LAMA Memo 804:
Effects of Global Warming on Precipitable Water Vapor Above Sub-millimeter Wavelength Astronomical Sites

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Abstract

Global warming due to increased levels of CO_2 in the atmosphere is a virtual scientific certainty. The predictions for the amount of warming which the earth will experience depend upon both the future (unknown) increase in made-made CO_2 emissions and the details of the model used to compute the warming, but a mean earth surface temperature increase ranging from 2 to 5 K by 2080 is considered reasonable.

As the air temperature increases, the air holds more water vapor in a rather non-linear fashion, which can be easily calculated by the Clausius-Clapeyron equation. There is some uncertainty about how global warming will affect a site such as Chajnantor, where the air is far below saturation in water vapor. We assume that the mean relative humidity remains constant. The water vapor scale height, fixed by the physics of the water molecule, should not change. An average increase of only 3 K at Chajnantor, a non-extreme value for expected warming in north-eastern Chile over the next 50 years, will result in a 24% increase in the water vapor above Chajnantor. Hence, during the expected lifespan of the ALMA telescope, we expect to see a measurable but modest decline in the sub-millimeter transparency.

Warming of a given amount will have a larger effect on the atmospheric water vapor above the South Pole because the temperature there is much colder than at Chajnantor. Furthermore, since the air above the South Pole is saturated with water vapor, the effect is more predictable.

As global warming proceeds and more water vapor is held in the air, storm systems are expected to become more severe, but there is not unity in the community of atmospheric researchers as to whether storms will become more frequent. More frequent or more severe storms would likely increase the mean relative humidity, and hence increase the PWV and opacity even more than what is expected from the increase in the saturation water vapor pressure with temperature as noted above.

While there is essentially nothing that we can do in the ALMA project to counteract these predicted changes, we should be aware of them, as knowledge of a changing climate could be an important input to dynamic scheduling algorithms. As global warming progresses, we will have less time with the best atmospheric conditions, and we will be able to perform fewer observations at the highest frequencies which demand those best conditions.

We should recognize that the coming decades may be the golden age of ground-based sub-millimeter astronomy.

1 Introduction

Global warming over the last century is an established fact. Ground-based temperatures averaged over the year and averaged over the earth have increased by about 0.6 C. Relating this measured increase in global temperature to increased levels of carbon dioxide in the atmosphere is somewhat conjectural. Complex hydrodynamic simulations of the atmosphere/ocean system, using the known CO_2 increase as an input, predict not only the observed increase in temperature, but also the distribution of those increases. To date, the oceans have warmed very little, the land has warmed more, and the lands around the arctic have warmed quite dramatically. Most climate researchers and atmospheric scientists believe a causal link exists between the increased concentration of CO_2 in the atmosphere and the observed global warming. While the internet is full of sites which claim to debunk global warming, these seem to call more attention to just how unreliable information you get off the internet can be.

And what of the future? Human-made emissions of CO_2 and other greenhouse gasses are accelerating, while the means to quickly store up CO_2 in plants or in the ocean are becoming saturated, and doubling of atmospheric CO_2 in the coming decades is very likely. Needless to say, there is significant uncertainty in the future time series for CO_2 in the atmosphere, and hence, uncertainty in the temperature anomaly as well.

Climate researchers take the CO_2 concentration with time as input to the hydrodynamic codes, which take into consideration solar heating, reflection, infrared cooling (including line-by-line models of atmospheric emission and absorption, not unlike our millimeter-wavelength transmission codes), clouds and aerosols, weather patterns, ocean mixing and ocean currents, and various ways the planet can take CO_2 out of the atmosphere. These models are monstrously complicated, and they give somewhat different results. However, in the region of Chajnantor, we should expect a rise in temperature between 2 and 5 K to occur over the next 80 years.

