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Enhancing Atmospheric Estimates via Surface Pressure Observation

by Brian P. Reen

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14. ABSTRACT
In applications where vertical profiles of weather data are required but numerical weather prediction (NWP) data and vertical profile observations are unavailable, meteorological profiles referred to as standard meteorology are often used. In 2024, Reen demonstrated that an easily obtainable observation (surface temperature) can be combined with a regional NWP climatology to create better temperature profile estimates than standard meteorology, and that making the NWP climatology season-specific provides better estimates than not accounting for season. These NWP climatology techniques that estimate temperature profiles are extended here to also provide estimated pressure and density profiles by leveraging a surface pressure observation. Pressure and density profile estimates created by these techniques are better estimates than the standard atmosphere profile; additionally, just as accounting for season was previously found to improve temperature estimates, using season-specific NWP climatology improves the pressure and density estimates. The revised technique provides a method to produce more accurate estimated temperature, pressure, and density profiles than those provided by standard meteorology by relying on two observations that can easily be made using inexpensive equipment in combination with regional NWP climatology.

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standard meteorology, climatology, pressure, density, profile estimation, surface pressure, Military Information Sciences

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1. Introduction

"Standard" meteorological conditions are sometimes assumed when better estimates of atmospheric conditions (e.g., from numerical weather prediction [NWP] forecasts or observations) are not available; these standard meteorological conditions might be enhanced by leveraging easily obtainable observations and climatological data. Reen (2024) showed that a surface temperature observation can be used with an NWP-based regional climatology to find an estimate of the temperature profile that is more accurate than the standard temperature profile for a specific region (Ukraine). The current report investigates the value of having a surface pressure observation in addition to the surface temperature observation in estimating atmospheric profiles.

Standard meteorological conditions are often defined based on the conditions specified in the International Civil Aviation Authority (ICAO) standard atmosphere (ICAO 1993), and equivalently by the International Organization for Standardization (ISO) document ISO 2533 (ISO 1975). This ICAO standard atmosphere specifies profiles of quantities including temperature, pressure, and density, but assumes that there is no wind and no moisture. The ICAO standard atmosphere is meant to be used as a representative atmospheric profile, and it is well known that actual conditions can vary substantially from the ICAO standard atmosphere. However, in situations wherein no information is available about the atmospheric conditions, the standard atmosphere can provide an estimate of the meteorological conditions. Such situations may occur due to communication bandwidth limitations preventing transmission of NWP data, due to the challenges involved in obtaining accurate observations of an atmospheric profile, or due to capabilities not being in place to ingest NWP data or observational profile data and provide it to the application requiring weather information.

Reen (2024) leveraged an easily obtainable weather observation (surface temperature) and other easily determined information in concert with a regional NWP-based climatology to estimate the temperature profile and found that this estimate was on average more accurate than the ICAO standard atmosphere. Unlike observations of vertical profiles of temperature, surface temperature observations can be made by non-expert observers with minimal instruction using inexpensive sensors. For the two techniques developed in Reen (2024) that are leveraged in the current study, one of them required the current season be specified and both required that it be known that the point was within the specified region (Ukraine). NWP data from two times on 72 days each in 2 years was used to determine both season-specific and season-agnostic climatological temperature profiles associated with surface temperature bins. NWP data from a different 2 years was then used to evaluate the profile estimation technique. For each temperature profile in the NWP evaluation dataset, the NWP surface temperature was used to determine the appropriate bin-averaged climatological temperature profile to use as the temperature profile estimate and then this estimate was compared to the temperature profile in the NWP evaluation dataset. The evaluation indicated that the estimated profiles better matched the NWP profiles than the ICAO standard atmosphere. Additionally, the season-specific climatological temperature profiles provided better estimates than the season-agnostic profiles.

This study investigates whether a surface pressure observation can be combined with the temperature profile estimated using surface temperature and NWP climatology to provide estimates of the pressure and density profile that are better than the ICAO standard atmosphere. Because the methodology builds on that of Reen (2024), some of the content in subsequent sections will exactly match or closely resemble Reen (2024). Section 2 describes the methodology used, Section 3 documents the results of applying this methodology, and Section 4 provides a summary and conclusions and describes potential future research.

2. Methodology

2.1 Overview

NWP forecasts from the Global Forecast System (GFS) over Ukraine and its vicinity are used to evaluate the ability of a surface pressure observation, when combined with temperature profiles estimated from a surface temperature observation and GFS climatology (as described in Reen [2024]), to provide better estimates of pressure and density profiles than the ICAO standard atmosphere. 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.

A very rough estimate of the border of Ukraine was used to exclude most GFS grid points outside Ukraine. Because it is anticipated that climatologically the meteorological conditions will be very similar just outside Ukraine to those inside Ukraine, it should not be problematic that points outside the borders of Ukraine and yet near Ukraine are included in the analysis. All GFS grid points at which GFS considered the land surface to be water are excluded from the analysis because land areas are the focus of the current investigation and vertical temperature profiles near the surface over water are likely to differ from those over land. Figure 1 shows the GFS grid points included in the analysis based on these criteria. GFS changed the classification of one grid point in the area of interest from water to land sometime in the year 2021—this results in either 1551 or 1552 GFS grid points being used in the analysis at any given time. Among these grid points, the GFS terrain height varies between approximately 0 and 1202 m.

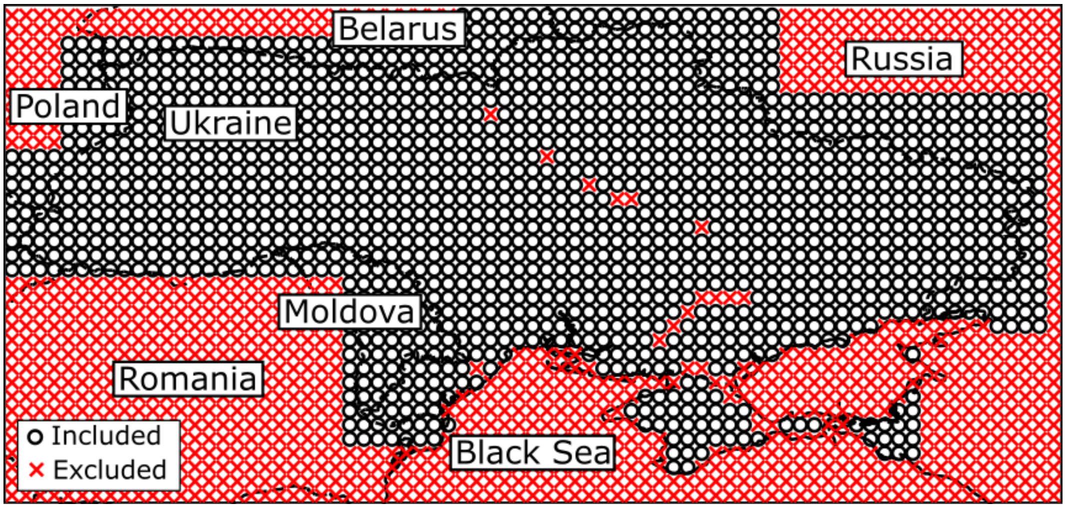


Figure 1. Map of GFS points included in analysis (black circle) and GFS points excluded from the analysis (red X). The plot is for the period of time in which GFS indicates 1551 non-water grid points are available in the area of interest.

