

Dew Formation and Water Availability at High Elevation in the Atacama Desert, Chile

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Abstract

The Atacama Desert, Chile, is among the least habitable environments on the planet largely because of its extreme aridity; nevertheless, ecosystems continue to function in many locations there, at least intermittently when water is available. This study addresses the question of whether dew could ever form at high-elevation sites in the Atacama region. Two distinct modeling approaches were used to model dew formation on volcanoes using data from climate stations at 2950, 4720, and 5820 meters above sea level (m.a.s.l.) to help explain the presence of a recently discovered simple microbiological ecosystem existing in soils from 5200 to over 6000 m.a.s.l. on other volcanoes in the region. The first model uses field data for air temperature and relative humidity to calculate dew point (temperature at which dew would form) and compares it with field soil temperatures at different depths as well as with air temperature. The second model calculates and compares the maximum amount of water vapor that air of the respective air temperature at each elevation could hold (saturation vapor pressure) to the actual amount of water vapor present (actual vapor pressure) at the time of measurement. Both models show that dew formation would not occur regularly at any of the elevations or months measured in the field. However, given that there are times just before sunrise when conditions are close to allowing for dew, it is possible that a rare and atypical weather event may result in dew formation. Given the known ability of organisms adapted to arid environments to survive long periods of no water availability, it is possible that this intermittent access to liquid water is sufficient to sustain the ecosystem found on high elevation volcanoes in the Atacama region.

Introduction

Life as we know it cannot exist without access to liquid water (O'Malley-James et al. 2013). It follows that wherever life exists there must be liquid water in some quantity, although this may be very small and infrequently available. Therefore, the discovery of a “low diversity, low energy ecosystem of unique and previously uncharacterized microbes” at sites above 6000 meters above sea level (m.a.s.l., 19,600 ft. above sea level) in the soil of volcanoes in the Atacama Desert, northern Chile (Lynch et al. 2012), leads directly to the question of where such an ecosystem gets water in the driest environment on the Earth and, on a larger scale, how life adapts and survives in such extreme environments. Ultimately, answering this question could lead to a more complete understanding of the limits to life on Earth, as the complexities allowed by abundant resources are stripped away, leaving the organisms that remain at their most basic. This is also one of the defining goals of the field of astrobiology, which considers the question of whether and where life could exist on planets other than our own. Sites in the Atacama are considered to be some of the best extraterrestrial analog locations on Earth and therefore may give insight into the potential for life to survive or even to have developed outside the bounds of our planet (Heldmann et al. 2013).

The Atacama Desert region is located in northern Chile around 24° South, 69° West, west of the Chilean Andes. This desert is divided into elevational zones with different meteorological and biological features, which arise from prevailing wind patterns (Halloy 1991, D. Schmidt 1999). The effect of these zones on the distribution of vegetation is presented in Figure 1, which has been reproduced from Richter and D. Schmidt (2002). These mountains follow a standard pattern of increased moisture availability, and therefore plant life, in middle elevations from air masses being forced upwards by the slope of the mountain, creating a vegetation belt (Arroyo et al. 1988). Across the Atacama region, the span of this band of vegetation is at its maximum

from 2800 to 5000 m.a.s.l. (Richter and D. Schmidt 2002), with the width of the band varying among individual mountains (Costello et al. 2009, Lynch et al. 2012). Above and below these elevations there is no plant life except for that found at uniquely sheltered and resource-rich locations such as those explored by Costello et al. (2009), where water, carbon dioxide, methane, and heat are provided by geothermal processes. The lower elevation desert scrub band leads down into the Atacama Desert proper (Arroyo et al. 1988). The upper band (above the vegetation zone) receives more precipitation, but the sheer aridity and solar energy input result in rapid and near-complete loss of water due to sublimation (the process of ice transitioning directly into water vapor without passing through a liquid water stage) of ice and snow (Lynch et al. 2012, Arroyo et al. 1988, D. Schmidt 1999).

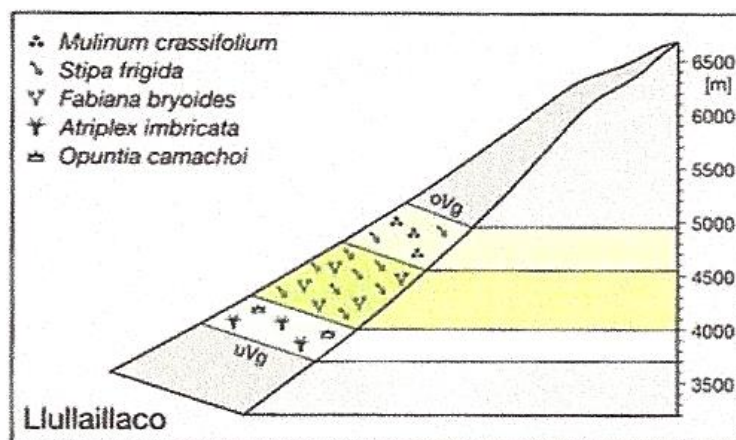


Figure 1: Distribution of vegetation by elevation on Lulllaillaco, the second highest active volcano on Earth (Richards and Villeneuve 2004) at 6740 m.a.s.l. (22,100 ft). (reproduced from Richter and D. Schmidt 2002)

