WAVE IMPACTS ON NEARSHORE PROCESSES IN COUPLED WAVE-FLOW MODELS

Wave-Flow Coupling

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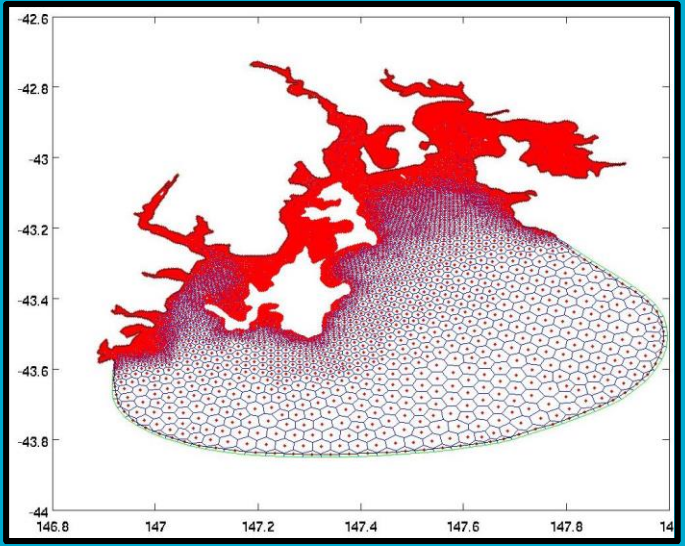
05/10/2023

Australia’s National Science Agency



3RD INTERNATIONAL WORKSHOP ON

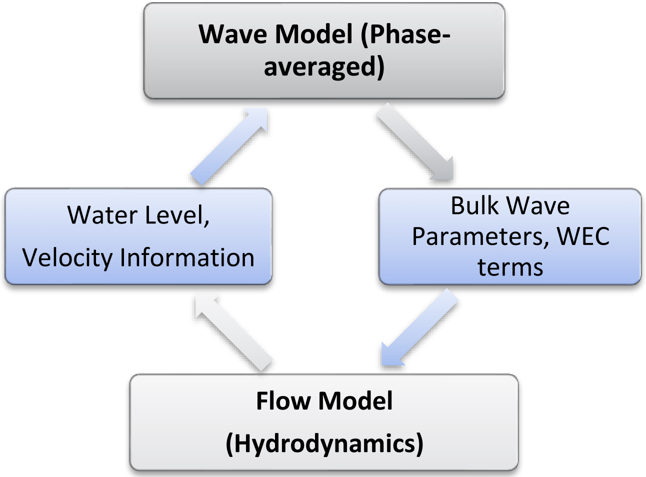
Waves, Storm Surges, and Coastal Hazards

Wave-Flow Coupling

"Surface waves affect the upper-ocean circulation, air–sea fluxes, and cross-shelf exchange due to both conservative and non-conservative effects."

WEC terms can impact;

- Addition of waves can improve elevation
- Influence hydro-sedimentary dynamics in the coastal zone
- Contribute to storm surge, extreme water levels
- Wave impacts on currents & currents influence on waves



COMPAS- SWAN Coupling

Evaluate and develop next-generation numerical modelling techniques and tools for incorporation, with the aim of improved prediction of littoral dynamics at a greater range of spatial scales

The models: COMPAS & SWAN

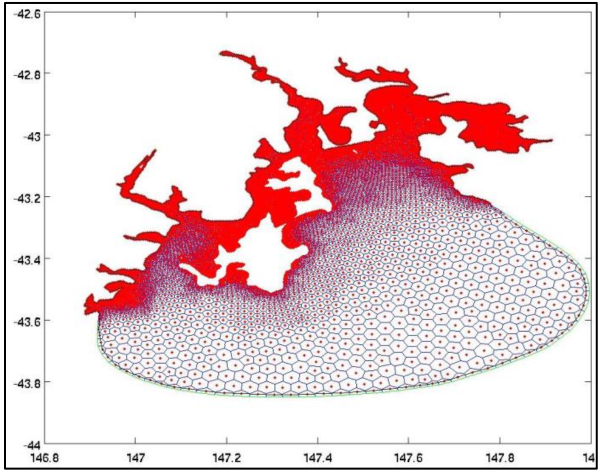
❖ **COMPAS (Coastal Ocean Marine Prediction Across Scales)** - 3D finite volume hydrodynamic model in CSIRO's Environmental Modelling System (EMS). (Herzfeld,2006; Herzfeld et al.,2020)

- Used at scales ranging from estuaries to regional ocean domains
- Uses the adapted the unstructured C-grid discretisation employed in the MPAS (Model for Prediction Across Scales) global ocean model for use in Coastal Modelling.
- Operates on Arakawa C-grid, whereby normal velocity components are staggered at the edges of Voronoi cells, with fluid height and tracer variables located at cell centres (Herzfeld et.al., 2020)
- **Advantages of hexagonal mesh:**

  -spurious modes associated with triangular C-grid meshes are absent in these hexagonal cases.

  - works well with finite-volume models

❖ **SWAN (Simulating Waves Nearshore)** (Booij et al., 1999; Zijlema et al., 2010)
3rd gen phase averaged wave model



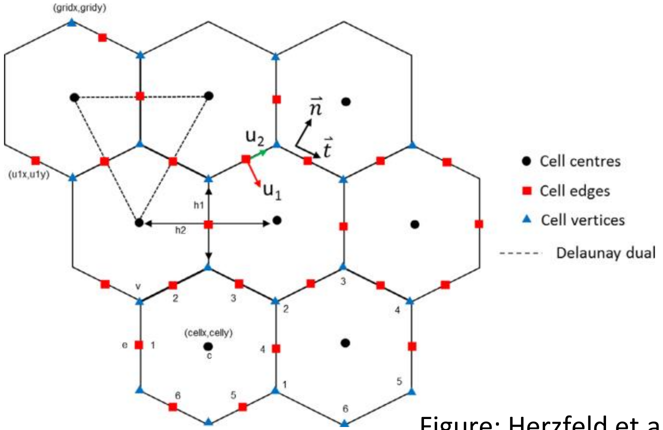


Figure: Herzfeld et.al., 2020

Mesh Generation

- JIGSAW (Engwirda, 2017) designed for TRiSK FV scheme Delaunay triangulation - Centroidal Voronoi Tessellation

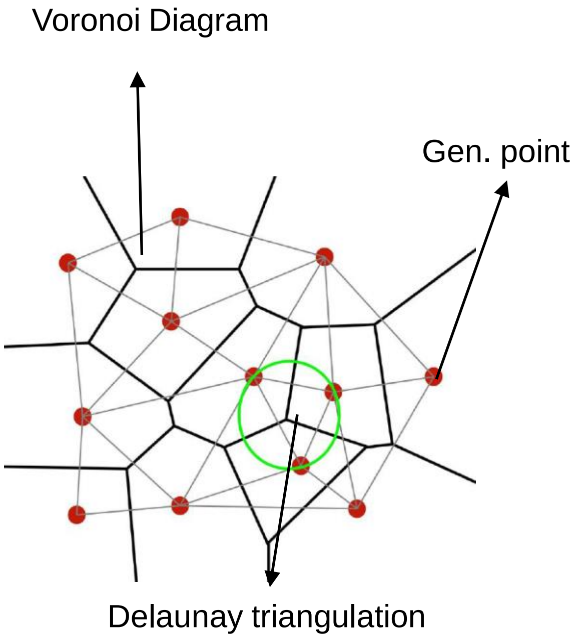


Figure:Herzfeld, 2018

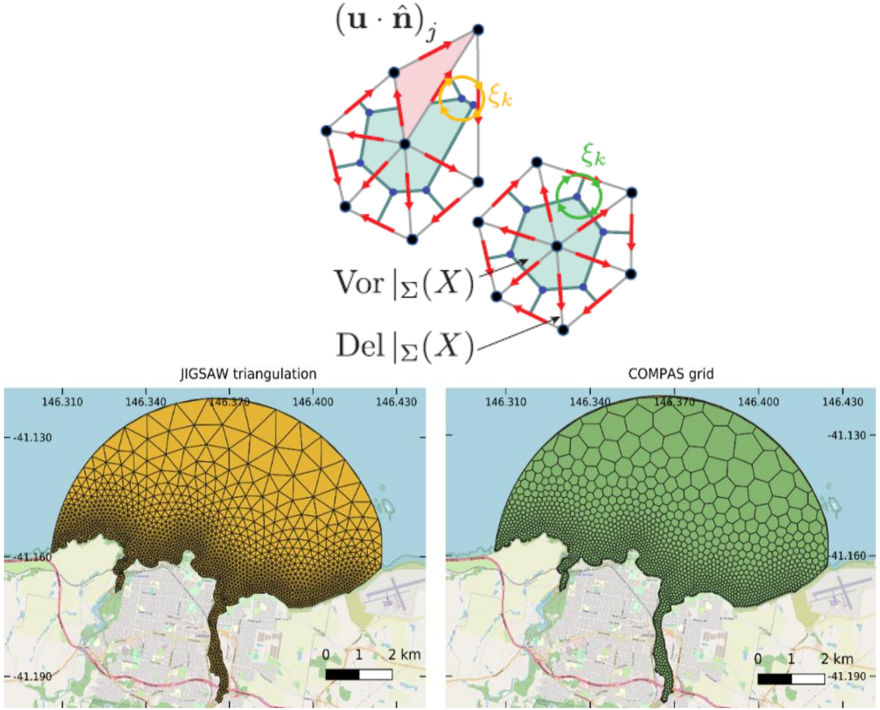


Figure: Farhan Rizwi

Vortex- Force Formalization and Why?

