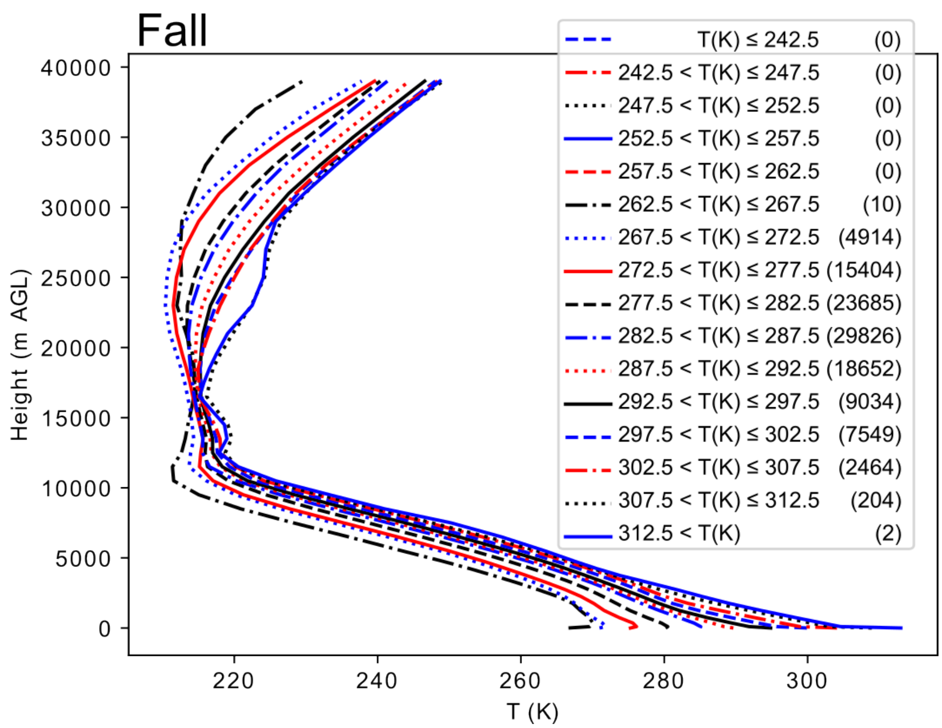

Fig. 5 Climatological temperature profiles in terms of height AGL for 5 K bins of surface air temperature calculated using GFS profiles from the years 2021 and 2023 for a) winter, b) spring, c) summer, and d) fall. The number of profiles used to create each profile is noted in parentheses. (continued)

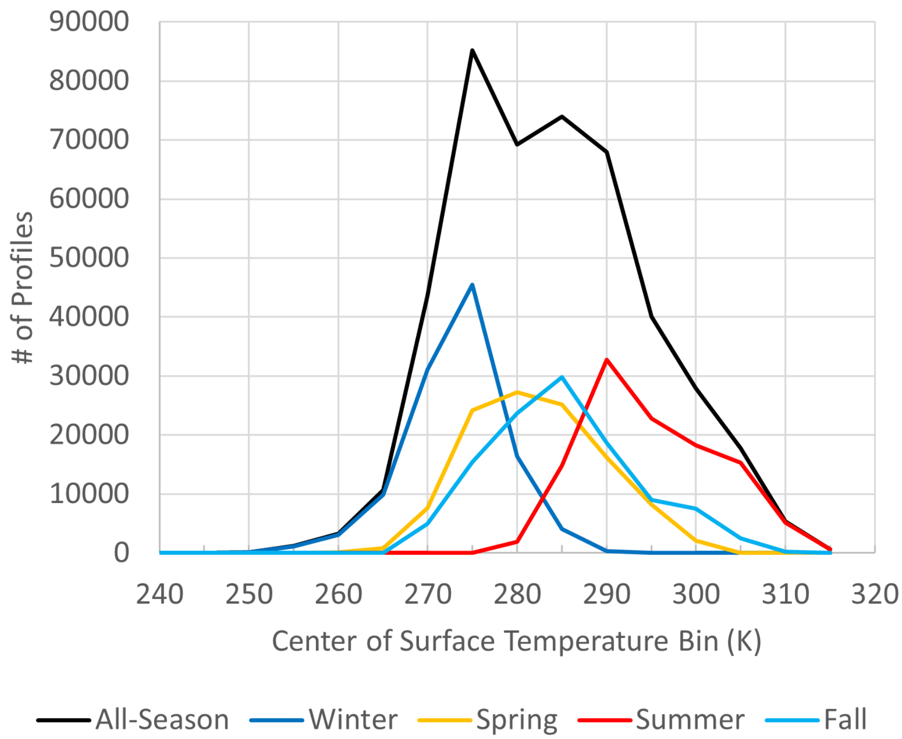

Fig. 6 Number of profiles used to create each bin-averaged profile for each season and overall (all-season)

Climatological bin-average profiles were also calculated in terms of height MSL in addition to those calculated in terms of height AGL (Figs. 4 and 5). The all-season bin-average profiles for height MSL are shown in Fig. 7. The AGL (Fig. 4) and MSL (Fig. 7) bin average profiles are quite similar. Since the season-specific bin-average profiles for height MSL are also very similar to those for AGL, they are not shown here.

