Sensitivity of Simulated Tropical Cyclones to Air-Sea Flux Parameterizations and Implications for Parameter Estimation

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Background

- Emanuel's potential intensity theory for TCs

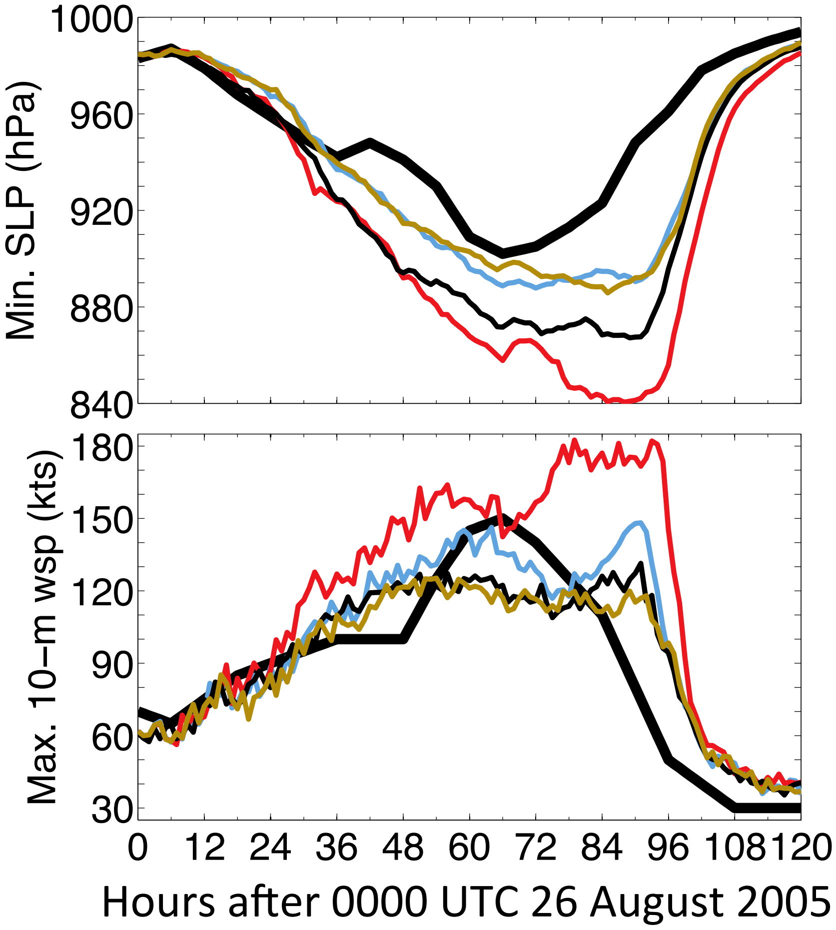
$$V_{\max}^2 = \frac{C_k}{C_D}\left(\frac{1-0.25r_0^2}{1-\frac{\gamma}{2}\frac{C_k}{C_D}}\right) \qquad P_{\min} \approx -\frac{V_{\max}^2\left(1-0.5AH\right)-0.25r_0^2}{1-AH}$$

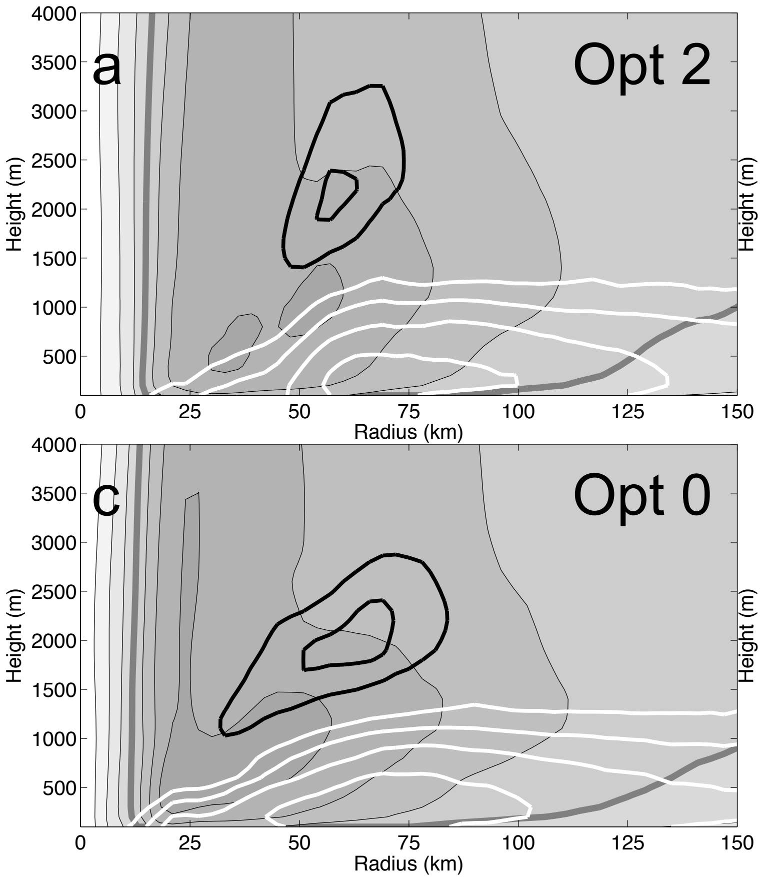
- Increase C_k and/or decrease C_D = stronger TC (faster winds and deeper central pressure)
- Problem: uncertainty/error in C_k and C_D parameterizations = error in TC forecasts

Emanuel (1986; 1995a,b)

Impact of C_D and C_k on WRF simulations

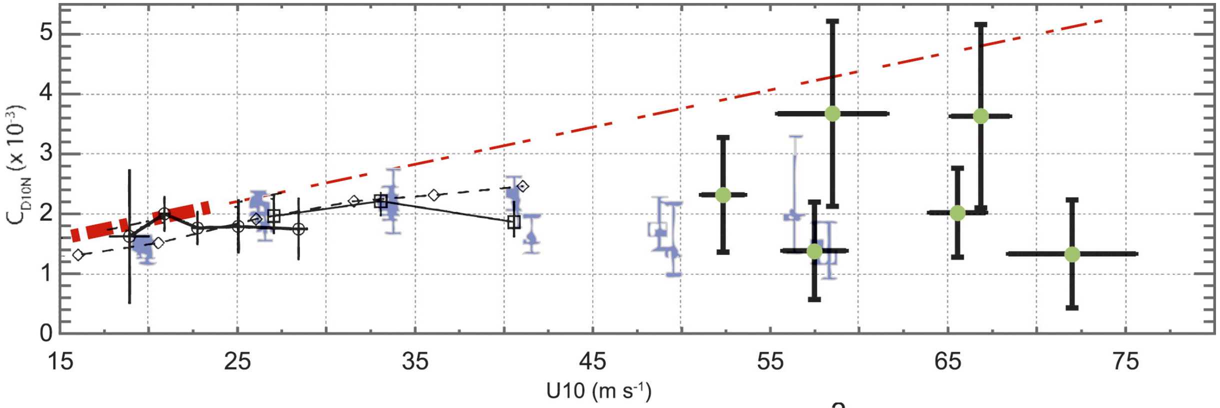
- Tests of available surface flux options in WRF motivates more systematic investigation





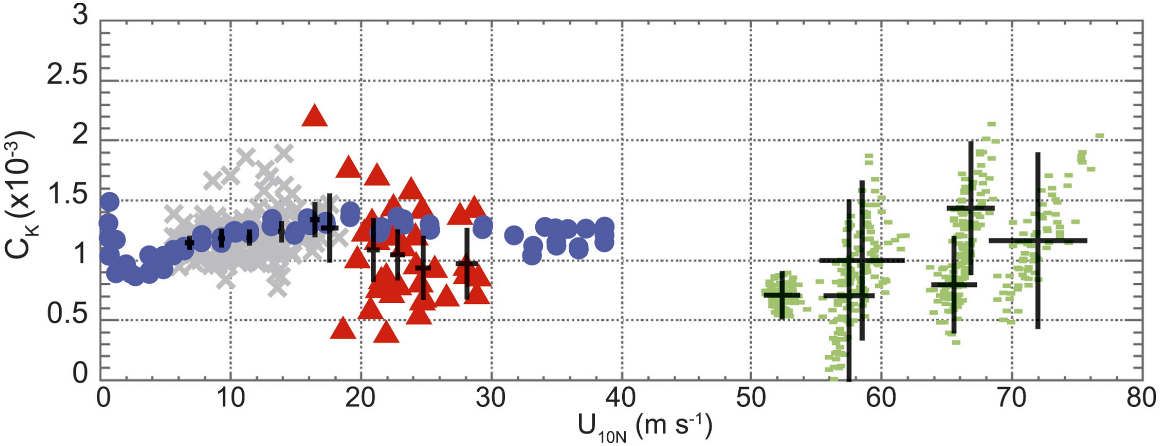
Green and Zhang (2013, MWR)

