Investigating the Time Signature of North and Central African Rainfall with Convection Permitting Simulations

Monticello Foundation and Robert and Delpha Noland Summer Internship Proposal

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I. Introduction

Drought plagues much of north and southern Africa. Cape Town, South Africa reports that they may run out of water by April of this year[1]. With the local government in Cape Town considering shutting off the tap, an explanation for the severe droughts over this continent is desperately needed. Therefore, our ability to accurately describe and predict precipitation across Africa, as well as the effects climate change may have on future precipitation, is integral to developing sound solutions.

The Sahel is a semi-arid region of North Africa with a monsoon climate. In recent history, the Sahel has had severe droughts every several years: during the 1910s, 1940s, 1960s, 1970s, and the 1980s. Recently, increased rainfall partially abated the decadal drought of the 1970s and 80s, but episodic droughts have occurred as recently as 2012.It is unclear whether the droughts are due to natural variability or anthropogenic forcing[3]. 80% of Sahel rainfall comes from mesoscale convective systems which are smaller storm systems that last several days during monsoon season; therefore, understanding the monsoon season could impact the millions who live in this region. Predicting seasonal variability in the Sahel could help to alleviate drought impacts[4].

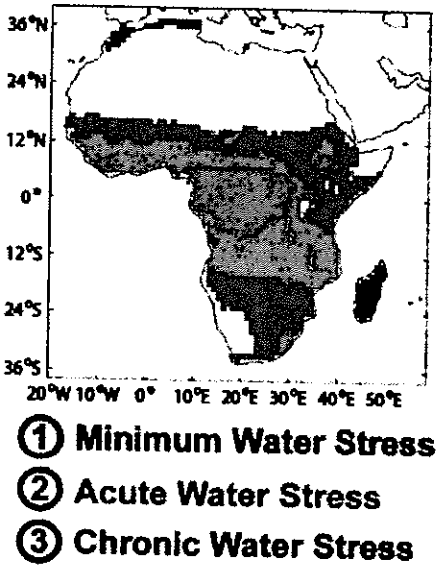

Figure 1: Map of water stress across Africa. Regions with chronic water stress include the Sahel and South Africa, among others[4].

The West African monsoon (WAM) is a major meteorological system which occurs annually between 9 and 20 degrees north[2]. Characterized by the seasonal reversal of the winds, the monsoon accounts for a significant portion of the annual precipitation[2]. During the summer, the WAM is dominated by southwesterly winds. The monsoon forms along a low-level pressure gradient toward the Sahara, with precipitation that is "essential to the livelihood of millions"[2]. Sahel farms depend on not just the volume but also the timing of the rain for a successful agricultural season.

Planting crops too soon before the seasonal monsoon could lead to huge financial loss and famine – yet another reason why modeling the West African Monsoon could aid African farmers[4].

Current climate models fail to accurately describe Sahel rainfall patterns. Several models incorrectly describe West Africa "as a moisture source rather than a sink" over the summer[2]. Models which parameterize convective clouds have too much light rainfall, but not enough heavy rainfall[2]. Additionally, there is no consensus between models in projections of future rainfall changes. It is unclear how or even whether the disparate simulations of future climate are linked to disparate biases in the current climate and in particular to the inability of coarse resolution climate model to resolve convective patterns in mesoscale convective systems[2].

