An Uncertainty Quantification (UQ) Framework for Multiple Parameters: Case Study on Evaluating the Sensitivities of AGCM-Simulated Tropical Cyclones (TCs) to Initial Conditions

Fei He[1], Derek J. Posselt[1], Naveen N. Narisetty[2], Colin M. Zarzycki[1], and Vijayan N. Nair[2]

1. Department of Atmospheric, Oceanic and Space Science, University of Michigan

2. Department of Statistics, University of Michigan

Introduction

- Our atmosphere contains numerous dynamical systems, such as tropical cyclones, extratropical cyclones, frontal systems, jets, teleconnection patterns, etc.
- The growth and decay of these systems are strongly influenced by the atmospheric dynamical and thermodynamical conditions such as atmospheric disturbances, sea surface temperature, atmospheric stability, relative humidity, etc.
- It has long been of interest to study how various atmospheric conditions affect the evolution of the dynamical systems and how the characteristics of the dynamics systems involves with each other.
- **Tropical cyclone (TC)** is one such example.

Introduction

Initial Conditions (Parameters)

- Initial disturbance
- Sea surface temperature
- Background vertical lapse rate
- Environmental humidity
- Vertical wind shear
- Background translational flow
- Etc.

Tropical Cyclone Evolution

Characteristics

- Size
- Vertical extent
- Storm track
- Intensity
- Surface pressure
- Precipitation
- Cloud distributions
- Cloud water content
- Etc.

Scientific Interests: During the evolution of tropical cyclones,

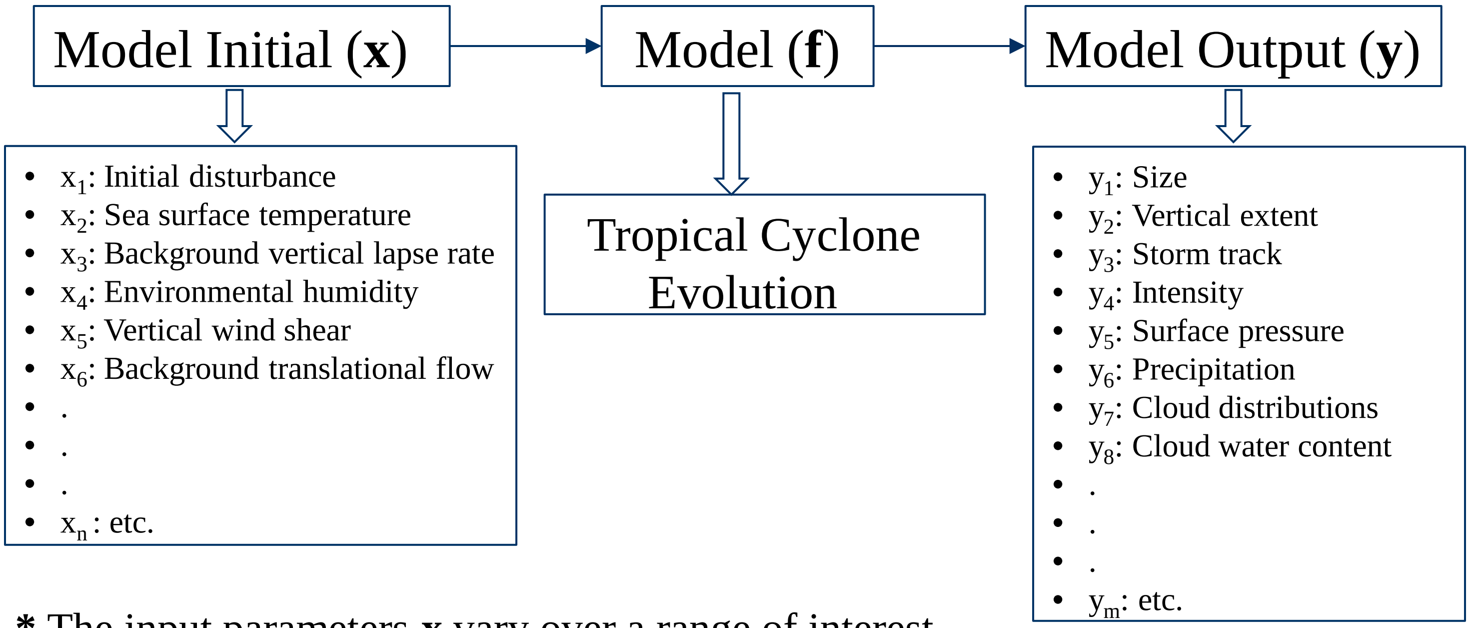
Q1: How the initial conditions affect the TC characteristics? E.g. how the sea surface temperature affects the TC size, which determines its destructiveness.

Q2: How the interactions among initial conditions affect the TC characteristics? E.g. the interaction of vertical wind shear and sea surface temperature on TC intensity.

Q3: How the TC characteristics involves with each other? E.g. wind-pressure, intensity-precipitation, intensity-size, etc.

Introduction

Numerical models are the main tools to study such problems: **y**=**f**(**x**).