Why should the ALMA project be concerned with a little bit of warming on Chajnantor? Because with increased temperature comes increased water vapor. The trend is exponential with temperature. The Clausius-Clapyron equation (Castellan, 1971) describes how the saturation partial pressure of a gas like water vapor depends upon temperature:

$$p \propto e^{-Q_{vap}/RT},\tag{1}$$

where p is the partial pressure of water vapor, Q_{vap} is the heat of vaporization of water, R is the gas constant, and T is the temperature in K. Q_{vap} for water is 1.053e+4 cal/mole, and the gas constant R is 1.9872 cal/mole/K. We can recast this equation as

$$\frac{p_2}{p_1} = e^{-Q_{vap}(T_1-T_2)/(RT_1T_2)},\tag{2}$$

which indicates the ratio change in the saturation partial pressure of water vapor which results from changing the atmospheric temperature from T_1 to T_2. Chajnantor typically has very low relative humidity, so at first glance it is uncertain how to apply this equation to PWV above Chajnantor. We can do so by making two assumptions: that the mean relative humidity remains constant as the climate changes, and that the water vapor scale height also remains constant. The water vapor scale height is a result of the physics of the water molecule (ie, Van der Waals forces) and the temperature/pressure structure of the atmosphere, and is not expected to change with climate change. The assumption of constant mean relative humidity seems intuitively reasonable to me in that the physical processes which dry out the air before it

reaches Chajnantor may operate on the relative humidity, but I cannot rigorously defend that assertion. Anyway, an increase in temperature from 271 to 276.7, 5.7 degrees C, will result in an increase of the saturation partial pressure of water vapor of 50%. If this translated into a 50% increase in the PWV above Chajnantor, this would seriously degrade ALMA's ability to perform sub-millimeter observations, as the sub-millimeter opacity and the system temperature would increase dramatically.

2   What Does the Data say for Chajnantor?

2.1   The Instruments

We measure the temperature in the shade about a meter off the ground every 10 minutes. The atmospheric opacity at 225 GHz is measured with a tipping radiometer every 10 minutes as well. For our purposes here, we have aligned these data and removed either temperature or opacity when both are not present for a given 10 minute time period.

2.2   Is Chajnantor Warming?

We look at the mean temperature at Chajnantor, measured near the ground, and averaged over each year from 1996 through 2003 (Figure 1). There appear to be trends of a few years, probably related to el Nino/la Nina cycles. A best fit line shows a negative slope. Not unexpectedly, we can't yet say anything about global warming from the temperature data from the site, as we appear to be dominated by 2-3 year cycles. Note that the 225 GHz radiometer and the weather station were down between 5% and 25% of the time each year, so this is not particularly the best data set to seek trends in the annually averaged temperature.

However, this is no reason to doubt that the temperature will rise at Chajnantor in the coming decades.

2.3   Verifying Opacity Trends With Temperature

What else can we do with the data? Instead of looking for a long term trend in this 8-year-long data set, lets seek to verify that warmer temperatures are associated with more moisture. Figure 2 shows the median opacity at 225 GHz, taken over each calendar year, as a function of the mean temperature. We take the median opacity, rather than the mean opacity, because the tipping radiometer produces ill-conditioned results during the worst conditions (ie, when the opacity is greater than about 0.3, or when there are clouds). Using the median will be largely immune to this deficiency in the instrument.

There are two somewhat discrepant years, the coldest (2001) and the hottest (1998). A least squares fit to all of these points results in a slope of 0.007 nepers/K, while omitting 1998 results in a slope of 0.014 nepers/K. While these data are suggestive of a statistical relationship between the opacity and the temperature, we can't really say anything too quantitative from this data.

So, to get more data points, we'll just not average over such a long time. By averaging over a month at a time, we'll get 12 times as many data points (oh boy!). In Figure 3, we show the monthly median 225 GHz opacity vs monthly average temperature as filled squares. About 90% of the time, the winds on Chajnantor come out of the west. When the winds come out of the east (ie, the so-called Bolivian winter), they bringing moist warm air from the amazon

