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Vertical Gradient Thresholds for Diagnosing Potentially Erroneous Gridded Meteorological Messages (METGMs)

by Brian P Reen and Patrick A Haines

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Brian P Reen and Patrick A Haines
DEVCOM Army Research Laboratory

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14. ABSTRACT Vertical gradient criteria are identified that suggest atmospheric fields may not be trustworthy in the three-dimensional/ four-dimensional gridded meteorological message (METGM) files used for calculating artillery firing solutions. Initially, criteria designed to apply to a one-dimensional meteorological file are evaluated for a METGM file. Climatological vertical gradients, comparison with numerical weather prediction output, and observed extreme gradients are leveraged to determine the final gradient criteria recommended by this study. The gradient criteria can be used to warn when a METGM file may contain untrustworthy meteorological fields and may warrant further investigation as to whether the METGM accurately represents the numerical weather prediction forecast on which it is based.					
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1. Introduction

The METGM format is a North Atlantic Treaty Organization (NATO)-standard gridded meteorological message (STANAG 6022 [NATO 2010]; AMETOCP-4 V1 [NATO 2019]) that contains meteorological fields on a grid with horizontal, vertical, and (optionally) temporal axes. Numerical weather prediction (NWP) model forecasts are used to create the meteorological fields contained within a METGM. METGMs are then used to provide meteorological input to artillery firing solutions and for chemical, biological, radiological, nuclear (CBRN) applications.

The accuracy and resolution of NWP forecasts have been and continue to be steadily improved since their initial implementation over 70 years ago. Nonetheless, the NWP predictive equations are still slightly imperfect numerical representations of the underlying partial differential equations governing fluid flow and the conservation of energy and mass. In addition, it is necessary to account for unresolved or imperfectly resolved processes such as turbulence by parameterizing them in terms of the resolved forecast parameters. Finally, the initial atmospheric representation at the start of an NWP forecast contains small errors due to observational and other sources. Even if the initial error is small and the other factors described previously add only small errors during the model integration, due to the nonlinearity of the NWP equations, the error eventually grows large enough to degrade the forecast, creating differences between the forecast and the actual state of the atmosphere.

These differences cause errors in the applications to which the METGM is being applied. For example, errors in the meteorology provided to an artillery firing solution will result in firing solution errors that ultimately could result in the artillery not achieving first-round fire for effect or experiencing degraded guided munition effects. As mentioned, this is due to the slight inexactness in the equations and physics the model uses to represent the atmosphere, limitations in the data and its processing used to initialize the model, and other factors. However, much larger errors can be introduced into a METGM in the process of extracting the relevant data from the NWP model forecasts, processing it to obtain the desired variables on the desired grids, and then placing the data into the METGM format. For example, if the pressure field is inadvertently flipped vertically, very large pressure errors would be in the resultant METGM and could cause severe errors in the processes using the METGMs.

A technique that can diagnose whether a METGM might have large errors would allow METGM users to know if a particular METGM should be viewed with caution. If METGMs were consistently marked as potentially having large errors,

the user would be able to investigate if there was an error in the processing used to create the METGM from the NWP model forecast data. Since all NWP forecasts have some level of error, the goal of the technique would be to determine when the meteorological fields have characteristics that make them meteorologically unlikely. For operational purposes, a manual technique is not tenable because of 1) the vast volume of data that can exist in a METGM with its 3-D/4-D grid, 2) the importance of up-to-date meteorological data being quickly provided to end users, and 3) the subject-matter expertise required to manually evaluate the fields.

Determining whether variables fall within physically possible ranges is an important part of diagnosing whether a METGM may be considered meteorologically unlikely, but looking only at physically possible ranges cannot recognize all unrealistic fields easily introduced by errors in METGM extraction. In the example referenced earlier, the vertical flipping of the pressure field would not be caught by checking whether the pressure values at each point are within the possible range of pressures in the atmosphere, since the pressures in the flipped pressure field are all possible somewhere in the atmosphere. Devising criteria to check vertical variation in fields allows for the detection of the results of various errors that can be made in the extraction of a METGM. This report focuses on the formation of criteria to check for meteorologically improbable vertical variations in METGMs.

The methodology used is described in Section 2, followed by the resultant criteria in Section 3 and a summary and conclusions in Section 4.

2. Development of METGM Thresholds

2.1 METCM Vertical Variation Thresholds

The computer meteorological message (METCM) format (AMETOC4 V1 [NATO 2019]) is 1-D, as it only includes the vertical variation of the meteorology rather than also including the horizontal and optionally temporal variation of meteorology as in the 3-D/4-D METGM. METCM validity checks that address vertical variation are described in the NATO Fire Control Inputs All, Appendix 3 (NFCI ALL [ARDEC and FFI 2019]). The criteria are the following:

- 1) The air pressure should decrease as the line number increases.
- 2) Air pressure divided by air temperature should decrease as the line number increases.
- 3) The line-to-line change in air temperature should be no more than 20 K.

- 4) The line-to-line change in wind speed should be no more than 10 kt.
- 5) The line-to-line change in wind direction should be no more than 1000 mil when wind speeds exceed 10 kt (1000 mil = 56.25°).
- 6) The air pressure gradient should not exceed 1 hPa/m.

These METCM criteria are subsequently referred to by their number, preceded by “C” (e.g., C3), to indicate that they are the METCM criteria. NFCI ALL indicates that violation of C1–C5 should produce warnings, whereas violation of C6 should produce an error. Each vertical layer in a METCM is a “line” and so the references to “line-to-line change” in the criteria refer to changes between adjacent vertical layers.

Since these criteria to evaluate the vertical variation of meteorology already existed, the goal is to determine if these criteria can be adapted for application to METGMs. An important difference between METCMs and METGMs is that METCMs are on a standard set of layers specified in heights above ground level (AGL), whereas the vertical levels in a METGM are chosen by the user. Since the criteria that do not specify specific line-to-line differences (C1, C2, and C6) are not dependent on the vertical spacing, the initial hypothesis is that these criteria can also be applied to the METGM. Thus, the focus of the effort is to adjust the criteria specifying line-to-line differences (C3–C5) to be applicable to METGMs. The goal is to replace the line-to-line differences with vertical gradients, so that the criteria are applicable to the user-defined levels in a METGM.

2.2 METCM-Criteria-Based Thresholds

The first methodology attempts to find vertical gradient criteria for METGMs by translating the METCM criteria into vertical gradients. The vertical spacing between the midpoints of the METCM layers varies substantially with height (100–2000 m; Fig. 1), so translating the line-to-line differences to vertical gradients results in criteria containing vertically varying vertical gradients (Fig. 2, “Vertically-Varying”). Since many METCM layers are 1000 m thick, the vertical gradient equivalent to the line-to-line change over a 1000-m-thick layer is used as another potential vertical gradient threshold (Fig. 2, “Constant”).

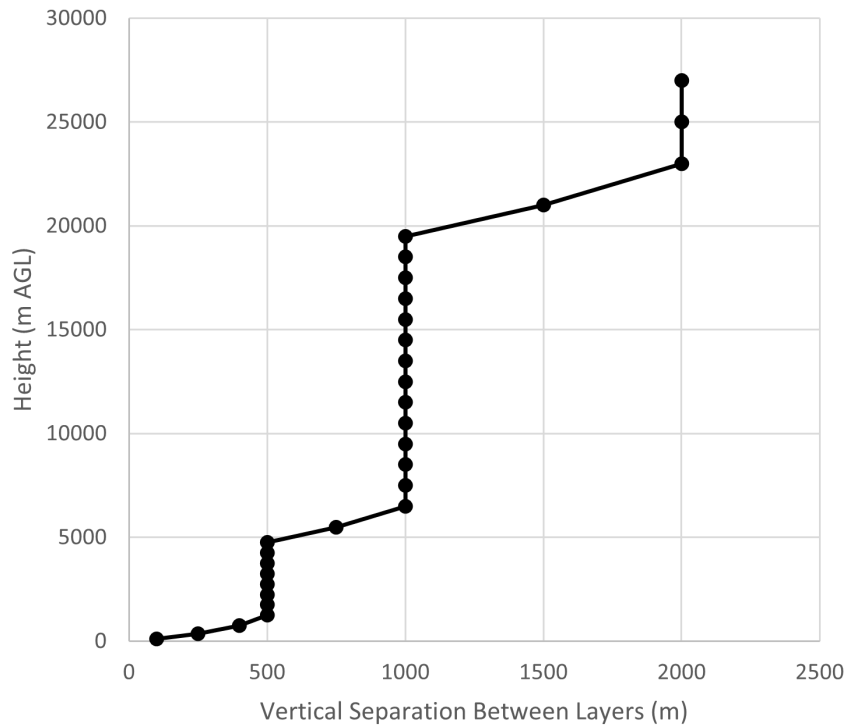


Fig. 1 Vertical separation between the midpoints of vertically adjacent layers in a METCM