* The input parameters **x** vary over a range of interest.

Essentially, two types of relationships:

➢ Input-Output relationships (IO)

➢ Output-Output relationships (OO)

Latin Hypercube Sampling

How to design the simulations?

- 1. Change one-factor-at-a-time while other parameters at a constant value.

  Only examine the relationships from one dimension

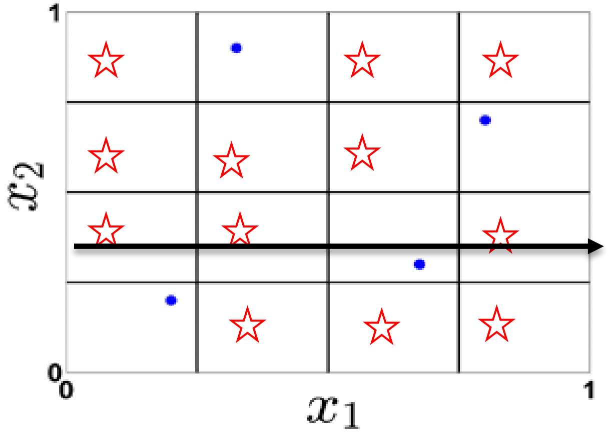
  Cannot examine the impact of interaction among initial parameters on targeted dynamical

  systems.

- 2. Change parameters simultaneously over range of interest with full coverage.

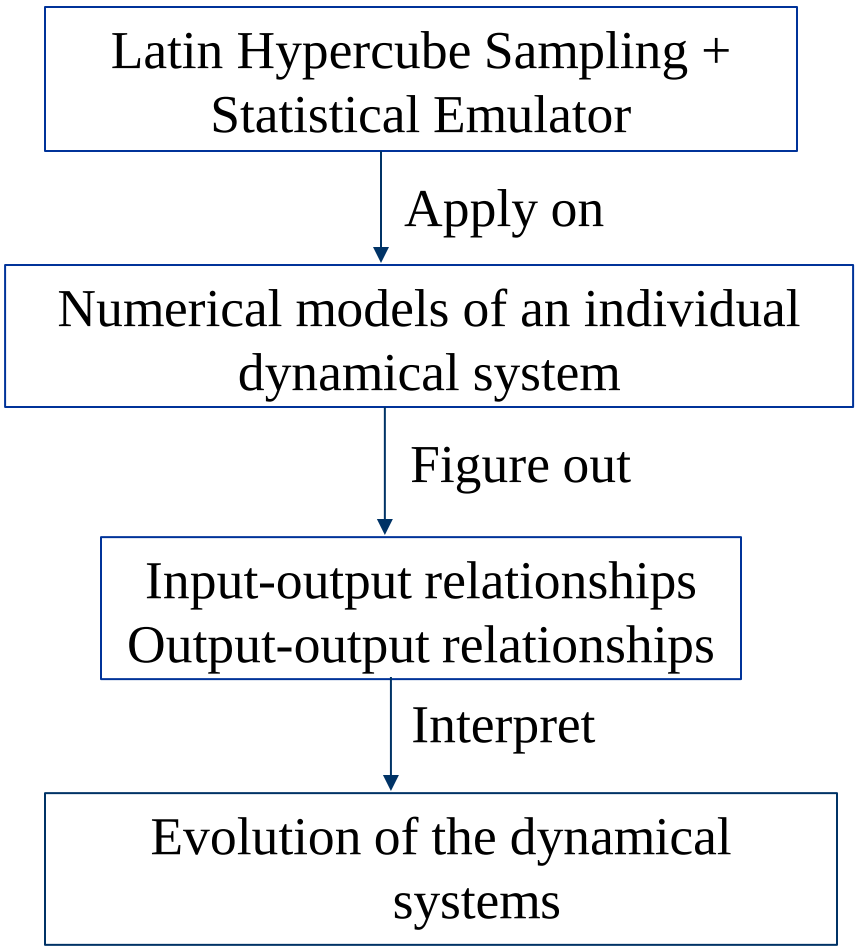
  Quite computationally expensive, especially for models that require intensive computing resources.

An alternative solution:
Latin Hypercube Sampling (LHS)



How to get the values marked by red star?
Statistical emulator: a type of regression tool

Schematic Summary



Example？

The sensitivities of AGCM-simulated Tropical Cyclones to initial conditions.