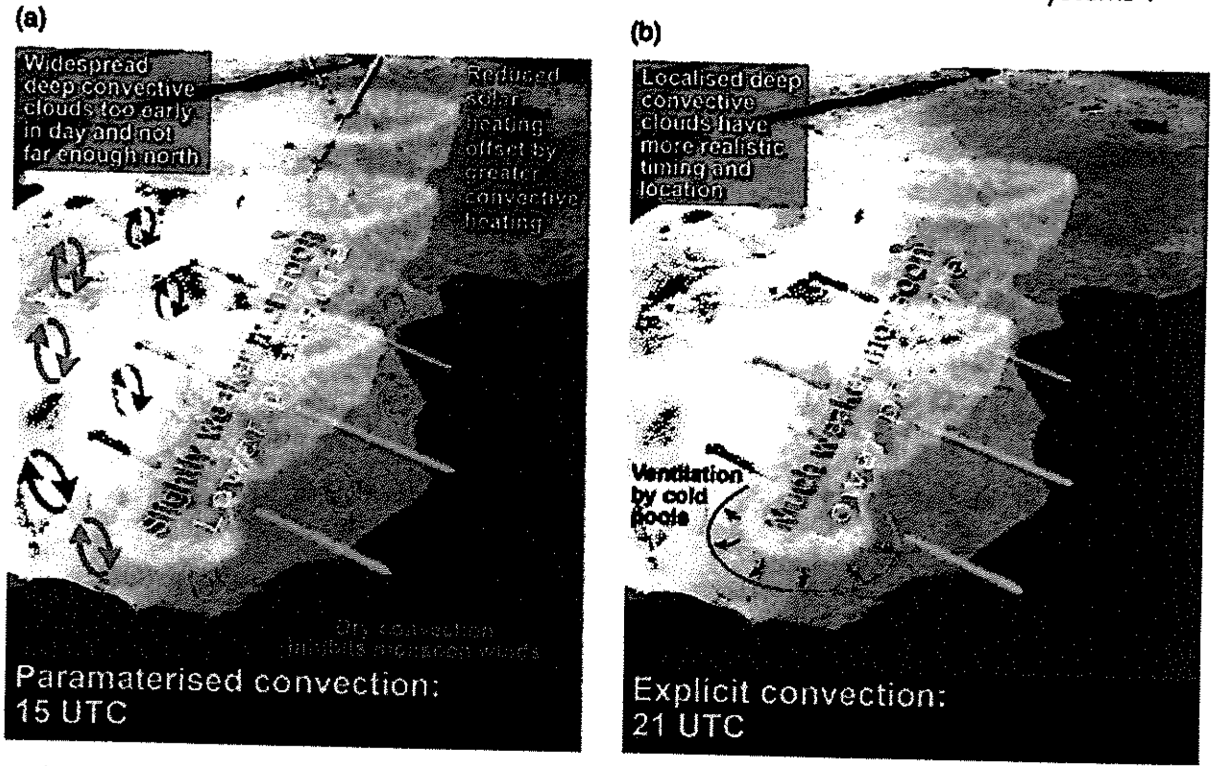

Figure 2. Map displaying clouds which formed in the parameterized convective model against the clouds which form in the explicit convective model[2].

Marsham et al. compares models with enough resolution to explicitly resolve convection versus models which rely on simplified relationships between large-scale motions and convection (convective parameterizations). Marsham et al. find that models with explicit convection are more realistic than those with parameterized convection, having more intense rainfall later in the day. With rainfall later in the day, the explicit models have more daytime radiative heating and evening latent heating which drives stronger pressure gradients during the day than at night[2]. As shown in figure 2, the parameterized model failed to capture the same convective process[2]. Marsham et al. concludes that this inter-model comparison displays how poorly understood parameterized convection is, but also how important parameterizations are for predictive modeling of the West African Monsoon.

II. Objective and Methods

Researchers with the National Center for Atmospheric Science, UK and the University of Leeds have developed 4km-resolution simulation of 10 years of climate over Africa, UK Met Office Unified Model (UM)[2]. As previously mentioned, at high resolutions, the model reproduces some characteristics of rainfall that are seen in observations but not in models with parametrized convection. Rainfall observations show mesoscale convective systems form later in the day and dissipate at night. This time signature is mirrored in explicit convective models, in which the increased radiative heating leads to a stronger pressure gradient, as mentioned above. This important time signature is missing in parameterized models.

For my project, I will use data from this model in collaboration with the UK researchers to investigate the source of the peculiar time signature of north and central African rainfall. We will attempt to explain this behavior by analyzing fields with similar differences in the time signature which we know are important to permit and to organize convection, (precipitable water, wind shear, surface fluxes, etc.). You will also continue to compare model data to observed data as well as perform reanalysis of the observed data.

