Air-sea surface flux parameter sensitivity and estimation for tropical cyclone simulations
A. Current state of tropical cyclone (TC) prediction

B. Sensitivity of TC simulations to model parameters

C. Can EnKF-based simultaneous state and parameter estimation (SSPE) be implemented in TC forecasts?
Tropical cyclone forecast errors

Overarching research question: Can we improve upon intensity forecasts?

Figure source: http://www.nhc.noaa.gov/verification/verify5.shtml
Track vs. Intensity: Scale dependence

- Planetary/synoptic scale flow drives TC track
  - Global models have become much better at resolving large-scale features

- Multiple factors influence TC intensity
  - Position: Land or cold water will kill off a TC
  - Synoptic scale vertical wind shear
  - Also important: mesoscale and microscale
    - Fluxes of momentum and enthalpy between air & sea
    - Intrusions of dry air
    - Vortex dynamics
    - Moist convection, cloud microphysics, and radiation
Background on TC intensity (i)

- Emanuel develops *maximum potential intensity* (MPI) theory for a steady-state TC
  - Thermal and gradient wind balances
  - Sub-cloud layer RH is not a function of radius

Minimum central pressure [(27) in E95]:

\[ P_c \approx - \frac{V_m^2}{1 - \frac{1}{2}} \left( 1 - 0.5HA \right) - 0.25r_0^2 \]

Maximum azimuthal wind [(18) in E95]:

\[ V_m^2 = \left( \frac{C_k}{C_D} \right) \left( 1 - 0.25\gamma r_0^2 \right) \left( \frac{1}{1 - 2C_k \gamma} \right) \]

Emanuel (1986, 1995)
Background on TC intensity (ii)

• MPI finds $C_k/C_D$ important for TC intensity
  – Observations support MPI, despite its simplicity

• Large uncertainty in $C_k$ and $C_D$ at high wind speeds over the ocean

Overarching research *hypothesis*:
Better representations of $C_k$ and $C_D$ in models such as WRF will improve TC intensity forecasts
Methodology

• Run simulations (WRF-ARW V3.4.1) of actual TCs
  – Start with Hurricane Katrina for now
    • Initialize at 0000 UTC 25 August 2005
      – Run 14.5 hours with a 60-member ensemble
      – Assimilate P3 radial velocity data between 1430 and 2000 UTC by EnKF
      – Run ensemble mean at 2000 UTC forward to 0000 UTC 26 August, and make restart files
    • Run deterministic forecasts from restart files for 120 hours
  – Test $C_k$ and $C_D$ sensitivity
    • ISFTCFLX options built-in to WRF (completed)
    • Other formulae that involve estimable parameters (in progress)
  – Incorporate most sensitive parameters into EnKF-based SSPE (future)
Surface flux formulas

- **Momentum**
  \[ \tau = -\rho u^* = -\rho C_D U^2 \]

- **Sensible heat**
  \[ H = -\rho c_p u* \theta* = -\left( \rho c_p \right) C_H U \Delta \theta \]

- **Latent heat**
  \[ E = -\rho L_v u* q* = -\left( \rho L_v \right) C_Q U \Delta q \]

- **Two methods to calculate fluxes**
  - Use $u^*$, $\theta^*$, and $q^*$
  - Use *bulk formulas* if we know $C_D$, $C_H$, and $C_Q$
    - MPI assumes $C_H = C_Q = C_k$

Ch. 7 of Stull (1988); HFIP powerpoint; Garratt (1992); WRF source code
Bulk exchange coefficient formulas

\[ C_D = \frac{u_*^2}{U^2} = \frac{k^2}{\left[ \ln\left( \frac{z_{ref}}{z_0} \right) - \psi_m \right]^2} \]

\[ C_H = \frac{k^2}{\left[ \ln\left( \frac{z_{ref}}{z_0} \right) - \psi_m \right] \times \left[ \ln\left( \frac{z_{ref}}{z_0} \right) + \ln\left( \frac{z_0}{z_T} \right) - \psi_h \right]} \]

\[ C_Q = \frac{k^2}{\left[ \ln\left( \frac{z_{ref}}{z_0} \right) - \psi_m \right] \times \left[ \ln\left( \frac{z_{ref}}{z_0} \right) + \ln\left( \frac{z_0}{z_Q} \right) - \psi_h \right]} \]