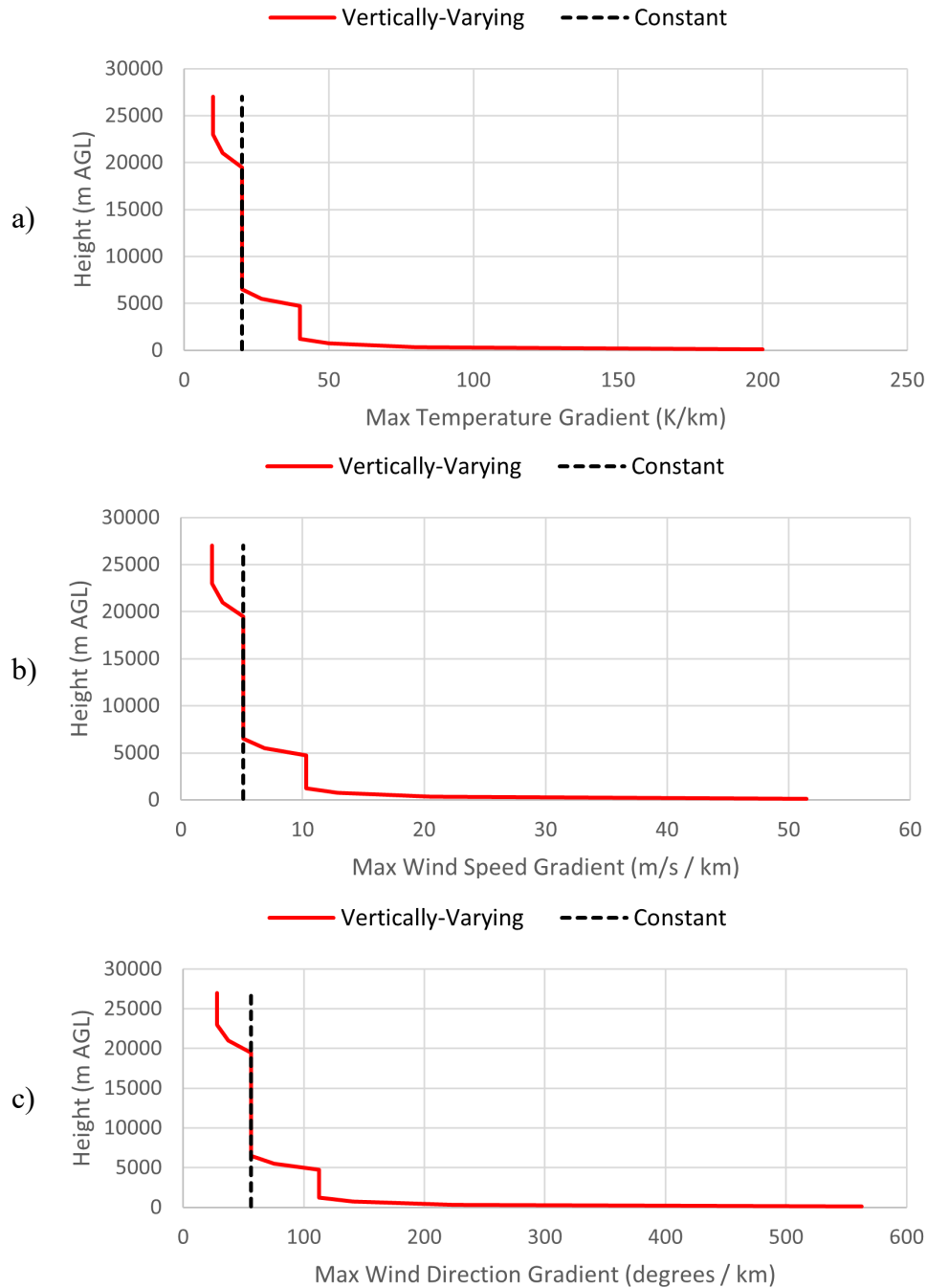


Fig. 2 Vertical gradients of a) temperature, b) wind speed, and c) wind direction resulting from converting METCM line-to-line criteria to gradients using the vertical separation between the midpoints of the METCM layers (Vertically-Varying) and using the most common vertical separation, namely, 1000 m (Constant)

The use of the height-varying and constant-with-height vertical gradient criteria is explored by applying both sets of criteria to sample NWP model output from a single model run using the Advanced Research version of the Weather Research

and Forecasting (WRF-ARW [Skamarock et al. 2019]) model, version 4.1.2. Since the vertical levels in a METGM are user-defined, the midpoints of the METCM layers are used as a first guess of the METGM levels for this evaluation. The model output is vertically interpolated to these heights and the points along the horizontal edges of the domain are omitted to avoid boundary effects. This is used as a proxy for a METGM. Both sets of criteria (vertically varying and constant-with-height) are applied to the proxy METGM, and the percentage of grid points where the model exceeds the threshold is calculated at each time and averaged over the times evaluated.

The vertically varying temperature criterion is not exceeded for this test case (Fig. 3a), but the constant-with-height criterion is exceeded for the majority of the grid points near the surface. The large contrast in the exceedance of the constant-with-height criteria at the surface (approximately 60% of grid points) compared to points above the surface (0% of grid points) is consistent with the METCM having thinner layers near the surface and the atmosphere often having larger vertical temperature gradients near the surface. This also suggests that a gradient criterion that successfully differentiates meteorologically likely versus meteorologically unlikely temperature gradients may need to be vertically varying. From a single case, it is difficult to know whether the vertically varying temperature gradient criteria are a good discriminator of meteorologically unlikely temperature gradients.

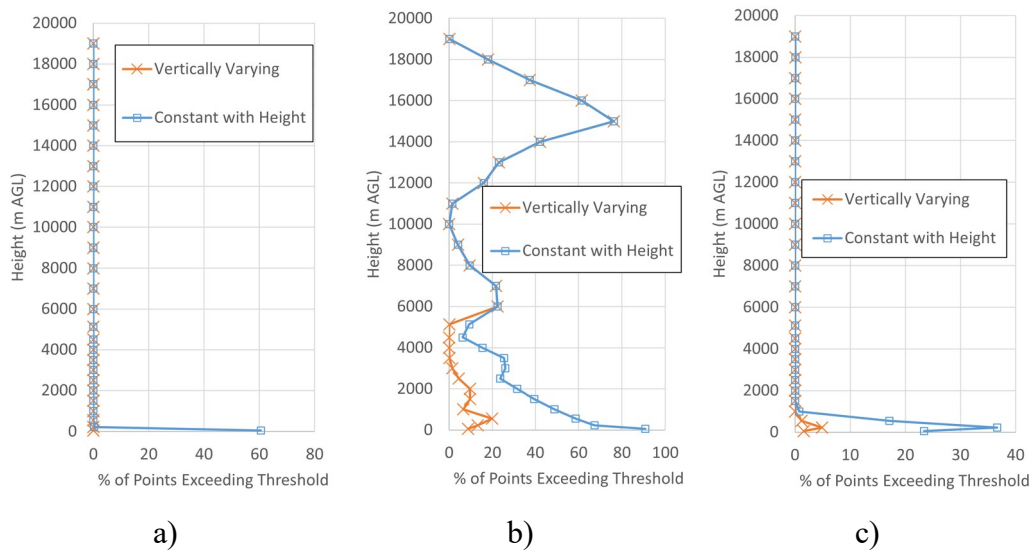


Fig. 3 Percentage of NWP forecast grid points exceeding vertically varying and constant-with-height vertical gradient thresholds derived from METCM thresholds for a) temperature, b) wind speed, and c) wind direction

Both the vertically varying and the constant-with-height wind speed and wind direction vertical gradient thresholds are exceeded in this case (Fig. 3b, 3c). For wind speed the constant-with-height criterion is violated by approximately 90% of grid points near the surface, but also for notable percentages at many other heights. The vertically varying wind speed criterion is violated less frequently at heights where levels are thinner than 1000 m, but still is violated by approximately 90% of grid points for a level near the surface. For wind direction, exceedances occur for both criteria but are constrained to near the surface. That the only test case evaluated violates the wind criteria for such a large percentage of the model grid points strongly suggests that the wind criteria are too strict. Application of the current wind criteria to METGMs will likely lead to many METGMs being diagnosed as having vertical gradients of horizontal wind that are too large when the METGMs are not actually meteorologically unlikely. This in turn would lead to “overwarning” the user that the wind field is potentially problematic, which will likely lead to users eventually ignoring the warning that the threshold is exceeded. When the vertical gradient of wind is meteorologically unlikely, the user may not be aware of this, since the overwarning has conditioned the user to ignore the warnings. Therefore, the wind criteria tested in this section should not be applied to determine whether METGMs are meteorologically likely.

