Wave-flow coupling of SWAN with an unstructured model

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Wave coupling is not new…..

- Waves can influence ocean circulation due to:
  - Radiation stress, Stokes vortex and Coriolis (Hasselmann, 1971, Leibovich, 1980)
  - Enhanced bottom friction (Madsen, 1994)
  - Enhanced vertical mixing (Monismith, 2008)
  - Nearshore processes
- Coupling with flow is achieved by averaging waves over long time-scales ⇨ Wave Effect on Currents (WEC)
- Well summarized by:
  - Uchiyama et. al., (2010)
  - Kumar et., al., (2012)

Third generation spectral wave models in use

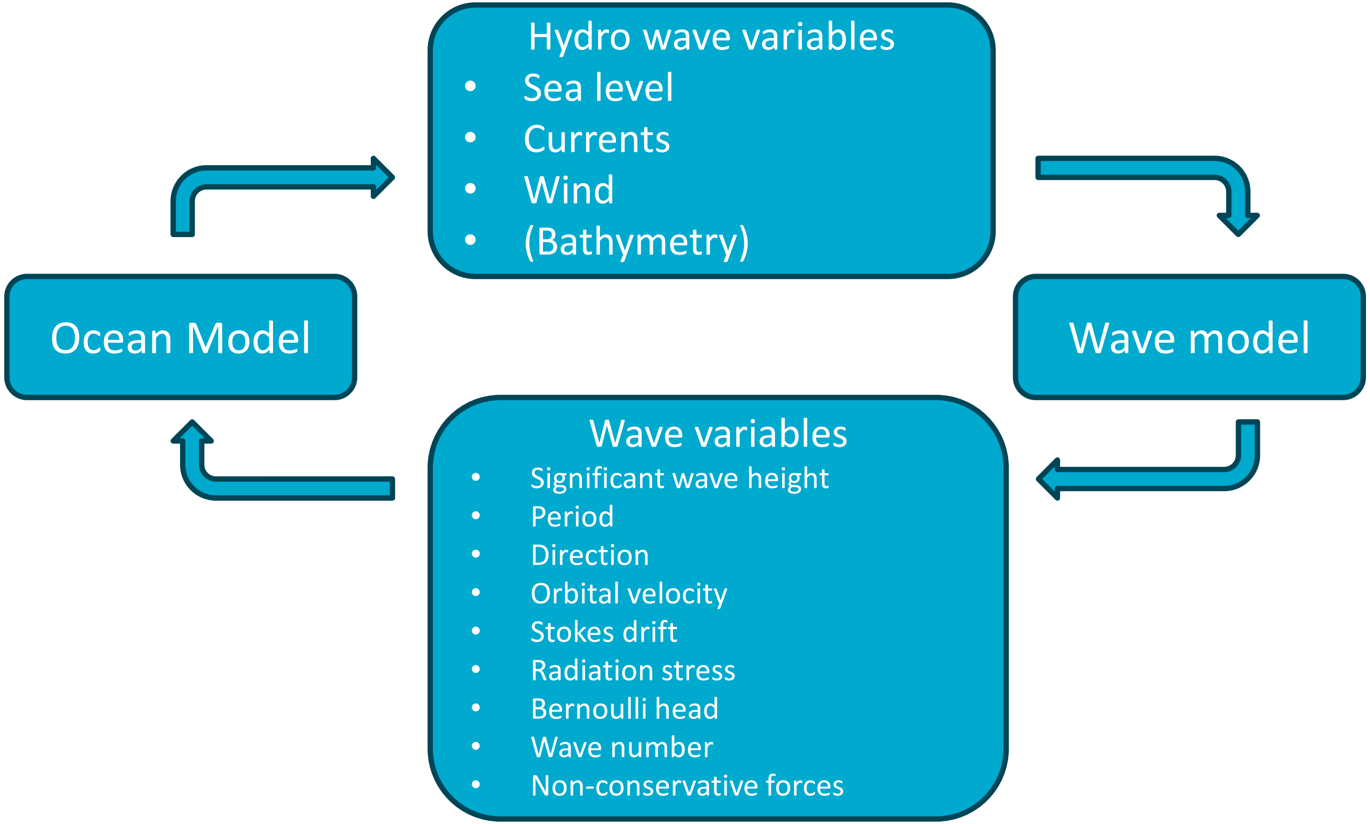
- Deliver wave quantities;
  - Wave amplitude (significant wave height), period, direction, wavenumber
  - Wave orbital velocity
  - Stokes drift
  - Radiation stress
  - Bernoulli head*
  - Non-conservative forces (breaking, white-capping ….)
- Common wave models;
  - SWAN (Simulating Waves Nearshore, Booij, 1999)
  - WWIII (Wave Watch III, Tolman, 1997)
  - WAM (Wave Ocean Model, WAMDIG, 1998)
  - WWM-II (Wind Wave Model, Roland, 2009)

* Bernoulli head is an adjustment to the pressure in accommodating incompressibility

Previously coupled to ocean models

- Structured
  - ROMS-SWAN (COAWST model, Uchiyama, Kumar)
  - COHERENS-SWAN (Liang et., al., 2007)
  - POM-WWIII (Moon, 2005)
  - POM-WAM (Xie et. al., 2001)
- Unstructured
  - ADCIRC-SWAN (Dietrich et. al., 2012)
  - SELFE-WWM (Roland et. al., 2012)
  - Schism-WWM (Schloen et. al., 2017)

Wave coupling



Hydro wave variables

- Sea level
- Currents
- Wind
- (Bathymetry)

