Effects of Humidity on Tropical Climates

Abstract

One of the most useful tools in climate modelling and simulation is the fact (reproduced independently by general circulation models) that relative humidity remains constant at progressively higher elevations, even as water vapour pressure and saturation vapour pressure fall in accordance with the lapse rate. Historically, modeling attempts have assumed that surface relative humidity remains constant spatially and temporally - however, recent data reveal this is not the case. In particular, temporal trends in surface relative humidity are revealed to be most pronounced in the Tropics. Our understanding of water vapour interactions in the atmosphere relies on our understanding of relative humidity distribution and behaviour - since tropical regions in general have crucial impacts on larger climate systems, by understanding the effect of this behaviour on surface temperatures, we stand to build better paleoclimate models and simulations of not just Earth but other planetary systems. We describe a model to take into account the effects of changing surface relative humidity on the atmosphere using NASA PDS data from the southwestern US as well as from the MODIS and AIRS instruments onboard NASA satellites. We outline a plan to apply this model to paleoclimatic records on Earth to assess the model's validity in describing climate reconstructions and future simulations.

Research Question

The central research question may be defined as follows:

How do fluctuations in surface relative humidity affect tropical surface temperatures on Earth-like planets?

Background

The Tropics are an integral part of all global climate systems, owing primarily to the dynamic interplay of key climatic variables in the presence of large irradiation. Processes such as the El-Niño Southern Oscillation on Earth, for instance, affect extra-tropical climate systems and patterns on a global scale[1]. Neglecting questions of axial tilt, we here consider the Tropics to be the zone that receives the largest insolation (irradiation) of any region on a planet (as seen on Earth)[2]. Sizable research has demonstrated the criticality of this zone to the subsequent behavior of any climate system, particularly on Earth - it is to this end that the tropical Pacific, the largest tropical ocean basin on Earth, has been deemed the 'sleeping dragon' by planetary scientist Ray Pierrehumbert.

Although the role of water vapor in the tropics should be well-understood given the essential role it has in planetary climate systems, there are still a number of outstanding questions about water vapour feedbacks, transport, and representation in climate models[3]. Water vapor, being twice as effective a greenhouse gas as carbon dioxide, is directly responsible for an important climatological feedback mechanism known as water vapour feedback, whereby temperature increases cause subsequent water vapour concentration increases which in turn amplifies temperatures via greenhouse effects – however, the full extent of its interactions with the rest of the environment is not entirely clear. The main source of this uncertainty comes from a still remarkably poor understanding of how water vapour affects cloud distribution, and numerical uncertainty continues to hinder accurate estimates of more complex phenomena central to the atmospheric heat budget, such as latent heat release and horizontal models of water vapour transport[4], both of which contribute to local weather systems. Further, many of the systems controlling water vapour are parameterized in general circulation models, adding to the uncertainty[5].

Until the 1980s, paucity of data on water vapor forced climate workers to depend upon general approximations, most significantly the notion of fixed (constant) relative humidity[6]. Scientists assumed that the water vapor concentration in the atmosphere as a whole did not fluctuate, or at least did not demonstrate significant fluctuation over time. However, while relative humidity trends are statistically indistinguishable from zero on the largest spatial and temporal scales, they can be significant at smaller scales[5]. Meanwhile, statistically significant increases in specific humidity are widespread, with a global mean trend of 0.07 g kg^{-1} $10yr^{-1}$ (given

[1] John H. Chiang, *The Tropics in Paleoclimate.* Annual Review of Earth and Planetary Sciences, January 26, 2009. doi: `10.1146/annurev.earth.031208.100217`

[2] Pierrehumbert, Raymond T. *Thermostats, Radiator Fins, and the Local Runaway Greenhouse.* Journal of the Atmospheric Sciences, Vol. 52, No. 10. 1st December 1994.

[3] Chahine, Moustafa T. *The hydrological cycle and its influence on climate.* Nature, Vol. 359, October 1, 1992

[4] Pierrehumbert, Raymond T. *The Hydrologic Cycle in Deep-Time Climate Problems.* Nature. Vol. 419, 12 September 2002

[5] Willett, Katherine M. *Creation and Analysis of HadCRUH: a New Global Surface Humidity Dataset.* Climate Research Unit (Uni. Of East Anglia). Ph. D. Thesis, March 2007. `www.cru.uea.ac.uk/cru/pubs/thesis/2007-willett/`