III. Work Plan and Travel

1. Weeks 1-6
   Perform data analysis of UM data with Prof. Biasutti at the International Centre for Theoretical Physics in Trieste, Italy
2. Weeks 7-10
   Continue data analysis of model outputs and comparison to rainfall observations at Columbia University in New York, New York

IV. Personal Statement and Qualifications

I chose to study planetary sciences only after beginning to study mechanical engineering. I decided to radically change my academic goals while the Sierras pass by on my first geology field trip. Since then, I've explore a wide range of courses ranging from physical geology to astrobiology to Earth's atmosphere. I've become increasingly aware that those least responsible for climate change are the most effected – and the reverse, that those countries more responsible see few consequences. To make matters worse, these consequences disproportionately harm women, children, and the elderly. Not only is climate change a ripe area of research, but I feel I can make the most impact on the global community through this area of research. This research project follows naturally from my previous research projects, my courses, and my academic goals.

I've spend the previous three summers performing research at Caltech/JPL. My previous projects include analyzing the metallicity of a lithium-rich star, mapping the temperature dependent properties of ferroelectric alloys, and implementing a C/C++ based dynamic vegetative model within a larger model intercomparison project through JPL/NASA. Most specifically, my project last year with the Carbon and Ecosystems group at JPL gives me the computer science background to work on this project. I've become proficient with Python, Matlab, and LaTex, and I am familiar with C/C++, bash, IDL, and Mathematica. My breadth of coding skills speaks toward my ability to complete this project and also my ability to learn new languages while completing a project. As a planetary science major and environmental science and engineering minor, I've had a variety of classes on atmospheric and oceanic dynamics, as well as sustainability, which provide me with the necessary theoretical foundation. JPL researcher Dr. Joshua B. Fisher and Assistant Professor Andrew Thompson will provide my letters of recommendation.

V. Mentor

Professor Michela Biasutti is Lamont Associate Research Professor with the Lamont-Doherty Earth Observatory at Columbia University. She received her BS from the University of Trieste and received her Ph.D in Atmospheric Sciences from the University of Washington. Her research focuses on tropical climate systems and anthropogenic climate change.

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Origins of Cyanides in Protoplanetary Disks

[redacted]

Mentor: Karin Öberg
Co-Mentor: Romane Le Gal

Introduction/Background

One of the defining characteristics of life on Earth is the existence of an informational genetic polymer such as DNA or RNA. The "RNA world" hypothesis dictates that RNA was the first of these molecules to form, however, there exists much debate as to how such a process could occur on the early Earth spontaneously. While ribonucleotides will, under certain conditions, polymerize to form RNA, the constituent pieces of these ribonucleotides (ribose and bases) are difficult to form and connect to one another.

However, there are some potential formation pathways that bypass these steps. Powner et al. [1] found that pyrimidine ribonucleotides can be formed in a reaction sequence that skips the formation of free ribose and bases. This pathway involves various aldehyde, acetylene, and amide molecules that could all be plausibly found on a primordial Earth according to current geochemical models.

One interesting molecule is acetonitrile (CH_3CN), whose C-N bonds are of the same sort as those involved in abiotic amino acid synthesis. This molecule has been detected in comets around our own sun [2], and studies of solar nebula analogues indicate that simple volatiles commonly survive disk formation.

Studies of icy protoplanetary disks suggest that they have a somewhat high abundance of these molecules and other complex cyanides, suggesting that the rich organic chemistry that produced Earth is not unique to our solar-system [3]. Sophisticated models have been developed in order to account for the existence and abundances of these molecules in an attempt to garner further information on the synthesis of ribonucleotides and the origins of life on Earth.

As described in Öberg et al. [3], the relationship between gas-phase and ice abundance ratios depends on the desorption characteristics and chemistry of the molecules involved. HCN, HC_3N, and CH_3CN are characterized by similar freeze-out and desorption kinetics, but different chemical pathways. In particular, the existence of efficient grain surface pathways to CH_3CN enhances it with respect to other cyanides in the ice mantles of developing systems. The scale of this enhancement factor varies among models, but they all agree that it is at least one order of magnitude [3].