- Vortex-force representation decomposes the main wave-averaged effects into two physically understandable concepts of vortex force and a Bernoulli head
  - explicit inclusion of different type of wave–current interaction
  - incorporate impacts of depth-limited wave dissipation terms (e.g. wave breaking), higher order nonlinear wave impacts.
  - Vertical components of the 3d Radiation stress tensors wave radiation stress change very fast with depth
- Uchiyama et al., (2010) and Kumar et al., (2012) extended McWilliams et al. (2004) to consider non-conservative conditions by adding breaking waves, roller waves, bottom and surface streaming and wave-enhanced mixing through empirical formulas. (ROMS, COAWST, SCHISM)

Bernoulli Head*

Nonconservative WEC terms*

Momentum

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

Surface Streaming

Whitecapping Disp.*

Wave Roller

$$\mathbf{F}^w(\mathcal{F}^{w\xi}, \mathcal{F}^{w\eta}) = \mathbf{B}^{bf} + \mathbf{B}^{sf} + \mathbf{B}^{wb} = \mathbf{B}^{bf} + \mathbf{B}^{sf} + \mathbf{B}^{wcap} + \mathbf{B}^{b} + \mathbf{B}^{r}$$

Bottom Dissipation*

Wave Breaking*

Depth-Limited wave Breaking*

Continuity

$$\frac{\partial p}{\partial z} + \frac{g\rho}{\rho_o} = -\frac{\partial \mathcal{K}}{\partial z} + \boldsymbol{u}_s\cdot\frac{\partial \boldsymbol{u}}{\partial z}$$

Conservative Vortex Force*

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

Stokes Drift*

Transport

$$\frac{\partial c}{\partial t} + (\mathbf{u}\cdot\nabla_\perp)c + w\frac{\partial c}{\partial z} - \mathscr{C} = -(\mathbf{u}^{St}\cdot\nabla_\perp)c - w^{St}\frac{\partial c}{\partial z} + \frac{1}{2}\frac{\partial}{\partial z}\left[\mathscr{E}\frac{\partial c}{\partial z}\right]$$

*calculated in SWAN

COMPAS-SWAN Coupling Technical

- No model coupler
- Compile SWAN as a library object to which COMPAS can link using C interoperability protocols
- During initialisation within SWAN, pointers to variables within this data structure are set up.
- COMPAS initialises and manages memory for wave variables
- SWAN updates information for those variables by writing directly to the memory addressed rather than transferring the actual data

Variable	Description	Method
COMPAS STE	Stokes Drift	Romero et al. (2021)
COMPAS K	Effective Wavenumber	Romero et al. (2021)
COMPAS KB	Bernoulli Head (Wave-Induced Pressure)	WW3, Bennis et al. (2011)
COMPAS FWCAP	Whitecapping	SWAN + Uchiyama et al. (2010)
COMPAS FBRE	Depth-induced wave breaking	SWAN + Uchiyama et al. (2010)
COMPAS FBOT	Bottom Friction Dissipation	SWAN + Uchiyama et al. (2010)
COMPAS FSUR	Surface Streaming	SWAN + Kumar et al. (2012)
COMPAS FROL	Surface Roller Dissipation	Svendsen(1984) + Kumar et al. (2012)
COMPAS WFD	Wave Form Drag	WW3 + Kumar et al. (2012)
COMPAS WOVS	Wave Ocean Viscous Stress	WW3 + Kumar et al. (2012)

Stokes Drift

- Difference between Eulerian and Lagrangian velocities and may significantly change the transport properties of the system at equilibrium.
- has a crucial importance for the wave-current interactions and upper ocean mixing

Composite Iterative Approach based on Romero et al. 2021

Monochromatic (Shallow and at Depth)

$$u_s(z) = \frac{A^2}{2}\sigma k \frac{cosh2k(z+d)}{sinh^2 kD}$$

+

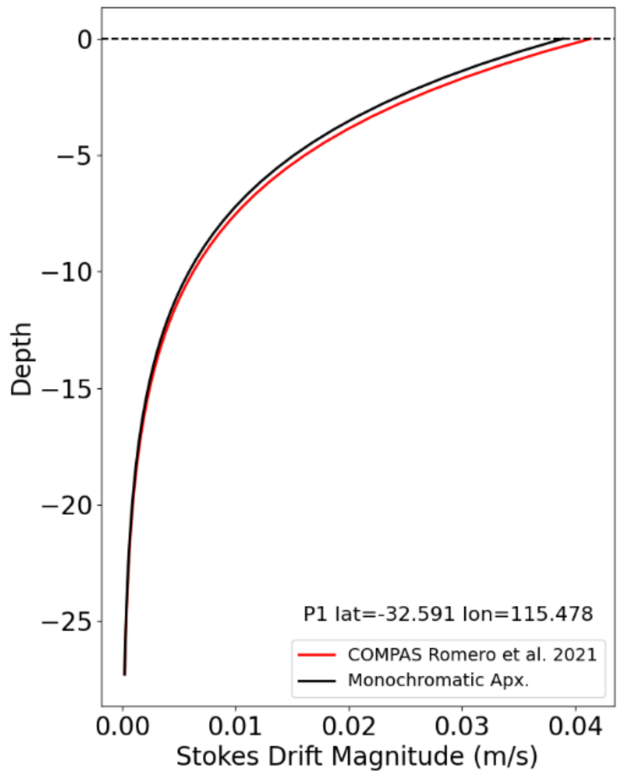
Spectral (DW and Intermediate depths)

$$u_s(z=0) = \iint \sigma cosh2kd \frac{(kcos(\theta), ksin(\theta))}{sinh^2 kd} S(\sigma,\theta) d\sigma d\theta$$

$$u_{se} \approx u_0 \frac{cosh2k_{se}(z+d)}{sinh2k_{se}D} \qquad k_{se} = \frac{u_s(z=0)}{2U_s} \qquad H(z) = tanh\left(\frac{|z|k_{se}}{2}\right)^{1/2}$$

$$u_{sf}(z) \approx H(z)u_{sp} + (1-H(z))u_{se}$$

Switch Function



"The framework improves over existing methods not limited by water depth or monochromatic assumptions."

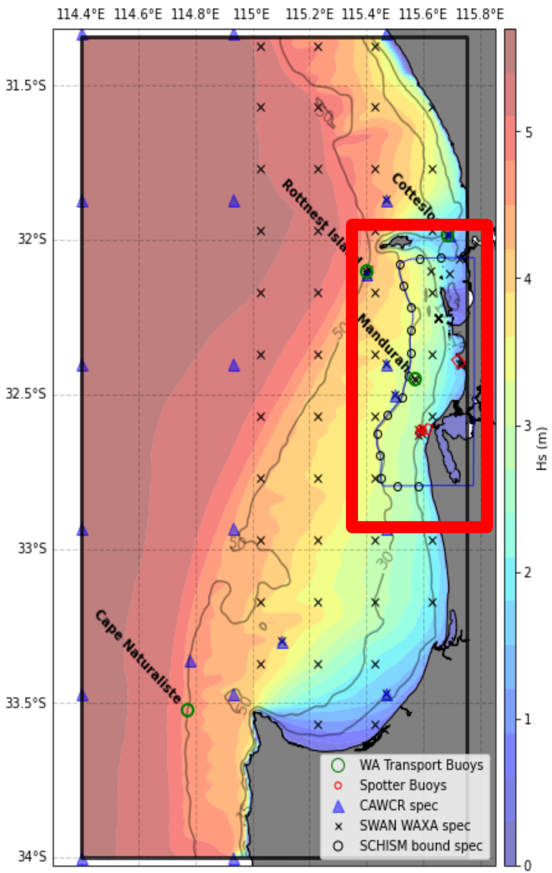
Testbed region: Mandurah, Western Australia