Parameterizing C_k and C_D over the ocean



- Very noisy data, especially at high wind speeds

Figs. 19 and 20 of Bell et al. (2012)

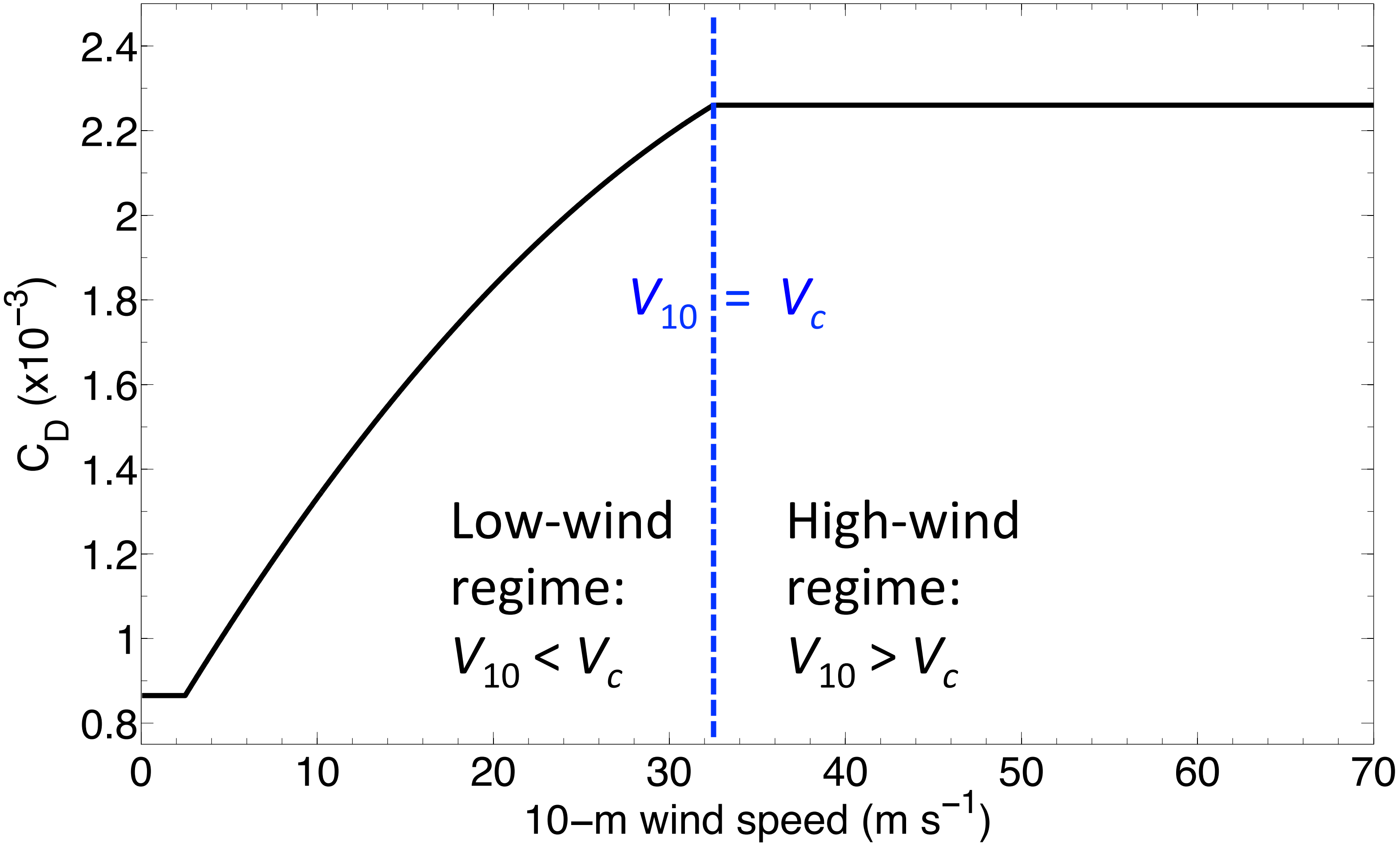


- What determines C_k and C_D?
  - Reality: Sea state (need wave model coupling)
  - Atmosphere only models: low-level wind speed and curve-fitting empirical parameters

C_D as a function of wind speed (1)

- Sraj et al. (2013), from Kara et al. (2002):

$$C_{D,N} = 10^{-6}\left[692 + 71\tilde{V} - 0.7\tilde{V}^2\right] \qquad \tilde{V} = \max\left[2.5, \min\left(V_{10}, V_c\right)\right]$$



C_D as a function of wind speed (2)

- Adjust C_D curve (prev. slide) with 3 parameters

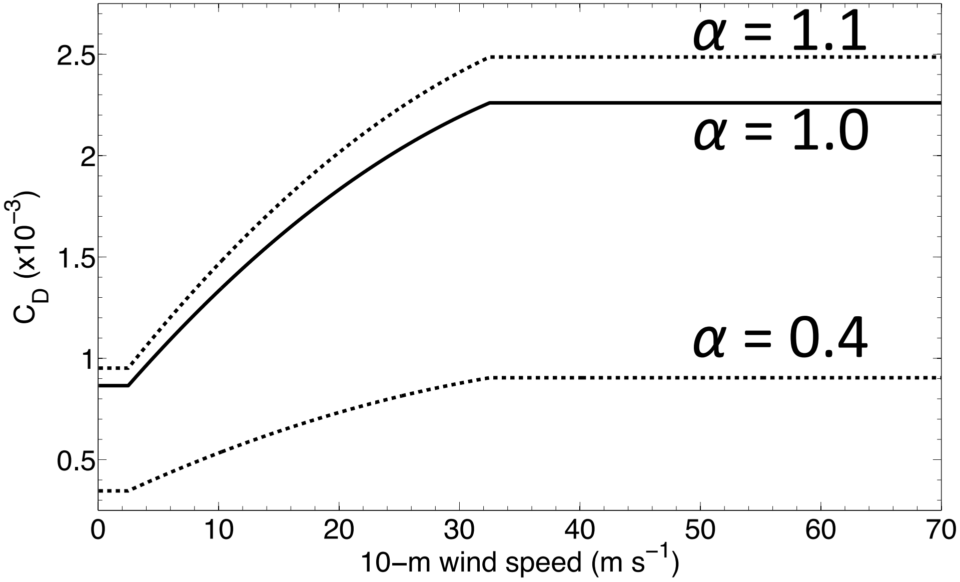
$$C'_{D,N} = \begin{cases} \underline{\alpha} C_{D,N} & , \quad V_{10} < V_c \\ \underline{\alpha} C_{D,N} + \underline{\alpha m}\left(V_{10} - \underline{V_c}\right) & , \quad V_{10} \geq V_c \end{cases}$$

- V_c is where high-wind regime starts
  - – V_c has minimal impact on C_D (not shown)
- m only matters when $V_{10} > V_c$ (not shown)
- α is very important for all V_{10}: see next slide

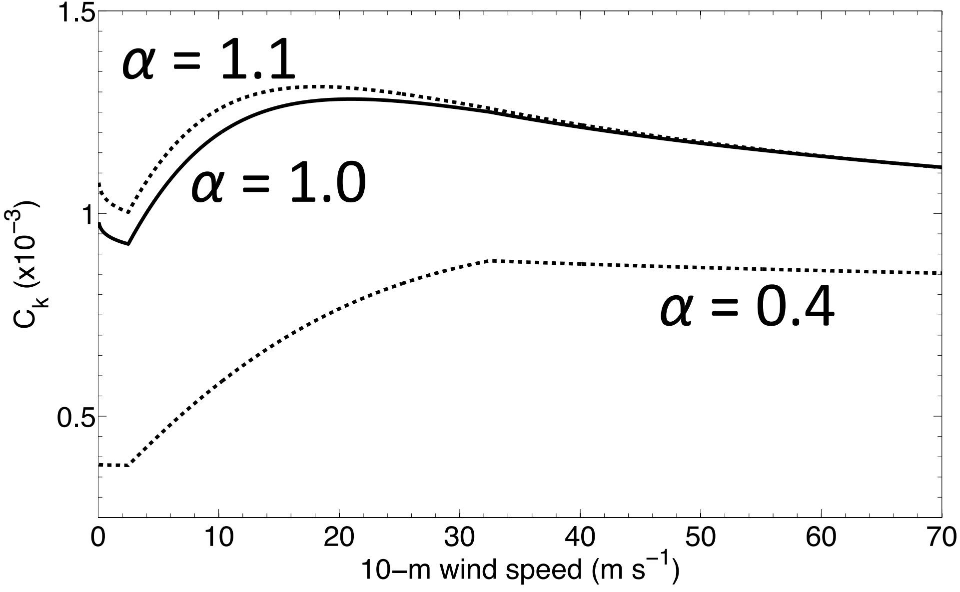
Zedler et al. (2012); Sraj et al. (2013); Green and Zhang (2014)