For all GFS grid points in Figure 1, GFS profiles from various times of year and times of day were used to evaluate the ability of the technique described herein to predict the pressure and density 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. While this is more important for the temperature profile estimation of Reen (2024) than the pressure and density estimation completed here, there is still relevance because the latter is dependent on the estimated temperature profile. Accounting for the number of horizontal grid points 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 combined to form profiles of temperature, pressure, and relative humidity (RH). The height levels are defined in terms of height above ground level (AGL) and thus are referred to as AGL levels. The AGL levels and pressure levels on which data are available varies among the parameters; for pressure levels it also depends on whether data from the 0-h forecast or from the 3-h forecast is being used. The height levels at which data are available are shown in Table 1 and the pressure levels at which data are available are shown in Table 2. While temperature is available in the GFS data at 0-, 2-, 80-, and 100-m AGL, pressure and RH are available at a subset of these levels. For the pressure-level data at the 0-h forecast time, temperature, height, and RH are all available at the same 41 pressure levels; this means that at each of the 41 pressures listed in Table 2, temperature, height, and RH are available. However, for the 3-h forecast time, temperature and height are both available at 34 pressure levels, while RH is available at 31 of these 34 pressure levels. If a variable (namely pressure or RH) is not present on any height AGL or pressure level for which temperature is available, that variable is interpolated to that height or pressure level. RH is interpolated linearly in height while the logarithm base 10 of pressure is interpolated linearly in height. Since the height of pressure levels varies spatially and temporally, each of the combined (height level and pressure level) profiles are on slightly different heights. RH on the combined levels is used in combination with temperature and pressure to calculate water vapor mixing ratio (q_v) on the combined levels.

Table 1. Height AGL levels at which temperature, pressure, and RH are available in the GFS output. Levels at which a parameter is available are marked with "Y" and levels at which a parameter is not available are marked with "N."

Height AGL (m)	Temperature	Pressure	RH
100	Y	N	N
80	Y	Y	N
2	Y	N	Y
0	Y	Y	N

Table 2. Pressure levels at which temperature, height, and RH are available in GFS output at the 0-h forecast time and the 3-h forecast time. Levels at which a parameter is available are marked with "Y" and levels at which a parameter is not available are marked with "N."

Pressure	Temperature/height		RH	
	Forecast hour		Forecast hour	
(hPa)	0 h	3 h	0 h	3 h
0.01	Y	N	Y	N
0.02	Y	N	Y	N
0.04	Y	N	Y	N
0.07	Y	N	Y	N
0.10	Y	N	Y	N
0.20	Y	N	Y	N
0.40	Y	Y	Y	N
0.70	Y	N	Y	N
1	Y	Y	Y	Y
2	Y	Y	Y	Y
3	Y	Y	Y	Y
5	Y	Y	Y	Y
7	Y	Y	Y	Y
10	Y	Y	Y	Y
15	Y	Y	Y	N
20	Y	Y	Y	Y
30	Y	Y	Y	Y
40	Y	Y	Y	N
50	Y	Y	Y	Y
70	Y	Y	Y	Y
100	Y	Y	Y	Y
150	Y	Y	Y	Y
200	Y	Y	Y	Y
250	Y	Y	Y	Y
300	Y	Y	Y	Y
350	Y	Y	Y	Y
400	Y	Y	Y	Y
450	Y	Y	Y	Y
500	Y	Y	Y	Y
550	Y	Y	Y	Y
600	Y	Y	Y	Y
650	Y	Y	Y	Y
700	Y	Y	Y	Y
750	Y	Y	Y	Y
800	Y	Y	Y	Y
850	Y	Y	Y	Y
900	Y	Y	Y	Y
925	Y	Y	Y	Y
950	Y	Y	Y	Y
975	Y	Y	Y	Y
1000	Y	Y	Y	Y

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 that are

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 ICAO 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 (and similarly for RH).

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 3). These combined profiles 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. The levels at which the evaluation is carried out are those shown in Table 3. 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 and because evaluations in height MSL allow the errors to be converted to the percent of ICAO standard atmosphere values (since the standard atmosphere is defined in terms of height MSL).

Table 3. 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 beneath the surface of 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

Pressure and density from GFS are ultimately compared to profiles of these quantities generated using other methods. While pressure is available on the combined vertical levels, density is not. Density is calculated using virtual temperature and pressure:

$$\rho = \frac{p}{RT_v} \tag{1}$$

where p is pressure, ρ is density, R is the gas constant for dry air (287.05287 J K^{-1} kg^{-1}; ICAO 1993), and T_v is virtual temperature. T_v is calculated using temperature and q_v, which are both available on the combined levels:

$$T_v = T(1 + 0.608q_v) \quad (2)$$

Mean absolute difference (MAD) is the metric used to evaluate pressure and density estimations from the profile-generation techniques. The pressure and density generated by each profile-generation technique is compared to the GFS pressure and density 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 pressure and density MAD are shown in later sections to compare the performance of profile-generation techniques.

2.2 Methods to Predict Profiles

Some of the temperature profile estimation methods described in Reen (2024) are used here to generate temperature profiles, but unlike Reen (2024) pressure and density profiles are also estimated. The two techniques from Reen (2024) that leverage an NWP-based climatology are extended to determine if they perform better than using the ICAO standard atmosphere values of pressure and density. The LEEDR technique (based on techniques in the Laser Environmental Effects Definition and Reference software) is not used here because the two NWP-based climatology techniques outperformed LEEDR in Reen (2024) in estimating temperature. The following sections describe the profile estimation techniques used in this study.

2.2.1 Standard Atmosphere

The ICAO standard atmosphere described in ICAO (1993) specifies profiles of atmospheric quantities from –5 to 80 km MSL (and is identical to the standard atmosphere in ISO 2533 [ISO 1975]). The technique referred to as Std_Atm in Reen (2024) calculates the ICAO standard atmosphere temperature profile. Similarly, in this study the values used in Std_Atm for pressure and density are those from the ICAO standard atmosphere. Note that the Std_Atm temperature, pressure, and density profiles are not dependent on the surface temperature or pressure, and thus the Std_Atm method will predict the same temperature, pressure, and density at a given height MSL regardless of the observed surface temperature and pressure.