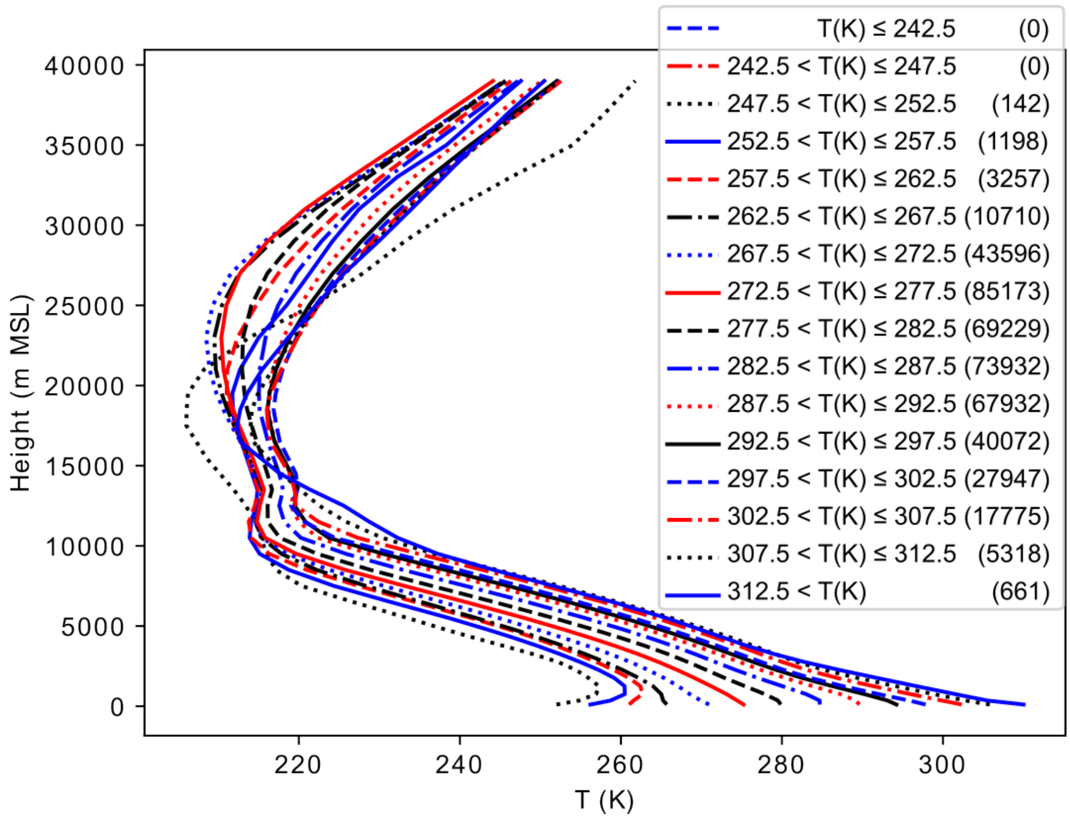

Fig. 7 All-season climatological temperature profiles in terms of height MSL for 5 K bins of surface air temperature calculated using GFS profiles from the years 2021 and 2023. The number of profiles used to create each profile is noted in parentheses.

The limited nature of the differences between the AGL and MSL profiles is likely due to the terrain height being relatively low over much of the study area. The average GFS terrain height for the gridpoints used in the analysis is approximately 175 m, with the largest terrain height approximately 1202 m. A histogram of terrain height (Fig. 8) shows that most (approximately 92%) of the gridpoints included in the analysis have terrain heights less than 300 m.

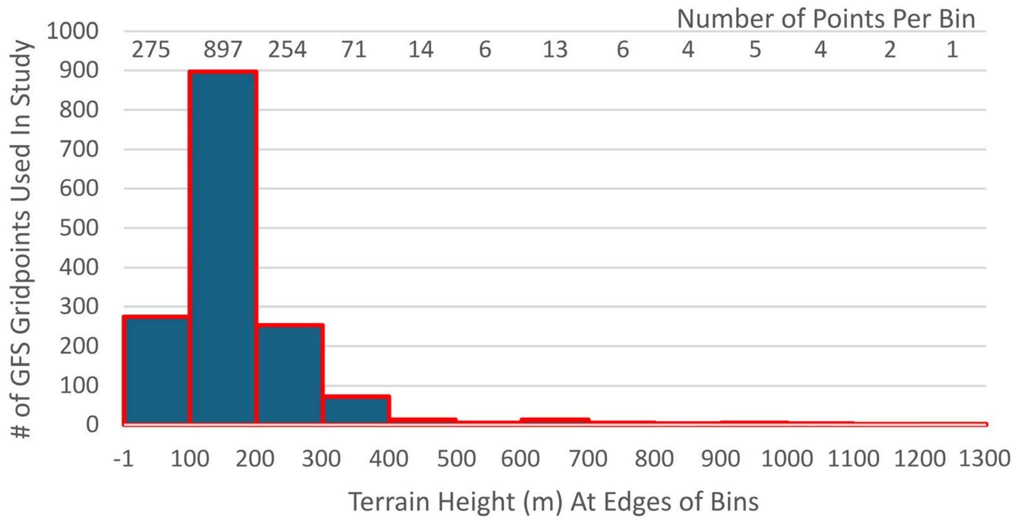

Fig. 8 Histogram showing the distribution of GFS terrain height (m) among the GFS grid points used in this analysis. This histogram was created from GFS data during the portion of the study when 1552 land points are available for use.

