Quantifying the sensitivity of tropical cyclone structure to momentum flux in CAM6

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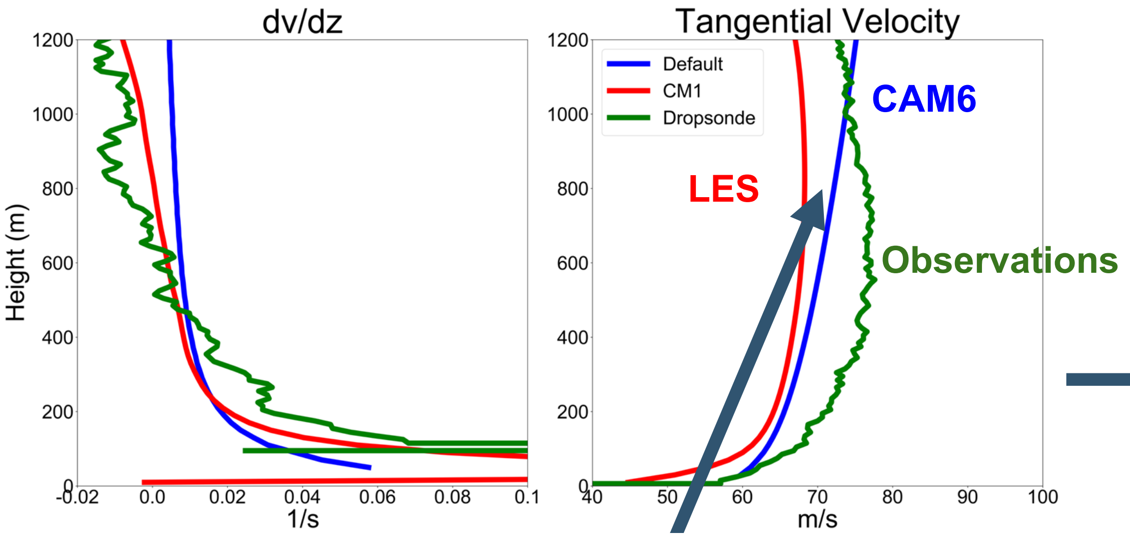
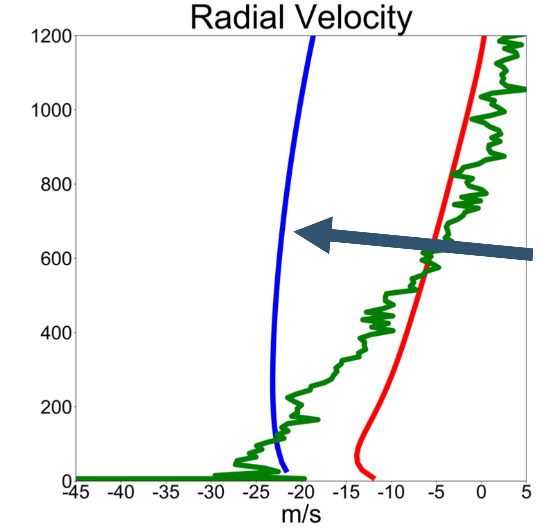
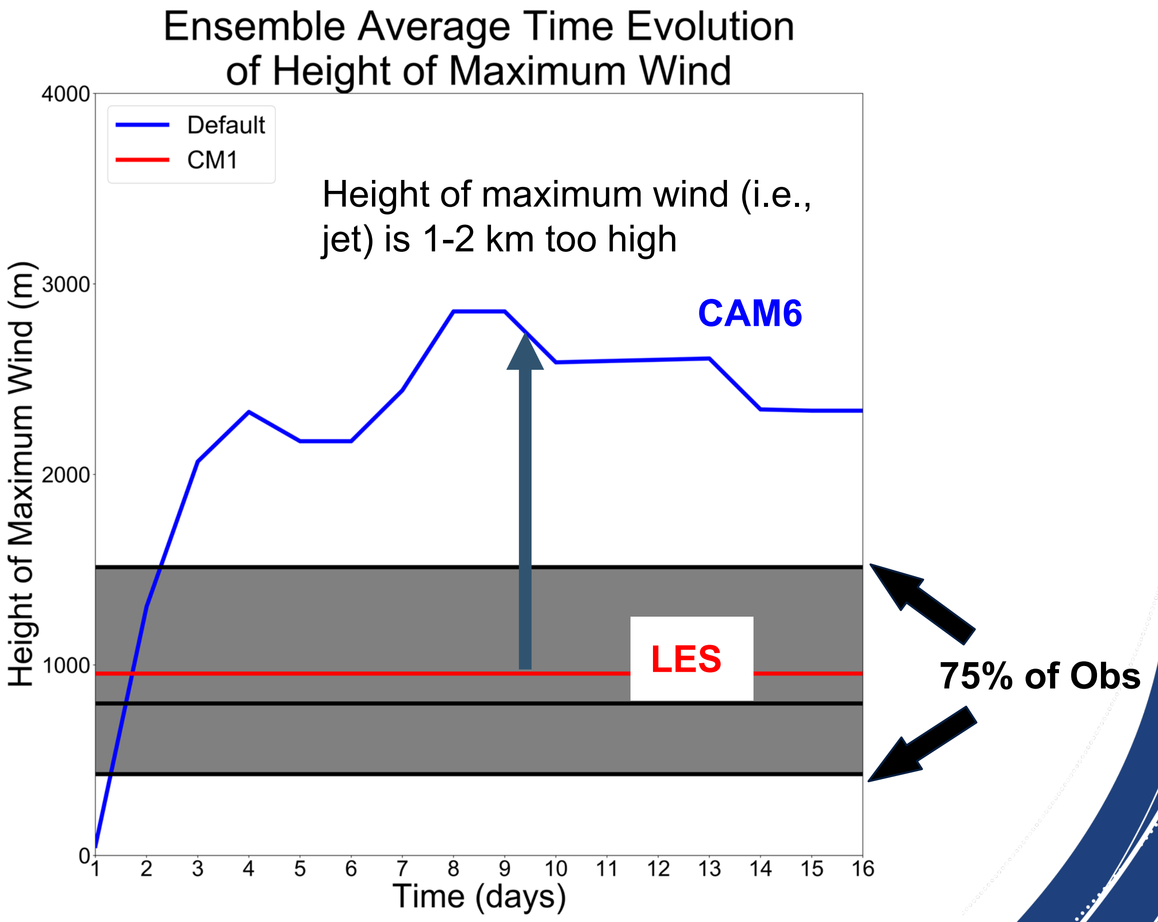
CAM6 produces notable biases in the structure of the TC PBL