2.2.2 Climatology

In Reen (2024), climatological temperature profiles were created using 446,942 profiles in or near Ukraine from the GFS NWP model. Specifically, on the 1st, 5th, 10th, 15th, 20th, and 25th of each month in 2021 and 2023, 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 GFS grid points used are the same as those shown in Figure 1 as being used in the evaluation of the estimation techniques. Climatological temperature profiles were created for bins of surface temperature 5 K in width. One set of climatological bin-average temperature profiles was created using all of the case days and another set of bin-average temperature profiles was calculated that was season-specific. Additionally, the bin-average temperature profiles were calculated both for height AGL and height MSL; however, since approximately 92% of the grid points included in the analysis have terrain heights less than 300 m, the two sets of profiles were very similar. The experiment wherein the all-season temperature profiles were applied was called Climo_AS (AS = all-season) and the experiment wherein the single-season temperature profiles applicable to the season were applied was referred to as Climo_SS (SS = season-specific)

For the current study, the climatological methods are extended by using the bin-average temperature profile relevant for a given surface temperature observation in combination with the observed pressure to calculate the estimated pressure and density profile. First, the methodology described in Reen (2024) is used to estimate the temperature profiles based on the surface temperature observation. Next, the surface pressure observation (p_0) and both the surface temperature in the estimated temperature profile (T_0) and the temperature at the level above this in the estimated temperature profile (T_1) are used to calculate pressure at the level above the surface (p_1). This process is then repeated to calculate pressure at the level above this (p_2) using the calculated pressure at the level above the surface (p_1) and the temperature value in the estimated pressure profile at this level (T_1) and the level above it (T_2). The pressure calculation equations from ICAO (1993) are used for this calculation of pressure at level n+1 using values at both this level and the level below (n):

$$p_{n+1} = p_n \left[1 + \frac{\beta}{T_n}(z_{n+1} - z_n)\right]^{-g/\beta R} \text{ for } \beta \neq 0 \tag{3}$$

$$p_{n+1} = p_n exp\left[-\frac{g}{RT_n}(z_{n+1} - z_n)\right] \text{ for } \beta = 0 \tag{4}$$

where z is height MSL, g is the acceleration due to gravity, and

$$\beta = \frac{T_{n+1} - T_n}{z_{n+1} - z_n}. \tag{5}$$

Two aspects regarding this pressure calculation should be highlighted. First, although the pressure calculation equations are from the document describing the standard atmosphere, applying these equations here will not yield the standard atmosphere profile of pressure unless the observed surface pressure and the climatological temperature profile exactly match the standard atmosphere profiles. Second, the standard atmosphere assumes there is no moisture, but this is consistent with the assumption here that we have no information regarding the moisture profile.

The estimated density profile for the climatological techniques (Climo_AS and Climo_SS) is calculated using the estimated temperature and pressure profiles generated using the technique. Specifically:

$$(5)\rho = \frac{p}{RT}. \quad (6)$$

This equation uses T rather than the T_v used to calculate the GFS density, which serves as the "truth" against which the profile estimation techniques are evaluated. Virtual temperature is not used here because the profile estimation assumes there is no information available regarding the current moisture content whereas the "truth" GFS data leverages the GFS moisture profile.

The Climo_SS and Climo_AS techniques from Reen (2024) are extended here from provision of only an estimated temperature profile from a surface temperature observation to leveraging the estimated temperature profile and a surface pressure observation to provide estimated pressure and density profiles. Climo_* will be used to refer to both Climo_SS and Climo_AS. While temperature profiles estimated using the Climo_* techniques rely on bin-averaged (by surface temperature) NWP temperature profiles, the Climo_* pressure and density profiles estimates do not rely on bin-averaged NWP pressure or density profiles. Instead the Climo_* pressure and density profiles rely on the bin-averaged NWP temperature profiles, surface pressure, and equations to calculate pressure and density.

3. Results

Techniques for generating temperature, pressure, and density profiles from surface temperature and pressure (Std_Atm and climatological) were applied to create profiles for selected times during 2020 and 2022 as described in Section 2. For the climatological technique, two variants were applied: the all-season Climo_AS method, which makes no distinction among seasons, and the season-specific Climo_SS method. 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 and surface pressure was extracted, each technique was used to generate temperature, pressure, and density profiles, and then the generated pressure profile and density profile were compared to the GFS pressure profile and density profile for that time and location (only limited temperature results are included here since those are described in Reen [2024]). This results in 446,832 profiles on which to evaluate these techniques. In Reen (2024), Climo_SS performed best in estimating temperature profiles.

The MAD between the GFS NWP "truth" data and the Std_Atm, Climo_AS, and Climo_SS estimates of the pressure profile when applied in height AGL is shown in Figure 2a. In general, the pressure MAD increases with height to around 8-km AGL and then decreases above this (the exception to this is that Std_Atm MAD decreases with height near the surface). The Climo_* methods produce profiles that better match the GFS profiles than profiles created based on the ICAO standard atmosphere (Std_Atm) match the GFS data, indicating that the Climo_* methods perform better. Between the two Climo_* methods, the season-specific method (Climo_SS) outperforms the method that ignores the season (Climo_AS). The pressure and density profiles created by Climo_SS only differ from those created by Climo_AS due to the different temperature profiles created by the two methods. Also, since the Climo_* method uses a surface pressure "observation" extracted from the GFS data to define the surface pressure, the MAD is zero at the surface for Climo_*.

Figure 2b shows the improvement that results after changing from Std_Atm to both Climo_* methods. The improvements are largest near the surface and generally decrease with height. In estimating a specific pressure profile, the only "observed" information we have about the profile is at the surface (i.e., the surface pressure and surface temperature) and so it is reasonable that the largest improvements would be nearest the level at which we are leveraging observations. Additionally, the magnitude of pressure itself decreases substantially with height, which decreases the potential magnitude of improvements as height increases. The improvement from moving from Std_Atm to the method ignoring season (Climo_AS) is generally 3.5 hPa or larger below 10-km AGL, whereas the improvement from moving from Std_Atm to the method accounting for season (Climo_SS) is generally 4.0 hPa or larger below 10-km AGL. There is no height at which Climo_AS appears to perform better than Climo_SS.