In their biogeochemical and microbiological studies, Lynch et al. (2012) investigated water, carbon, and nitrogen content of soils from high in the upper elevation band (>6000 m.a.s.l.), finding extremely low values for these parameters, which are necessary for life. Water was found to constitute only about 0.25% of the soil and nitrogen was extremely scarce (below the detection limit of 25 $\mu\text{g N / g soil}$). Coupled with the enormous daily amplitude of soil temperature of 66.4°C observed at 5500 m.a.s.l. (Lynch et al. 2012) and the high frequency of

freeze-thaw cycles, which D. Schmidt (1999) reports as occurring 350 days per year, it is not surprising that the Lynch study discovered only a very rudimentary ecosystem at these sites.

However, given the discovery of extremely well-preserved mummies (which are rich in carbon and nitrogen) above 6000 m.a.s.l. on Llullaillaco (Wilson et al. 2007), it would seem that water is much more of a limiting factor than either of the latter two nutrients because the quality of their preservation indicates that bacteria that cause decay are either not present or not functioning.

The question then arises again of how the soil microorganisms discovered by Lynch et al. (2012) obtain water. It has been shown for other arid and semi-arid environments, including in low elevation reaches of the Atacama Desert (Azúa-Bustos et al. 2011), that where the amount or frequency of precipitation is insufficient to sustain the life forms present, non-precipitation water sources such as fog, water vapor adsorption, and dew provide enough water to sustain complex ecosystems (Agam and Berliner 2006, Jacobs et al. 2002, Kidron et al. 2002, Matimati et al. 2013). As fog seemed unlikely given the meteorological conditions of the area, which normally include high wind (D. Schmidt 1999), and because water vapor adsorption (the process of water vapor adhering directly to the surface of soil particles, forming an extremely thin film of liquid water) has been little studied and there is currently no method to calculate its contribution to water in the soil without knowing how much water there was in total (Agam and Berliner 2006), the present study examined whether and when dew formation could occur in this environment.

Materials and Methods

The climatological data used in the present study came from the only identifiable study that had measured relative humidity, soil temperatures, and air temperatures at elevations above 5000 m.a.s.l. in the Atacama Desert region. These data are contained in a dissertation written by D. Schmidt and published by the Technical University of Dresden in 1999, titled “Das

Extremklima der nordchilenischen Hochatacama unter besonderer Berücksichtigung der Höhengradienten” (“The extreme climate of the north Chilean high Atacama under particular consideration of elevational gradients”). Data tables and figures from this dissertation were translated from German into English and entered into spreadsheets for further processing. The numerical data presented in figures, particularly those displaying average daily time courses of air temperature by season, soil temperature at varying depths by season, and relative humidity for three different mountains at three different elevations, were extracted using Adobe Photoshop before entry into a spreadsheet. Soil depths at which the temperature was measured by D. Schmidt (1999) were 0, 5, 10, 20, and 50 cm. The names of the volcanoes on which D. Schmidt collected his data and their elevations are Volcán Pelón at 2950 m.a.s.l., Jorquencal at 4720 m.a.s.l., and Sairécabur at 5820 m.a.s.l.

The studies by D. Schmidt (1999) and Lynch et al. (2012) did not take place on the same mountains. The weather stations of the former were set up on mountains to the north and east of the Salar de Atacama (the salt plain at the hyper-arid core of the Atacama Desert; there are many such salars in the region) near or on the Chile-Bolivia border, while the soil samples taken by the latter are from mountains to the south of the Salar de Atacama on the Chile-Argentina border (named Volcán Socompa and Lullailaco), at varying elevations. The approximate locations of all sites relevant to the current study are given in Figure 2, below, using a map reproduced from Costello et al. (2009). Because of the similarity of the mountains and their relatively close locations this difference in latitude was not assumed to be significant for the present study.

