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A STUDY OF THE ARMY HELICOPTER DESIGN HOVER CRITERION USING TEMPERATURE AND PRESSURE ALTITUDE

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Ambient temperature and altitude are used to determine design points for helicopters. In this paper, pressure altitude is used to determine the probabilities of Hover Out of Ground Effect (HOGE) capability rather than geophysical elevation. This strategy is applied to the state of Colorado. First this paper displays variations between geophysical elevation and pressure altitude. Then it shows that substituting pressure altitude for elevation leads to more conservative estimates for the HOGE capability. It is concluded that modern computational resources can be used to tailor helicopter design points to expected areas of operations rather than specifying a single generic temperature /pressure altitude combination.

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HOGE: Hover Out of Ground Effect; Pressure Altitude, Design Points, ACMES: Advanced Climate Modeling and Environmental Simulations

1. Abstract

Ambient temperature and altitude are used to determine design points for helicopters. In this paper, pressure altitude is used to determine the probabilities of Hover Out of Ground Effect (HOGE) capability rather than geophysical elevation. This strategy is applied to the state of Colorado. First this paper displays variations between geophysical elevation and pressure altitude. Then it shows that substituting pressure altitude for elevation leads to more conservative estimates for the HOGE capability. It is concluded that modern computational resources can be used to tailor helicopter design points to expected areas of operations rather than specifying a single generic temperature /pressure altitude combination.

2. Design Point

The two most significant atmospheric conditions affecting rotorcraft performance are pressure and temperature [Stepniewski and Keys, 1984]. The density of air is proportional to pressure and inversely proportional to temperature. Compressibility effects are inversely proportional to the square root of the temperature of ambient air. Both compressibility and air density determine the amount of work that a rotor has to accomplish in order to propel a rotorcraft. Thus, the choice of a unique pressure and temperature design point for a rotorcraft ultimately decides its capability.

In the mid-1950s the United States Army promulgated a requirement that future Army helicopters should be capable of hover out of ground effect at a pressure altitude of 6,000 feet and an ambient temperature of 95 degrees Fahrenheit (6K/95). This combination of temperature and pressure altitude was judged as being representative of limiting atmospheric conditions in areas of possible future military operations.

Over the next couple of decades, the 6K/95 standard was criticized as being overly conservative (Dodd, 1960), and several helicopter acquisition programs downgraded the temperature/pressure altitude HOGE requirement to 4,000 feet pressure altitude and 95 degrees Fahrenheit (4K/95), the Standard Hot Day [Ferrell, Frederickson and Kishi, 1974]. This 4K/95 HOGE design point also became controversial due to its neglect of diurnal temperature variation and aircraft performance losses due to weight gain and mechanical degradation. In 1968, the United States Army Combat Developments Command (USACDC) conducted another study recommending a 500 feet per minute vertical rate of climb (VROC) capability with 5 percent power margin at 4,000 feet pressure altitude and 95 degrees Fahrenheit ambient temperature design point [Lavallee and Sing, 1965]. However, this recommendation did not account for diurnal temperature variation.

In 1975, the Advanced Scout Helicopter Special Study Group reexamined the design point requirement. They recommended increasing the design point pressure altitude requirement to 6,000 feet while maintaining the 500 feet per minute VROC with 5 percent power margin capability to account for realistic helicopter operating conditions. However, the design point remained at 4K/95 for development and modernization of rotorcraft for the next three decades. Recently, there has been renewed interest in increasing the design point to 6K/95 due to experience gained in military operations in Southwest Asia.

A previous paper estimated hover probabilities based on elevation and mean minimum, average and maximum temperatures [Horacek and Calvert, 2005]. In this paper, mean maximum pressure altitude and mean minimum, average and maximum temperatures were used to estimate probabilities of hover. Probabilities for the worst case, mean maximum pressure altitude and mean maximum temperature yield much lower probability of hover than elevation and mean maximum temperature.

2.1 Hypothesis

The atmospheric pressure for a given region may be correlated to a pressure altitude, allowing rotorcraft design to be guided by the intended area of operation.