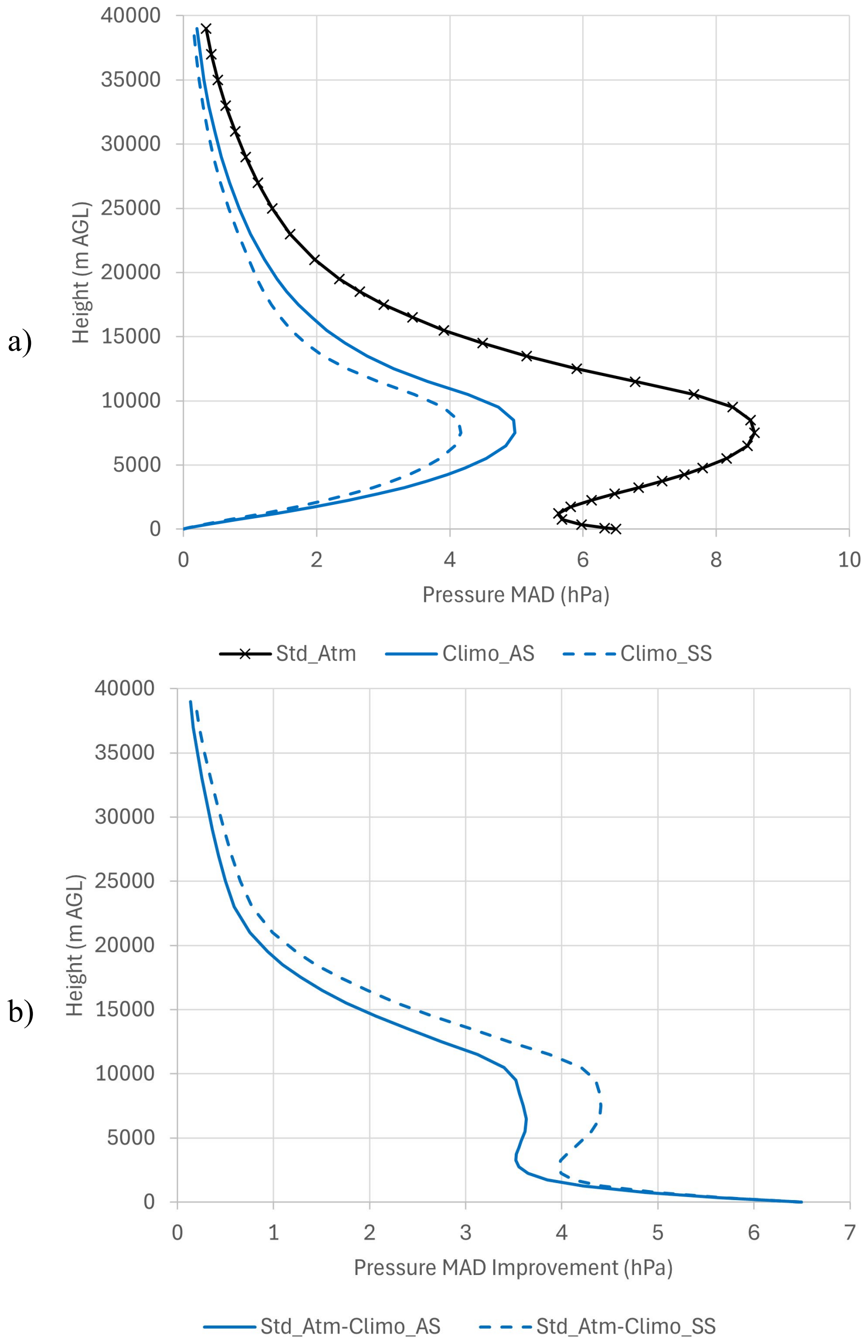
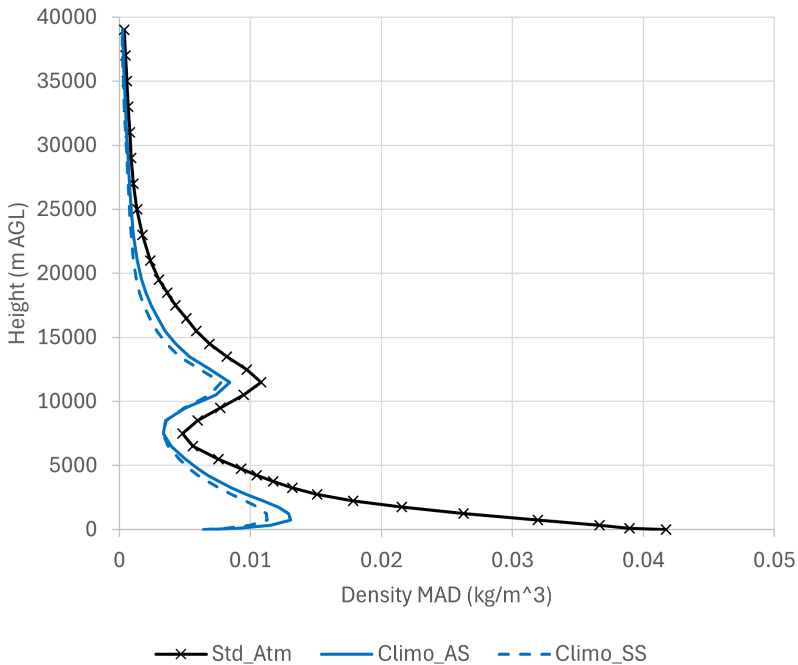


Figure 2. a) Pressure MAD (hPa) between GFS profiles from the evaluation dataset and profiles predicted using various methodologies applied in terms of height AGL, and b) the difference in this quantity between both climatological methods and Std_Atm (positive values indicate the Climo_* method outperforms Std_Atm).

Figure 3 shows the analogous figure for density to what Figure 2 shows for pressure. The magnitude of MAD of the difference between density profiles estimated by the various techniques and the density profiles from the NWP GFS "truth" generally decreases with height (Figure 3a). However, for the Climo_* techniques there is a local minimum in the difference at the surface, and for all techniques there is a local maximum in the difference around 12-km AGL. The MAD is smaller for the Climo_* methods than Std_Atm, especially near the surface, and the Climo_SS technique outperforms the Climo_AS technique. The improvement from using either Climo_* method instead of Std_Atm decreases rapidly with height in the lowest kilometers AGL (Figure 3b), but there does not appear to be any height at which Std_Atm outperforms either of the Climo_* methods.

While the focus of this report is on pressure and density, the temperature MAD is shown in Figure 4 because density is calculated here using pressure and temperature. In addition, temperature errors typically cause larger density errors than those resulting from pressure errors. For the Climo_* methods, the increase in density MAD just above the surface (Figure 3a) is consistent with the increase in temperature MAD just above the surface (Figure 4) and is further supported by the increase of pressure MAD with height through a much deeper layer (see Figure 2a). Similarly, for Std_Atm the decrease in density error in the lowest 2-km AGL is consistent with the decrease in temperature MAD in this region (pressure MAD decreases with height near the surface but begins increasing with height before reaching 2-km AGL). The local maximum in density MAD for all experiments around 12-km AGL is consistent with a local maximum in temperature MAD around this height. Some of the other aspects of the pressure and temperature MAD profiles are not seen in the density MAD profile, presumably at least partly due to the significant decrease in the magnitude of density with height supporting a decrease in the density MAD with height.

a)