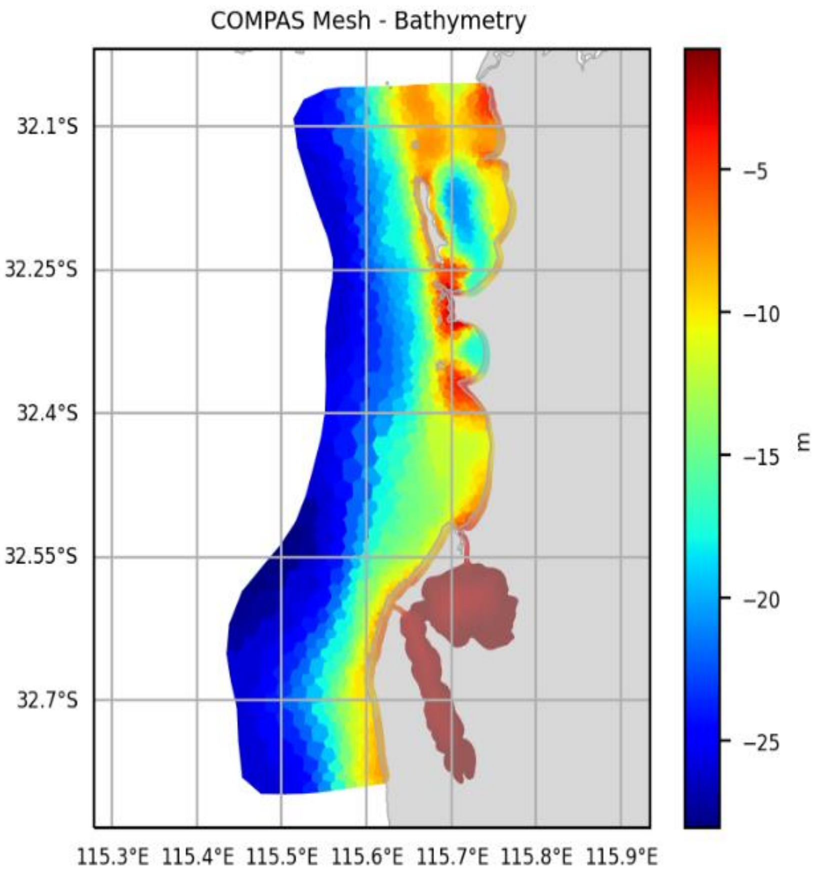
- Geographical Features

- The nearshore reefs
- Tidal channels
- Estuary
- Leeuwin Current

-Observation Points

in-situ coastal wave and circulation observations are available in this region





Manduruh Testbed : June 2019

Resolution

- 50 m resolution at the coast
- 4000 m at the open boundary
- ~40000 indices
- SWAN t=15 min , COMPAS t=0.5 sec

Forcing Fields

- **Winds**

  Conformal Cubic Atmospheric Model (C-CAM) , McGregor (2005)

- **Wave Forcing**

  Regional SWAN hindcast (500m) downscaled from

  CAWCR (WW3) Hindcast (4 arc sec),

  Durrant, T. (2014); Trenham, C. E (2014).

- **Water Level**

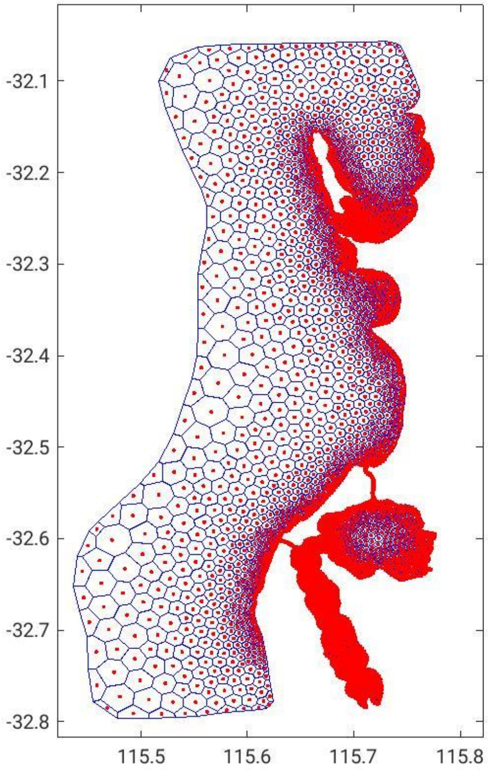
  BRAN2020 OFAM3 (MOM5) (0.1 degree)

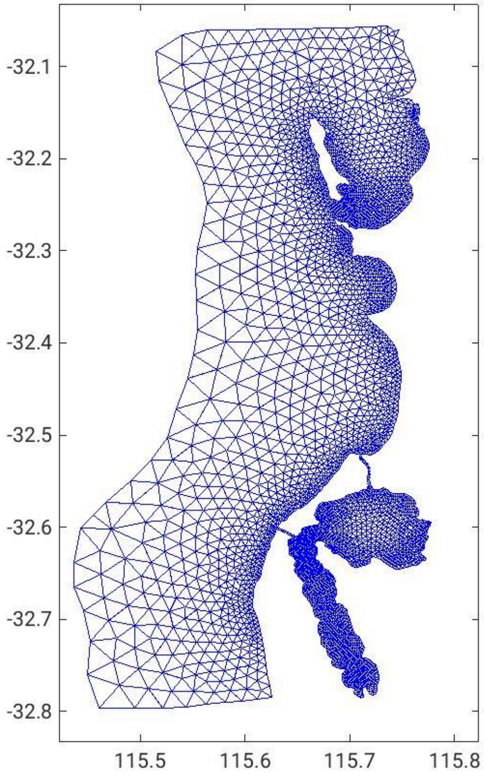
  Chamberlain et al. (2021)

- **Tides**

  TPXO Tides

  Egbert, G.D. and Svetlana Y.E (2002)

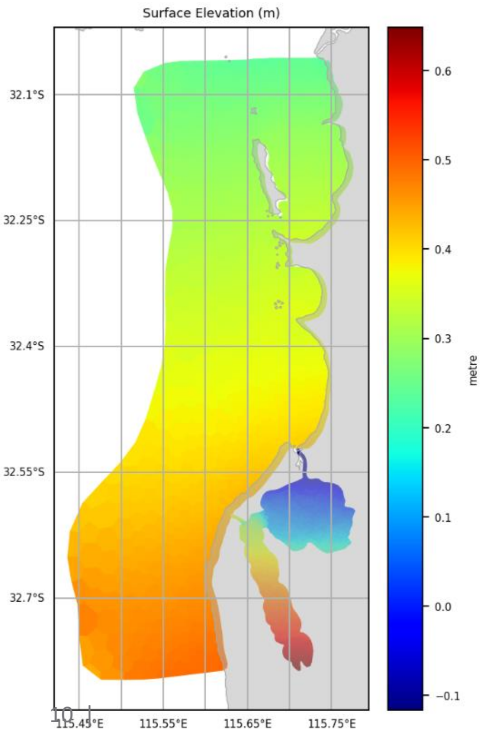




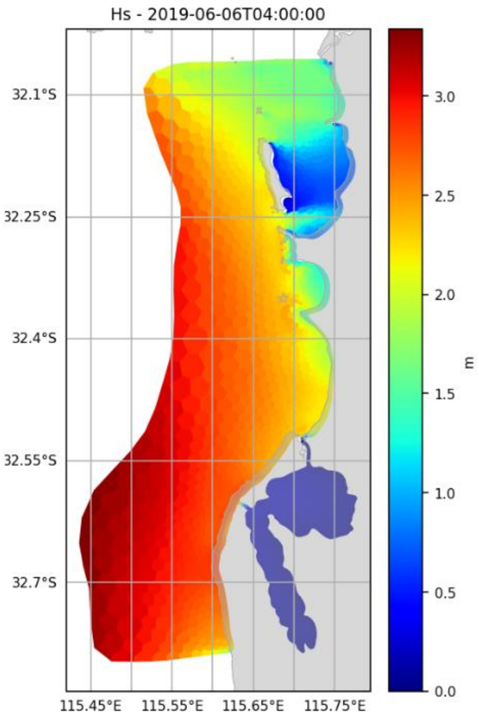
Mandurah, WA Test Bed - June 2019

- Surface Elevation (η)