3. Results

As described in Section 2, the three techniques for generating temperature profiles from surface temperatures (Std_Atm, LEEDR, and climatological) were used to create profiles for selected times during 2020 and 2022. For two times each day for 6 days each month during these years at GFS land points in and near Ukraine, the GFS surface temperature was extracted, each technique used to generate a temperature profile, and then the generated temperature profile was compared to the GFS temperature profile for that time and location. This results in 446,832 profiles on which to evaluate these techniques.

The MAD measuring the difference between profiles from each technique and the GFS profile is shown in Fig. 9 when evaluated in terms of height AGL. For the climatological technique, there are two variants evaluated here: all-season (Climo_AS) and season-specific (Climo_SS). In general, LEEDR, Climo_AS, and Climo_SS all provide better estimates of the temperature profile than Std_Atm. The magnitude of the improvement in MAD for each of the methods compared to Std_Atm is shown in Fig. 10. Except for at the lowest two levels examined (2- and 100-m AGL), the Climo_SS technique performs best.

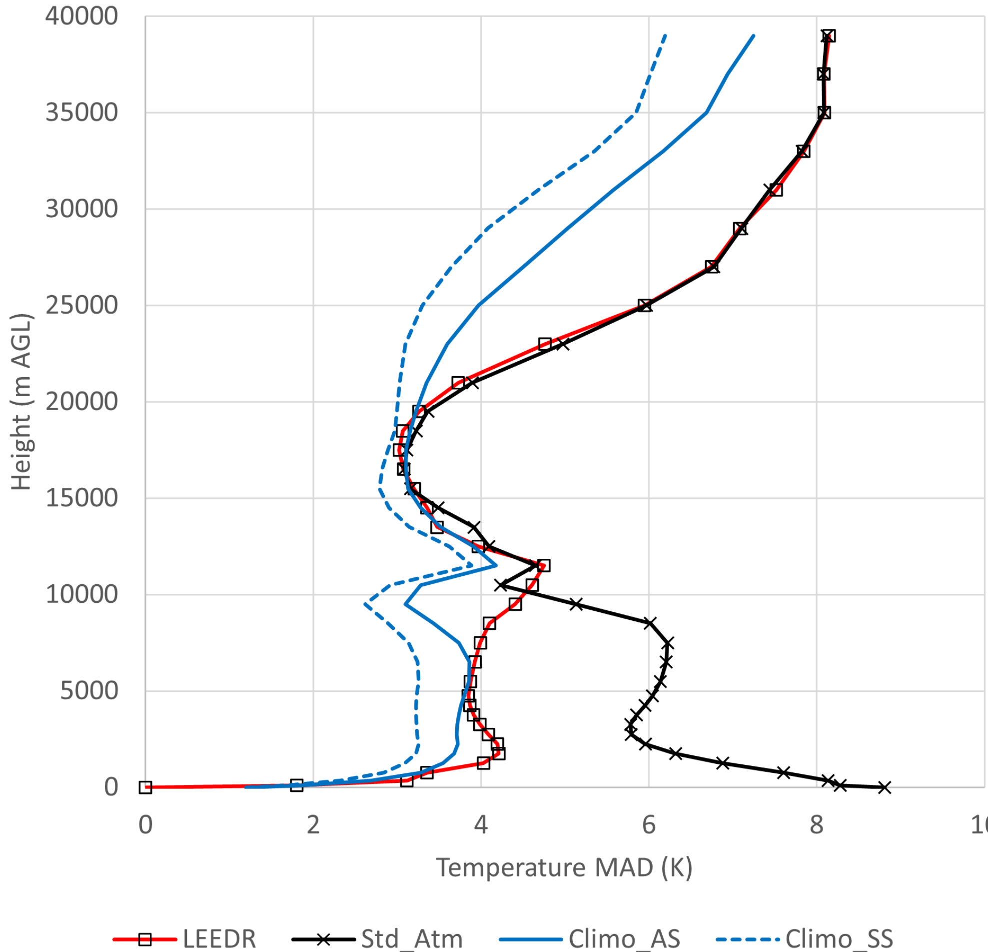

Fig. 9 Temperature MAD (K) between GFS profiles from evaluation dataset and profiles predicted using various methodologies applied in terms of height AGL

a)

b)