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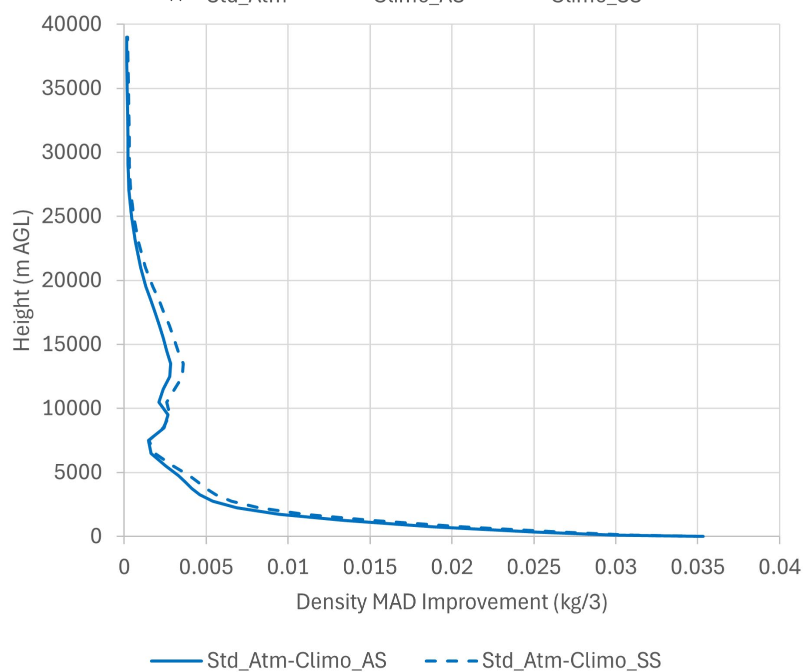


Figure 3. **a) Density MAD (kg m^{-3}) between GFS profiles from the evaluation dataset and profiles predicted using various methodologies applied in terms of height AGL, and b) the difference in this quantity between both climatological methods and Std_Atm (positive values indicate the Climo_* method outperforms Std_Atm).**

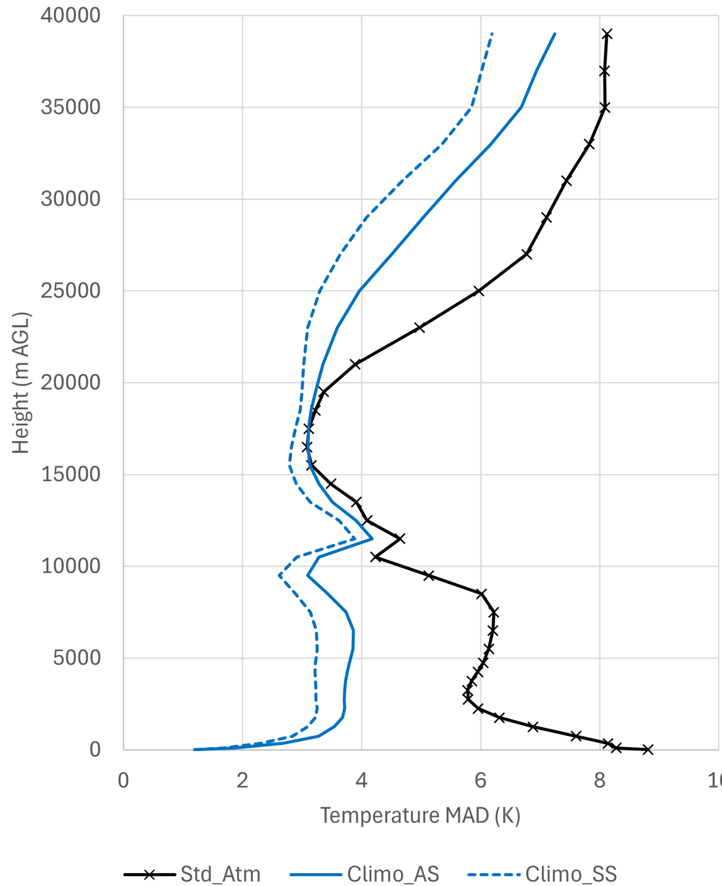
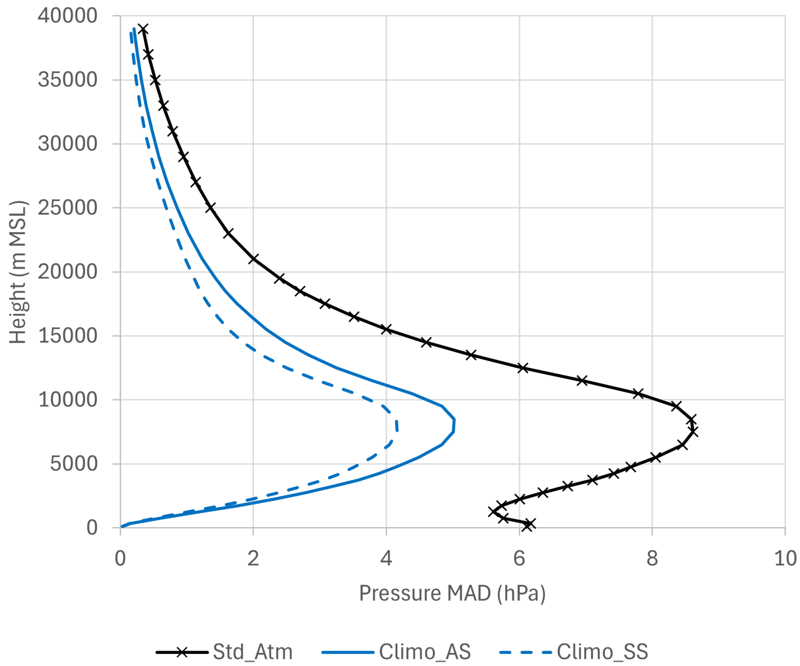


Figure 4. Temperature MAD (K) between GFS profiles from the evaluation dataset and profiles predicted using various methodologies applied in terms of height AGL.

In addition to evaluating the ability of the Climo_* methodologies to estimate pressure and density profiles in terms of height AGL, the methodologies were also used to estimate profiles in terms of height MSL. It is anticipated that well above the surface the direct influence of the surface will be minimal and thus height AGL may be a less important factor than height MSL in estimating the atmospheric conditions. The Climo_* methodologies are using surface temperature to determine the climatological temperature profile to use, and thus the entire temperature profile is chosen based on the surface temperature. However, this estimated profile may better match the GFS profile if determined in terms of height MSL rather than height AGL for heights well above the surface.