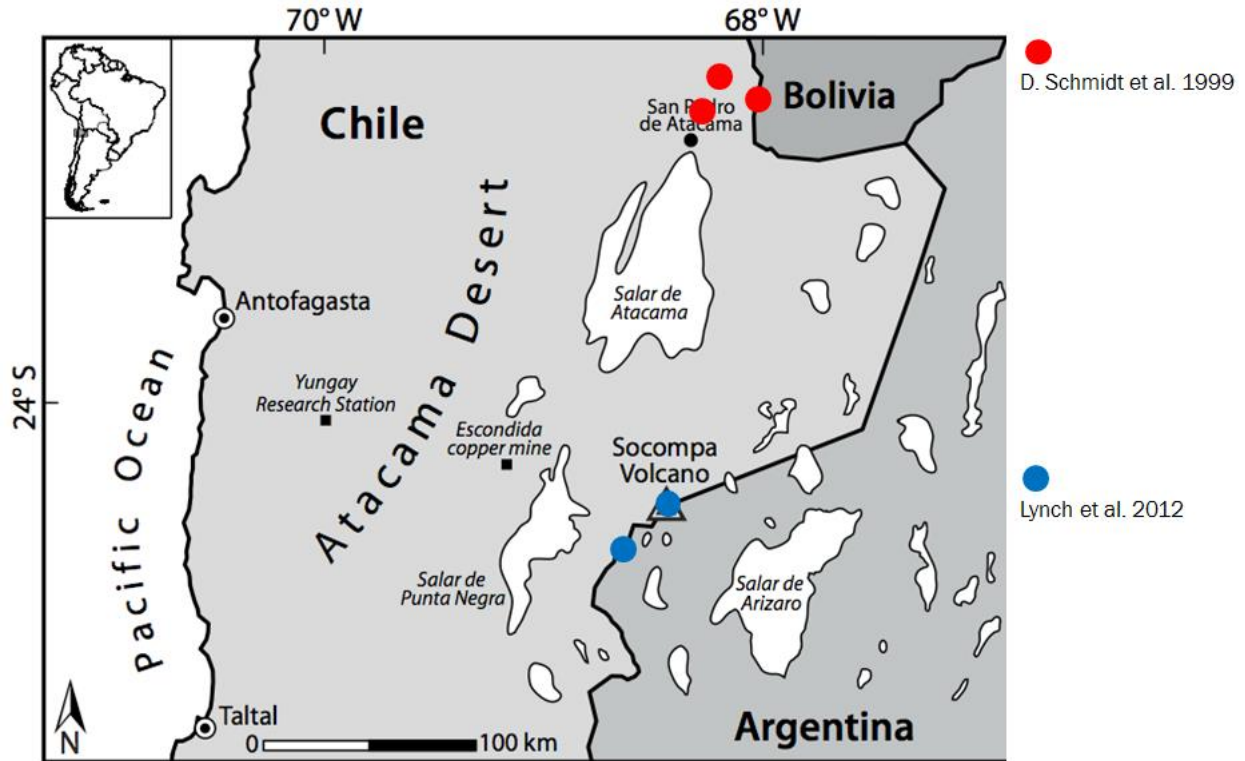


Figure 2: Map of the central Atacama Desert region. Study sites of D. Schmidt (1999) and Lynch et al. (2012) are shown in red and blue, respectively. (map reproduced from Costello et al. 2009)

Using information from meteorological and climatological studies two models of dew formation were created in collaboration with Mr. Jack Darcy (Ecology and Evolutionary Biology, University of Colorado Boulder). The first, using a version of the Magnus-Tetens equation (Buck 1981), calculated dew point using air temperature and relative humidity and plotted it with soil temperatures and air temperature across an average day in summer (December) and in winter (July) at three different elevations using data from D. Schmidt (1999). This equation calculates dew point in two steps:

$$\gamma(T, RH) = \ln\left(\frac{RH}{100}\right) + \frac{bT}{c + T} \quad [1a]$$

$$T_{dp} = \frac{c\gamma(T, RH)}{b\gamma(T, RH)} \quad [1b]$$

where T is air temperature ($^{\circ}\text{C}$), RH is relative humidity, and T_{dp} is dew point ($^{\circ}\text{C}$). The values b and c are constants given by Buck (1981) as 17.368 and 238.88 for temperatures between 0 and

50 °C and 17.966 and 247.15 for temperatures between -40 and 0 °C, respectively. The measured temperature at 5 soil depths (D. Schmidt 1999) was included to determine whether dew would form at that temperature before dealing with the question of whether enough water vapor could even penetrate the soil to that depth. If soil temperature were to fall below the dew point, the rate of condensation would surpass the rate of evaporation and dew would be expected to form (Agam and Berliner 2006). Similarly, if air temperature were to fall below the dew point, fog would be expected to form (Jacobs et al. 2002). The code for the iteration of this model for the 2950 m.a.s.l. site in December (created in R Statistics 3.0.1) is given in Appendix A.

The second model that was used to explore if dew would form at these sites relied on the barometric equation and the ideal gas law (both given below) to estimate how much water vapor the air could maximally hold at the measured soil temperatures at each elevation and how much water vapor the air was actually holding based on air temperature and relative humidity across an average day in summer and winter using data from D. Schmidt (1999). The barometric equation is used to calculate the pressure of a gas at a given elevation and temperature and is given as

$$P_h = P_0 e^{-mg h/RT} \quad [2]$$

where P_h is the pressure of a gas at elevation h , P_0 is the pressure of that gas at sea level, m is the molar mass of the gas, g is acceleration due to gravity, h is elevation, R is the gas constant, and T is the temperature of the gas (U.S. Standard Atmosphere 1976). The ideal gas law, when solved for moles of water (n), is given as

$$n = \frac{RT}{PV} \quad [3]$$

where R is the gas constant, T is temperature, P is pressure, and V is volume. The model first uses equation [2] to calculate the partial pressure of water vapor (the portion of air pressure contributed by the presence of water vapor alone) at the air temperature of each measurement

and then uses this value in equation [3] to calculate moles of water molecules per square meter, before converting this to grams of water per square meter of air. If the actual water vapor density were to rise to the saturation water vapor density, water vapor would condense and form liquid water as dew. The code for this model (also for the 2950 m.a.s.l. site in December and using R Statistics) can be found in Appendix B.

