Wind forcing methods for storm surge modeling

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- Review of storm surge physics
- Hurricane parametric wind models
- MSU parametric scheme
- The potential for surrogate modeling
6. Contribution of Physical Components

[73] The shallow water momentum equation can be described in terms of its components (\(L\): local acceleration, \(A\): advection, \(C\): Coriolis, \(Z\): surface gradient, \(P\): atmospheric pressure, \(T\): tidal potential, \(W\): wind stress, \(R\): wave radiation stress gradient, \(B\): bottom stress, \(D\): diffusion):

\[
\tau_{\text{wind}} = \rho C_d U_{10}^2
\]

\[0 = -\frac{\partial u}{\partial t} + u \cdot \nabla u - f \times u - g \nabla \zeta - \frac{\nabla p_s}{\rho_0} \]

\[+ g \nabla \alpha \eta + \frac{\tau_{s,\text{winds}}}{\rho_0 H} + \frac{\tau_{s,\text{waves}}}{\rho_0 H} - \frac{\tau_b}{\rho_0 H} + \frac{M}{H} + \frac{M}{\rho_0 H} \]

where \(u\) represents the depth average velocity, \(f\) is the coriolis term, \(\zeta\) represents the free surface departure from the geoid, \(p_s\) represent the atmospheric pressure at the sea surface, \(\alpha\) is the earth elasticity reduction factor, \(\eta\) is the Newtonian equilibrium tide potential, \(\tau_{s,\text{winds}}\) and \(\tau_{s,\text{waves}}\) represent the imposed surface stresses for winds and waves respectively, \(\tau_b\) represents the bottom stress, and \(M\) represents lateral stress gradients.
Fundamental surge components

• Pressure setup - *increase in water level due to lower atmospheric pressure in storm interior*. A slight surface bulge occurs within the storm, greatest at the storm’s center, decreasing at the storm’s periphery. For every 10-mb pressure drop, water expands 3.9 inches.
  
  • *Effect is a constant*

• Wind setup - *increase in water level due to the force of the wind on the water*. As the transported water reaches shallow coastlines, bottom friction slows their motion, causing water to pile up. Further enhanced near land boundaries.
  
  • *Depends on bathymetry, size, and intensity. MOST IMPORTANT IN TERMS OF MAGNITUDE!*

• Geostrophic adjustment – *water levels adjust to a developing longshore current*.
  
  • *Impact increases for slow-moving tropical cyclones*
  • *Impact increases for larger tropical cyclones*
  • *Causes a storm surge “forerunner”*

• Wave setup - *increase due to onshore waves*. Incoming water from wave breaking exceeds retreating water after wave runup.
  
  — *Impact minor in shallow bathymetry (0.5-1 ft); may contribute up to 3 ft surge in deep bathymetry (still the subject of debate)*
Pressure setup

Wind setup

Wave setup
Geostrophic adjustment (creates surge “forerunner”)

The slower the hurricane moves, the more important (Fitzpatrick et al. 2012)

http://www.seos-project.eu/modules/oceancurrents/oceancurrents-c06-s02-p01.html
Effect of hurricane intensity, size, and speed on storm surge

Cat 1, 3, 5 hurricanes, average size, average speed

Correction factors for speed and size

Size
- Zone 2: \( \pm 1.5 \) (Cat 3–5)
- Zone 3: \( \pm 1.0 \) (Cat 1–2), \( \pm 1.6 \) (Cat 3), \( \pm 2.5 \) (Cat 4–5)
- Zone 4: \( \pm 1.6 \) (Cat 1–2), \( \pm 2.5 \) (Cat 3), \( \pm 3.6 \) (Cat 4–5)
- Zone 5: \( \pm 2.3 \) (Cat 1–2), \( \pm 3.3 \) (Cat 3), \( \pm 4.3 \) (Cat 4–5)

Speed
- Zone 4: \( \pm 1.5 \) (Cat 1–2), \( \pm 2.0 \) (Cat 3), \( \pm 2.6 \) (Cat 4–5)
- Zone 5: \( \pm 3.0 \) (Cat 1–2), \( \pm 3.9 \) (Cat 3), \( \pm 5.2 \) (Cat 4–5)
Storm surge models wind forcing
Parametric equation philosophy

• \( V_{\text{sym}}(\tilde{V}_{\text{max}}, r_{\text{max}}, r, x_1, x_2, x_3 \ldots) \) \( \rightarrow \) symmetric wind field; often a shape factor is used

• \( V_{\text{total}} = V_{\text{sym}} + A \) \( \rightarrow \) asymmetry (A) added for total wind field from storm motion

\( \tilde{V}_{\text{max}} \) is 10-m \( V_{\text{max}} \) increased above PBL, and decreased for motion