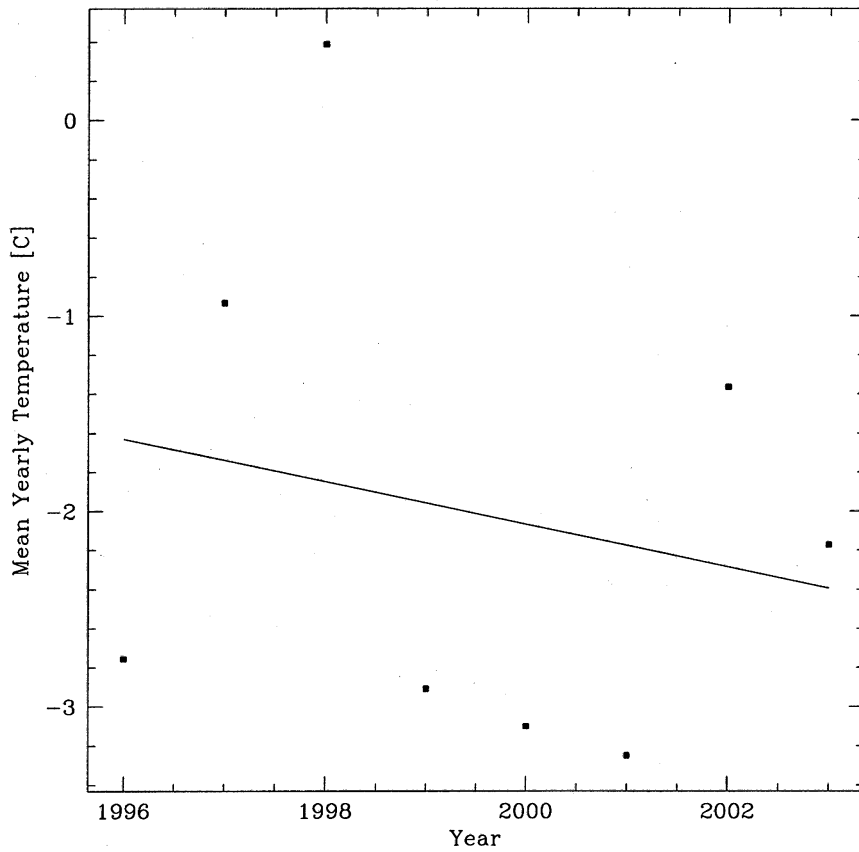There is no clear long-term trend in Chajnantor Temperature

