Role of Coastal HF Radars in Storm-Surge Forecasting

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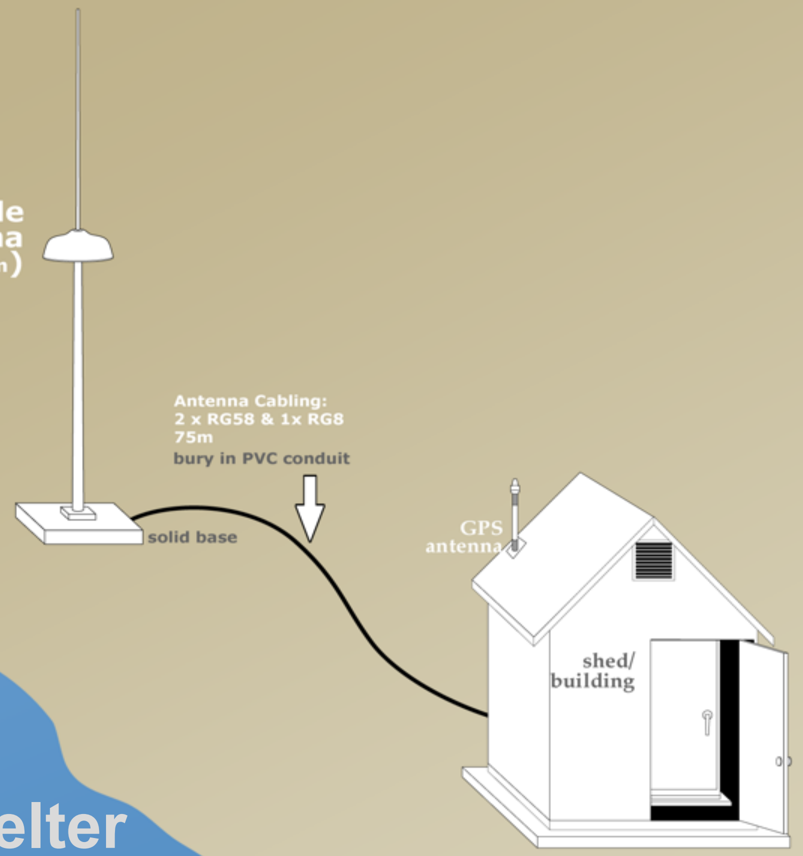
Waves & Storm Surge Workshop -- November 10, 2015

- **Where are Radars Useful in Three Phases of Storm Surge?**
  - **Inundation or rise: the most important – need to know how high water will rise in order to manage impacts**
  - **Steady-state or equilibrium – max wind speed reached, bottom return flow balances surface onshore flow**
  - **Relaxation – wind drops, shoreward surface flow ceases, gravity allows all flow offshore**