• Compute pressure field from \( V_{\text{sym}} \) assuming gradient wind balance

or, as in SLOSH, compute \( V_{\text{sym}} \) from pressure deficit

• Reduce total wind field to 10-meter height

• Adjust for inflow angles

Used in most storm surge model applications. Also used in hurricane risk assessments and many other purposes
SLOSH methodology – three steps

1) \( V_{\text{max}} \) computed from \( p_c - p_{\text{env}} \) using an empirical equation similar to gradient wind balance

\[
2) \quad V_{\text{sym}}(V_{\text{max}}, r_{\text{max}}, r) = V_{\text{max}} \frac{2rr_{\text{max}}}{r^2 + r_{\text{max}}^2}
\]

3) Asymmetry added using equation similar to \( V_{\text{sym}} \) format

Deficiencies with wind forcing:

- Not based on observed wind observations
- Storm size information, such as radius of 34 knots winds, not considered. In fact, storm size only a function of \( r_{\text{max}} \), which has nothing to do with storm size
- Storm motion probably inflating intensity
- Storm motion asymmetry not based on observations. In fact, original paper even states it’s a “gross correction” which provides a reasonable asymmetry
MSU parametric scheme “Fitz winds”

The hurricane winds are based on a variant of the Holland (1980) wind profile:

\[
p(r, B, p_{en}, p_c, R_{max}) = p_c + \left[p_{en} - p_c\right]e^{-\frac{r^2}{2}}
\]

\[
V(r, B, f, p_{en}, p_c, R_{max}) = \left[\frac{AB[p_{en} - p_c]e^{-\frac{r^2}{2}}}{\rho r f}\right]^{0.5} + \left[\frac{rf}{2}\right]^2 - \left[\frac{rf}{2}\right]
\]

\[
V_{max}(B, p_{en}, p_c) = \left[\frac{B}{\rho e}\right]^{0.5} \left[p_{en} - p_c\right]^{0.5} ; A(R_{max}, B) = R_{max}^2
\]

where \( f \) is the Coriolis parameter, \( p_c \) is the storm central pressure, \( p_{en} \) is the environmental pressure (set to 1013 mbar), and \( e \) is Euler’s number (the base of the natural logarithm, approximately 2.71828). \( A \) and \( B \) are scaling parameters which control the radial wind profile. This formulation includes storm motion in \( V \). Given storm motion, \( V_{max}, R_{max}, p_{en}, \) and \( R34 \), the algorithm iterates for \( B \) and then calculates \( p_c \).

Because these equations apply above the boundary layer, but \( V_{max} \) and \( V34 \) (34-kt winds at R34) are at 10-m height within the boundary layer, \( V_{max} \) and \( V34 \) are multiplied by 1.11 before the \( B \) iteration. On average, winds are 11% faster above the boundary layer (see [http://www.nhc.noaa.gov/aboutwindprofile.shtml](http://www.nhc.noaa.gov/aboutwindprofile.shtml) and Powell and Black (1990)). However, little sensitivity in the \( B \) distribution was seen with this adjustment.
c function statement for iteration

c The function is derived as follows

c It can be shown from Holland's paper that:
c
penv-pc=Vmax*Vmax/(B/(rho*2.71828))
c
substitute this into the gradient wind equation (from Holland)
c where the wind is 17.5 m/s (34 knots)
c
now everything is known except B. Find B by iteration

c note that 17.5 m/s has been increased by windF then the storm speed
c is subtracted

c******************************************************

function f(B,Vmax,storm_speed,Rmax,size,Coriolis,windF)

implicit none

double precision  B, Vmax, Rmax, storm_speed, size, Coriolis
double precision Wind34ktInMeterPerSec, rho, f, ts, windF
parameter(Wind34ktInMeterPerSec=17.5, rho=1.15)

  ts = Wind34ktInMeterPerSec * windF - storm_speed

  f=(sqrt(((Rmax**2)*B*(Vmax*Vmax/(B/(rho*2.71828))) *
    exp(-((Rmax**2)/(size**B)))/(rho*size**B)) +
    ((size**2)*(Coriolis**2)/4.0)) - (size*Coriolis/2.0)
  f = ts

end function f
Parametric hurricane wind model flow chart

Step 1:
- Input Data:
  - Storm Center(lon,lat)
  - Max Wind Speed
  - Min Central Pressure
  - Radius at Max Wind
  - Radius at 34kt Wind
  - Storm Speed

- Holland’s Wind Profile Algorithm

- Output:
  - Scaling Parameters A & B
  - Environmental Pressure

Step 2:
- Input Data:
  - Grid Points
  - Storm Center(lon,lat)
  - Max Wind Speed
  - Min Central Pressure
  - Radius at Max Wind
  - Radius at 34kt Wind
  - Storm Speed
  - Storm Motion U Component
  - Storm Motion V Component
  - Environmental Pressure
  - Scaling Parameter B