- WRF calculates roughness lengths \((z_0, z_T, z_Q)\) rather than calculating \(C_D, C_H,\) and \(C_Q\) directly

Brutsaert (1975); Garratt (1992); HFIP powerpoint; WRF source code
Different surface flux options (isftcflx in WRF namelist) available (except for “PSU”)

“PSU” is just like Opt 2 except $C_D$ doesn’t level off at high winds

From Green and Zhang (2012, accepted subject to major revision)
Results for isftcflx options

Track not very sensitive to isftcflx

Intensity very sensitive to isftcflx

Green and Zhang (2012, accepted subject to major revision)
Pressure/wind relationships for EnKF forecasts of 2008-2011 Atlantic TCs

C_D appears to change PWR much more than C_k!

- Best Track
- Opt 0
- Opt 1
- Opt 2
- PSU

Green and Zhang (2012, accepted subject to major revision)
Finding parameters to estimate

- Functional forms (and actual values) of $C_D$, $C_H$, $C_Q$ at high winds over the ocean are unknown

- TC intensity is sensitive to isftcflx option
  - Certain *model parameters* in these options govern TC intensity
  - Thus *parameter estimation* may be helpful

- Ideal parameters to estimate should be:
  - Observable: Changes to parameter yield noticeable changes in state variables
  - Simple: Changes to parameter yield smooth variations in state variables
  - Distinguishable: Strong correlation between parameter and state variables

Nielsen-Gammon et al. (2010)
New formula for $C_D$

- Kara et al. (2002) formula; Zedler et al. (2012) parameters

$$C_D = C_{D0} = 10^{-3} \left[ 0.692 + 0.071\tilde{V} - 0.0007\tilde{V}^2 \right]$$

$$\tilde{V} = \max \left[ 2.5, \min(V, V_c) \right]$$

$$C_D' = \alpha \left( C_D + m \times \max[0, V - V_c] \right)$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Range</th>
<th>HYCOM default</th>
<th>Sraj et al. (2012) estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Magnitude across all wind speeds</td>
<td>[0.4, 1.1]</td>
<td>1</td>
<td>1.026</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Transition to high wind regime</td>
<td>[20 m/s, 35 m/s]</td>
<td>32.5 m/s</td>
<td>34 m/s</td>
</tr>
<tr>
<td>$m$</td>
<td>Slope at high wind speeds</td>
<td>[-3.8×10^{-5}, ??]</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Adding a parameter to $z_T$ & $z_Q$ (and $C_H$ & $C_Q$)

- Parameter $\beta$ (range 0.5 to 2.2, default 1)

\[
z_T = z_0 \exp\left[-\beta k \left(7.3 \text{Re}_*^{1/4} \text{Pr}^{1/2} - 5\right)\right]
\]

\[
z_Q = z_0 \exp\left[-\beta k \left(7.3 \text{Re}_*^{1/4} \text{Sc}^{1/2} - 5\right)\right]
\]

