A baseline storm surge ensemble methodology for Pacific islands – the PACSURGE system

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BACKGROUND

Storm surge is inherently sensitive to tropical cyclone track, speed, intensity, and wind structure, rendering 2- to 5-day deterministic forecasts impracticable. Ensemble surge forecasts therefore are recommended for emergency preparedness during a pending tropical cyclone impact. High-resolution simulations are typically finite-element models such as ADCIRC, FVCOM, or Delft3D which require supercomputers, labor-intensive grid configurations, and numerous track scenario tests to identify and fix instability issues. Additionally, while such models are useful for case studies or hindcast of surge events, they are unfeasible for operational ensemble runs due to limited computer resources. Other optimized models, such as SLOSH, still require resources for grid configuration, cannot support hundreds of runs, and lack community model support. However, since storm surge is governed primarily by four components which bound the solutions – wind setup, pressure setup, current-induced geostrophic adjustment processes (typically called the forerunner), and wave setup – such advanced systems may not be necessary to generate ensemble forecast spread.

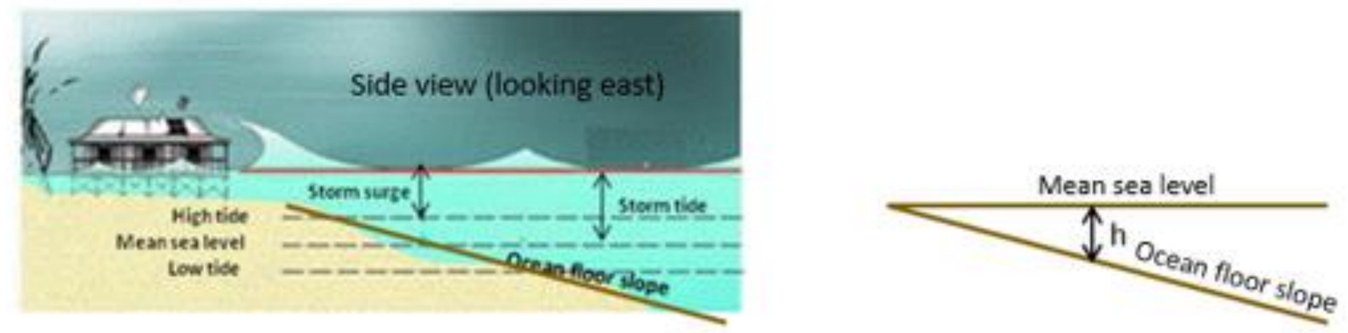
Based on these constraints, this poster discusses a 1D storm surge ensemble guidance two-part package developed for rapid deployment and fast solutions. The initial focus target are Pacific islands, but other ocean basins and coastal continents are applicable. The first product is a 1D model called *PACSURGE-M*, and the second product assumes steady-state 1D peak surge conditions at landfall called *PACSURGE*. Each wind forcing run is from official tropical cyclone wind speed probabilities (DeMaria et al. 2009, 2013) disseminated through operational tropical cyclone forecast centers. However, any gridded wind ensemble product, such as the COAMPS-TC ensemble system, can be used. Wave input is generated by a wave forecast ensemble that is consistent with this wind speed probability product (Sampson et al. 2016). If pressure is not available, it is computed from the Courtney and Knaff (2009) relationship. Options for the geostrophic adjustment in PACSURGE are empirical terms, or computed based on empirical ocean current equations from Chiang et al. (2016). Options for wave setup are based on a percentage of inshore breaking wave height or offshore significant wave height (Dean et al. 2005). In cases where a coral reef attenuates wave setup impact, or the geostrophic adjustment process is negligible (as in small islands), either term can be turned off. The tide range is superimposed on the surge, providing additional ensemble members.

Surge validation results of 6 tropical cyclones for Okinawa's Buckner Bay (Nakagusuku Bay), using water level data from the Japan Oceanographic Data Center On-line Service System (J-DOSS), are presented. While high-fidelity models are needed in complex basins, PACSURGE performs reasonably well for open bays and coast, and will provide reasonably bounded solutions for ensemble runs in Pacific islands.

Both codes are written in FORTRAN and internally documented. An earlier version of *PACSURGE-M* is coded in python and available on drfitz.net . A spreadsheet of *PACSURGE* is also available for Windows machines, and is ideal for classroom instruction on storm surge in conjunction with notes on Fitzpatrick's teaching website weatherclasses.com . Beta versions of *PACSURGE* and *PACSURGE-M* are ready for deployment, just requiring bathymetry cross-sections and tidal data for new locations.

PACSURGE-M

PACSURGE-M solves the one-dimensional shallow water equations where the y axis is perpendicular to the shoreline positive in the inland direction, and the x axis parallels the shoreline positive in the east direction.



$$\frac{\partial u_{water}}{\partial t} = \frac{(\tau_{sx} - \tau_{bx})}{\rho_{water}(h+\eta)};\ \tau_{sx} = -\rho C_D|\vec{V}|u;\ ;\ \tau_{bx} = -\rho_{water} C_k |\vec{V}_{water}| u_{water}$$

$$\frac{\partial \eta}{\partial y} = (wind\ setup) + (geostrophic\ adjustment) + (pressure\ setup) + (wave\ setup)$$

$$geostrophic\ adjustment = -\frac{f u_{water}}{g}$$

$$pressure\ setup = -\frac{1}{\rho_{water} g}\frac{\partial p}{\partial y}$$

$$wind\ setup = \frac{\tau_{sy}}{\rho_{water} g (h+\eta)};\ \tau_{sy} = -\rho C_D |\vec{V}| v$$

f is Coriolis parameter, (2)(0.00007292)sin(latitude)

u_{water} is water current along coast; v_{water} is water current perpendicular to coast, assumed to be zero