[6] Isaac Held and Brian Soden, *Water Vapor Feedback.* Annual Review of Energy and The Environment, 2000. 25:441-75

reported temperature trends, the expected specific humidity trend at a constant relative humidity of 70% is 0.08g kg^{-1} $10yr^{-1}$)[5]. The trends themselves are strongest in the Tropics and Northern Hemisphere Summer, regions of comparatively higher ambient temperature[5]. The HadCRUH dataset was created in 2007, as a compilation of land and sea surface data on relative humidity from 1973 to 2003 that was suitable for climate studies. However, HadCRUH does not parameterize water vapor distribution over ranges of the atmosphere, and scientists acknowledge a lack of precision in ocean data collected prior to 1982[5]. Modern general circulation models of the atmosphere manage to reproduce a trend of constant relative humidity as a result of model computations rather than explicit assumption[7], although it is not disclosed what spatial scale this trend has been observed for.

This discussion of relative humidity in modelling and reality is essential, as it informs our understanding of water vapour distribution, in turn indispensable to understanding the scale of water vapor's effects. The idea that water vapour distribution is governed by fixed relative humidity over large spatial and temporal scales has enabled largely successful modelling over the last four decades; however, as has been mentioned, this axiom is not similarly vindicated in the Tropics, nor does it always hold at smaller temporal and spatial scales. This fact motivates this proposal: a need to estimate the effect of water vapour fluctuations for specific regions and timescales exists.

What sorts of interactions between water vapour and climate systems exist? A vast amount of the literature devoted to understanding and quantifying water vapor's influence focuses on water vapour feedback[6], leaving aside contributions from the less easily modelled phenomenon of cloud distribution and cover. Water vapour feedback is predominantly positive – as more and more water vapor in the atmosphere accretes more and more water vapour via enhanced evaporation, temperatures rise via enhanced greenhouse effects. Investigations of this effect have generally been couched in parallel discussions of the climatological effects of a potential doubling of the atmospheric levels of carbon dioxide by anthropogenic emissions, promoting evaporation in the tropics, rather than fluctuations in relative humidity. Advection, convection and condensation processes have also been suggested to mitigate the effect of water vapour feedback in the Tropics[6] – however, it is generally agreed that microphysical cloud formation processes are the major mitigating factor for water vapour feedback globally. Cloud cover acts somewhat like a mirror, as it absorbs and reflects both incoming solar and outgoing terrestrial radiation – depending on height and type, clouds can have albedos varying anywhere between 0 to 0.8. Thus, cloud cover has the potential to both add to as well as diminish the impact of water vapour, by altering the energy budget. Finally, a related concept – precipitation efficiency – also affects climates by affecting water vapour concentration in the atmosphere, causing depositions of water in the form of condensate over regions[6,8].

Besides HadCRUH, water vapour content and distribution throughout the atmosphere has also been studied from orbit (e.g. via the NASA Aqua satellite). These data provide absorption spectrum information for water vapor concentration at various elevations above the earth surface. From knowledge of these trends, I intend to develop a one-dimensional radiative-convective model for how variations in surface humidity could affect tropical surface temperatures, using the considerations outlined in the preceding discussion; what constraints both humidity and tropical surface temperatures exist under; and empirically test these models against known (as well as unknown) temperatures.

Because the instrumental record of atmospheric humidity is limited to several decades (up to a century in some cases), geochemical proxies, which provide temperature and humidity data over longer timescales, are becoming increasingly important in the study of global climate. Specifically, paleoclimate data provide a valuable tool to test the veracity of climate models. Therefore, one proposed application of this model, intended as a proof-of-concept, would be in paleoclimate, where clumped isotope thermometry (a kind of thermometer capable of determining temperatures at which carbonate minerals have formed) as well as the model could be employed to predict temperature-humidity relationships from ancient hydrologic systems.

Methodology

Operational Overview

To carry out this research, I propose, in principle, to do the following:

1. Use NASA PDS data from the Southwestern US, as well as data from the NASA-centered Earth Observing System and existing HadCRUH data, to characterize seasonal, yearly, and longer-term changes in humidity

[7] Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, 2001. `http://www.ipcc.ch/ipccreports/tar/wg1/269.htm`

[8] O'Gorman, A. Paul. *The Relative Humidity in an Isentropic Advection-Condensation Model: Limited Poleward Influence and Properties of Subtropical Minima.* American Meteorological Society, December 2011. DOI: 10.1175/JAS-D-11-0671

levels over the tropics

2. Develop (or employ existing) models to explain how seasonal, yearly, and longer-term changes in humidity levels over the tropics are affected by water vapor radiative forcing.