3. Pressure Altitude

It is known from basic fluid mechanics that the hydrostatic pressure in a gas decreases with increasing elevation. The temperature variation with altitude has been standardized by analysis of data gathered from atmospheric studies. Using the hydrostatic behavior of air, and the temperature variation with altitude, it is possible to define atmospheric pressure by the corresponding pressure altitude according to the standardized atmosphere model. Assuming a linear relationship between temperature at altitude and sea-level temperature:

$$T = T_0 - Bz \tag{1}$$

the relationship between pressure and altitude may be written as

$$z = \frac{T_0}{B}\left[1-\left(\frac{P}{P_0}\right)^{\frac{RB}{g}}\right] \tag{2}$$

where z is altitude, T is temperature, B is the atmospheric lapse rate, P is pressure, R is the gas constant for air, g is gravitational acceleration, and the subscript 0 denotes sea-level standard atmospheric conditions.

There are several physical factors that can cause pressure altitude to differ from geophysical elevation for a given location. The first is that temperature lapse rate B at the location can vary from the Standard Atmosphere Model, as would occur if an inversion layer is present [Griffen, 1994]. It is also possible that the intercept constant T_0 in equations (1) and (2) would not be equivalent to the sea-level standard temperature. If the air is colder, the pressure altitude will be higher than the geophysical elevation. If the air is warmer the pressure altitude will be lower than the geophysical elevation. [Hess, 1959] It is also possible for the P_0 term in equation (2) to vary from the sea-level standard. This condition occurs due to the presence of meteorological high and low pressure systems [Hess, 1959]. A high pressure system would reduce the effective pressure altitude while a low pressure system would increase it.

4. Analysis

4.1 Climate Model

The U.S. Air Force Combat Climatology Center is home to the Advanced Climate Modeling and Environmental Simulations (ACMES) that models the atmospheric conditions anywhere in the world. The present model estimates temperatures and elevations on a 40 kilometer grid then interpolates the temperature data to a 10 kilometer grid, the 10 kilometer elevation is determined from 1 kilometer grid accuracy of satellite data. Tables of monthly mean maximum, mean average, and mean minimum temperatures and pressure altitudes with elevations for the 10 kilometer grid are produced by this computer program.

4.2 Discussion

Figure 1 shows a graph of cumulative probability of elevation occurrence (CPPA) as a function of probability of mean maximum pressure altitude occurrence (CPA) for Colorado. Figure 2 shows a graph of cumulative probability of elevation occurrence (CPPA) as a function of probability of mean minimum pressure altitude occurrence (CPA) for Colorado. As may be noted from the figures, mean pressure altitude does vary considerably for a given elevation, both for the mean maximum graphs and the mean minimum graphs, as well as between the two graphs.

Figures 3 and 4 are maps showing variations between the geophysical elevation and mean maximum pressure altitude for the months of January and August. Contrary to what might be expected, the largest differences are seen in the month of January, which are on the order of 1,000 feet being indicated by the reddish colors. The differences do not occur in the more mountainous regions of the state, but rather in the eastern plains. The August map show that most of the differences are between 500 – 700 feet, with the greatest differences occurring in the non-mountainous regions.

Figures 5 shows a graph of probability of elevation occurrence as a function of probability of mean maximum temperature occurrence. Figure 6 shows a graph of mean maximum pressure altitude occurrence as a function of mean maximum temperature occurrence. As may be seen from the figures, the use of mean maximum pressure altitude instead of elevation tends to shift the mean maximum temperature isopleths to the left. This shift is due to the change in pressure altitude from the variation in mean maximum temperature away from the standard atmosphere model.

The blue line running across Figures 5 and 6 demarcates the boundary of HOGE capability for a generic helicopter design representative of those produced in the latter half of the last century. On these graphs, HOGE is possible in the region below the curve. As may been seen from the graphs, the HOGE boundary on Figure 6 encloses a smaller area than the curve on Figure 5. The variation in mean maximum pressure altitude from geophysical elevation limits the HOGE capability of the representative helicopter significantly beyond what would be expected if only geophysical elevation was used for the design point.

Figures 5 and 6 give a consolidated view of the generic helicopter view for a given region, whether it be state, country, or continent. What is missing from these graphs, however, is the ability to determine exactly what areas of the region under consideration are HOGE limited. By using the output from the ACMES model directly with the HOGE capability boundaries shown in Figures 5 and 6, it is possible to create maps of the region of interest that reveal the generic helicopter's HOGE capability as a function of month.

