ORDINATION OF NORTH AMERIOCAN VEGETATION USING A THERMODYNAMIC DIAGRAM

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1. INTRODUCTION

Coordinate systems, which have axes that are meteorological or climatological variables, have long been used to ordinate the geography of vegetation and to quantify and illustrate the connections between climate and vegetation. The earliest is that of Ball (1910). Ball's climograph used mean monthly precipitation as the x-axis and mean monthly temperature as the y-axis. Plots of the 12 monthly values resulted in polygons that characterized the climate of a site.

Thornthwaite's (1948) climograph used a precipitation-evaporation (x-axis) and a thermal efficiency index (y-axis). Each axis was the sum of 12 monthly values. Clearly, Thornthwaite attempted to enrich the information content of his climograph by including both rainwater input and evaporative losses on the one hand and a measure of the accumulated "heat" by the summing growth supporting temperatures above 0 C. Within the space of this diagram Thornthwaite charted the major vegetation biomes.

Oliver's climograph of 1968, like Ball's of 1910 used mean monthly precipitation as the x-axis and mean monthly temperature as the y-axis, however, in order to provide a more useful graphical space, Oliver applied non-linear transformations to the scales on each axis. Temperature was scaled according to the fourth power of temperature in degrees Kelvin (plotted in Fahrenheit) and precipitation was scaled as the square root of precipitation (in inches).

The climatological data used in the analyses presented in this paper (average daily monthly temperature and average daily dewpoint temperatures) were taken from the World Wide Airfield Climatological Summaries. Data on the distribution vegetation types for each airfield location were extracted from Kuckler's map of potential vegetation of the United States.

2. THERMODYNAMIC NOMOGRAMS

These climographs differ from the thermodynamic nomograms or diagrams widely used in meteorology in an important way. In thermodynamic diagrams, the x-axis (usually temperature) and y-axis (usually pressure) are related through a system of fundamental equations to other thermodynamic variables which are presented on the diagram as a family of curves. For example, the Stuve thermodynamic diagram includes temperature (x-axis) and pressure or pressure altitude (y-axis), and on the pressure and temperature gaphical space additional axes arecharted as isopleths of potential temperature, equivalent potential temperature and saturation mixing ratio. Any two of these 5 variables defines a particular locus on the chart.

As a general rule, thermodynamics diagrams have not been used for climatological purposes nor have they been used as a basis for the ordination of vegetation. In most climate based ordinations of vegetation the focus is on rainfall and temperature. In this paper vegetation is conceptualized as thermodynamic "wicks". These wicks are under the greatest evaporative stress at the time of maximum daily temperature. This evaporative flux from the wick (vegetation) to the atmosphere is also related to the actual vapor pressure of the air and the vapor pressure deficit at the time of maximum air temperature. Accordingly, the thermodynamic diagram designed here consists of monthly average daily maximum temperature on the x-axis and atmospheric vapor pressure on the y-axis. Isopleths of relative humidity, vapor pressure deficit and the maximum height of the mixed layer are provided on the thermodynamic diagram as families of curves.

The saturation vapor pressure at the time of daily maximum temperature may be calculated from the Clausius-Clapeyron equation or taken from published tables of the solution to the equation. In Figure 1 the line of saturated vapor pressures (100% relative humidity) as function of temperature is plotted. Also plotted are isopleths of relative humidity in 10% increments. This simple nomogram permits the estimation of vapor pressure if the relative humidity at the time of maximum temperatures is known. In a more general sense given relative humidity and contemporary temperature, actual vapor pressure of the atmosphere can be estimated.

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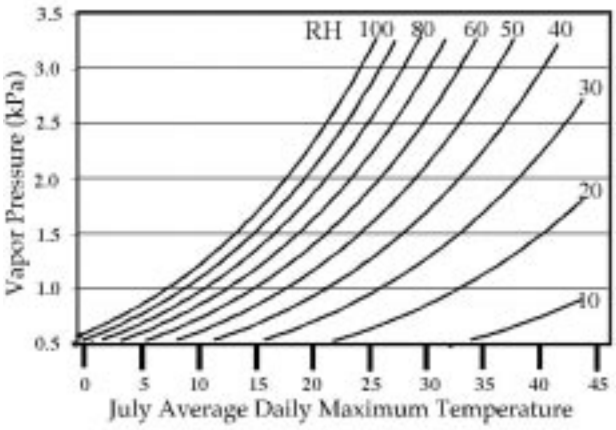

Figure 1. Relative humidity (%) as a function of temperature and vapor pressure.

