995 NARR-Based Climatology of Estimated Altimeter Error Due to Non-Standard Temperatures

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1. INTRODUCTION

A pressure altimeter senses only one atmospheric parameter, the pressure at flight level. Altitude is inferred through use of the hypsometric equation assuming a linear standard atmosphere (SA) temperature profile. Therefore, when the environmental temperature differs from standard, the indicated altitude will be in error. As a result, avoiding collisions with terrain becomes problematic for pilots when temperatures are colder than standard, especially for flights over mountainous regions at night or in clouds. In these instances, the altimeter will indicate a higher altitude than the aircraft is flying, putting the pilot and crew at risk of controlled flight into terrain (CFIT). Wiener (1977) defines CFIT accidents as those that occur when an airworthy aircraft, under the control of a pilot, is flown (unintentionally) into terrain, water, or obstacles with inadequate awareness on the part of the pilot (crew) of the impending collision. Shappell and Wiegmann (2003) evaluated over 14,086 general aviation (GA) accidents between 1990 and 1998 and attributed 1,407 (10%) accidents to CFIT. Bailey et al. (2000) completed a similar study focused on Alaskan commercial flights during the same period and found that of 126 fatal accidents, 89 (71%) were attributed to CFIT. Furthermore, a Federal Aviation Administration (FAA) advisory circular (FAA 2003) estimated 17% of all general aviation accidents were directly attributed to CFIT. This same advisory listed "increased pilot awareness" as the top proposed intervention strategy to improve CFIT safety, which also serves as a primary motivator for this research.

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The impact of non-standard atmospheric pressures and temperatures on accurate altimeter readings dates back to the earliest days of aviation (Meisinger 1920; Brombacher 1926, 1934; Kiefer 1936). Modern pressure altimeters can easily correct for non-standard sea-level pressure through the setting of the altimeter subscale (base reference pressure) but correcting for non-standard temperature remains problematic. Pilots must rely on FAA regulations to add additional altitude when traversing mountainous terrain or during instrument approaches in extreme cold temperatures. While these safety measures are effective, they provide less experienced GA pilots little educational value or increased awareness in understanding the magnitude and seasonal variability of altimeter errors resulting from nonstandard temperatures. To help improve pilot awareness of potential altimeter errors, Guinn and Mosher (2015) created model-based current and forecast "corrected" D-value images to graphically visualize estimated altimeter error due to non-standard temperature using real-time North America Mesoscale (NAM) model output. The traditional D-value (or altimeter correction), first introduced by Bellamy (1945), measures the difference between the true altitude (height above mean sea level) and the pressure altitude (height above the standard datum plane in the SA). This is useful for commercial flight operations in Class A airspace (above 5,500 m or 18,000 feet) where pilots are required to set their altimeter subscale to the standard datum plane (1013 hPa) because changing the altimeter subscale for operations at these altitudes and aircraft speeds is impractical. The altimeter readings for these flights therefore provide the pressure altitude. Thus, the traditional D-value provides the amount of correction to be added to the pressure altitude to obtain the true altitude. However, below Class A airspace, where most GA flights occur, pilots are required to set their altimeter subscale to the current altimeter setting (mean sea-level pressure calculated assuming an SA pressure reduction). This ensures the altimeter always indicates the station elevation when the aircraft is on the ground. The corrected D-value therefore measures the difference between the true altitude and the indicated altitude when the altimeter subscale is set to the current altimeter setting. In other words, corrected D-value is the traditional D-value "corrected" for non-standard pressures. Similar to traditional D-value, the corrected D-value can be considered the amount of correction necessary for the altimeter's indicated altitude to equal the true altitude. While current and short-term forecasts of corrected D-value are useful for GA flight planning, they do not provide the climatological and seasonal variation of estimated altimeter error. With the advent of the North American Regional Reanalysis (NARR) data base (Mesinger et al., 2006), such climatology maps are now possible. The focus of this paper is to provide a 30-year climatology of the monthly variation in corrected D-value. For comparison, we also constructed a similar 30-year climatology based on the temperature at a single level using a simplified rule-of-thumb (ROT) provided by the International Civil Aviation Organization (2006). It should also be noted that although climate research supporting aviation operations has recently seen a surge in activity (Coffel and Horton, 2015; Storer et al., 2017; Goodman and Griswold, 2018), the focus has largely been on climate-change impacts to commercial aviation. In contrast, this project is focused on creating a baseline climatology aimed at improving GA awareness and safety.

