Generating accurate numerical predictions for tropical cyclones is one of the most challenging problems in weather forecasting. These storms are among the most powerful and destructive extreme weather events on Earth, causing over $1.3 trillion in damages and over 6800 deaths in the US since 1980. The devastating impact of these storms underscores the importance of early warnings, which can allow for extra time and preparedness for government, emergency services, and the general public to take preventive measures and safeguard their homes and lives.

Joseph Knisely, a Ph.D. candidate at the University of Maryland, College Park, is the recipient of the Weather Program Office (WPO) Innovation for Next Generation Scientists (WINGS) Dissertation Fellowship, supported by NOAA WPO and administered by UCAR's Cooperative Programs for the Advancement of Earth System Science. This program aims to develop and foster the next generation of atmospheric scientists.

"The opportunities provided by WINGS have been invaluable for my education and career," says Joseph. "Exploring research that interests me while advancing essential science has been a privilege. I've gained practical experience working with my co-mentor, Daryl Kleist, head of the Data Assimilation and Quality Control Group at the Environmental Modelling Center, and attended conferences and workshops nationwide."

At its core, Joseph's research seeks to advance the science of tropical cyclone prediction through more accurate treatment and assimilation of satellite radiance measurements in the Hurricane Analysis and Forecast System (HAFS), NOAA's operational numerical weather model for tropical cyclones. This model comprises one application of the broader, more general Unified Forecast System, the development of which is a high priority for NOAA's Earth Prediction Innovation Center (EPIC) Program mission. Joseph conducts his research under the guidance of Dr. Jonathan Poterjoy, who encouraged him to apply for the WINGS Fellowship and whose expertise have been instrumental in shaping his academic journey.

Tropical cyclones are particularly difficult to model due to a number of factors, including the complex physical processes between ocean and atmosphere, which are not wholly understood and therefore difficult to model; the scale of these storm systems; as well as the unpredictable nature of rapid intensification.

These challenges are compounded by the nature of tropical cyclone formation and evolution over remote areas of the Atlantic and Pacific oceans, for which we have very few in-situ measurements. Unlike over land, where we possess dense and varied observation networks, we are limited to extremely sparse observation networks over this massive expanse of ocean. As a result, numerical weather models rely heavily on microwave and infrared radiance measurements, which are collected via satellite instruments, such as the advanced microwave sounding unit aboard NOAA polar-orbiting satellites. These instruments are able to derive important atmospheric information at high spatial and temporal resolutions, including temperature and humidity profiles, from which variables such as wind speed and direction can be inferred. The fact that these satellite instruments can collect detailed information across the entire Earth surface, particularly over open oceans, makes them extremely valuable for hurricane prediction.

However, a significant challenge remains: observation error. Satellite instruments do not directly observe atmospheric variables, instead collecting data on electromagnetic energy emitted from Earth's surface and atmosphere from which useful variables such as temperature and humidity are derived from. This derivation requires a radiative transfer model to compare geophysical variables in weather models to measurements collected from satellites. These radiative transfer processes are highly complex and can introduce complicated observation errors, oftentimes producing significant systematic biases. Furthermore, observation errors can arise from other sources, such as improper calibration of the instrument itself.

As a result, radiance measurements must be corrected of biases prior to assimilation into numerical weather models. This important step must be done without knowing the true atmospheric state. "Since these biases depend on specific weather conditions, we can produce statistical models that are constructed based on our physical knowledge of these bias sources. In this way, we are able to leverage our imperfect knowledge of atmospheric conditions to form a relatively accurate estimate of bias for these radiance measurements."

That being said, Knisely and Poterjoy (2023) show that the effectiveness of these bias correction methods varies widely depending on the weather model they are trained on. It also highlights the importance of uninterrupted basin-wide data assimilation methodologies, as opposed to more limited, ad-hoc model initialization steps common in operational hurricane models. "This work serves as both a proof of concept and a motivation for ongoing research exploring continuous basin-wide data assimilation with HAFS. With this research, we investigate new ensemble data assimilation techniques that aim to transition HAFS into a fully probabilistic prediction system. Ultimately, we seek to understand how these methods can improve tropical cyclone forecasting, as well as how they may synergize with the bias correction methodology outlined in my first paper."

Simultaneously, Joseph is exploring more fundamental questions about the bias correction process in idealized, low-dimensional modeling frameworks that replicate known challenges for weather forecasting. "Here, I am examining new strategies for decoupling model and observation bias, which is a major obstacle for effectively using satellite observations for weather prediction." This research is motivated by findings from his first paper, which show how operational bias correction systems, despite their sophistication and effectiveness, still struggle to estimate observation bias without the influence of forecast model errors.

"I can't imagine where my career would be without WINGS," says Joseph. "This opportunity has allowed me to contextualize my work and expand my perspective on what's important and cutting-edge in this field. It's been an invaluable experience."