Tangential velocity keeps increasing beyond z = 1 km



Radial velocities are too high



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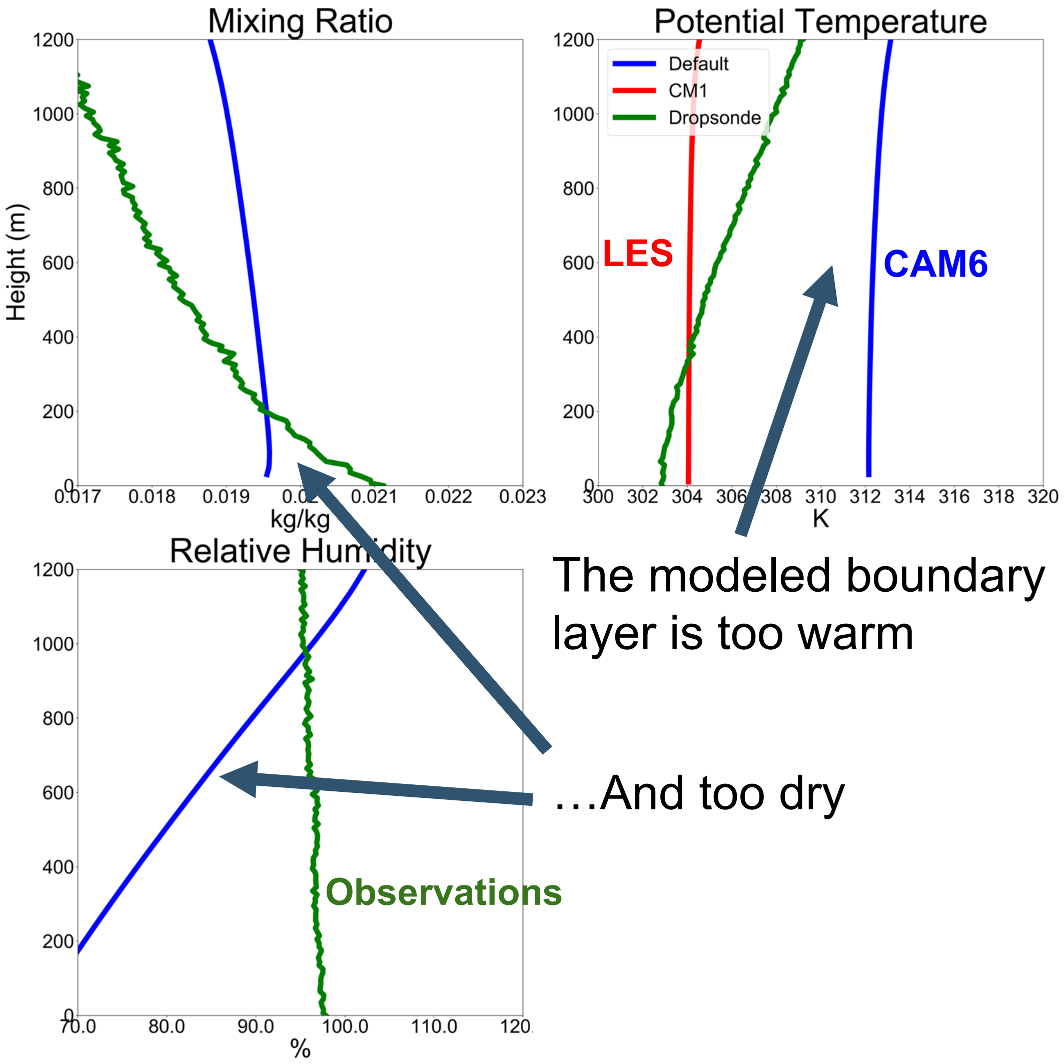

