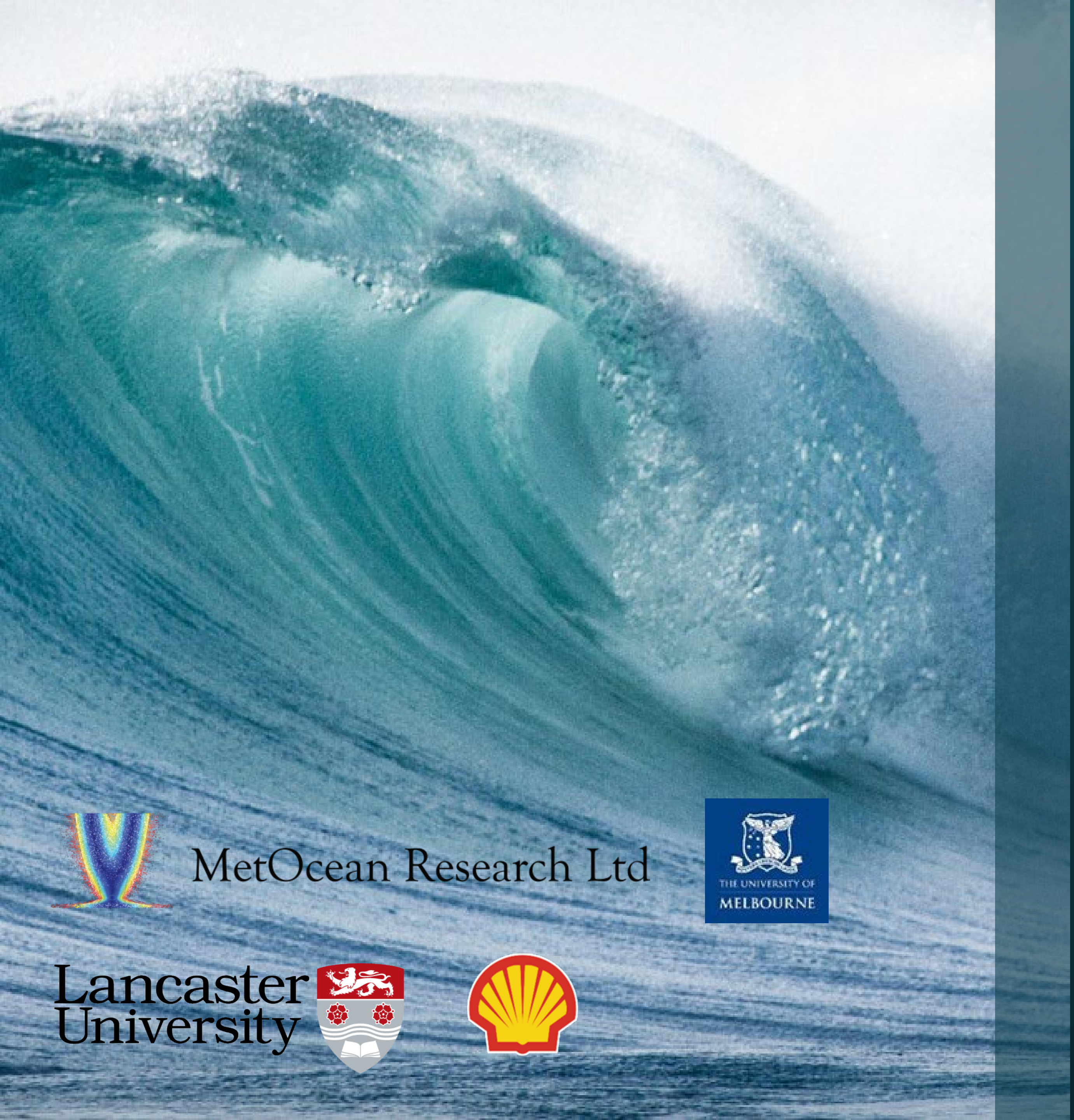


MetOcean Research Ltd

THE UNIVERSITY OF MELBOURNE

Lancaster University

Wind and wave design criteria subject to climate change effects

Kevin Ewans, Phil Jonathan

UWA TIDE Seminar
Perth 9-Jun-23

Acknowledgements

Albert Meucci

THE UNIVERSITY OF MELBOURNE

Tom Durrant

OCEANUM
OCEAN NUMERICAL

Motivation

- Media coverage of extreme events
- Global wave climate studies – e.g., Meucci et al. (2020)
- Implications for coastal & offshore industry – existing and future infrastructure
- Specify metocean design criteria to future-proof assets
- How accurately can we estimate future “design criteria”?
- Can we determine a change in 100-year return-period criteria?
- How do address these questions?

Articles

1. Hs100 East of Madagascar & South of Australia (Ewans & Jonathan, 2023)

   https://www.sciencedirect.com/science/article/pii/S002980182300224X

   https://arxiv.org/pdf/2212.11049.pdf

2. Tasman Sea study
   https://ygraigarw.github.io/EwnJnt23ClmChnTsm.pdf

Non-stationary EVA

Non-stationary EVA

- Generalised Pareto (GP) regression to model observations $\{x_{t_i}, t_i\}_{i=1}^{n}$ of H_s^{sp} at times $t_i \in (0, P)$
- Assume $X_t | X_t > \psi_t$ follows GP distribution

$$\begin{aligned} F_{\mathrm{GP}}(x | X_t > \psi_t, \psi_t, \sigma_t, \xi_t) &= 1 - \left[1 + \frac{\xi_t}{\sigma_t}(1 - \psi_t)\right]^{-1/\xi_t} & \xi_t \neq 0 \\ &= 1 - \exp\big(-(x - \mu_t / \sigma_t)\big) & \xi_t = 0 \end{aligned}$$

where ξ_t is shape, σ_t is scale, and ψ_t is threshold

Assume any parameter, η_t, varies linearly with time

$$\eta_t = \eta(t) = \eta^S + \frac{t}{P}(\eta^E - \eta^S), \text{ for } t \in (0, P)$$

Non-stationary EVA

- GP models over four choices of EV threshold NEP1-NEP4 set using non-exceedance probability (NEP), τ
  - NEP1 corresponds to $\tau = 0.5$
  - NEP4 corresponds to NEP leaving 30 threshold exceedances
  - NEP2 and NEP3 τ values are equally spaced (log scale) between NEP1 and NEP4
- Threshold ψ_t estimated using quantile regression
- Annual rate of occurrence, ρ_t, of threshold exceedances in time for given τ, is determined with Poisson regression
- ψ_t and ρ_t also assumed to vary linearly in time

Non-stationary EVA

- For GP threshold exceedances, and Poisson rate of threshold exceedance, the annual maxima are GEV-distributed
- Hence, T-year return value Q_t at year t (for $T = 100$ years) is estimated as the $p = 1 - 1/T$ quantile:

$$Q_t = \begin{cases} \dfrac{\sigma_t}{\xi_t}\left[\left(-\dfrac{\log p}{\rho_t}\right)^{-\xi_t} - 1\right] + \mu_t & \xi_t \neq 0 \\ \mu_t - \sigma_t \log[-(1/\rho_t)\log p] & \xi_t = 0 \end{cases}$$

- Parameter estimation using Bayesian inference (MCMC)
- Compare Q_1 and Q_{86} 100-year H_s for Start and End of the 86-year period.