Effect of α on C_D and C_k curves

- α is a multiplicative factor for C_D
- **Similarity theory**: Increased C_D = increased C_k
  - – α has large impact on C_D and C_k for all V_{10}



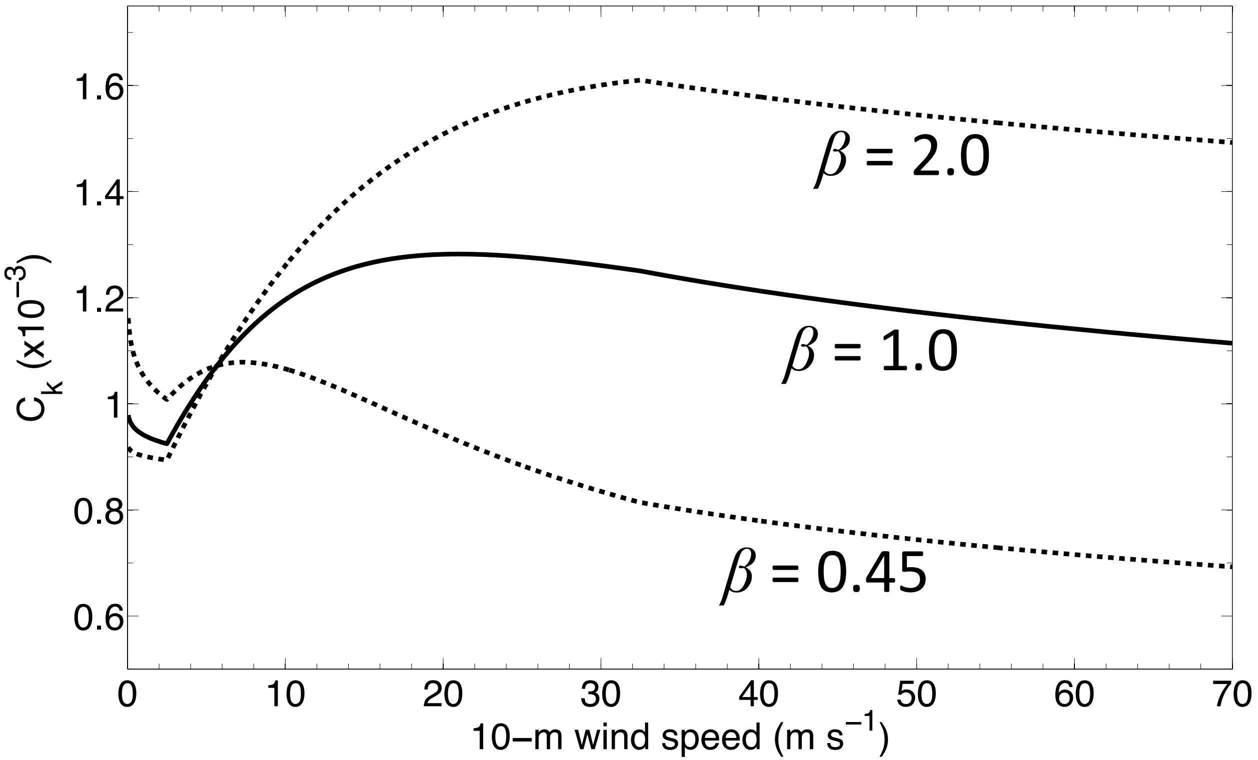
C_D as a function of V_{10}



C_k as a function of V_{10}

Test C_k independent of C_D

- Change C_k without changing C_D
- Introduce β, which is somewhat like a multiplicative parameter for C_k (cf. α for C_D)
- β has a larger impact than α on C_k



Experimental setup

- Run WRF simulations of Hurricane Katrina
  - Spinup: EnKF assimilation of airborne Doppler velocities
  - Deterministic runs started at 00Z on 26 and 27 August (80 runs each time)
- Incorporate new parameters (α and β) into "MM5" surface layer scheme: see next slide
- WRF V3.4 model details:
  - 3 km horizontal grid spacing
  - YSU PBL scheme

Green and Zhang (2013, 2014)

How do α and β affect simulated TCs?

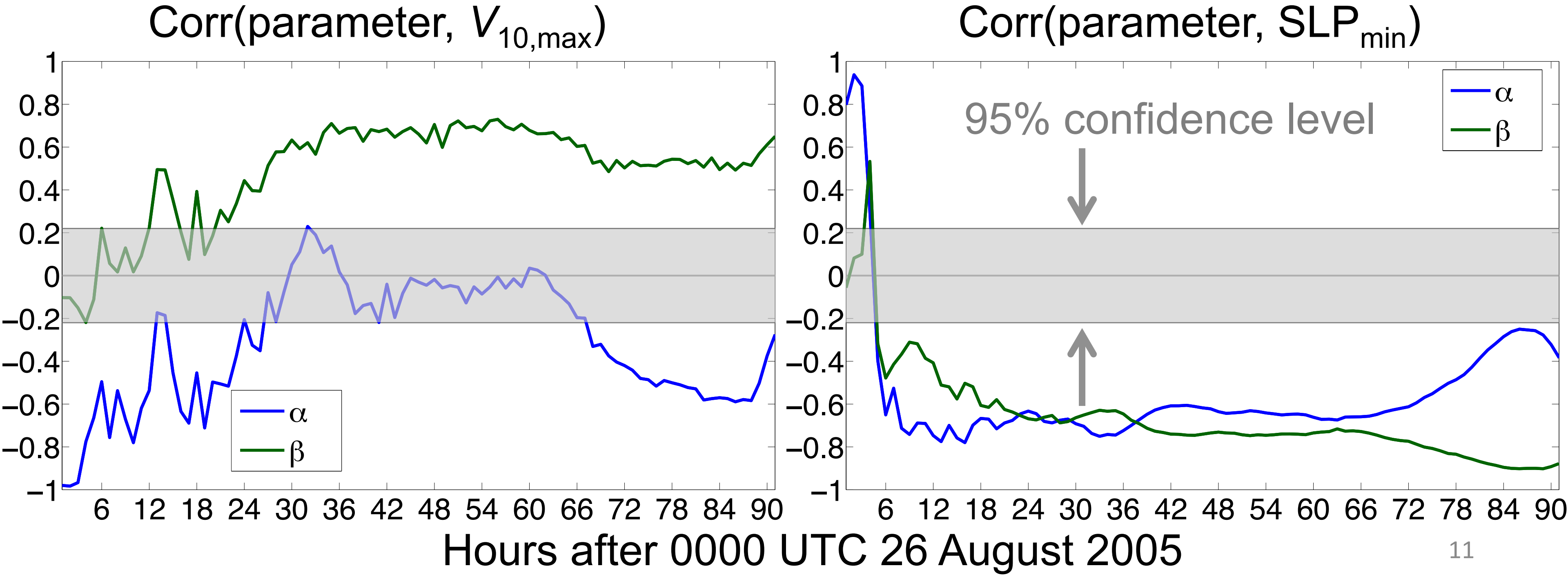
- Multi parameter experiments: Vary all parameters simultaneously (look for signals in the noise)
- Generate 80 unique, randomly chosen sets of parameter values
- Each parameter can have 1 of 20 (evenly spaced) values in given ranges:

Parameter	Min value	Max value
α	0.4	1.1
β	0.45	2.0

Green and Zhang (2014)