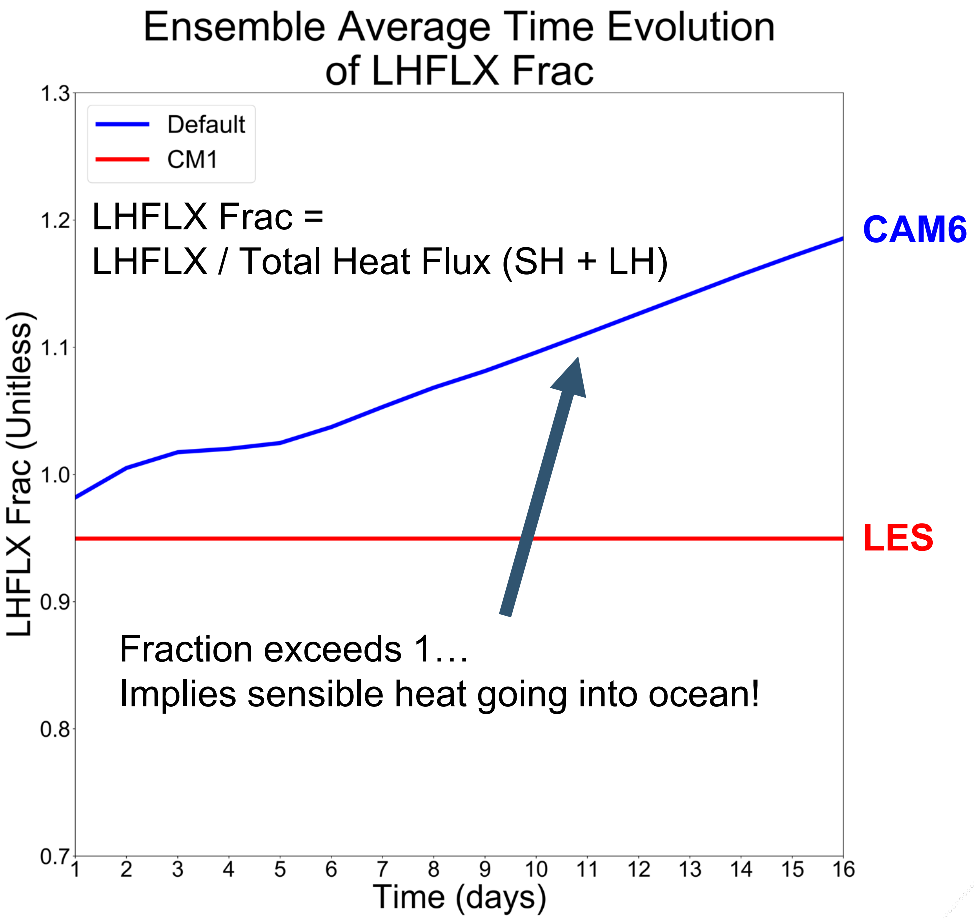

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In this talk, we wish to address two noted model biases:

1. The height of maximum tangential wind (too high)
2. The latent heat flux fraction (also too high)

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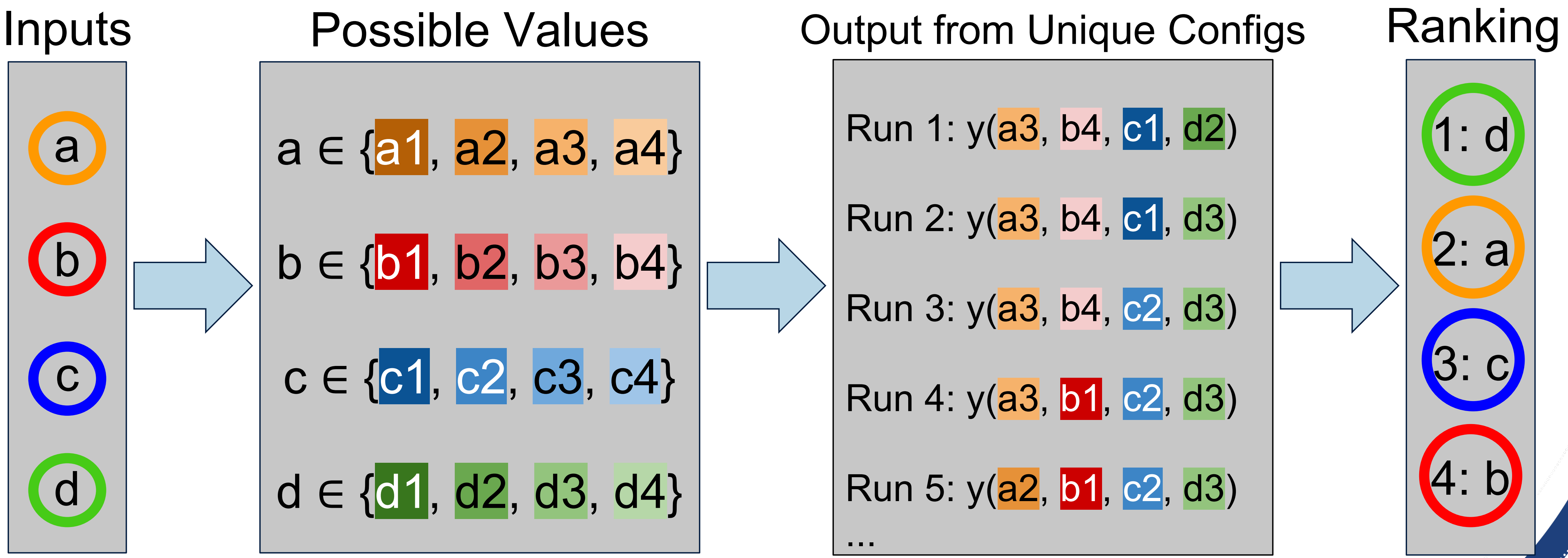
Hypothesis: Certain parameters in the momentum flux parameterization can reduce model biases in the simulated TC PBL structure

Question: Given the large number of possibilities, how do we choose which aspects of the parameterization are important?