Uncertainties in estimated Hs100

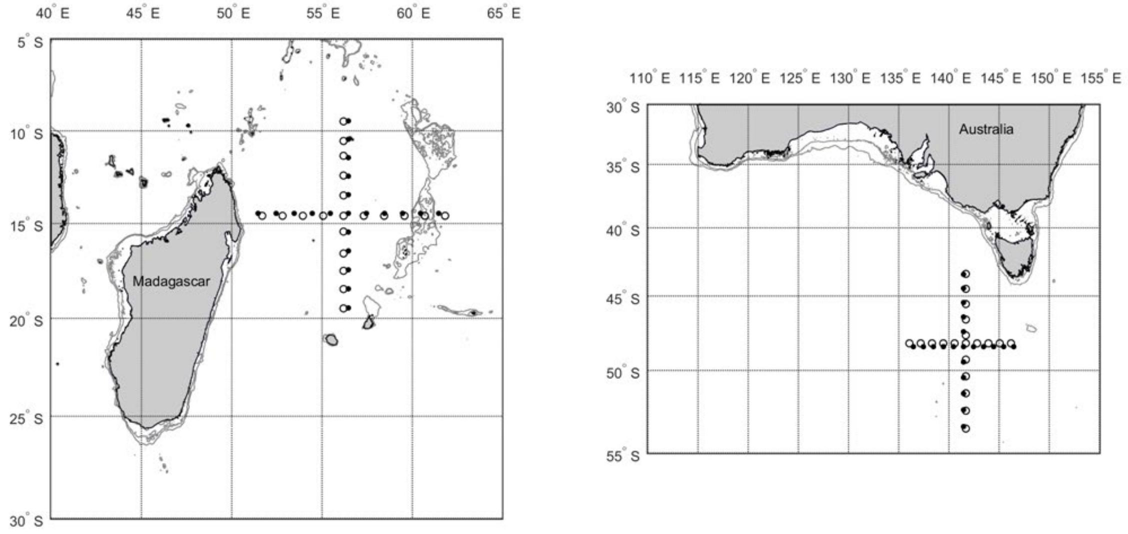
East of Madagascar & South of Australia

Data sources

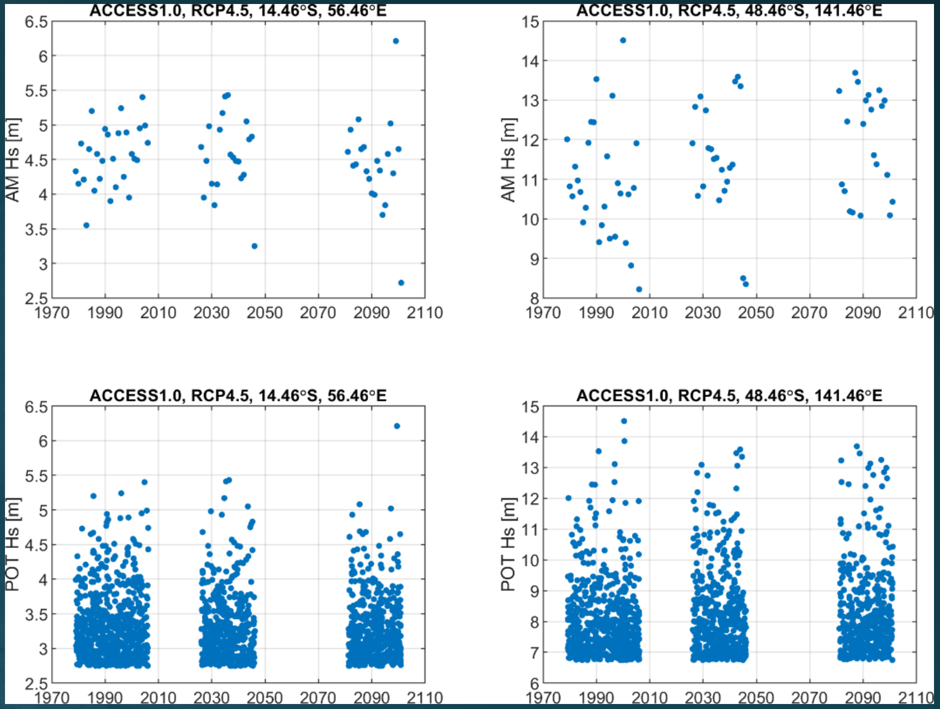
- CMIP 5:
  - WAVEWATCH-III model output: Hs at 6-hourly intervals
    - Wind forcing from seven GCMs: ACCESS1.0, BCC-CSM1.1, GFDL-CM3, HadGEM2-ES, INMCM4, MIROC5, and MRI-CGCM3. (Meucci et al., 2020)
    - Historical 27-year period (1979-2005)
    - Mid-21st century 20-year period (2026-2045)
    - End-21st century 20-year period (2081-2100)
    - RCP4.5 (intermediate emission scenario)
    - RCP8.5 (high emission scenario)
- CMIP 6:
  - WAVEWATCH-III model output: Hs at 3-hourly intervals
    - FIO-ESM v2.0 model data (Song et al., 2020)
    - 700-year pre-industrial period (pi-Control: nominal years 301-1000)
    - 165-year historical period (years 1850-2014)
    - 86-year future scenarios (SSP126, SSP245 and SSP585), all for years 2015-2100)

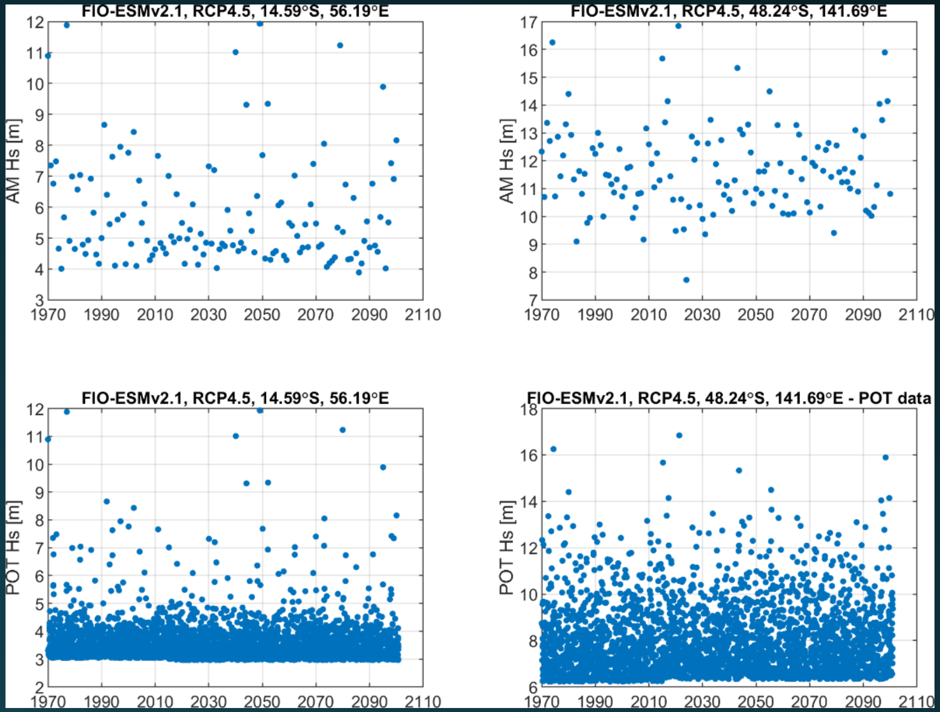
Data sources - locations

- Two regions EoM, SoA
- Hs data selected for meridional & zonal transects
- SoA depths > 1000 m
- EoM depths > 1000m
    - some zonal locations in more shallow water of Nazareth Bank



