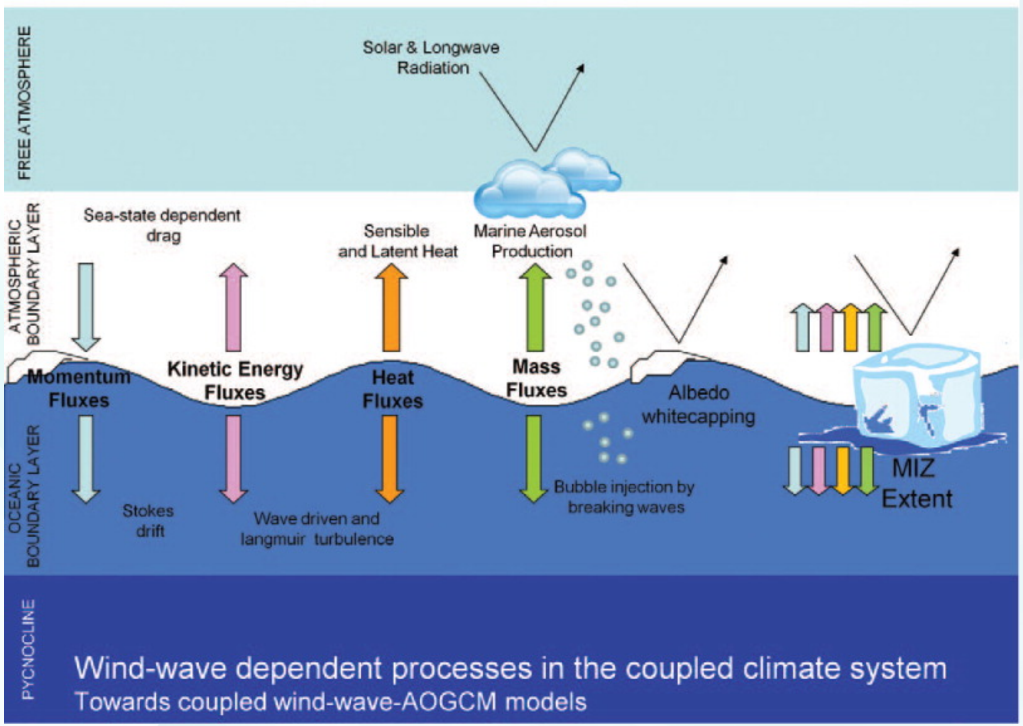
Unstructured Wave Modeling in E3SM

Steven Brus, Phillip J. Wolfram,
Jon Wolfe, Andrew Roberts, Elizabeth Hunke,
Qing Li, Luke Van Roekel, &
the E3SM community

E3SM Coastal Waves NGD

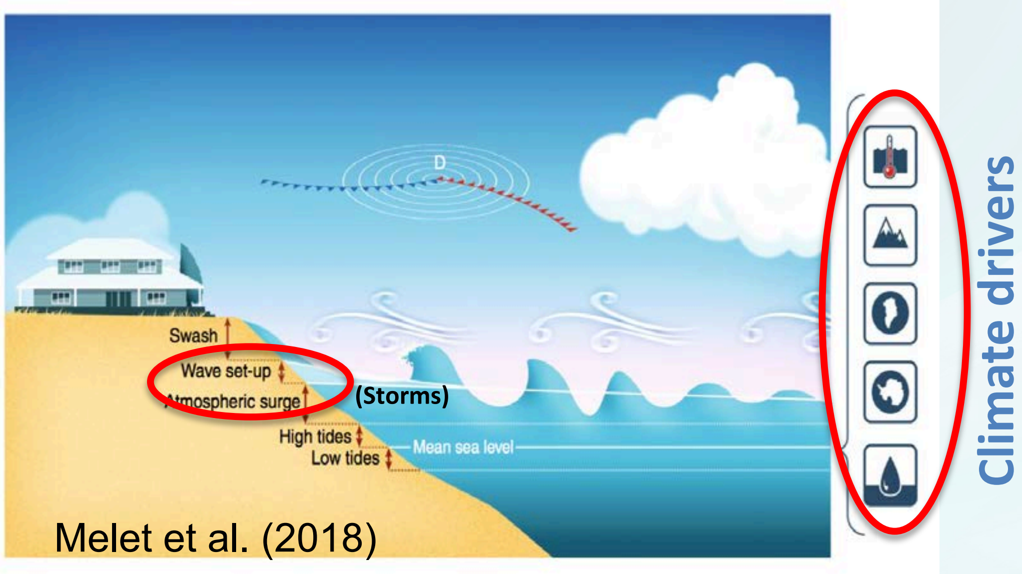
Role of Waves in the Coupled Climate System



Cavaleri et al. (2012)

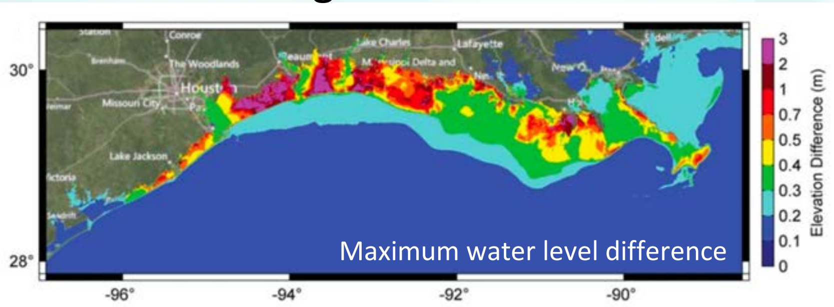
- Wind-generated waves are an important interfacial process in the climate system
- Some cross-component interactions include:
  - Ocean vertical mixing
  - Sea-state dependent drag
  - White-capping albedo
  - Sea-ice floe size

Role of Waves in Coastal Flooding



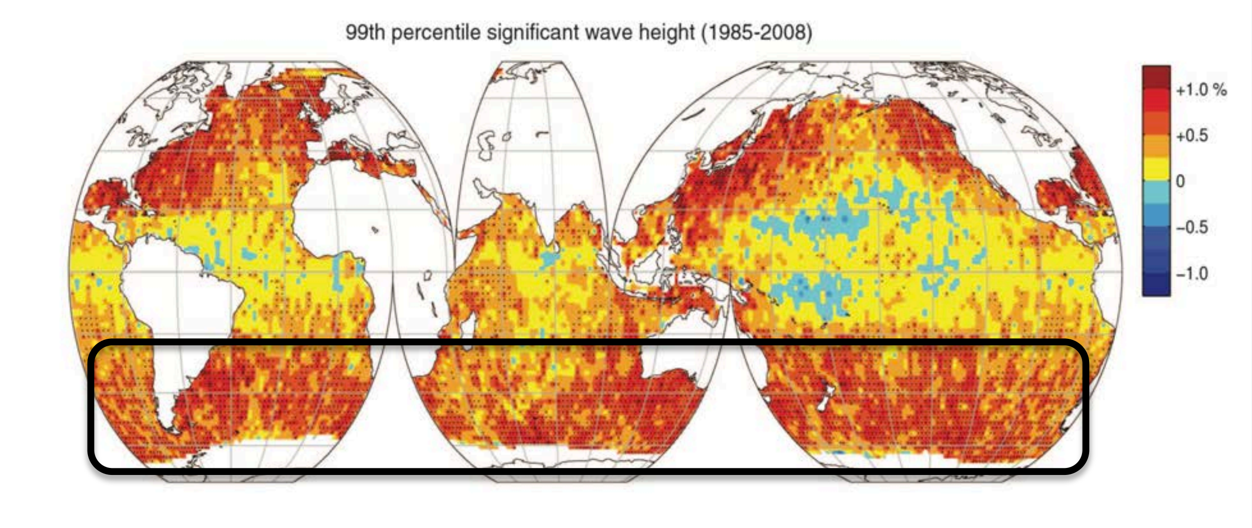
Melet et al. (2018)

Wave contribution to water levels during Hurricane Ike



Kerr et al. (2013)