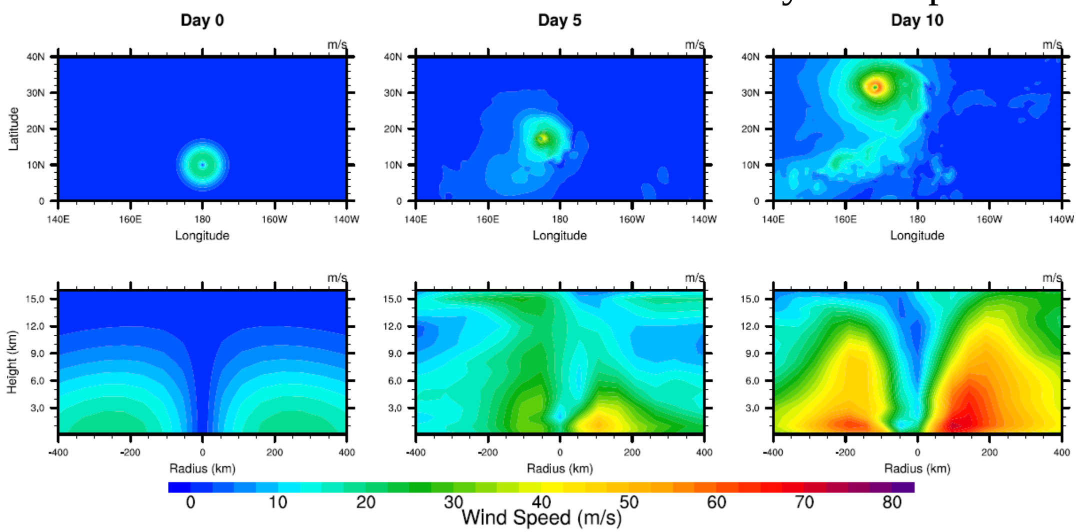
Example: Model Selection

Recall that **y**=**f**(**x**):

Model Initial (**x**) → Model (**f**) → Model Output (**y**)

1. Model Selection:

Reed-Jablonowski TC test case in Community Atmosphere Model



Integration time:
10 simulation days

Construction:
The finite volume (FV) dynamical core is paired with CAM 5.1.1.
The horizontal resolution is 0.5x0.5.
Vertical levels are 30 in total.
The dynamical and physical time step is 90s and 900s, respectively.

Snapshots of the tropical cyclone-like vortex at days (left) 0, (middle) 5, and (right) 10 at the resolution 0.5° L30.

Example: Input and Output Selection

2. Model Input: 300 sampling points

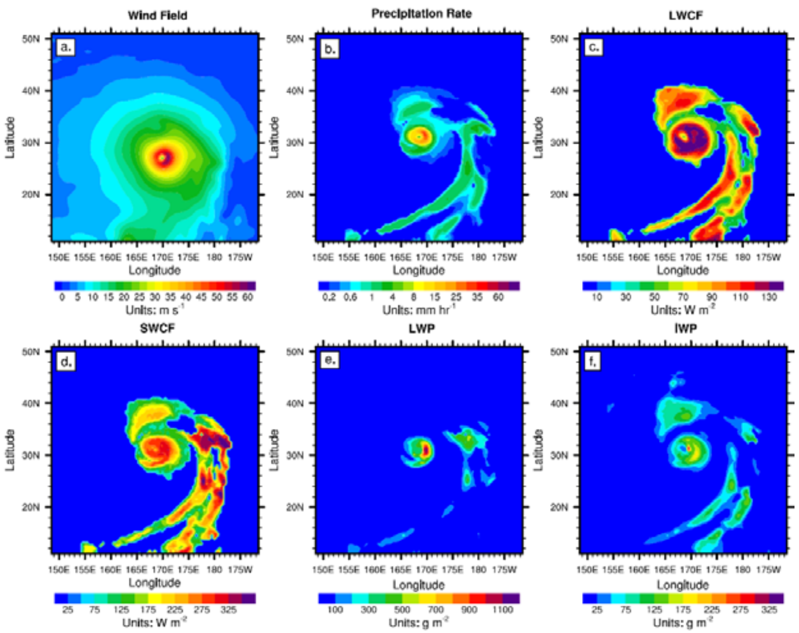
x1: Vortex size
x2: Vortex intensity
x3: Atmospheric instability
x4: Sea surface temperature
x5: 500 hPa relative humidity

Parameters	Range
Radius of Maximum Wind Speed (RMW, km)	[175, 300]
Maximum Wind Speed (MWS, m/s)	[12.5, 25.0]
Temperature Lapse Rate (Gamma, K/km)	[5.5, 7.5]
Sea Surface Temperature (SST, C degree)	[22.5, 34.0]
500-hPa Relative Humidity	[0.4, 0.7]

3. Model Output

y1: Intensity (MWS)
y2: Precipitation rate (PRECT)
y3: Longwave cloud radiative forcing (LWCF)
y4: Shortwave cloud radiative forcing (SWCF)
y5: Cloud liquid water path (LWP)
y6: Cloud ice water path (IWP)

*y1 is defined by the maximum wind speed at 100-m above surface.
*y2-y6 is governed by the area-weighted average over the tropical cyclone region.