Figure 1: The average yearly temperature at Chajnantor. There appear to be el Nino/la Nina cycles, but no clear overall trend reflecting climate change. A best fit line shows a negative slope.
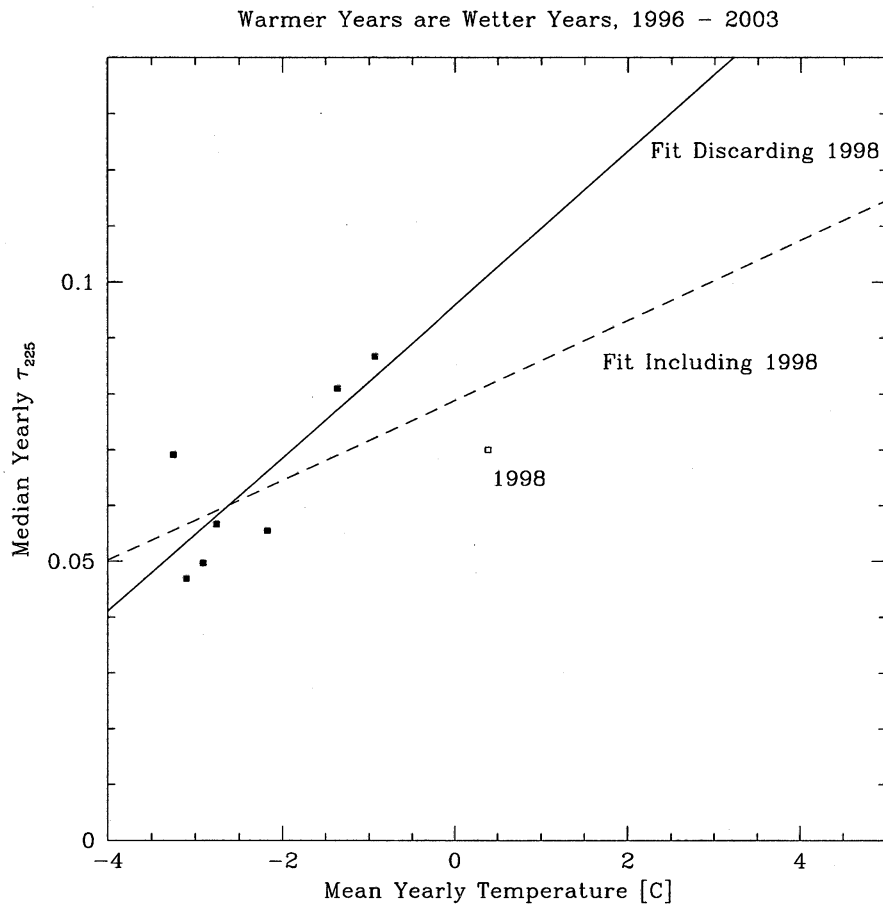
Figure 2: The *median* yearly 225 GHz opacity and the *average* yearly temperature at Chajnantor. We present two different fits to the data, one including 1998 and one neglecting 1998. The slope changes from 0.007 nepers/K to 0.014 nepers/K by omitting 1998.
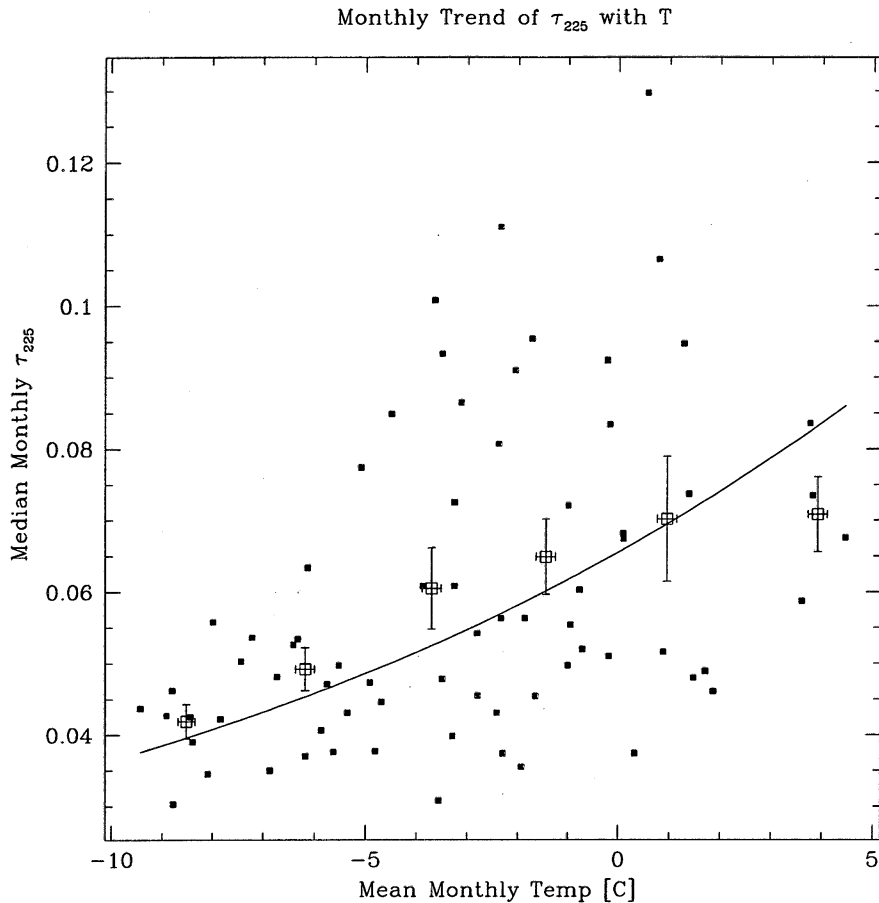
Monthly Trend of τ_{225} with T

Figure 3: The *median* monthly 225 GHz opacity and the *average* monthly temperature at Chajnantor are plotted with solid squares. We've left off every January and February, which are affected by the Bolivian winter (ie, they are anomalously wet due to winds from the east bring moisture from the amazon basin) and three other anomalously wet months out of the 96 months in our database. The open squares with errors bars are the average of the scattered monthly temperature and opacity (ie, the solid squares) dumped into 2.5 deg bins. The curved line is the shape of the increase in water vapor pressure with temperature suggested by the Clausius-Clapyron equation. This verifies that, statistically, warmer months are wetter months, and suggests that the Clausius-Clapyron equation can reasonably be used to predict the effects of global warming on opacities.