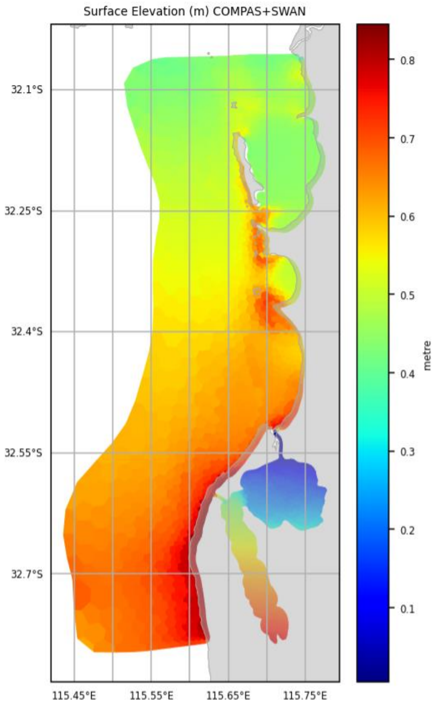
Hydro only



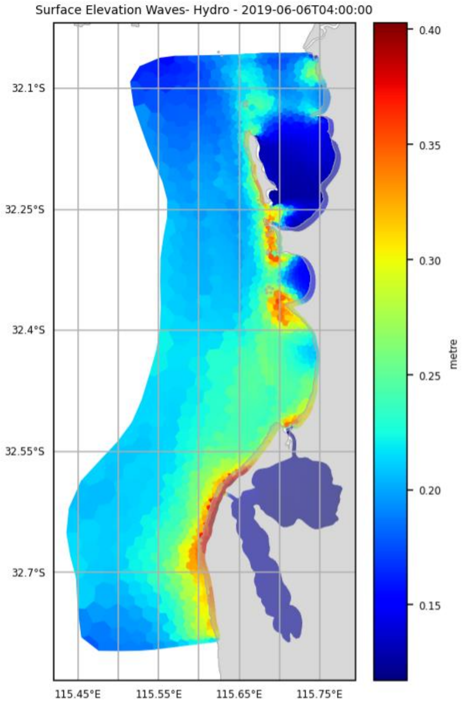
Hs



Hydro + Waves



Waves- Hydro



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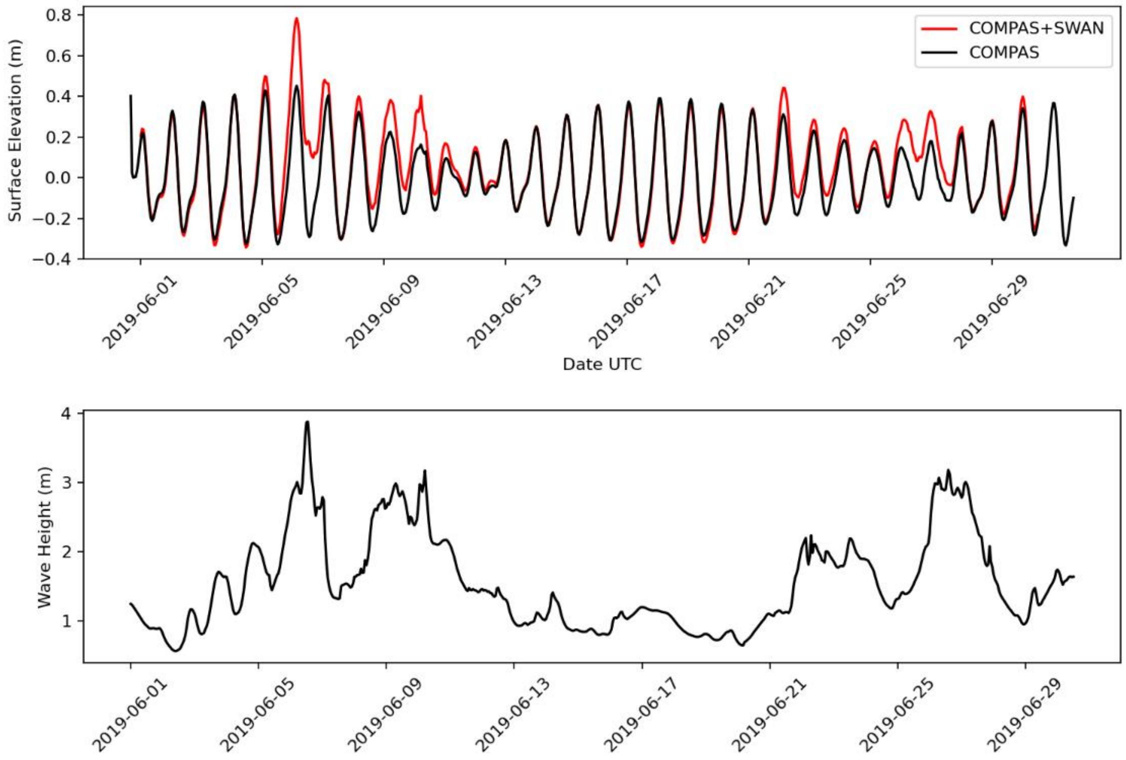

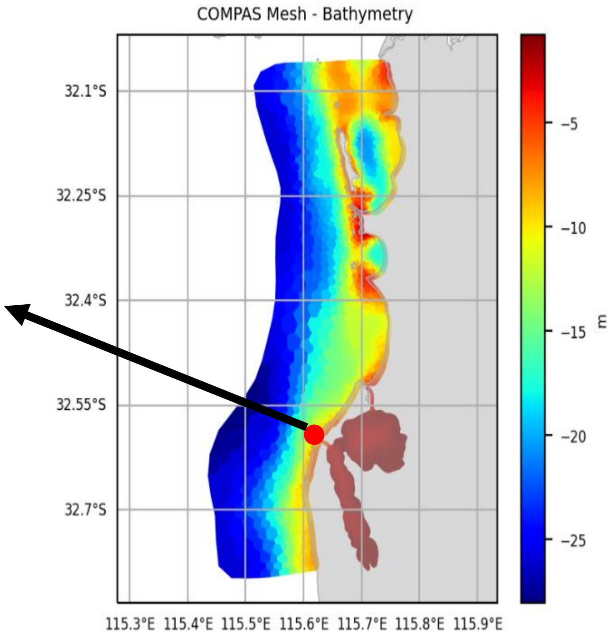

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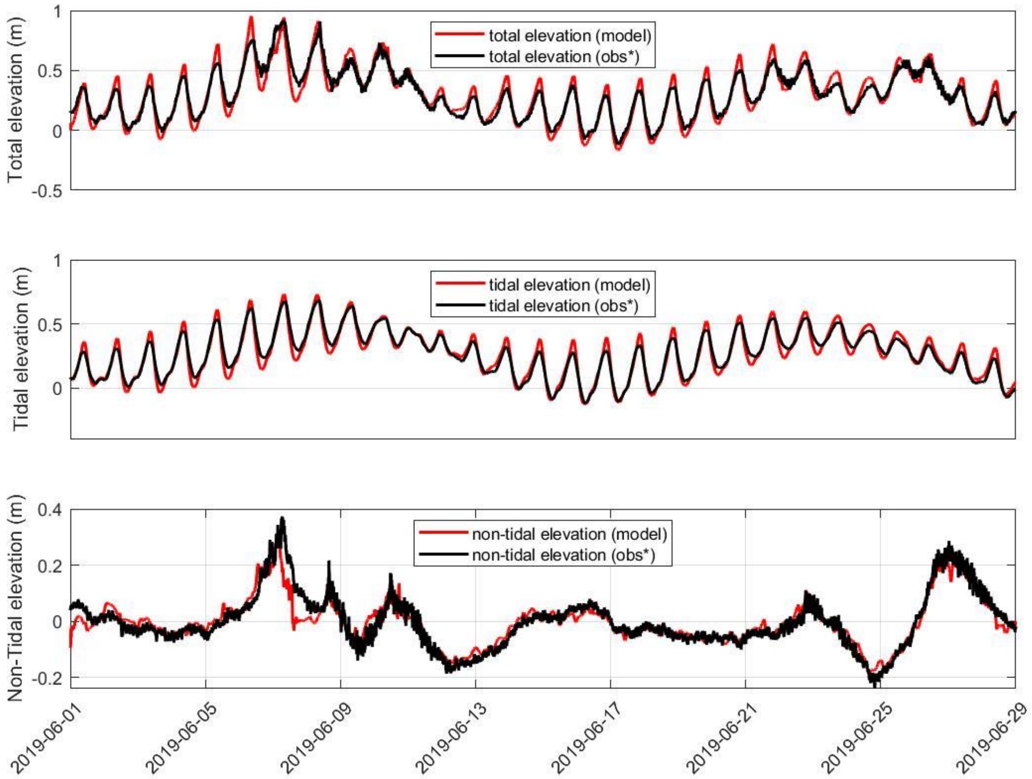