Methodology

A sensitivity analysis calculates the effect of changing particular inputs on model output *y*



Morris One-at-a-Time (MOAT or MM) based on Covey et al. (2013) and Morales et al. (2019)

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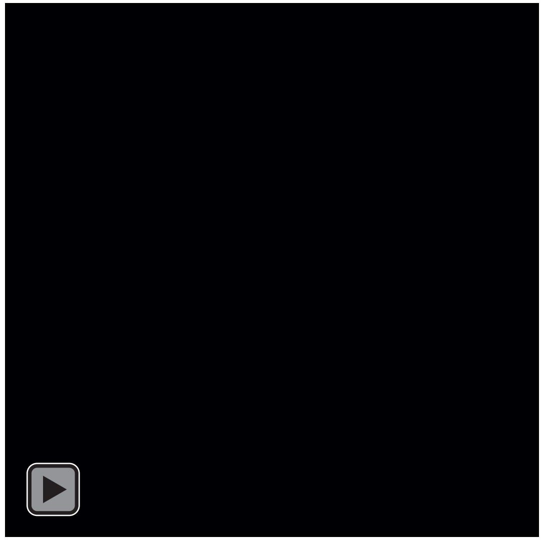
The sensitivity analysis uses an idealized configuration of CAM6 with CLUBB



- Characteristics
  - RCE-type configuration
  - f-plane, aquaplanet, fixed SSTs
  - 56 vertical levels
  - Nominal grid spacing of 0.25^{o}
  - **C_d saturation at high wind speeds (Large and Yeager 2009)**
  - **Cloud Layers Unified by Binormals Scheme (CLUBB):**
    - **Modified to use prognostic equation for momentum flux**
    - **Turbulent length scale diagnosed using eddy timescale (τ)**
    - **τ based on wind shear, buoyancy, and proximity to surface**

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We perturb the input parameters over fixed ranges that represent realistic values

Input Parameter Name	Description	Default Value	Perturbed Range
clubb_c14	Constant for $u'u'$ and $v'v'$ terms	2.2	1.0-4.0
clubb_c7	Low skewness term in C7 skewness function	0.5	0.25-1.00
C6rt_Lscale0	Damping term for low skewness coefficient in C6rt skewness function	14.0	10.0-15.0
C4	Coefficient in the w' return-to-isotropy term	5.2	3.0-7.0
C_invrs_tau_bkgnd	Background coefficient in formula to calculate $\frac{1}{\tau}$	1.0	0.5-4.0
C_invrs_tau_sfc	Near-surface coefficient in formula to calculate $\frac{1}{\tau}$	0.1	0.05-0.40
C_invrs_tau_shear	Shear coefficient in formula to calculate $\frac{1}{\tau}$	0.02	0.01-0.06
C_invrs_tau_N2	Buoyancy coefficient in formula to calculate $\frac{1}{\tau}$	0.1	0.05-0.40
LY09_sat	The 10-meter wind speed at which the surface drag coefficient maxes out	33.0	20.0-50.0

Experimental CLUBB parameters

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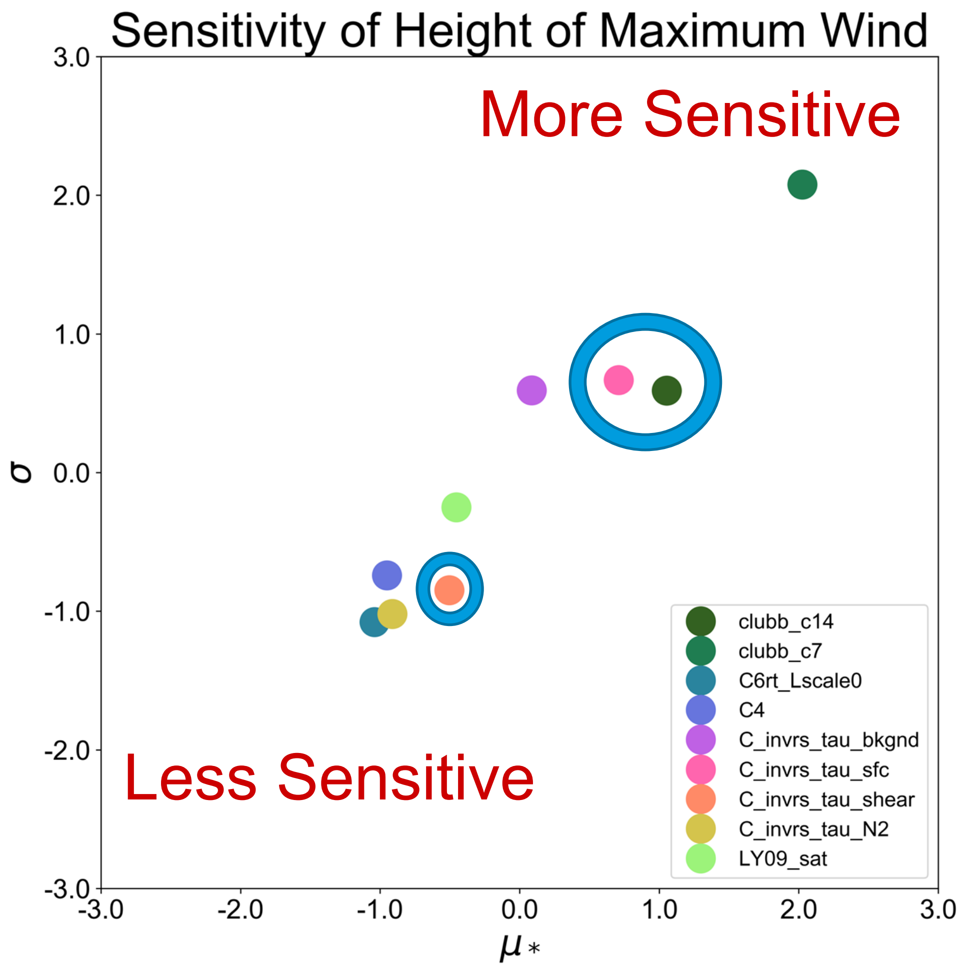
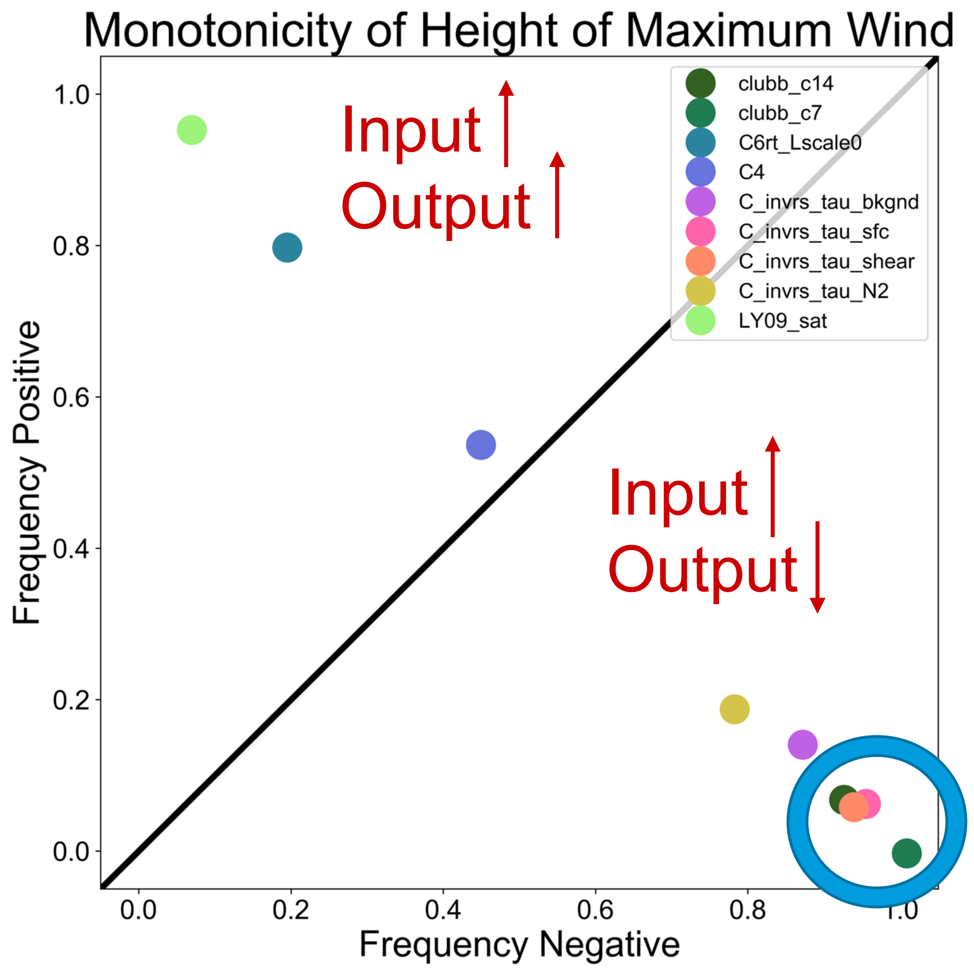
Results