Ocean Model

Wave model

Wave variables

- Significant wave height
- Period
- Direction
- Orbital velocity
- Stokes drift
- Radiation stress
- Bernoulli head
- Wave number
- Non-conservative forces

WEC Equations (see Uchiyama, Kumar)

Momentum

Dynamic pressure

Bernoulli Head

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla_{\perp})\boldsymbol{u} + w\frac{\partial \boldsymbol{u}}{\partial z} + f\hat{\mathbf{z}} \times \boldsymbol{u} + \nabla_{\perp}\emptyset - \boldsymbol{F} = - \nabla_{\perp} \mathcal{K} + \boldsymbol{J} + \boldsymbol{F}^{w}$$

Non-wave, non-conservative force

RHS = WEC terms

Stokes vortex / Coriolis

$$\boldsymbol{J} = -\hat{\mathbf{z}} \times \boldsymbol{u}^{St}((\hat{\mathbf{z}} \cdot \nabla_{\perp} \times \mathbf{u}) + \mathrm{f}) - w^{St}\frac{\partial \boldsymbol{u}}{\partial z}$$

Non-conservative WEC

$$\boldsymbol{F}^{w} = \underset{\text{Bottom dissipation}}{\boldsymbol{B}^{bf}} - \underset{\text{Surface streaming}}{\boldsymbol{B}^{sf}} + \underset{\text{White-capping}}{\boldsymbol{B}^{wcap}} + \underset{\text{Wave breaking}}{\boldsymbol{B}^{b}} + \underset{\text{Wave roller}}{\boldsymbol{B}^{r}}$$

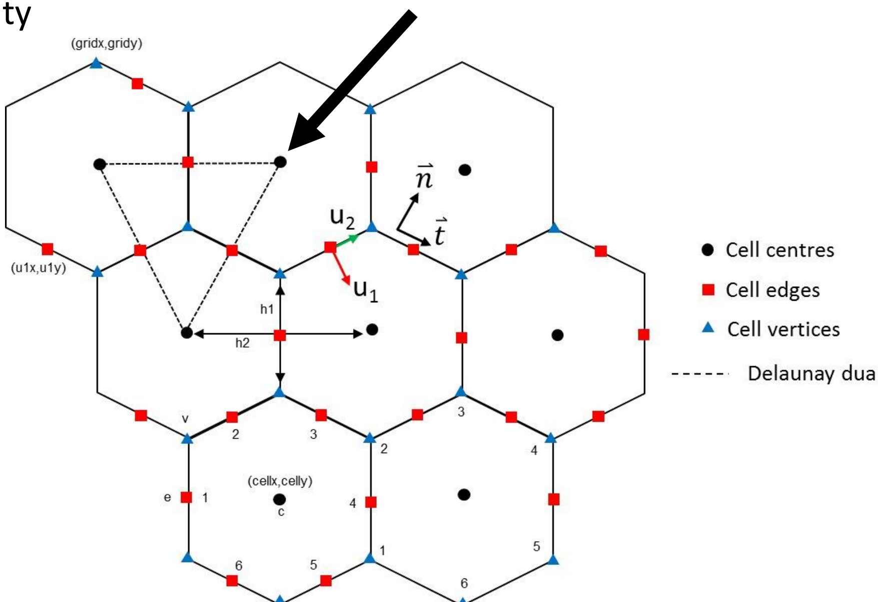
Plus

- Continuity equation
- Tracer equation
- Depth averaged eq^{n}
- Boundary conditions

Unstructured model – COMPAS

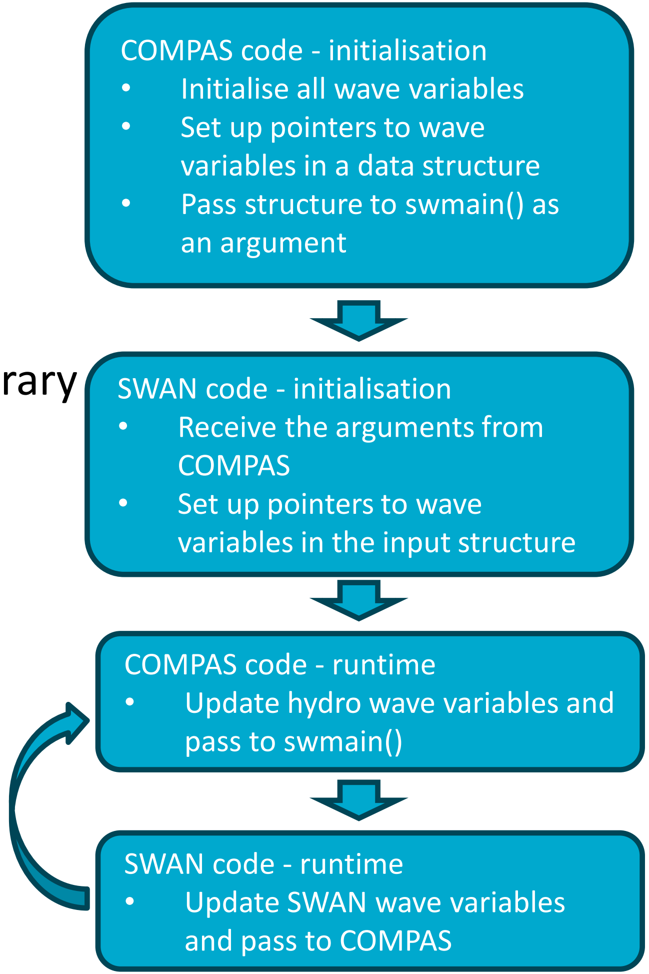
- Ocean model is COMPAS (Coastal Ocean Marine Prediction Across Scales)
- Unstructured model using TRiSK numerics (e.g., as used in MPAS)
- Operates on a C-grid with a Voronoi tessellation
  - Hexagons represent the perfect Voronoi tessellation
  - Cell centres for tracers
  - Normal velocity at edges, reconstructed tangential velocity
  - No spurious modes on the C-grid
- Dual is a Delaunay triangulation
- Wave Model SWAN
  - Implicit
  - Can operate on unstructured meshes (triangulation)
  - Computational nodes are triangle vertices
- No remapping / interpolation required

