High-resolution compound flood modeling with publicly available datasets
A case-study over Madagascar land-ocean continuum

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Compound Flooding

Pluvial Flooding
• Storm rainfall

Fluvial Flooding
• Runoff

Non-linear Interactions?

Coastal Flooding
• Tide
• Storm Surges
• Waves

Compound Flooding

Coastal + Pluvial + Fluvial
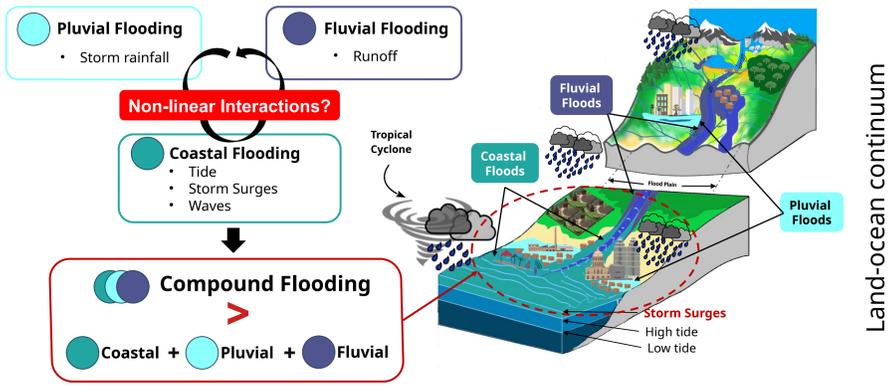
Fig 1: Schematic view of cyclone-induced compound flooding and its various components in in the land-ocean continuum. The impact of compound flooding is larger than the sum of individual impacts.

Cyclonic Exposure in Madagascar

Saffir-Simpson Storm Category

>3 cyclones per year

Madagascar
32 Million Inhabitants

Highly exposed, extremely poor and vulnerable
(188th per capita GDP)

~5000 Km long coastline
Diverse geographic, hydrologic and oceanographic features

No published scientific papers on cyclonic flooding!
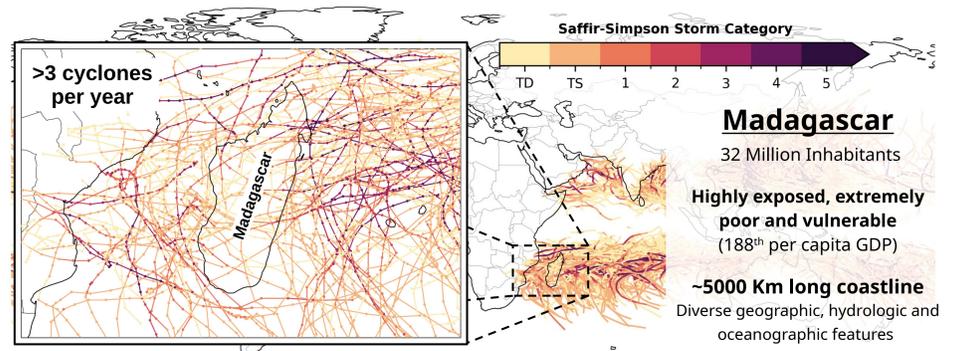
Fig 2: Historical tropical cyclone tracks passing around Madagascar based on IBTrACS dataset, with color showing the category of the cyclonic wind speed.

Cyclone Batsirai (2022)

~600 mm rainfall in 24 hours over Mananjary

185 km/hour wind

Max daily rainfall (mm)
0 10 50 100 200 300 500
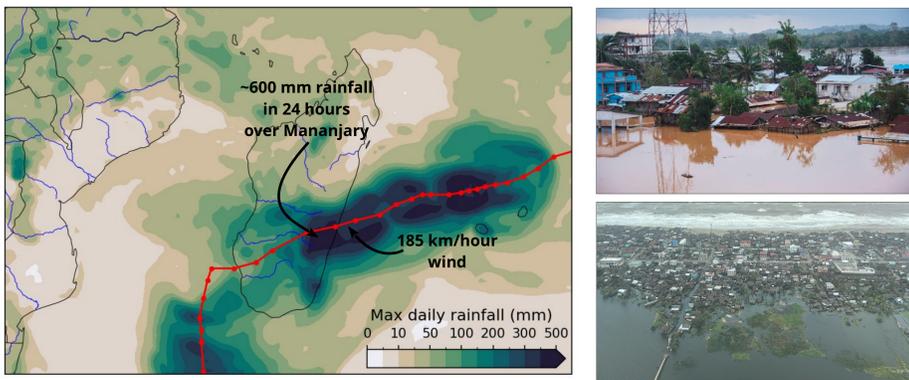
Fig 3: Track of the Cat-4 cyclone Batsirai (red) overlaid on the daily maximum rainfall (Bias corrected ERA5). During landfall, Batsirai had a Cat-3 strength and caused more than 600 mm rainfall in a day. Photos show Continental (top) and coastal (bottom) flooding in Mananjary basin (our focus area).