2. METHOD

Guinn and Mosher (2015) provided a detailed review of how temperature impacts the estimation of height from pressure measurements using the hypsometric equation. The crux of the problem is determining the mean temperature of the layer between the two pressure levels of interest: the pressure sensed by the altimeter's internal aneroid barometer and that of the altimeter subscale. Since the mean temperature of the layer is unknown, altimeter indicated height (h_{IA}) is determined by the altimeter equation (1), which assumes an SA linear temperature lapse rate (L) of -6.5 K km^{-1}, a SA mean sea-level (MSL) temperature (To) and pressure (po) of 288.15 K and 1013.25 hPa, respectively. Here R is the gas constant for dry air (287.053 J kg^{-1} K^{-1}) and g is gravity (9.8065 m s^{-1}). These values were taken from US Standard Atmosphere (National Oceanic and Atmospheric Administration 1976). Finally, the reference pressure for the altimeter subscale is the altimeter setting (p_{alstg}).

$$h_{IA} = \frac{T_o}{L}\left[\left(\frac{p}{p_o}\right)^{-\frac{RL}{g}} - \left(\frac{p_{alstg}}{p_o}\right)^{-\frac{RL}{g}}\right] \quad (1)$$

If we instead use high vertical-resolution model data, such as from the NARR, we can obtain height values based on more representative layer-mean temperatures with no assumption of a linear temperature profile. We therefore expect the NARR height fields (h) to provide a more accurate measure of true altitude. Using these two different measures of height, h and h_{IA}, we can define the corrected D-value (D_c) as:

$$D_c = h - h_{IA} \quad (2)$$

Using this definition, a negative D_c indicates the atmosphere is colder than standard; that is, the aircraft is lower than indicated (most dangerous), while a positive D_c indicates the aircraft is higher than indicated. Note the calculation of D_c used here is slightly different than that of Guinn and Mosher (2015) because we use the altimeter setting for the pressure at mean sea-level rather than the traditional mean sea-level pressure. The difference being that the altimeter setting provides a reduction to sea-level pressure assuming a standard atmospheric temperature profile, while the mean sea level pressure calculation accounts for non-standard temperatures. Using the altimeter setting is therefore more consistent with aviation altimeter readings because GA pilots use this for their altimeter subscale. In doing so, pilots ensure the altimeter always indicates the station elevation while on the ground. Since the NARR data set does not include altimeter setting data, we calculated p_{alstg} using the NARR (nearest grid point) surface pressure (p_{sfc}) and nearest grid point terrain height (h_{sfc}) using the altimeter setting equation (3).

$$p_{alstg} = p_{sfc}\left[1-\left(\frac{p_o}{p_{sfc}}\right)^{-\frac{RL}{g}}\left(\frac{Lh_{sfc}}{T_o}\right)\right]^{-\frac{g}{RL}} \quad (3)$$

Using (1) and (2), we calculated the 12 UTC h_{IA} for three different NARR pressure levels (875 hPa, 750 hPa, and 650 hPa). These pressure levels correspond to pressure altitudes of approximately 1,200 m, 2,400 m, and 3,600 m, which approximates general aviation flight altitudes of 4,000, 8,000 and 12,000 feet. We chose these values both because of their relevance to GA flight and the availability of NARR data for these levels. For the estimated true altitude (h), we used the 12 UTC NARR height values for each of the corresponding three pressure levels. The monthly mean values of the 12 UTC corrected D-value were calculated from (2) for each month for years 1981 to 2010 following the World Meteorological Organization (2017) guidelines for climate normals with the exception that we used a single time rather than the daily maximum and minimum. The 12 UTC time was chosen to approximate the coldest time of day for the NARR region and therefore yield the greatest margin of safety for aviation. Once the monthly means were computed, we then computed the 30-year mean for each month to obtain our climatology.