Example: Choice of emulator

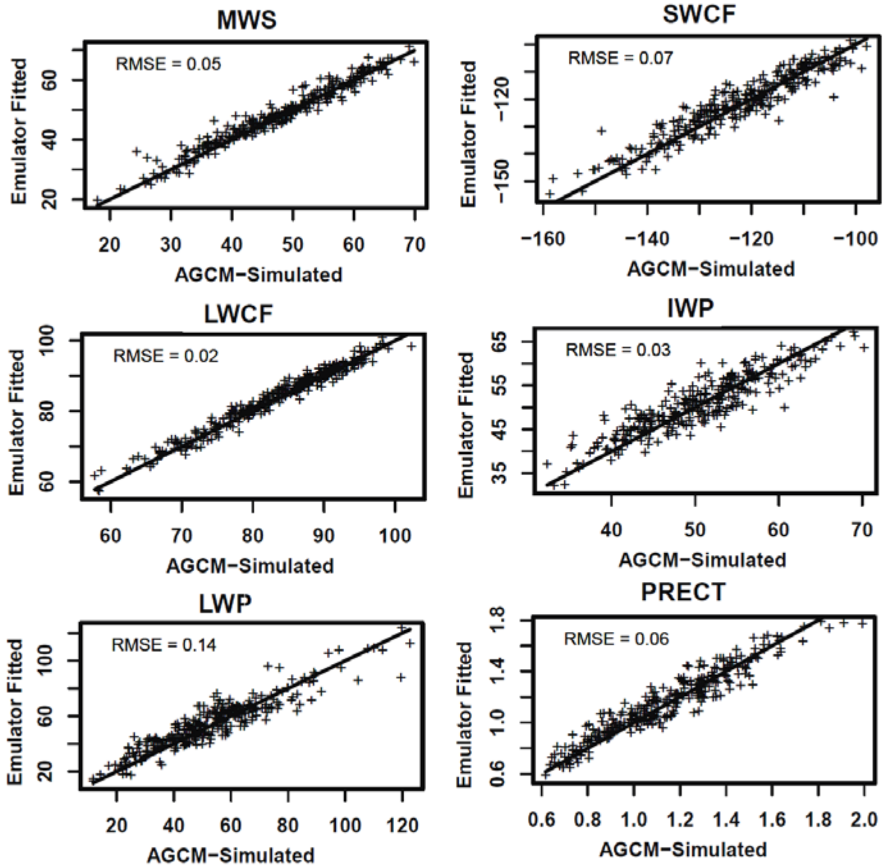
Expanded Multivariate Adaptive Regression Splines (EMARS): emulator/surrogate model/meta-model

- a newly developed non-parametric regression technique.
- an extension of Multivariate Adaptive Regression Splines method.
- automatically models non-linearities and interactions between variables.
- has the advantage of allowing quadratic or higher order components in the model building process.