At every point in the temperature/vapor pressure space there is a unique value of the difference between the saturation vapor pressure and the actual vapor pressure, i.e. the vapor pressure deficit (VPD). In figure 2 the family of isopleths are lines of constant VPD. Because VPD is a calculated rather than a measured quantity, the thermodynamic diagrams may be used to estimate VPD from temperature and vapor pressure or from dewpoint temperature.

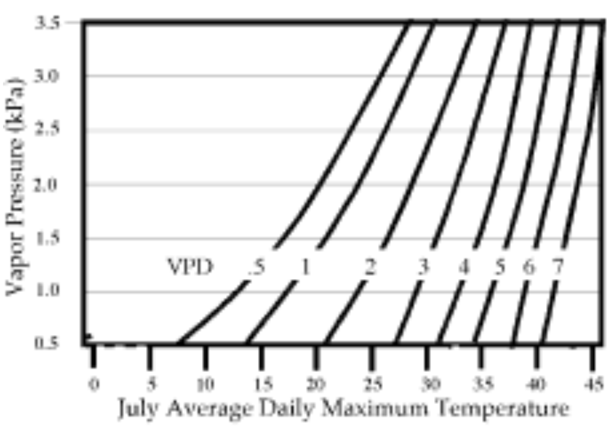

Figure 2. Vapor pressure deficit (kPa) as a function of vapor pressure and temperature.

The dry mixed layer of the atmosphere reaches its maximum thickness, maximum mixing depth (MMD), at the time of maximum daily temperature. If the maximum temperature and vapor pressure or dewpoint temperature is known, the thickness of this dry mixed layer can be calculated using the adiabatic lapse rate (1 C / 100 m). In Figure 3 a family of curves of constant maximum mixing depth (in kilometers) is shown. As a general rule the height of the mixed layer at the time of daily maximum temperature is within a few tens of meters of base of the planetary boundary layer clouds. If these clouds subsequently develop into cumulus convective clouds and thunderstorms, the base of these clouds is at the MMD as well. The air between the surface and this level is mixed dry adiabatically and the rate of temperature fall with altitude in this layer is nearly 1 C / 100 m. Above this layer condensation and cloud formation begins. This altitude is indicated by the elevation of MMD. At the top of the dry mixed layer there is usually a small temperature inversion that is often visible to the eye as an accumulation of smog like particles.

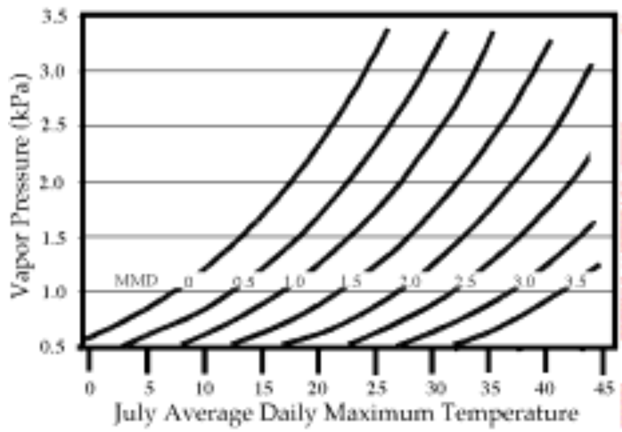

Figure 3. Maximum mixing depth (km) as a function of temperature and vapor pressure.