- Then $C_H$ and $C_Q$…

\[
C_H = \frac{k^2}{\ln\left(\frac{z_{\text{ref}}}{z_0}\right) - \psi_m\left(\frac{z_{\text{ref}}}{L_0}\right)} \times \frac{k^2}{\ln\left(\frac{z_{\text{ref}}}{z_T}\right) - \psi_h\left(\frac{z_{\text{ref}}}{L_0}\right)}
\]

\[
C_Q = \frac{k^2}{\ln\left(\frac{z_{\text{ref}}}{z_0}\right) - \psi_m\left(\frac{z_{\text{ref}}}{L_0}\right)} \times \frac{k^2}{\ln\left(\frac{z_{\text{ref}}}{z_Q}\right) - \psi_h\left(\frac{z_{\text{ref}}}{L_0}\right)}
\]

\[
\text{Re}_* = \frac{u_* z_0}{\nu} = \frac{kV}{\ln\left(\frac{z_{\text{ref}}}{z_0}\right)} \times \frac{z_0}{\nu}
\]

Pr = 0.71
Sc = 0.60
$\nu = 1.5 \times 10^{-5}$ m$^2$ s$^{-1}$
Effects of varying $\alpha$ and $\beta$ on exchange coefficients

Coefficient ($x10^{-3}$)

$C_D (\alpha = 0.4)$

$C_D (\alpha = 0.75)$

$C_D (\alpha = 1.1)$

$C_D$ (all $\beta$)

$C_Q (\beta = 0.5)$

$C_Q (\beta = 1.35)$

$C_H (\beta = 2.2)$

Ratios

$C_Q / C_D (\alpha = 0.4)$

$C_Q / C_D (\alpha = 0.75)$

$C_H / C_D (\alpha = 1.1)$

$C_Q / C_D (\beta = 0.5)$

$C_Q / C_D (\beta = 1.35)$

$C_H / C_D (\beta = 2.2)$

10–m wind speed (m s$^{-1}$)
Effects of varying $V_c$ and $m$ on exchange coefficients

$C_D$ ($m = 3.8 \times 10^{-5}$)

$C_D$ ($m = 0$)

$C_D$ ($m = -3.8 \times 10^{-5}$)

$C_D$ ($V_c = 20$)

$C_D$ ($V_c = 35$)

$C_H$ ($V_c = 20$)

$C_H$ ($V_c = 35$)

$C_Q$ ($V_c = 20$)

$C_Q$ ($V_c = 35$)

$C_H/C_D$ ($V_c = 20$)

$C_H/C_D$ ($V_c = 35$)

$C_Q/C_D$ ($V_c = 20$)

$C_Q/C_D$ ($V_c = 35$)

$C_H/C_D$ ($m = 0$)

$C_Q/C_D$ ($m = 3.8 \times 10^{-5}$)

$C_H/C_D$ ($m = 3.8 \times 10^{-5}$)

Effects of varying $V_c$ and $m$ on exchange coefficients

$10$–$m$ wind speed (m s$^{-1}$)

$10$–$m$ wind speed (m s$^{-1}$)
Single-parameter results

1. **SLP over time**
2. **Max. 10-m wind over time**
3. **Pressure/wind relationship**

- **$\alpha$**
  - Low $\alpha$ (low $C_D$)
  - High $\alpha$ (high $C_D$)

- **$V_c$**
  - Low $V_c$ (low $C_D$)
  - High $V_c$ (high $C_D$)

- **$m$**
  - Low $m$ (low $C_D$)
  - High $m$ (high $C_D$)

- **$\beta$**
  - Low $\beta$ (high $C_k$)
  - High $\beta$ (low $C_k$)
Correlation between parameters and intensity for initial time of 0000 UTC 26 Aug., 3 domains

Short-term correlations (estimation): $\alpha$, $V_c$, $\beta$ w/ 10-m wind (TC too weak for $m$ to apply)

Long-term correlations (physics): $\beta$ with SLP and 10-m wind; $\alpha$ with SLP; $m$ with 10-m wind (and SLP at certain times... maybe eyewall replacement cycle?)
Evaluating SSPE performance

• Method 1: Real storms
  – Compare with (and assimilate) actual observations
  – Advantages:
    • Directly applicable to future storms
  – Disadvantages:
    • Observational errors
    • Additional model errors