For comparison, we also computed a 30-year climatology of the estimated altimeter error using the simple 4% altimeter correction ROT. With this ROT, the indicated altitude is reduced (increased) by 4% for every 10 K the observed temperature is below (above) the SA temperature for the same height. To understand where the 4% ROT error originates, consider the relative error between the indicated and observed true altitude as given in (4).

$$E \equiv \left(\frac{h_{obs}-h_{IA}}{h_{obs}}\right) \quad (4)$$

By applying the hypsometric equation, the relative error in (4) can be directly related to the observed layer-mean temperature (Tobs) and the SA layer-mean temperature (T_{SA}), both measured in Kelvin, as given by (5).

$$E = \left(\frac{\bar{T}_{obs}-\bar{T}_{SA}}{\bar{T}_{obs}}\right), \quad (5)$$

When the observed layer-mean temperature equals 250 K (-23.15 °C), the relative error becomes

$$E = 0.004(\bar{T}_{obs}-\bar{T}_{SA}). \quad (6)$$

In this case, the magnitude of the error will be exactly 4% for a 10 K difference in layer-mean temperatures between the SA and observed atmosphere. The approximation becomes less reliable when the layer-mean temperature is colder than 250 K, at which point the ROT will begin to under-predict the error. For the range of temperatures between 225 K to 275 K the error for a 10 K difference ranges from 4.4% to 3.6%, respectively.

Since the observed layer-mean temperature is unknown, implementing the ROT requires another assumption. As with the SA temperature profile, we again assume the observed temperature profile also decreases linearly with height with a lapse rate, L. In doing so, the ROT can be applied using only the observed temperature at a single altitude, typically the outside air temperature (OAT) at flight altitude. To see this, consider the observed mean temperature ($\bar{T}_{obs}$) of the layer between the observed flight altitude (h_{obs}) and mean sea level pressure (assuming a linear temperature lapse rate) as well as the SA mean temperature (T_{SA}) of the layer between h_{IA} and mean sea level pressure, i.e.

$$\bar{T}_{obs} = T_{obs} - \frac{1}{2}Lh_{obs}, \quad (7)$$

and

$$\bar{T}_{SA} = T_{SA} - \frac{1}{2}Lh_{IA}, \quad (8)$$

For this study, T_{obs} is the NARR temperature for the specified pressure level (i.e., 650 hPa, 750 hPa or 875 hPa), and T_{SA} is the SA temperature at the same pressure level as given by $T_{SA} = To + Lh_{PA}$. In addition, h_{PA} is the pressure altitude of the specified pressure level, which can be obtained from (1) by setting $p_{alstg} = p_o$. Using these relationships, we can relate the difference in the layer-mean temperatures to the difference in the single-level temperatures, T_{obs} and T_{SA}.

$$\bar{T}_{obs} - \bar{T}_{SA} = (T_{obs} - T_{SA}) + \frac{1}{2}L(h_{IA} - h_{obs}). \quad (9)$$

As a further simplification, the second term on the RHS is much smaller than the first term and can therefore be neglected. Even for the extreme case of a 500 m difference between indicated and observed altitude, the term contributes less than 1.6 K to the total temperature difference. This is equivalent to an error of approximately 21 m for a pressure altitude of 3,600 m. Comparatively, considering only the first term on the RHS, a 500 m difference requires a temperature difference of over 38 K. Since the height difference is proportional to the temperature difference, the first term will always dominate and be an order of magnitude larger than the second term, allowing the difference in mean temperatures to be approximated by

$$\bar{T}_{obs} - \bar{T}_{SA} \approx (T_{obs} - T_{SA}). \quad (10)$$

To implement the 4% ROT, we define the approximate corrected D-value, $\widetilde{D}_c$, which is the relative error applied only to the portion of the indicated altitude that lies above the surface, i.e. $(h_{IA} - h_{sfc})$.

$$\widetilde{D}_c = 0.004(T_{obs} - T_{SA})(h_{IA} - h_{sfc}), \quad (11)$$

The reason we only apply the relative error to the layer above the surface is because the calculation of the altimeter setting from station pressure assumes a standard atmospheric lapse rate within the ficticious layer between the surface and mean sea level. Thus, by design, non-standard temperatures have no impact on this layer. Once the aircraft takes flight, however, the assumption of a standard atmospheric lapse rate is no longer valid, and thus a correction is required.