3. THE THERMODYNAMIC DIAGRAM

The thermodynamic diagram used here is the assemblage of the isopleths of relative humidity (RH), vapor pressure deficit (VPD) and maximum mixing depths (MMD). The families of lines shown in figures 1, 2 and 3 are presented in a single diagram in Figure 4. .For every point on this thermodynamic diagram the values of seven variables are specified:: vapor pressure, average daily maximum temperature, relative humidity, dewpoint temperature, vapor pressure deficit, maximum mixing depth and the average saturation vapor pressure of the air.. If daily maximum temperature and one of the atmospheric moisture variables is known, then these other variables may be estimated from the families of isopleths on the tthermodynamic diagram.. By way of example, if the daily maximum temperature is 30 C and the dewpoint temperature is 20 C, the relative humidity of the surface air should be 65%, the actual vapor pressure of that air 2.35 kPa and the vapor pressure deficite amounts to 1.9 kPa.. The saturation vapor pressure of the air may be estimated by extending a vertical line from the average daily maximum temperature to the point where it intersects the 100% relative humidity curve. The value on the y-axis for this level then is the satturatiion vapor pressure. If the actual vapor pressure is specified or determined from the diagram, the dew point temperature is determined by dropping a line from the intersection of the 100% relative humidity contour and the actual vapor pressure level to the x-axis and read the temperature there as the dewpoint temperature. While the nomogram can be used in this way as a thermodynamic calculator, the purpose here is to use the diagram to ordinate the biogeography of vegetation in thermodynamic space.

4. VEGETTION ORDINATION IN THERMODYNAMIC SPACE

In the vegetation ordination performed here, the potential natural vegetation (Kuchler, 1964), in the local regions of North American, was matched with airports and airfields data: the July average daily maximum temperatures and the July average dewpoint temperatures. Kuchler identified 123 vegetation types in the continental US, Alaska and Hawaii. Many of these vegetation types have very limited geographic extents and thus contain few airfields for which airfield climate data is available. In the present study I restricted the analysis to those vegetation types that are geographiically extensive. For each major vegetation type, points were plotted on the thermodynamic diagram (Figure 5) and clusters of points were outlined with ellipses.