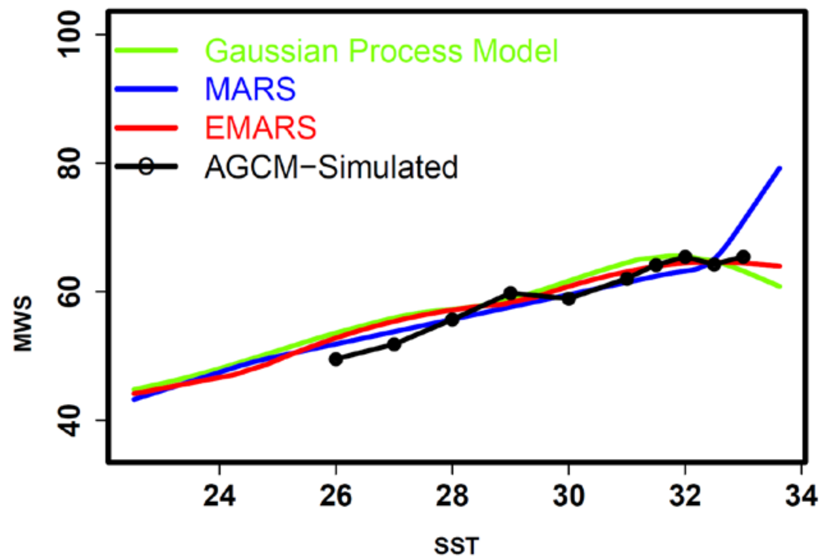
MARS: piecewise linear functions

EMARS: piecewise polynomial functions

Example: Evaluate the fit from EMARS emulator

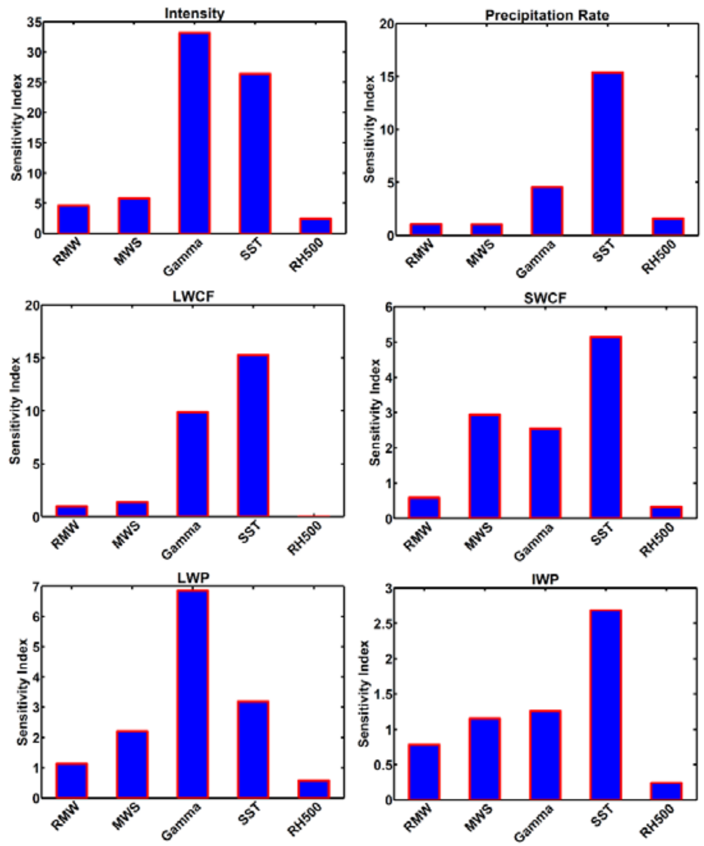


Comparison between AGCM-simulated output values and Emulator fitted output values for the same input points.

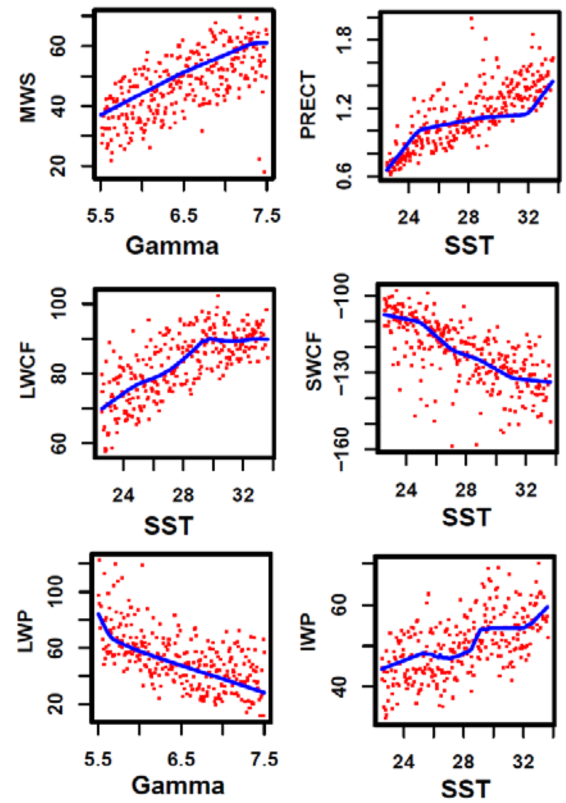


Comparisons of fitted TC intensity by three different emulators and the AGCM-simulated TC intensity.

Example: Input-Output (IO) Relationships



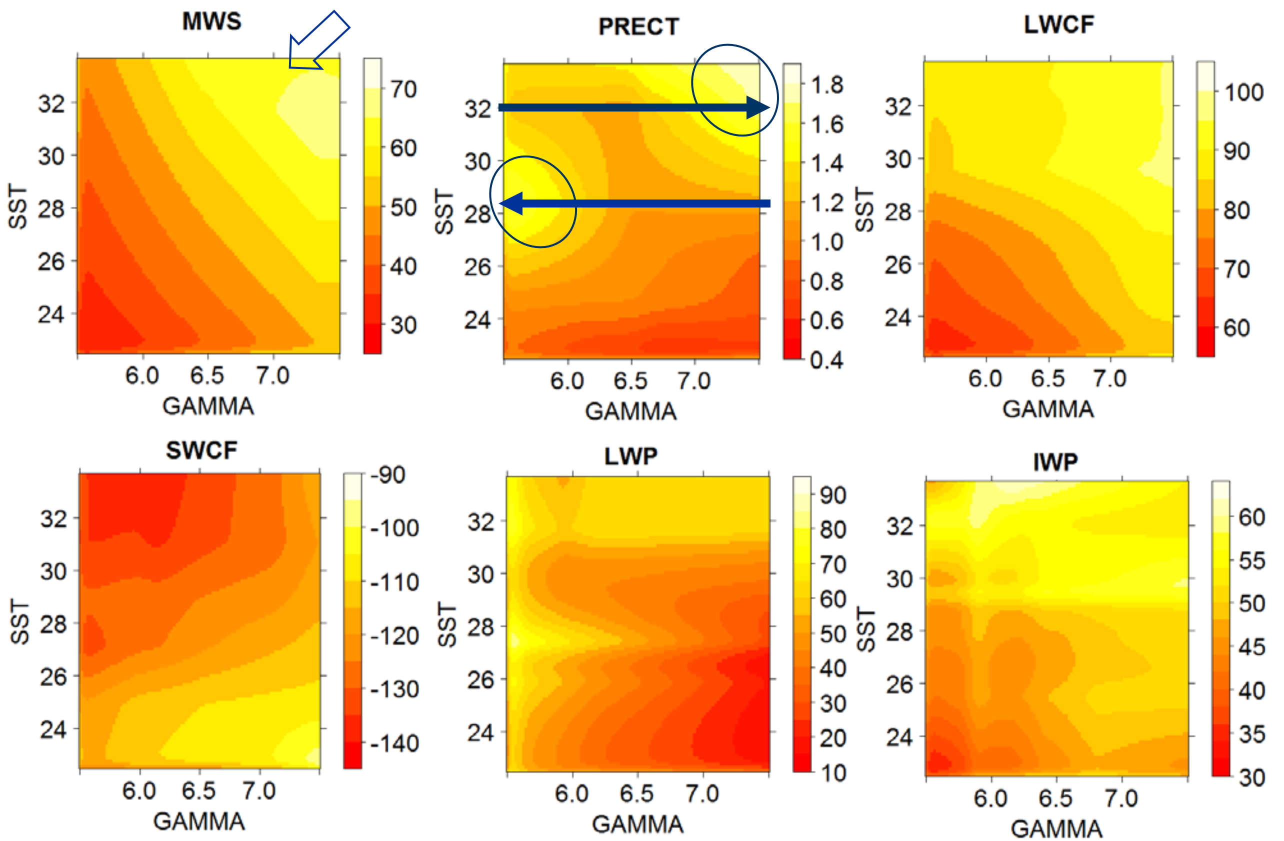
The sensitivity index of the six output variables to the five initial parameters. Sensitivity index is proportion of increase in residual sum of square. It is a measure of importance of the variable. Higher values imply high sensitivity of the variable.