2.3 Climatology-Based Thresholds

To determine which vertical gradients are meteorologically unlikely, climatological data are analyzed. Specifically, the United States Air Force’s 14th Weather Squadron (USAF 14WS) calculated vertical gradients in radiosonde data from seven sites with widely varying climates for a period of approximately 22 years (1995–2017). The location and associated station identifier of each of the seven sites is as follows:

- Santa Teresa, New Mexico, USA (KEPZ)
- Wilmington, Ohio, USA (KILN)
- Fairbanks, Alaska, USA (PAFA)
- Pago Pago, American Samoa (NSTU)
- Resolute, Nunavut, Canada (CYRB)
- Kandahar, Afghanistan (OAKN) (only available for part of 22-year period)
- Osan Air Base, Republic of Korea (RKSO)

The vertical gradients were calculated using 200-, 500-, and 1000-m-thick layers to demonstrate how the magnitude of gradients in the METGMs would be expected to vary depending on the METGM vertical spacing. The USAF 14WS calculated percentiles based on these vertical gradients and supplied that data. The 200-m gradients were calculated up to 20 km AGL, whereas the 500- and 1000-m gradients were calculated up to 30 km AGL.

Since temperature vertical gradients can be negative or positive, to formulate a candidate temperature vertical gradient criterion we examined the maximum of the absolute value of the 99th percentile vertical temperature gradient and the 1st percentile vertical temperature gradient:

$$T_{99_1} = \max \left(\left| \frac{dT}{dz} \right|_{99th}, \left| \frac{dT}{dz} \right|_{1st} \right)$$

The 100th and 0th percentiles (i.e., the maximum and minimum values) were not used, since it was thought that these values were likely to include erroneous data that quality control failed to remove.

The vertical profiles of this quantity for each location and for each layer thickness are shown in Fig. 4. As expected, evaluating the gradient over thinner layers results in larger gradients at some heights (i.e., gradients evaluated using 200-m-thick layers [Fig. 4c] are generally larger than those evaluated using 500-m-thick [Fig. 4b] or 1000-m-thick [Fig. 4a] layers). The sensitivity to the thickness of the layers over which the climatological gradients are determined is especially large near the surface.

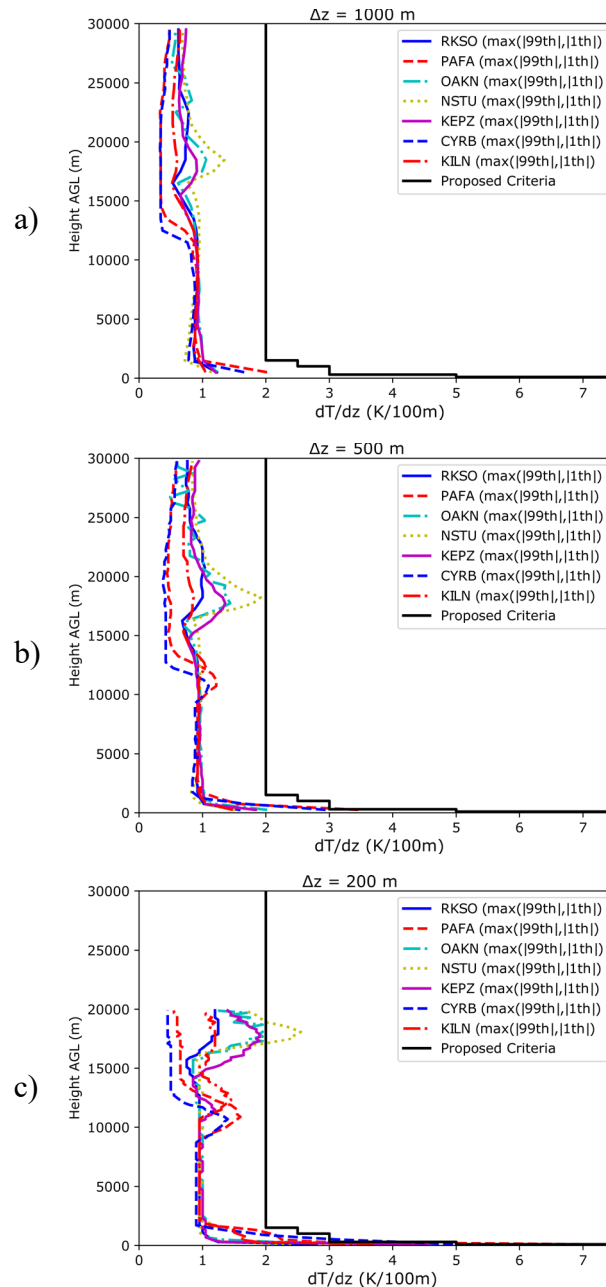


Fig. 4 The colored lines show the climatological vertical temperature gradient metric T_{99_1} for seven locations. The gradient metric is shown as calculated for a) 1000-m-thick, b) 500-m-thick, and c) 200-m-thick layers. The solid black line shows the vertical temperature gradient criteria proposed based on the climatological gradients.

Based on the climatological vertical gradients, vertical temperature gradient criteria are devised that are larger than most of the T_{99_1} values for the layer thickness with the largest gradients (200 m) and are included in Fig. 4. At the NSTU location, T_{99_1} exceeds the devised criteria from 17 to 19 km AGL for a layer thickness of 200 m, reached the criteria at about 18 km AGL for a layer thickness of 500 m, but does

not reach or exceed the criteria for the 1000-m layer thickness. This exceedance may be related to the tropical tropopause and so may suggest that to account for the tropical tropopause, a larger criterion should be used near this height for METGM levels with less than 1000-m vertical spacing. However, no METGMs are known to have vertical spacing less than 1000 m at this elevation.

A similar technique is used to formulate candidate vertical wind gradient criteria from the climatological data. However, the formulation of the climatological wind metric differs from the climatological temperature metric (T_{99_1}). While wind speed and wind direction are the wind variables used in the METCM criteria, this can be problematic because the significance of a wind direction error of a given magnitude varies based on the magnitude of the wind speed. At very low wind speeds, large wind direction errors are not unexpected, whereas at higher wind speeds, large wind direction errors will be much less frequent. The METCM criterion acknowledged this via its condition that the wind direction criterion only be applied if the wind speed is significantly large. To avoid this issue and enable treatment of the wind in a single metric, the vector wind difference (VWD) is used here as the wind variable. VWD is calculated as follows:

$$VWD = \sqrt{(u_2 - u_1)^2 + (v_2 - v_1)^2} \quad (1)$$

Since the vertical gradient of wind is under evaluation, u_1 and v_1 are the u- and v-wind components at a given point, and u_2 and v_2 are the u- and v-wind components at the same horizontal point but at the level above or below the initial point. Unlike temperature, VWD cannot be negative and thus the 99th percentile value can be used alone to determine climatologically unlikely values.

The 99th percentile of VWD evaluated vertically for the seven locations is shown in Fig. 5. Larger VWD values are found when the VWD is formulated using thinner layers, as expected, and as was seen with temperature. Proposed criteria for VWD evaluated vertically are formulated based on the climatological values and are shown alongside the climatological values in the plots.