• Method 2: OSSE
  – Generate “truth” run from WRF and assimilate “observations” from “truth”
  – Advantages:
    • Don’t need observed data
    • Only source of model error is in surface fluxes
  – Disadvantages:
    • Doesn’t say anything about real storms
Summary

• Goal: Improve numerical forecasts of TC intensity
• Hypothesis: Better representation of momentum and moist enthalpy fluxes across the sea surface in NWP models will yield more accurate TC intensity forecasts

• Results so far
  – Flux option affects TC intensity
    • $C_D$ affects pressure/wind relationship (e.g. Bao et al. 2012)
    • $C_Q$ (and $C_H$) affects intensity but not pressure/wind relationship
  – Single parameter tests
    • Multiplicative parameters ($\alpha$, $\beta$) have most impact
    • Strong correlations w/ wind speed in near-term (good for estimation)

• Research to be completed:
  – Vary all parameters simultaneously (multi-parameter tests)
  – EnKF-based SSPE
Acknowledgments

• Dr. Fuqing Zhang, Dr. Daniel Stern, and rest of PSU EnKF research group

• Dr. George Bryan, Dr. Kerry Emanuel, and two anonymous reviewers for Green and Zhang (2012, accepted subject to revision)
Reference


Extra slides
Background on TC intensity (i)

- TCs are like Carnot engines
  - Energy source: Enthalpy flux from sea surface
  - Energy sinks: Dissipation
    - Boundary layer
    - Upper-level outflow

- Early numerical simulations found TC intensity depends on surface exchange coefficients
  - Drag coefficient $C_D$
  - Enthalpy exchange coefficient $C_k$

Ooyama (1969); Rosenthal (1971); Emanuel (1986, 1988)
Part 1: TC surface flux options in WRF

- Conduct sensitivity experiments using different formula options for ocean-based surface fluxes
- Metrics used to examine flux options:
  - Track
  - Intensity
    - Minimum sea level pressure
    - Maximum 10-meter wind speed
  - Spatial structure
    - TC size and secondary circulation (not diagnosed by MPI)
    - Sensible and latent heat fluxes
- But first, discuss background physics…
Dynamics controlled by surface properties
- Surface friction and enthalpy flux are important
- Coriolis negligible

Sea-surface gravity waves reside here

FLUXES

Outer layer
- Ekman layer
- Mixed layer

Inner layer
- Surface layer
- Roughness layer

Coriolis negligible
Formulas for \( u_*, \theta_*, q_* \)

- **Most general case**

\[
\begin{align*}
  u_* &= \frac{kU(z_{\text{ref}})}{\ln(z_{\text{ref}}/z_0) - \psi_m} \\
  \theta_* &= \frac{k\Delta \theta}{\ln(z_{\text{ref}}/z_0) + \ln(z_0/z_T) - \psi_h} \\
  q_* &= \frac{k\Delta q}{\ln(z_{\text{ref}}/z_0) + \ln(z_0/z_Q) - \psi_h}
\end{align*}
\]

- \( z_0, z_T, \text{ and } z_Q \) are roughness lengths
- \( \psi_m \) (momentum) and \( \psi_h \) (heat and water vapor) are stability correction functions

Brutsaert (1975); Garratt (1992); HFIP powerpoint
Some notes on surface flux formulas

- WRF uses **roughness lengths** (instead of $C_D$, $C_H$, and $C_Q$ directly) to calculate surface fluxes

- Only consider fluxes across air-sea *interface*
  - Interface is not simple for choppy waters
    - Sea-surface roughness is not static
    - We do not *explicitly* account for the likely important effects of sea spray
### TC surface flux options in WRF (i)