These models were each used to generate results for three different sites at different elevations (2950, 4270, and 5820 m.a.s.l.) using averaged daily data from December and from July. These 12 plots give an indication not only of what time of day dew may form, but of how elevation and season affect moisture availability. From this, it may be possible to extrapolate where and when most microbial life will be found, including at what soil depth. Combined with measurements and samples taken by the S. Schmidt lab at the University of Colorado Boulder (Lynch et al. 2012) it may be possible to evaluate the accuracy of our understanding of the dry limit of life (the minimal amount of water required to sustain life) as well as to gain insight into the life cycle of the life forms found in dry soils at high elevations.

Results

Results obtained here indicate that dew formation would not occur in this system, at least not during the periods covered by the data from D. Schmidt (1999). According to both models, at no point in the course of the temperature and humidity cycle of an average day, at any soil depth, elevation, or season measured does soil temperature drop below the dew point (model 1), nor does actual water vapor density rise above saturation water vapor density (model 2). Figure 3 on page 10 displays the results of the dew point model, model 1.

The closest point of intersection between dew point and temperature curves in Figure 3 is generally in the early hours of the day just before dawn, 06:00 to 06:30 hours. The curves are

closer to intersecting in the winter (July) than in the summer (December). Any observed elevational trend appears to be non-linear, where the gap separating soil and air temperatures from the dew point at the middle elevation is slightly narrower than at the highest elevation, and is by far the widest at the lowest elevation. The temperature at 0 cm depth (the soil surface) is consistently the closest of all soil temperatures to intersecting the dew point. Air temperature generally remains above soil surface temperature at the times of the day when the gap between measured temperatures and dew point is narrowest.

The water vapor density comparison model (model 2) likewise returned a consistently negative result in regard to dew formation. The results of this model are summarized visually in Figure 4 on page 11.

From Figure 4 it is clear that on an average day actual water vapor density does not rise above saturation water vapor density at any time, elevation, or season. There appears to be very little difference in actual or potential humidity over the course of a day regardless of season, unlike what was observed via the temperature-based model. However, there is a slight rise in potential humidity in the winter at all elevations. There does appear to be a linear elevational trend in this model, as the gap between saturation and actual vapor densities narrows consistently from the lowest elevation to the highest. This narrowing appears to be about equally attributable to a lowering of the saturation vapor density as to a rise in actual moisture content of the air. Saturation density drops from a general value of slightly over $500 \text{ g H}_2\text{O/m}^3$ at 2950 m.a.s.l. to around $400 \text{ g H}_2\text{O/m}^3$ at 5820 m.a.s.l. and the difference in actual density rises from around 100 to about 200. There is considerably greater daily variation in actual water vapor density than saturation density at all elevations, although that at 4270 m.a.s.l. varies more than at the other two elevations.