Scalar location in COMPAS =
Computational node in SWAN



Code Coupling

- SWAN is written in Fortran F95
- COMPAS is written in C
- Coupling achieved via C Interoperability Protocols
  (https://gcc.gnu.org/onlinedocs/gfortran/Interoperability-with-C.html)
- COMPAS allocates and manages wave coupling variables
- Main SWAN (swmain) routine is isolated as a stand-alone library function
- Wave coupling variables are passed to swmain() as function arguments
- Interoperability Protocols pass all this data within one data structure
- SWAN accesses the wave variable memory via pointers
- No direct data transfer results in very efficient coupling



COMPAS code - initialisation
- Initialise all wave variables
- Set up pointers to wave variables in a data structure
- Pass structure to swmain() as an argument

SWAN code - initialisation
- Receive the arguments from COMPAS
- Set up pointers to wave variables in the input structure

COMPAS code - runtime
- Update hydro wave variables and pass to swmain()

SWAN code - runtime
- Update SWAN wave variables and pass to COMPAS

Stokes Coriolis / vortex

- ROMS uses the flux form (Uchiyama, Kumar) : $\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla_\perp)\mathbf{u} = \boldsymbol{J}$
  - Uchiyama adds Stokes drift added to Eulerian velocity ($\boldsymbol{u}^{\ell} = \boldsymbol{u} + \boldsymbol{u}^{St}$) to give:

$$\frac{\partial \boldsymbol{u}}{\partial t} + \nabla_\perp \cdot \left(\boldsymbol{u}^{\ell}\boldsymbol{u}\right) = \boldsymbol{u}^{St}\nabla_\perp \cdot \mathbf{u}$$

  - Kumar seems to evaluate Stokes vortex explicitly on the RHS

- COMPAS uses vector invariant form of momentum advection

Vector invariant momentum

$$\frac{\partial \boldsymbol{u}}{\partial t} + ((\underbrace{\hat{\mathbf{z}}\cdot\nabla_\perp\times\mathbf{u}}_{\substack{\text{Relative}\\\text{vorticity}}}) + \underset{\substack{\uparrow\\\text{Planetary}\\\text{vorticity}}}{\mathrm{f}}) \times (\underbrace{\hat{\mathbf{z}}\times\boldsymbol{u}}_{\substack{\text{Tangential}\\\text{velocity}}}) + \nabla_\perp\, \underset{\substack{\nwarrow\\\text{Kinetic energy}}}{\mathrm{K}}$$

Stokes vortex / Coriolis

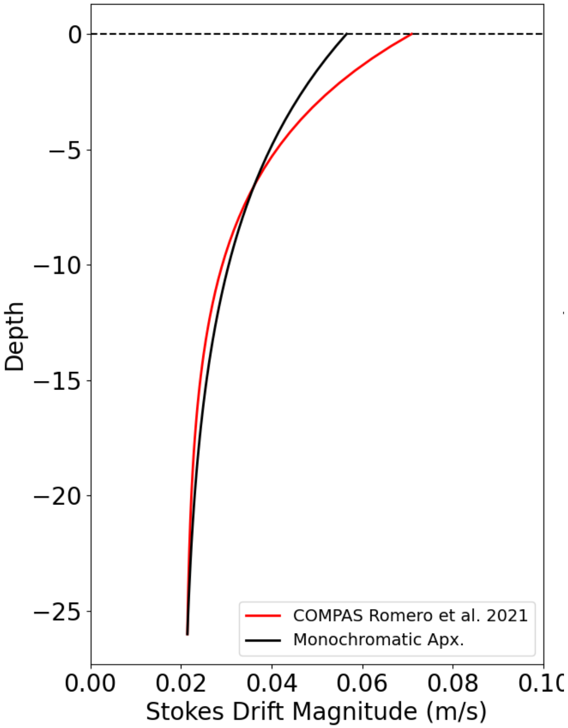
$$\boldsymbol{J} = ((\hat{\mathbf{z}}\cdot\nabla_\perp\times\mathbf{u}) + \mathrm{f}) \times (\hat{\mathbf{z}}\times\boldsymbol{u}^{St}) - w^{St}\frac{\partial \boldsymbol{u}}{\partial z}$$

Momentum + Stokes vortex / Coriolis

$$\frac{\partial \boldsymbol{u}}{\partial t} + ((\hat{\mathbf{z}}\cdot\nabla_\perp\times\mathbf{u}) + \mathrm{f}) \times (\hat{\mathbf{z}}\times(\boldsymbol{u}+\boldsymbol{u}^{St})) + \nabla_\perp \mathrm{K} = 0$$

Stokes drift

- COAWST computes Stokes drift hydro-side using mean and peak wave variables
- COMPAS-SWAN compute 3D Stokes drift SWAN-side using the full spectrum
  - Composite Iterative Approach based on Romero et. al., (2021) following Breivik et. al., (2014)



Romero, L., Hypolite, D., & McWilliams, J. C. (2021). Representing wave effects on currents. Ocean Modelling, 167, 101873.