Data sources - annual maxima & POT

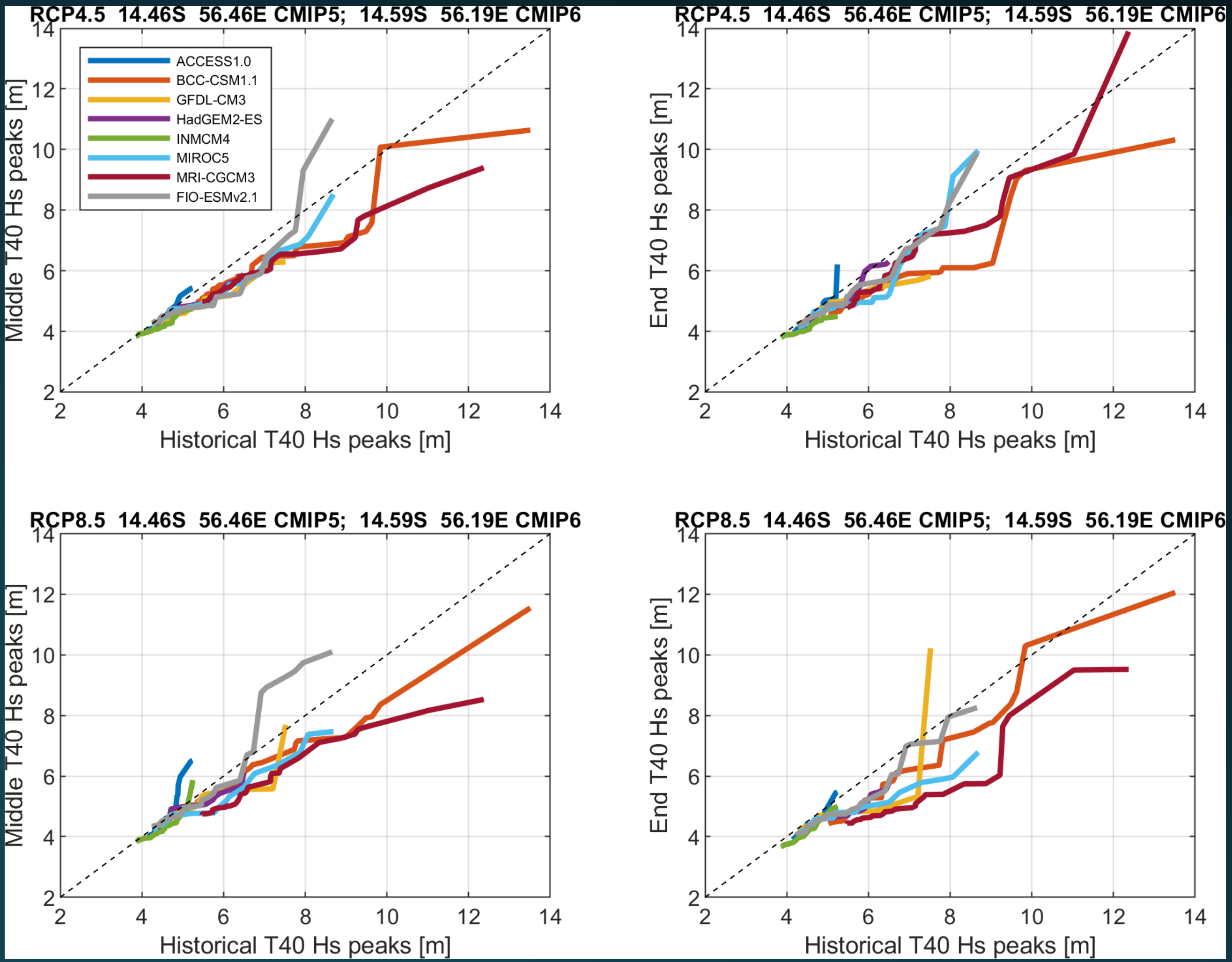




Exploratory data analysis

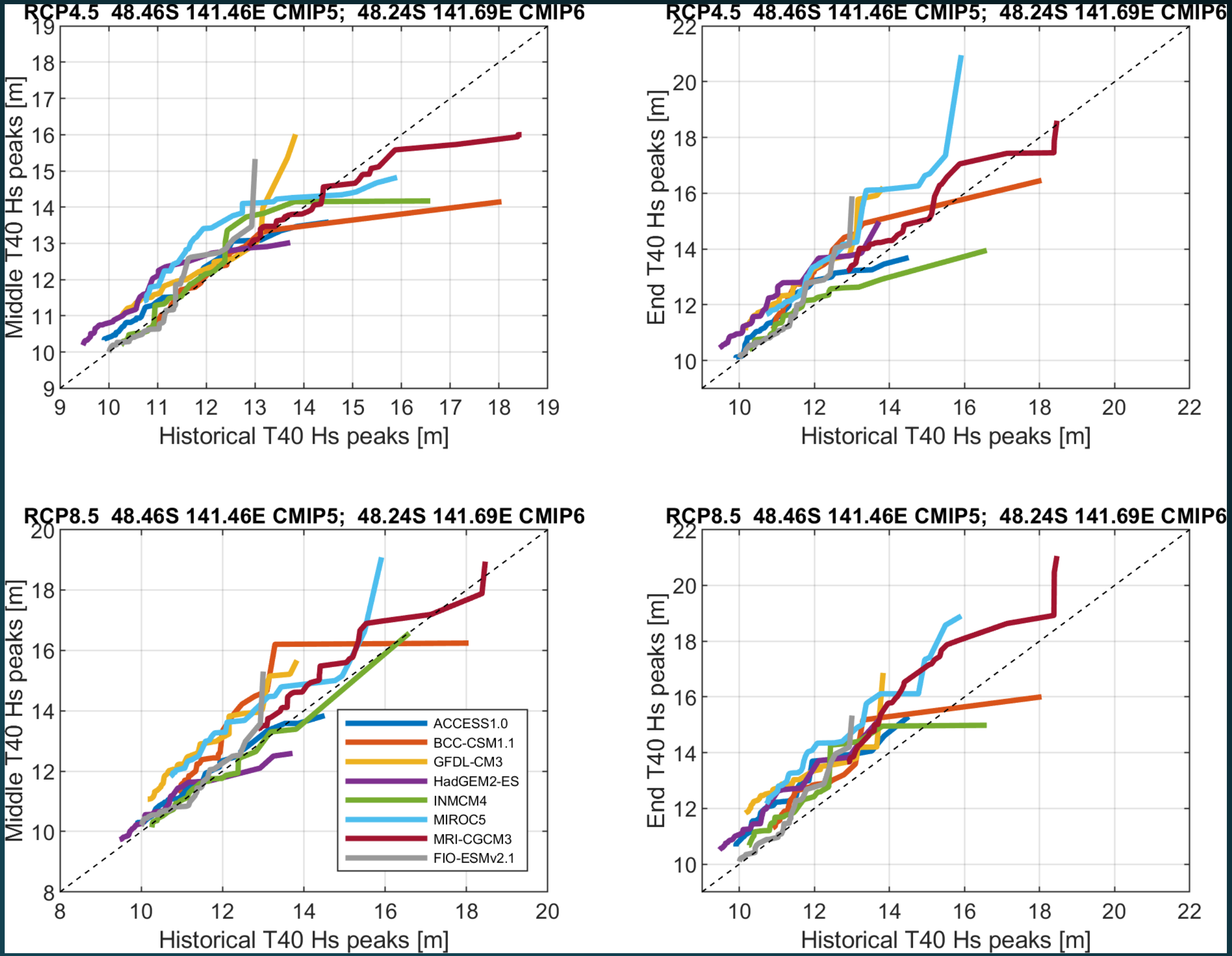
Empirical tails – EoM Centre

- 40 largest POT Hs – Middle & End periods with Historical
- Decrease in POT Hs re. Historical
- Considerable variability between GCMs
    - GCMs differences at least as large as
        - effect of RCP choice, or
        - choice of pair of time periods to compare.