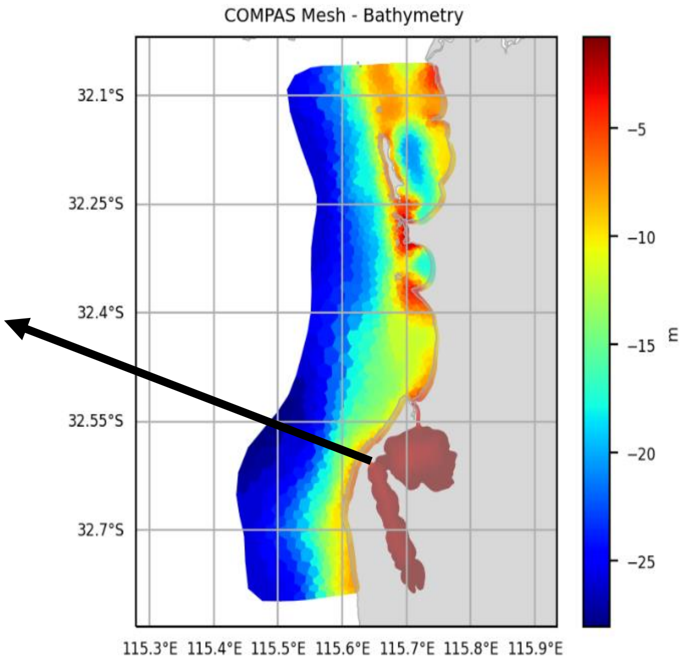

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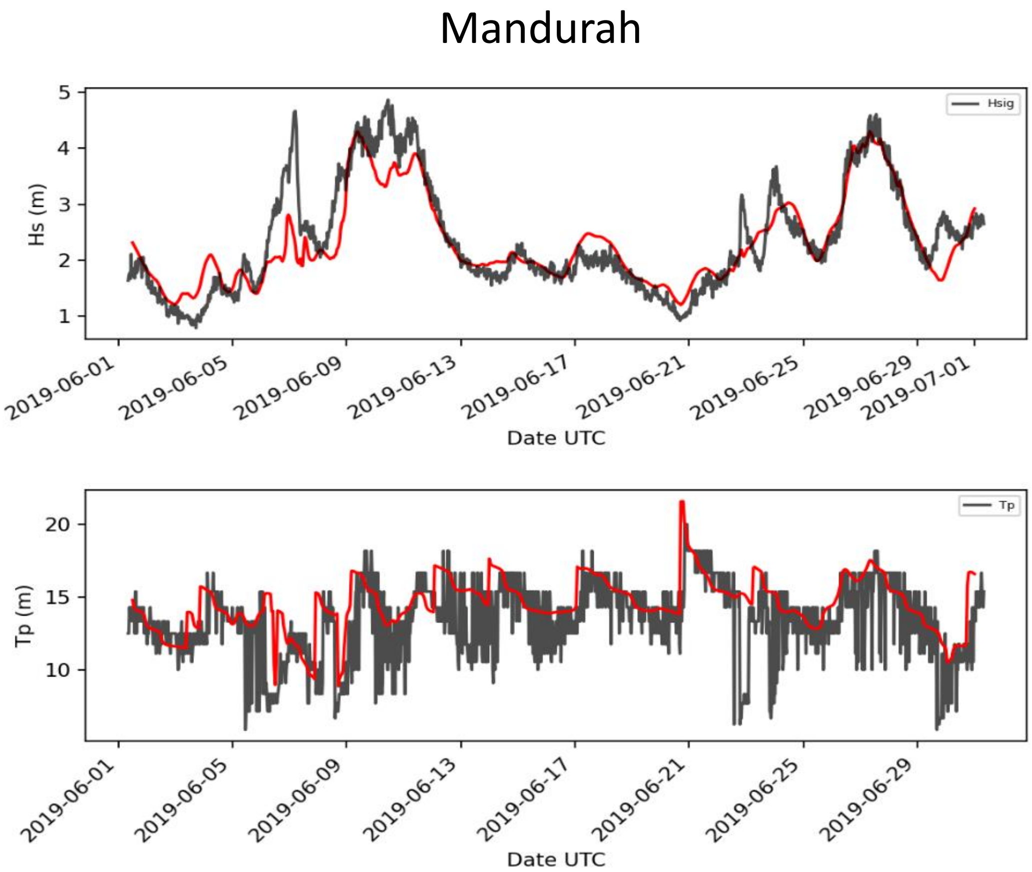

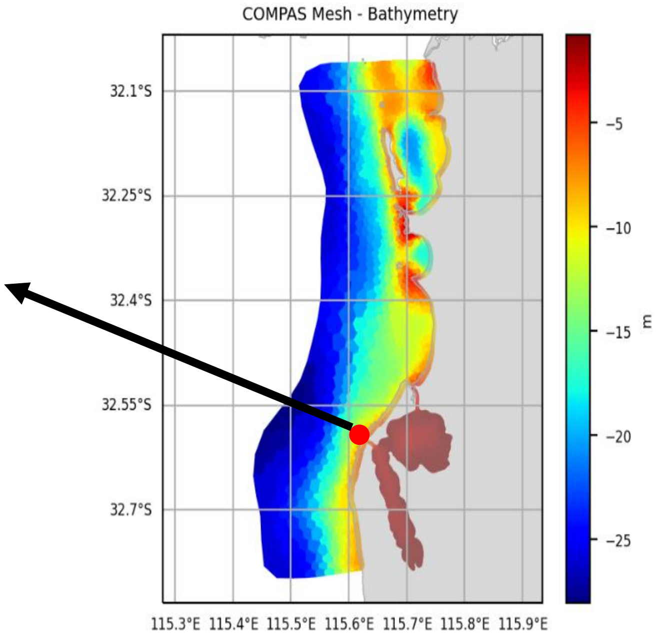

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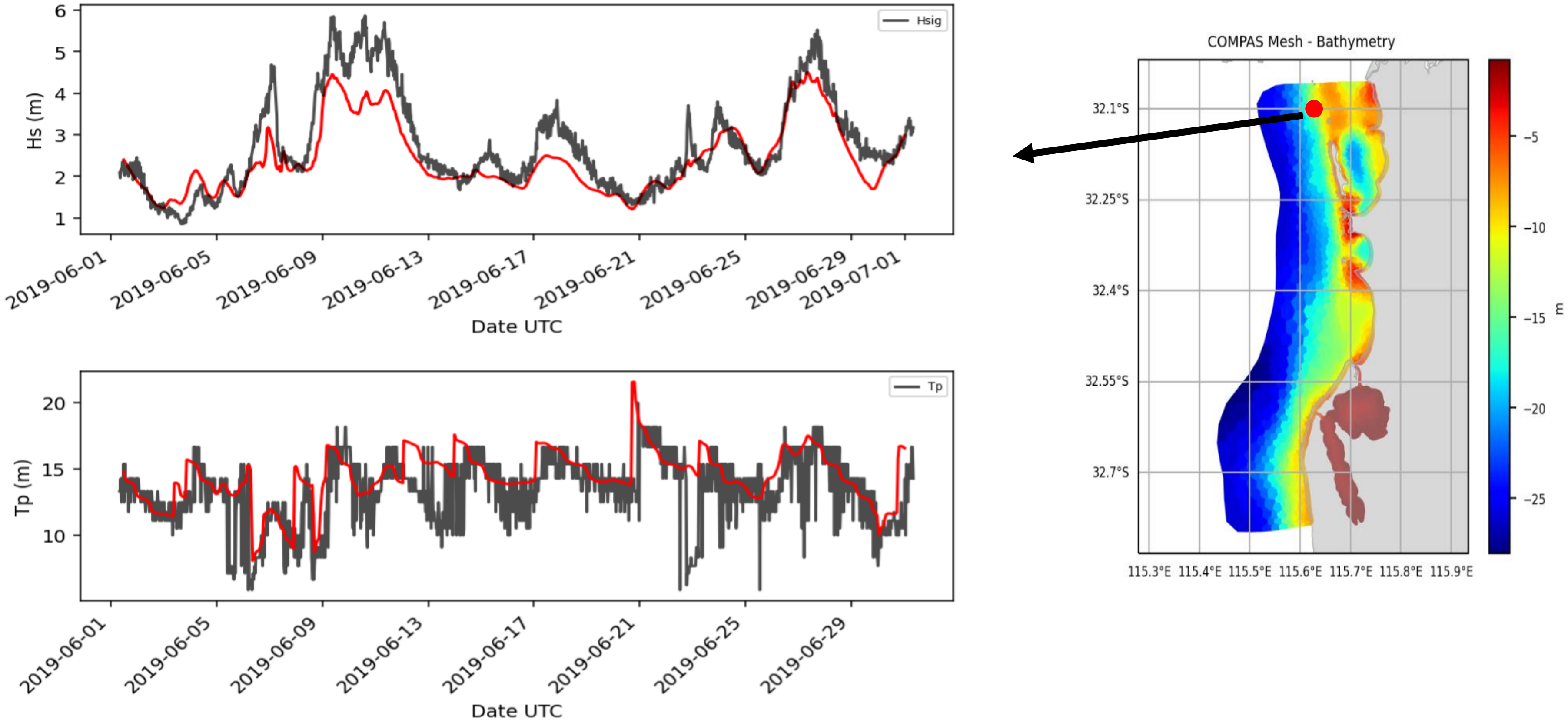
Rottnest Island