Figure 7 shows the generic helicopter HOGE capability for Colorado during July, based upon mean temperature distribution and geophysical elevation. The green areas represent mean maximum temperature and elevation combinations that fall below the blue curves on Figures 5 and 6. The red areas represent mean minimum temperature and elevation combinations that fall above the blue curves in Figures 5 and 6. The yellow areas represent points where the mean minimum temperature and elevation combination falls below the blue curve, but the mean maximum temperature and elevation combination falls above the blue curves on Figures 5 and 6 above.

To summarize the last paragraph, the green areas represent mean maximum temperature and elevation combinations where HOGE is statistically likely during all times of the month. The red areas represent where HOGE is statistically unlikely during all times of the month. The yellow represents areas where HOGE is statistically likely during some times of the month, but not all times of the month.

The probabilities given at the top of Figure 7 are calculated via a Monte Carlo-like process. The Maximum probability of HOGE is calculated by counting up the total number of green and yellow points and then dividing the total number of points in the graph. The Minimum probability of HOGE is determined by counting the number of green points and then dividing by the total number of points on the graph. (For completeness, the Average probability of HOGE is calculated by counting the number of sample points where the mean average temperature and elevation combination lies below the curve shown on Figures 5 and 6, then dividing by the total number of sample points.)

Figure 8 is a variation of Figure 7, where elevation was replaced with mean maximum pressure altitude for the purpose of determining probability of HOGE. The coloring scheme remains the same. It may be observed that the yellow is greatly expanded over that seen in Figure 7, mostly at the expense of the green area. The red area is slightly consolidated over the red area seen in Figure 7. As was seen from Figure 5 and 6, the use of mean maximum pressure altitude reduces the total probability of HOGE for a given region. However, the maps show where the actual reduction in HOGE capability occurs.

From the previous discussion it is possible to see that there are several possibilities for defining HOGE capability for a given region. Figure 9 is a plot of the various mean temperature and mean pressure altitude combinations, along with the three mean temperature and geophysical elevation combinations, for monthly HOGE capability for Colorado. The mean minimum temperature and mean minimum pressure altitude combination gives a HOGE capability of almost 100 percent for the entire year, while the mean maximum temperature and mean maximum pressure altitude combination gives a HOGE capability approaching 0 percent for the hottest months of the year. The other combinations group between these two extremes.

Ultimately, the design point for a helicopter has to be determined by the user of the helicopter. If maximum HOGE capability is desired, regardless of cost, the mean maximum temperature and mean maximum pressure altitude combination provides the worst-case scenario that can be used in evaluating designs. The other levels define the available trade space for performance. The significant point is that modern computational resources give the user the ability to understand the practical limitations inherent for a given design, rather than using a "one number fits all" approach.

5. Conclusion

1. Variation in pressure altitude away from geophysical altitude can significantly impact helicopter performance.
2. The power of modern computational resources can allow users to understand geophysical limitations of proposed helicopter designs.

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Biographies

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Currently serves as an Operations Research Analyst for the U.S. Army Aviation and Missile Command. Uses U.S. Air Force Climatology Data to determine Hover Capability and where Helicopters Hover. Has a Bachelor of Science Degree in Applied Mathematics with an Area of Concentration in Physics from the University of Nebraska at Omaha in December of 1986 with some graduate work at Washington University in St. Louis Missouri and University of Alabama at Huntsville. Currently is a member of the American Physics Society. In October of 1992 received a Special Act Award and the Civilian Service Medal for a paper on the Hurst Ratio.

Mark E. Calvert

Mark Calvert is an aerospace engineer on the Rotors and Aerodynamics Team of the Aeromechanics Division in the Aviation Engineering Directorate of the U. S. Army Aviation and Missile Research, Development and Engineering Center at Redstone Arsenal in Huntsville, Alabama. He received a Doctorate of Philosophy in Mechanical Engineering from the University of Alabama in Tuscaloosa, Alabama in 2002.