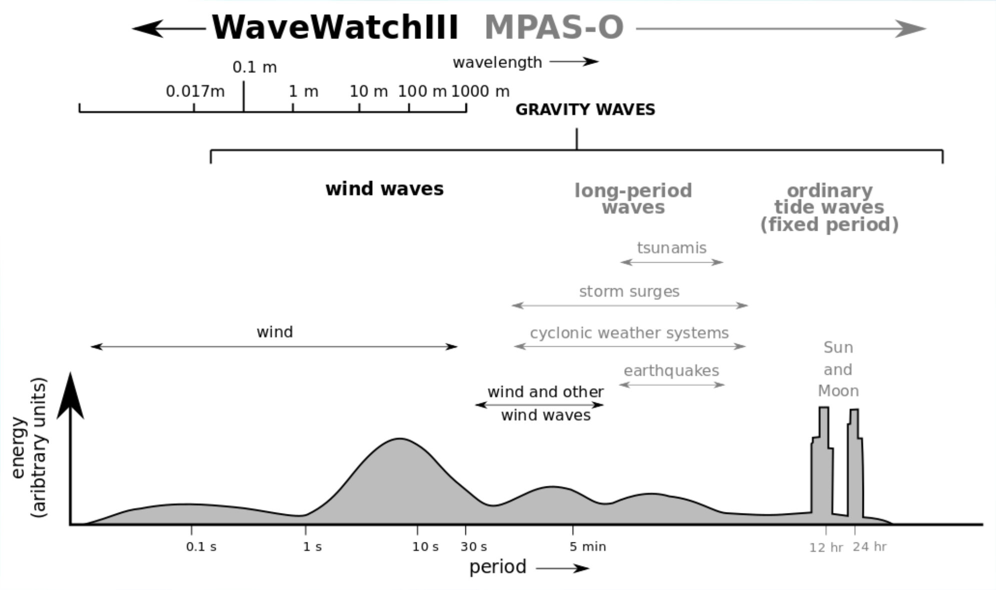
Trend in Global Wave Climate



Young et al. Science (2011)

- Global wave (and wind) extremes have been increasing
- Especially at high latitudes

Wave Energy Spectrum



- Wind waves represent a distinct portion of the energy spectrum
- Wavelengths order 10-100 m
- Periods order 1-10s
- Require separate modeling approach
- Phase averaged paradigm vs. directly modeling sea surface

Spectral Description of Waves

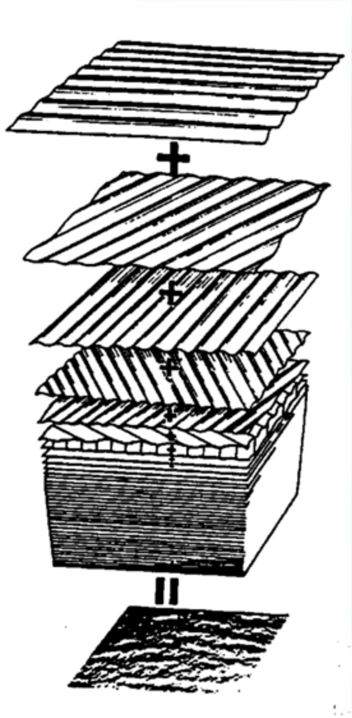


Image Credit: ECMWF

- Actual water surface represented by summation of sinusoidal components with different frequencies and directions

- Spectrum: Distribution of energy among the components

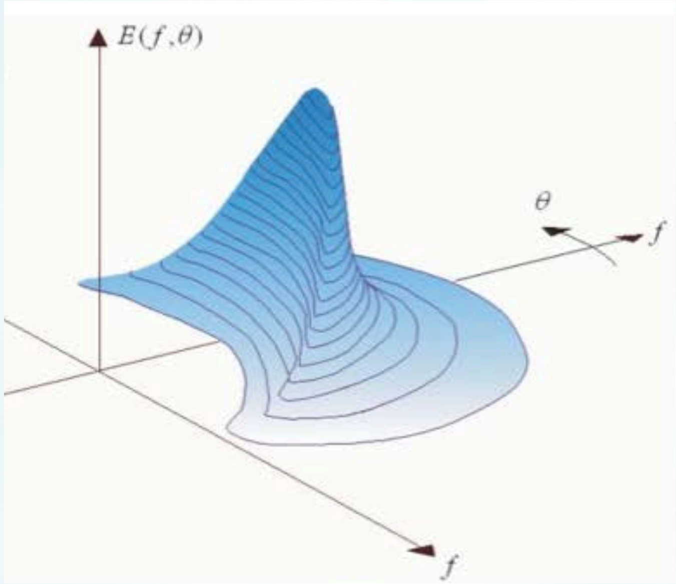


Image Credit: ECMWF

Spectral (Phase-Average) Wave Modeling

Describes evolution of action density:

$$N(\phi, \lambda, \sigma, \theta, t) = \frac{F}{\sigma}$$

energy density

lon lat relative fequency direction time

$$\frac{\partial N}{\partial t} + \frac{\partial (c_\phi N)}{\partial \phi} + \frac{\partial (c_\lambda N)}{\partial \lambda} + \frac{\partial (\sigma N)}{\partial \sigma} + \frac{\partial (c_\theta N)}{\partial \theta} = \sum_i S_i$$

Advection by group velocity and currents

Frequency dispersion (stretching)

Refraction (bending)

Production, Dissipation, Non-linearities

- S_{in} - Atmosphere-wave interaction
- S_{ds} - Dissipation
- S_{nl} - Non-linear wave interactions
- S_{tr} - Triad interactions
- S_{sc} - Wave scattering
- S_{bot} - Wave-bottom interactions
- S_{db} - Depth-limited breaking
- S_{ice} - Wave-ice interactions
- S_{ref} - Reflection

Mean Wave Parameters

- Significant Wave Height

$$H_s = 4\sqrt{E}$$

$$E = \int_0^{2\pi}\int_0^{\infty} F(\sigma,\theta)d\sigma d\theta$$

- Mean Wave Period

$$T_m = E^{-1}\int_0^{2\pi}\int_0^{\infty} \sigma F(\sigma,\theta)d\sigma d\theta$$

- Mean Wave Direction

$$\theta_m = \tan^{-1}\frac{\int_0^{2\pi}\int_0^{\infty}\sin\theta\, F(\sigma,\theta)d\sigma d\theta}{\int_0^{2\pi}\int_0^{\infty}\cos\theta\, F(\sigma,\theta)d\sigma d\theta}$$

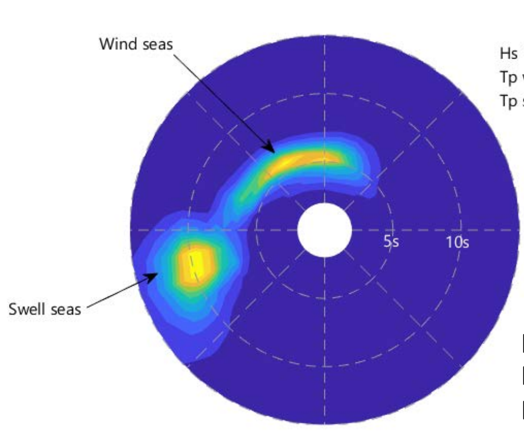
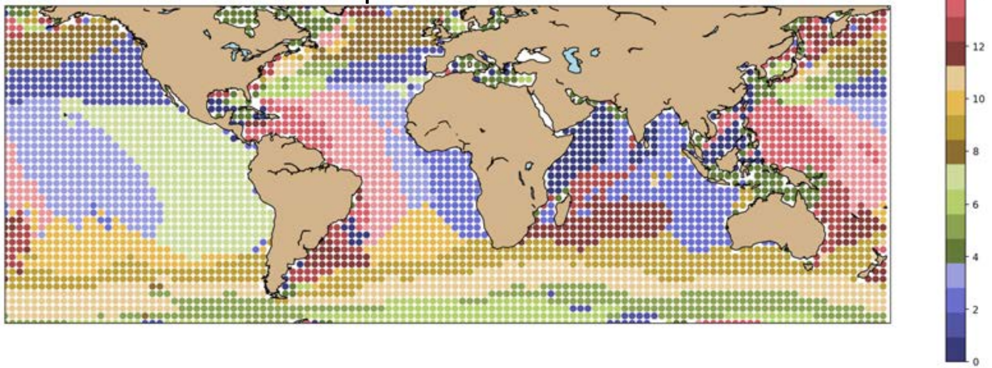