The height MSL profiles for MAD and MAD difference for pressure is in Figure 5 and for density in Figure 6. These profiles bear a strong resemblance to the equivalent profiles in terms of height AGL (Figure 2 for pressure and Figure 3 for density). As noted in Reen (2024), the average terrain height of the grid points used in this analysis is approximately 175 m. Thus, the difference between height AGL and height MSL is generally small. In regions with more significant terrain variability, the differences between using height AGL and height MSL may be more substantial. Ultimately, using profiles calculated in terms of height AGL near the surface and in terms of height MSL well above the surface might be optimal.

a)



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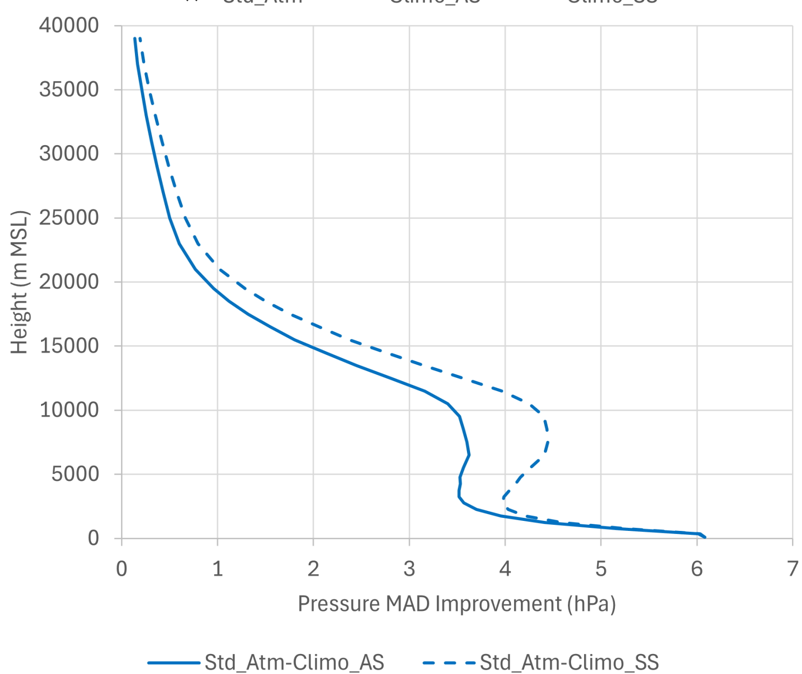

Figure 5. a) Pressure MAD (hPa) between GFS profiles from the evaluation dataset and profiles predicted using various methodologies applied in terms of height MSL, and b) the difference in this quantity between both climatological methods and Std_Atm (positive values indicate the Climo_* method outperforms Std_Atm).

a)
b)

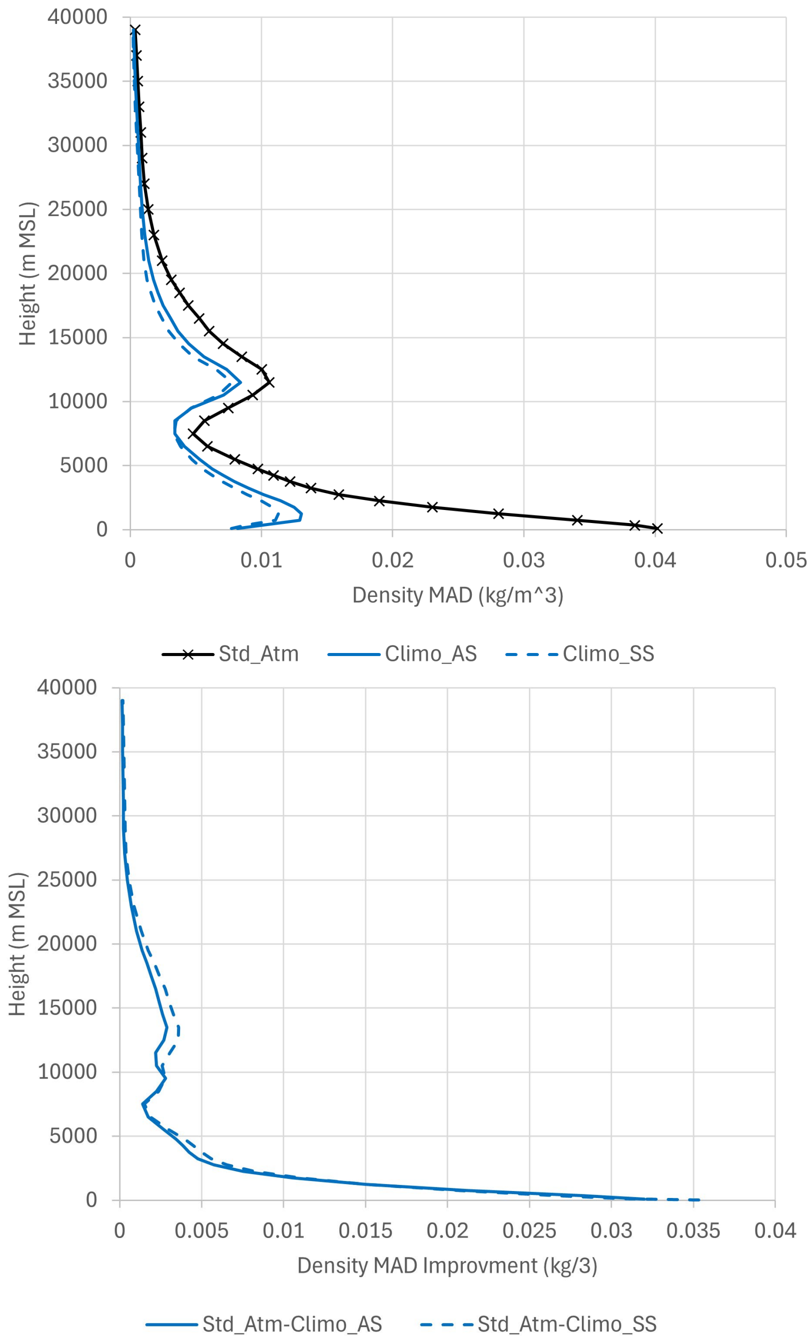

Figure 6. a) Density MAD (kg m^{-3}) between GFS profiles from the evaluation dataset and profiles predicted using various methodologies applied in terms of height MSL, and b) the difference in this quantity between both climatological methods and Std_Atm (positive values indicate the Climo_* method outperforms Std_Atm).

Since the magnitude of pressure and density are much smaller at the top of the profiles being estimated (39 km) compared to near the surface, and the magnitude of errors may scale with the magnitude of the values, plots of pressure- and density-related profiles may be more informative if plotted in terms of the percent of the standard atmosphere (%SA). The standard atmosphere pressure at 0-km MSL is 1013.25 hPa, while at 39-km MSL it is 3.18 hPa, approximately 0.31% of the value at the surface. Similarly, the standard atmosphere density at 0-km MSL is approximately 1.225 $\mathrm{kg\,m^{-3}}$, while at 39-km MSL it is 0.00447 $\mathrm{kg\,m^{-3}}$, approximately 0.36% of the value at the surface. Plotting in terms of %SA involves dividing the pressure (density) by the pressure (density) specified by the ICAO standard atmosphere at that level. Since the ICAO standard atmosphere is defined in terms of height MSL, %SA plots are only created for height MSL.