Coupled Tide-Surge-Wave-Watershed Model

Bathymetry
• FES Chart (sounding, LEGOS)
• Navy Chart (sounding, SHOM)
• Intertidal topography (10m, Khan et al. 2019)
• FABDEM (30m, Hawker et al. 2022)
• River network & depth (Lin et al. 2019)
• GEBCO (400m, GEBCO 2022)

Inland/Hydrology
• Land use/Land cover (Copernicus 30m)
• Soil effective porosity (Zhang et al. 2020)
• Curve number (Jaafar et al. 2019)

Forcing
• Merged ERA5+Analytic Wind and Pressure fields (Khan et al. 2021)
• Bias-corrected ERA5 rainfall (Mazza and Chen 2023)

Calibration/Validation
• Altimetry water level (Hydroweb)
• Altimetry Tide (pyAltide, Coulet et al. 2025)
• Flood frequency (Pekel et al. 2015)
• Flood extent (Copernicus EMS)

FES (water level)
WW3 (wave spectra)

Coupled Tide-surge-wave Ocean model
SCHISM-WWM (Zhang et al. 2016)
→ Coupling →
SFINCS-Subgrid (Van Ormondt et al. 2025)
Reduced-physics hydrology-enabled Inland model

Fig 4: (left) Mesh of large-scale ocean-wave-model covering Madagascar and (right) bathymetry of high-resolution inland hydrology-flood model over Mananjary watershed.

Compound Flooding During Cyclone Batsirai

Disturbance =
Water depth (topography > MSL)
Water level (topography < MSL)

Disturbance (m)
0.05 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50
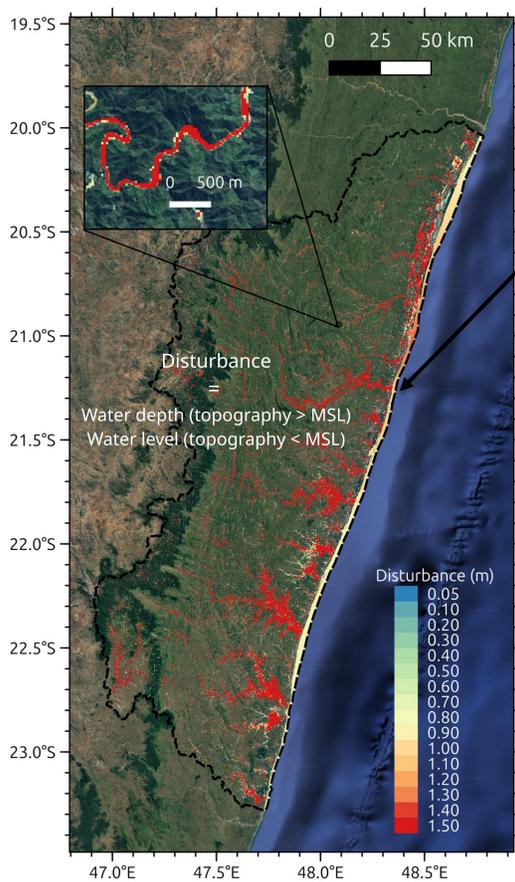
Fig 5: Maximum water extent modeled during Batsirai (2022-01-24 to 2022-02-11), shown as "disturbance". The colorbar is restricted to 1.5 m for clarity. Model shows large-scale flooding across the land-ocean continuum of Madagascar.

$$\text{Hit ratio} = \frac{\#green}{\#(red+green)} = 0.83$$

Model vs Observed
■ Permanent
■ Model Dry/Obs Wet
■ Model Wet/Obs Wet
■ Maximum Flooded
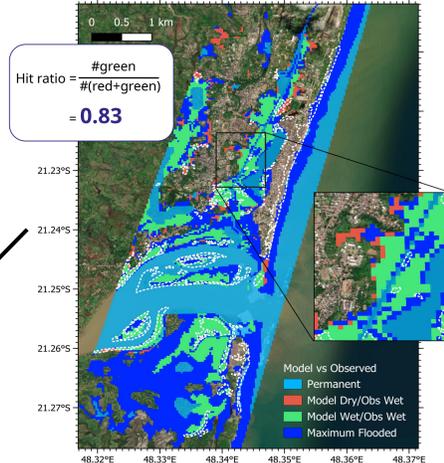
Fig 6: One-to-one validation with satellite observation of flood extent from Copernicus EMS over Mananjary city derived from WorldView Satellite on 2022-02-07 shows a good model performance (Hit ratio = 0.83). Maximum flood extent (blue) captures extended flooding during the full period of cyclone Batsirai.