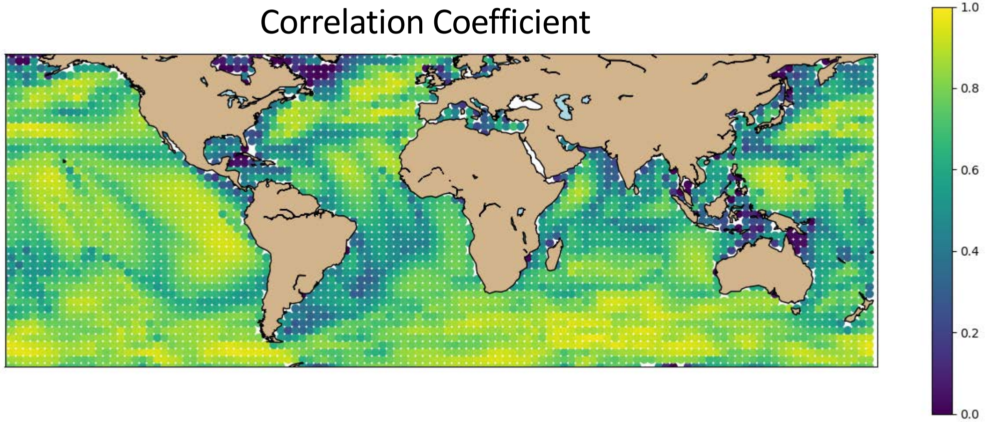
Image credit: Motion Forecasting

Global Wave Spectra ML Classification

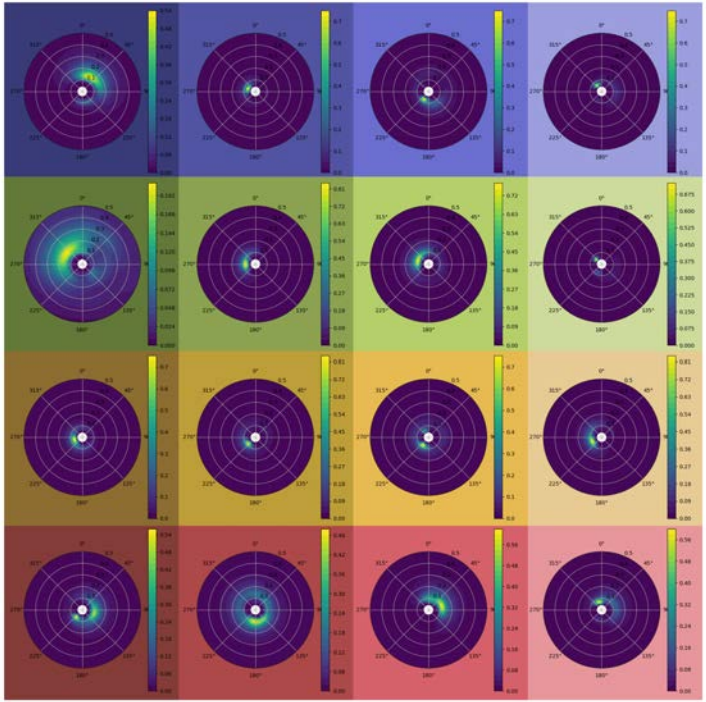
Wave spectrum clusters



Correlation Coefficient

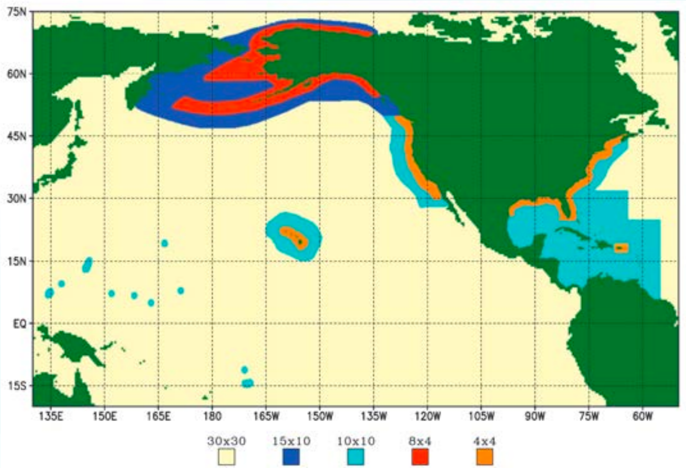


Representative cluster wave spectra



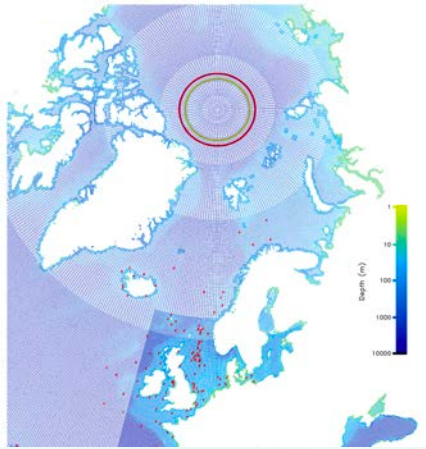
WaveWatchIII Mesh Configurations

Current operational WWIII nesting



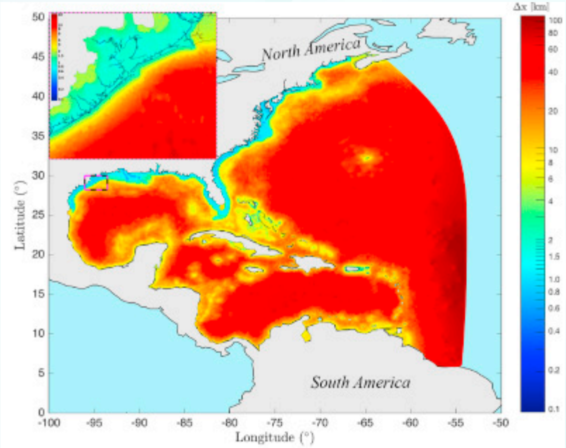
Chawla et al. (2013)

Spherical Multi Cell WWIII grid



Li (2012)

Regional Triangular Mesh



Abdolali et al. (2020)

Integration of WaveWatchIII into E3SM

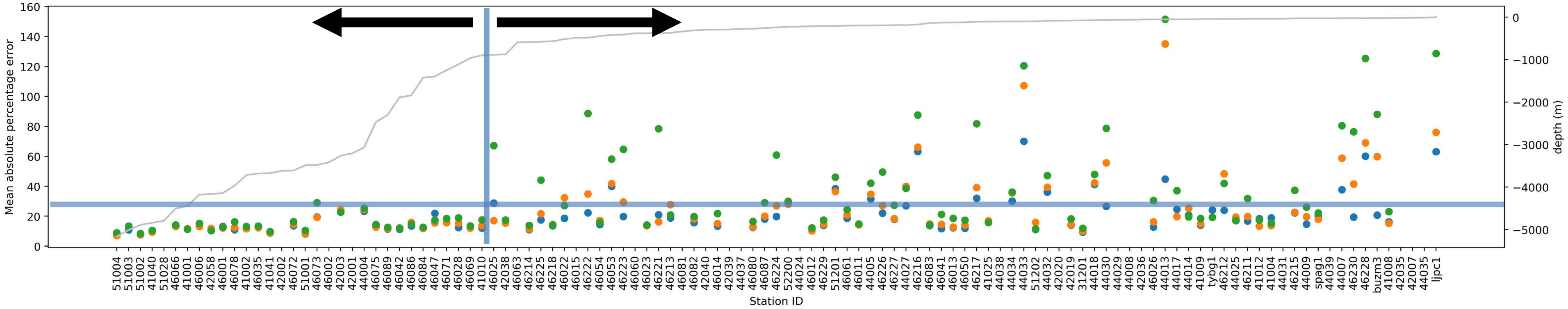
- WaveWatchIII is now available via GitHub: https://github.com/NOAA-EMC/WW3
- Latest version 6.07 has been made a submodule in E3SM
- WaveWatchIII uses "switches" to define physics/formulation options. Source code must be pre-processed to generate compliable code.
- Several auxiliary programs are necessary for processing grids, initial conditions, and output