- Compute distances of each grid point from the storm center

- Compute tangential wind and radial wind with inflow angle based on Holland’s Wind Profile Algorithm

- Compute U, V and wind direction from tangential wind, radial wind, and UV components of storm motion

- Output:
  - Wind Speed and Direction for each grid point
Advantage of this method

- 10-meter surface winds **match** the observed peak **eyewall wind**
- 10-meter surface winds **match** the observed **radius of 34-knots winds**
- Holland B an **iterated solution**, not predetermined
- **Specification of wind direction** that can vary radially
- **Storm motion is included in the iteration, not added afterwards**
  - $V_{\text{max}} =$ storm speed plus hurricane vortex eyewall
  - $V_{34} =$ storm speed plus edge of hurricane vortex
- This allows a parametric model which:
  - **Matches the National Hurricane Center forecast**
  - Can **match hindcast hurricane data** for JPM studies, theoretical studies, risk modeling, etc.
- **Correctly uses storm motion.** Many schemes superimpose storm speed translation. This is incorrect usage. Observed winds already include storm motion.
- Version 1 released 6/11 as open source. Its also now being incorporated into SMS software. Version 2 will include a new asymmetry factor, but funding is always a problem.
Comparison of hypothetical storm (left) fitted by Fitz Wind Model (right)
The future of storm surge modeling
ADCIRC_Lite: Rapid Tropical Cyclone Surge and Wave Evaluations using Pre-computed ADCIRC Solutions

Brian Blanton, Rick Lueftich, Jesse Bikman
*University of North Carolina at Chapel Hill*

Alexander Taflanidis, Andrew Kennedy
*University of Notre Dame*

*ADCIRC Users Group Meeting 4/3/2014*

Funded by the Department of Homeland Security’s Science & Technology Coastal Hazards Center of Excellence at UNC
The Issue

• Short forecast windows
  • Forecast cycle typically 6 hours
  • Need information well within this 6-hour window
  • Want guidance information ASAP

• High-resolution, dynamic surge & wave simulations are resource intensive
  • Typical 1 - 3 hours run time on 192 processors
  • Multiple member ensemble requires more

• How to accelerate model throughput
  • Much more computer hardware (someday...)
  • Take advantage of pre-computed, high resolution solutions (e.g., Surge Atlas)
Surrogate Modeling

Implement a surrogate model that rapidly predicts a response (storm surge, waves) using familiar variables (hurricane parameters)

• Surrogate models approximate complex systems
  • Replace ADCIRC with AdcircLite

• Leverage *existing* database of high-resolution storm surge simulations
  • recent FEMA coastal National Flood Insurance Program Study for North Carolina
  • similar FEMA NFIP databases available for other areas
  • Supplement existing databases as desired / needed
AdcircLite Surrogate Model
Response Surface Method

- Long history in engineering, chemistry...
- More recently used for storm surge – JPM OS D. Resio; also J. Irish
- AdcircLite uses 2nd order moving least squares
- Much better accuracy compared to zeroth-order methods

\[
\hat{z}_i(x) = \sum_{j=1}^{NB} b_j(x) a_{ij} \{x\}
\]

- response estimate
- vector of hurricane parameters
- basis functions
- database of dynamic model solutions x weighting coefficient found by optimization
Historical Storm Results – Isabel 2003
Maximum Water Level

AdcircLite-NC Model Prediction
- 4 secs to compute

FEMA Validation Study
- ~6 hrs to compute
Historical Storm Results – Isabel 2003

Maximum Significant Wave Height

AdcircLite-NC Model Prediction
- 4 secs to compute

FEMA Validation Study
- ~6 hrs to compute
Ongoing Activities

• Ensemble Forecasting with AdcircLite
  • Method to perturb NHC forecast track
  • Outputs ADCIRC fort.22 files
  • Basic parameter variation, test distributions for RMW, Heading, Forward Speed
  • 135 ensemble members (5*7*3)
Ongoing Activities

Hurricane Irene (2011), Advisory 24

50% Exceedence Level

10% Exceedence Level
Conclusions

- Surrogate modeling approach can fill a storm surge / wave prediction gap between coarse resolution (fast) and high resolution (slow) dynamic models

- AdcircLite – Moving (Local) Least Squares Response Surface Method
  - Robust and fast once surrogate model is defined
  - Quantifiable error estimates can be obtained

- Simple to run once surrogate model defined

- Provides a mechanism to develop large, ensemble-based (probabilistic) high-resolution water level predictions