The one parameter input-output relationships with other four parameters fixed to median value of their range.

Example: Input-Output (IO) Relationship with co-vary input parameters

The relationship that quantifies how the output variables change when the input parameters SST and Gamma (vertical lapse rate) change simultaneously with other three input fixed to median.



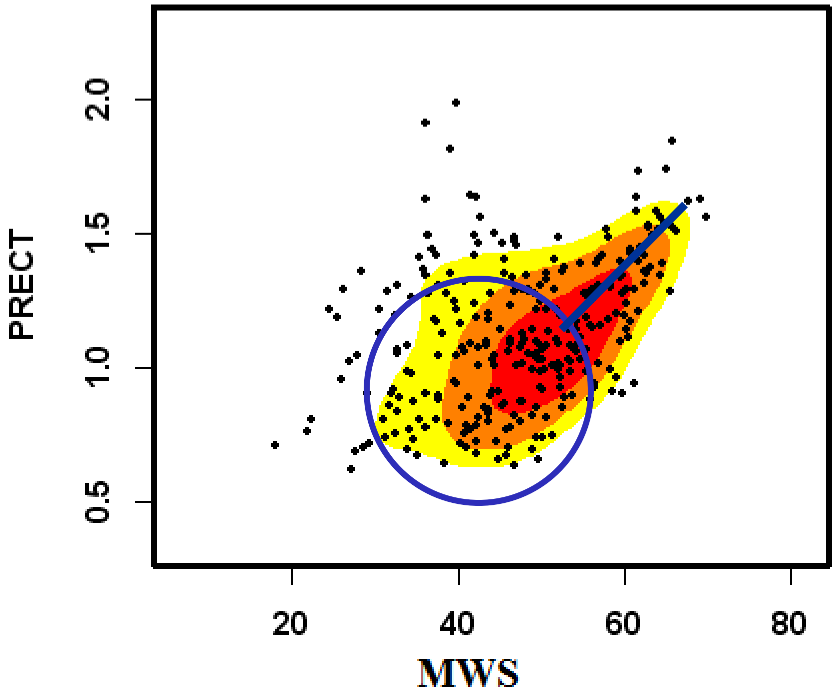
Linear:

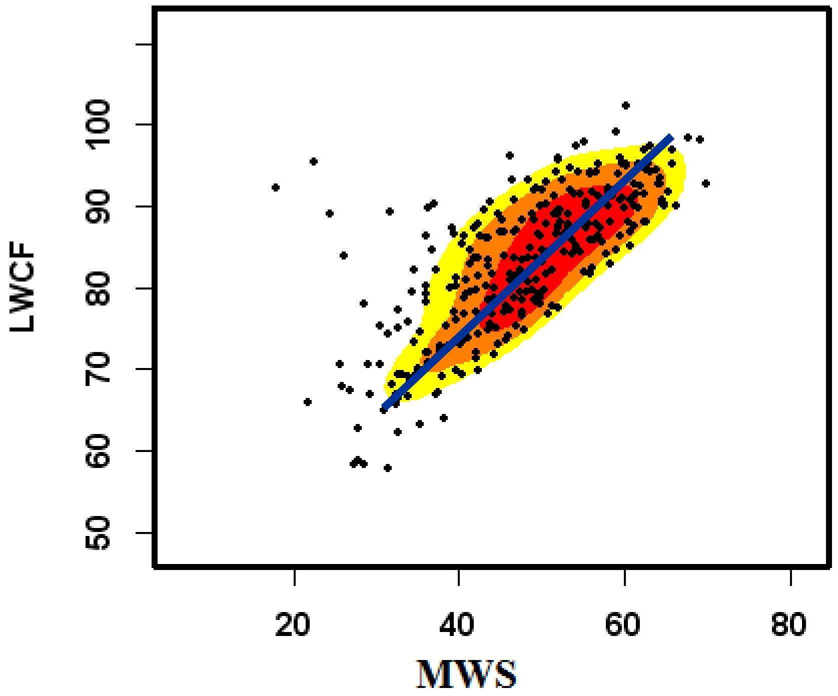
- Intensity
- LWCF

Nonlinear:

- PRECT
- SWCF
- LWP
- IWP

Example: Output-output (OO) Relationships





Intensity-precipitation relationship:
When TC intensity is small (<50 m/s), precipitation tends to be independent with it;
When TC intensity is strong (>= 50 m/s), precipitation has positively linear correlation with it.

Intensity-LWCF relationship:
TC LWCF has positively linear correlation with TC intensity.

Conclusions

- We have explored the new utility of a proven uncertainty quantification framework on the analysis of the dynamical systems.
- Using tropical cyclone as an example, we illustrate how to apply the uncertainty quantification framework to achieve this goal. Namely, it figures out numerous input-output relationships and output-output relationships in numerical simulations.
- The results show that the framework has the potential to apply on other similar problems and improves our understanding the relationships between dynamical systems and atmospheric conditions.

Questions?

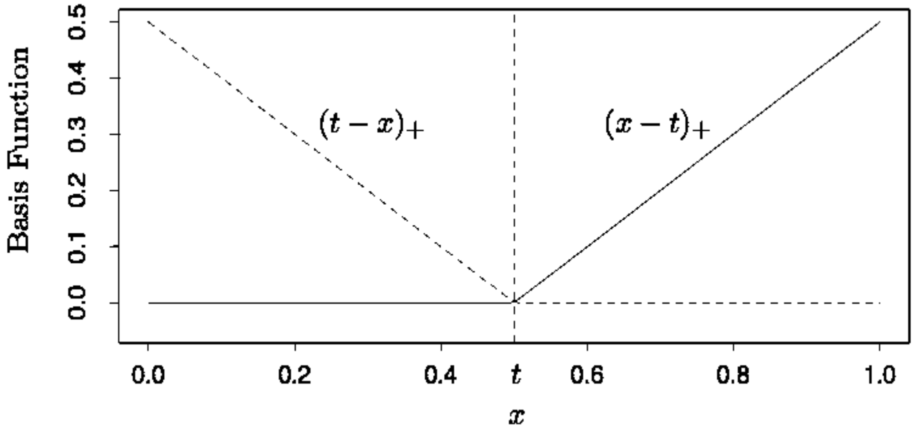
Expanded MARS

Formally, MARS builds a statistical model of the form: $\hat{f}(x_1,\ldots x_n) = \alpha_0 + \sum_j \alpha_j B_j(x_1,\ldots x_n)$

B_j : either a hinge function or product. The coefficients α are estimated using a least square form of criterion.

The algorithm for Expanded MARS (EMARS) is:

1. For a multi-dimensional problem with n predictors ($x_1,\ldots,x_n$) , expand the predictor space from n to $L\times n$ by augmenting the original predictors with $\tilde{x} = (x_1,\ldots,x_n; x_1^2,\ldots\ldots,x_n^2;\ldots;x_1^L\ldots x_p^L)$.
2. Fit the ordinary MARS model based on the expanded predictor space $\tilde{x}$.

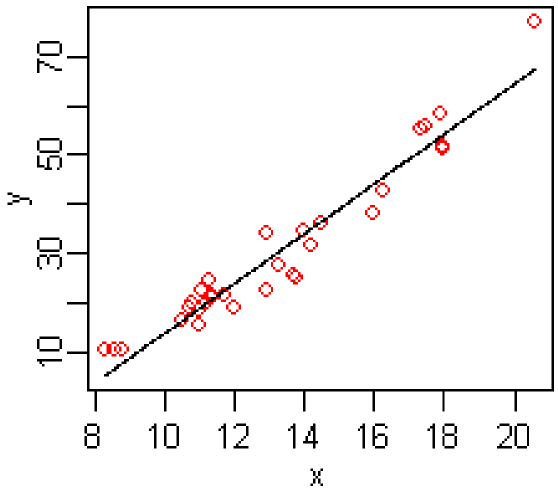


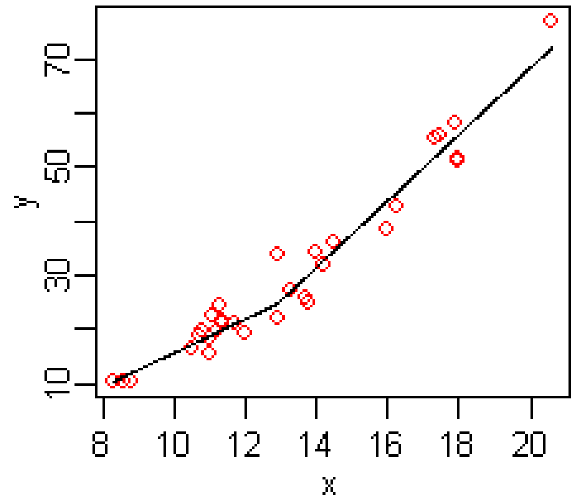
$$\hat{f}(x) = \sum_{i=1}^{k} c_i B_i(x)$$

$$B_i(x) = \begin{cases} \max(0, x - const) \\ \max(0, const - x) \end{cases}$$

Multivariate Adaptive Regression Splines

- Model is constructed of additive and multiplicative hinge functions $B_i(x)$
- Result is an improvement over linear fit, multiplicative hinges address nonlinearity and interaction.