Several parameters produce 1) high sensitivity AND 2) a consistent directional response





Left: relative impact of perturbing input
Right: direction of response

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Several parameters produce 1) high sensitivity AND 2) a consistent directional response

Given an increase in the parameter

Sensitivity

Input Parameter	r_{vmax}	θ_{in}	z_{vmax}	SLP_{min}	$u_{10,max}$	$SLP-u$ Sim	v_{tan} Sim	K_m Sim	$Area_{TC}$	dv/dz	LH_{frac}	θ	q
LY09_sat	4	4	5	3	3	3	5	6	9	7	7	8	7
C_invrs_tau_N2	9	8	7	7	7	5	8	7	7	6	5	5	5
C_invrs_tau_shear	7	6	6	6	6	7	3	5	6	5	6	6	6
C_invrs_tau_sfc	1	2	3	2	2	2	2	1	2	2	3	2	2
C_invrs_tau_bkgnd	5	5	4	5	5	6	4	2	4	4	2	4	4
C4	6	7	8	8	8	8	6	8	5	9	8	7	8
C6rt_Lscale0	8	9	9	9	9	9	9	9	8	8	9	9	9
clubb_c7	2	1	1	1	1	1	1	3	1	1	4	3	3
clubb_c14	4	3	2	4	4	4	7	4	3	3	1	1	1

Output Metric

Least Sensitive — Most Sensitive

Directional Response

Input Parameter	r_{vmax}	θ_{in}	z_{vmax}	SLP_{min}	$u_{10,max}$	$SLP-u$ Sim	v_{tan} Sim	K_m Sim	$Area_{TC}$	dv/dz	LH_{frac}	θ	q
LY09_sat	0.9	0.9	0.9	0.9	0.1	0.9	0.5	0.9	0.7	0.7	0.9	0.4	0.5
C_invrs_tau_N2	0.8	0.9	0.2	0.5	0.5	0.4	0.5	0.2	0.3	0.7	0.0	0.1	0.8
C_invrs_tau_shear	0.5	0.7	0.1	0.5	0.7	0.5	0.6	0.1	0.0	1.0	0.0	0.1	0.7
C_invrs_tau_sfc	0.5	0.7	0.1	0.5	0.5	0.4	0.6	0.1	0.1	0.9	0.0	0.2	0.5
C_invrs_tau_bkgnd	0.5	0.7	0.1	0.2	0.7	0.2	0.5	0.1	0.3	0.8	0.0	0.1	0.4
C4	0.7	0.5	0.5	0.7	0.5	0.3	0.7	0.7	0.9	0.2	0.7	0.6	0.6
C6rt_Lscale0	0.9	0.7	0.8	0.6	0.3	0.5	0.5	0.5	0.6	0.6	0.5	0.3	0.3
clubb_c7	0.5	1.0	0.0	0.5	0.4	0.5	0.8	0.0	0.0	0.7	0.1	0.6	0.4
clubb_c14	0.5	0.9	0.1	0.3	0.4	0.3	0.9	0.1	0.2	1.0	0.0	0.1	0.9