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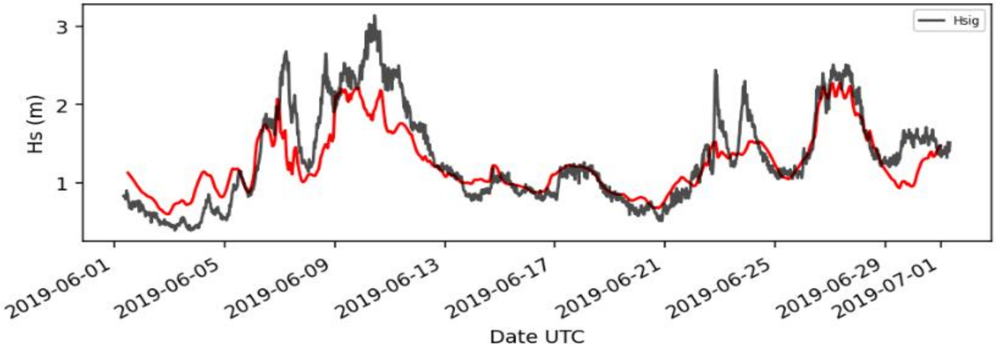
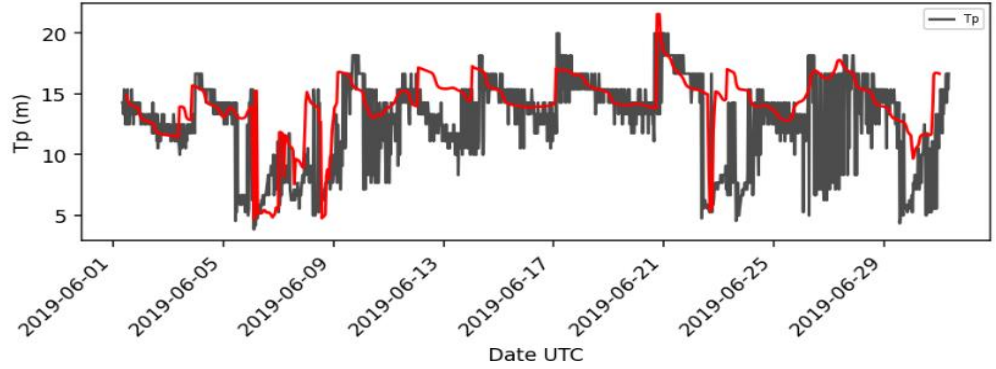
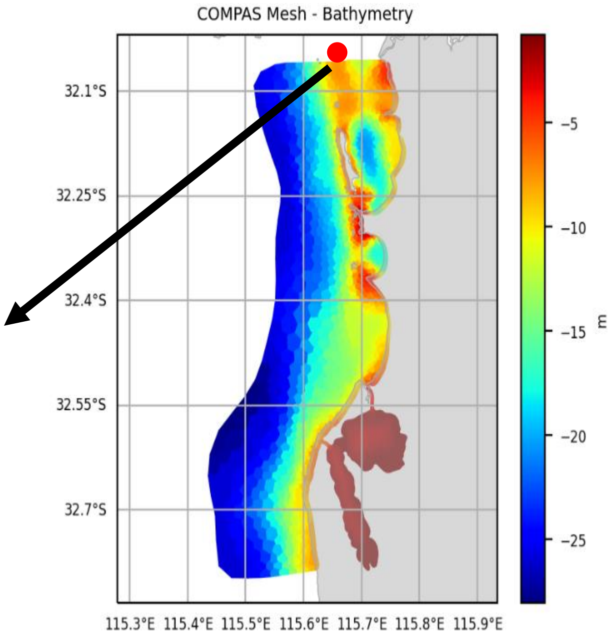
Cottlesloe