3. Use clumped isotope thermometry and accompanying paleoclimate records to establish temperature profiles in the tropics over the last 20,000 yrs as well as water isotope ratios. The oxygen isotope composition of waters will provide some constraints on net evaporation and vapor transport. These reconstructed planetary conditions will be employed in the stated model.

4. Apply the models examined (in point 2) to compare the result of the estimated effect on surface temperatures with experimentally acquired clumped isotope data (in point 3).

In order to ease modelling computation requirements, I will be employing a simple radiative-convective model and implementing the same in Sage, an open-source and powerful computational software implemented in Python 2.7x.

Model Overview

The meteorological version of the Clausius-Clapeyron relation for water vapor is:

$$\frac{\mathrm{d}e_s}{\mathrm{dT}} = \frac{L_v(T)e_s}{R_v T^2}$$

where e_s is the saturation water vapour pressure, T is temperature, R_v is the water vapour gas constant, $L_v(T)$ is the (temperature-dependent) specific latent heat of evaporation.

This equation tells us how we may expect the saturation water vapour pressure to change at any given temperature. This is important, as relative humidity (RH) is defined (for a given water vapour pressure e and corresponding e_s) as

$$RH = 100 \cdot \frac{e}{e_s}$$

so that the temperature dependence of RH can be readily established by application of the chain rule. Given that the temperature-dependence of the latent heat of vaporization complicates things, we employ instead the Magnus-Tetens approximation[9]

$$e_s(T) = 6.1904 \exp\left(\frac{17.625T}{T + 243.04}\right) \tag{1}$$

which has historically been borne out immensely well by experiment, having only a relative error of $< 0.4\%$ over the range $-40°\mathrm{C} < \mathrm{T} < 50°\mathrm{C}$.

Our goal at this stage is to be able to simulate effectively what e might look like at every height. Our final step will be to compute the quantity $\frac{\mathrm{d}e}{\mathrm{dz}}$ by writing

$$e = \frac{e_s \cdot \mathrm{RH}}{100}$$

and using the equations of the lapse rate and the Clausius-Clapeyron relation which will allow us to estimate changes in water vapor pressure distribution over height:

$$\frac{\mathrm{d}e}{\mathrm{dz}} = \frac{1}{100} \cdot \left(\frac{\mathrm{d}e_s}{\mathrm{dT}} \cdot \frac{\mathrm{d}T}{\mathrm{dz}} \cdot \mathrm{RH} + \frac{\mathrm{dRH}}{\mathrm{dz}} \cdot \mathrm{e_s}\right) \tag{2}$$

where we choose to parameterise RH by the following equation (due to Manabe and Wetherald)[10]

$$RH = RH_0 \cdot \left(\frac{e - 0.02e_0}{0.98e_0}\right)$$

where both e_0 and RH_0 are the surface vapour pressure and the surface relative humidity respectively. Such a parameterisation renders the distribution dependent on the surface relative humidity. However, it is important to note that this relationship was originally derived for an explicitly linear vertical distribution of data, and

[9] Lawrence, Mark G. *The Relationship between Relative Humidity and the Dewpoint Temperature in Moist Air: A Simple Conversion and Applications.* American Meteorological Society, February 2005

[10] Manabe, Syukuro; Wetherald, Richard T. *Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity.* J. Atmospheric Sciences. May 1967

may have to be modified to properly account for experimental observations.

All this is intermediary - we wish to estimate the influence this change in water-vapor distribution actually has on the surface. In this regard, we will begin by dividing up the height into a series of layers, with each layer having constant water vapour pressure as computed by (2). To each such layer we will apply a greenhouse model to calculate the heat engendered in the layer immediately below.

We will then attempt to establish a cloud distribution. A cloud, in this model, can form either at its dew-point (which can be established by knowledge of relative humidity) or at its saturation water vapor pressure for that temperature. To establish when the dewpoint temperature will be achieved, we use the following formula (starting at $t_d = t$, the dry-bulb temperature, when the relative humidity is 100%)[9]:

$$t_d = \frac{243.04\left[\ln\left(\frac{RH}{100}\right) + \frac{17.625T}{243.04+T}\right]}{17.625 - \ln\left(\frac{RH}{100}\right) - \frac{17.625T}{243.04+T}} \tag{3}$$

which is well-known as a highly accurate (an approximate relative error of $< 0.4\%$ over the range $-40° \leq T \leq 50°$, having been derived directly from equation (1)) empirical formula for the dewpoint temperature within the meteorological community. Given that we already have the Magnus-Tetens approximation for e_s, we now have all the ingredients for a good approximation of cloud distribution without the effects of advection. A suitable choice of the lapse rate to be inclusive of entrainment can also address the fact that clouds can be formed by the mixing of air parcels at different temperatures.