When using the ROT, the ICAO recommends avoiding use for altimeter-setting source temperatures colder than 258.15 K (-15°C). If we assume the altimeter setting source station is located at MSL (worst case), this minimum station temperature equates to observed layer-mean temperatures of 262 K, 266 K, and 270 K for layers of depths 3,600 m, 2,400 m, and 1,200 m, respectively. Thus, in all cases, the 4% rule would slightly over-predicts the necessary correction, giving a greater margin of safety for terrain and obstacle clearance. We should also note when assuming the worst-case scenario of a station at sea level with a linear temperature lapse rate, the recommended minimum surface temperature of 258.15 K results in SA temperatures (T_{SA}) of approximately 250 K (-23°C), 243 K (-31°C) and 235 K (-39°C) at altitudes of 1,200 m, 2,400 m, and 3,600 m MSL, respectively. The 30-year climatology for $\widetilde{D}c$ was computed in a similar fashion to D_c. Lastly, we note that if the terrain elevation exceeds the indicated altitude, such as in mountainous terrain, D_c is set to zero and the data is masked in the plots.

3. PRELIMINARY RESULTS

To quantify the bounds of the maximum altimeter error a GA pilot could reasonably expect, we plotted the absolute maxima and minima for each month the entire period of record (POR) for both methods of calculation as shown in Figs. 1-3. While both positive and negative values are shown, the negative values errors are more signifcant to flight safety because they imply the pilot is lower than indicated by the altimeter. This puts the pilot at significant risk of CFIT. In examining Figs. 1-3 we see the ROT overpredicts the maximum negative error (larger margin of safety) at the lower flight levels and tends to underpredict at higher altitudes. This does not imply the entire domain follows this same pattern, as well be seen next.

Using the same figures, we also see the altitude error is greatest in February, so for comparison we plotted maps of the 30-yr mean altimeter error for the month of February at three different flight atlitudes (4 kft, 8 kft, and 12 kft) for both the corrected D-value and the ROT (Figs. 4-6, panels a and b, respectively). Not surpisingly the maps show the greatest negative error over the interior portions of the continent. The overall pattern within the maps is similar between the two methods of calculation, demonstrating the utility of the ROT. Figures 4c-6c show the difference between the two methods of calculation (D_c – ROT) for the three different flight levels. In all three cases, the ROT tends to overpredict the error compared to the corrected D-value method over the interior portion of the continent where CFIT would be most likely. The errors are generally less than 10 m in magnitude at a flight level of 4 kft and less than 70 m in magnitude at a flight level of 12 kft. Thus, the ROT works remarkably well climatologially, producing a realtive error of <1% compared to the D_c method, and the error tends to add an additional margin of safety.

4. CONCLUDING REMARKS

It's important to note that refer to both the corrected D-value and ROT calculated error values as "estimated" altimeter error because the true error is unknown. While the NAAR height calculations make use higher vertical resolution temperature profiles, which should lead to more accurate height values, the number of layers is still finite. Thus, there will always be some amount of uncertainty, which is difficult to quantify without actual height measurements. Despite these limitations, the goal is to provide a basic climatology of altimeter error using the most representative data to aid GA pilot education and training.

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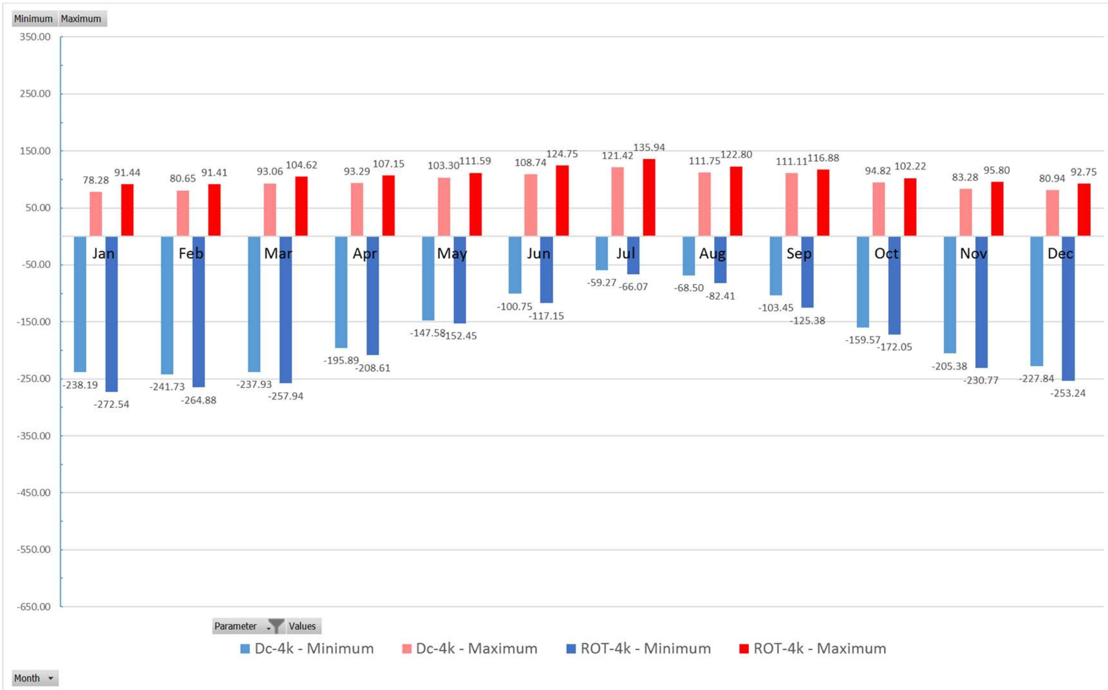