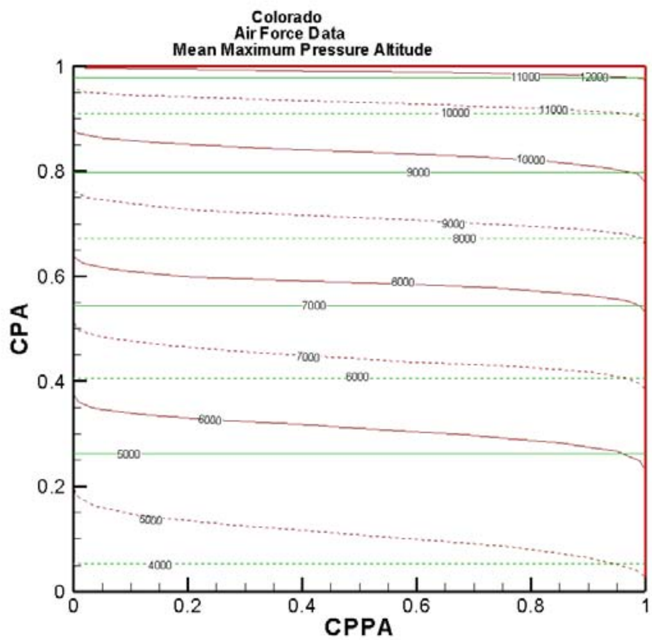

Figure 1. Cumulative probability of elevation vs. cumulative probability of mean maximum pressure altitude for Colorado.

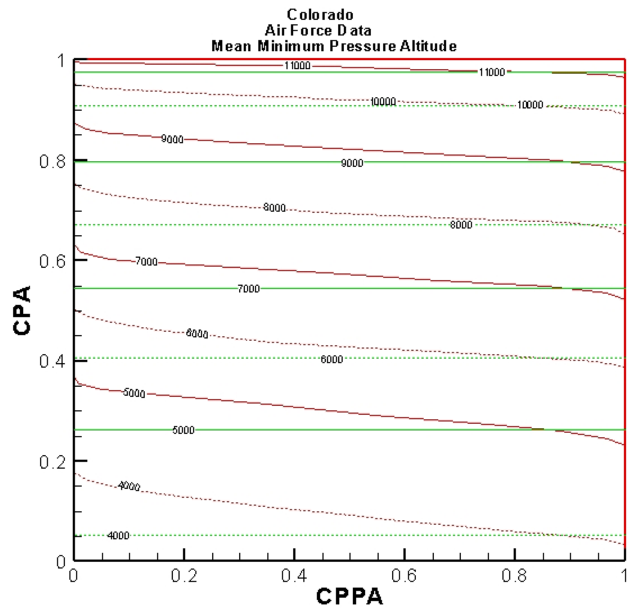

Figure 2. Cumulative probability of elevation vs. cumulative probability of mean minimum pressure altitude for Colorado.

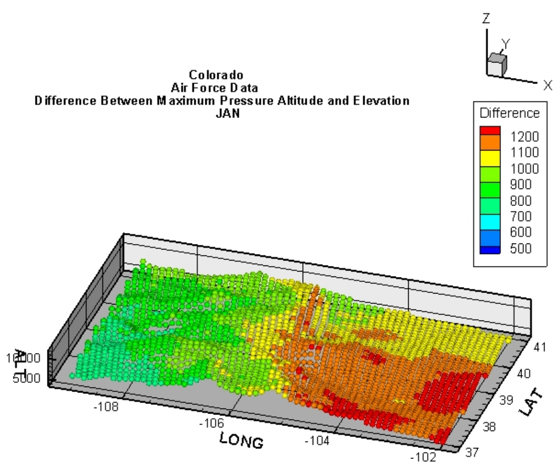

Figure 3. Difference between mean maximum pressure altitude and geophysical elevation for January.

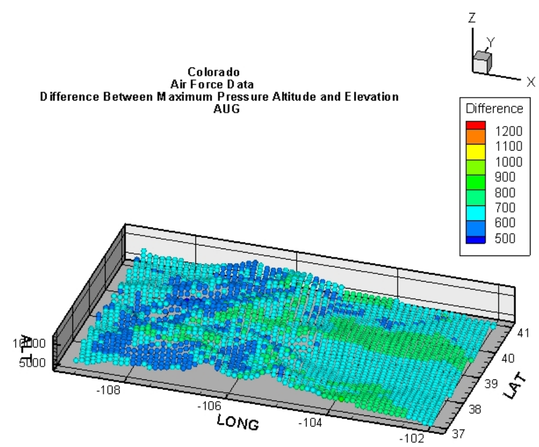

Figure 4. Difference between mean maximum pressure altitude and geophysical elevation for August.