basin. The Bolivian winter can dominate weather patterns in January and February. These points have much larger opacities than the months which are dominated by drier winds from the west. Bolivian winter conditions are basically a lost cause for high frequency observing; we'd have to observe at 90 GHz or below during these high opacity conditions. For now, we wish to focus on the times when anomalously high opacities are not present, so we have removed all points from Januaries and Februaries, and three other individual months which had very large opacities (ie, perhaps they were afflicted by several storm fronts from the west, or perhaps they were afflicted by a longer-than-typical Bolivian winter). In addition to the monthly data represented by the filled squares, we also organize the monthly data into 2.5 degree wide bins and take the average of the monthly data points, which are then plotted as the open squares with error bars.

The exponential trend of water vapor with temperature which we expect from the the Clausius-Clapyron equation is also shown among the data points. As the air above Chajnantor is usually undersaturated with respect to water vapor, we cannot get an absolute curve from the Clausius-Clapyron equation. Rather, we have performed a least squares fit to the scale.

First, we see a general agreement between the theoretical curve and the data points. Remember, we don't expect or require that this curve be a good fit to all the monthly data points, only that the average of these data points be reasonably represented by the curve. During the hottest four monthly data points, there seems to be less water vapor than predicted by theory.

Second, the Clausius-Clapyron equation, while non-linear, has a mean slope of 0.0035 nepers/K in the temperature range of the data. This is much lower than the values of 0.007 or 0.014 we see in the plot of the annual averages. The larger slopes in the annual plot are presumably due to the inclusion of the warm and wet Bolivian winter months, which have higher relative humidities (breaking one of the assumptions we made to get an analytical relationship between PWV and temperature). Some years have more severe Bolivian winter conditions, and will tend to be warmer and much moister.

Third, we ask the question: "What does this demonstrate?" Which is cause and which is effect? When there is more moisture, cooling is less efficient and we expect warmer temperatures. Or, when it is warmer, the air can hold more water vapor, and less water vapor will be wrung out of the air on its way across the Atacama desert and up the mountain. I assert that higher temperatures and higher water vapor content go hand in hand, and it doesn't really make sense to call one cause and the other effect. From our point of view, we could perhaps rename "global warming" to "global warming and moistening".

Fourth, the general agreement between the data points and the theoretical curve indicate to me that we can use the Clausius-Clapyron equation to estimate the level of increase we might expect in the water vapor, and hence the millimeter opacity, due to increases in mean temperature.

3 Specific Predictions of Global Warming

3.1 Speculation About the PWV Above Chajnantor

Owing to it's high, dry atmosphere and excellent transparency, Chajnantor is poised to become one of the premier sites for sub-millimeter astronomy in the world. How will the warming/moistening trends we expect in the coming decades affect our ability to perform sub-millimeter observations from Chajnantor?

| ΔT | Increase in PWV |
K	[%]
1	7
2	15
3	24
4	33
5	42
6	52

Table 1: For a given mean increase in temperature at Chajnantor, what is the percent increase in the saturation PWV?

The IPCC, or Intergovernmental Panel on Climate Change, operates a Data Distribution Center which can be accessed at the URL http://ipcc-ddc.cru.uea.ac.uk. Here, the results of 20 different climate model scenarios (including different levels of curtailment of human-generated greenhouse gases) are available for the years 2020, 2050, and 2080. Perhaps the best news is that climate in North America and Northern Europe is predicted to exhibit a very large amount of warming as early as 2020 – so that hopefully we will get the message that concrete action needs to take place very soon.

For the region of South America where Chajnantor is located, the models predict between 0.5 and 2 K (median of 1 K) of warming by 2020, between 0.5 and 4 K (median 2.5) of warming by 2050, and between 2 and 5 K (median 3.5) of warming by 2080. These models include a wide range of scenarios for human behavior, ranging from aggressively reducing emission of greenhouse gases, to continuing down our current path of blatant disregard for our impact on the planet. The latter will obviously result in larger temperature increases.