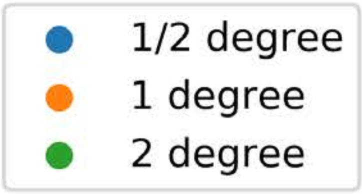
```
      TYPE SRCP
        REAL                              :: WWNMEANPTAIL, SSTXFTFTAIL
!/ST1         REAL                        :: SINC1, SDSC1
!/ST2         REAL                        :: ZWIND, FSWELL, SHSTAB,          &
!/ST2                                        OFSTAB, CCNG, CCPS, FFNG, FFPS,   &
!/ST2                                        CDSA0, CDSA1, CDSA2, SDSALN,      &
!/ST2                                        CDSB0, CDSB1, CDSB2, CDSB3, FPIMIN,  &
!/ST2                                        XFH, XF1, XF2
!/ST3         INTEGER                     :: SSDSISO, SSDSBRFDF
!/ST3         REAL                        :: AALPHA, BBETA, ZZ0MAX, ZZ0RAT, ZZALP,&
!/ST3                                        SSINTHP, TTAUWSHELTER, SSWELLF(1:6), &
!/ST3                                        SSDSC1, SSDSC2, SSDSC3, SSDSBR,      &
!/ST3                                        SSDSP, WWNMEANP, SSTXFTF, SSTXFTWN,  &
!/ST3                                        FFXPM, FFXFM,                        &
!/ST3                                        SSDSC4, SSDSC5, SSDSC6, DDELTA1,     &
!/ST3                                        DDELTA2, ZZWND
!
!/ST4         INTEGER                     :: SSWELLFPAR, SSDSISO, SSDSBRFDF
!/ST4         INTEGER,  POINTER           :: IKTAB(:,:), SATINDICES(:,:)
!/ST4         REAL,     POINTER           :: DCKI(:,:), SATWEIGHTS(:,:),CUMULW(:,:),QBI(:,:)
!/ST4         REAL                        :: AALPHA, BBETA, ZZ0MAX, ZZ0RAT, ZZALP,&
!/ST4                                        SSINTHP, TTAUWSHELTER, SSWELLF(1:7), &
!/ST4                                        SSDSC(1:11), SSDSBR,                 &
!/ST4                                        SSDSP, WWNMEANP, SSTXFTF, SSTXFTWN,  &
!/ST4                                        FFXPM, FFXFM, FFXFA, FFXFI, FFXFD,   &
!/ST4                                        SSDSBRF1, SSDSBRF2, SSDSBINT,SSDSBCK,&
!/ST4                                        SSDSHCK, SSDSABK, SSDSPBK, SSINBR
!/ST4         REAL                        :: ZZWND
!/ST4         REAL                        :: SSDSCOS, SSDSDTH, SSDSBR2, SSDSBM(0:4)
!
!/ST6         REAL                        :: SIN6A0, SDS6A1, SDS6A2, SWL6B1, &
!/ST6                                        SIN6WS, SIN6FC
!/ST6         INTEGER                     :: SDS6P1, SDS6P2
!/ST6         LOGICAL                     :: SDS6ET, SWL6S6, SWL6CSTB1
!
!/STX         REAL                        :: DUMMY
      END TYPE SRCP
```

Importance of Regional Refinement

Deeper (open ocean):
Accurate with
lower resolution

Shallower (coastal):
Requires higher resolution





- Structured lon-lat meshes
- June-August 2005 CFSR winds
- Comparison with NDBC buoys

Global Unstructured WaveWatchIII Meshes

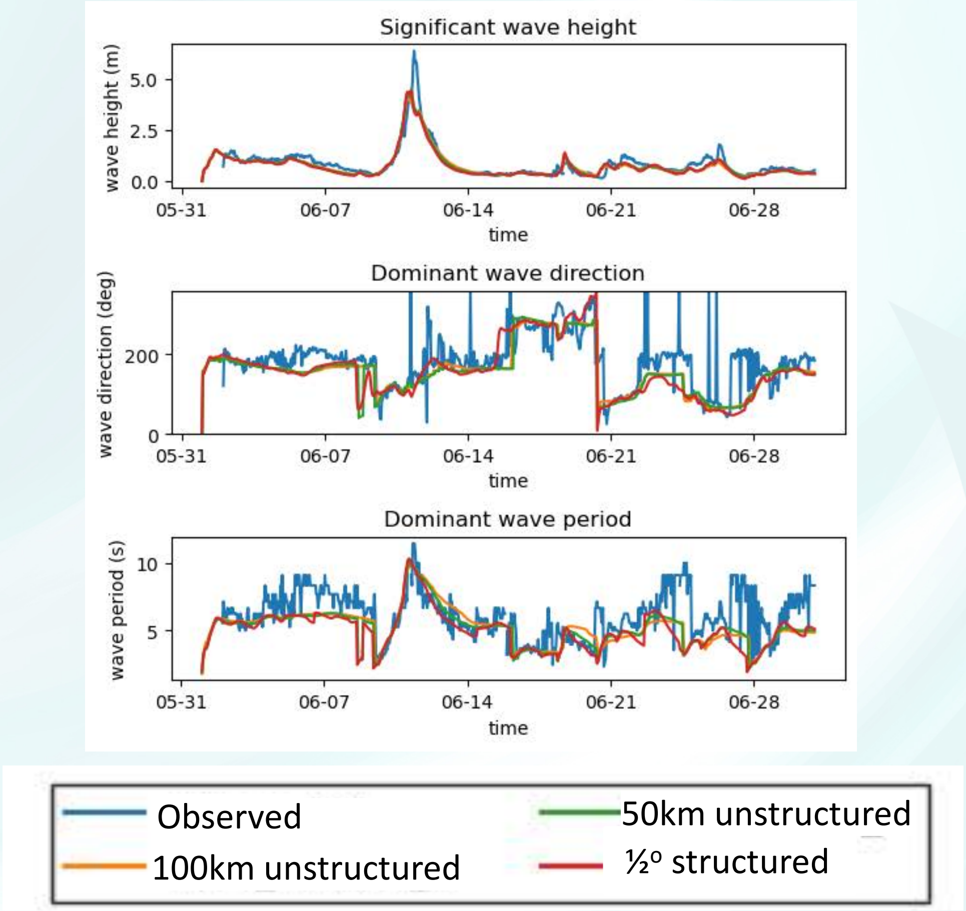
Quasi-uniform 50 km

Regionally Refined Delaware Bay
240km – 4km

NeSMA COASTAL

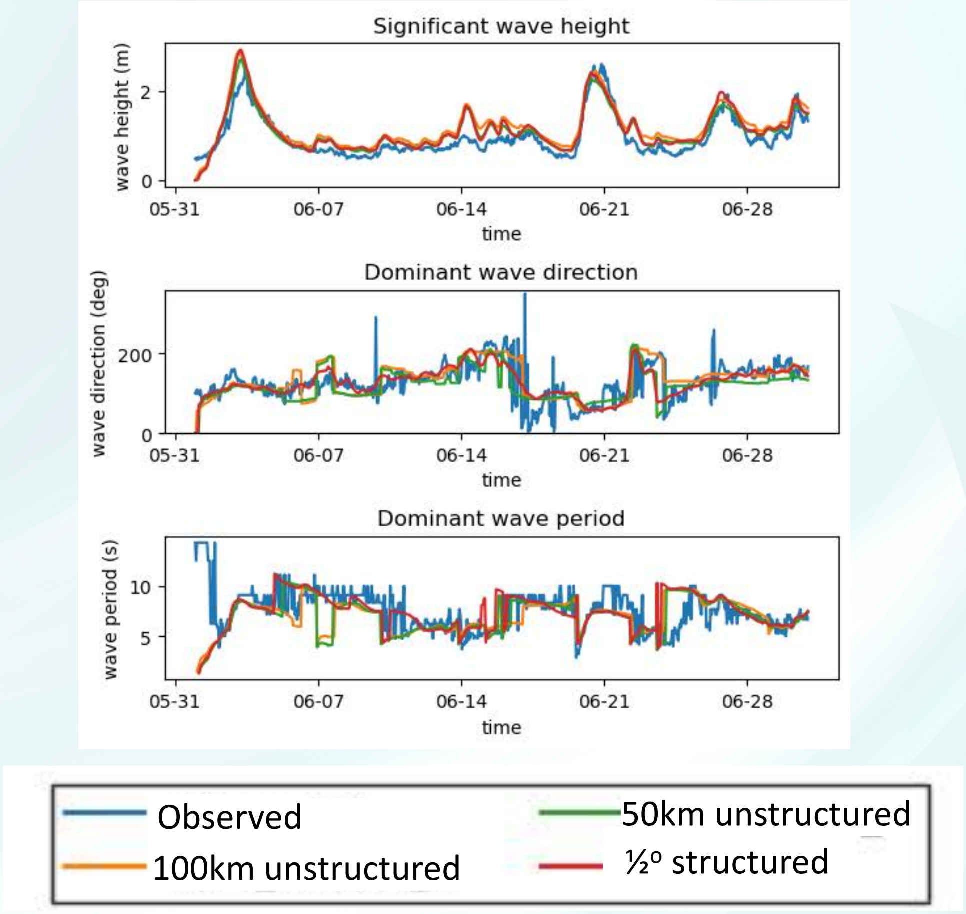
Meshes generated with OceanMesh2D software:
https://github.com/CHLNDDEV/OceanMesh2D