Output Metric

Negative Response — Neutral Response — Positive Response

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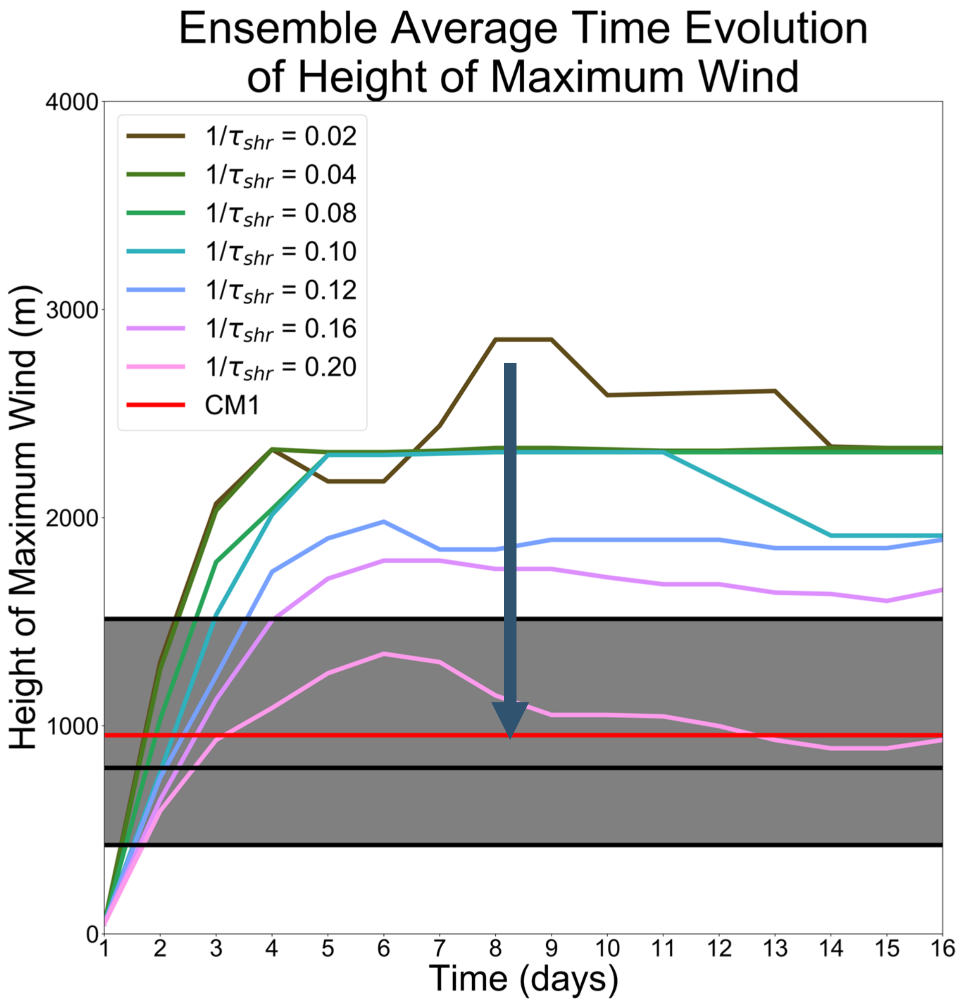
For both highlighted metrics, several input parameters are **influential** and, **when increased, consistently decrease the metrics**

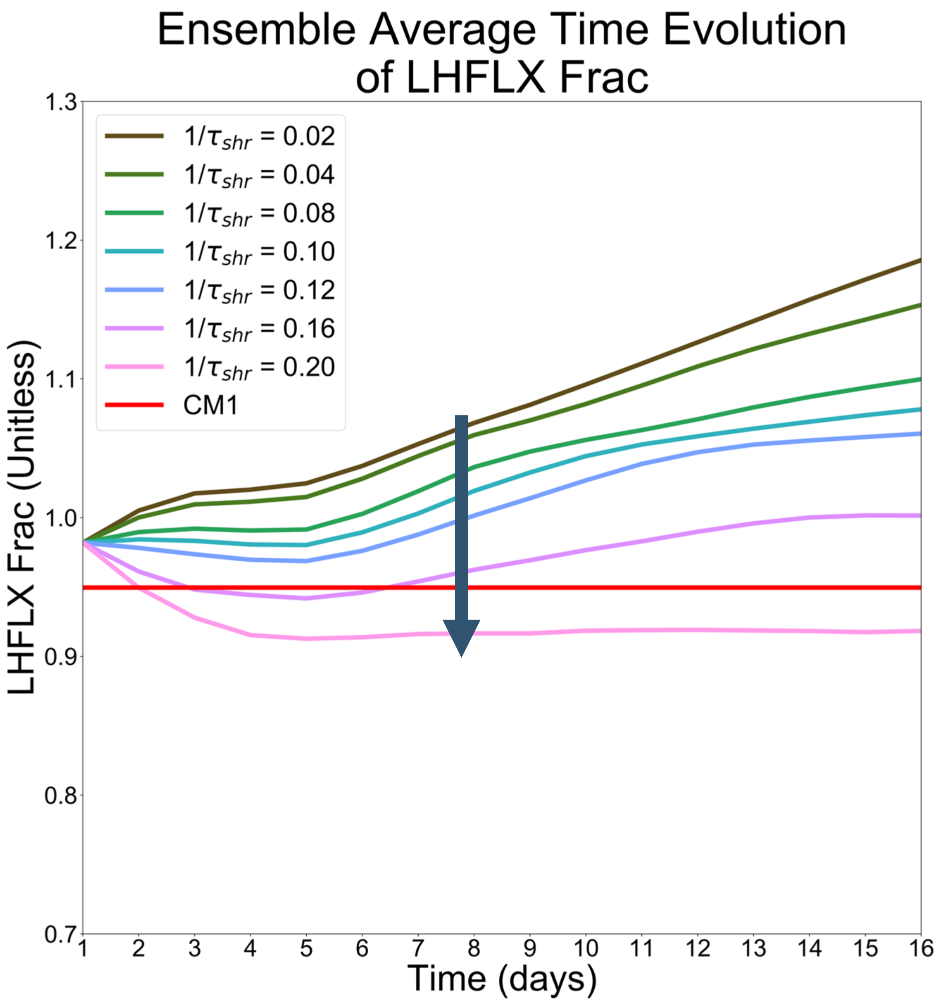
If we **increase** one of these inputs, we expect:

1. Decreased height of maximum tangential wind
2. Decreased latent heat flux fraction

…both of which are desired model improvements

Increasing *C_invrs_tau_shear* reduces the height of maximum wind and latent heat flux fraction





C_invrs_tau_shear ↑

Turbulent length scale ↓

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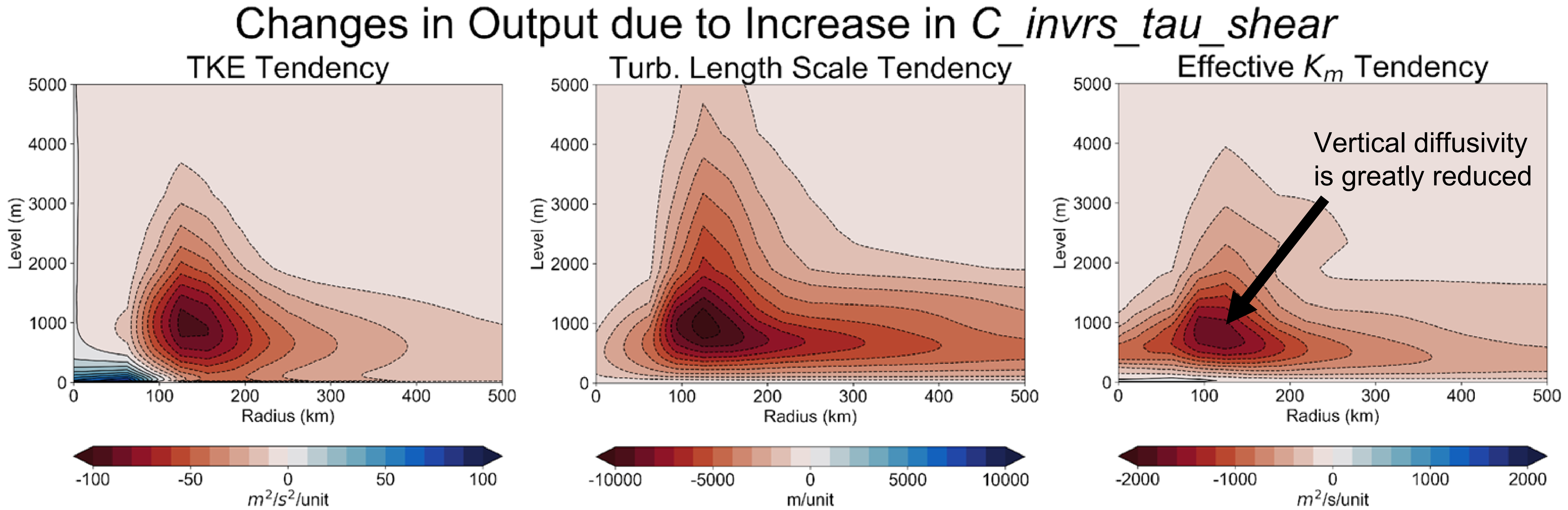
Increasing *C_invrs_tau_shear* decreases the turbulent length scale, TKE, and effective eddy diffusivity



Reds: Increasing *C_invrs_tau_*shear **reduces** the magnitude
Blues: Increasing *C_invrs_tau_shear* **increases** the magnitude