In addition to changes in mean temperature, these models predict changes in relative humidity. For most scenarios, the changes in relative humidity are near zero for the Chajnantor region. However, some have negative relative humidity increments. Statistically, the water vapor content above Chajnantor will go up with increasing temperature, but if the relative humidity goes down, this indicates that the water vapor content might not increase as much as predicted by the Clausius-Clapyron equation. Anyway, we'll ignore that complication for now. Table 1 tabulates the increase in water vapor predicted for a warming of 1-6 degrees from a base temperature of 272 K. At most frequencies that permit ALMA observations, the opacity is dominated by the PWV, so to first order, the sub-millimeter opacity will be increase by the same factor as the PWV is increased.

3.2 Speculation About Antarctica

The South Pole is one of the other premier sub-millimeter sites in the world, but it owes its excellence more to the cold than to being that dry. It is about 2800 m in elevation, but because of the equatorial atmospheric bulge, the lower air pressure at the pole is equivalent to an elevation of about 3700 m. Comparison of radiosonde data, 225 GHz opacity data, and transmission models indicates a picture in which the air above the South Pole is completely saturated by water vapor, but because the winter temperatures are quite typically 190-220 K, the air is able to hold much less water vapor.

ΔT	Increase in PWV
K	[%]
1	11
2	24
3	38
4	54
5	71
6	90

Table 2: For a given mean increase in temperature at the South Pole, what is the percent increase in the saturation PWV?

Due to the typical saturation of the air, it is easier to apply the Clausius-Clapyron equation to the South Pole. Because the temperatures at the South Pole are lower, an increase of 1 degree will have more of an effect on the saturation water vapor pressure. We start with a base temperature of 220 K. The results for our South Pole calculations are in Table 2.

3.3 Storms

Climate change researchers do point to an increase in the severity of storms as the global climate warms, but predictions as to the frequency of storms are mixed. Increasing just the severity of storms will mainly make the bad conditions worse. The median conditions will not change a lot, though they will probably be affected by second order effects. Consider, for example, that the effects of a storm can be seen in the opacity data for a few days before the storm front passes through, and a few days after as the air dries out. A more severe storm front could take longer to dry out and return to the background good opacity conditions. On the other hand, if the frequency of storms increases, we will find that the median opacity conditions will degrade significantly, this effect being in addition to the increase in water vapor due to the increase in temperature.

It is very difficult to quantify these effects, but they are likely to degrade the median opacity *more* than what is suggested by the Clausius-Clapyron equation alone.

3.4 Cold Nights Are The Biggest Recipients of Global Warming

Another factor which we should be aware of is that global warming is expected to impact the cold nights the most. For example, in Tucson, AZ, the year 2003 had the highest ever average of the low temperatures, but the average temperature for the whole year was only the third highest ever. The additional carbon dioxide and water vapor in the air inhibits cooling at night. While it is difficult to quantify the effect this fact will have on the opacity at Chajnantor (during the winter months, there is very little diurnal variation in opacity), we can say qualitatively that the very best conditions during cold dry nights might be in jeopardy.

3.5 Possible Shifts in Weather Patterns

When a massively complex system such as the earth's atmosphere and oceans begins to change, unexpected sudden shifts in weather patterns are possible. For example, there is strong evidence

for the ice ages ending and glaciers melting over the time scale of only a few years. Now, consider the Bolivian winter, which occurs roughly 10% of the time, basically ruining sub-millimeter and millimeter observing at Chajnantor for one or two months a year. While I have seen no predictions concerning this weather pattern, it is not impossible that global circulation patterns could shift in such a way as to result in the Bolvian winter occurring for a larger fraction of the year than it currently does. If this happened, it would be really bad.

4 Phase Stability Considerations

There is a modest correlation between opacity and phase fluctuations above Chajnantor. While it certainly is not a one-to-one correspondence, it stands to reason that if there is statistically more water vapor at the location of the turbulence, we will see larger amounts of inhomogeneously distributed water vapor and hence larger phase fluctuations. On the other hand, lower altitude sites with more water vapor do not show phase fluctuations which are proportional to that water vapor increase, but more modestly increased phase fluctuations with respect to a site like Chajnantor.

An increase in the strength or number of storms will also affect the phase stability.

Acknowledgments

References

Castellan, Gilbert W., 1971, "Physical Chemistry", Addison-Wesley, Reading, Massachusetts.

Intergovernmental Panel on Climate Change Data Distribution Center:
http://ipcc-ddc.cru.uea.ac.uk