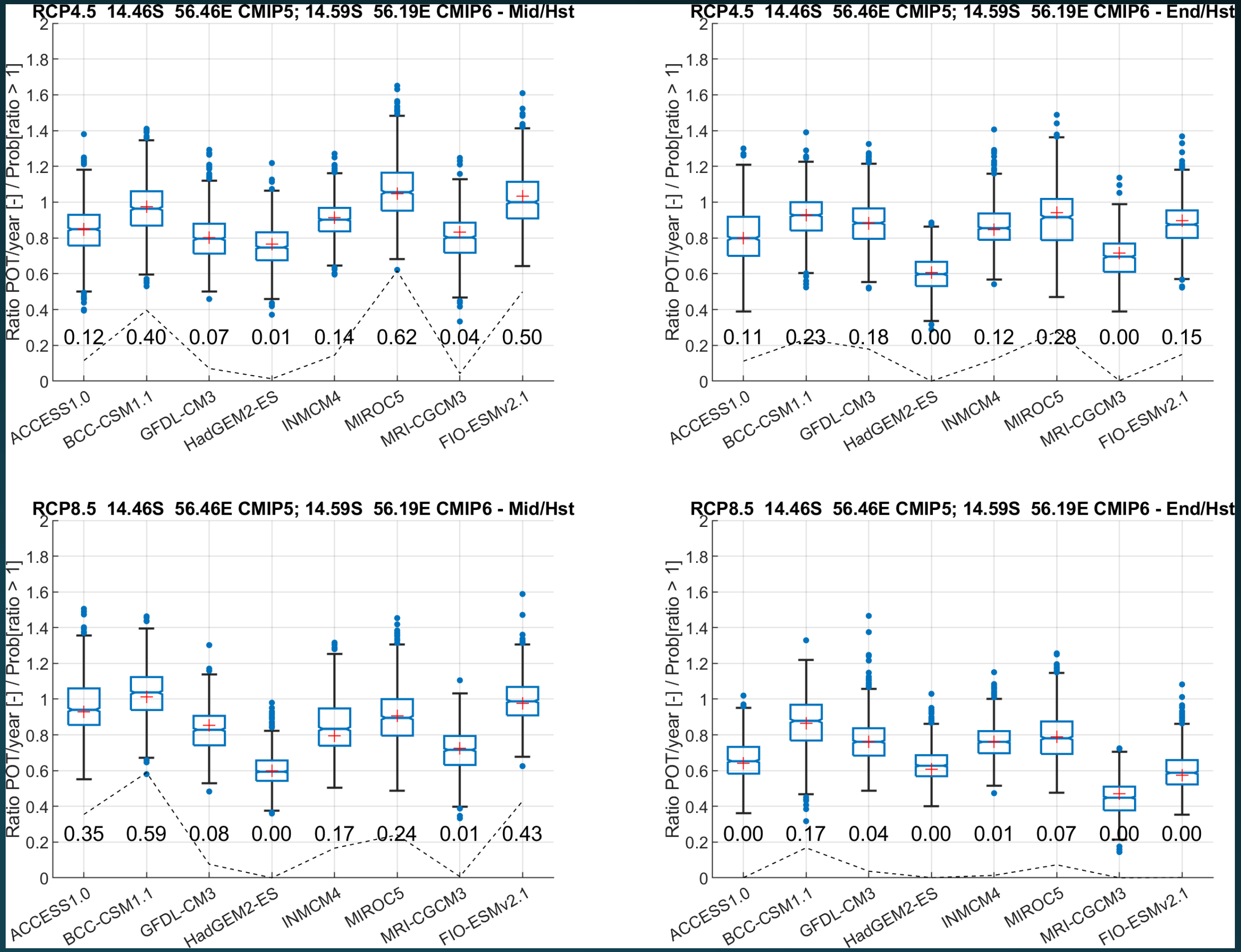
Empirical tails – SoA Centre

- Similar to EoM, but…
- Increase in POT Hs re. Historical



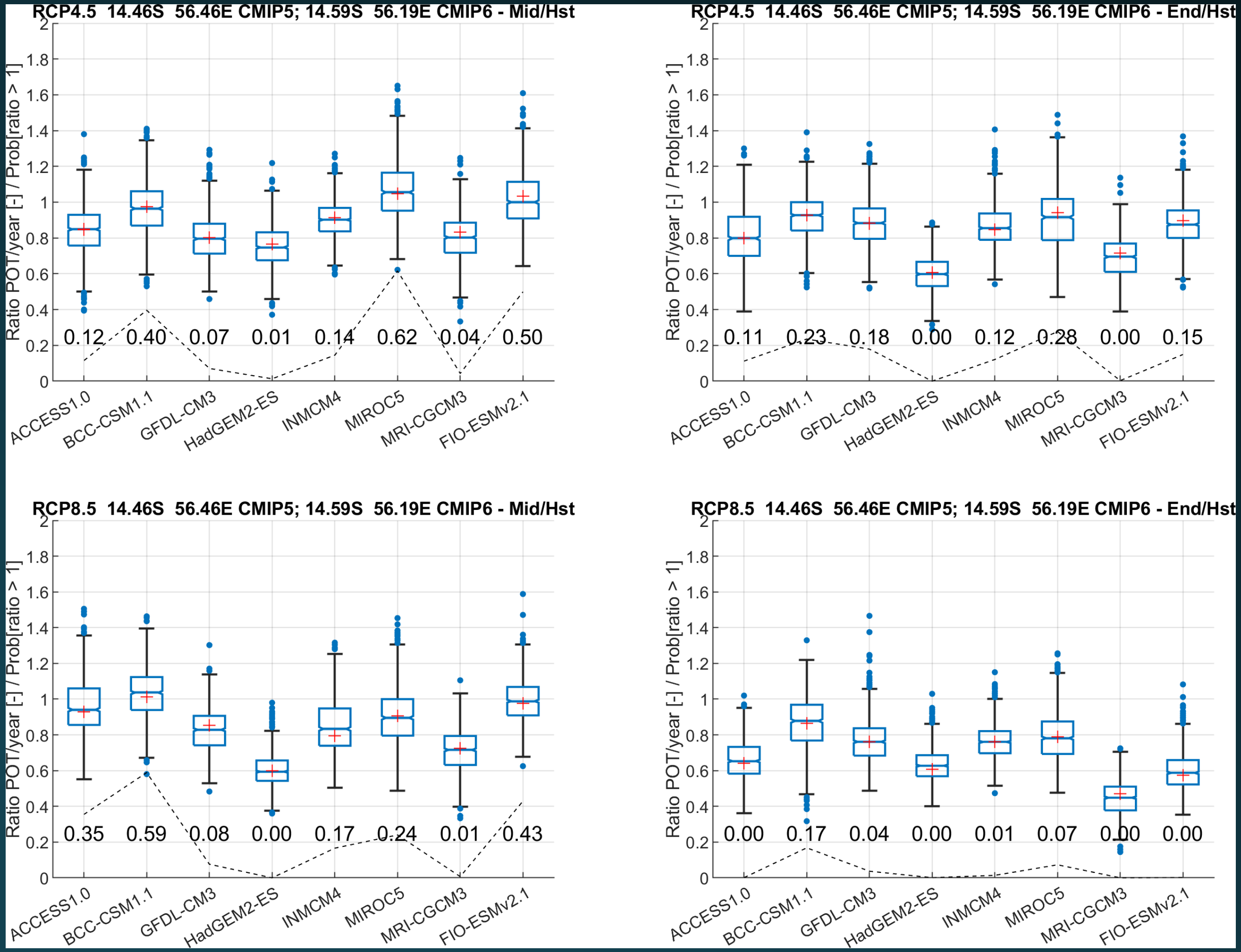
Empirical rate of threshold exceedance – EoM Centre

- Box-whisker gives ratio of annual rates of exceedance of 80%ile for each GCM to historical period
  - mean red cross
  - median, 25%, 75% blue lines
  - smallest and largest values not exceeding 1.25 × inter-quartile range from the median black lines
  - outliers as blue dots
  - probability ratio exceeds unity as dashed line
- Uncertainties estimated with bootstrapping



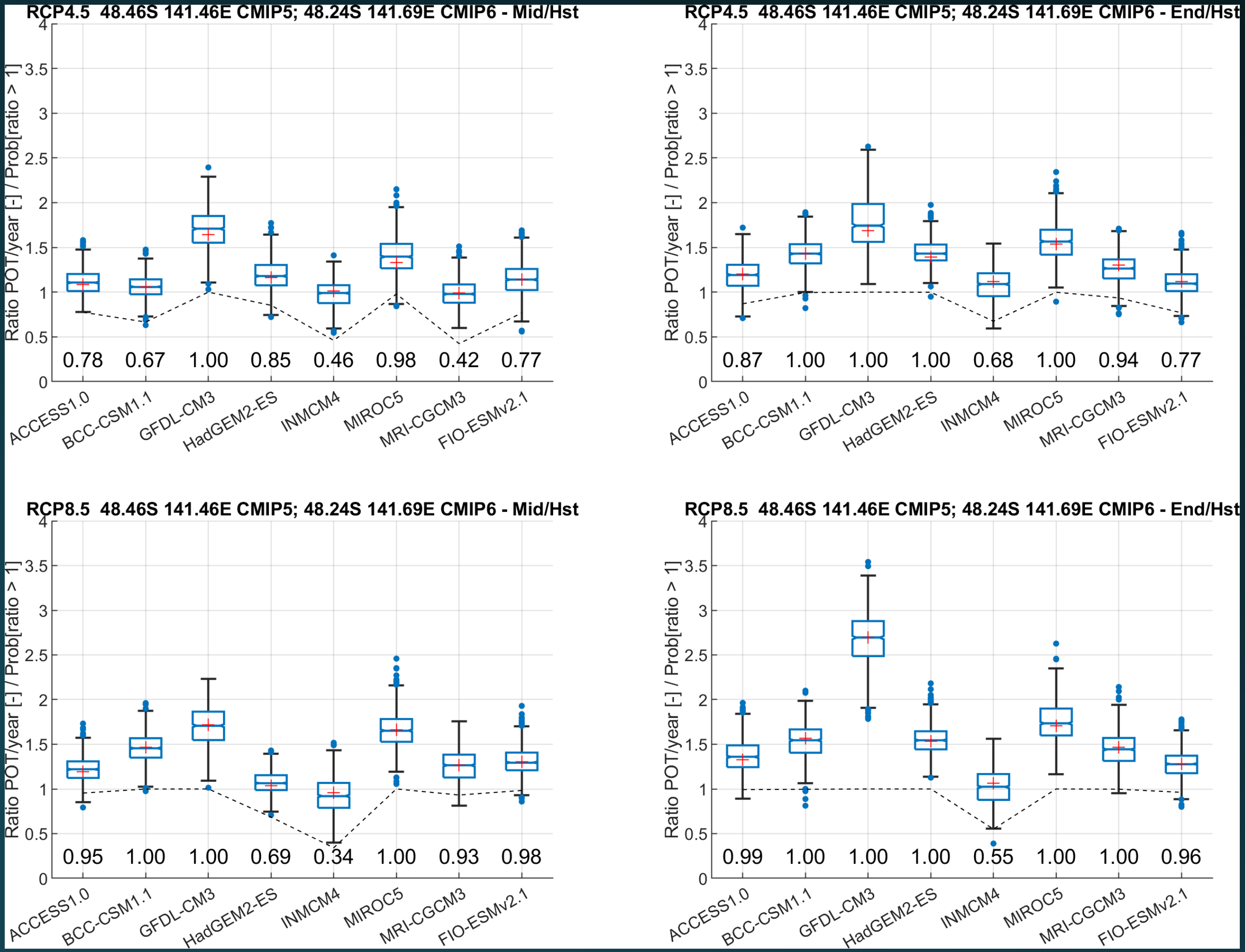
Empirical rate of threshold exceedance – EoM Centre

- mean and median ratio of rates is around unity or below
- Considerable uncertainty
  - within GCM
  - between GCMs
- Clearest trend for End:Historical comparison RCP8.5
  - Probabilities of ratio > 1 are near zero



Empirical rate of threshold exceedance – SoA Centre

- mean and median ratio of rates is around unity or larger
- Uncertainty similar to EoM
- Clearest trend for End:Historical comparison RCP8.5
  - Probabilities of ratio > 1 are near one
  - Some exceptions



Observations

- EoM storms could be less intense and less frequent in the future
- SoA storms could be more intense and more frequent in the future