- **Namelist option isftcflx**: *oceanic* surface fluxes

<table>
<thead>
<tr>
<th>Option</th>
<th>Momentum</th>
<th>Sensible heat</th>
<th>Latent heat</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Option 0</strong></td>
<td>$z_0 = z_T$ increases monotonically with wind (Charnock 1955)</td>
<td>Carlson and Boland (1978)</td>
<td></td>
</tr>
<tr>
<td><strong>Option 1</strong></td>
<td>Donelan et al. (2004): $z_0$ levels off at high winds</td>
<td>$z_T = z_Q = 10^{-4}$ meters (ad hoc formula)</td>
<td></td>
</tr>
<tr>
<td><strong>Option 2</strong></td>
<td></td>
<td></td>
<td>Brutsaert (1975)</td>
</tr>
</tbody>
</table>

- **Formulas** – as coded in WRF V3.4.1 – are given on the next 3 slides
TC surface flux options in WRF (ii)

- Drag coefficient $C_D$ (really roughness length $z_0$)

$$C_D = \frac{u_*^2}{U^2} = \frac{k^2}{\left[ \ln\left( \frac{z_{ref}}{z_0} \right) - \psi_m \right]^2}$$

<table>
<thead>
<tr>
<th>Option</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 0</td>
<td>$z_0 = 0.0185 \frac{u_*^2}{g} + 1.59 \times 10^{-5} \text{ m}$</td>
</tr>
<tr>
<td>Options 1 and 2</td>
<td>$z_0 = \max\left(1.27 \times 10^{-7}, \min\left[ z_w z_2 + (1 - z_w) z_1, 2.85 \times 10^{-3} \right]\right)$</td>
</tr>
<tr>
<td></td>
<td>$z_w = \min\left(1, \left[ \frac{u_*}{1.06} \right]^{0.3} \right)$</td>
</tr>
<tr>
<td></td>
<td>$z_1 = 0.011 \frac{u_*^2}{g} + 1.59 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$z_2 = \frac{10}{\exp\left(9.5 u_<em>^{-1/3}\right)} + \frac{1.65 \times 10^{-6}}{\max(u_</em>, 0.01)}$</td>
</tr>
</tbody>
</table>

Wu (1980); Davis et al. (2008); HFIP powerpoint; WRF source code
TC surface flux options in WRF (iii)

• Heat coefficient $C_H$ (really roughness length $z_T$)

$$C_H = \frac{k^2}{\left[ \ln\left( \frac{z_{ref}}{z_0} \right) - \psi_m \right] \ast \left[ \ln\left( \frac{z_{ref}}{z_0} \right) + \ln\left( \frac{z_0}{z_T} \right) - \psi_h \right]}$$

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 0</td>
<td>$z_T = z_0 \quad \text{AND} \quad \ln\left( \frac{z_{ref}}{z_0} \right) - \psi_h \leq 2$</td>
</tr>
<tr>
<td>Option 1</td>
<td>$z_T = z_Q = 10^{-4} \text{m (fixed constant)}$</td>
</tr>
<tr>
<td>Option 2</td>
<td>$z_T = z_0 \exp\left[ -k \left( 7.3 \text{Re}_{*}^{1/4} \text{Pr}^{1/2} - 5 \right) \right]$</td>
</tr>
</tbody>
</table>

where

$$\text{Re}_{*} = u_{*}z_0 / \nu$$

Pr is the Prandtl number (WRF uses $\text{Pr} = 0.71$)

$\nu$ is the kinematic viscosity of air

Brutsaert (1975); Wu (1980); Garratt (1992); HFIP powerpoint; WRF source code
TC surface flux options in WRF (iv)

- Vapor coefficient $C_Q$ (really $z_Q$)

$$C_Q = \frac{k^2}{\left[ \ln\left(\frac{z_{ref}}{z_0}\right) - \psi_m \right] \ast \left[ \ln\left(\frac{z_{ref}}{z_0}\right) + \ln\left(\frac{z_0}{z_Q}\right) - \psi_h \right]}$$