Global Unstructured Mesh Validation



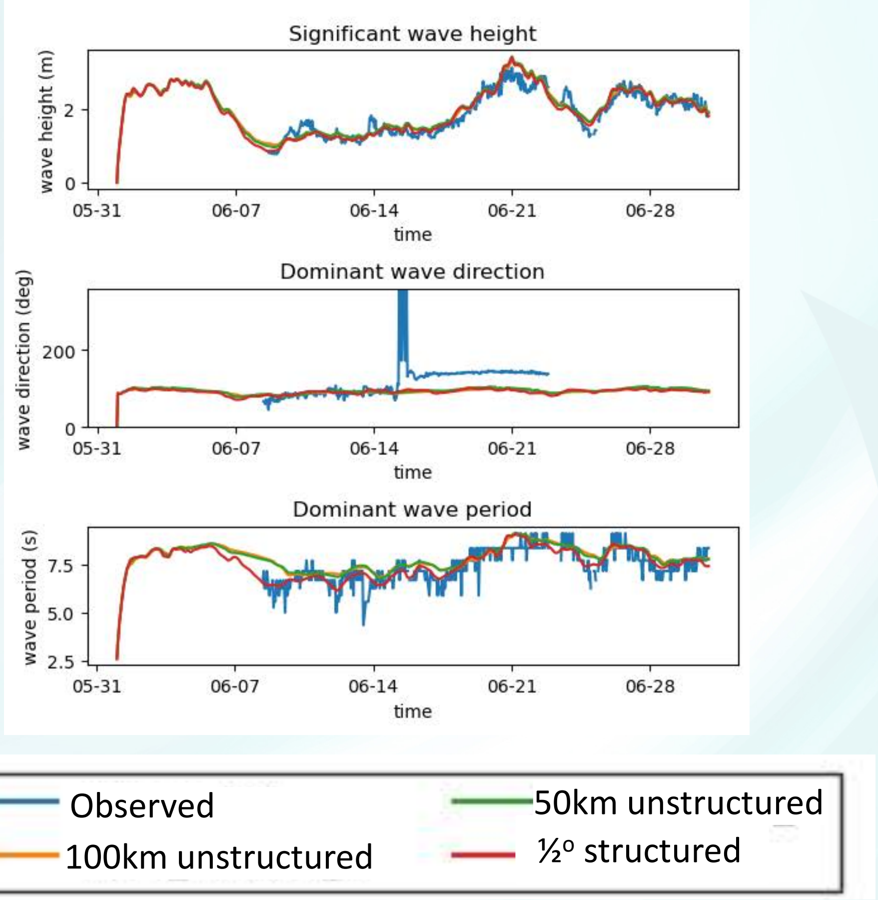
- June-August 2005
- CFSR winds (1/2 degree resolution)
- Comparison with NDBC buoy data

Global Unstructured Mesh Validation



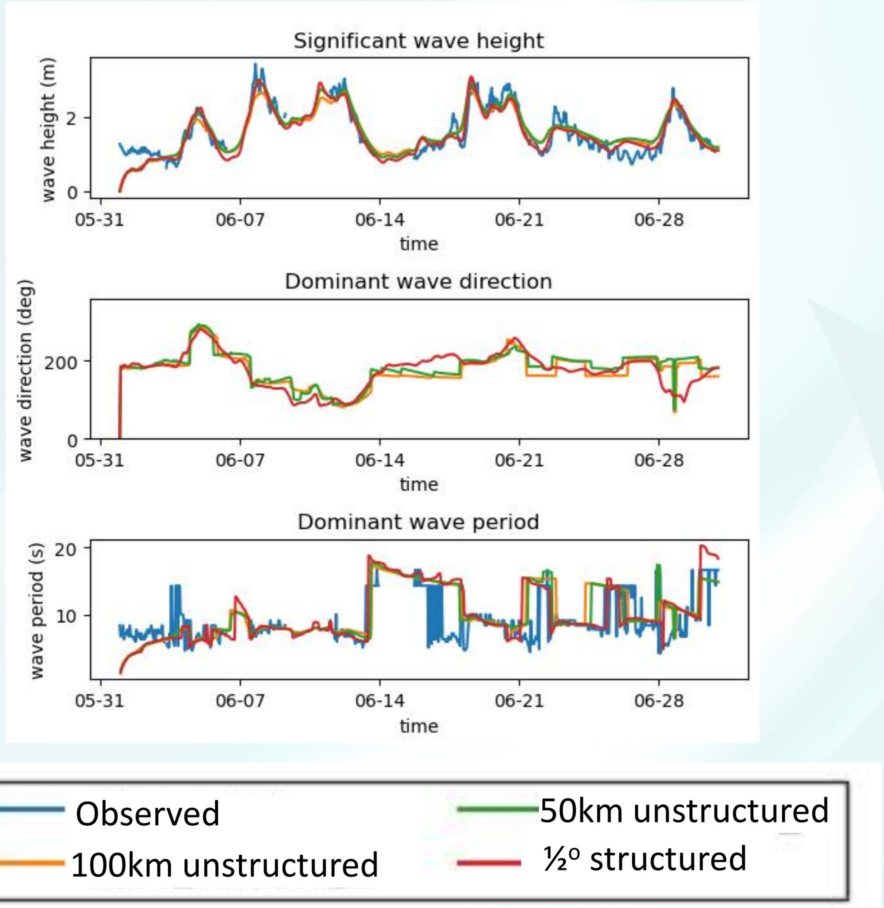
- June-August 2005
- CFSR winds (1/2 degree resolution)
- Comparison with NDBC buoy data

Global Unstructured Mesh Validation



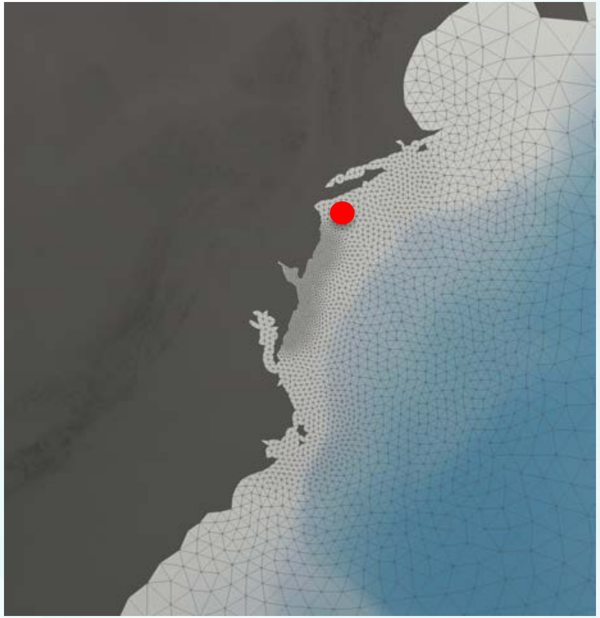
- June-August 2005
- CFSR winds (1/2 degree resolution)
- Comparison with NDBC buoy data