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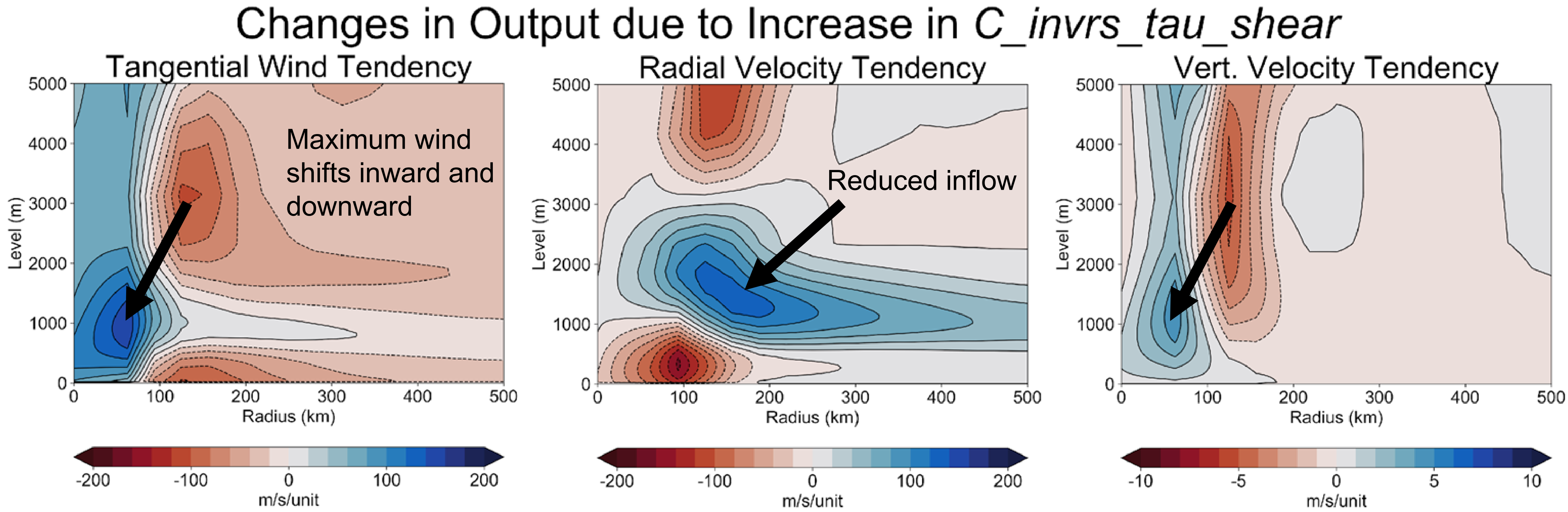
Increasing *C_invrs_tau_shear* reduces the height of maximum wind and shifts peak vertical motion inward



Reds: Increasing *C_invrs_tau_*shear **reduces** the magnitude
Blues: Increasing *C_invrs_tau_shear* **increases** the magnitude

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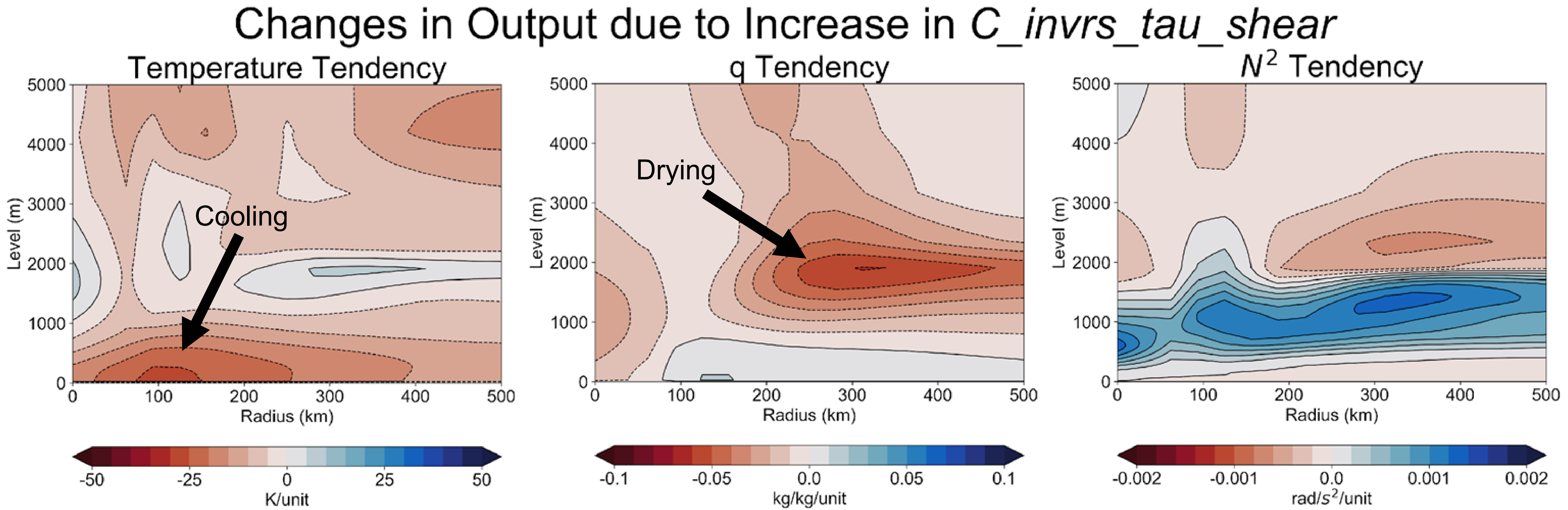
Increasing *C_invrs_tau_shear* produces near-surface cooling and a layer of drying above z = 1 km



Reds: Increasing *C_invrs_tau*_shear **reduces** the magnitude
Blues: Increasing *C_invrs_tau_shear* **increases** the magnitude

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Key Takeaways

- Sensitivity analysis helps identify model configurations that influence output metrics describing the structure of the TC PBL
- New updates to CLUBB permit momentum fluxes that can be targeted to specific atmospheric regimes
- Decreasing vertical mixing and eddy diffusivity in CLUBB produces more realistic TC wind profiles evaluated against observations and LES

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Next Steps

- A deeper analysis of the physical basis for the sensitivity of the output metrics is ongoing
- These perturbed configurations need to be tested in a more realistic global climate simulation
- If results are promising in global climate simulations, these perturbations can be used to improve subseasonal to seasonal forecasts of tropical cyclones

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We thank our partners in this work:

Nardi, K.M., C.M. Zarzycki, V.E. Larson, and G.H. Bryan: Assessing the sensitivity in depicting the tropical cyclone boundary layer to1changes in the parameterization of momentum flux in the Community Earth System Model, *Mon. Wea. Rev.*, in prep.

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