<table>
<thead>
<tr>
<th>Option</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 0</td>
<td>$z_Q = \left( z_0^{-1} + ku_*/K_a \right)^{-1}$</td>
</tr>
<tr>
<td>Option 1</td>
<td>$z_Q = z_T = 10^{-4}$ m (fixed constant)</td>
</tr>
<tr>
<td>Option 2</td>
<td>$z_Q = z_0 \exp\left[ -k \left( 7.3 \text{Re}_*^{1/4} \text{Sc}^{1/2} - 5 \right) \right]$</td>
</tr>
</tbody>
</table>

where $\text{Re}_* = u_* z_0 / \nu$

Sc is the Schmidt number (WRF uses $\text{Sc} = 0.60$)

$\nu$ is the kinematic viscosity of air

Background diffusivity $K_a = 2.4 \times 10^{-5}$ m$^2$ s$^{-1}$ (Bao et al. 2000)
"PSU" is just like Opt 2 except \( z_0 \) doesn't level off at high winds.
Success of EnKF in TC prediction

EnKF Performance Assimilating Airborne Radar OBS

Meant Absolute Error for 74 P3 TDR missions during 2008-2011

ABS Error of position (km) for 2008–2011–homogeneous

ABS Error of maxWSP (kts) for 2008–2011–homogeneous

Corrected $V_{\text{max}} = V_{\text{max}} - \left( \frac{30h-t}{30h} \times \text{Bias \_at\_initial\_time} \right)$

Figures courtesy Fuqing Zhang and Yonghui Weng
Finding $z_0$ from $C_D'$

- Work backwards...

\[
C_D' = \left[ \frac{k}{\ln(z_{\text{ref}} / z_0) - \psi_m(z_{\text{ref}} / L_0)} \right]^2 \quad \Rightarrow \quad z_0 = z_{\text{ref}} \exp\left[ \frac{-k}{\sqrt{C_D'}} - \psi_m\left(\frac{z_{\text{ref}}}{L_0}\right) \right]
\]

- For $z_{\text{ref}} = 10$ m,

\[
z_0 = 10 \exp\left[ -k \left( \alpha C_{D0} + \alpha m \ast \left[ \max(0, V - V_c) \right] \right)^{-1/2} - \psi_m(10/L_0) \right] \]

\[
C_{D0} = 10^{-3} \left[ 0.692 + 0.071\tilde{V} - 0.0007\tilde{V}^2 \right]
\]

\[
\tilde{V} = \max[V_{\text{min}}, \min(V, V_c)]
\]

- We incorporate non-neutral stability into the formula for $z_0$ (through $\psi_m$)
**Example**

Finding ideal parameters

- Vary each parameter by its experimental uncertainty
- Determine effect on $C_D$, $C_H$, $C_Q$
- If impacts on exchange coefficients are large, determine sensitivity of state variables by modifying WRF code

<table>
<thead>
<tr>
<th>Parameters to estimate:</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.011, $1.59 \times 10^{-5}$, $2.85 \times 10^{-3}$</td>
</tr>
<tr>
<td>Pr and Sc</td>
</tr>
<tr>
<td>7.3, 5, $\frac{1}{2}$, $\frac{1}{4}$</td>
</tr>
</tbody>
</table>
Results

SLP over time

Max. 10-m wind over time

pressure/wind relationship
Part 3: SSPE

• Also known as Simultaneous State and Parameter Estimation

• Very similar to state-only estimation in EnKF
  – Augment state vector to include model parameters
  – Parameters estimated *simultaneously* with state variables
  – SSPE shown to be better than state-only EnKF (but not tested yet for TC applications)

Aksoy et al. (2006a); Hu et al. (2010)
Proven benefits of SSPE

RMSE and bias for non-TC SSPE experiment using WRF (Hu et al. 2010)
SSPE outperforms state-only EnKF!
Quantifying SSPE performance

- Method 1 (real data):
  - Track
  - Point intensity (minimum pressure, maximum winds)
  - Size (radii of maximum winds and of hurricane force winds)

- Method 2 (OSSE):
  - Direct comparison between state variables