— Research Statement —

Motivation: Heat waves present a severe threat to human health. The European heat wave of 2003 alone is estimated to have killed over seventy thousand people [1]. Moreover, it is expected that both the *frequency* and *intensity* of heat waves will increase significantly in a warming planet, making **the understanding of heat waves an urgent issue in anticipating the impacts of climate change** [2]. In order to fully understand heat waves, one would require a model of the thermodynamic interactions taking place at the land surface that results in extreme heating of near-surface air. However, land-atmosphere modeling remains a difficult task, as various complex representations of the land surface (which dictate, for example, the interplay between near-surface air temperature and soil moisture) often dampen our ability to glean the underlying cause of extreme heating events. Hence, a first-principles theory underpinning the formation and persistence of heat waves remains elusive, especially one that is independent from large-scale numerical models. **I propose to utilize conceptual models and existing datasets to develop a novel theory of heat waves in terms of fundamental interactions between the atmosphere and the land surface.**

Intellectual Merit: Forecasts of changes in heat waves rely on projections from general circulation models (GCMs) [3]. GCMs attempt to model *every* relevant component of the climate system by incorporating a full suite of interconnected, codependent physical processes, such as ocean and atmospheric circulation and the carbon cycle. The resulting forecast often amounts to insufficiently understood emergent behavior [4]. The sheer complexity of GCMs, and disagreement in the representation of physical processes key to heat waves, makes model comparison and verification challenging [5]. **Therefore, supplementing GCM simulations with conceptual models of the underlying physics has the potential to lead to rapid progress on understanding how heat waves are generated** [6].

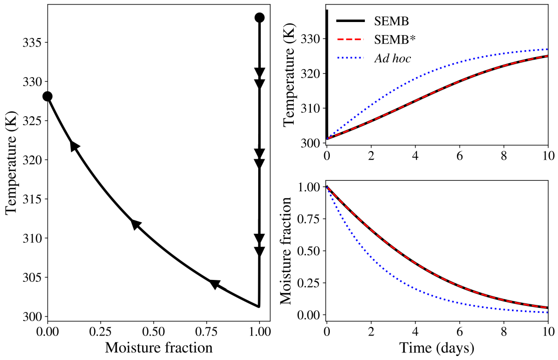

Figure 1: *(Left.)* A phase-space trajectory in SEMB. Double (single, resp.) arrows indicate fast (slow, resp.) evolution. *(Right.)* On top (bottom, resp.) is the temperature (moisture, resp.) time series found using SEMB, SEMB*, and the *ad hoc* approach; notice SEMB* considerably outperforms the *ad hoc* method.

Conceptual models are a set of equations that reflect *identifiable physical interactions between state variables*, and have been used to elucidate the underlying physics of processes such as climate variability [7] and the El Niño-Southern Oscillation [8]. Recently, the Surface Energy and Moisture Budget (SEMB) model has been developed to describe near-surface temperature and moisture thermodynamics in a conceptual framework; this model was used to investigate the mechanisms of temperature extremes over land [9]. However, SEMB relies on the introduction of an *ad hoc* parameter to decouple the moisture and temperature dynamics. **This parameter has no physical interpretation, and moreover, it is unclear how it will evolve under climate change.** This hinders the ability of SEMB to forecast how temperature extremes will change under global warming. **In addition, the *ad hoc* approach only approximately recaptures the dynamics of SEMB**, see Figure 1. Hence, it would be *highly valuable* to eliminate this parameter entirely, and develop a model for temperature extremes in terms of parameters whose evolution under climate change is well understood. Once such a model is formulated, one can force the equations with stochastic noise (meant to represent random weather events) to investigate how the temperature distribution evolves as the climate changes. **This will be the goal of my project: to develop a model for temperature and moisture thermodynamics, and use it to build a first-principles theory of how heat waves arise and change under global warming.**

Existing Progress: Over the past months, I have worked with Prof. Cristian Proistosescu and Lucas Vargas-Zeppetello (the developer of SEMB) to formulate a model for temperature and moisture thermodynamics without using *ad hoc* approximations. To do so, I exploited timescale separation within SEMB; using the fact that moisture only evolves on slow timescales, I derived an evolution equation for moisture (coined as SEMB* herein) that is both independent of temperature and in terms of fundamental physical parameters. One can use the output of SEMB* to solve for the temperature time series (also in terms of fundamental physical parameters) via a simple mapping. **I then solved SEMB* analytically, which reproduces the output of SEMB, unlike the *ad hoc* approach taken in [9]**, see Figure 1. Forcing SEMB* with stochastic noise allows us to analytically study the moisture and temperature probability distribution functions (PDFs). This provides us with insight on how the temperature distribution evolves in time, which will serve as a springboard for our study of extreme heating events.