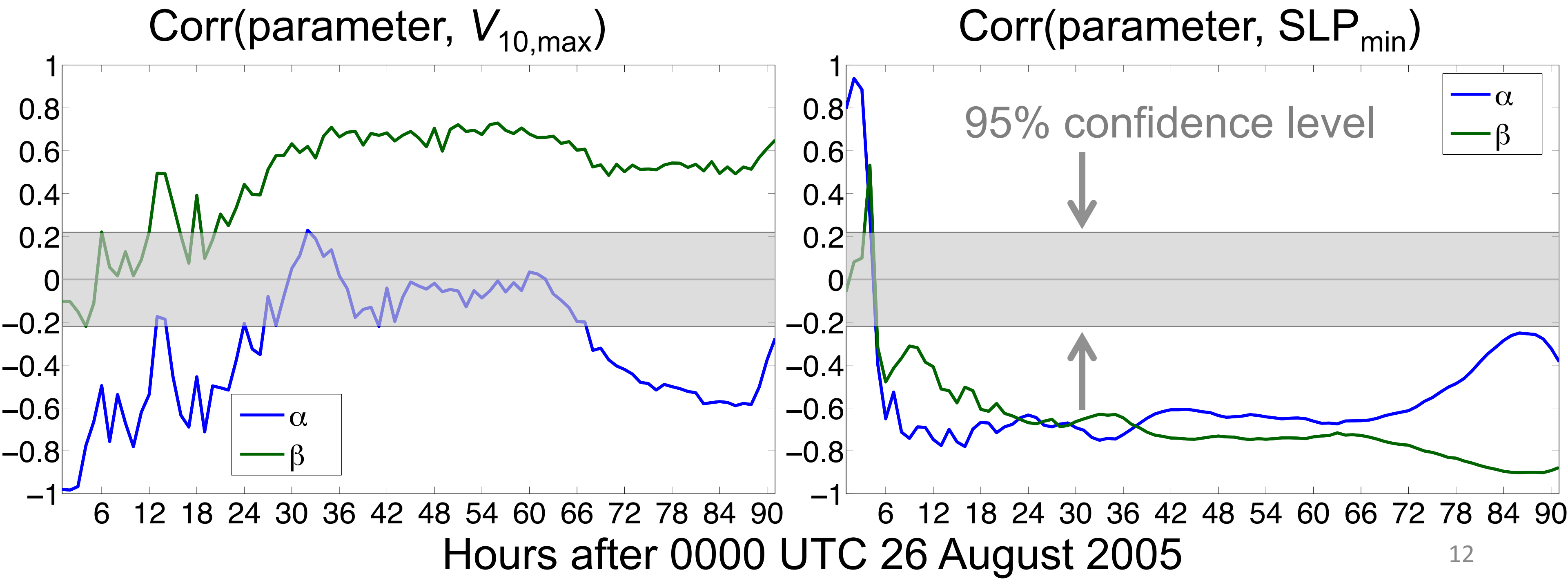
Correlations with max V_{10} and min SLP (1)

- α (C_D multiplier, blue) changes pressure-wind relationship (PWR)
  - Larger α (more drag at all speeds) decreases maximum V_{10} (weaker storm) for much of TC's life
  - Larger α deepens minimum SLP (**stronger** storm)



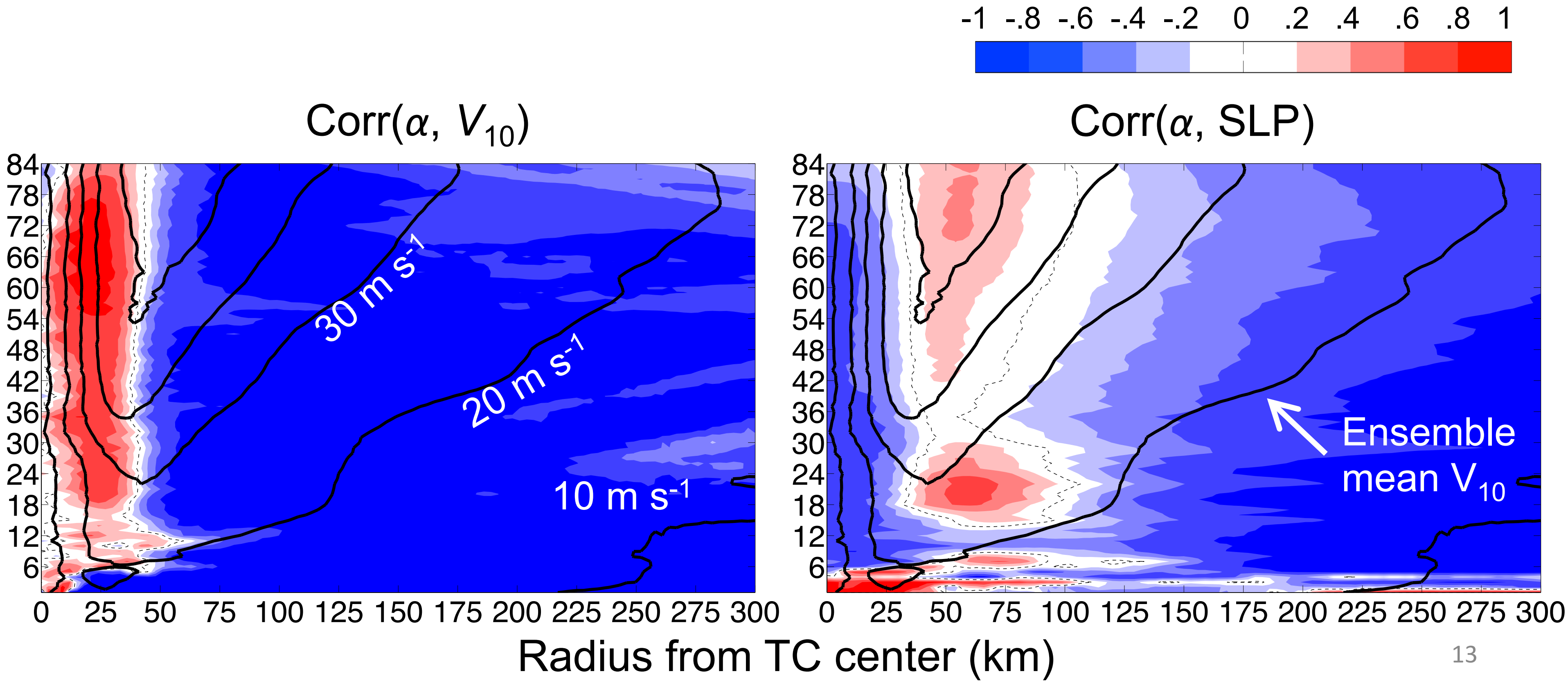
Correlations with max V_{10} and min SLP (2)

- β (C_k multiplier, green) has a **minimal** impact on PWR (unlike α)
  - Larger β (higher C_k) increases max V_{10} (stronger storm)
  - Larger β deepens minimum SLP (stronger storm)



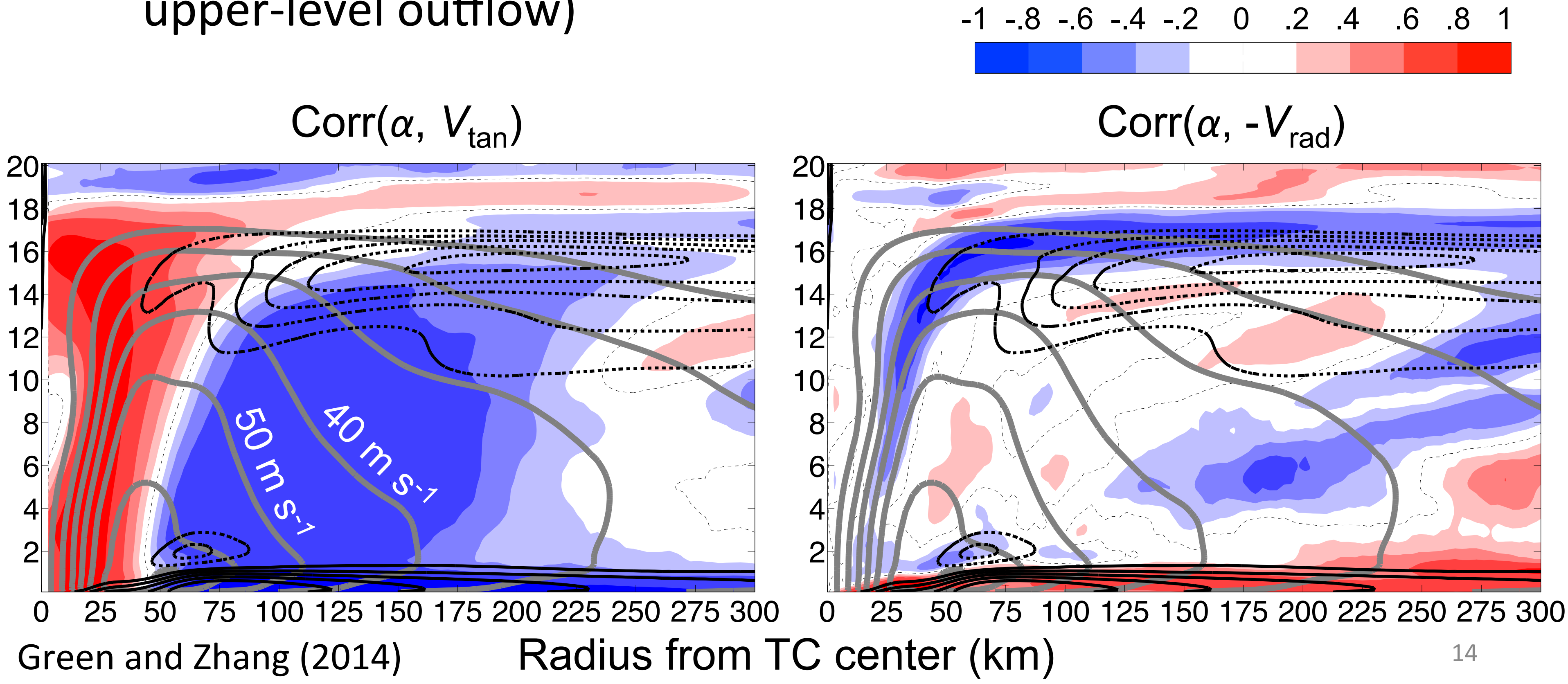
Time evolution of azimuthally-averaged V_{10} and SLP