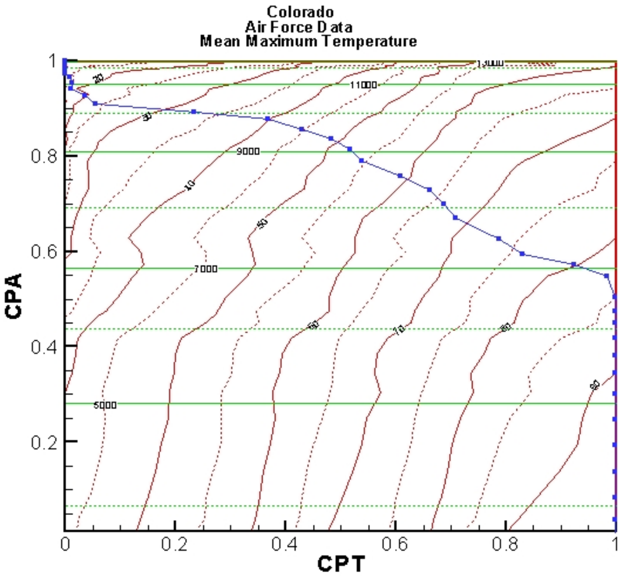

Figure 5. Probability of elevation vs. probability of mean maximum temperature occurrence for Colorado.

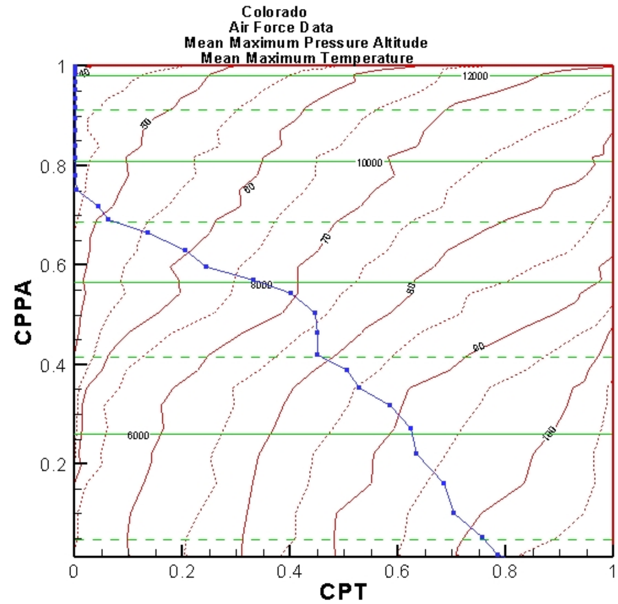

Figure 6. Probability of mean maximum pressure altitude occurrence vs. probability of mean maximum temperature occurrence for Colorado.

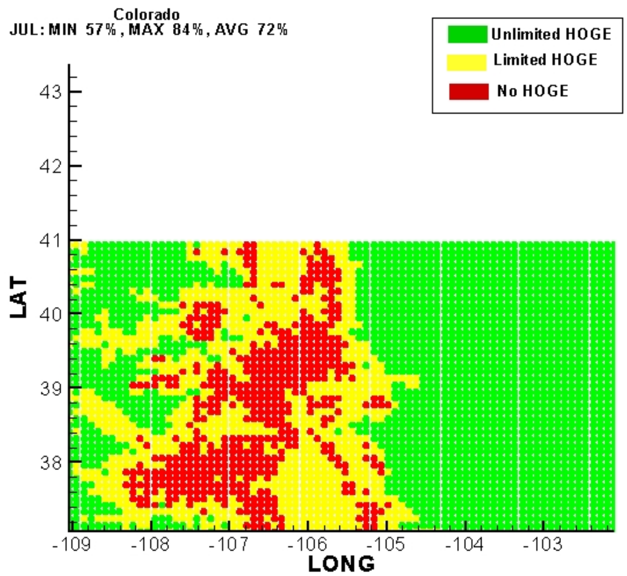

Figure 7. Map of HOGE for the generic helicopter during July in Colorado, based upon elevation.