— Project Outline —

Task 1: Compute the moments of the moisture and temperature distributions. *(Year 1)*
Forcing SEMB* with stochastic noise gives rise to a Hasselmann-type model [7] that allows us to quantify land-surface variability. Using the analytic solution to SEMB*, I will compute the moments of the moisture PDF using stochastic calculus. I will then translate the moisture PDF moments to temperature PDF moments using the mapping described in *Existing Progress.* We expect this step to be mathematically technical, and have begun collaboration with Prof. Lee DeVille, a specialist in probability, to ensure success on this phase. The skewness and kurtosis of the temperature PDF, which give us information about the PDF tails, are especially important in estimating the probability of extreme events such as heat waves. These quantities can be solved for in terms of the PDF moments. **Therefore, by deriving the temperature moments in terms of fundamental physical parameters, we will glean insights into the controls on heat wave intensity and frequency.**

Task 2: Verify analytic calculations using observational and GCM data. *(Year 2)*
My next task will shift the focus of the project from analytic calculations to statistical and computational work. *I propose to use public data from terrestrial sources and GCMs to verify my predictions for the relationship between the temperature and moisture PDFs and physical parameters.* For example, by fitting an exponential decay profile to the soil moisture content after a rain event, I can compare my prediction for the characteristic timescale of soil dry-down to the data. This work will be performed on Keeling, an on-campus High Performance Computing cluster which we already have access to.

Task 3: Investigate the sensitivity of temperature moments to climate change. *(Year 2 & 3)*
My final task will be to investigate the sensitivity of the temperature distribution moments under climate change. This is the crux of our efforts: a first-principles prediction of how the moments of the temperature distribution — and thus the distribution of extreme events — will evolve in a changing climate. To carry out this forecast, I will use the analytic relation between distribution moments and quantities such as mean relative humidity over land and mean precipitation (from *Task 1*), whose evolution under climate change is well understood. **Using the projected value of these parameters, I will quantify how heat wave frequency and intensity is expected to change in a variety of future climate scenarios.**

Broader Impacts: The work proposed here will shed light on the underlying physics of heat waves, and how the near-surface temperature distribution evolves in a warming planet. In order to complete this work, we will rely on fostering *interdisciplinary collaboration* between physicists, mathematicians, and climate scientists. **Completing this project will greatly improve our ability to forecast extreme temperature and humidity events, therefore making the outcome of this work essential in addressing the human, economic, and ecosystem risk associated with climate change.** For example, understanding how heat wave intensity and frequency will evolve as the climate changes will help economists better forecast the economic damages associated with global warming. In turn, this can improve our estimates of important figures such as the cost of carbon. Hence, this work not only benefits the climate science community, but many other academic disciples as well, with the potential to influence public policy directly. *This reality motivates my desire for an NSF fellowship, so I can contribute to our understanding of heat waves, both as they function now, and how they will evolve in the future.*

References: [1] J. M. Robine et al., *CRB*, 331(2), 2008 — [2] S. E. Perkins-Kirkpatrick et al., *NC*, 11, 2020 — [3] R. Huth et al., *CC*, 46, 2000 — [4] M. P. Clark et al., *WRR*, 47, W09301, 2011 — [5] R. A. Fisher et al., *JAMES*, 12, 2020 — [6] K. Emanuel, *AGU Adv.,* 1(2), 2020 — [7] K. Hasselmann, *Tellus*, 28(6), 1976 — [8] C. Wang, *JoC*, 14(1), 2001 — [9] L. R. Vargas Zeppetello et al., *JoC (in review)*, 2021.