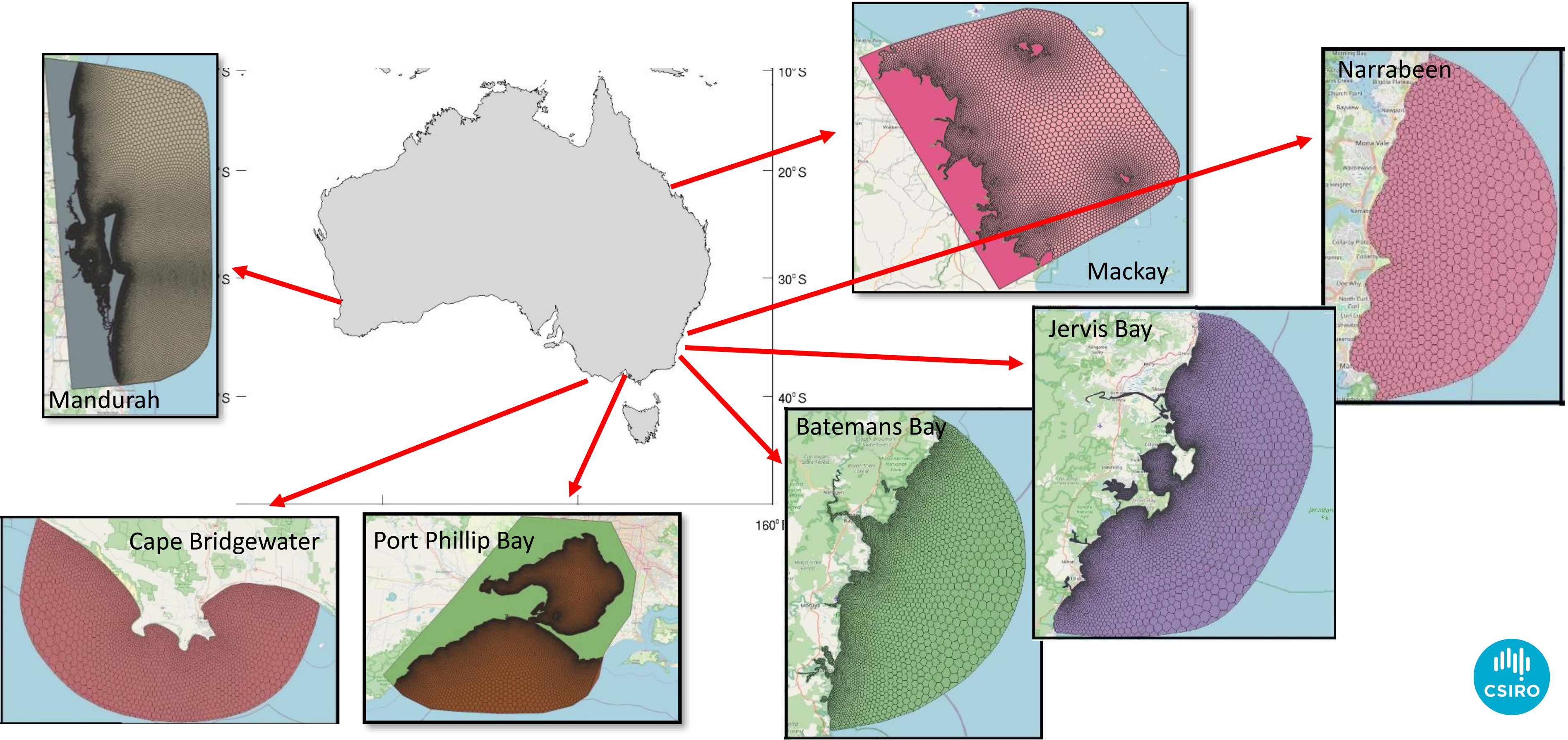
Breivik, O, Janssen, A.E., Bidlot, J. (2014) Approximate Stokes Drift Profiles in Deep Water. JPO, 44, 2433-2445.

Coupled wave model features

- COMPAS-SWAN is an efficient and modular solution to hydrodynamic-wave coupling
- Also includes;
  - Enhanced bottom friction
  - Enhanced vertical mixing (including Harcourt (2015) scheme)
- No SWAN-specific configuration is required when running
  - Mesh generation
  - Bathymetry
  - Forcing and open boundary data
  - Input; leverage efficient high order (unstructured) interpolation (e.g., Sibson)
  - Output; cf-compliant UGRID netCDF
- Examples