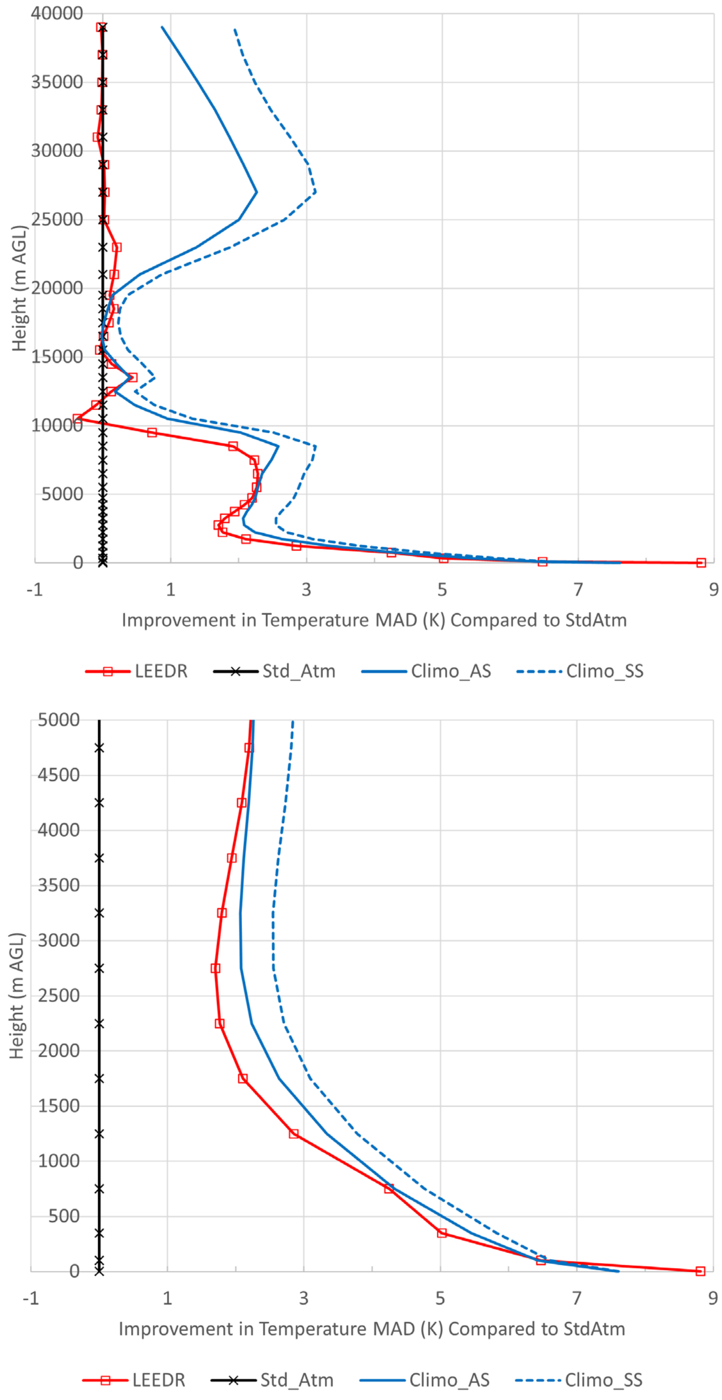

Fig. 10 Improvement in temperature MAD calculated by comparing the MAD for each profile-generation method applied in terms of height AGL to that of Std_Atm for a) 0–39 km AGL and b) 0–5 km AGL

The magnitude of the improvement from not using Std_Atm is largest near the surface (Figs. 9 and 10). While comparing the magnitude of improvements in temperature near the surface can be challenging when examining the full profile

(Fig. 10a), it can more easily be compared using Fig. 10b, which only shows the lowest 5000-m AGL. At the lowest level examined (2-m AGL), LEEDR performs better than Climo_AS and Climo_SS. The LEEDR and Climo_* techniques both depend on a known surface temperature to create the profiles (in "Climo_*", the asterisk serves as a wildcard and thus refers to both Climo_AS and Climo_SS). The LEEDR technique specifies that the known surface temperature is the surface temperature in the profile it generates. However, the Climo_* techniques use the known surface temperature to determine which temperature bin's bin-average profile will be used. Thus, in the Climo_* technique, the surface temperature will be the average surface temperature for the bin in which the known surface temperature falls. One could modify the Climo_* techniques to assign the known surface temperature as the surface temperature in the profile it generates, which would result in the LEEDR and Climo* techniques having identical temperature MAD at the surface. However, without that change, the Climo_* techniques do not require the user to have an observation of the exact surface temperature, but only to determine which 5 K (9 °F) wide bin the surface temperature is in.

Below 10-km AGL, generally Climo_SS performs best, followed by Climo_AS, and then LEEDR (Fig. 10). Performance at 2-m AGL was discussed previously, while at the next lowest level (100-m AGL), LEEDR, Climo_AS, and Climo_SS all perform very similarly. Other than at the two lowest levels, below 10 km the two layers where Climo_AS does not outperform LEEDR are at 750-m AGL and around 5000-m AGL where their performance is nearly identical. Weighting the temperature MAD values based on the thickness of each layer results in MAD improvements compared to Std_Atm in the lowest 10 km of 2.3 K for LEEDR, 2.6 K for Climo_AS, and 3.2 K for Climo_SS (Table 6). The weighting assigns the MAD at a level to the layer whose bottom is the midpoint between the level below and the current level and whose top is the midpoint between the current level and the level above.