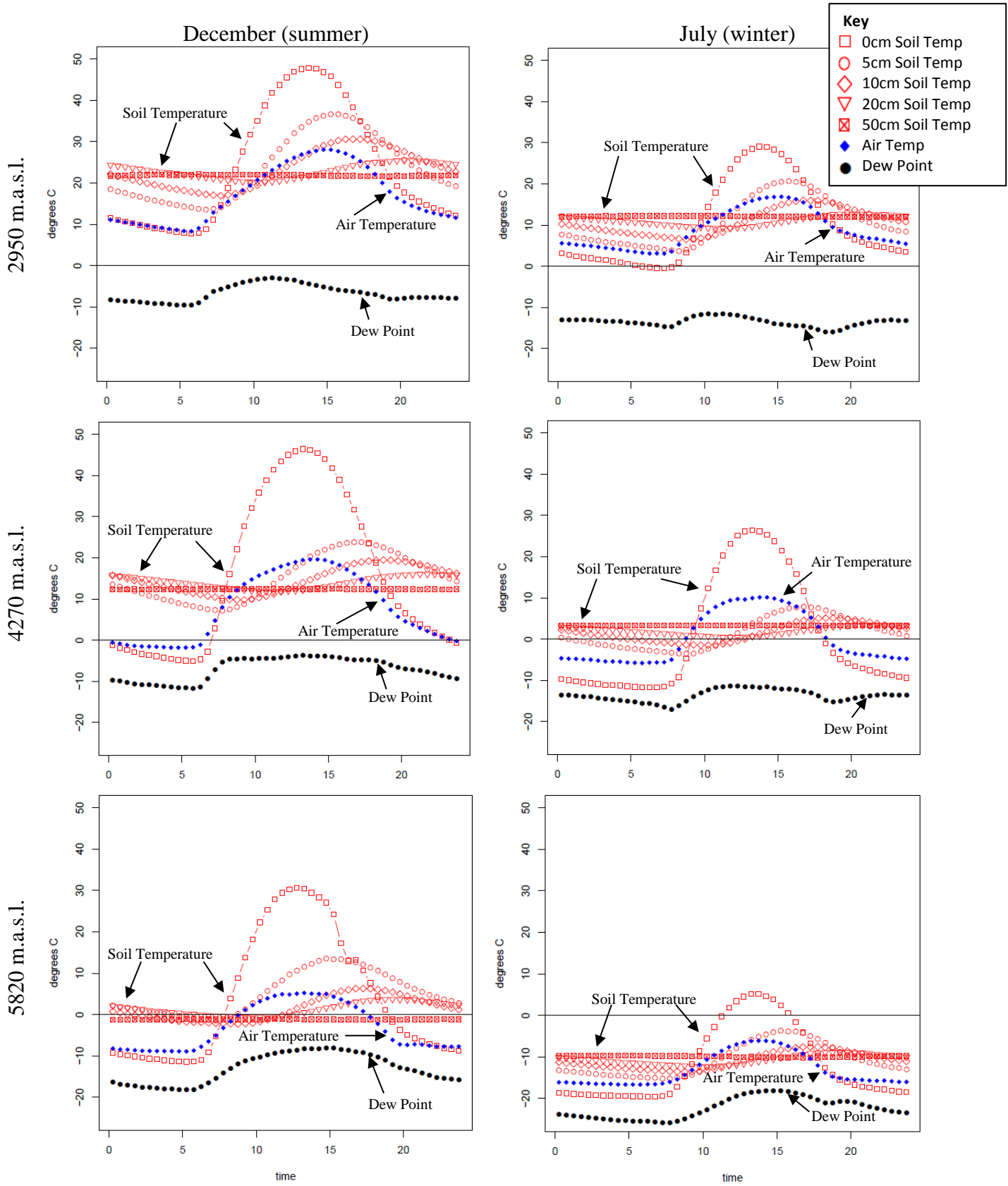


Figure 3: Average daily course of soil temperature at depths of 0, 5, 10, 20, and 50 cm, air temperature, and dew point in December and in July as measured at 2950, 4270, and 5820 m.a.s.l. (temperature data from D. Schmidt 1999)