The Horsehead Nebula, located in Orion, is an excellent location to study stellar formation and system development. Due to its proximity, it is extremely luminous and occupies a large angular size on the night sky. In addition, its geometry gives us an "edge-on" view of the system [4]. Recent studies of the Horsehead Nebula by WHISPER [1] (Wideband High-resolution Iram-30 m Survey at two Positions with Emir Receivers, PI: J. Pety) show that the CH_3CN spectral lines are far stronger in the surveyed photodissociation region (PDR) than in other regions of the Horsehead Nebula. Meanwhile, HC_3N was found in relatively low abundance in this region [5]. A PDR is a neutral cloud of interstellar gas subject to strong UV radiation typically found in star-forming regions. The chemistry of such environments is of interest with respect to the chemistry of developing planetary systems.

The intensity of the CH_3CN spectral lines suggest that surface desorption processes should be efficient enough to release organic molecules into the gas phase in far-UV dominated regions of a given system [6]. Models developed by Le Gal et al. [6] coupling the Meudon PDR [7] and Nautilus [8] codes underestimated the abundance of CH_3CN in the PDR by around two orders of magnitude, and could only reproduce observed ratios for higher visual extinctions, suggesting that the species might not be found in the same position as the other detected cyanides (HC_3N and C_3N). The high abundance observed might be explained by a higher photodesorption rate and lower ice photolysis rate than those currently assumed in the models.

In this project, we will update the models on the production of CH_3CN and HC_3N in an effort to explain these observations and predict any potential correlations between the two molecules. We will then develop a new disk chemistry model to complement the existing PDR model and evaluate predicted molecular abundances.

Objectives/Approach

The goal of this SURF project is to more accurately quantify and describe production pathways of CH_3CN and HC_3N in PDRs. In addition, we hope to implement these pathways in an updated code that will allow us to check whether our

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[1] http://www.iram-institute.org/ horsehead/Horsehead$_{Nebula/WHISPER.html}$