- α (C_D multiplier) impacts more than just "point metrics"
- Radial correlation dipoles imply structural changes
  - Increasing α (C_D) = inward shift of RMW
  - Increasing α = steeper radial pressure gradient



Radius-height correlations with α

- Azimuthal averages 48 hours after 00Z/27 Aug initialization
  - Increasing α (C_D) = weaker tangential wind in PBL
  - Increasing α = tighter primary vortex (correlation dipole)
  - Increasing α = stronger secondary circulation (PBL inflow **and** upper-level outflow)



Green and Zhang (2014)

Simultaneous State and Parameter Estimation (SSPE)

- DA traditionally only for state variables (U,V,T,P,Q,…)
- In EnKF, treat <u>model parameter</u> (here, *α*) like a state variable and use state augmentation:

$$\mathbf{x}_*^a = \mathbf{x}_*^f + \mathbf{K}\left(\mathbf{y}^o - \mathbf{H}_*\mathbf{x}_*^f\right)$$

$$\mathbf{K} = \mathbf{P}^f\mathbf{H}_*^{\mathrm{T}}\left(\mathbf{H}_*\mathbf{P}^f\mathbf{H}_*^T + \mathbf{R}\right)^{-1}$$

$$\mathbf{x}_*^f = \begin{bmatrix} \mathbf{x}^f \\ \alpha^f \end{bmatrix} \begin{array}{l} \longleftarrow \text{State variables} \\ \longleftarrow \text{Model parameters} \end{array}$$

$$\mathbf{P}^f = \begin{bmatrix} \mathbf{P}_{xx} & \mathbf{P}_{\alpha x}^{\mathrm{T}} \\ \mathbf{P}_{\alpha x} & \mathbf{P}_{\alpha\alpha} \end{bmatrix}$$

$$\mathbf{H}_* = \begin{bmatrix} \mathbf{H}_x & \underset{\uparrow}{\mathbf{0}} \end{bmatrix}$$

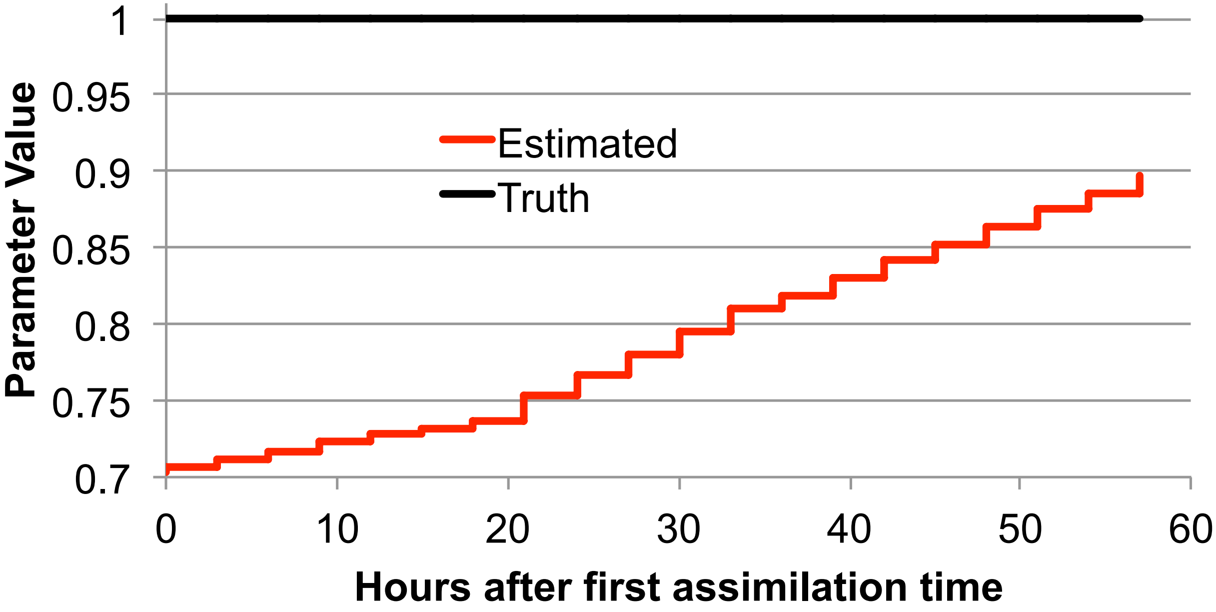
Model parameters are not observed

- Ultimate goal: Use SSPE to estimate *α* and improve model forecasts

See, e.g., Yang and DelSole (2009)

Preliminary SSPE results

- OSSE for Katrina at Δx = 9 km using WRF
  - Truth: Deterministic forecast initialized at 00Z/25 Aug. (α = 1.0)
  - SSPE: 40-member ensemble, assimilate min SLP from truth every 3 h starting at 00Z/26 Aug.
- All increments of ensemble mean α are towards truth
  - More obs and/or stronger TC could yield larger increments



Concluding remarks

- C_D changes TC structure & pressure-wind relationship
  - More drag = tighter vortex, stronger secondary circulation
  - More drag = weaker winds and <u>deeper</u> pressure
- C_k has simple impact (higher C_k = stronger TC)

- SSPE: OSSE shows great promise for estimating α
- Ongoing SSPE work:
  - Run OSSE when members have stronger TCs
  - Go down to Δx = 3 km
  - Assimilate real data (including airborne Doppler velocities)

- Future work: Expand SSPE to coupled (air-sea-wave) models

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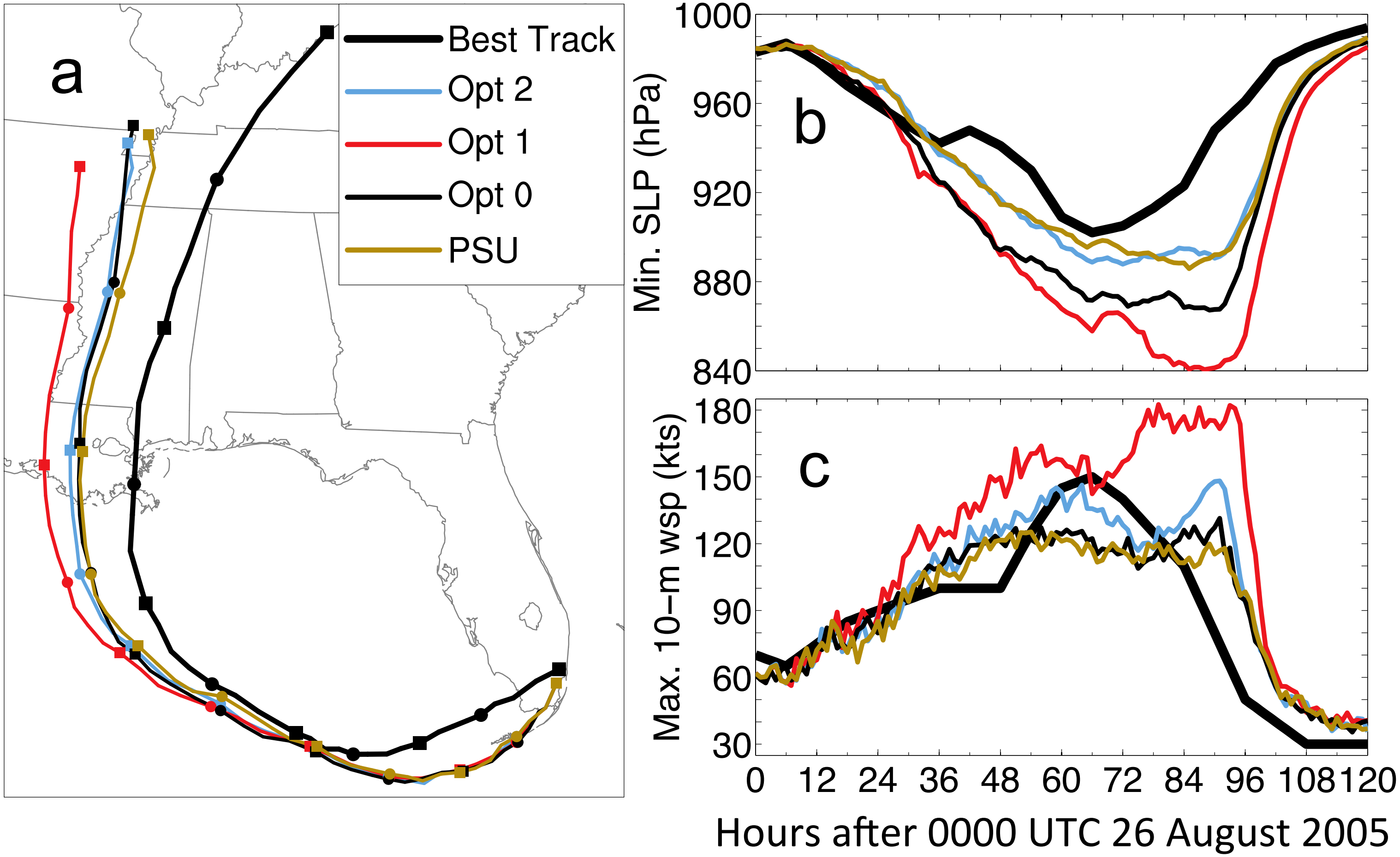
Extra/Backup slides