$$\text{Compound Ratio} = \frac{\text{Ocean only}}{\text{Ocean only} + \text{Continent Only}}$$

(b) Ambohitsara
(c) Mananjary
(d) Faraoni River

Compound Ratio
1 Ocean only
0.5 Equal contribution
0 Continent only
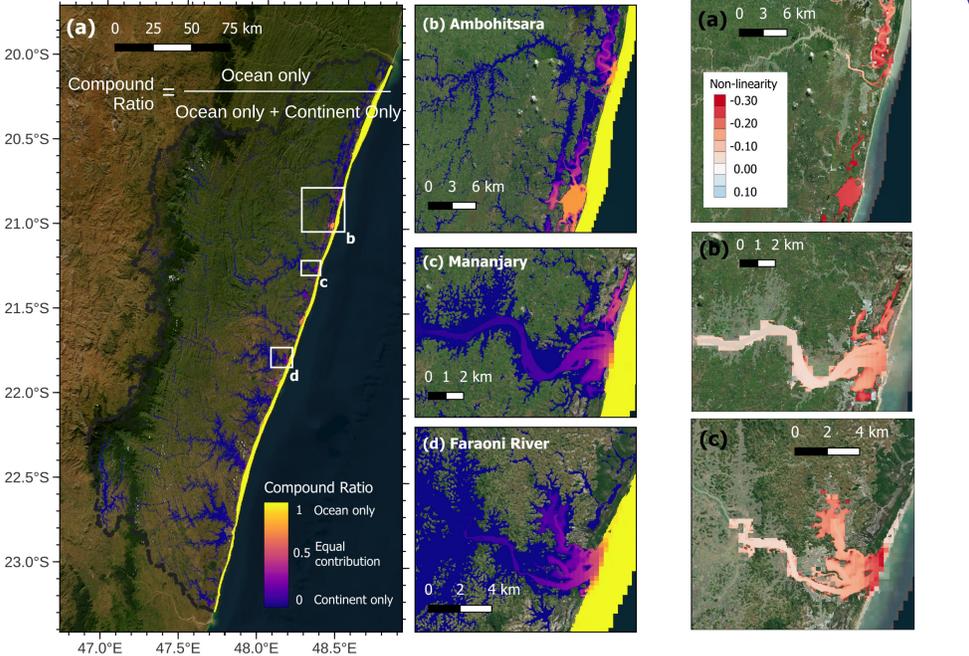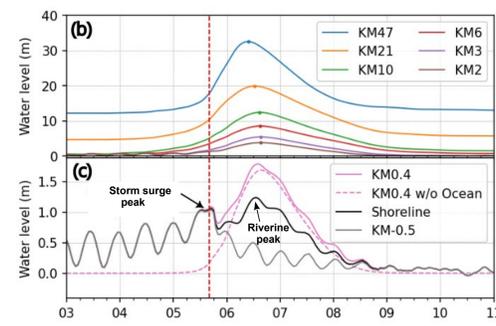
Fig 7: Compound ratio in color shows the relative contribution (linear) of ocean and inland forcing across the continuum (a). Significant compounding is found in the estuaries (b-d).

Non-linearity
-0.30 -0.20 -0.10 0.00 0.10

Fig 8: For Batsirai, non-linear interaction reduces the water level up to 30% relative to a linear sum.

Storm surge peak
Riverine peak
KM0.4
KM0.4 w/o Ocean
Shoreline
KM0.5
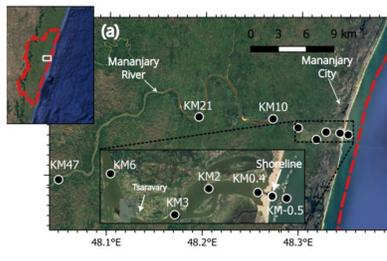
Fig 9: (a) Location of virtual stations and corresponding total water level (b-c). Landfall is shown by the red line. In addition to the modulation, two flood peak at the Shoreline corresponds to storm surge and riverine flood, separated by 18h – an example of temporal compounding of in a flooding event.

Conclusions and Perspectives

✔ High-resolution coupled compound flood modeling is feasible using careful processing and application of spaceborne public dataset.
✔ Compound flooding is the key consideration needed to study cyclone induced flooding in Madagascar.
✔ Non-linear interaction and spatio-temporal compounding can not be ignored in the land-ocean continuum.
✔ Opens up the opportunity to forecast compound flooding at high-resolution with physics-based modeling in both data-poor and data-rich regions.

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Full Paper Here!

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