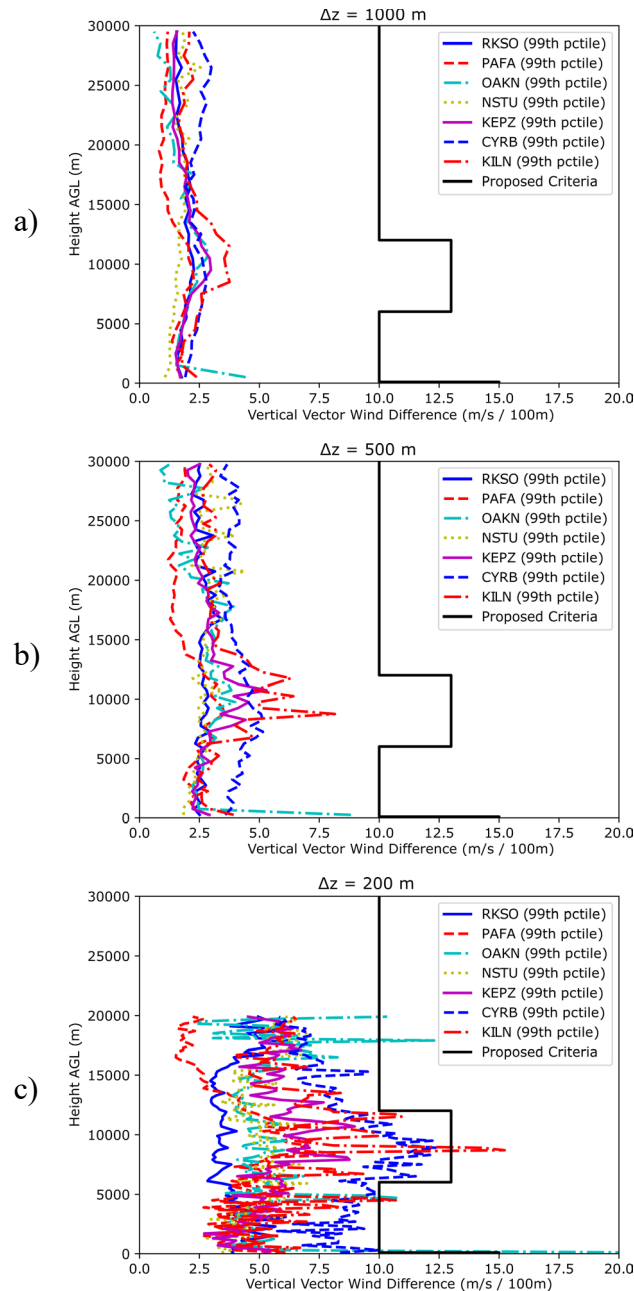


Fig. 5 The colored lines show climatological 99th percentile VWD evaluated vertically for seven locations. VWDs are shown as calculated for a) 1000-m-thick, b) 500-m-thick, and c) 200-m-thick layers. The solid black line shows the VWD criterion proposed based on the climatological vertical VWDs.

The candidate criteria are applied to a series of NWP forecasts covering 72 h. Specifically, WRF-ARW is used to create 9-km horizontal grid spacing simulations with hourly output. The output is then vertically interpolated to the METCM levels to represent a METGM using the METCM levels. These 72 h of model forecasts

provides approximately 5 million profiles against which to evaluate the candidate criteria.

A profile of the percent of samples for which the candidate criteria are exceeded is shown in Fig. 6. At a given height, one sample is the value at one horizontal grid point at one time. The percent of samples exceeding the criteria is quite small (no heights exceed 0.1%) and the thresholds are only exceeded near the surface. However, for the criteria to be useful in alerting the user to potentially unrealistic meteorology, the criteria should only be exceeded extremely rarely. That the criteria are exceeded in the 72 h of NWP output evaluated suggests that criteria are too strict and would result in a large number of false alarms wherein the user is warned that a METGM containing reasonable meteorology is potentially unrealistic.

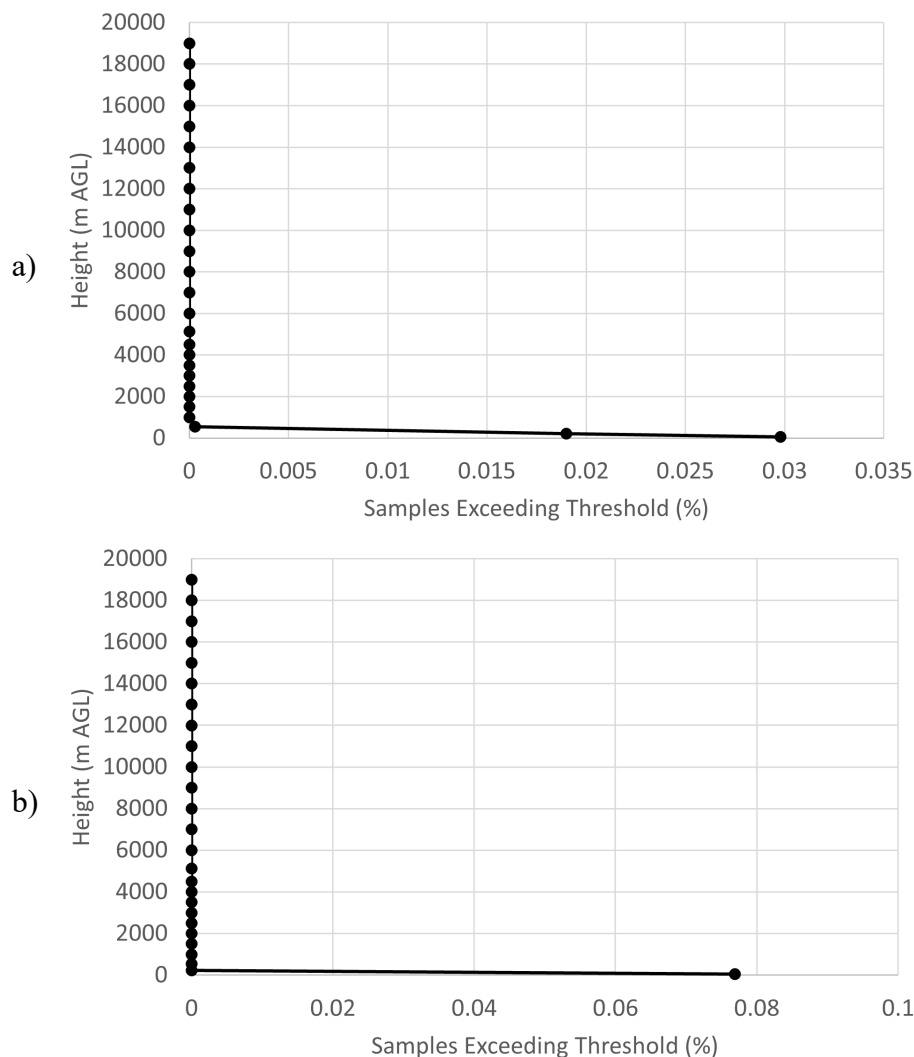


Fig. 6 Profile of the percent of samples (one sample is one horizontal grid point in the model at one forecast time) where the candidate threshold is exceeded for a) the vertical gradient of temperature and b) VWD evaluated vertically

Two factors seem likely to contribute to the candidate criteria being too strict. One factor is that the criteria are formulated based on the 99th percentile (and for temperature on the 1st percentile also) and one would expect 1% of points to exceed the 99th percentile. The criteria are generally set somewhat larger than the percentile values, which should obviate this issue somewhat, but it remains unclear how much larger the actual climatological maximum values are compared to the 99th percentile values given that it is suspected that the 100th percentile values provided in the climatological vertical gradient data include erroneous data. Another factor is that the thinnest layers over which the climatological gradients were calculated is 200 m, whereas the lowest two levels chosen as METGM levels to evaluate the criteria are only ≈ 100 m apart. Since atmospheric gradients can be larger in thinner layers and since atmospheric gradients are often larger near the surface, the reliance on climatological gradients calculated using 200-m-thick layers likely results in an underestimate of maximum climatological vertical gradients near the surface.

2.4 Adjusted Climatology-Based Thresholds

While Section 2.3 evaluated vertical gradient criteria using the midpoint of the METCM layers as the METGM levels, this approach may produce criteria that are not well suited for application to some METGMs currently being produced. Since the levels in a METGM are user-defined and since atmospheric gradients can be larger in a thinner layer, vertical gradient criteria that are effective for one METGM may be too restrictive for another METGM with thinner layers. Therefore, we constructed a set of METGM levels with layers at each height as thin as the thinnest METGM layer among the known set of METGM levels in use at that height. This set of METGM levels is used in adjusting the climatology-based thresholds from Section 2.3.

A profile of the minimum METGM thickness was constructed by comparing the METGM levels used by four nations as well as two sets of levels (Torben ballistics and Torben low level) recommended by the NATO Army Armaments Group (NAAG) Integrated Capability Group Indirect Fires (ICGIF) Sub-Group 2. One of the four nations provided two sets of METGM levels that are in use: one set is used for artillery application and the other for CBRN applications. A fifth nation indicated that their METGM levels closely matched one of the four nations whose METGM levels were included. The profile of minimum layer thicknesses among these METGMs is shown in Fig. 7 and labeled “Minimum METGM thickness.” The thicknesses of the METGM set of levels used in the previous section to validate the vertical gradient criteria are also shown in this figure and labeled “Previous Validation Thickness.” The minimum METGM thickness is identical to the

previous validation thickness from about 10 km AGL to the top of the layers used in the previous validation (the METGM levels used in the formulation of the minimum METGM thicknesses here includes levels extending higher in the atmosphere than that previous validation). Below 10 km AGL, the minimum METGM thickness is much smaller than the previous validation thickness. While the thickness of the previous validation levels is twice that of the minimum METGM thickness for $\approx 5\text{--}10$ km AGL (Fig. 7a), at lower levels, larger ratios occur including four times as thick for $\approx 1\text{--}2$ km AGL (Fig. 7b). This suggests that the previous validation levels had a coarser vertical resolution than should be used to validate vertical gradient criteria.