Impact of C_D and C_k on WRF simulations

- Sensitivity to available surface flux options in WRF motivates more systematic investigation



Green and Zhang (2013, MWR)

C_D and C_k in an atmosphere-only model

- In similarity theory, C_k is a function of C_D (scalar flux proportional to momentum flux)

$$-\tau/\rho = u_* \times u_* = C_D U\left(\Delta U\right) = u_* \times C_D^{1/2} U$$

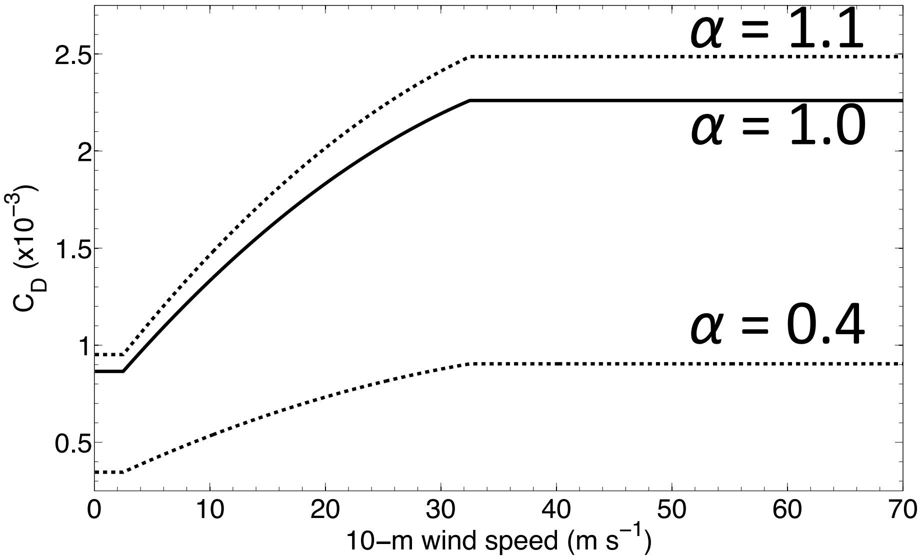
$$-H\Big/\left(c_p \rho\right) = u_* \times \theta_* = C_k U\left(\Delta\theta\right) = \theta_* \times C_D^{1/2} U$$

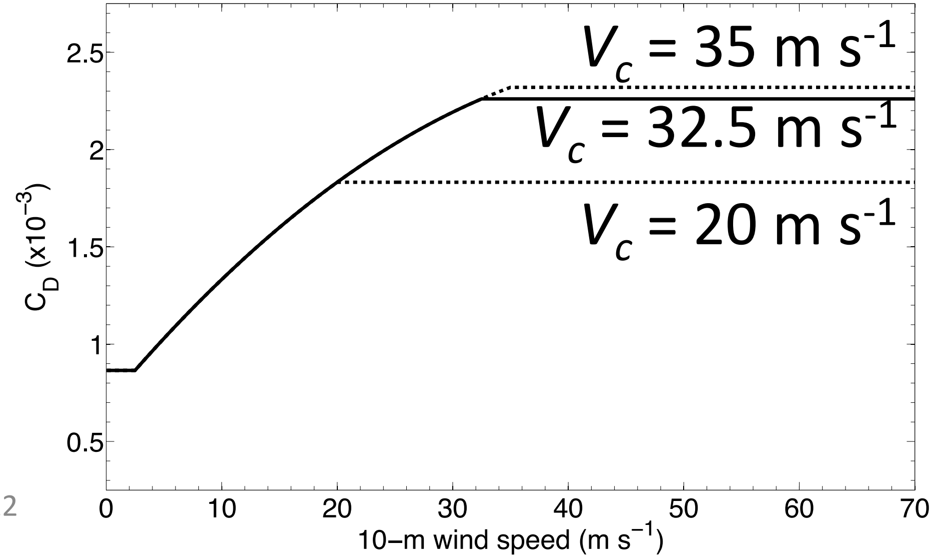
$$-E\Big/\left(L_v \rho\right) = u_* \times q_* = C_k U\left(\Delta q\right) = q_* \times C_D^{1/2} U$$

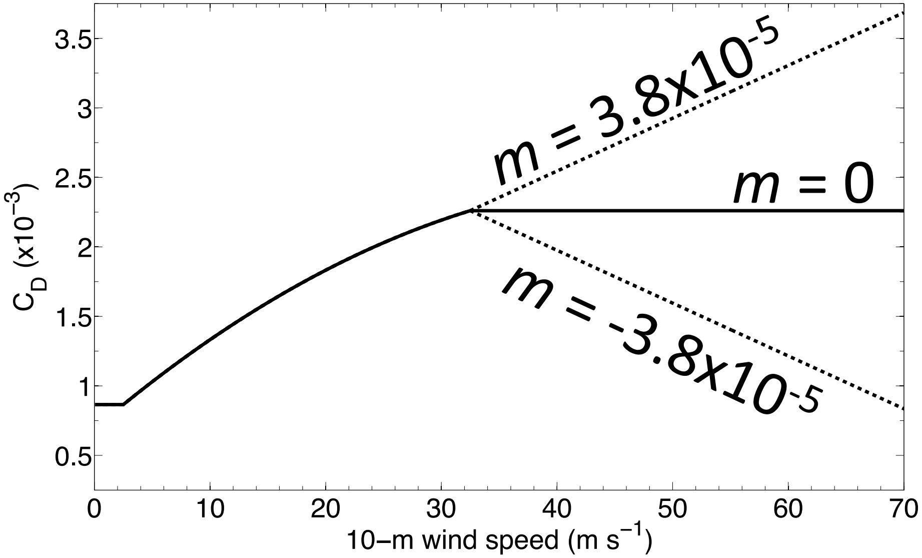
- This means *α*, V_c, and *m* also impact C_k!

Effects of α, V_c, and m on C_D curves

- Not all parameters are created equal
  - α has huge impact everywhere
  - m has large impact only at high winds
  - V_c not as important