Figure 1. 30-year maximum (red) and minimum (blue) altimeter error at approximately 4 kft for entire model domain, calculated using both the corrected D-value and Rule of Thumb.

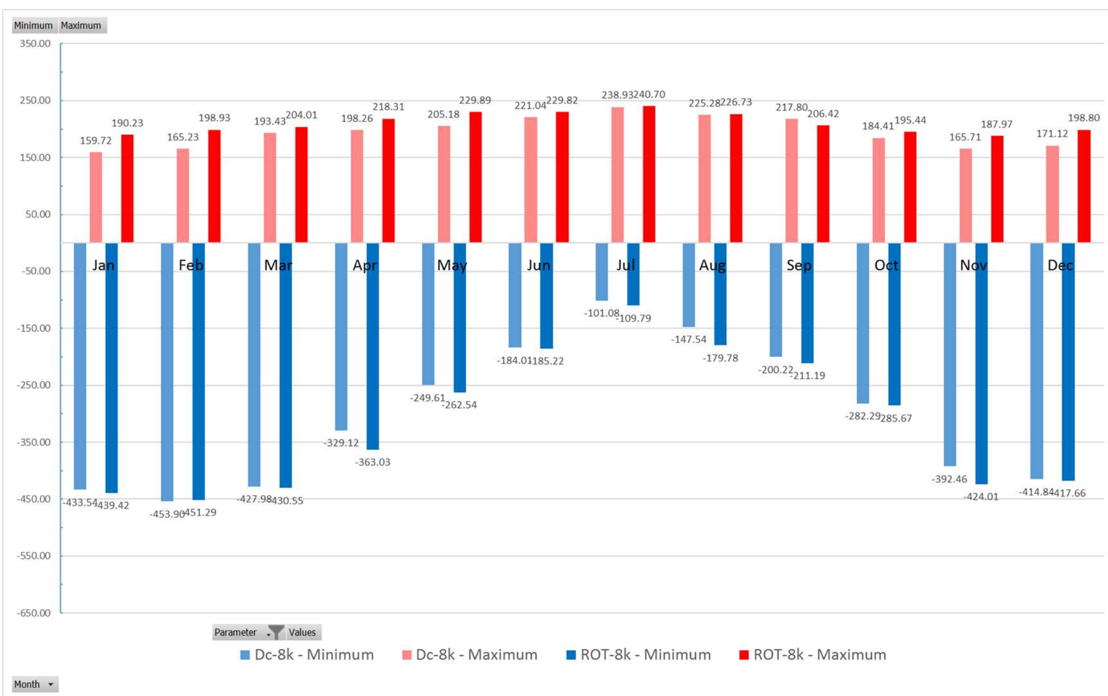

Figure 2. Same as Fig. 1 but for 8 kft.