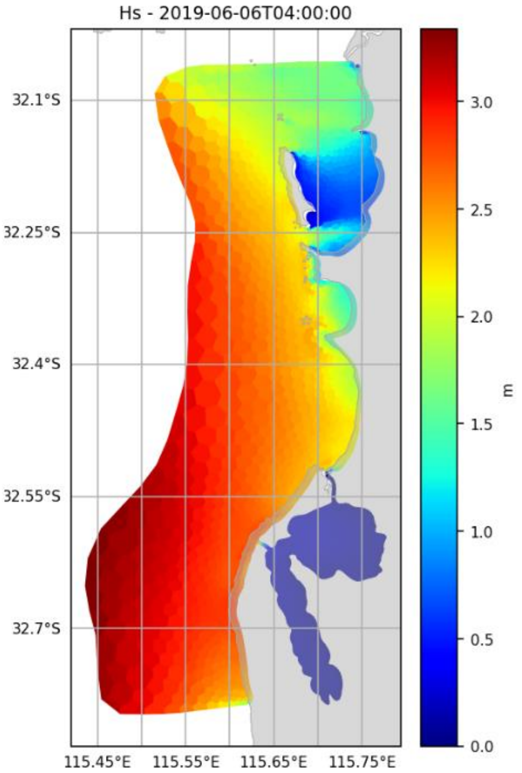


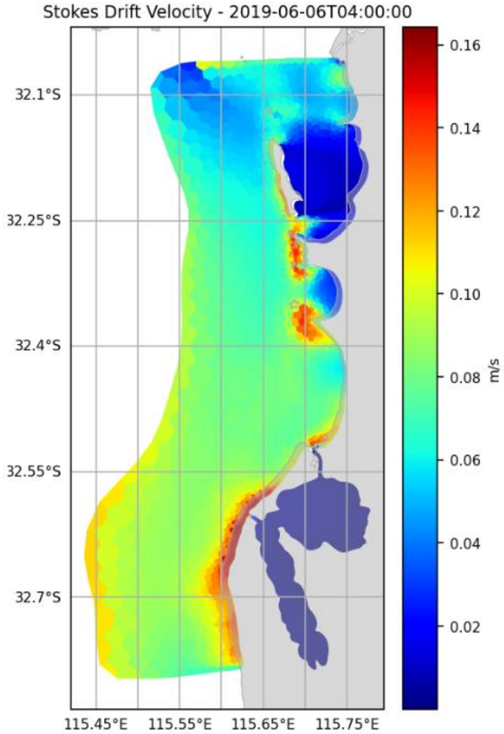


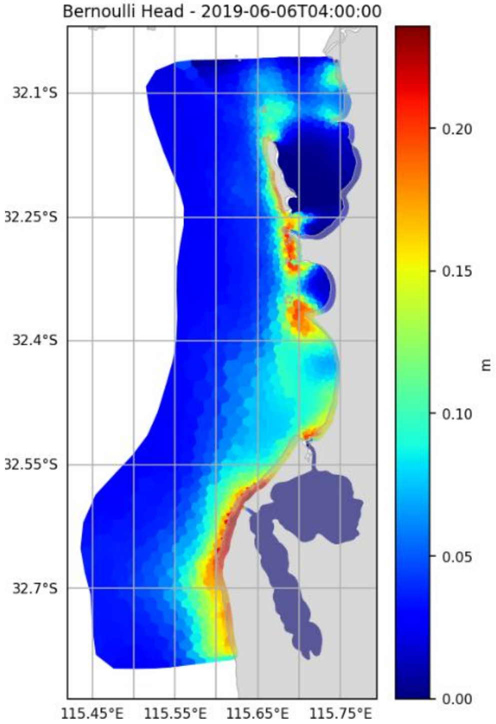


Mandurah, WA Test Bed - June 2019

- Stoke Drift and Bernoulli Head







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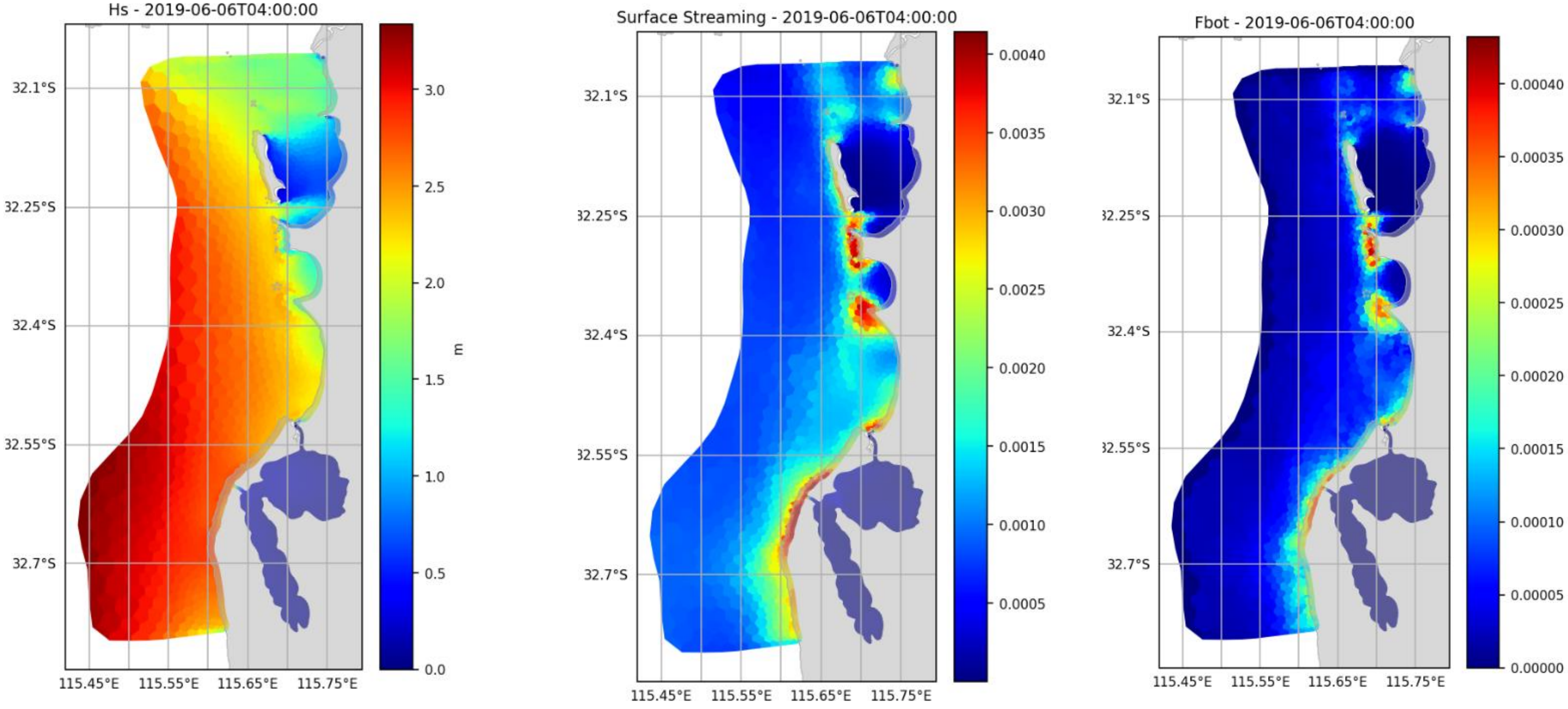
- Non-conservative WEC Terms



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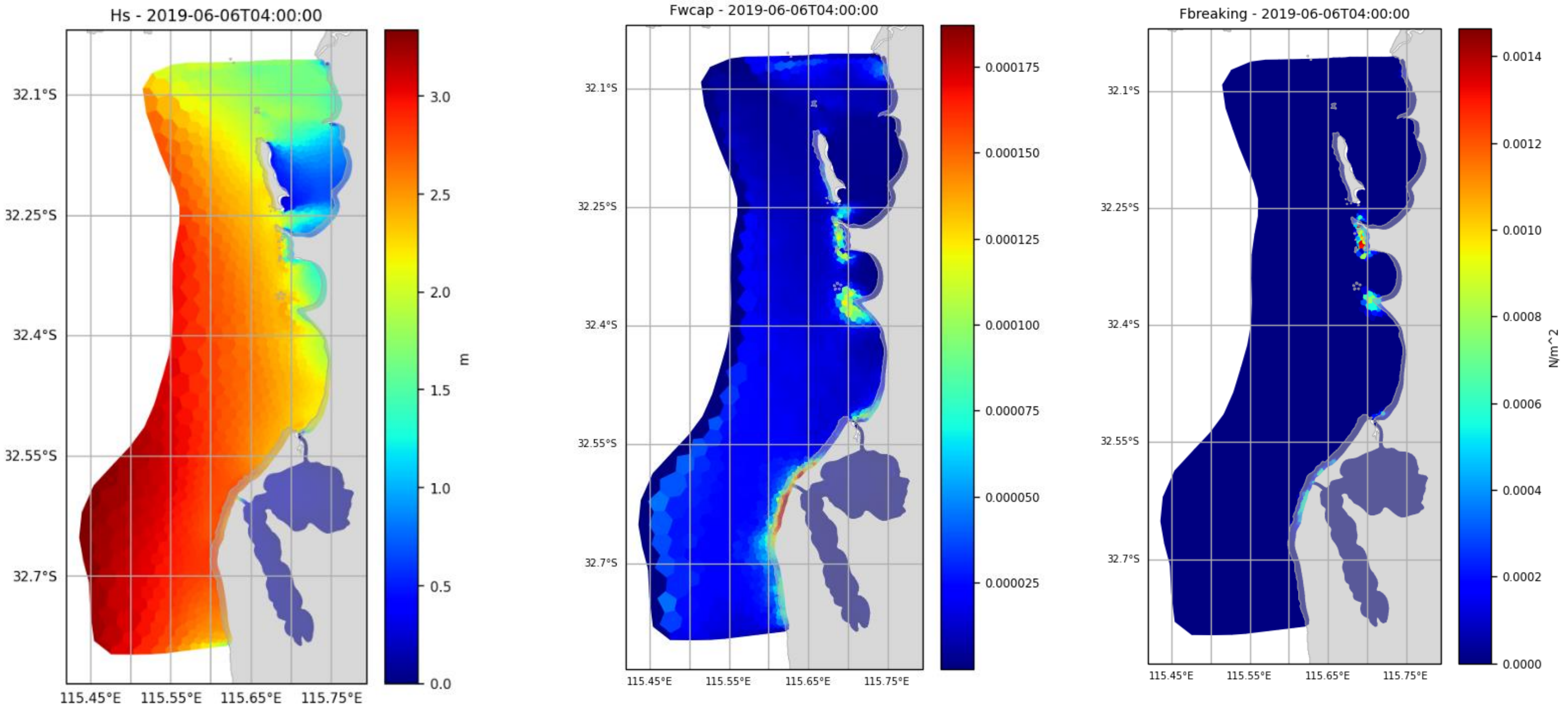

Summary and Future Work

- COMPAS-SWAN coupled model available https://github.com/csiro-coasts/EMS

COMPAS

Coastal Ocean Marine Prediction Across Scales

- Importance of incorporating WEC terms into hydrodynamic modelling, particularly for surface elevation
- Vortex-Force Formalization
- Romero et al.,2021 Stokes Drift not limited by water depth or monochromatic assumption.

- Wave Roller Model of Svendsen (1984) →applied
- Using Roller Energy Density (Reniers, 2004) → application in progress

Thank you

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Wave Roller Dissipation

- Wave rollers act as storage of dissipated wave energy, which is gradually transferred to the mean flow causing a lag in the transfer of momentum

- Depth – Induced Wave Breaking $$\mathbf{B}^b = \frac{(1-\alpha^r)\epsilon^b}{\rho_0\sigma}\mathbf{k}\cdot f^b(z)$$

- Wave Roller Contribution $$\mathbf{B}^r = \frac{\epsilon^r}{\rho_0\sigma}\mathbf{k}\cdot f^b(z) \qquad \varepsilon^r = \frac{g\cdot\sin\beta\cdot E^r}{c}$$

- Wave Roller Model of Svendsen (1984) ➔applied

- Using Roller Energy Density (Reniers, 2004) → application in progress $$\frac{\partial \mathcal{A}^r}{\partial t} + \nabla\cdot(\mathcal{A}^r\mathbf{c}) = \frac{\alpha_r\varepsilon^b - \varepsilon^r}{\sigma}$$

References

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Summary

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- Importance of incorporating WEC terms into hydrodynamic modelling, particularly for surface elevation
- Vortex-Force Formalization
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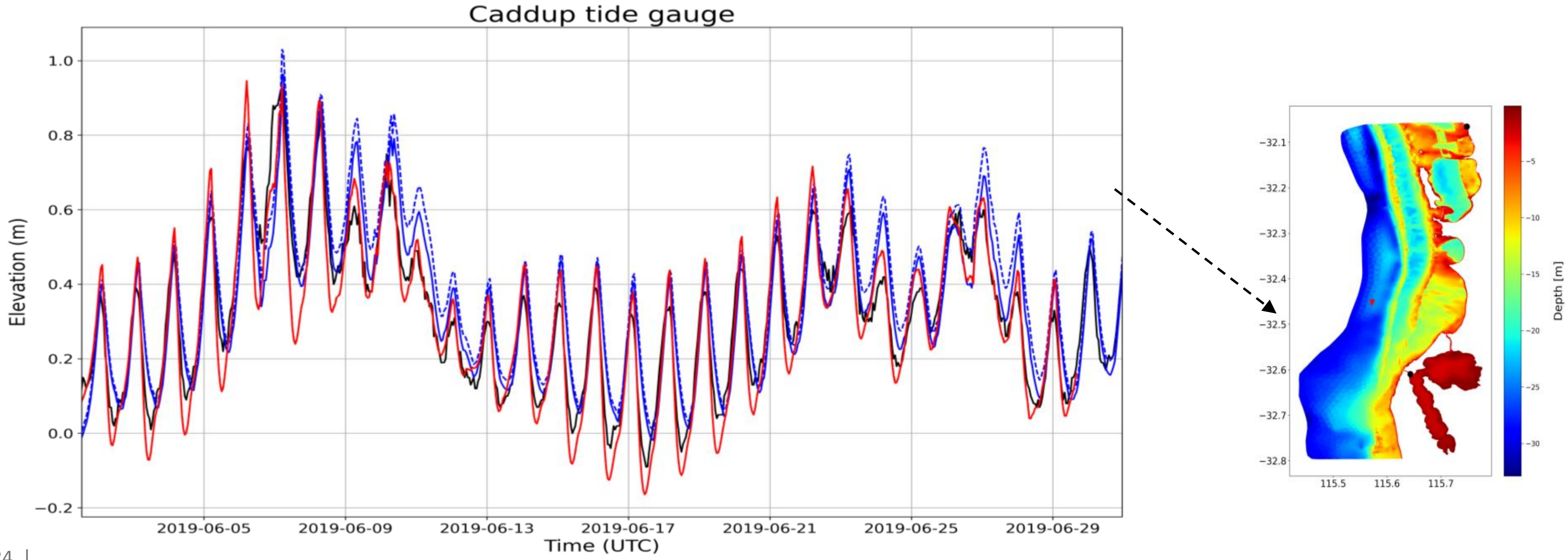
Mandurah Testbed Simulations