Table 6 Layer thickness weighted temperature MAD improvements compared to Std_Atm for height AGL

Layer edges (m AGL)		Temperature MAD improvement compared to Std_Atm (K)		
Bottom	**Top**	**LEEDR**	**Climo_AS**	**Climo_SS**
0	10,000	2.3	2.6	3.2
10,000	20,250	0.1	0.2	0.5
20,250	40,000	0.0	1.5	2.3
0	40,000	0.6	1.5	2.1

Between 10- and 20-km AGL (Fig. 10), the three Std_Atm alternatives do not improve on Std_Atm as much as in other layers, with some levels where no improvement is seen for some techniques or even a small degradation is seen (e.g., LEEDR performs worse than Std_Atm by 0.4 K at 10,500 m AGL). Overall, the layer thickness weighted temperature MAD improvement over Std_Atm for 10,000–20,250 m AGL is 0.1 K for LEEDR, 0.2 K for Climo_AS, and 0.5 K for Climo_SS (Table 6). Even in this layer where alternative techniques improved on Std_Atm less than in other layers, the Climo_SS technique still performed best.

Above 20-km AGL, Climo_AS, and Climo_SS performed better than LEEDR, and Climo_SS continued to outperform Climo_AS (Fig. 10). LEEDR has limited improvement over Std_Atm at the bottom of this layer, and then no improvement above approximately 25-km AGL. Layer thickness weighted temperature MAD improvement over Std_Atm for 20,250–40,000 m AGL is 0.0 K for LEEDR, 1.5 K for Climo_AS, and 2.3 K for Climo_SS (Table 6).

Some of the profile-generation techniques can be applied in terms of height MSL in addition to height AGL. Since the LEEDR technique incorporates an ABL at the surface, it cannot be applied in terms of height MSL. The Std_Atm technique is based solely on MSL and thus could be applied to height AGL solely by converting height AGL to height MSL using the relevant terrain height. The Climo_* techniques can be applied in terms of height MSL by building climatological temperature profiles in terms of height MSL rather than height AGL. Well above the surface it is expected that climatological temperature may be better correlated with height MSL rather than height AGL.

The performance of Std_Atm and the Climo_* techniques applied in terms of height MSL in predicting temperature profiles is shown in Fig. 11. The results are quite similar to those found when applying the techniques in terms of height AGL (Fig. 9). Likewise, the improvement in temperature MAD due to applying the Climo_* techniques with climatological profiles calculated in terms of MSL is shown in Fig. 12 and is quite similar to the improvements when applied in terms of height AGL (Fig. 10). It is important to note that the height AGL and height MSL plots are not using the same MAD statistics for the Climo_* techniques and then just plotting them with a different height coordinate. Rather, the bin-average temperature profiles whose performance is being evaluated are formulated in terms of height AGL in one case and in terms of height MSL in the other.