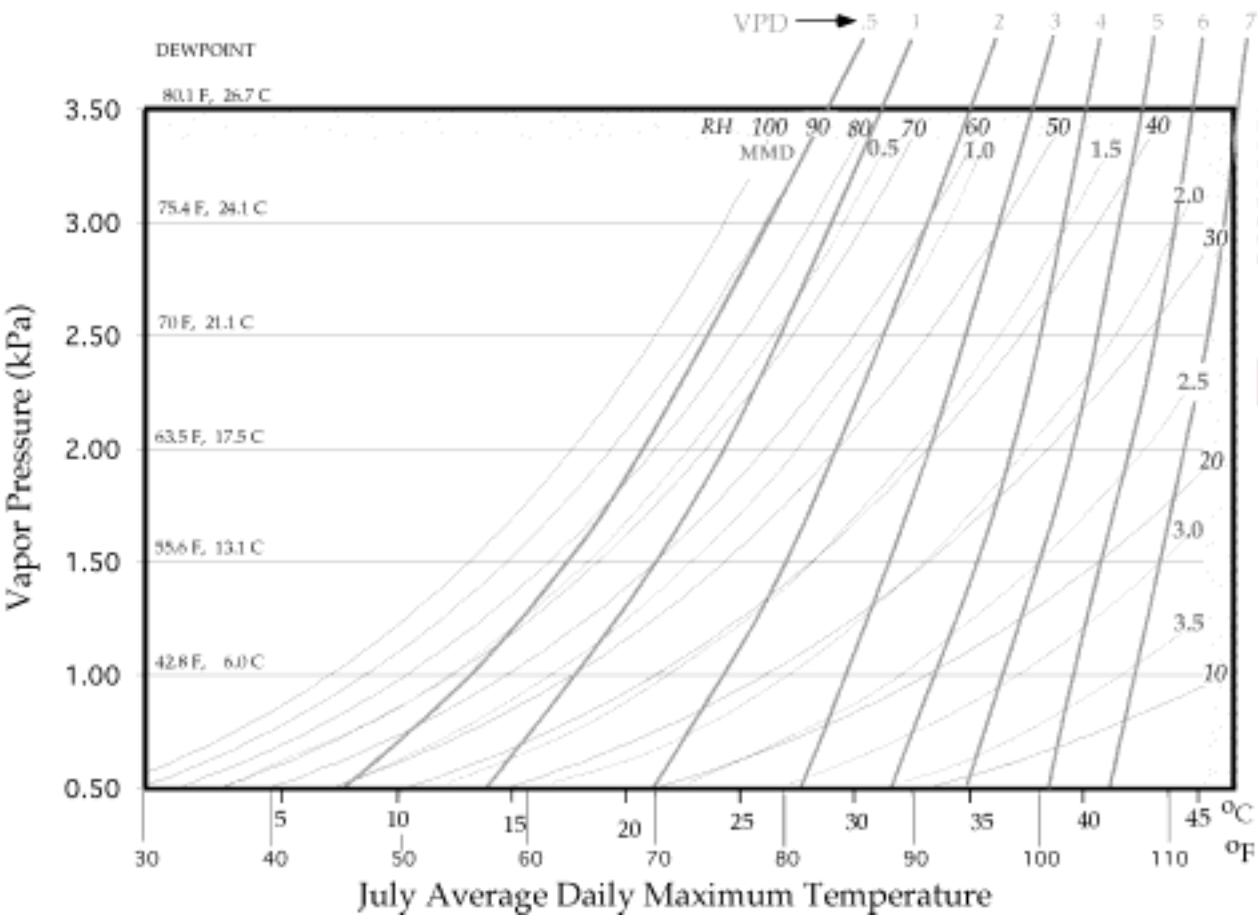

Figure 4. This thermodynamic diagram is a composite of Figures 1, 2 and 3. Both a centigrade and a Fahrenheit scale is provided on the x-axis. The dewpoint temperatures in Centigrade and Fahrenheit are provided for the commensurate saturation vapor pressures. Relative humidity is given in %, vapor pressure deficits in kPa, and maximum mixing depth in kilometers.

Three of Kuchler's vegetation types, oak-hickory-pine forests, northern hardwood forests, and a sagebrush steppes, illustrate the ordination process. Airfields in the region of these vegetation types are numerous and permit the definition of clusters of points on the thermodynamic diagram around which ellipses are drawn. The northern hardwood forest is found in cooler but less humid climates than the oak-hickory-pine forests to the south. The centroid of the northern hardwood forests cluster ellipse indicates a July average daily maximum temperature of about 27 C. This implies an average vapor pressure of the air of about 1.7 kPa which in turn implies an average dewpoint temperature of 15C. In contrast the same assessments for the oak-birch-pine forest region has an average maximum temperature of 32 C, a vapor pressure of 2.3 kPa which implies a dewpoint temperature of about 20 C. The average relative humidity at the time of maximum temperature is 50% for both forests. In contrast the sagebrush steppe grassland has an average relative humidity of only 20%, average maximum temperature in July of 32 C, and an average vapor pressure of 0.9 kPa The average daily July dewpoint temperature was about 5 C.