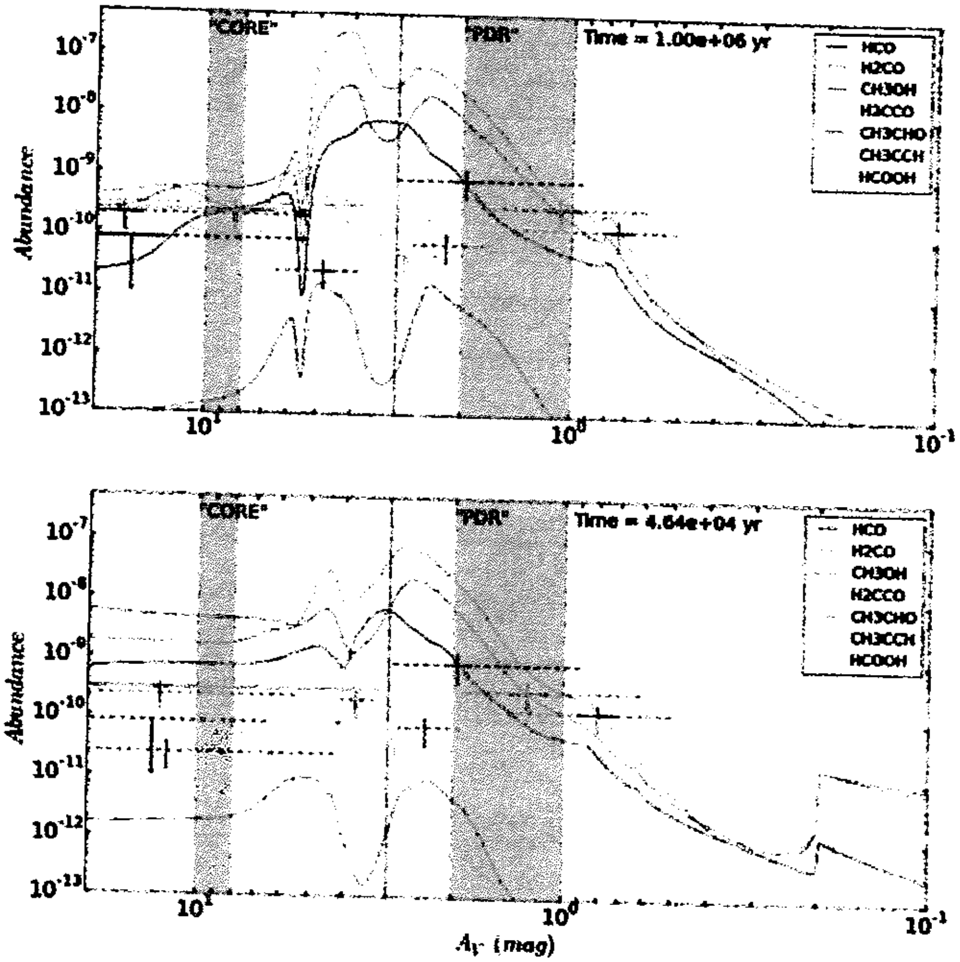

Figure 1. Plot from Le Gal et al. [6] comparing observed and modelled abundances of various molecular species of the Horsehead Nebula at two different cloud ages. The model results are depicted with solid curves. The observations are depicted with vertical error bars and horizontal lines, which are solid where the model reproduces observed abundances fairly accurately and dashed where they agree only within a factor of ten.

theories agree with observations of molecular abundances in these regions. By doing this, we hope to update current PDR models and shed further light on how ribonucleotides form abiotically.

The Meudon PDR model code [7] considers a steady-state plane of gas and dust illuminated by an ultraviolet radiation field. At each point in the field, it solves iteratively for UV radiative transfer and chemical reactions, taking into account various thermal processes in the cloud. This program is able to compute species abundances, column densities, and overall cloud emissivity. While the steady-state approximation prevents the results from being compared to rapidly evolving systems, studies have shown that photoprocess timescales are typically such that this approximation yields satisfactory results. The code used in Le Gal et al. [6] uses both the 1D gas-grain code Nautilus and the Meudon PDR code to model the chemical evolution from a parent molecular cloud into the Horsehead Nebula.

At the beginning of the summer, we will search through the currently existing literature on the abiotic production of cyanide molecules in an effort to supplement the pathways currently described in the Le Gal et al. [6] model. We will also communicate with current astrochemistry theorists in an effort to come up with new production paths of CH_3CN that are not considered in disk models.

After exploring the theories regarding molecular production pathways, we will then run a large grid of 0-D disk models (varying properties such as density, temperature, radiation, C/O ratios, and C/H ratios) with both the original and supplemented chemical networks. We will study the results of these models and determine what situations result in the production of large quantities of CH_3CN and HC_3N and how the molecules correlate with each other. To perform these simulations, we will use the model developed by Le Gal et al. [6] and the public Meudon PDR code.

Once we are satisfied with our findings, we will implement the enhanced reaction network in an existing disk chemistry model and evaluate its predicted molecular abundances at different disk locations and check to see how they compare with observations. Ideally, we hope to end the summer by developing a new model that agrees with protoplanetary disk observations.

Work Plan

The timeline for the project is as follows:

1. **Before the summer program**, I will prepare for the project by familiarizing myself with cosmochemistry literature and the general reaction pathways more commonly found in space.
2. By **week 2**, I will work alongside astrochemistry theorists to develop and describe additional formation pathways of CH_3CN and HC_3N in PDRs.
3. By **week 4**, I will run PDR models with the Meudon code to describe how various disk properties impact molecular abundances.
4. By **week 6**, I will compare my model predictions to observed stellar disk properties.
5. By **week 8**, I will write the first draft of my paper.
6. By **week 10**, I will write the final draft of my paper.

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