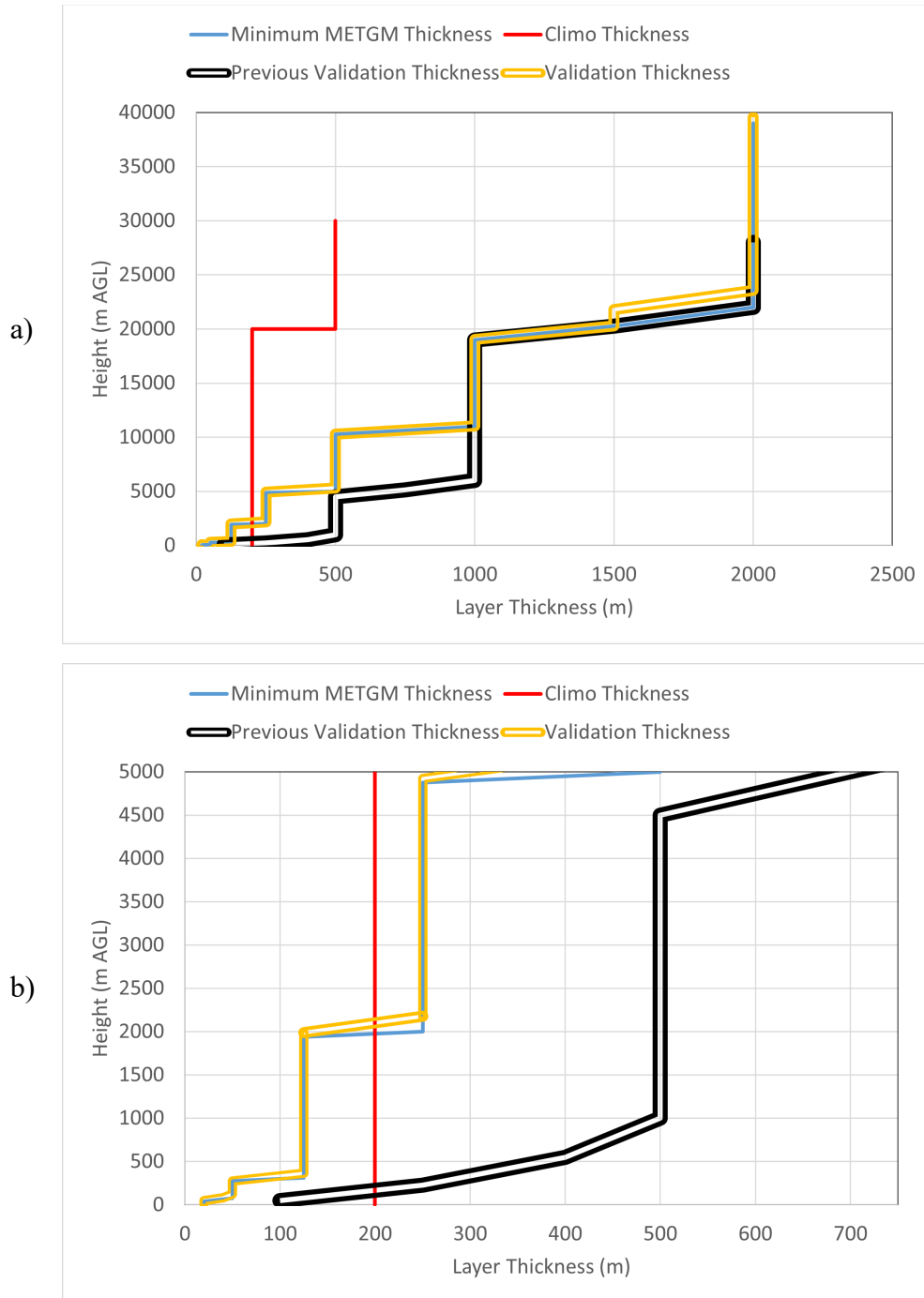


Fig. 7 Vertical profiles of the minimum thickness between METGM levels among various METGM levels (“Minimum METGM Thickness”), the minimum thickness of the layers for which climatological vertical gradients were calculated (“Climo Thickness”), and the thickness of the layers for the METGM levels used to validate the vertical gradient criteria in the previous section (“Previous Validation Thickness”) and in this section (“Validation Thickness”) for a) 0–40,000 m AGL and b) 0–5,000 m AGL

To account for the layer thicknesses present in METGMs used by various nations, a set of METGM levels is constructed with thicknesses no thicker than the minimum METGM thickness at each height; this is labeled in Fig. 7 as “Validation Thickness.” This set of 66 levels has a 20-m vertical spacing near the surface to 2000 m at its top level of 40,550 m AGL. The levels are shown in Table 1.

Table 1 Levels used for validation of the vertical gradient criteria in this section and that are constructed based on minimum METGM thickness. The levels are grouped by the thickness of the layer formed between the level and the level immediately below it in the atmosphere.

Thickness (m)	20–50	125	250	500	1000	1500	2000
Levels (m AGL)	300	2050	5050	10550	19550	22550	40550
	250	1925	4800	10050	18550	21050	38550
	200	1800	4550	9550	17550		36550
	150	1675	4300	9050	16550		34550
	100	1550	4050	8550	15550		32550
	60	1425	3800	8050	14550		30550
	40	1300	3550	7550	13550		28550
	20	1175	3300	7050	12550		26550
	0	1050	3050	6550	11550		24550
		925	2800	6050			
		800	2550	5550			
		675	2300				
		550					
		425					

The minimum thickness of the layers used to calculate the climatological vertical gradients is also shown in Fig. 7 (labeled “Climo Thickness”). While for most of the vertical extent, the thickness of layers used to calculate the climatological vertical gradients are smaller than the minimum METGM thickness (Fig. 7a), below 2 km AGL, this is not the case (Fig. 7b). For the 300–2000 m AGL layer, the minimum METGM thickness is 125 m, whereas the climatological vertical gradients were available at a minimum of 200-m thickness. Below 300 m AGL, the minimum METGM thickness is less than 125 m, with thinnest layers of 20 m occurring near the surface, but 200 m is the thinnest layers over which the climatological vertical gradients are available.

In the 300–2000 m AGL layer, the ratio between the thickness of the thinnest layers used in calculating climatological gradients (200 m) and the minimum METGM thickness (125 m) is smaller than at lower levels. The climatological gradients

calculated using 200-m layers were divided by those calculated using 500-m layers to provide rough guidance on the likely increase from 200 m to 125 m. Based on this, in the 300–2000 m AGL layer, the temperature vertical gradient criteria were increased by a factor of 1.6 and the vector wind vertical criteria were increased by a factor of 2.0.

Below 300 m AGL, the mismatch between the minimum thickness used to calculate the climatological gradients and the minimum METGM thicknesses is larger than at higher levels. To provide guidance for adjustments of the criteria below 300 m AGL, examples of strong observed vertical gradients were examined. For temperature, this included examination of vertical gradients during extreme cold events in PAFA in Fairbanks, Alaska, USA. For VWD, this includes studies of low-level wind shear.

To test these revised criteria, a set of NWP forecasts are created to cover a wide range of conditions. Specifically, WRF-ARW (also referred to as simply WRF) is used to create eleven 24-h forecasts with hourly output with 9-km horizontal grid spacing. The 11 forecasts are each over a different region and some of the cases are chosen to represent extreme conditions in that region. Information regarding the 11 cases is shown in Table 2. This set of cases allowed for the evaluation of vertical gradient criteria over a total of approximately 4.5 million vertical profiles.

Table 2 Description of cases for which WRF forecasts are created to test vertical gradient criteria. The weather conditions are noted for certain cases for which the weather is noteworthy in establishing the significance of the case. The latitude (“Lat”) and longitude (“Lon”) are for the center of the WRF domain.