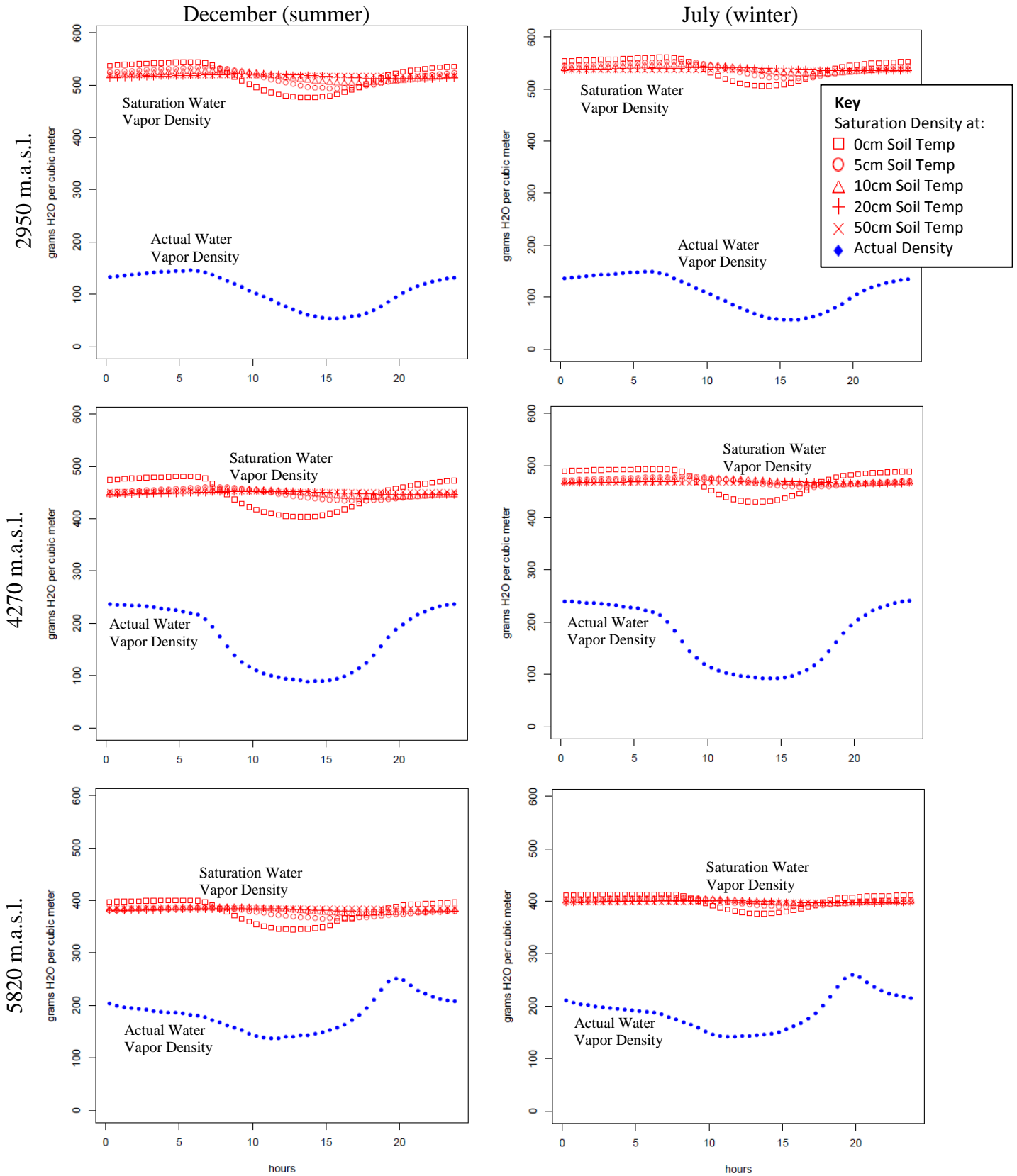


Figure 4: Average daily course of saturation water vapor density based on temperature at 0, 5, 10, 20, and 50 cm soil depth and actual water vapor density in December and in July as measured at 2950, 4270, and 5820 m.a.s.l. (temperature data from D. Schmidt 1999)

Discussion

The results presented here indicate that dew does not form regularly in the environment of high elevation soils in the Atacama Desert. Thus, this environment is more extreme than other desert environments where dew formation has been detected (Jacobs et al. 1999, Kidron 1999, Li 2002). While there is a growing consensus that dew is often a critical source of moisture for organisms in deserts when water from precipitation is unavailable (Agram and Berliner 2006, Chen et al. 2013, Jacobs et al. 2002, Kidron et al. 2002) these studies have all taken place at lower-elevation arid and semi-arid areas with greater moisture availability such as the Negev Desert, Israel (Kidron et al. 2002, Jacobs et al. 2002), at an elevation of 190 m.a.s.l., the Succulent Karoo, South Africa (Matimati et al. 2013), at an elevation of 160 m.a.s.l., and the Tengger Desert, China (Pan et al. 2010), at an elevation of 1339 m.a.s.l., with all being locations that receive enough moisture to support plant life. It should be noted, however, that the middle elevation of the present study at 4270 m.a.s.l. lies within the elevational band from 2800 to 5000 m.a.s.l. in the Atacama region where plant life is supported, probably through precipitation in summer (Lynch et al. 2012, Richter and Schmidt 2002). This presence of plant life can be plainly seen in Figure 5 below, a photograph of the climate station at this elevation, reproduced from D. Schmidt (1999).



Figure 5: Jorquencal climate station (4270 m.a.s.l.), surrounded by plant life. *Reproduced from D. Schmidt 1999.*

The comparative abundance of plants at this elevation versus the other two elevations is consistent with the present finding that dew formation was the most likely here, even though no regular dew formation was shown. It seems likely that this site was chosen by D. Schmidt (1999) in light of the pattern of elevational banding of vegetation in this region (see Figure 1) in order to investigate the meteorological differences that give rise to the much more complex ecosystem seen in Figure 5. A comparison of the physical makeup of the soil as well as the soil microorganism ecosystem between this vegetated site versus the unvegetated sites could be the target of a future study. A previous study (Drees et al. 2006) showed that microbial diversity and abundance increased with elevation from the hyper-arid lowlands to the vegetated highlands (up to 4500 m.a.s.l.), but only the studies of Costello et al. (2009) and Lynch et al. (2012) have thus far examined microbial communities above 5000 m.a.s.l.

In addition to differences arising from the potential presence of non-dew water sources, it is possible that the soil temperature could drop below the dew point, resulting in dew formation, on rare individual days in view of the close proximity of dew point to soil temperature in several

instances in Figures 3 and 4. Although such an event (actual dew formation) is evidently not common enough to provide a dependable and periodic source of moisture, D. Schmidt (1999) reports that relative humidity at each station reached 99% (making dew or fog formation likely as a consequence of the amount of moisture in the air reaching the saturation point of the air) at some point during the 3 years of that study. Given the known capacity of some organisms inhabiting extremely arid environments to lie dormant for long periods between times of water availability and to survive extreme desiccation (Wierzychos et al. 2006), such rare events must be seriously considered as a principal source of moisture for the microbial community in these soils. Unfortunately, without access to the raw data from the study by D. Schmidt (1999), it is impossible to tell if and when such events may have occurred.

Another likely source of moisture in this system is the melting of snow. While rain has never been observed above 5000 m.a.s.l. (Lynch et al. 2012, D. Schmidt 1999), it does snow on these mountains especially at high elevations. The presence of transitory snow and ice fields is confirmed visually in Figure 6 (reproduced from D. Schmidt 1999), which clearly shows snow at the highest elevation weather station (5820 m.a.s.l.) of the D. Schmidt (1999) study. The extremely low amount of moisture in the air, the large daily temperature swings, and the persistent winds do, however, indicate that snow or frost would either quickly sublimate or remain as solid ice (D. Schmidt 1999). The transient nature of these snow fields is further confirmed by the often-noted absence of glaciers on mountains in this region (Halloy 1991, Lynch et al. 2012) as well as by the absence of signs of erosion from water flow on these volcanoes. However, some melting of snow does occur, to a degree that the soil next to an ice field is moist to the touch before the water evaporates (S. Schmidt, personal communication, March 11, 2014). While some snow melt would certainly be a source of water for the organisms

inhabiting those soils adjacent to temporary ice fields, the same does not apply to the entire volcano.