Global Unstructured Mesh Validation

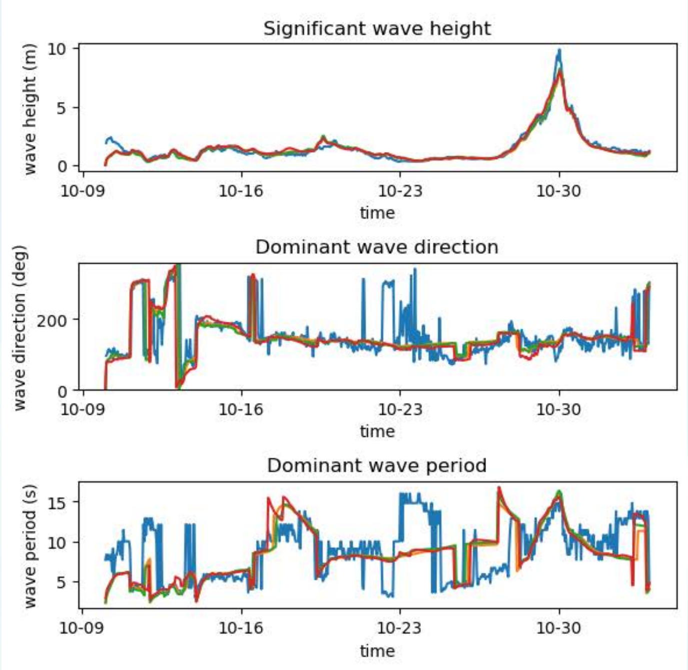


- June-August 2005
- CFSR winds (1/2 degree resolution)
- Comparison with NDBC buoy data

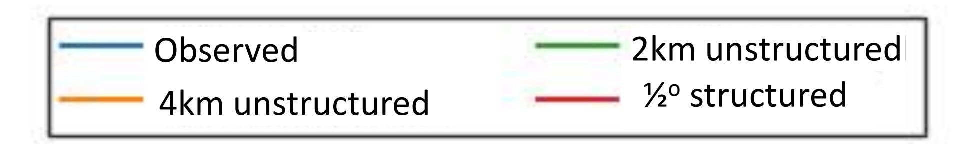
Global Regionally Refined Mesh Validation



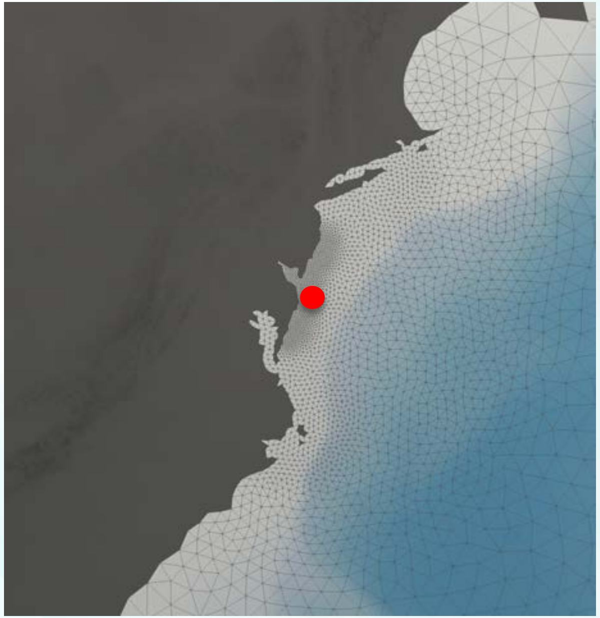
4km unstructured
14x faster than
1/2° structured



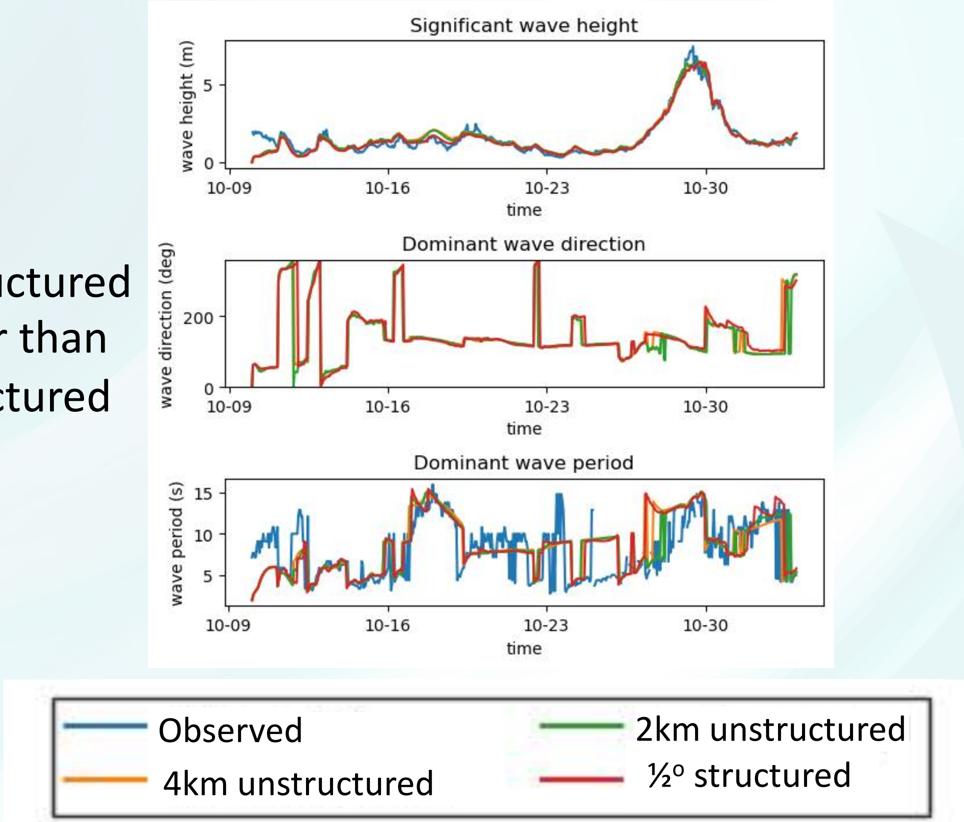
- Hurricane Sandy 2012
- CFSv2 winds (0.2 degree resolution)
- Comparison with NDBC buoy data