P is air pressure

g is gravity

h is water depth

η is storm surge

ρ is density of air

ρ_{water} is density of water

u is zonal wind (west-east component); v is meridional wind (north-south component)

$|\vec{V}|$ is magnitude of wind vector; $|\vec{V}_{water}|$ is magnitude of ocean current vector

$$|\vec{V}| = \sqrt{u^2+v^2};\ |\vec{V}_{water}| = \sqrt{u_{water}^2 + v_{water}^2} \approx u_{water}\ \text{(since } v_{water} = 0\text{)}$$

C_k is ocean bottom drag coefficient

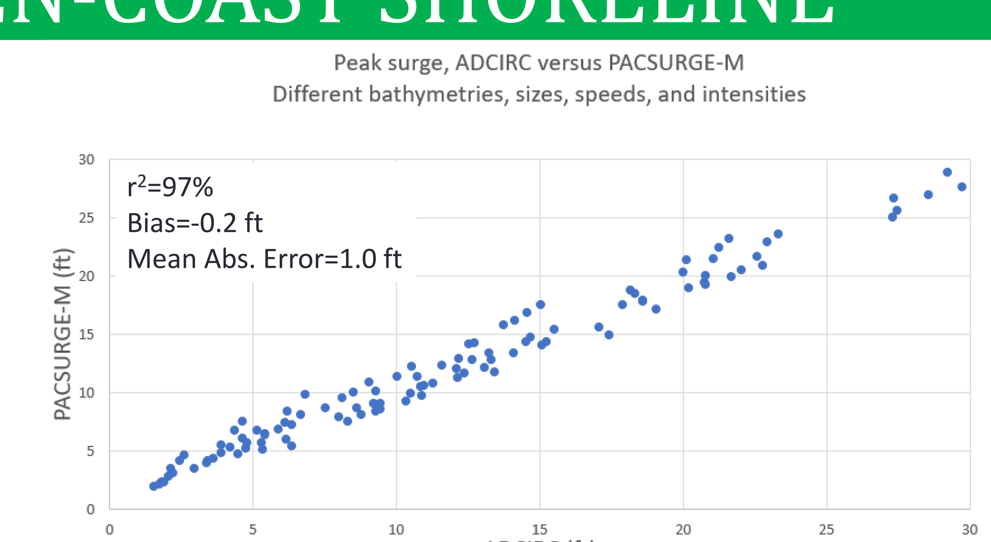
C_D is wind drag coefficient

τ_{sx} is zonal wind stress (west-east component); τ_{sy} is meridional wind stress (north-south component)

τ_{bx} is zonal bottom stress (west-east component)

The *wave setup* contribution options are 18% of the nearshore water depth (Southgate 1988; FEMA 2015), or 8% of the offshore significant water height (Dean et al. 2005). If reefs exist offshore such that breaking waves are not near the shoreline, it may be best to turn this term off if wave rollers cannot be regenerated.

PACSURGE-M VERSUS ADCIRC, OPEN-COAST SHORELINE



PACSURGE

- PACSURGE is the steady-state version of PACSURGE-M.
- Wind setup, pressure setup, and wave setup are analytically computed at time of peak wind at shoreline using same formulations as PACSURGE-M.
- The geostrophic adjustment term is parameterized from an empirical fit to a PACSURGE-M dataset for different bathymetries. Alternatively, it can be computed from empirical equations developed by Chiang et al. (2016) for a tropical cyclone ocean current dataset.
- Available as a FORTRAN program or in a spreadsheet.

PACSURGE VALIDATION AT BUCKNER BAY, OKINAWA

Buckner Bay was chosen for beta tests due to the military base presence, and the potential for a devastating impact as demonstrated by Typhoon Louise (1945). Water gauge observations are also available as well as mesoscale winds. Because many typhoon tracks are recurving or offshore, peak onshore winds into the bay are limited opportunities. Combined with a deep bathymetry, surges are constrained in the current database, with the fastest onshore winds from Jelawat (2012) of 64 knots. However, PACSURGE indicates a direct eyewall onshore impact from a supertyphoon with 155-knots winds could create a surge up to 15 feet and potentially 22 feet water elevation at high tide. In addition, Louise created waves of 35 feet.

	PACSURGE (ft)	Observed at Baten (ft)
Halong (2002)	2.2	2.1
Hattie (1990)	4.0	2.0
Jelawat (2012)	5.3	4.6
Kinna (1991)	5.1	3.0
Nakri (2014)	0.7	1.2
Man-yi 2007)	3.4	3.0

Wind observations for input were obtained from http://agora.ex.nii.ac.jp/digital-typhoon/ , the *Digital Typhoon* website. A mirror site exists at http://www.digital-typhoon.org . Water level data was downloaded from the Japan Oceanographic Data Center On-line Service System (J-DOSS) at: http://www.jodc.go.jp/jodcweb/JDOSS/index.html .

Results from PACSURGE-M are pending, and will be made available on drfitz.net in a few weeks.

REFERENCES AND SUPPORT

References are available by request, and also see accompanying handout.
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