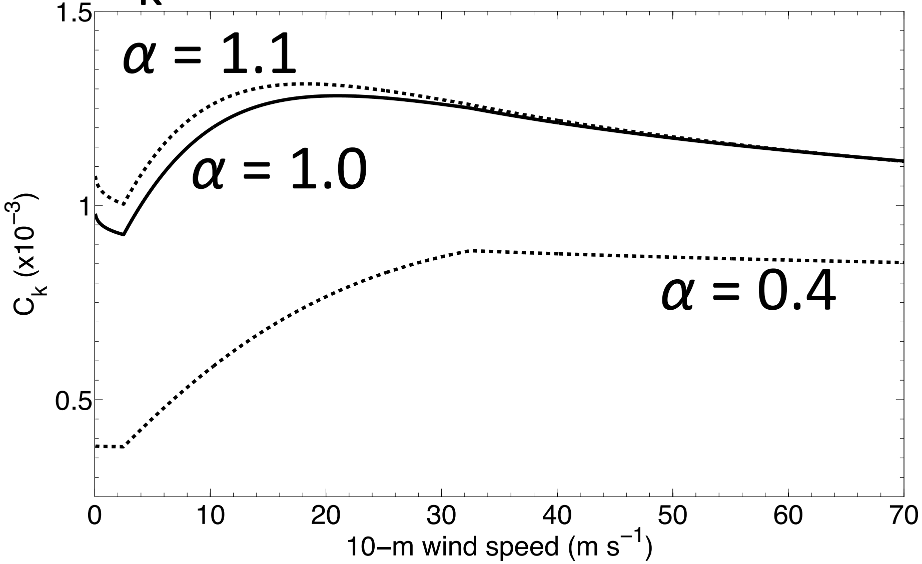


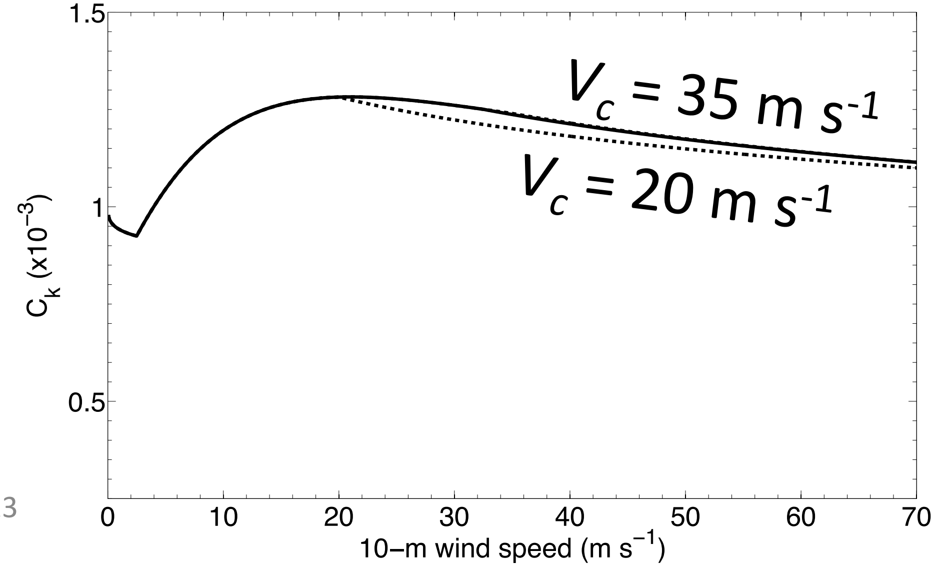


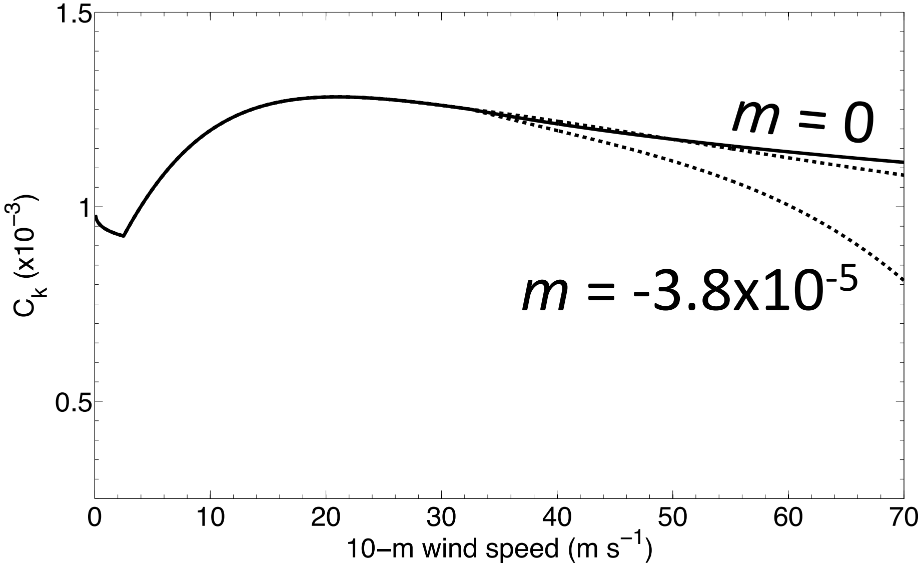


Effects of α, V_c, and m on C_k curves

- Increased C_D = increased C_k
  - α has large impact everywhere
  - m has some impact at very high winds
  - V_c is negligible

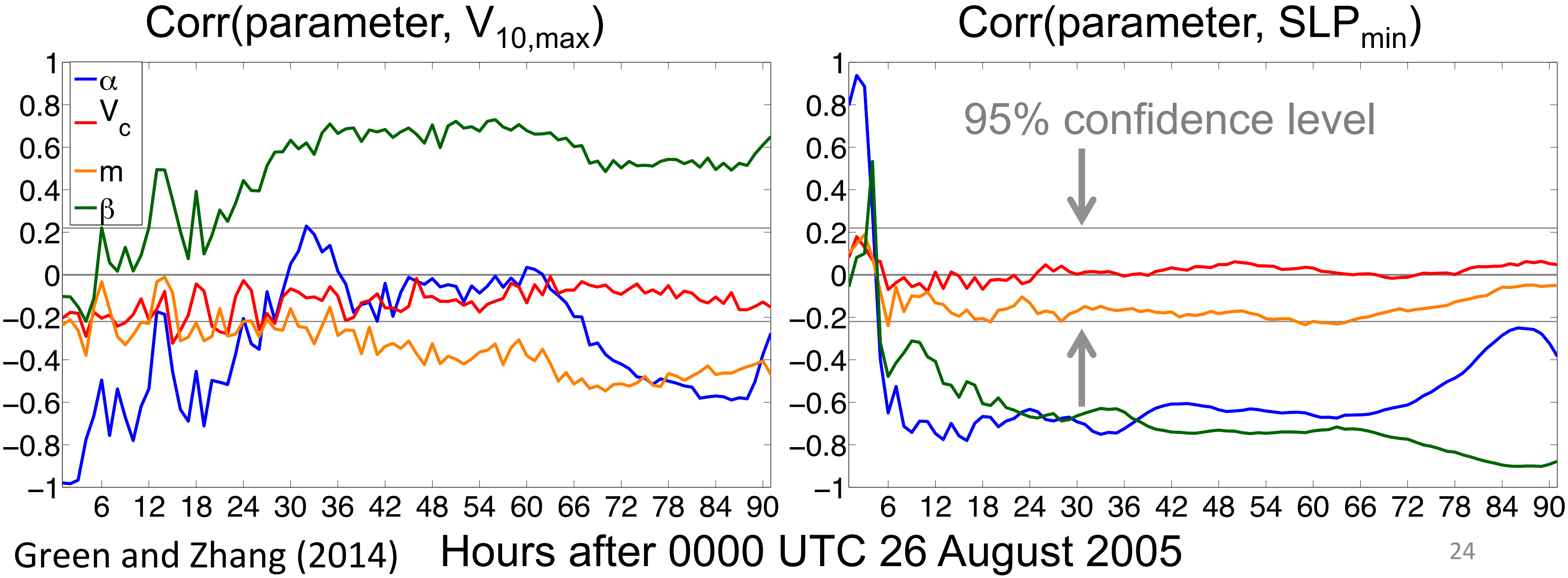






Correlations with min SLP and max V_{10}

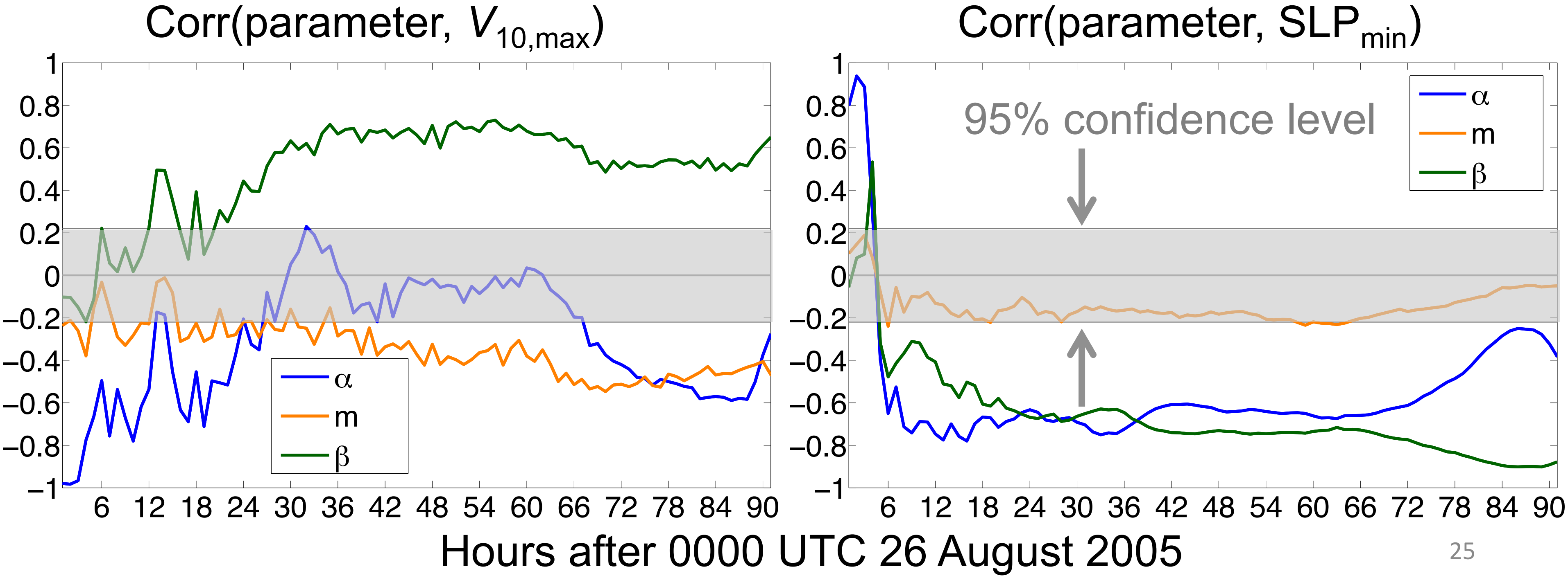
- Multi-parameter experiments can find signal in the noise (which parameters are more important?)
- First result: V_c (red curves) uncorrelated with intensity