The improvement in estimated pressure resulting from estimating using Climo_AS or Climo_SS instead of using the ICAO standard atmosphere (e.g., Std_Atm), is shown in terms of %SA in Figure 7. This plot is created using the same underlying data as Figure 5b, but whereas Figure 5b plots the difference in terms of hPa, here the difference is plotted in terms of %SA. While in terms of hPa the improvements from using the climatological methods were smallest at the top of the profile, in terms of %SA the improvements are largest at the top of the profile. At 39-km MSL, Climo_AS results in an improvement of greater than 4 %SA while Climo_SS results in an improvement of 6 %SA.

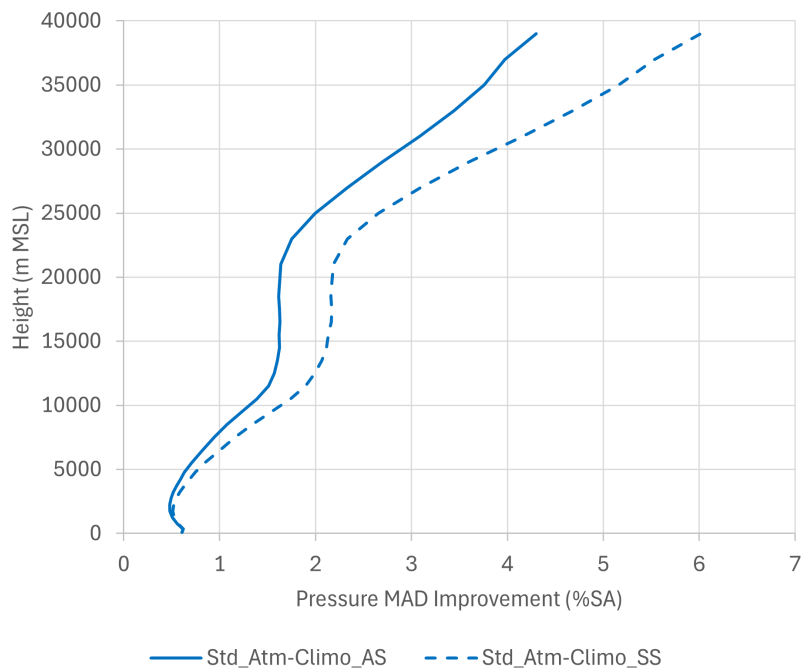

Figure 7. Decrease in pressure MAD in terms of %SA resulting after changing from Std_Atm profiles to profiles predicted using either Climo_AS or Climo_SS applied in terms of height MSL (positive values indicate the Climo_* method outperforms Std_Atm). MAD is calculated against the GFS profiles from the evaluation dataset. This figure differs from Figure 5b only in that this figure is in terms of %SA whereas Figure 5b is in terms of hPa.

Figure 8 shows the improvement in %SA in the density estimation resulting after changing from estimates based on the ICAO standard atmosphere to those based on an NWP climatology. When plotted in terms of kilogram per cubic meter (Figure 6b), the improvements decreased rapidly with height in the lowest kilometers, varied between increasing and decreasing with height between approximately 7- and 13-km MSL, and then decreased with height to a value that appeared to be approximately zero given the axis limits. While in terms of %SA there is still a rapid decrease in the lowest kilometers, the error generally increases between 7- and 18-km MSL, then decreases up to approximately 27 km, and finally increases up through 39-km MSL. The largest improvements (in terms of %SA) due to leveraging the climatological techniques are at the top of the profile where Climo_AS results in an improvement greater than 3 %SA and Climo_SS in an improvement of greater than 4 %SA.

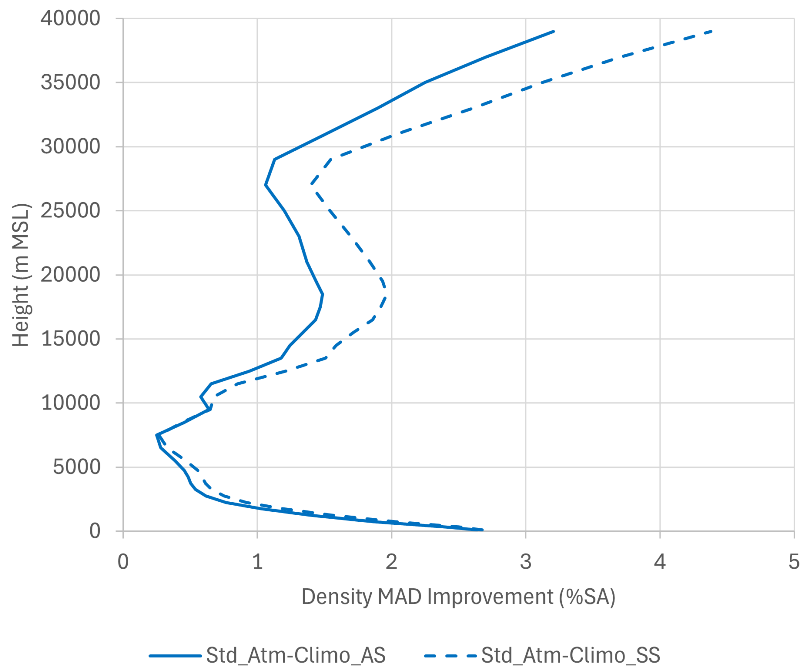

Figure 8. Decrease in density MAD in terms of %SA resulting from changing from Std_Atm profiles to profiles predicted using either Climo_AS or Climo_SS applied in terms of height MSL (positive values indicate the Climo_* method outperforms Std_Atm). MAD is calculated against the GFS profiles from the evaluation dataset. This figure differs from Figure 6b only in that this figure is in terms of %SA whereas Figure 6b is in terms of kg m^{-3}.

To provide a quantitative measure of the relative performance of the profile estimation methods, layer-thickness-weighted MAD can be computed; this involves assuming that MAD values at a given height are representative of the layer encompassing all heights within which the MAD values at the given height are the closest MAD values available. Thickness-weighted MAD values are shown in Table 4 for height MSL since %SA is only available for height MSL. In the lowest

10-km MSL Climo_AS produces pressure estimates that are 3.84 hPa (0.75 %SA) better than Std_Atm, while Climo_SS produces pressure estimates that are 4.42 hPa (0.89 %SA) better than Std_Atm. For density, in the lowest 10-km MSL Climo_AS estimates are 0.0064 kg m^{-3} (0.71 %SA) better than Std_Atm and Climo_SS estimates are 0.0072 kg m^{-3} (0.79 %SA) better than Std_Atm. For the overall profile, pressure improvements are 2.03 %SA with Climo_AS and 2.71 %SA with Climo_SS, while density improvements are 1.35 %SA with Climo_AS and 1.77 %SA with Climo_SS.

Table 4. Layer-thickness-weighted pressure MAD improvements compared to Std_Atm for height MSL. Only the final two letters of the Climo_* technique names are included (i.e., AS = Climo_AS, SS = Climo_SS).