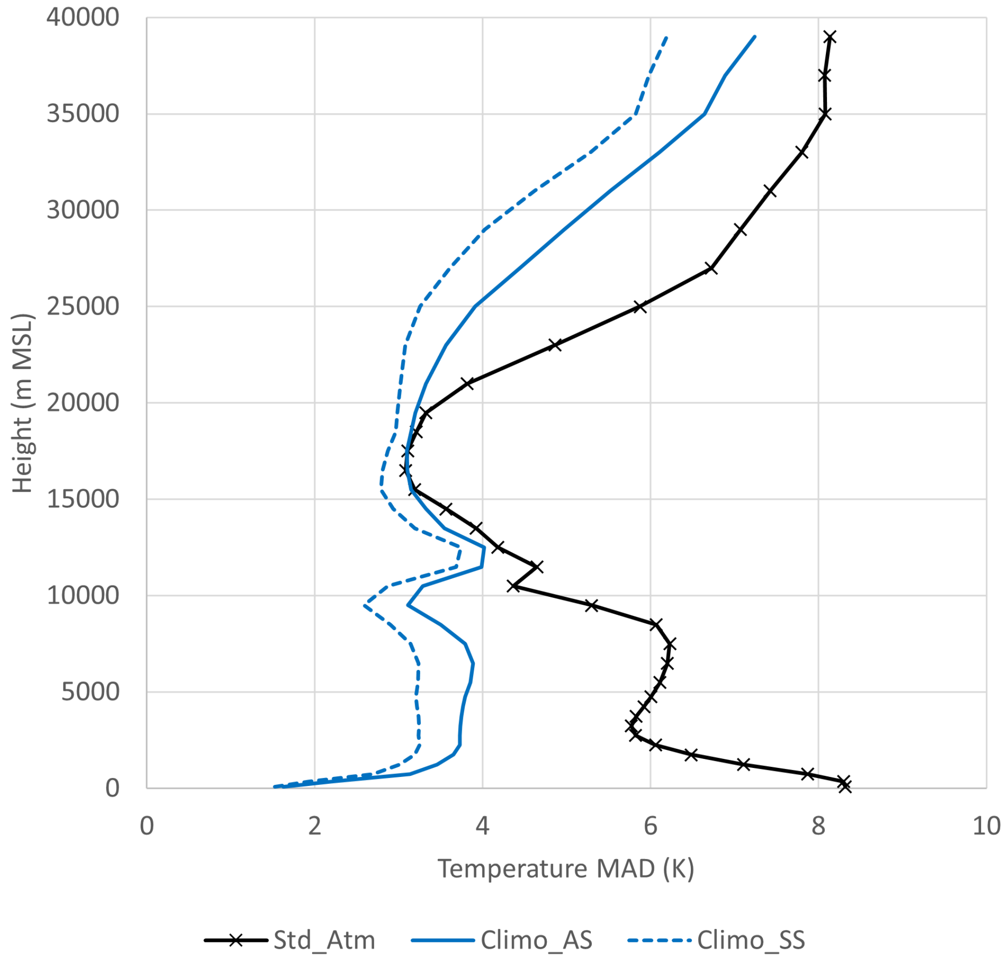

Fig. 11 Temperature MAD (K) between GFS profiles from the evaluation dataset and profiles predicted using various methodologies applied in terms of height MSL

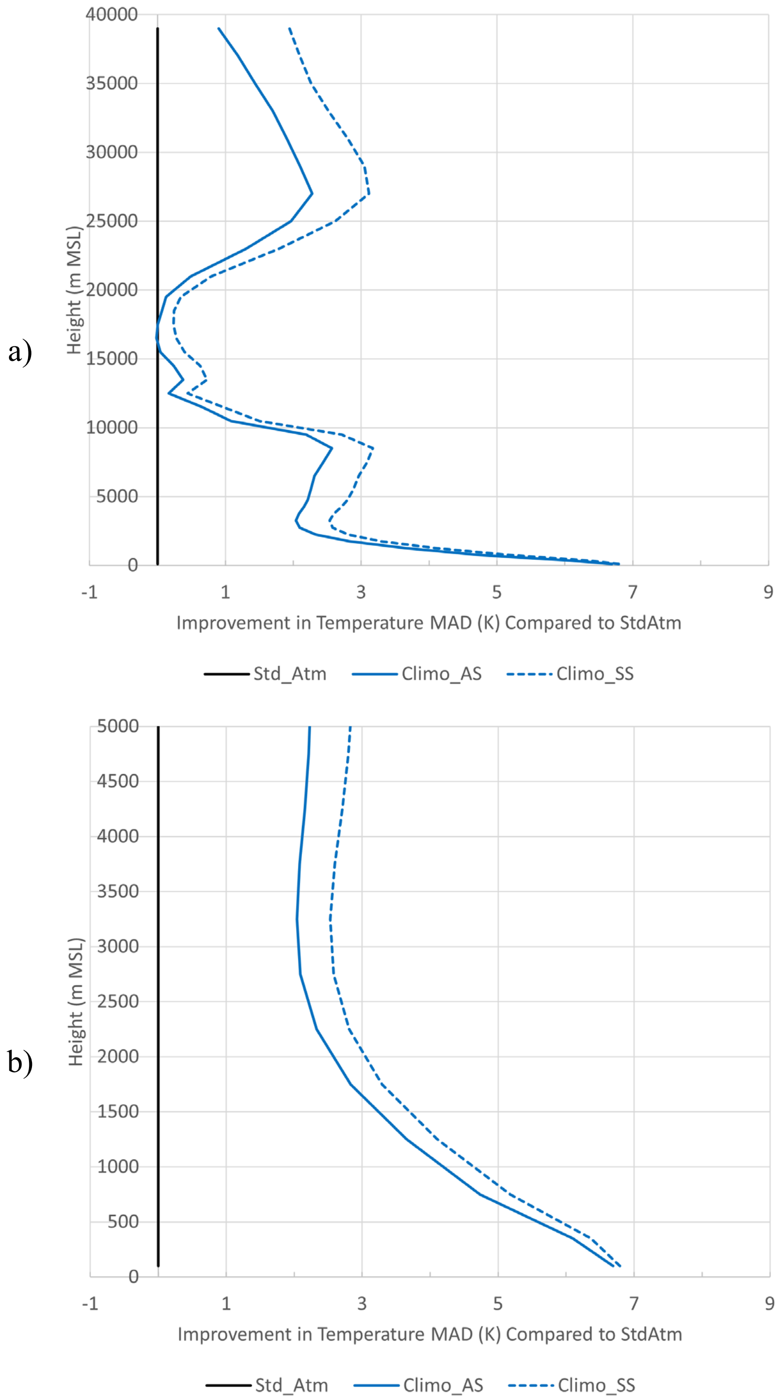

Fig. 12 Improvement in temperature MAD calculated by comparing the MAD for each profile-generation method applied in terms of height MSL to that of Std_Atm for a) 0–39 km MSL, and b) 0–5 km MSL

If temperatures were better predicted from surface temperatures based on climatological profiles calculated in terms of height MSL than climatological profiles calculated in terms of height AGL, lower errors would be expected on the height MSL plot than on the height AGL plot. Directly comparing the two plots is challenging since they use different height coordinates (AGL vs. MSL). However, if height MSL climatological profiles performed substantially better than height AGL climatological profiles, the difference should be seen even with the height coordinate mismatch. Thus, the similarity of MAD for the AGL and MSL plots suggests that for Ukraine, MSL-based climatological profiles do not perform substantially better in predicting temperature profiles from surface temperature than AGL-based climatological profiles.