Name	Location [weather]	Forecast start time	Lat	Lon
A	Alaska, USA [extreme cold]	2022-01-02 00 UTC	64.86	–147.75
B	Northcentral USA [wind/severe storms]	2021-12-15 06 UTC	41.25	–95.90
C	Mount Everest	2021-12-06 00 UTC	27.99	86.93
D	Southwest USA [hot]	2021-06-17 00 UTC	33.48	–112.10
E	Mid-Atlantic USA	2019-12-22 00 UTC	37.26	–76.72
F	Equatorial South America	2022-01-15 00 UTC	0.00	–64.00
G	Alps	2021-09-07 00 UTC	46.70	10.20
H	Siberia [extreme cold]	2022-01-03 00 UTC	68.50	112.43
I	Eastern Europe	2022-04-13 00 UTC	51.50	23.50
K	Northwest Europe [windstorm]	2022-01-28 00 UTC	52.72	3.70
L	Northeast Africa [hot]	2021-08-11 00 UTC	23.60	27.70

To prevent potentially nonrepresentative data from being included in the analysis, parts of the model output are omitted from the analysis. The 10 grid points along

each edge of the model domain are omitted from the analysis to prevent any distortions caused by the imposition of boundary conditions; after removal of these grid points, the area available to the analysis is a box approximately 1170×1170 km. The 0-h forecast lead time is omitted from the analysis to prevent any issues due to variables being not yet fully initialized at the time at which the 0-h field is written to the output file.

The vertical levels of the NWP simulations are chosen with the goal of allowing the model to produce realistic vertical gradients with maximum vertical gradients consistent with those possible in a METGM constructed using the minimum METGM thickness. Since stronger gradients can occur in thinner layers, WRF is configured with 148 vertical levels to ensure that its layers are as thin as the minimum METGM thickness. The model top is chosen to be above 40 km AGL to provide data for the highest METGM level (39 km AGL) among those compared to create the minimum METGM thickness. WRF, like other NWP models, produces a diagnostic value for temperature at 2 m AGL and a diagnostic value for wind at 10 m AGL, since these are levels at which these quantities are often observed and since NWP models often do not have prognostic levels at these heights. However, depending on the formulation of the diagnostic equations, there could sometimes be mismatches between what the model would predict if there were a prognostic level at those heights compared to what the diagnostic equations diagnose. Using a value at a diagnostic level together with a prognostic level to calculate a vertical gradient could thus result in an unrealistic vertical gradient. To prevent this potential issue, the lowest WRF layer is configured to be below 2 m AGL to allow prognostic levels to be interpolated to obtain a 2-m temperature and 10-m wind value to use in vertical gradient calculation.

The candidate vertical gradient criteria are compared to the maximum vertical temperature gradient present in each NWP case at each METGM level in Fig. 8. Based on this comparison, the criteria do not appear overly strict (i.e., too small) above approximately 4000 m AGL (Fig. 8a). Above 500 m AGL, the only case to exceed the threshold is case A (Fig. 8b), which involves extreme cold over Alaska where large vertical temperature gradients are expected. Between 250 and 500 m AGL, case B (northcentral USA during a wind and severe storm event) also exceeds the threshold (Fig. 8b). However, closer to the ground, additional cases exceed the threshold, especially below 50 m AGL (Fig. 8c). This indicates that further adjustment to the vertical temperature gradient thresholds is required.

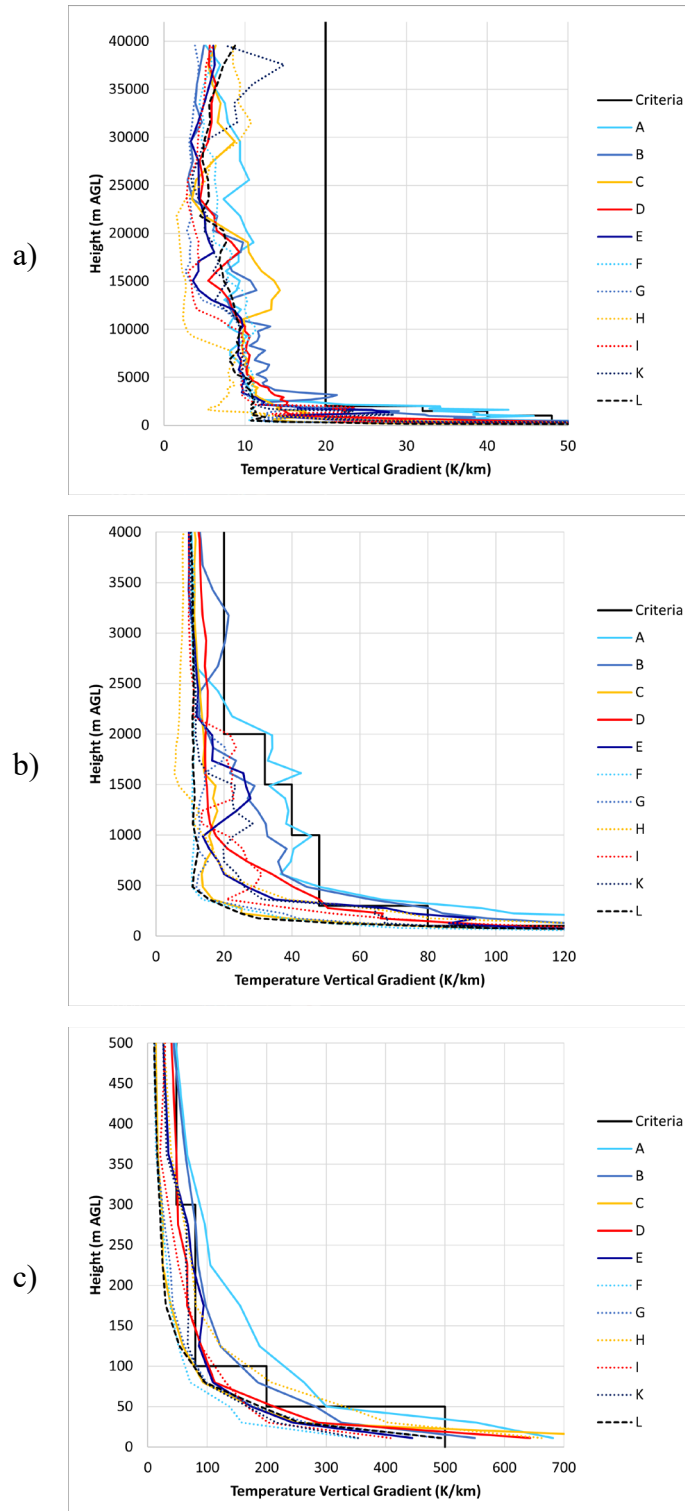


Fig. 8 Profiles of maximum vertical temperature gradient for each NWP case (cases indicated by single letter case name) compared to vertical gradient criteria (“Criteria”) for a) 0–40,000 m AGL, b) 0–4000 m AGL, and c) 0–500 m AGL

Similarly, the candidate VWD vertical gradient criteria are compared to the maximum VWD vertical gradients in the NWP cases at each METGM height in Fig. 9. For VWD, the criteria are only exceeded below 100 m AGL, but they are exceeded there for multiple cases.

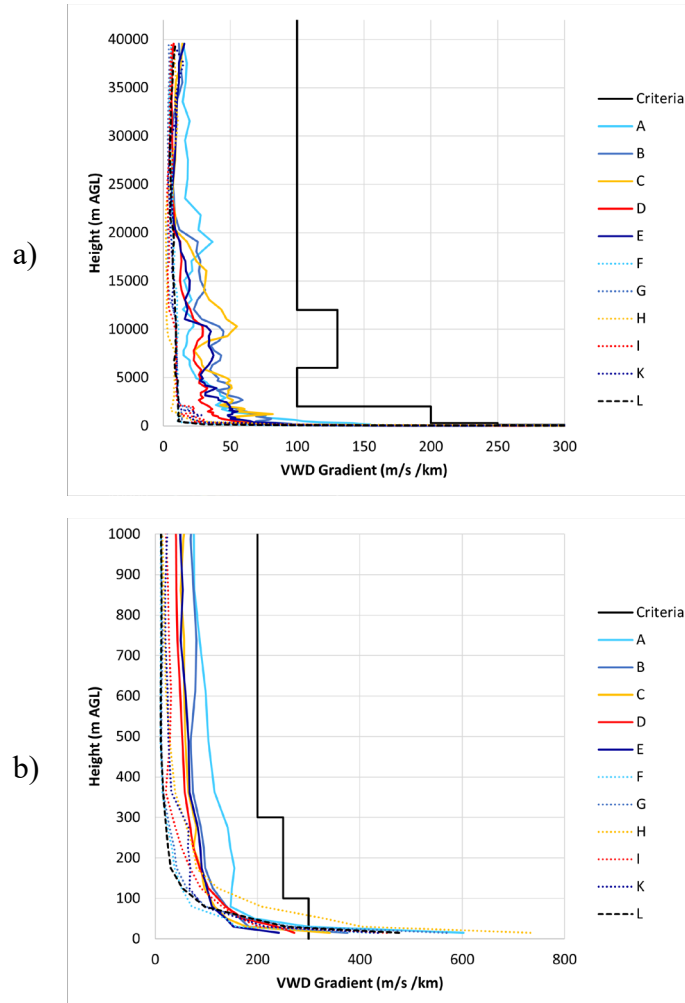


Fig. 9 Profiles of maximum vertical VWD gradient for each NWP case (cases indicated by single letter case name) compared to vertical gradient criteria (“Criteria”) for a) 0–40,000 m AGL and b) 0–1000 m AGL