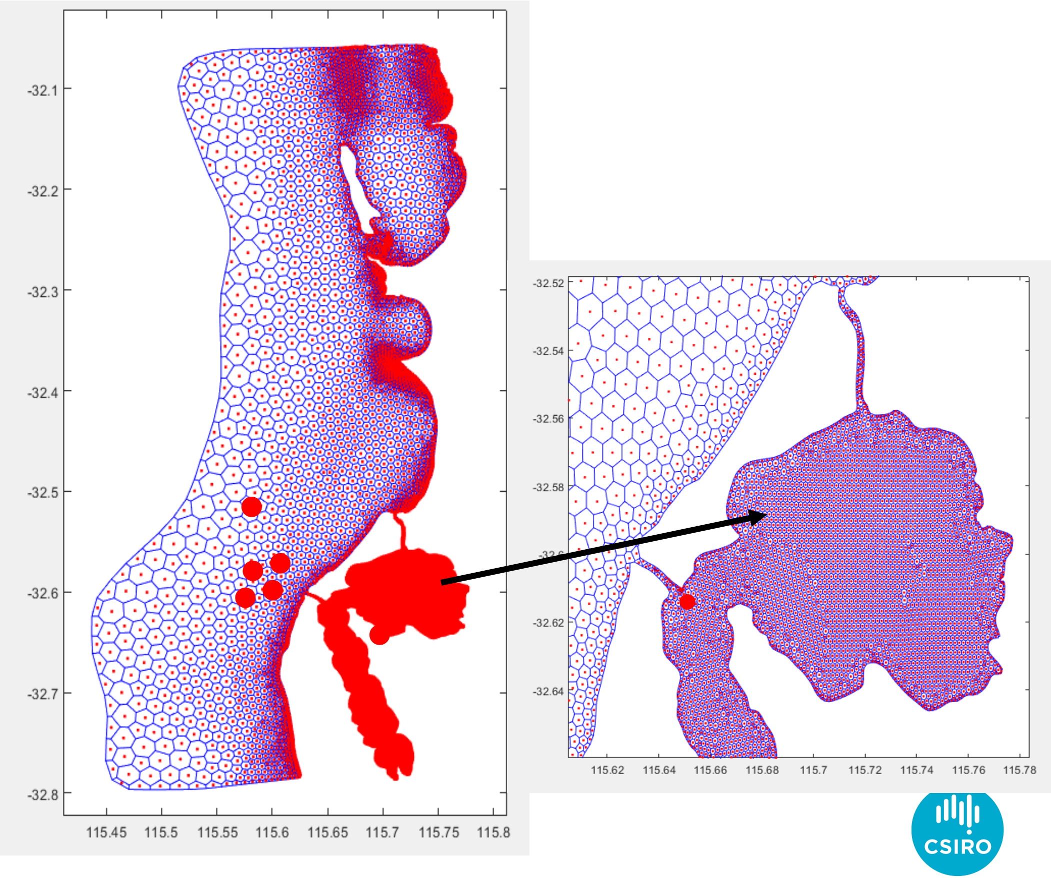
Required anyway for COMPAS

Study domains (thanks to Cagil)



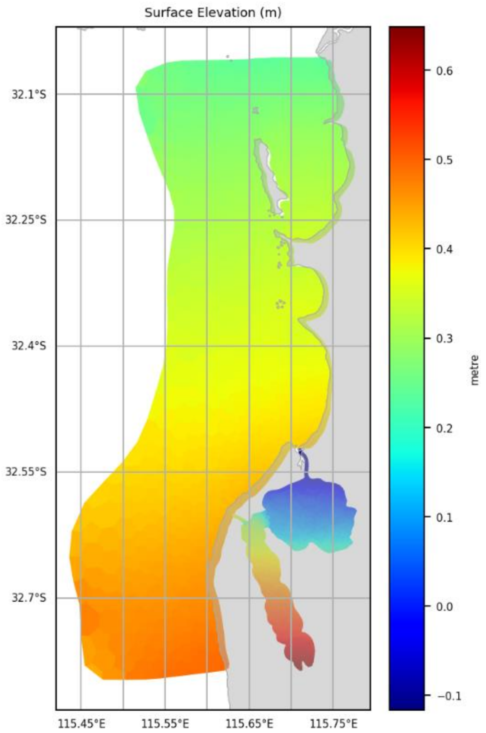
Mandurah test – June 2019

- 100 m coastal resolution
- 3 km offshore resolution
- TPXO tide forced
- Atmospherics:
  ACCESS winds (BoM, 12 km)
- Ocean OBCs:
  BRAN2020 (MOM5, 0.1 degree)
- Waves:
  Regional SWAN hindcast (500m)
  downscaled from Auswave G3
  Operational Wave Model (WW3)