Layer edges (m AGL)		MAD improvement compared to Std_Atm							
		Pressure (hPa)		Pressure (%SA)		Density (kg m^{-3})		Density (%SA)	
Bottom	Top	AS	SS	AS	SS	AS	SS	AS	SS
0	10,000	3.84	4.42	0.75	0.89	0.0064	0.0072	0.71	0.79
10,000	20,250	2.04	2.63	1.58	2.06	0.0022	0.0028	1.18	1.53
20,250	40,000	0.37	0.50	2.91	3.96	0.0004	0.0005	1.77	2.40
0	40,000	1.67	2.02	2.03	2.71	0.0024	0.0028	1.35	1.77

4. Summary, Conclusions, and Future Research

While Reen (2024) developed a methodology to create estimated temperature profiles based on a surface temperature observation and NWP climatology, the current effort extended the methodology to additionally leverage a pressure observation to support creation of estimated pressure and density profiles. As in Reen (2024), the goal is to obtain a more accurate profile estimate than that provided by the ICAO standard atmosphere for applications for which NWP forecasts are unavailable. Obtaining a surface temperature and a surface pressure observation and inputting these two numbers for use requires much less equipment and effort than launching a radiosonde to obtain the vertical profile of the desired fields and then inputting the entire profile for use. Thus, the techniques described may be feasible in applications where using a radiosonde is deemed untenable.

The Climo_* methods in Reen (2024) binned approximately 447,000 NWP temperature profiles from GFS by surface temperature, and then when estimating a temperature profile for a given surface temperature used the average temperature profile for the bin with the given surface temperature. For Climo_AS the bin-average temperature profiles were created without regard to season, whereas for Climo_SS, separate bin-average temperature profiles were created for each season. GFS data covering the Ukraine region, but excluding water points, were used. Specifically, approximately 1551 horizontal GFS grid points for two forecast times for 6 days in each month for 2 years (2021 and 2023) were used to develop the bin-average temperature profiles and the same grid points*, forecast times, and days of the month were used in two other years (2020 and 2022) to evaluate the techniques.

To extend the Climo_* methods to create pressure and density profile estimates, first the surface temperature observation is used to create the temperature profile estimate exactly as described in Reen (2024). Next, the estimated temperature profile's values at the surface, and the level above the surface, and the surface pressure observation are used to calculate the pressure at the level above the surface. The density is then calculated using the temperature and pressure estimates at this level. This process is then repeated for each subsequent level of the profile. Thus, unlike temperature, no bin-averaging of NWP climatology pressure or density is carried out.

Comparisons of the Climo_* methods' estimated pressure and density profiles indicate that the Climo_* methods perform better than simply using ICAO standard atmosphere values (Std_Atm), and that using the season-specific binned temperature profiles (Climo_SS) performs better than using all-season binned temperature profiles (Climo_AS). Whether the methods are applied in terms of height AGL or height MSL has little difference on the results; applying these techniques over a region with more significant terrain variation may result in more noticeable differences between height AGL and height MSL. Pressure improvements from using Climo_SS are generally greater than 4 hPa throughout the lowest 10-km AGL. In terms of %SA, pressure improvements from Climo_SS are 1 %SA or larger above 6500-m MSL (and 0.5 %SA or larger at all levels). For density, the %SA improvements from using Climo_SS instead of the standard atmosphere are greater than 1 %SA below 2500-m MSL and at and above 12,500-m MSL (and greater than 2 %SA above 31,000-m MSL).

While in certain applications the preferred sources of meteorological data are unavailable and the ICAO standard atmosphere is assumed, this investigation extended methods to estimate temperature in these situations from Reen (2024) to also estimate pressure and density. While observations could provide the most accurate representation of current atmospheric conditions, observations at all the desired locations and times are often not available. Gridded NWP output can be interpolated to provide a nowcast/forecast of atmospheric conditions (and can be enhanced via observations) at desired locations and times, but it may not be feasible to use NWP data in certain applications. In these situations, the ICAO standard atmosphere is often assumed. Reen (2024) demonstrated that given a surface

* The number of grid points changes from 1551 to 1552 sometime during 2021 due to an additional grid point being classified as a land point.

temperature observation and an NWP climatology, a better estimated temperature profile can be created than the standard atmosphere profile; incorporating knowledge of the season in which the temperature observation is taken allows additional improvement. The current study extended the methodology of Reen (2024) to demonstrate that given the additional data of a surface pressure observation, the estimated temperature profile and surface pressure observation can be leveraged to provide estimated profiles of pressure and density that are more accurate than those provided by the ICAO standard atmosphere.

The pressure and density estimation techniques described here rely on the region-specific surface-temperature-dependent temperature profile estimates from Reen (2024). Thus, to apply this methodology to regions other than Ukraine, an NWP climatology of the relevant region would need to be created. Given that the GFS NWP model used to create the climatology is a global model whose output is freely available via the Internet, NWP climatologies of any region should be able to be created using the methodology used to create the climatology in Reen (2024). If this method were applied in other regions, further investigation should be undertaken into the relative value of applying the methodology in terms of height AGL versus height MSL. In regions with more substantial variation in terrain it is anticipated that ultimately a blending of results from the two height systems might perform best. Specifically, the best results might be obtained by using height AGL near the surface and gradually moving to height MSL well above the surface.

The method used to determine the estimated temperature profile might be improved by blending temperature profiles from two bins. This study adopts the technique described in Reen (2024) wherein the estimated temperature profile is the climatological temperature profile for a bin defined by the surface temperature. This means that the estimated temperature profile will change abruptly when the surface temperature exceeds the current bin's boundaries (i.e., the surface temperature range of the bin). A better temperature profile estimate might be created if a weighted average were taken of the climatological temperature profiles from the two bins whose bin centers are closest to the surface temperature observation.

5. References

[ICAO] International Civil Aviation Organization. Manual of the ICAO standard atmosphere. 3rd ed. International Civil Aviation Organization; 1993. Document No.: 7488/3.

[ISO] ISO 2533-1975 (E). Standard atmosphere. International Organization for Standardization (ISO); 1975.

Reen BP. Climatology as an alternative to standard meteorology for temperature. DEVCOM Army Research Laboratory (US); 2024. Report No.: ARL-TR-9942.

List of Symbols, Abbreviations, and Acronyms

%SA	percent of the standard atmosphere
ABL	atmospheric boundary layer
AGL	above ground level
ARL	Army Research Laboratory
Climo_*	Climo_AS and Climo_SS
Climo_AS	profile estimation technique based on climatological all-season profiles
Climo_SS	profile estimation technique based on climatological season-specific profiles
DEVCOM	U.S. Army Combat Capabilities Development Command
GFS	Global Forecast System
ICAO	International Civil Aviation Authority
ISO	International Organization for Standardization
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
RH	relative humidity
Std_Atm	profile estimation technique based on the ICAO standard atmosphere
UTC	Coordinated Universal Time

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