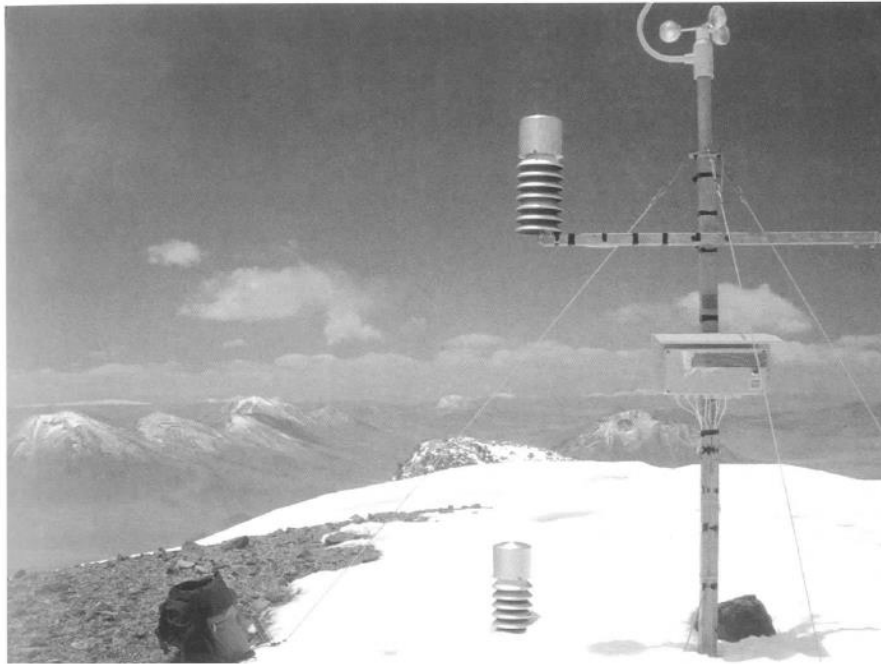


Figure 6: Snow at Sairécabur climate station (5820 m.a.s.l.). *Reproduced from D. Schmidt (1999)*

While direct adsorption of water vapor by the soil is another possible source of liquid water in this environment, the minimal research done on this process makes it impossible to draw conclusions regarding its influence on this system at this time (Agram and Berliner 2006).

As has been recognized in previous studies on the factors influencing dew formation, additional factors, such as the physical details of the soil surface (Jacobs et al. 2002) may play a role but are not taken into account in the present study. Nevertheless it has been recognized that in addition to the near-impossibility of including all relevant factors in this type of model, the impact arising from simplification is likely to be very small. Murray (1967) makes this argument in his paper refining and simplifying the Magnus-Tetens equation by calculating the saturation vapor pressure over a plane of water or ice.

In summary, the present study attempted to present a comprehensive picture of meteorological factors allowing for the existence of the rudimentary ecosystem discovered by

Lynch et al. (2012) in the high elevation, extremely arid soils of the volcanoes in and bordering the Atacama Desert. While dew formation is not a regularly occurring event in either winter or in summer at any of the locations for which data exist, it is still possible and perhaps likely that rare dew formation events occur that may sustain this ecosystem between periods of no water availability. It has also been suggested here that other sources of liquid water may be present as well, such as melting snow in particular areas and potentially direct water vapor adsorption. Future studies may be able to examine the role of direct water vapor adsorption more accurately or to examine the same meteorological factors under a finer temporal resolution (should the original 1999 data from D. Schmidt become available). It is hoped that the present paper will spur further study into the ecosystem functioning here, which because of the uniquely harsh environment it endures, exists in a uniquely simple state (Lynch et al. 2012).

Astrobiological (relating to the study of potential life on other planets) applications arising from similarities between harsh terrestrial environments such as the Dry Valleys of Antarctica or the Atacama Desert and extraterrestrial environments (O'Malley-James et al. 2013, Heldmann et al. 2013) lend further reason to undertake such studies beyond the intellectually worthy pursuit of understanding the essential structure and fundamental operation of cellular life. The study of ecosystems in extreme environments has important implications for, and may lead to, further insight into living communities in their most basic state.

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Appendix A: Dewpoint Model Code, for December 2950 m.a.s.l. (Pelón) Data

Dew Point Calculator and Plot Maker

By Jack Darcy and Zack Schubert, 23 January 2014

read in data

soil_temps <- read.csv(file.choose(),header=T)

rel_hums <- read.csv(file.choose(),header=T)

air_temps <- read.csv(file.choose(),header=T)

magnus function

air_temps vector of air temperatures

rel_hums vector of relative humidities

b_hot

b_cold

c_hot

c_cold

magnus <- function(air_temps, rel_hums, b_hot=17.368, b_cold=17.966, c_hot=238.88,
c_cold=247.15){

n <- length(air_temps)

b_all <- rep(NA, n)

c_all <- rep(NA, n)

for (i in 1:n){ # creates vectors of bs and cs

if(air_temps[i] < 0){

b_all[i] <- b_cold

c_all[i] <- c_cold

}else{

b_all[i] <- b_hot

c_all[i] <- c_hot

}

}

gamma_vals <- log(rel_hums/100) + (b_all * air_temps)/(c_all + air_temps)

output <- data.frame(gamma_vals, b_all, c_all)

return(output)