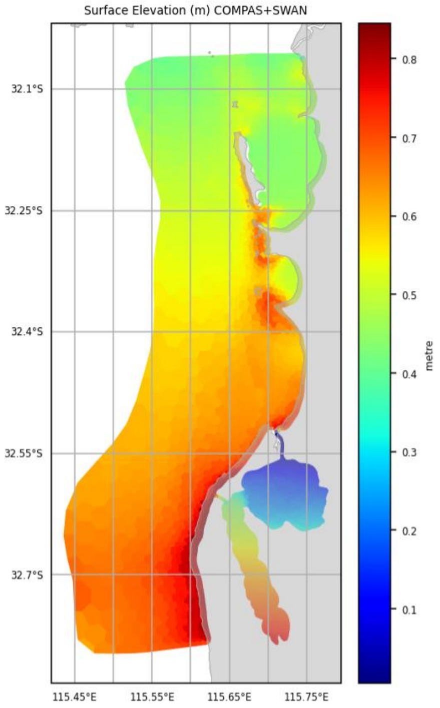


Sea surface elevation

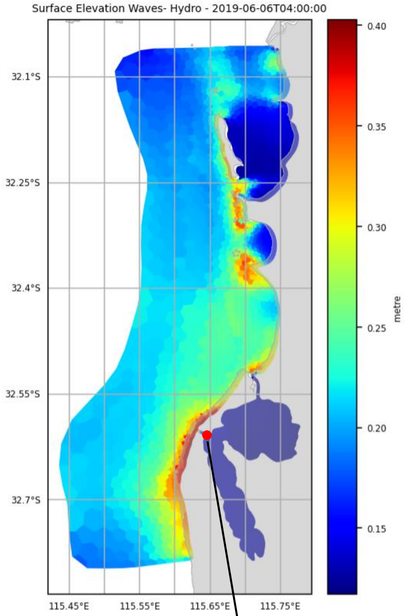
Hydro only



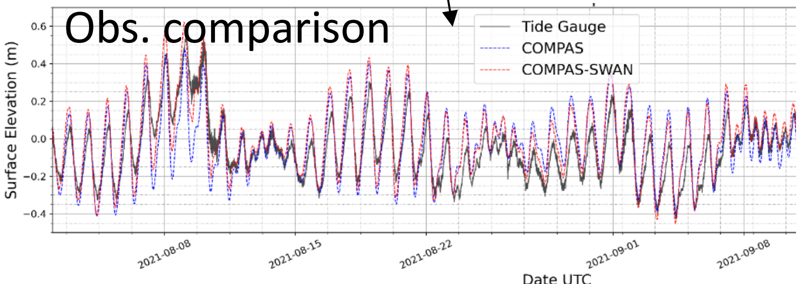
Hydro + Waves



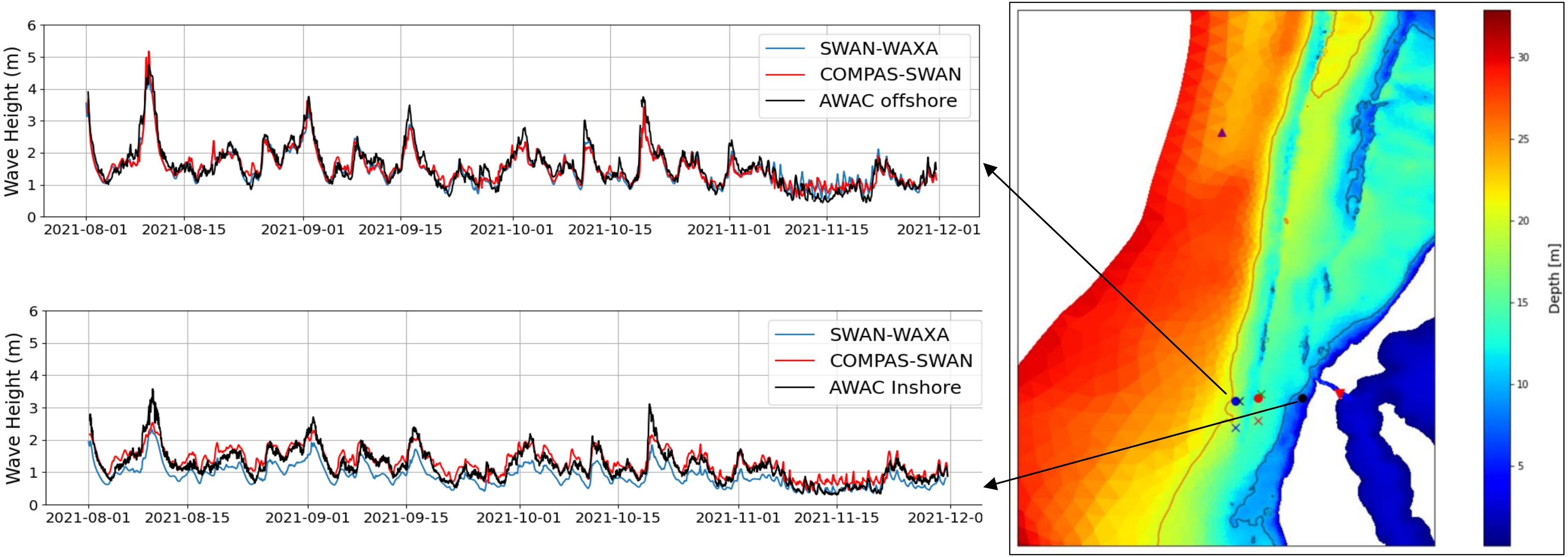
Difference (Waves – Hydro)