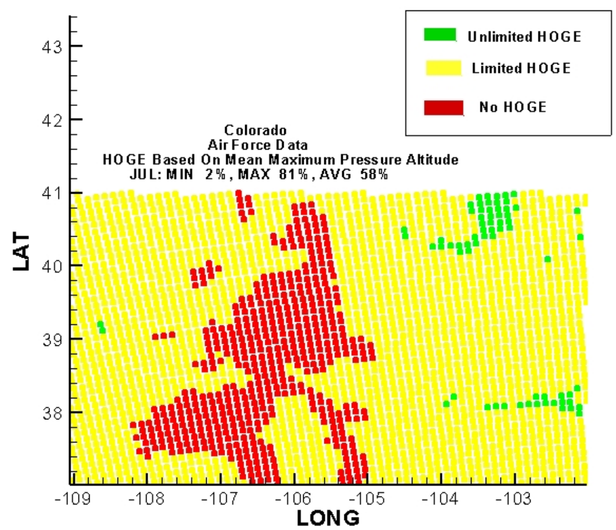

Figure 8. Map of HOGE for the generic helicopter during July in Colorado, based upon mean maximum pressure altitude.

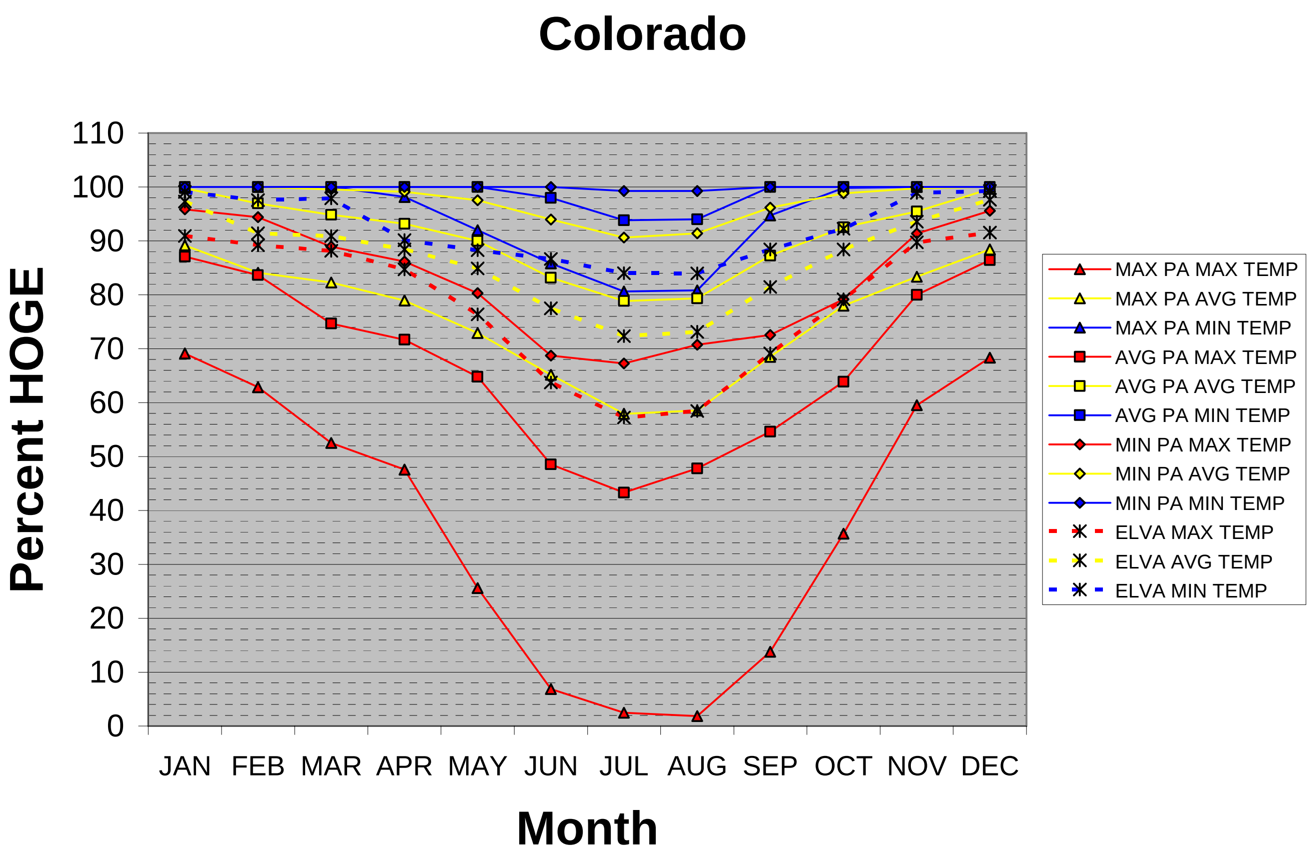

Figure 9. Monthly probability of HOGE capability for Colorado.

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