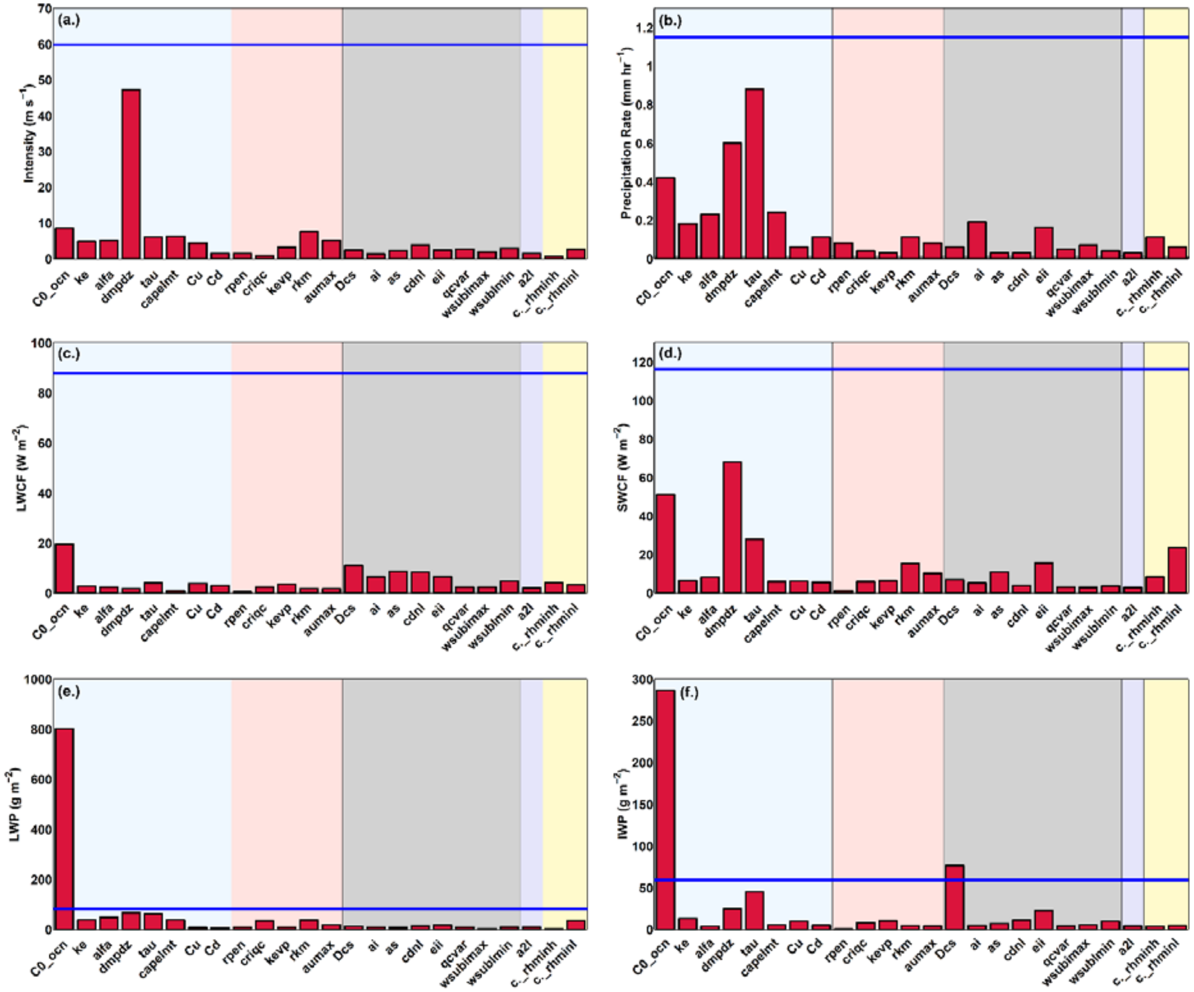




Left:
linear function
Right:
MARS

Hastie, Tibshirani, and Friedman (2009), Elements of Statistical Learning
http://link.springer.com/book/10.1007/978-0-387-84858-7/page/1

Future work – the impact of parameterized physical processes on TC simulations



24 parameters are selected from Zhang-McFarlane (ZM) deep convection (8), University of Washington (UW) shallow convection (5), Morrison-Gettelman (MG) two moment cloud microphysics (8) and cloud macrophysics (2).

Thank you!