Obs. comparison

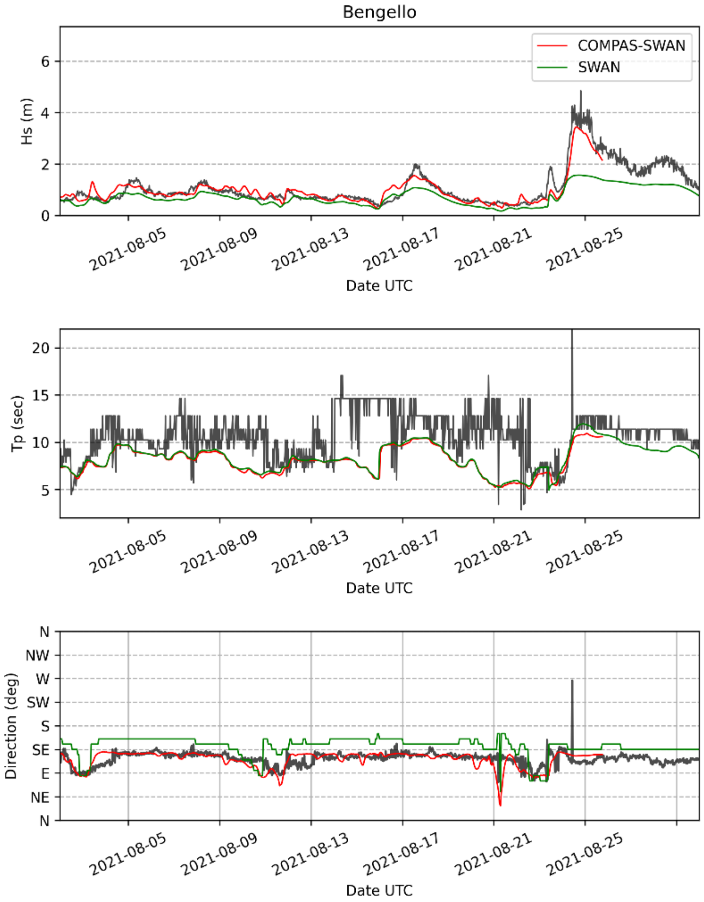


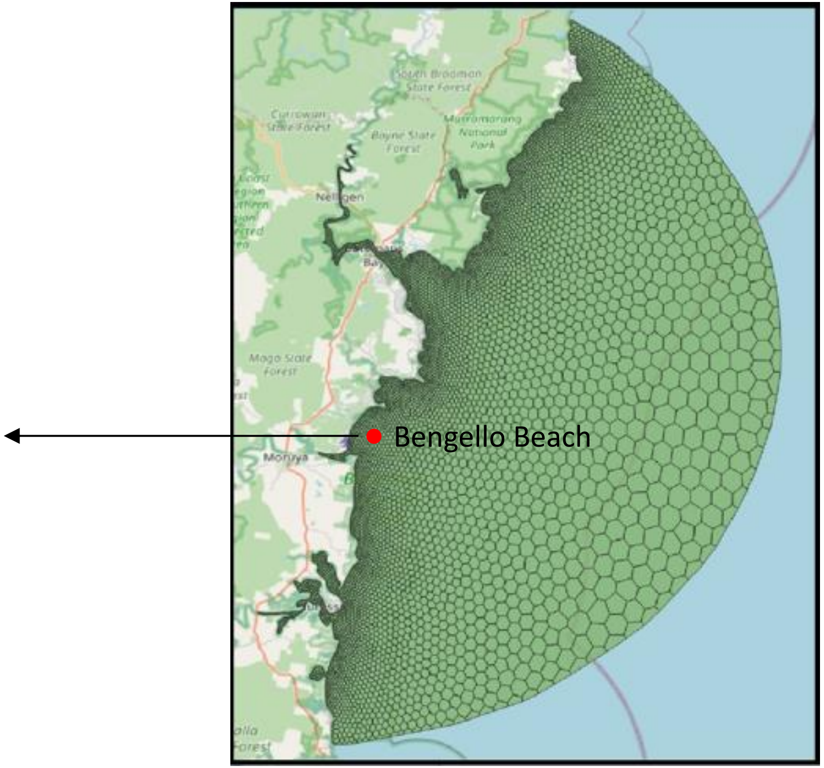
Wave height



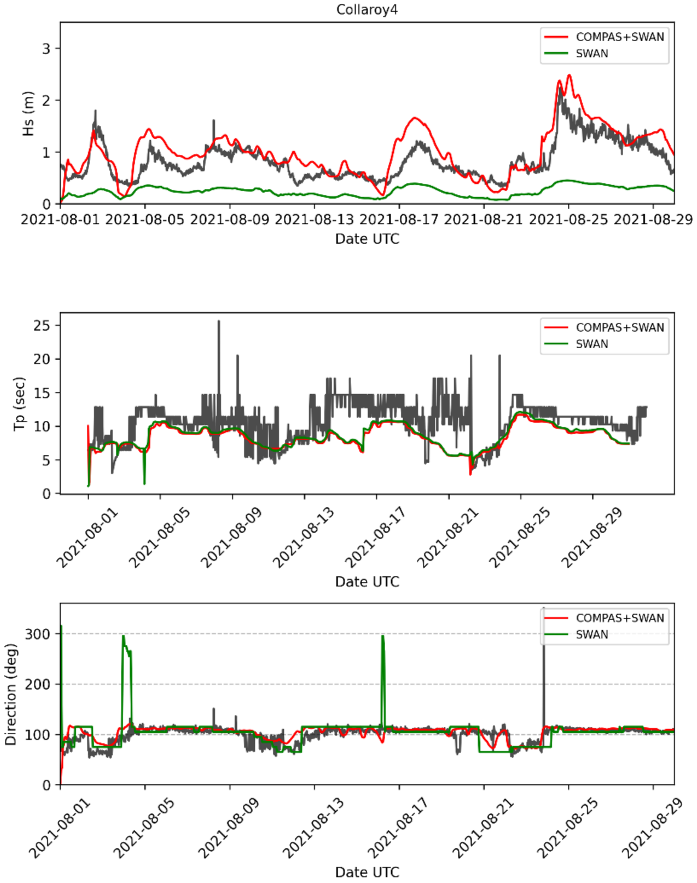
Wave Height (m)
0
1
2
3
4
5
6
SWAN-WAXA
COMPAS-SWAN
AWAC offshore
2021-08-01
2021-08-15
2021-09-01
2021-09-15
2021-10-01
2021-10-15
2021-11-01
2021-11-15
2021-12-01
Wave Height (m)
0
1
2
3
4
5
6
SWAN-WAXA
COMPAS-SWAN
AWAC Inshore
2021-08-01
2021-08-15
2021-09-01
2021-09-15
2021-10-01
2021-10-15
2021-11-01
2021-11-15
2021-12-0
30
25
20
15
10
5
Depth [m]