- **Where Can Radars Lead to Useful Short-Term Forecasts?**

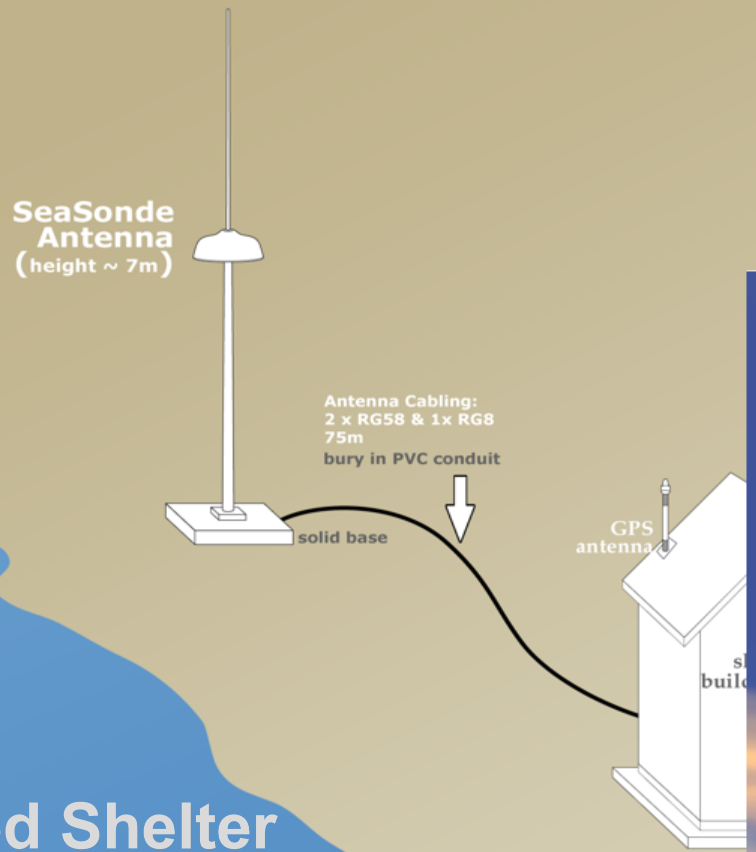
SeaSonde Site Layout



Climate-Controlled Shelter with Power, Communications

> 11 MHz: Single T/R antenna

SeaSonde Site Layout

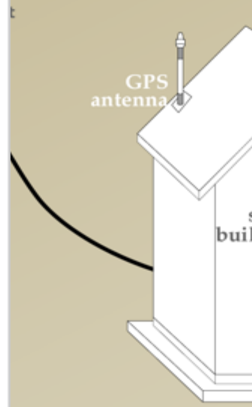


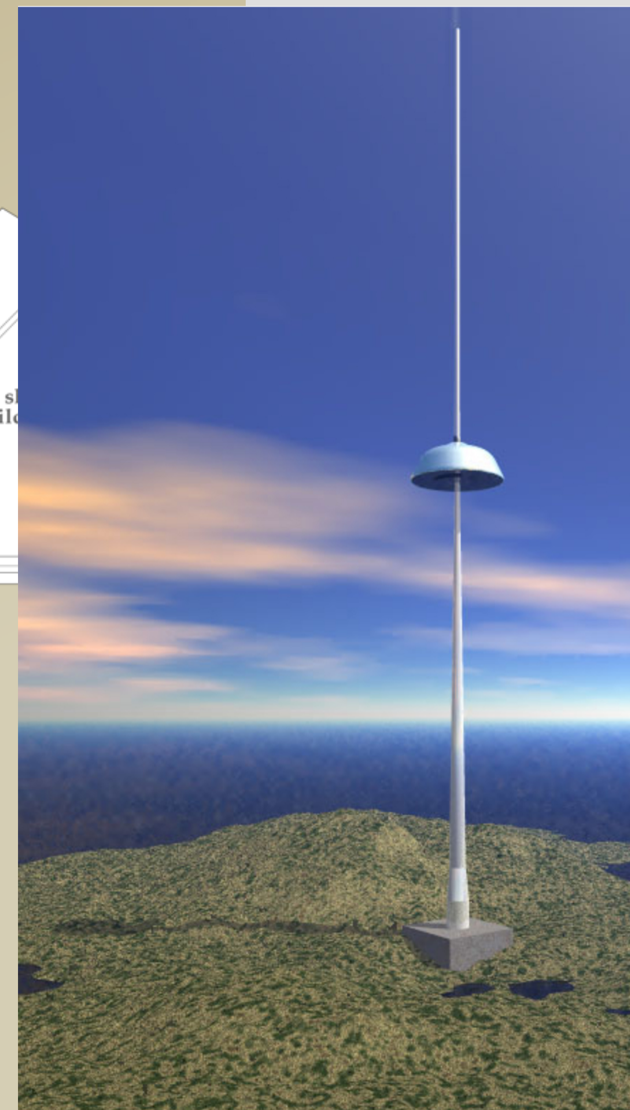
Climate-Controlled Shelter with Power, Communications

> 11 MHz: Single T/R antenna

A platform for SeaSonde antennas?

A hurricane-hardened "NOAA Sentinel" water-level observing station.