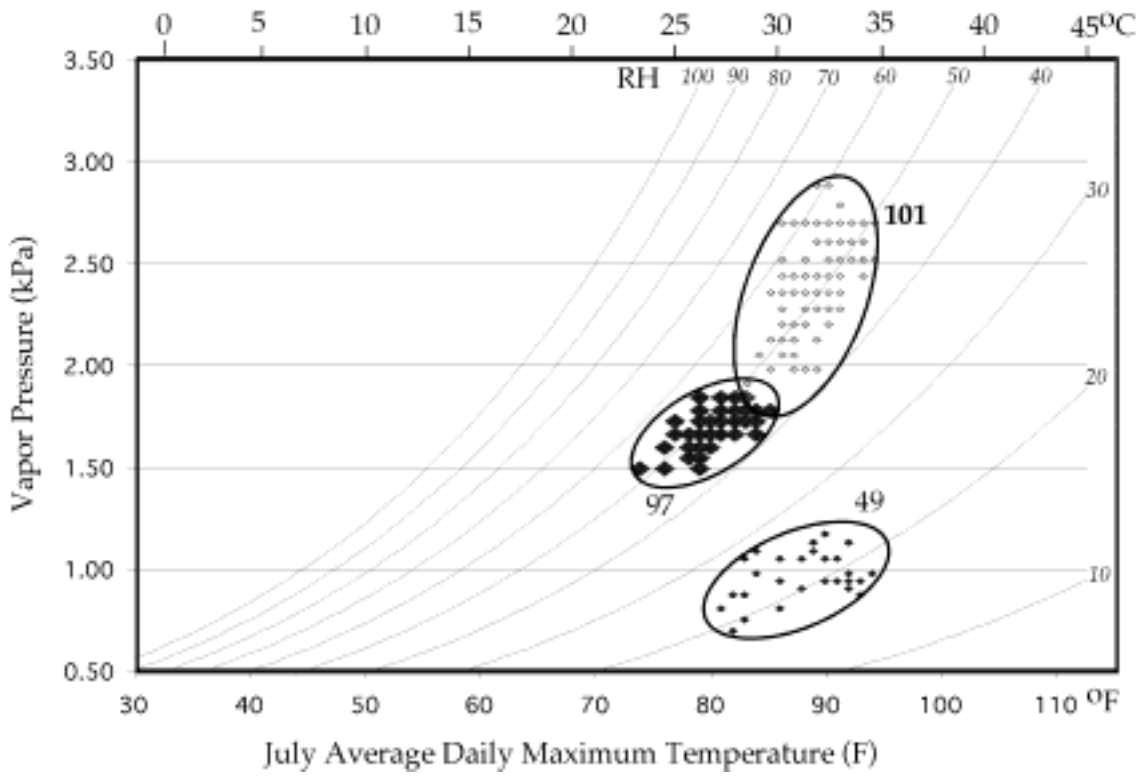

Figure 5. Oak-Hickory-Pine Forests (101), Northern Hardwood Forests (97) and Sagebrush Steppes (49) projected in the space of the thermodynamic diagram. Each point represents one or more airfield weather stations within the specified vegetation type. Ellipses were fitted to the clusters of points for the three vegetation types.

In Figure 6, 15 regionally extensive forest vegetation types are plotted on a single thermodynamic diagram. Taken as a collective, the centroids of these ellipses trace out a curved path with boreal forests in the lower left and tropical forests in the upper center part of the thermodynamic diagram. As a general rule, North American forests do not occur where VPD exceeds 3 kPa and where average July relative humidities fall below 40%. The thickness of the dry mixed layer over these forests range from 0.5 km in the northern boreal regions to about 1.5 km in the low latitudes. In addition, forests are not found in regions where July average daily maximum temperatures exceed 33 or 34 C. In Figure 7 the trace of the centroids of all the ellipses for 8 broad vegetation life-form classes is presented. Clearly the thermodynamic approach to vegetation ordination in climate space provides a unique perspective.

4. REFERENCES

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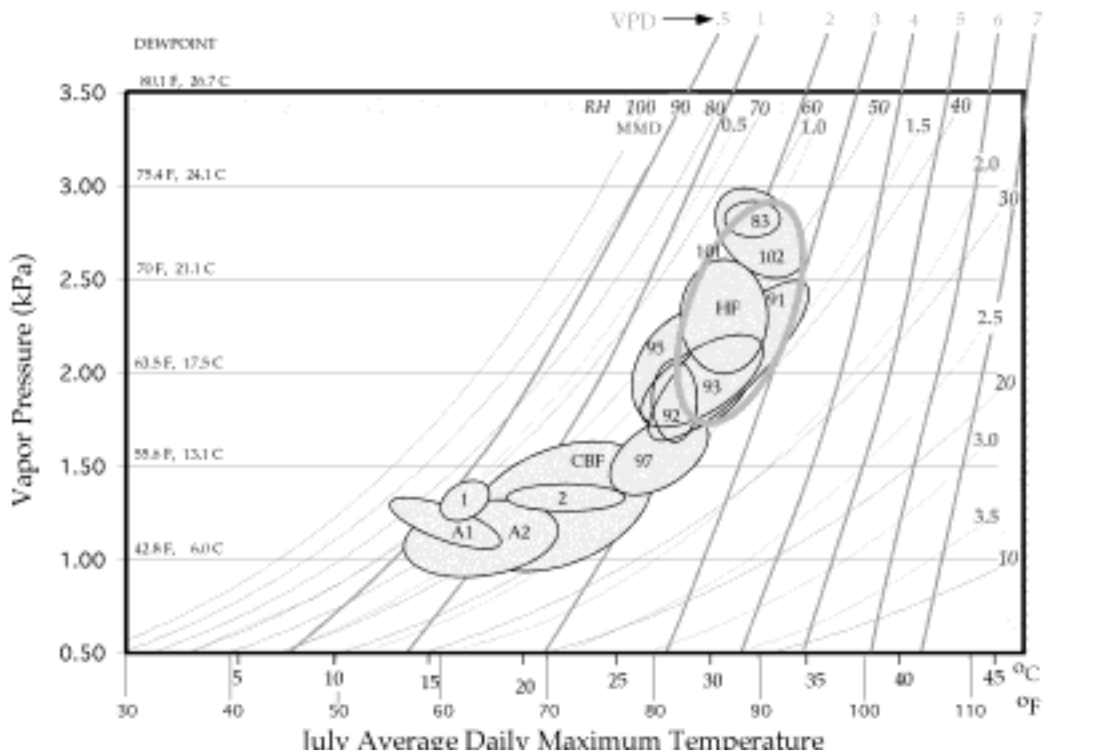