piControl – inherent steady-state variability

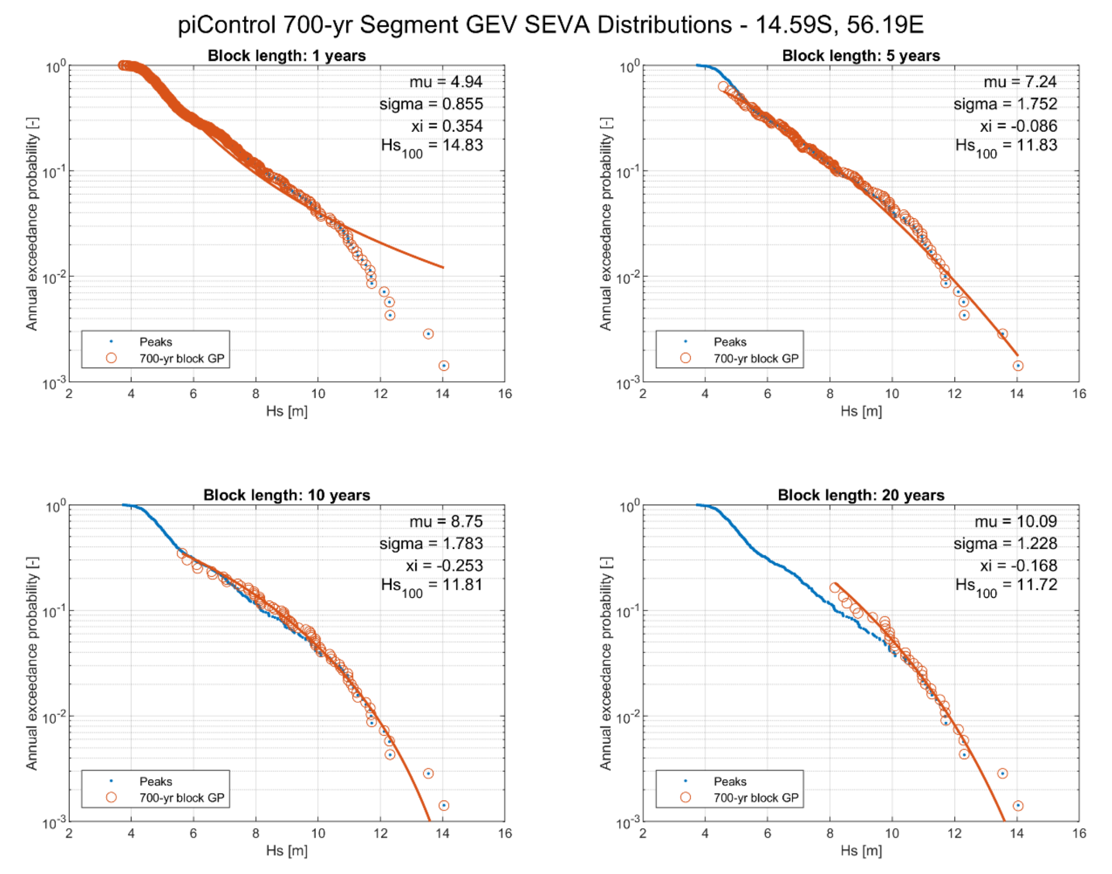
Natural climate variability

- Inter-annual and longer-term atmospheric oscillations give non-stationary temporal effects in metocean databases spanning several decades
- Climate might still be considered stationary in the long term
- Pre-industrial climate can be expected to be stationary
- piControl data set expected to represent a stationary climate
  - data set used to asses the natural variability of the wave climate at a location
    - assess the inherent variability in Hs100 when estimated from a typical (segment) length of data, using
      1. stationary extremal analysis (SEVA) model
      2. non-stationary extremal analysis (NSEVA) model
    - Examine serial variation of Hs100 over 700 years
      - EV threshold effect
      - Zonal and meridional variation

piControl – stationary EVA

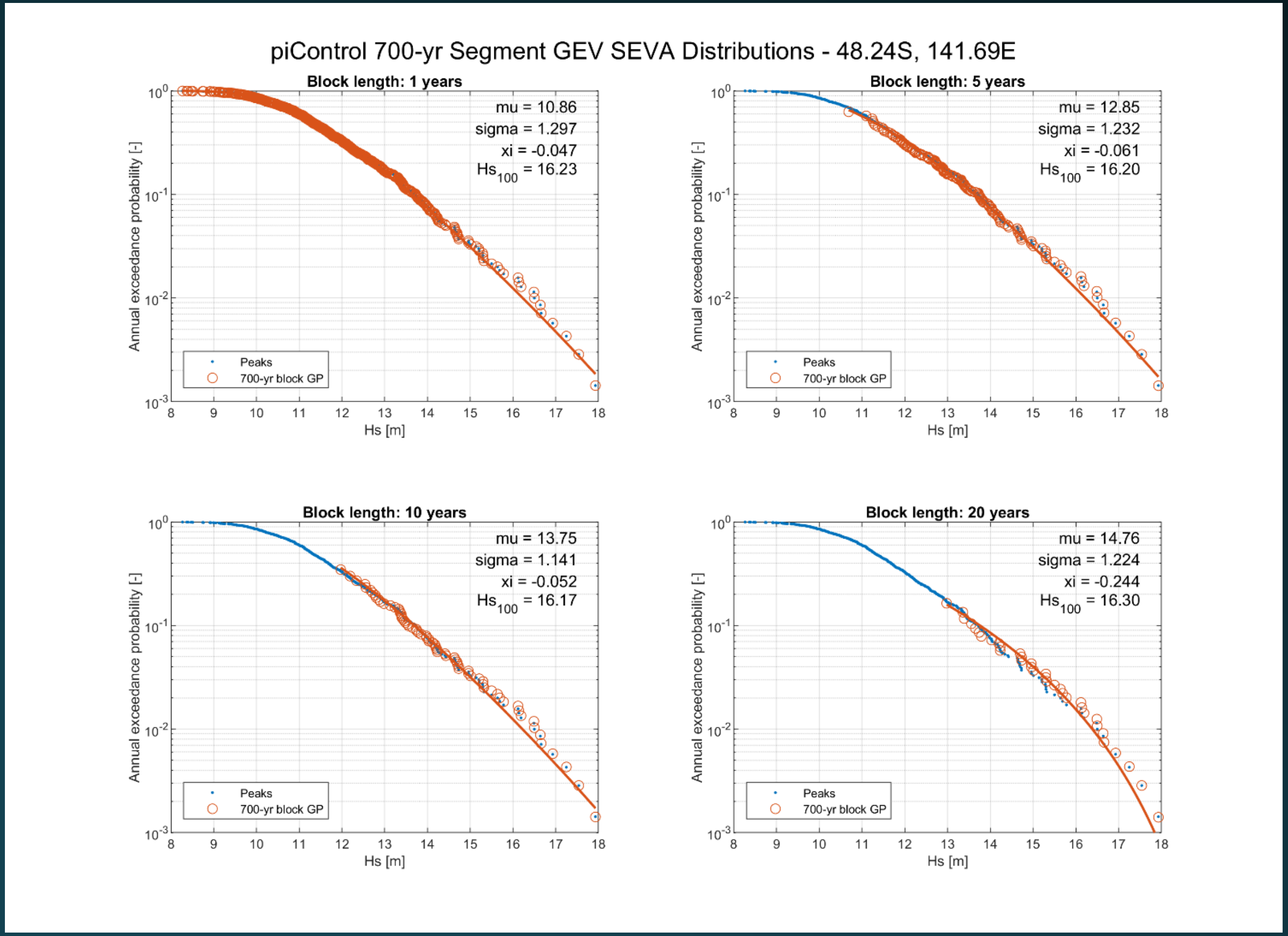
700-year segment length GEV tails – EoM Centre

- Block lengths 1, 5, 10, 20 years
- 5-year block lengths needed for stable estimates
- NEP3 threshold for GP analysis
- Mixed population – TCs + Extra-tropical



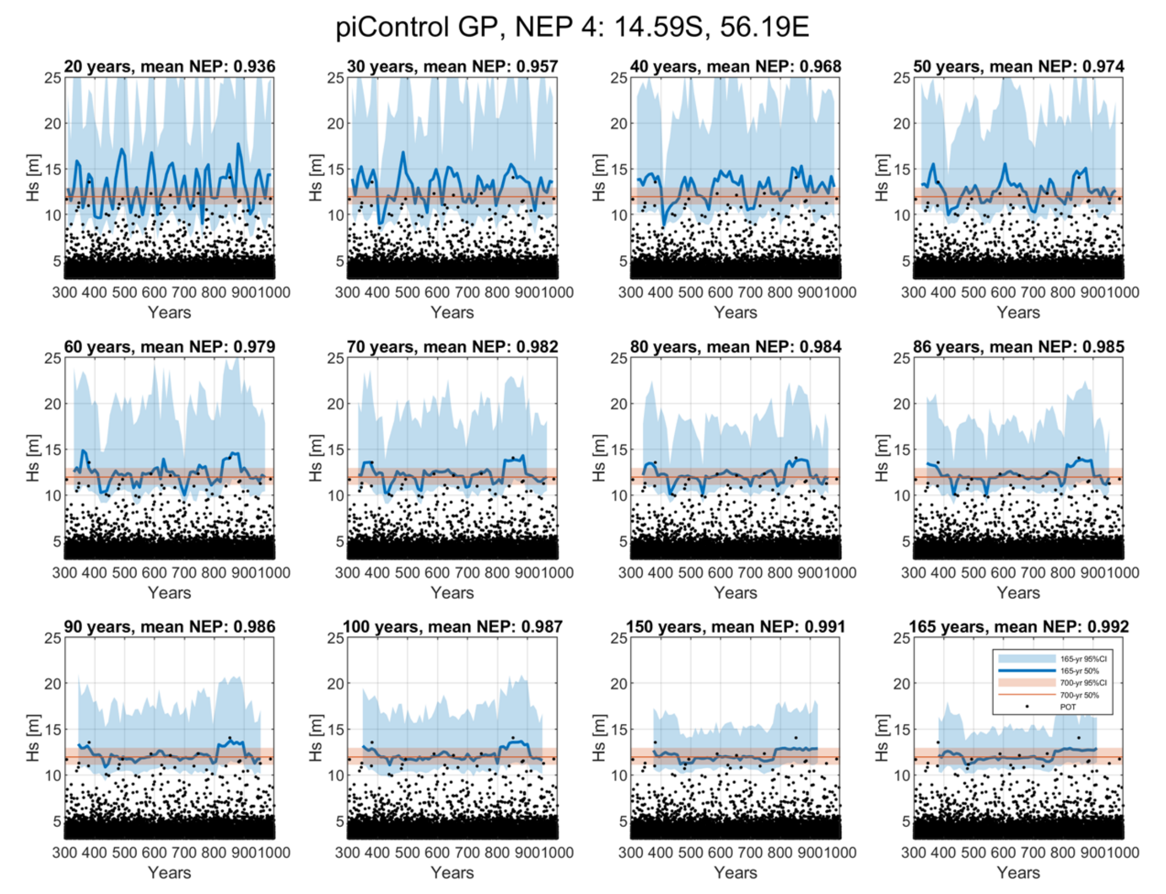
700-year segment length GEV tails – SoA Centre