The magnitude of the temperature criteria is increased at some heights based on the comparison of the criteria to the NWP cases. This increase in the criteria is needed to decrease the likelihood that reasonable NWP forecasts will be marked as potentially problematic by the criteria. These final vertical temperature gradient criteria are compared to the NWP cases in Fig. 10. None of the NWP cases contain vertical temperature gradients that exceed the final criteria.

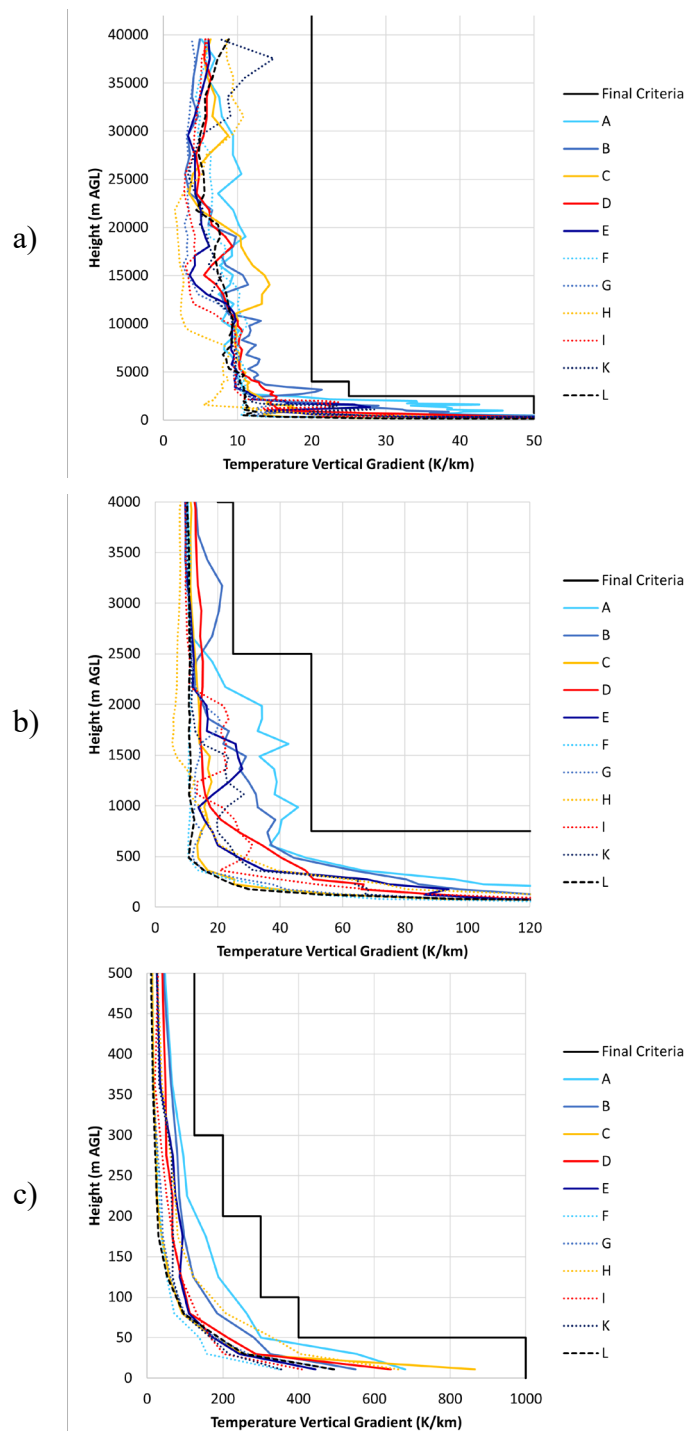


Fig.10 Profiles of maximum vertical temperature gradient for each NWP case (cases indicated by single letter case name) compared to final vertical gradient criteria (“Final Criteria”) for a) 0–40,000 m AGL, b) 0–4000 m AGL, and c) 0–500 m AGL

The VWD vertical gradient criteria have the values in the lowest 100 m increased since some of the cases exceed the criteria in that height range. The final vertical VWD gradient criteria are compared to the NWP values in Fig. 11.

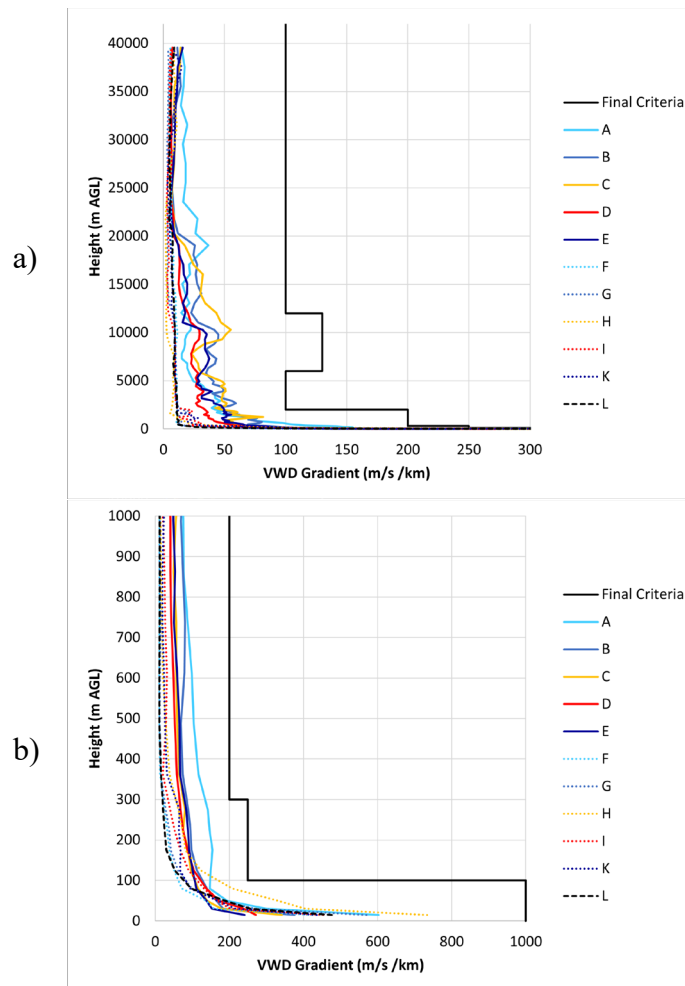


Fig. 11 Profiles of maximum vertical VWD gradient for each NWP case (cases indicated by single letter case name) compared to the final vertical gradient criteria (“Final Criteria”) for a) 0–40,000 m AGL and b) 0–1000 m AGL

2.5 METCM Criteria C2

It was initially assumed that METCM criteria that are not dependent on vertical spacing could be directly applied to METGMs. However, testing against NWP output interpolated to METGM levels revealed that the METCM criterion C2 was sometimes violated. That criterion states the following:

- Air pressure divided by air temperature should decrease as the line number increases.

This criterion essentially states that density should decrease with height. However, the criterion does not account for the impact of water on density. In analyzing NWP output, it is found that this criterion is sometimes violated when evaluated using the two METGM levels closest to the ground. This may be a transient state wherein the NWP model does not mix strongly enough to overcome strong surface heating. The METCM criteria C2 should thus be applied to METGMs only above 100 m AGL.

3. Resultant METGM Thresholds

Combining the METCM criteria C1 and C6 from Section 2.1, the vertical temperature and VWD criteria from Section 2.4, and the revised version of METCM criterion C2 discussed in Section 2.5 provides the following criteria that should be applied to determine whether the vertical atmospheric variation in a METGM indicates that it is potentially untrustworthy.