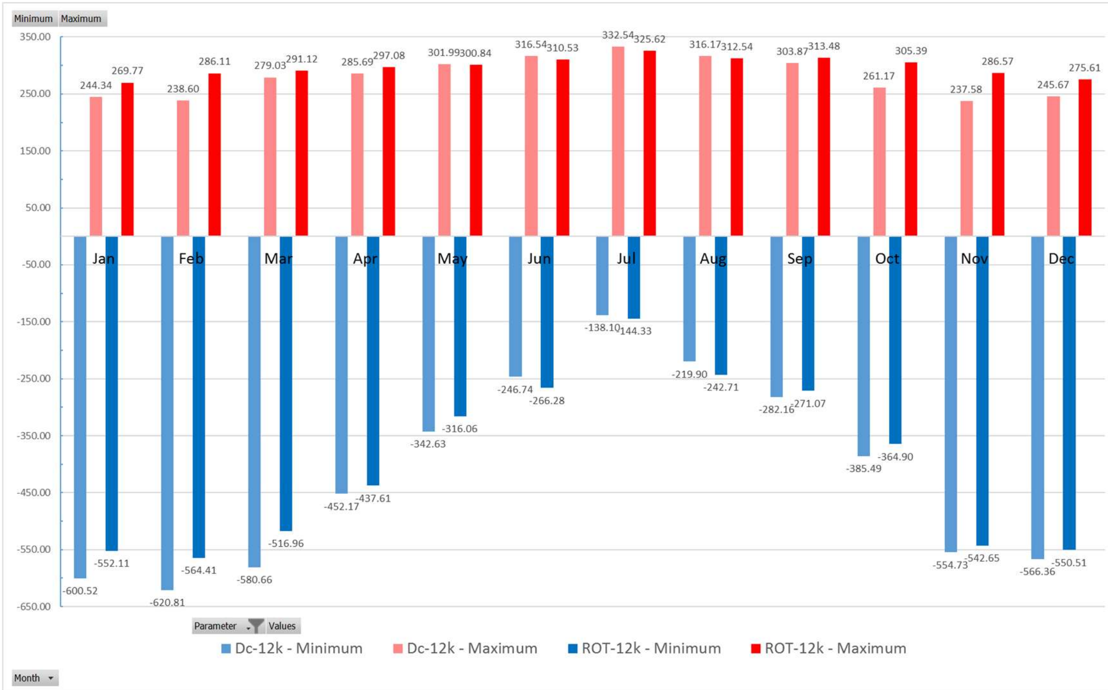

Figure 3. Same as Fig. 1 but at 12 kft.

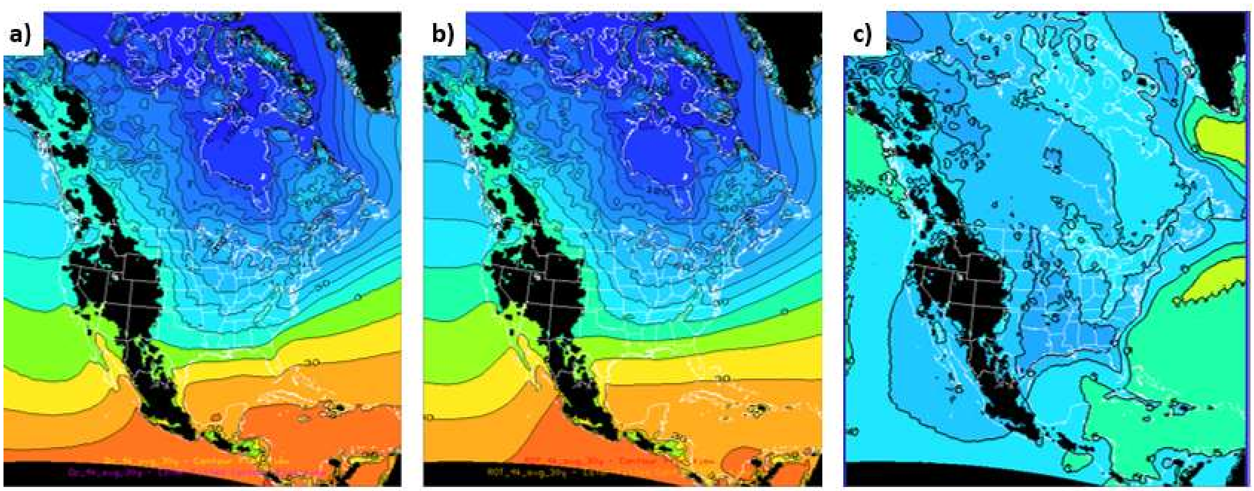

Figure 4. Calculation of altimeter error (m) at an approximate flight altitude of 4 kft using the corrected D-value (panel a) and the Rule of Thumb (panel b), while panel c shows the difference between the two. Negative (positive) values in panels a and c imply the aircraft is lower (higher) than indicated.