The lack of a substantial improvement from using MSL versus AGL climatological profiles in this case may be partially due to the terrain height across Ukraine generally remaining close to 0-m MSL. Specifically, the average terrain height of GFS grid cells in this study is 175-m MSL. For grid cells with relatively large terrain heights there may be a nontrivial improvement when using height MSL profiles well above the ABL as compared to using AGL profiles at these levels.

It may be that even when evaluated over all grid cells in this study, that using climatological profiles calculated in terms of height MSL for heights well above the surface would provide a small improvement in this case over using climatological profiles calculated in terms of height AGL for all heights. The visual comparison of the AGL and MSL MAD profiles would seem to rule out only substantial overall improvements, not more modest improvements. To evaluate whether there may be a small benefit when evaluated over all grid cells in this study, a profile could be generated using the height AGL climatological profile up to a certain height AGL, and then switching to the height MSL climatological profile above this height. The result could then be evaluated in terms of height AGL but would incorporate both height AGL and height MSL climatological profiles.

4. Summary, Conclusions, and Future Work

While the ICAO Std_Atm provides an estimate of the vertical profile atmospheric conditions when no other information is available, there may be information available that can be leveraged to provide an improved estimate of atmospheric conditions. Generally, vertical profiles of observations (e.g., radiosondes) or NWP forecasts will provide much more accurate estimates of atmospheric conditions than Std_Atm. However, in some cases neither radiosondes nor NWP forecasts can be used. In this study, information that will likely be available is leveraged through alternative profile-generation methods to determine whether a better estimate of the vertical profile of temperature can be obtained than that of Std_Atm. This investigation focuses on Ukraine and thus one of the pieces of information leveraged is that the location is in or near Ukraine.

One technique tested was adopted from those used in the LEEDR software. The LEEDR technique assumes that the surface temperature is known, estimates the ABL depth based on time of day and season, and then applies the dry adiabatic lapse rate to estimate the temperature in the ABL (while the LEEDR software switches to a moist adiabatic lapse rate at the height where saturation is reached [in this study this never occurs since the ICAO Std_Atm assumption of no water vapor is adopted]). Above the ABL, the LEEDR technique applies a climatological temperature profile based on region and season (the area of interest in this study falls entirely in the "midlatitude north" region since Ukraine is in the midlatitudes of the Northern Hemisphere).

The other techniques tested determined surface-temperature-dependent climatological temperature profiles based on NWP forecasts from the GFS model in or near Ukraine. NWP forecasts for the approximately 1551 horizontal gridpoints in the areas of interest that were not over water were collected for two forecast times for 6 days in each month for 2 years (2021 and 2023) leading to a total of 446,942 profiles. Average temperature profiles were calculated for 5 K surface temperature bins. For one technique (Climo_AS) temperature from all seasons was used to create a single set of bin-average temperature profiles, whereas for the other technique (Climo_SS) separate bin-average temperature profiles were calculated for each season. In addition to calculating bin-average climatological temperature profiles in terms of height AGL, profiles are also calculated in terms of height MSL as it was anticipated that temperatures are likely better correlated with height MSL than height AGL well above the surface.

Each of the four techniques requires the end user to provide a different set of information to find the relevant temperature profile for that technique in height AGL. As shown in Table 7, the least information is required to utilize Std_Atm as it simply needs terrain height to convert the MSL height-based ICAO standard atmosphere to AGL. The level of detail required for information in a specific category may differ between methods. For example, while LEEDR and the Climo_* methods both require location, LEEDR merely requires one to specify which of 6 regions of the earth the location of interest is in, whereas the Climo_* methods rely on climatology specific to one country, and thus requires more specific location information.

Table 7 Case-specific information required to calculate a temperature profile using each profile-generation method. Information required for a specific methodology is marked with a black circle and information not required is marked with ellipses.

Case-specific information	Std_Atm	LEEDR	Climo_AS AGL	Climo_AS MSL	Climo_SS AGL	Climo_SS MSL
Surface temperature	. . .	●	●	●	●	●
Terrain height	●	●	. . .	●	. . .	●
Season	. . .	●	. . .	. . .	●	●
Time of day	. . .	●	. . .	. . .	. . .	. . .
Location	. . .	●	●	●	●	●

The profile-generation techniques were tested using a set of GFS NWP forecasts for locations not over water in Ukraine and the surrounding region. Specifically, the techniques were evaluated at approximately 1551 horizontal gridpoints in the area of interest for two forecast times for 6 days in each month for 2 years (2020 and 2022); this led to a total of 446,832 profiles for evaluation. The evaluation period (2020 and 2022) is different from the period used to calculate the climatological profiles (2021 and 2023). For all but the Std_Atm technique, the GFS surface temperature from each profile was used to calculate a temperature profile for that technique. The MAD between the temperature profile calculated for each technique and the temperature profile in the GFS profile was used to determine how well each technique performed.