If any of the following four criteria are violated, then the METGM should be considered potentially untrustworthy:

- 1) Air pressure (p) should decrease with increasing height:

$$\frac{dp}{dz} < 0$$

- 2) Air pressure divided by air temperature (T) should decrease with increasing height above the lowest 100 m AGL:

$$\frac{d\left(\frac{p}{T}\right)}{dz} < 0 \text{ for } z > 100 \text{ m AGL}$$

- 3) The absolute value of the vertical gradient of air temperature (i.e., $|dT/dz|$) should not exceed the height-dependent values shown in Table 3.
- 4) The VWD calculated between winds at two adjacent vertical levels at the same horizontal location should not exceed the height-dependent values shown in Table 4.

VWD is calculated as

$$VWD = \sqrt{(u_2 - u_1)^2 + (v_2 - v_1)^2}$$

where u_1 is the u-component of wind and v_1 is the v-component of wind for a given horizontal grid point at a given vertical level and u_2 and v_2 are the wind components at the same horizontal grid point but at an adjacent vertical level.

Table 3 Height-dependent vertical gradient of temperature criteria whose exceedance indicates that a METGM is potentially untrustworthy

Height range m AGL	$ dT/dz $ K/km
>4000	20
>2500–4000	25
>750–2500	50
>300–750	125
>200–300	200
>100–200	300
>50–100	400
0–50	1000

Table 4 Height-dependent vertical gradient of VWD criteria whose exceedance indicates that a METGM is potentially untrustworthy

Height m AGL	VWD (ms^{-1})/km
>12000	100
>6000–12000	130
>2000–6000	100
>300–2000	200
>100–300	250
0–100	1000

If the fifth and final criterion is violated the METGM should be considered definitively untrustworthy:

- 5) Air pressure should decrease with height by no more than 1 hPa/m:

$$\frac{dp}{dz} \leq 1 \text{ hPa } m^{-1}$$

4. Summary and Conclusions

Criteria are needed to determine whether 3-D/4-D METGM meteorological messages may contain untrustworthy meteorology. While METGMs will always have some level of error, the goal is for the criteria to determine when the vertical variation in the meteorology varies substantially from the type of vertical variation expected to be observed in the atmosphere. METGMs are normally derived from NWP output and it is expected that the NWP model will not generally produce forecasts with vertical structures that suggest the meteorology is untrustworthy. However, incorrectly processing the NWP model forecast into the METGM format could cause vertical structures that are indicative of untrustworthy meteorological data.

Vertical criteria developed for the 1-D METCM message (NFCI ALL [ARDEC and FFI 2019]) were used as the starting point for this investigation. The criteria that were not based on the magnitude of differences between adjacent vertical layers in METCM were chosen as METGM criteria (with the caveat that a criterion that is a proxy for vertical density gradients is only to be applied to METGMs above 100 m AGL). The remaining METCM criteria are based on specific magnitudes of differences between one vertical layer and an adjacent vertical layer. While all METCMs have the same vertical layers, the user chooses which levels to include in a METGM, and so the specific layer-to-layer differences in the METCM criteria may not be well suited to a METGM. Therefore, the layer-to-layer difference criteria were translated into vertical gradient criteria using two methods. These criteria were tested against a limited amount of NWP output, and it was found that, for winds, the criteria were exceeded using both methods (sometimes for a substantial percentage of points), while the criteria for temperature are exceeded using one of the methods. Based on this, adapting METCM layer-to-layer difference criteria to vertical gradients for application to METGM leads to criteria that are too restrictive and could lead to significant overwarning of the user (i.e., frequently telling the user that a METGM has potentially untrustworthy meteorology when this is not true).

Climatological vertical gradients from seven locations were then analyzed to formulate new vertical gradient criteria for temperature and VWD. VWD is used in place of the wind speed and wind direction criteria to more holistically evaluate the wind and avoid the challenge of determining wind speed thresholds governing when wind direction differences are relevant. These gradient criteria were exceeded less than 1% of the time and only at the surface when evaluated against 72 h of forecast over a single NWP domain. However, as there is no indication that the meteorology from this NWP output is actually untrustworthy, this exceedance indicates that the criteria are too strict.

To determine vertical gradient criteria that are widely relevant, a set of METGM levels was constructed based on the thinnest layers among known METGM configurations. The thickness of these layers was compared to the thickness of the climatological vertical gradients, and where this difference was relatively small (300–2000 m AGL), the gradient criteria from climatology were increased based on a comparison of climatological gradients that were calculated by using layers of different thicknesses (i.e., the relationship between climatological gradients calculated using 200-m-thick layers vs. those using 500-m-thick layers). Below 300 m AGL, the gradient criteria based on climatological gradients were adjusted based on observations of strong vertical temperature and wind gradients.

These adjusted vertical gradient criteria were evaluated against 11 NWP forecasts over widely varying conditions. The NWP forecasts used vertical grid spacing as fine as that of the METGM to ensure that the NWP forecast could best represent the magnitude of vertical gradients possible with the level thicknesses in the METGM. Additionally, the vertical gradients in the NWP forecast were evaluated using the METGM levels to preserve the strength of vertical gradients possible with thin layers. This evaluation led to increases in the temperature vertical gradient criteria in the lowest 2500 m AGL and in the VWD vertical gradient criteria in the lowest 100 m AGL. This final temperature and VWD vertical gradient criteria are not exceeded in any of the test cases.

A set of vertical gradient criteria are proposed to evaluate whether a METGM is potentially untrustworthy. This set of criteria includes two of the METCM criteria, one METCM criterion with the caveat that it is not used in the lowest 100 m AGL, and the temperature and VWD vertical gradient criteria formulated in this study. For five out of the six criteria, violation of the criteria does not guarantee that the meteorological fields are untrustworthy, since they may be violated in highly unusual meteorological conditions. Violation of the criteria does indicate that caution is advised in the use of the meteorological fields; persistent violation of the criteria would indicate the METGM generation process should be investigated for potential errors. These criteria solely focus on the vertical structure of the METGM and should be used in concert with gross error checks that ensure that the magnitude of meteorological quantities is reasonable.

While these criteria are designed for 3-D/4-D METGMs, they should also apply to 1-D METCMs. The criteria look at single profiles individually and so should be applicable to the single profile present in a METCM. While METCMs may be created from both observations and model data, the same vertical gradient criteria would seem to be applicable to both sources.

5. References

NATO. AMETOC-4 volume 1: NATO meteorological and oceanographic codes manual. edition A, version 1. NATO Standardization Office; 2019.

NATO. STANAG 6022 (Edition 2) – Adoption of a standard gridded data meteorological message. NATO Standardization Office; 2010.

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Liu Z, Berner J, Wang W, Powers JG, Duda MG, Barker DM, Huang X-Y. A description of the advanced research WRF model version 4. National Center for Atmospheric Research; 2019. Report No.: NCAR/TN-556+STR. doi:10.5065/1dfh-6p97.

US Army Armament Research, Development and Engineering Center (ARDEC) and Norwegian Defence Research Establishment (FFI). North Atlantic Treaty Organization Fire Control Inputs All (NFCI ALL), appendix 3: description of meteorological inputs and algorithms required to integrate the point mass or modified point mass equations of motion. ARDEC and FFI; 2019. p. 24.

List of Symbols, Abbreviations, and Acronyms

1-D	one-dimensional
3-D	three-dimensional
4-D	four-dimensional
AGL	above ground level
ARL	Army Research Laboratory
C	criteria
CBRN	chemical, biological, radiological, nuclear
CYRB	Resolute, Nunavut, Canada (station identifier)
DEVCOM	US Army Combat Capabilities Development Command
ICGIF	Integrated Capability Group Indirect Fires
KEPZ	Santa Teresa, New Mexico, USA (station identifier)
KILN	Wilmington, Ohio, USA (station identifier)
Lat	latitude
Lon	longitude
METCM	computer meteorological message
METGM	gridded meteorological message
NAAG	NATO Army Armaments Group
NATO	North Atlantic Treaty Organization
NFCI ALL	NATO Fire Control Inputs All, Appendix 3
NSTU	Pago Pago, American Samoa (station identifier)
NWP	numerical weather prediction
OAKN	Kandahar, Afghanistan (station identifier)
PAFA	Fairbanks, Alaska, USA (station identifier)
RKSO	Osan Air Base, Republic of Korea (station identifier)
USAF 14WS	US Air Force 14th Weather Squadron
VWD	vector wind difference

WRF	Weather Research and Forecasting model
WRF-ARW	Advanced Research version of the Weather Research and Forecasting model

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