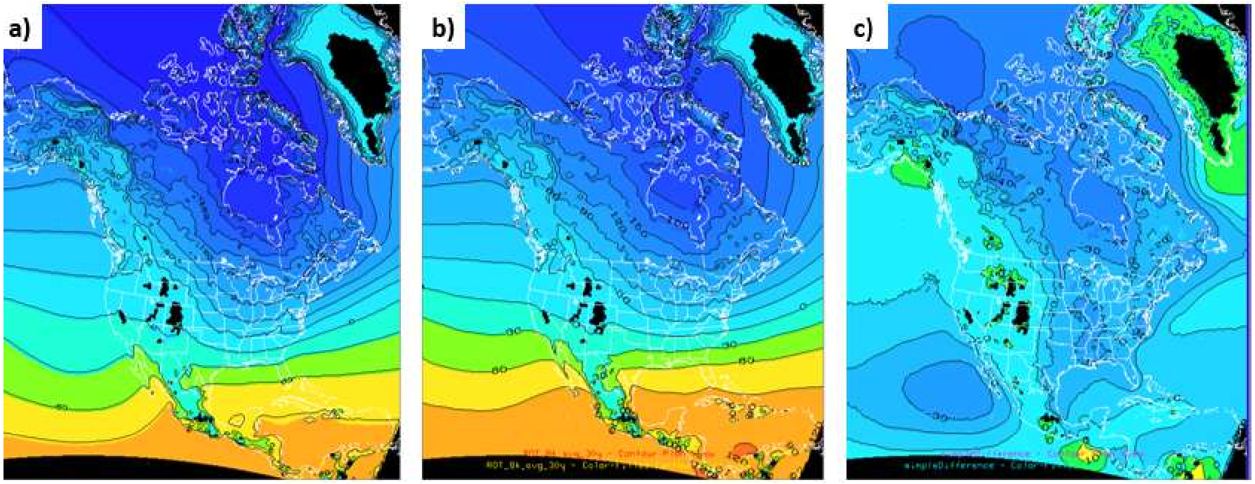

Figure 5. Same as Fig. 4 but for 8 kft.

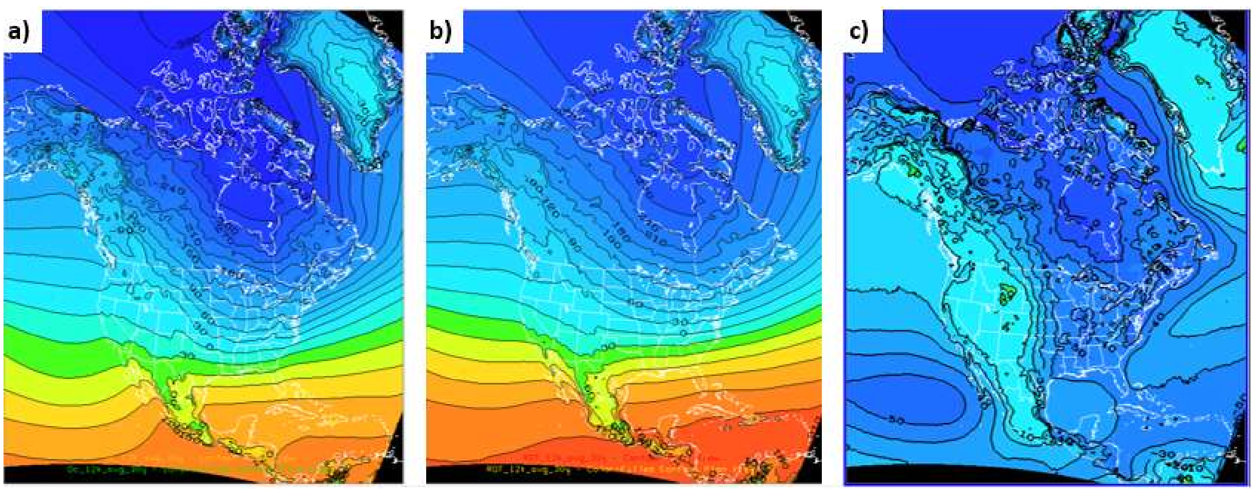

Figure 6. Same as Fig. 4 but for 12 kft