- Stable estimates for 1-year block lengths



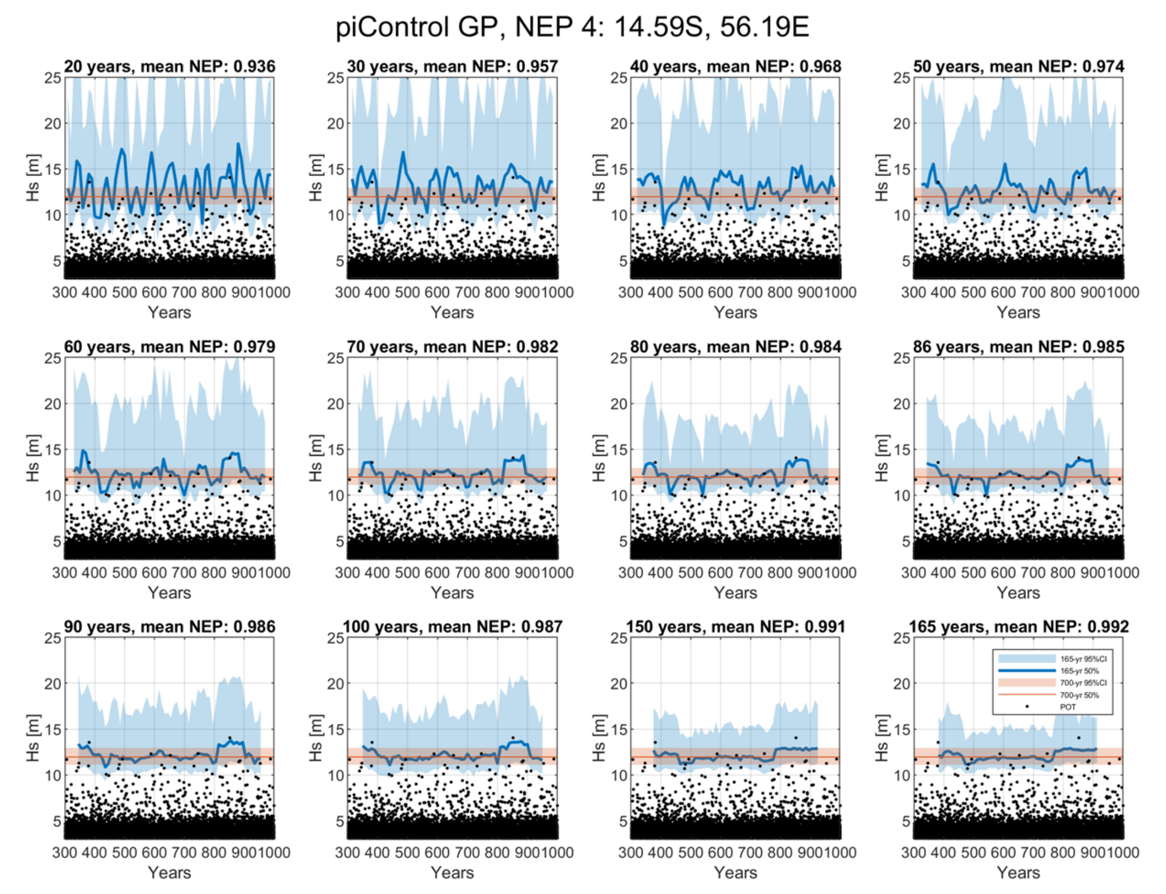
Evolution of POT Hs100 – EoM Centre

- Black points: POT Hs
- Blue line: Segment median Hs100
- Blue band: Segment Hs 95% credible interval
- Orange line & band: 700-year (truth?)
- Segment lengths:
  - Typically available
  - Scenarios & Experiments



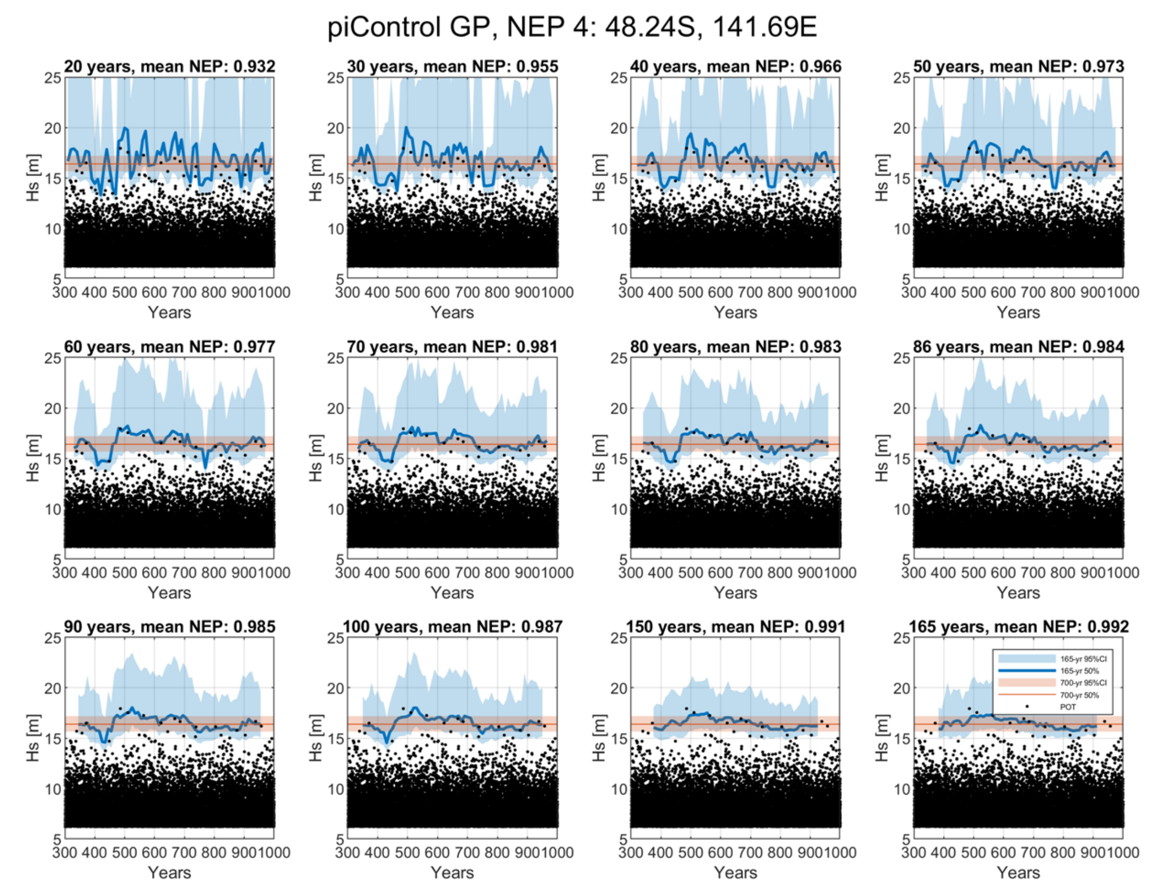
Evolution of POT Hs100 – EoM Centre

- Variability med Hs100
    - largest for short segment lengths
        - 5 m changes (50 yrs)
    - Decreases with segment length
    - Generally unbiased
- Hs100 95% CI
    - long-tailed
    - positive skew
        - often > 25 m (median 12 m)