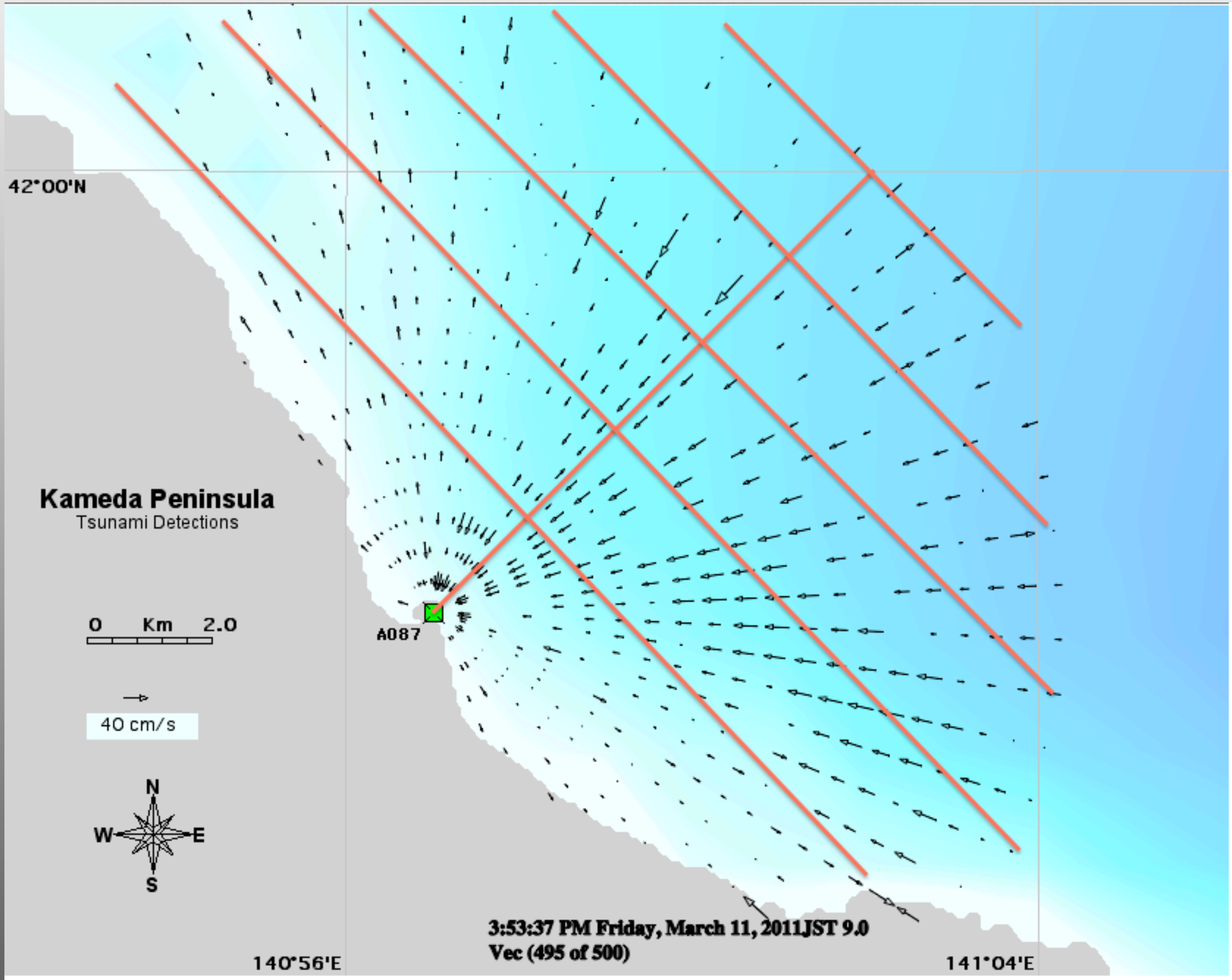


140 Candidate SeaSonde HF Radars for Near-Field Storm-Surge Modeling & Forecasting

"I am a SeaSonde coastal HF radar. What do I see and how can I help with short-term storm-surge forecasts?"

- Surface velocities mapped in bands out to ~200 km every hour
- Thence, deduce onshore water transport in upper layer forced by winds and waves
- Isn't this all that's needed for the space/time domain of HFR during 'inundation phase'?
- If so, winds/waves unnecessary for short-term forecasts (<12 h)

Example for Hokkaido of Bands and Fitting of Radials from Single SeaSondes



Inundation Phase-1: Transport Leading to Surge-Level Rise Occurs in Upper Layer

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- **Conservation of Momentum (Newton's Second Law)** [Resio et al., 2008]

(1)

$$\frac{\partial u(x,z,t)}{\partial t} = \frac{1}{\rho_s}\frac{\partial \tau_x(x,z,t)}{\partial z}$$

Acceleration Related To Wind Stress

Inundation Phase-1: Transport Leading to Surge-Level Rise Occurs in Upper Layer

- Conservation of Momentum (Newton's Second Law) [Resio et al., 2008]

- Reynolds Stress Related to Eddy Viscosity, μ

(2)
$$\tau_x(x,z,t) = \mu \frac{\partial u(x,z,t)}{\partial z}$$

$$10^{-5} \le \mu \le 10^{-3} \quad \frac{\mathrm{m}^2}{\mathrm{s}}$$

Inundation Phase-1: Transport Leading to Surge-Level Rise Occurs in Upper Layer

- Conservation of Momentum (Newton's Second Law) [Resio et al., 2008]