Global Regionally Refined Mesh Validation

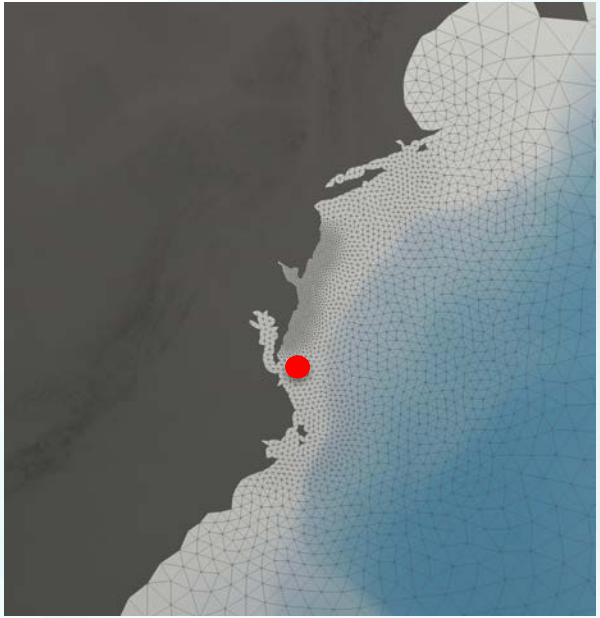


4km unstructured
14x faster than
1/2° structured

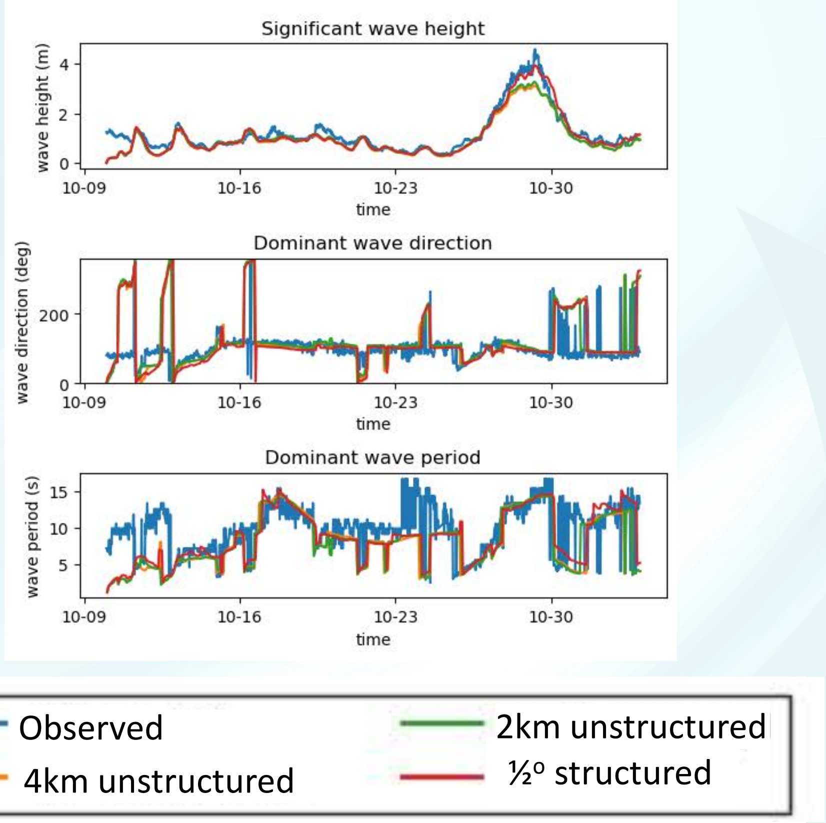


- Hurricane Sandy 2012
- CFSv2 winds (0.2 degree resolution)
- Comparison with NDBC buoy data

Global Regionally Refined Mesh Validation



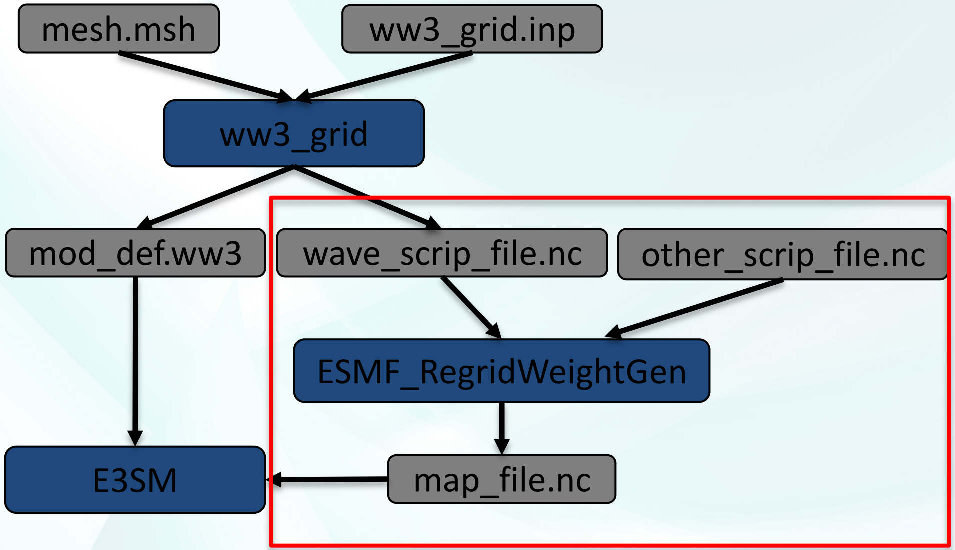
4km unstructured
14x faster than
1/2° structured



- Hurricane Sandy 2012
- CFSv2 winds (0.2 degree resolution)
- Comparison with NDBC buoy data

WaveWatchIII Coupler Mapping

- WaveWatchIII already uses SCRIP internally for mapping nested grids
- Repurposed for generating mapping files for E3SM



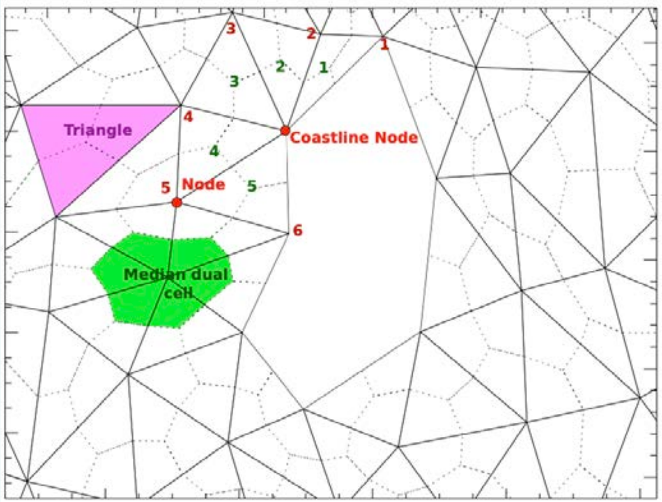
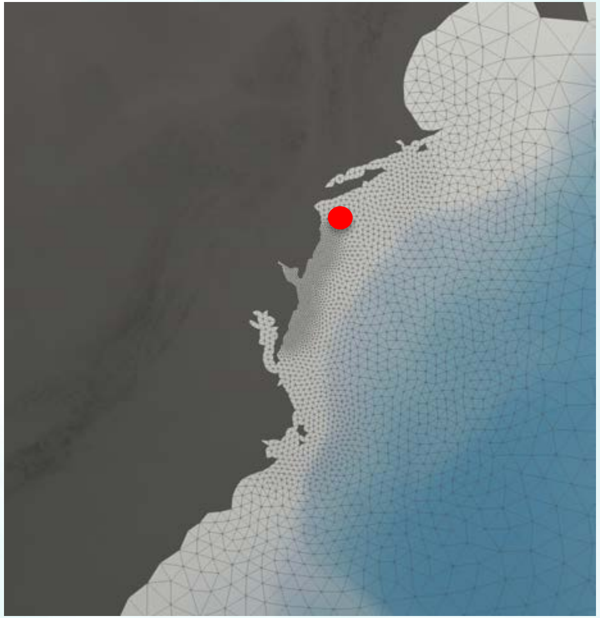
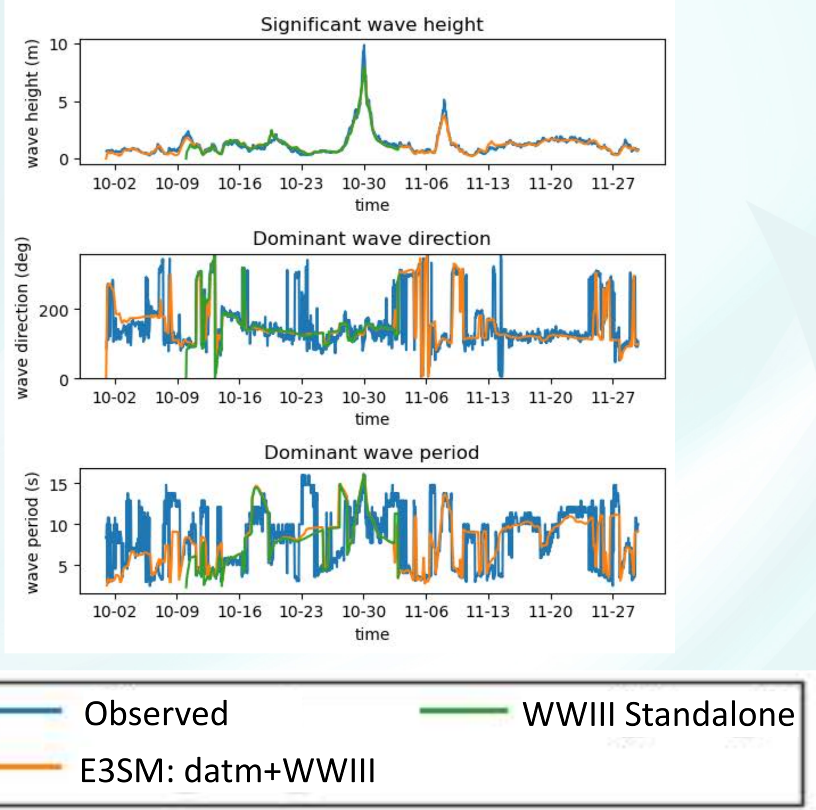