Because of the low resolution of the model, spatial variance of cloud cover cannot be determined: the width and height of clouds within these layers will remain a mystery. We will be forced to assume that the clouds so created will suffuse the layer completely - clouds created at different layers will carry varying albedos, and will reflect both incoming and outgoing radiation, absorbing what is received for the heating of its own layer. Manabe and Wetherald (1967) provide a table of cloud albedos with respect to height.

In principle, eqns. (1), (2), and (3), combined with a temperature-lapse rate (as employed in Tripati *et al.*[11]), a greenhouse model and knowledge of incoming solar flux and outgoing radiative flux, will be all that will be needed. Many of the properties of the model not explicitly described here - including the greenhouse model for water vapour, radiative incoming and outgoing flux, absorption spectra and parameterisation for vapour distributions, and the effect of selected atmospheric constituents such as volcanic aerosols - will be taken as directed from Mackay and Khalil[12]. We will begin by perturbing RH at the surface layer, using the relative humidity trends in HadCRUH at surface height to guide our analysis. The resulting changes in surface temperature will be of import.

How does this relate to astrobiology?

The search for life elsewhere in the solar system is driven largely by the search for habitable environments, both past and present. However, we cannot always reconstruct past climatic conditions directly, as hard data or proxies may be impractical to obtain. This research would add to a significant body of existing work that would allow for the next best alternative – paleoclimatic and paleo-environmental modeling. Moreover, it would provide insight into the atmospheric thermodynamics of water-bearing planets similar to Earth.

How would this make use of NASA PDS data?

I intend to use PDS data from the Geologic Remote Sensing Field Experiment (GSRFE, 1990), stored in the Geosciences node on the PDS website, to complement the other data sets in use. The GSRFE is an aircraft-collected dataset that includes atmospheric spectrometry for large regions, including the Southwestern US. Spectrometric data for water vapour distribution from this experiment will be incorporated into the model.

What is clumped isotope thermometry?

Clumped isotope thermometry assumes that there is a relationship between the temperature a carbonate material formed at and the concentration of a particular isotope (a doubly-substituted isotope) of the CO_2 released

[11] Tripati, Aradhna K.; Sahany, Sandeep *et al. Modern and glacial tropical snowlines controlled by sea surface temperature and atmospheric mixing.* Nature Geoscience **7**, 205 - 209, January 2014. doi: 10.1038/ngeo2082

[12] Mackay, R.M.; Khalil, M. A. K. *Theory and Development of a One-Dimensional Time Dependent Radiative Convective Climate Model.* Chemosphere. Vol. 22. Nos 3-4, pp. 383 - 417. Pergamon Press PLC. 1991

when the carbonate is dissolved in phosphoric acid. This allows estimation of the temperature of regions as they were in the past, and the principle involved is based on pure thermodynamic considerations, which overcome some of the limitations of oxygen-isotope based paleothermometers.

Timeline

January - March 2014	Begin preparing samples for clumped isotope analysis; continue to research best possible parameterisation scheme for model aspects. Continue literature review. Engage in learning the intricacies of Sage. Complete work circa beginning of March 2014
March - May 2014	Begin formally programming with Sage, implementing and testing model. Download data from the NASA Aqua project (stored in Goddard GEODISC retrieval systems, available online) corresponding to water vapour height distribution, collate and organise PDS data. Adjust parameters of model to ensure adequate representation of profile. Undergo training with respect to clumped isotope analysis for better understanding of the results, and reporting conventions.
May - August 2014	Review HadCRUH data, and begin runnng model in the context of the West Pacific Warm Pool, more specifically by adjusting parameters to match conditions in Indonesia. Run collected samples (from Lake Towuti, Indonesia) through mass spectrometer. Collect and formally analyse results. Begin - and end - abstract and write up paper on first results under mentor's guidance. Draft abstract for AGU conference.
August - September 2014	Examine further perturbations to model, attempt parameterisation of more processes. Investigate paleoclimatic implications by running the model for different values of initial temperature, and subsequently compare against historical record. Revise and submit abstract for AGU conference.
September - December 2014	Begin - and end - final paper write-up. Prepare poster for AGU conference.
January - March 2015	Submit final paper for consideration.