}

wrapper function

moisture_model <- function(air_temps, rel_hums, ground_temps, time, model_title){

gbc <- magnus(air_temps, rel_hums)

dew_pts <- dew_points(gbc)

all_temps <- c(dew_pts, ground_temps)

plot_lims <- c(min(all_temps), max(all_temps))

 plot(dew_pts ~ time, ylim=plot_lims, type="b", col="black", main=model_title,
ylab="Degrees C", xlab="Time")

points(ground_temps ~ time, col="red", type="b")

output <- data.frame(dew_pts, ground_temps, air_temps, rel_hums, time)

return(output)

```

}

# dew_points function
  # gbc data.frame with header c(gamma_vals, b_all, c_all)
dew_points <- function(gbc){
  tdp <- (gbc$c_all * gbc$gamma_vals) / (gbc$b_all - gbc$gamma_vals)
  return(tdp)
}

modell <- moisture_model(air_temps$X15cm.Height, rel_hums$X15cm.Height,
soil_temps$X0cm.Depth, soil_temps$time, "Dew Formation at 0cm Depth (15cm air)")

# all combined plot
pdf("magnus_december_2950m.pdf")
soil_pchs <- c(0,1,5,6,7)
plot(modell$dew_pts ~ modell$time, col="black", main="Dew Point (black), Air Temp (blue),
and\nGround Temps (red), December, 2950m", ylim=c(-25, 50), yaxt="n",pch=16, xlab="time",
ylab="degrees C", type="b")
for(i in 1:5){
  points(soil_temps[,i] ~ modell$time, pch=soil_pchs[i], col="red", type="b")
}
points(air_temps$X15cm.Height ~ modell$time, col="blue", pch=18)
abline(h=0, col="black")
axis(side=2,at=c(-20,-10,0,10,20,30,40,50),labels=c(-20,-10,0,10,20,30,40,50),pos=-0.7)
dev.off()

```

***Appendix B: Water Vapor Density Comparison Model Code, for December 2950
m.a.s.l. (Pelón) Data***

#Script to calculate actual water vapor density and saturation water vapor density

#By Zack Schubert and Jack Darcy, 13 February 2014

#Variables

air_temp <- read.csv(file.choose(),header=T)

time <- air_temp\$time

air_temp <- (air_temp[,1])+273.15

soil_temp <- read.csv(file.choose(),header=T)

soil_temp <- soil_temp+273.15

rel_hum <- read.csv(file.choose(),header=T)

rel_hum <- rel_hum[,1] # only first column

elevation <- 2950 # in meters

pressure <- 101325*(1-(2.25577*(10^(-5))))*elevation)^5.25588 # in PASCALS

soil_temp_cols <- c(0, 5, 10, 20, 50)

title <- "Saturation (red) and Actual (blue) Water Vapor\nDensities on Pelon (2950 m) in
December"

Wrapper function

SoilTempSatModel <- function(pressure, soil_temp_cols, soil_temp, air_temp, rel_hum){

make output data frame

soil_temp_cols <- as.character(soil_temp_cols)

out_colnames <- soil_temp_cols

for(i in 1:length(soil_temp_cols)){

out_colnames[i] <- paste("soilsat_", soil_temp_cols[i], "cm", sep="")

}

out_colnames <- c(out_colnames, "air_H2O")

output <- as.data.frame(mat.or.vec(nrow(soil_temp), length(out_colnames)))

colnames(output) <- out_colnames

fill output data.frame

for(i in 1:length(soil_temp_cols)){

calculate water capacity at soil temp

molwater2 <- pressure/(8.314*soil_temp[,i])

swd2 <- molwater2*18.01528 # max grams H2O per cubic meter POSSIBLE

given soil temp

output[,i] <- swd2

}

fill in air_H2O column

calc air water capacity

molwater1 <- pressure/(8.314*air_temp) # moles per cubic meter

swd1 <- molwater1*18.01528 # max grams H2O per cubic meter POSSIBLE

given air temp

Calculate actual atmospheric water density

```
        output$air_H2O <- swd1*(rel_hum/100) # grams H2O per cubic meter ACTUAL
VALUE
    return(output)
}

plot1 <- SoilTempSatModel(pressure, soil_temp_cols, soil_temp, air_temp, rel_hum)

# plotter function
PlotSTSM <- function(STSM, time, title){
  pchs <- c(0:7)
  y_range <- c(min(STSM), max(STSM))
  plot(STSM$air_H2O ~ time, ylim=y_range, main=title, col="blue", pch=20,
ylab="grams H2O per cubic meter", xlab="hours")
  for(i in 1:(ncol(STSM) - 1)){
    points(STSM[,i] ~ time, col="red", pch=pchs[i])
  }
}

PlotSTSM(plot1, time, title)

pdf("density_compare_P_Dec.pdf")
PlotSTSM(plot1, time, title)
dev.off()
```