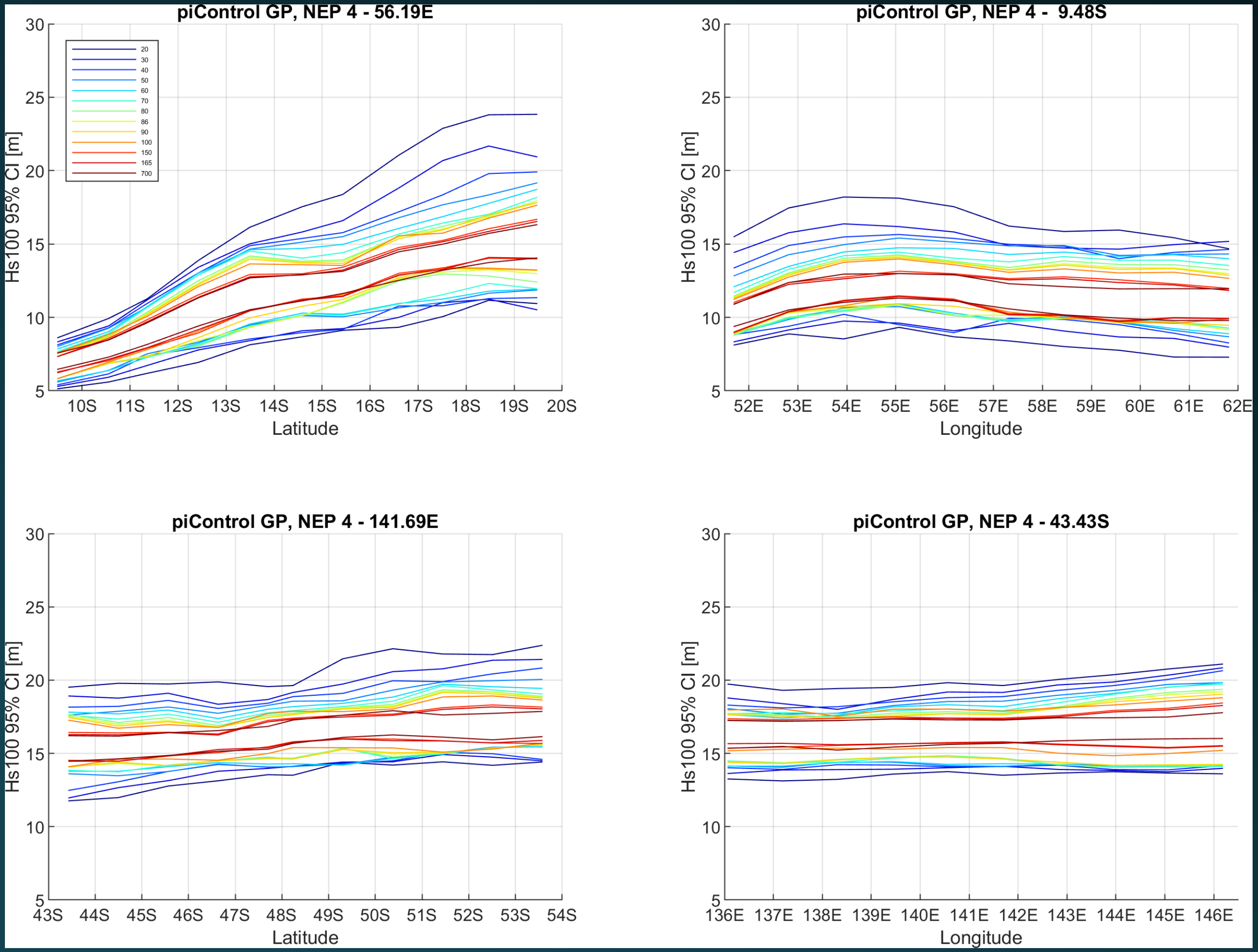
Evolution of POT Hs100 – SoA Centre

- Similar results to EoM



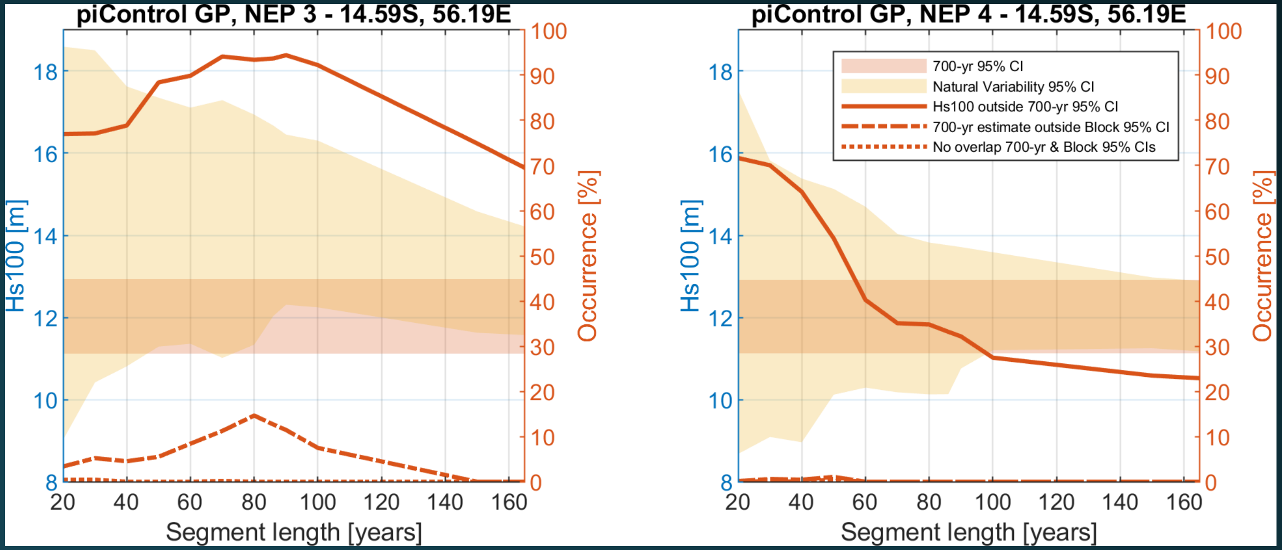
Meridional and zonal variation of CI for median Hs100 95%

- Gives indicative range of Hs100 for a random segment
- Increasing Hs100 latitude (EoM)
- No strong zonal trends



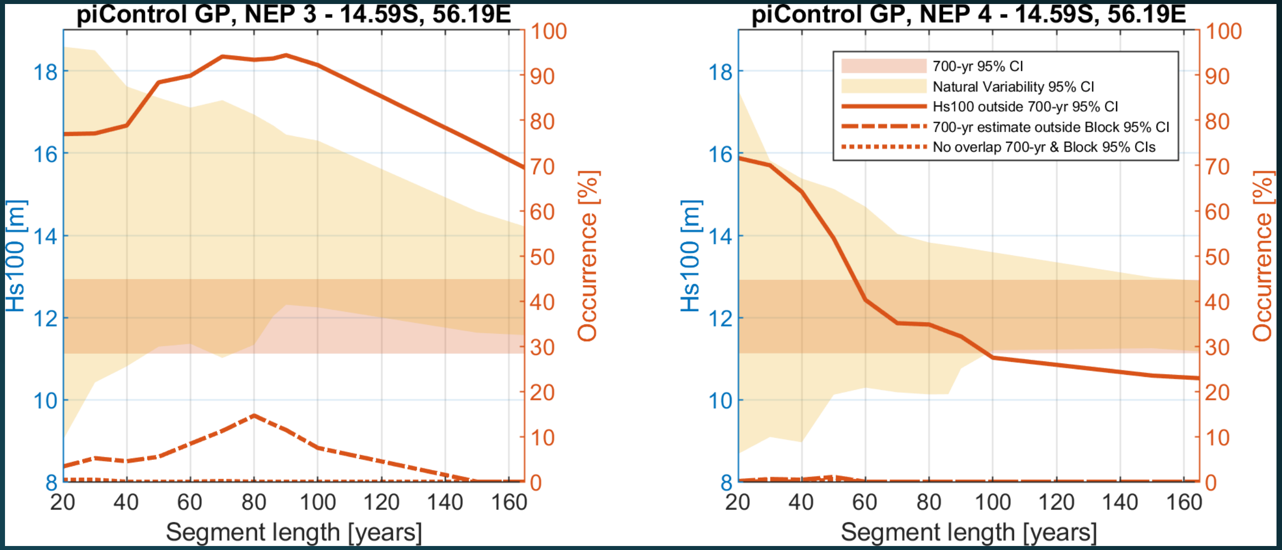
Meridional and zonal variation of CI for median Hs100 95% – EoM Centre

- Left axis:
  - Dark orange band 95% CI – full 700 years
  - Light orange band 95% range median Hs100
- Right axis gives percent:
  - med Hs100 outside 95% CI 700 years (solid)
  - med Hs100 of 700 years outside the 95% CI of a given segment length (dashed)
  - no overlap between 95% CIs 700 years and from a given segment length (dotted)



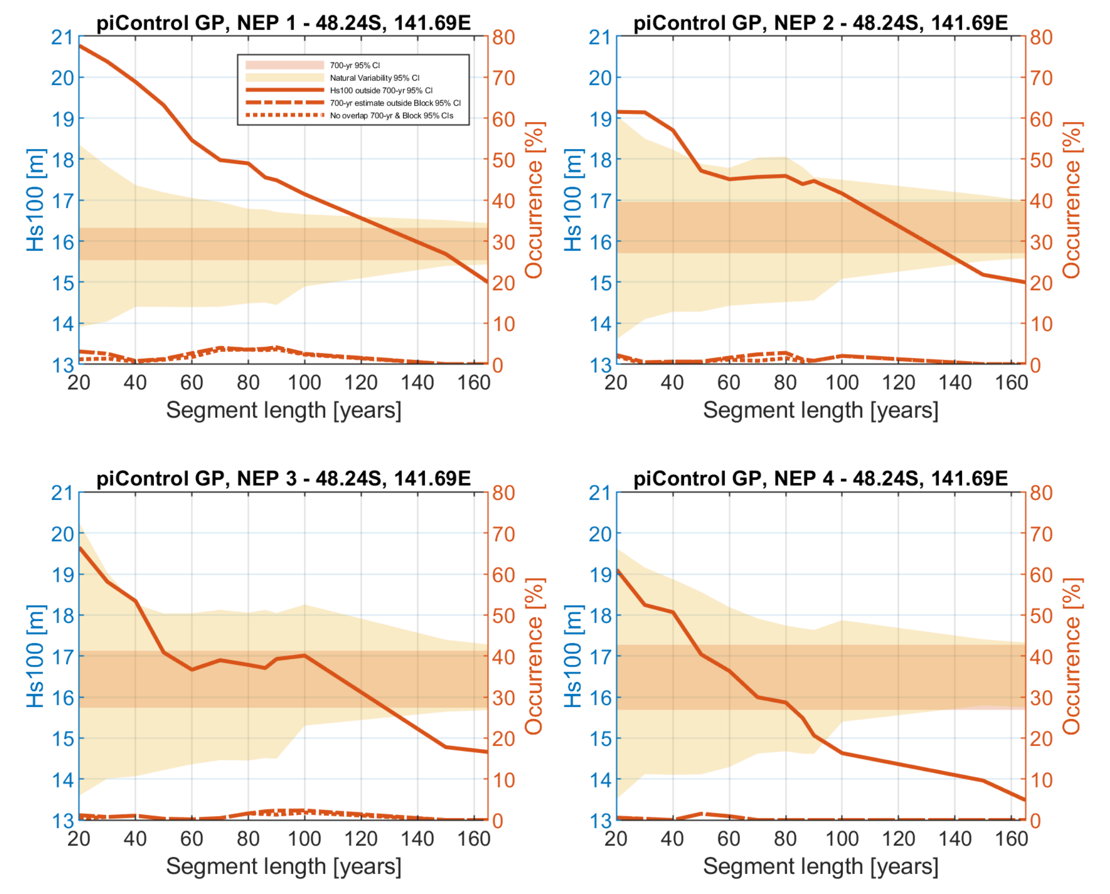
Meridional and zonal variation of CI for median Hs100 95% – EoM Centre