Overall, all three alternative profile-generation techniques performed better than Std_Atm, although for LEEDR this was generally limited to below 10-km AGL. The largest improvements for all three techniques were near the surface. Large variations in temperature occur near the land surface. Since surface temperature is provided to the profile-generation techniques and the Std_Atm technique is the only technique tested that does not use this information, it is not surprising that the largest improvements from these techniques compared to Std_Atm are at the surface. Examining the entire profile, generally Climo_SS performed the best, followed by Climo_AS, then LEEDR, and finally Std_Atm. However, the magnitude of improvements for all methods were limited in the 10- to 20-km AGL height range. The better performance of Climo_SS as compared to Climo_AS indicates that knowing and leveraging the time of year is important in estimating temperature profiles. The improvement from using the techniques implemented in terms of height AGL compared to using Std_Atm when measured by layer-thickness weighted temperature MAD is 0.6 K for LEEDR, 1.5 K for Climo_AS, and 2.1 K for Climo_SS.

Two differences between the Climo_* methods and the LEEDR method likely contribute to the better performance of the Climo_* methods than the LEEDR method. One is that the Climo_* methods can leverage climatology specific to

Ukraine whereas the LEEDR method relies on climatology over a much-larger area (approximately 119 times as large) and thus the climatology is not as tailored to Ukraine. Another difference is that the Climo_* method's entire profile is based on climatological values specific to the surface temperature bin for which a profile is being generated, whereas in the LEEDR method only the relatively shallow layer that is the ABL is influenced by the surface temperature. The Climo_* methods are thus able to leverage correlation between surface temperature and temperatures well above the surface. In the LEEDR method, the only effect well above the surface related to surface temperature is that the LEEDR method uses different climatological profiles depending on the season.

Evaluating climatological temperature profiles calculated in terms of height MSL did not suggest substantial improvement over those calculated in terms of height AGL. The generally low terrain height over Ukraine and its immediate surrounding (average of 175 m) probably limits the potential improvement from using height MSL-based climatological profiles well above the surface instead of height AGL-based climatological profiles. To more precisely determine the potential benefit of using height AGL-based profiles near the surface and height MSL-based profiles well above the surface, at each gridpoint a climatological profile could be constructed based on the relevant AGL-based bin-average temperature below some height AGL but use the relevant MSL-based bin-average temperature above that height AGL. While doing so would probably result in limited improvement over Ukraine, this seems likely to be more important over regions with terrain that varies more from sea level.

Given a surface temperature, the Climo_* methods here use the bin-average temperature profile for the 5 K surface temperature bin that this surface temperature falls in. The Climo_* methods may perform better if the bin-average temperature profiles from the two bins whose bin-center temperature is closest to the surface temperature are weighted and combined.

The only atmospheric quantity whose current value is required by the techniques tested is surface temperature, but additional benefits may be possible if the atmosphere can be further characterized. Surface temperature was chosen because it is a quantity that is easily observed by sensors and could be estimated by an observer even without sensors. While a human observer is unlikely to be able to estimate surface pressure without sensors, obtaining a measurement of surface pressure from a sensor does not seem particularly challenging. If a surface pressure were available, it could be used in combination with the temperature profile estimated from Climo_SS to likely improve on the Std_Atm estimates of the vertical profile of pressure and density.

The current study shows that the temperature profile can be better estimated than by Std_Atm if surface temperature and additional easily obtainable information is provided. The best methodology tested is Climo_SS. To further improve on the Std_Atm atmospheric estimate, future research should investigate the following:

1) Using a surface pressure observation to improve pressure and density estimates,

2) Creating a weighted average of the climatological temperature profiles from the two surface temperature bins whose bin-midpoint temperatures are closest to the surface temperature of interest so that the Climo_SS method provides profiles that more smoothly vary with surface temperature, and

3) Using a climatological AGL-based profile near the surface and a climatological MSL-based profile well above the surface.

5. References

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List of Symbols, Abbreviations, and Acronyms

ABL	atmospheric boundary layer
AGL	above ground level
ARL	Army Research Laboratory
Climo_*	Climo_AS and Climo_SS
Climo_AS	climatological all-season profiles
Climo_SS	climatological season-specific profiles
DEVCOM	US Army Combat Capabilities Development Command
GFS	Global Forecast System
ICAO	International Civil Aviation Authority
K	Kelvin
LEEDR	Laser Environmental Effects Definition and Reference
LST	local standard time
MAD	mean absolute difference
MSL	mean sea level
NCEP	National Centers for Environmental Prediction
NWP	numerical weather prediction
RMSE	root mean square error
Std_Atm	ICAO Standard Atmosphere
UTC	Coordinated Universal Time