Comparison of two models run on same mesh (both on COMPAS-generated mesh) and comparison of flow and waves for each model



Wave Induced Forcing -Stress

- Air Side – Ocean Side Stress

$$\tau_{oc} = \tau_a - (\tau_w - \tau_{ds}),$$

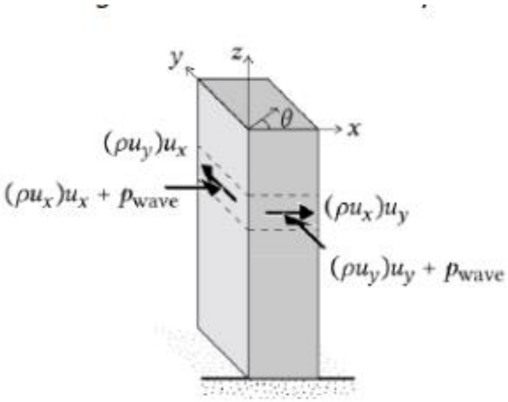
For winds and waves in equilibrium $\tau_w \approx \tau_{ds}$, thus $\tau_{oc} \approx \tau_a$, which corresponds to the common assumption used for ocean models. The

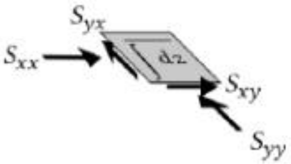
$$\vec{\tau}_{air} = \vec{\tau}_w + \vec{\tau}_v,$$

$$\vec{\tau}_{oc} = \vec{\tau}_{air} - (\vec{\tau}_w - \vec{\tau}_{ds}),$$

Radiation Stresses

- Radiation Stress Theory (Longuet_higgins and Stewart (1962,1964)
- The radiation stress is the momentum transferred through the water body per unit time (the flux of momentum)by wave orbital motion.
- In this approach the radiation stress representation is a two-dimensional (2D) tensor, and as such it is only suitable for depth-averaged numerical models.
- Nguyen et al. (2021) recently obtained 3D depth dependent radiation stress tensor using the Generalized Lagrangian Mean (GLM) Method





$$F_x = -\frac{\partial S_{xx}}{\partial x} - \frac{\partial S_{xy}}{\partial y}, \quad F_y = -\frac{\partial S_{yx}}{\partial x} - \frac{\partial S_{yy}}{\partial y}$$

$$S_{xx} = \rho g \iint [n\cos^2\theta + n - 0.5] S(\sigma,\theta) d\sigma d\theta,$$

$$S_{xy} = S_{yx} = \rho g \iint n\cos\theta \sin\theta S(\sigma,\theta) d\sigma d\theta,$$

$$S_{yy} = \rho g \iint [n\sin^2\theta + n - 0.5] S(\sigma,\theta) d\sigma d\theta,$$

Terms	Walstra, Roelvink [16]	Nguyen, Jacobsen [5]
Pressure gradient	$-\frac{1}{\rho}\frac{\partial \overline{p}_a}{\partial x} - g\frac{\partial \overline{\zeta}^L}{\partial x}$	$-\frac{1}{\rho}\frac{\partial \overline{p}_a}{\partial x} - g\frac{\partial \overline{\zeta}^L}{\partial x}$
Conservative wave forcing	$-\left(\frac{\partial \overline{\widetilde{u}^2}}{\partial x} + \frac{\partial \overline{\widetilde{u}\widetilde{v}}}{\partial y} + \frac{\partial \overline{\widetilde{u}\widetilde{w}}}{\partial z}\right)$	$-\left(\frac{\partial \overline{\widetilde{u}^2}}{\partial x} + \frac{\partial \overline{\widetilde{u}\widetilde{v}}}{\partial y} + \frac{\partial \overline{\widetilde{u}\widetilde{w}}_{CS}}{\partial z}\right) + \frac{1}{\rho}\frac{\partial \overline{p}^S}{\partial x} + T_1$
Non-conservative wave forcing	$-\frac{1}{\rho}\left(\frac{\partial \overline{\tau}^s_{11}}{\partial x} + \frac{\partial \overline{\tau}^s_{12}}{\partial y} + \frac{\partial \overline{\tau}^s_{13}}{\partial z}\right)$ $\frac{F_{br,1}}{\rho}$: applied as a surface stress $\frac{F_{fr,1}}{\rho}$: applied as a bottom stress	$\frac{F_{br,1}}{\rho}$: applied as a body force $\frac{F_{mx,1}}{\rho}$: applied as a body force $\frac{F_{fr,1}}{\rho}$: applied as a bottom stress
Turbulence	$\frac{1}{\rho}\left(\frac{\overline{\tau}^L_{11}}{\partial x} + \frac{\overline{\tau}^L_{12}}{\partial y} + \frac{\overline{\tau}^L_{13}}{\partial z}\right)$	$\frac{1}{\rho}\left(\frac{\overline{\tau}^L_{11}}{\partial x} + \frac{\overline{\tau}^L_{12}}{\partial y} + \frac{\overline{\tau}^L_{13}}{\partial z}\right)$
Mass conservation	$\frac{\partial \overline{\zeta}^L}{\partial t} + \frac{\partial}{\partial x}\left(\int_{-h}^{\overline{\zeta}^L} \overline{u}^L dz\right) + \frac{\partial}{\partial y}\left(\int_{-h}^{\overline{\zeta}^L} \overline{v}^L dz\right) = 0$	$\frac{\partial\left(\overline{\zeta}^L + h\right)}{\partial t} + \frac{\partial}{\partial x}\int_{-h}^{\overline{\zeta}^L} \overline{u}^L dz + \frac{\partial}{\partial y}\int_{-h}^{\overline{\zeta}^L} \overline{v}^L dz = \frac{\partial \overline{\zeta}^S}{\partial t}$

Terms	Kumar, Voulgaris [21]	Nguyen, Jacobsen [5]
Hydrostatic pressure	$-\frac{1}{\rho}\frac{\partial \overline{p}^H}{\partial x}$	$-\frac{1}{\rho}\frac{\partial \overline{p}^H}{\partial x}$
Conservative wave forcing	$-\frac{\partial J}{\partial x} + \overline{v}^s\left[f + \left(\frac{\partial \overline{v}}{\partial x} - \frac{\partial \overline{u}}{\partial y}\right)\right] - \overline{w}^s\frac{\partial \overline{u}}{\partial z}$	$-\frac{\partial (J+K)}{\partial x} + \overline{v}^s\left[f + \left(\frac{\partial \overline{v}}{\partial x} - \frac{\partial \overline{u}}{\partial y}\right)\right] - \overline{w}^s\frac{\partial \overline{u}}{\partial z}$
Non-conservative wave forcing	F_1^{br}: applied as a body force F_1^{sf}: surface streaming F_1^{bf}: bottom streaming	$\frac{F_{br,1}}{\rho}$: applied as a body force $\frac{F_{fr,1}}{\rho}$: applied as a bottom stress $\frac{F_{mx,1}}{\rho}$: applied as a body force
Turbulence	$-\frac{\partial}{\partial z}\left(\overline{u'w'} - \nu\frac{\partial \overline{u}}{\partial z}\right) + D_1$	$\frac{1}{\rho}\left(\frac{\partial \overline{\tau}_{11}}{\partial x} + \frac{\partial \overline{\tau}_{12}}{\partial y} + \frac{\partial \overline{\tau}_{13}}{\partial z}\right) + \nu\Delta\overline{u}$
Mass conservation	$\nabla.\overline{\mathbf{u}} = 0$	$\nabla.\overline{\mathbf{u}} = \frac{\partial \overline{Z}^S}{\partial t} - \nabla.\overline{\mathbf{u}}^S$