Green and Zhang (2014)

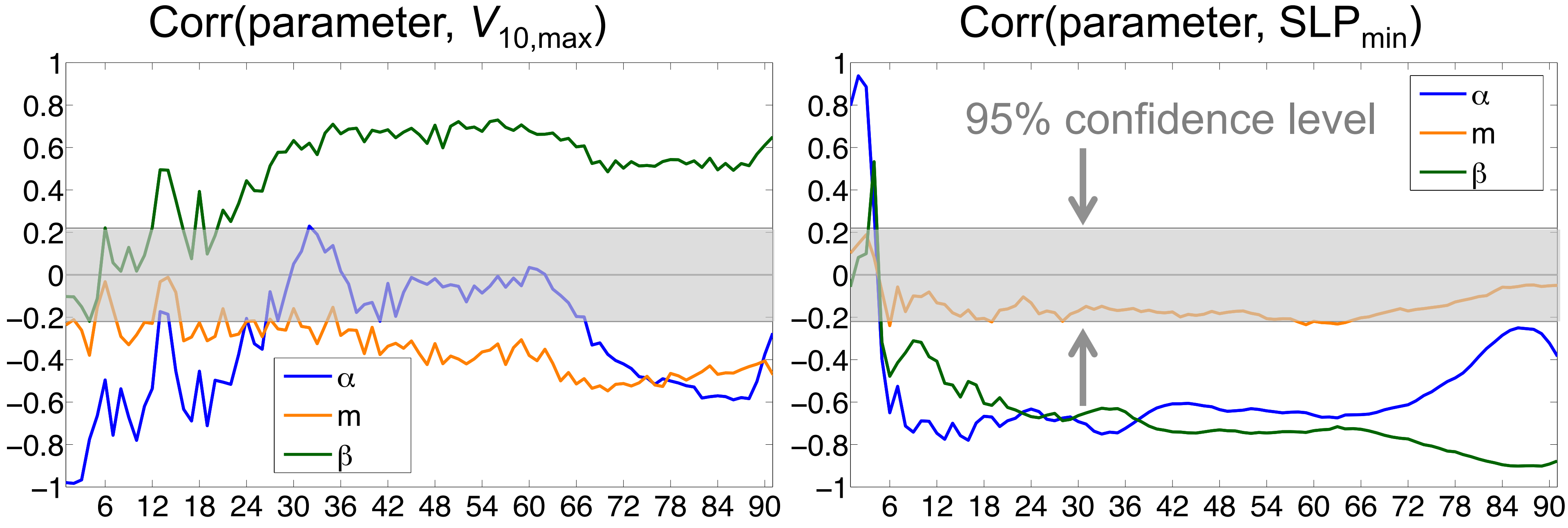
Correlations with max V_{10} and min SLP (1)

- α (C_D multiplier, blue) changes pressure-wind relationship (PWR)
  - Larger α (more drag at all speeds) decreases maximum V_{10} (weaker storm) for much of TC's life
  - Larger α deepens minimum SLP (**stronger** storm)



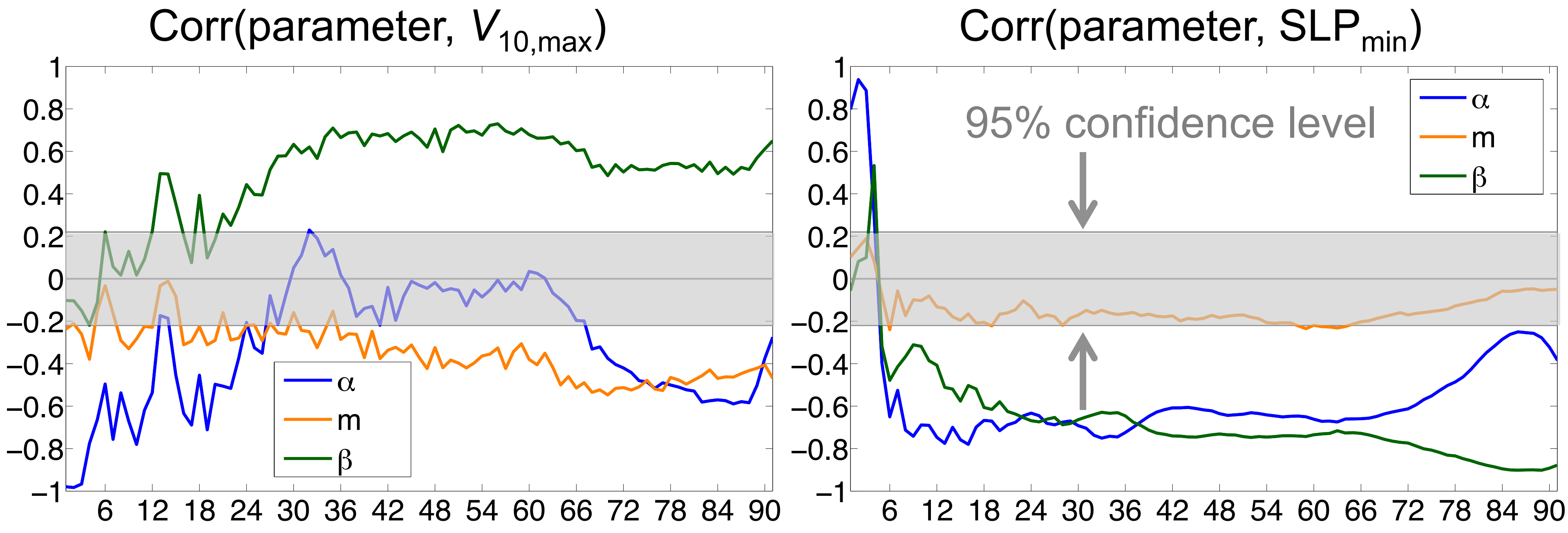
Correlations with max V_{10} and min SLP (2)

- β (C_k multiplier, green) has a **minimal** impact on PWR (unlike α)
    - Larger β (higher C_k) increases max V_{10} (stronger storm)
    - Larger β deepens minimum SLP (stronger storm)



Correlations with max V_{10} and min SLP (2)

- *m* (slope of C_D in high wind regime, orange) also changes PWR
  - – Larger *m* (more drag at high winds) only decreases maximum V_{10} when TC is very strong
  - – *m* is not correlated with minimum SLP



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Future work

- Move to Very Large Eddy Simulation (VLES)
  - The new “gold standard” of TC simulations
  - How does turning off PBL scheme impact results?

- Test C_D independent of C_k (Smith et al. 2012)
  - Goes against similarity theory and WRF
  - But can shed more light on problem

- Incorporate parameter estimation into Penn State’s WRF-EnKF system
  - Especially for α, the multiplicative parameter in C_D
  - Requires more near-surface observations

Concluding remarks

- Impact of C_D on TC intensity (PWR) and structure more complicated than Emanuel's PI theory
  - Increased C_D = weaker winds (no surprise)
  - Increased C_D = deeper pressure
  - Increased C_D = tighter vortex, stronger secondary circulation (e.g., Bao et al. 2012; Smith et al. 2012)

- Impact of C_k alone is obvious (higher C_k = stronger TC)

- Ongoing/future work
  - LES
  - Parameter estimation