- Reynolds Stress Related to Eddy Viscosity, μ

- **Combine to Get Parabolic Partial Differential Equation (Heat Eq.)**

(3) $$\frac{\partial u(x,z,t)}{\partial t} = \mu \frac{\partial^2 u(x,z,t)}{\partial z^2}$$

Horizontal x-Variation Is Slow

Inundation Phase-2: Transport Leading to Surge-Level Rise Occurs in Upper Layer

- **Conservation of Water (incompressibility)** [Resio et al., 2008]

(4)
$$\frac{\partial \eta(x,t)}{\partial t} = -\int_{-\eta}^{d} \frac{\partial u(x,z,t)}{\partial x} dz$$

When you squeeze water at sides of column, sea level must rise

- **Surface (storm-surge) height:** $\eta(x,t)$

Inundation Phase-2: Transport Leading to Surge-Level Rise Occurs in Upper Layer

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- Conservation of Water (incompressibility) [Resio et al., 2008]

- Surface (storm-surge) height: $\eta(x,t)$

- **Assume a plausible model for velocity:**

(5)
$$u(x,z,t) = a \exp\left(\frac{z}{\delta(x,t)}\right) \tanh\left(\frac{\tau_o(x,t)\,t}{a\rho_s\delta(x,t)}\right) \quad \text{for} \quad \begin{cases} x>0 \\ z<0 \\ t>0 \end{cases}$$

Inundation Phase-2: Transport Leading to Surge-Level Rise Occurs in Upper Layer

- **Conservation of Water (incompressibility)** [Resio et al., 2008]
- **Surface (storm-surge) height:** $\eta(x,t)$
- **Assume a plausible model for velocity:**
- **Typically water final velocity at surface due to wind stress is approximately:** $a \approx 0.03V_{10}$

Inundation Phase-3: Transport Leading to Surge-Level Rise Occurs in Upper Layer

- **Integrate model (5) within (4) over z (positive downward) to get at upper-layer e-folding depth at surface, $\delta(x,t)$**

(6) $$\frac{\partial \eta(x,t)}{\partial t} = -\delta(x,t)\frac{\partial u(x,0,t)}{\partial x}$$

Inundation Phase-3: Transport Leading to Surge-Level Rise Occurs in Upper Layer

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- Integrate model (5) within (4) over z (positive downward) to get at upper-layer e-folding depth at surface, $\delta(x,t)$

- Differentiate model (5) PDE (Heat Eq.) (3) over z:

(7)
$$\frac{\partial u(x,0,t)}{\partial t} = \frac{\mu}{\delta^2(x,t)} u(x,0,t)$$

Inundation Phase-3: Transport Leading to Surge-Level Rise Occurs in Upper Layer

- Integrate model (5) within (4) over z (positive downward) to get at upper-layer e-folding depth at surface, $\delta(x,t)$

- Differentiate model (5) PDE (Heat Eq.) (5) over z:

$$\frac{\partial u(x,0,t)}{\partial t} = \frac{\mu}{\delta^2(x,t)} u(x,0,t)$$

- **Solve the above equation to get e-folding upper-layer depth:**

$$\delta^2(x,t) = \mu \frac{u(x,0,t)}{\left[\dfrac{\partial u(x,0,t)}{\partial t}\right]} \quad (8)$$

Inundation Phase-4: Transport Leading to Surge-Level Rise Occurs in Upper Layer

Final Simple Model for Surge Rise in Terms of SeaSonde-Measured Surface Velocity Maps

- **Substitute (8) into (6):**

$$\frac{\partial\eta(x,t)}{\partial t} = -\frac{\partial u(x,0,t)}{\partial x}\sqrt{\mu\frac{u(x,0,t)}{\left[\frac{\partial u(x,0,t)}{\partial t}\right]}}$$