Figure 6. Ellipses for forest types: Spruce-Cedar-Hemlock (1), Cedar-Hemlock-Douglas Fir (2), Everglades (83), Oak-Hickory (91), Elm-Ash (92), Beech-Maple (93), Oak (95), Mangrove (96), Northern Hardwood (97), Oak-Hickory-Pine (101), Southern Mixed (102), Canadian Boreal Forest (CBF), Hemlock-Spruce (A1), spruce birch (A2), and Hawaii (HF).

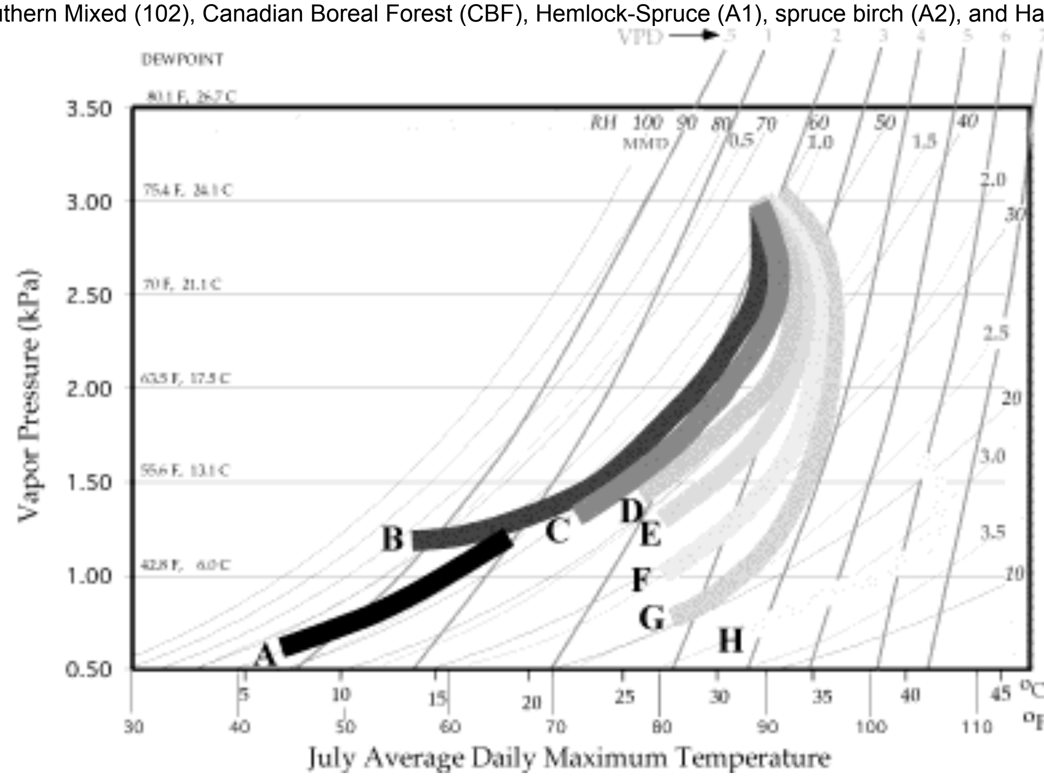

Figure 7. Centroid connectiing lines through tundra (A), Forests (B), Savannas (C), Tall Grass Prairies (D), Short Grass Prairies (E), Short Grass Steppes (F), Shrub Savannas (G) and Shrubs (H).