Image Source: WaveWatchIII User’s Manual

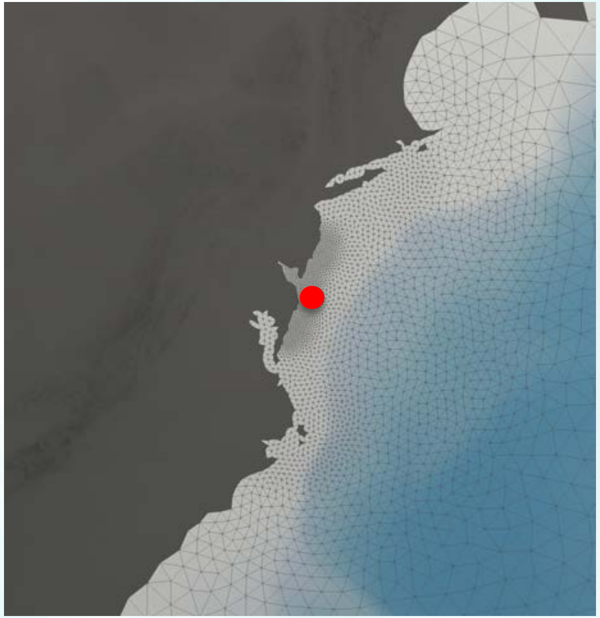
Data Atmosphere + Unstructured Waves Compset

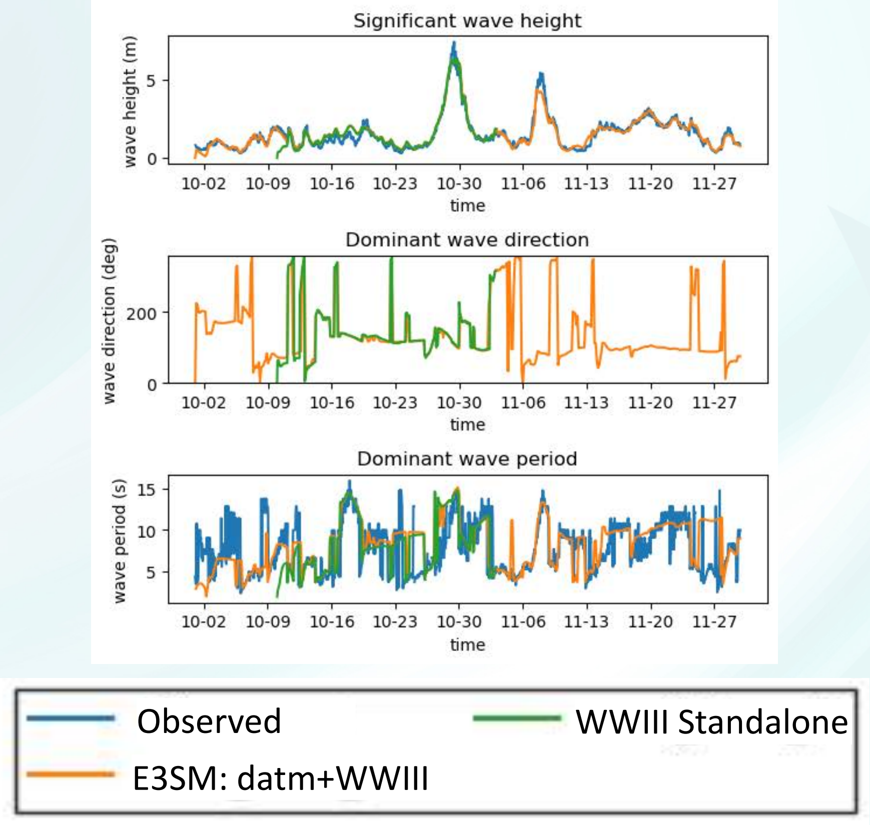




- Hurricane Sandy 2012
- CFSv2 winds (0.2 degree resolution)
- Comparison with NDBC buoy data

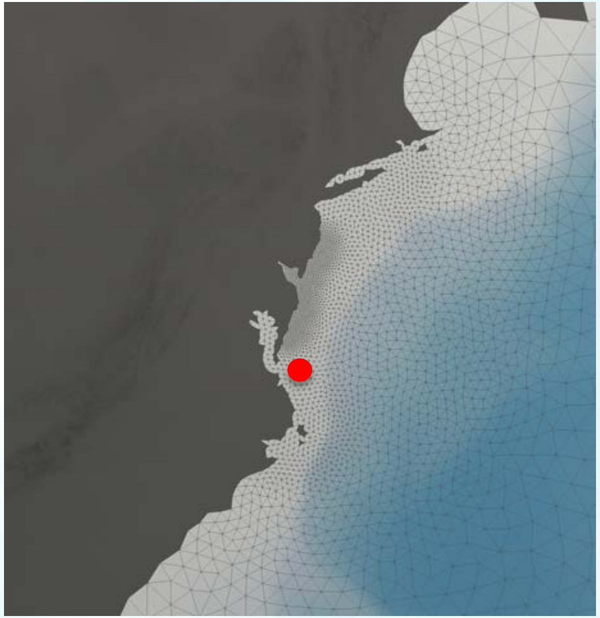
Data Atmosphere + Unstructured Waves Compset

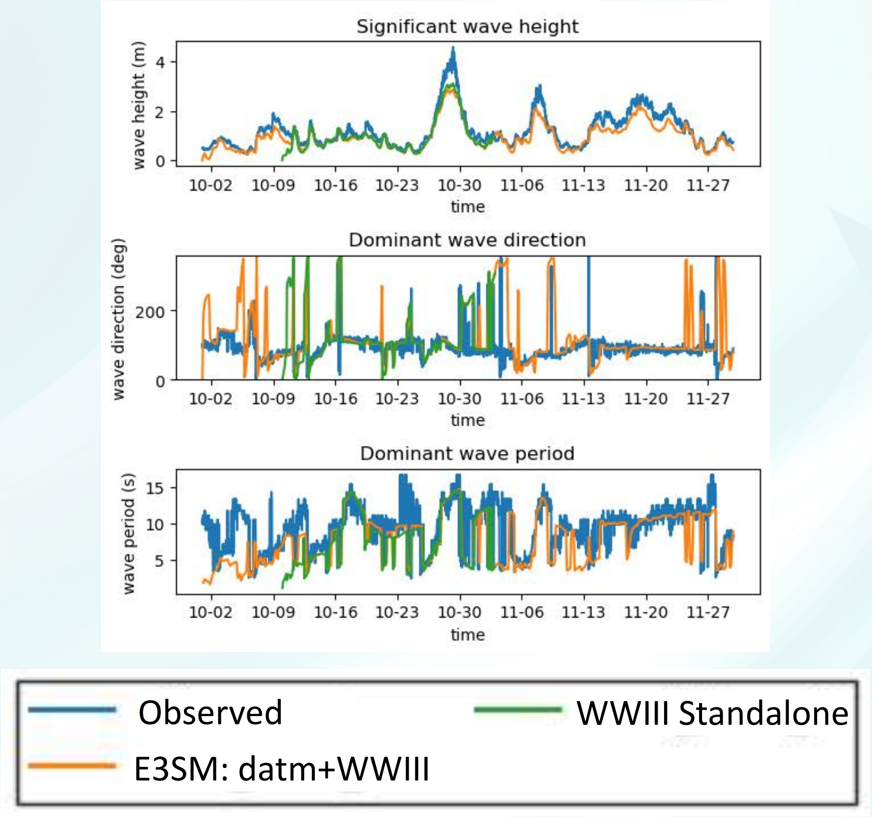




- Hurricane Sandy 2012
- CFSv2 winds (0.2 degree resolution)
- Comparison with NDBC buoy data

Data Atmosphere + Unstructured Waves Compset





- Hurricane Sandy 2012
- CFSv2 winds (0.2 degree resolution)
- Comparison with NDBC buoy data

Summary

- Waves are an important interfacial process in the climate system
- High latitude wave heights are increasing
- E3SM will have the first coupled, global unstructured WaveWatchIII configuration
- Our initial validation results have shown promise in balancing accuracy and cost

Next Steps

- Performance evaluation of global unstructured configuration
- One-way coupling from ocean and sea-ice to waves (verification)
- Two-way coupling between waves, ocean, and sea ice (G case+waves)
- Collaborate with InterFACE project on wave/ice couplings and simulations