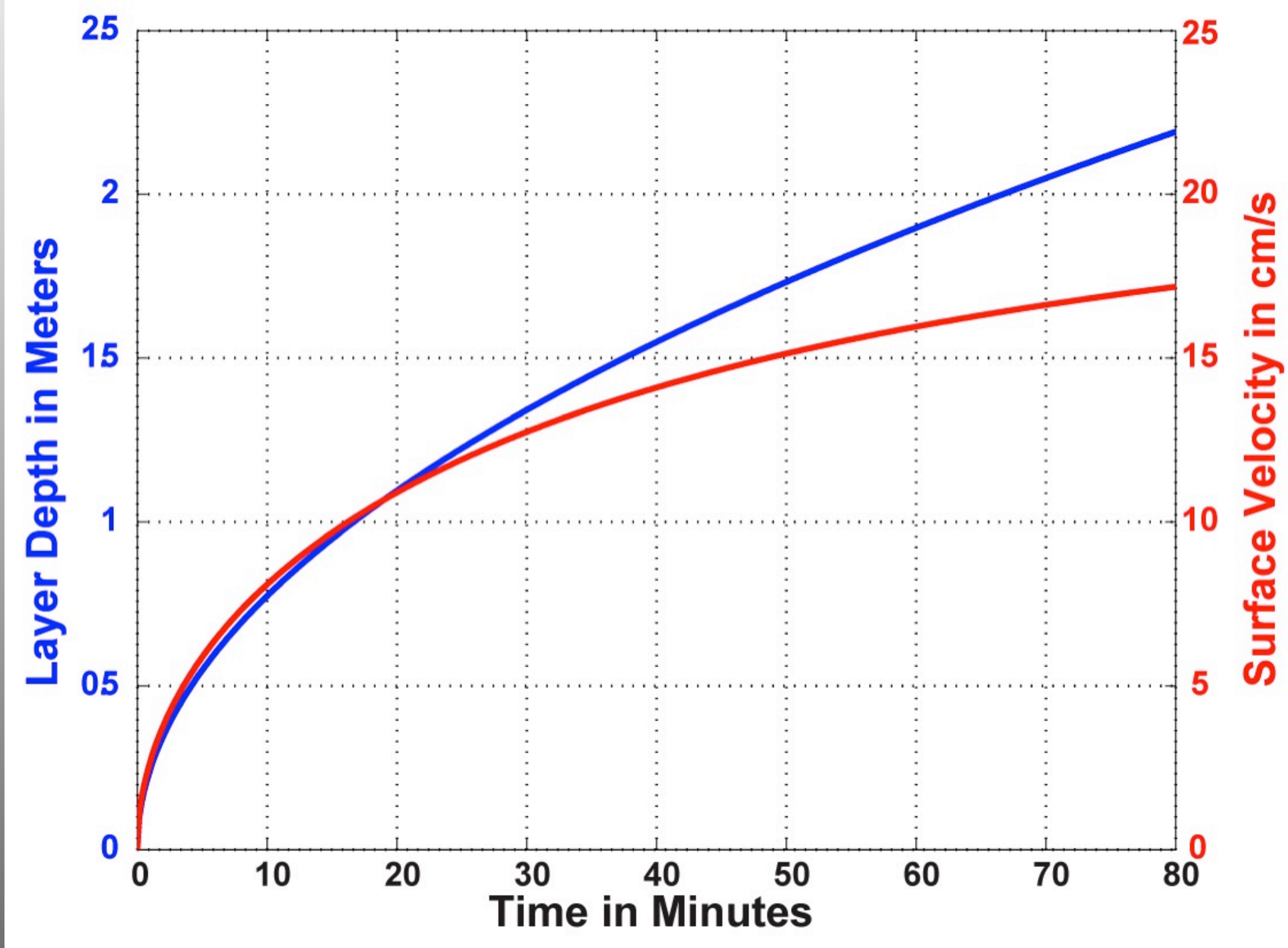
- **Radar measures:** $u(x_i,0,t_j)$

- **Integrate above equation over time to get:** $\eta(x_i,t_j)$

- **How far into future time can this be extended based on past measurement?**

Example of Upper Layer Below Radar Observation

- **Constant wind stress after 7 m/s wind jump;** $\mu = 10^{-4}\ \frac{m^2}{s}$



For later times Coriolis/Ekman effect becomes important

Conclusions and Way Forward

- **>100 U.S. coastal SeaSonde HF radars observe onshore surface flow/transport out to 200 km, continuous over space & time**
- **Premise: these can be used to forecast sea level rise during inundation phase, perhaps out to 12 – 24 hours**
- **We derived simple hydrodynamic example to demonstrate this**
- **Is this the final/best solution? Absolutely not, it is a start!**
  - **This is a "first-order" attempt**
  - **Better but still simple numerical model will include higher-order effects, allow longer forecasts**
- **Supplement Larger-Scale Wind/Wave Storm Surge Models with Local Radar-Forecasted Near Fields**