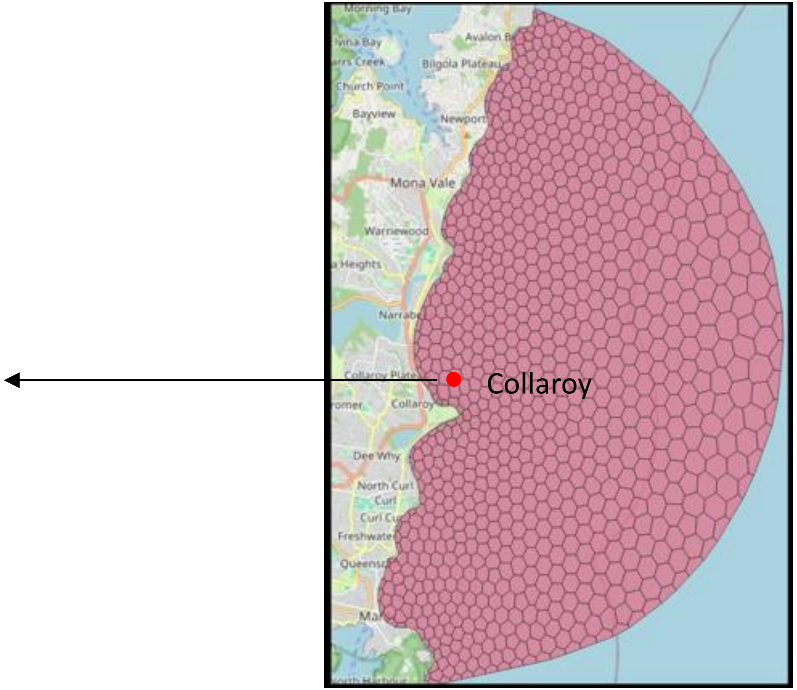
Batemans Bay – August21



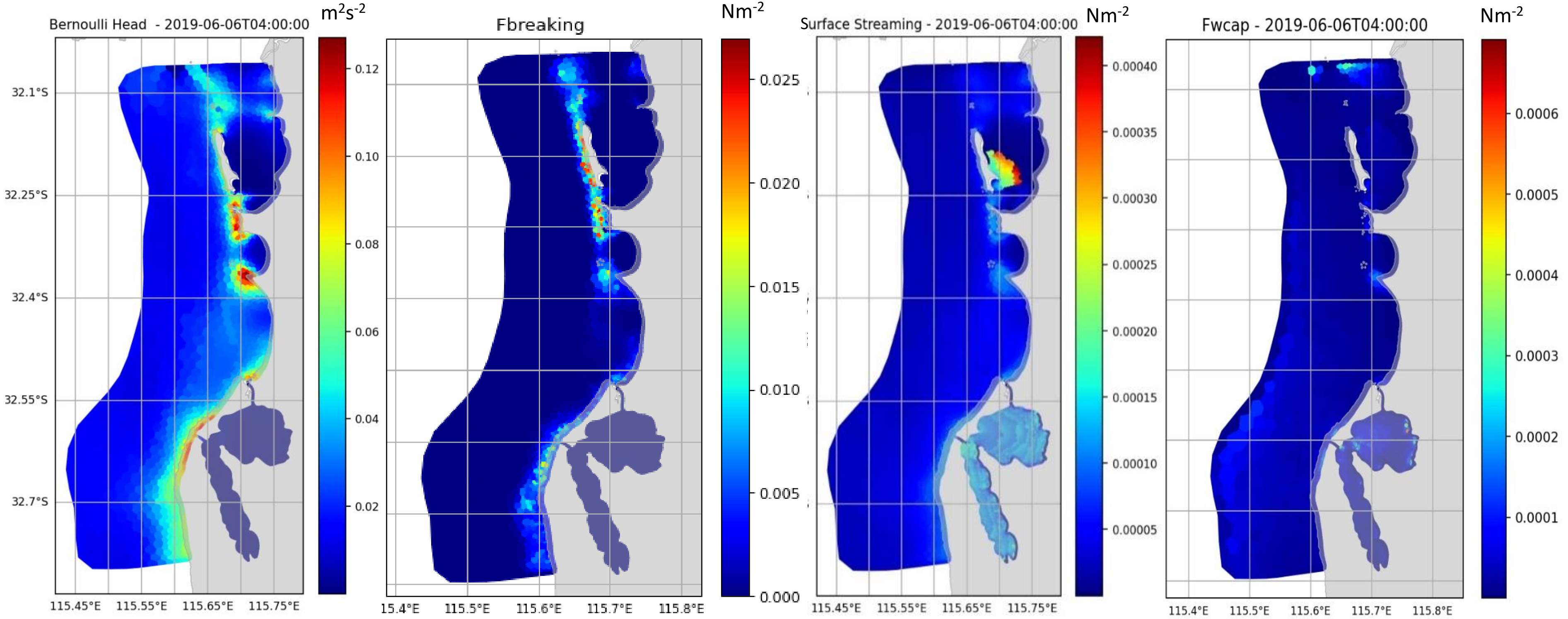


Narrabeen – August 21





Non-conservative WEC Terms



Summary

- An efficient and tightly coupled hydrodynamic-wave model was achieved using COMPAS-SWAN, leveraging
  - Co-location of hydrodynamic and wave scalar placement of variables
  - Data transfer using pointers
  - Streamlining Stokes Coriolis-vortex using hydrodynamic vector invariant momentum advection
  - Wave model access to hydrodynamic IO
- Model results appear promising

Thank you

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