- Width of 95% CI
  - Reduces with increasing segment length
  - very large (around 5 m) - 20-year segments
  - Around 1 m for 165-year segments
- 70% chance Hs100 lies outside 95% CI of 700-year – short segment lengths
- 30% chance Hs100 lies outside 95% CI of 700-year – 165 year segment length
- ≈5% med Hs100 of 700-year lies outside 95% CI of particular segment length



Meridional and zonal variation of CI for median Hs100 95% – SoA Centre

- Similar to EoM



Conclusions - piControl – stationary EVA

- 95% credible interval reduces with increasing segment lengths
    - 70% chance outside 95% credible interval of full sample, for small segment lengths
        - very large (around 5 m) for 20-year segments
    - 30% for a segment length of 165 years
- Indicative of inherent uncertainties of present design criteria – stationary climate

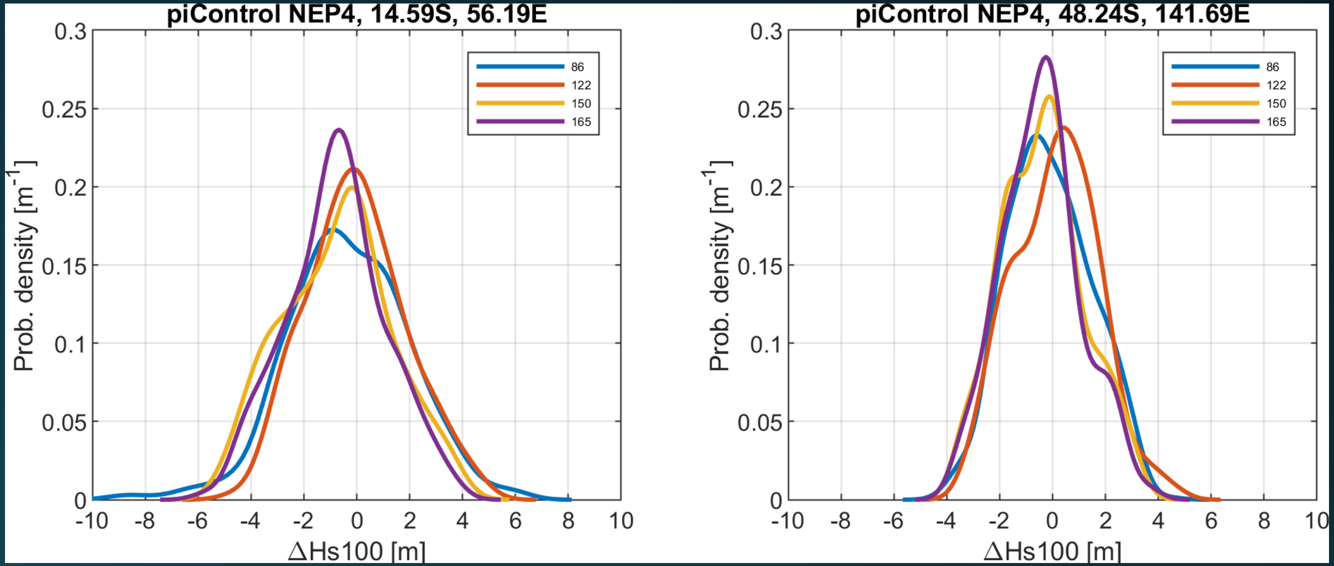
piControl – non-stationary EVA

Inherent variability – non-stationarity

- Gives quantification of Hs100 change for a specific time interval of data, due entirely to inherent steady-state climate variation
- Compare inherent variability in Hs100 with those from different forcing scenarios

Density of median difference (per segment)

- Segment lengths - CMIP5, CMIP6 scenarios
- Centre locations
- Densities relatively unaffected by segment length
- Approximately symmetric about zero
- ±3 m not surprising



Conclusions - piControl – non-stationary EVA

- Gives direct quantification of change in return value estimated from samples of specific time interval of data, due entirely to inherent steady-state climate variation.
- Variations in Hs100 of ± 3m not surprising

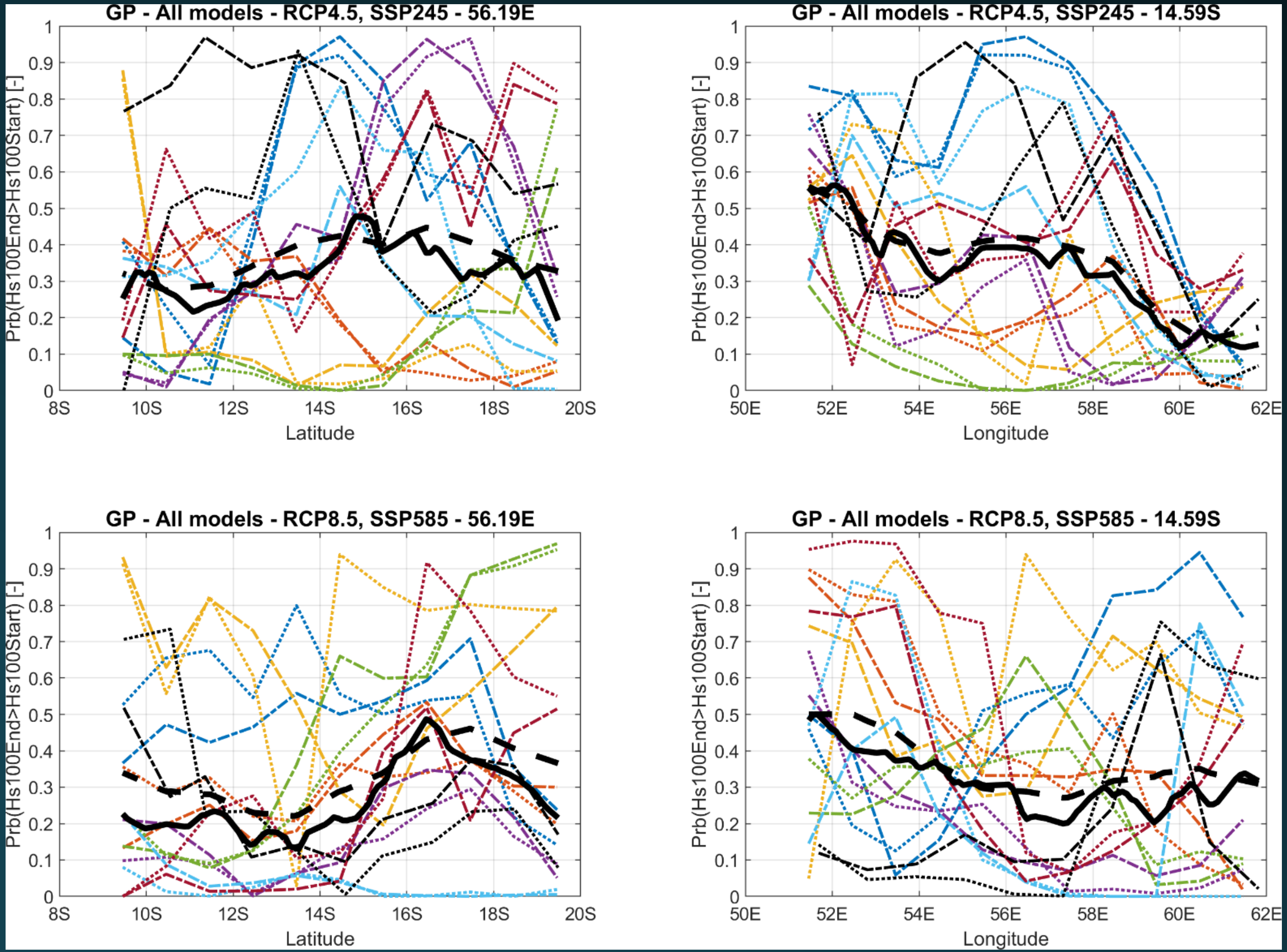
Scenarios – non-stationary EVA

Assessment of temporal trends

- Calculate joint posterior distribution of model parameters
  - Each combination of GCM and climate scenario
- Calculate corresponding distribution of other quantities: e.g., POT Hs100 at any time (say $t = 0$, $t = P$)
  - Probability that the return value will increase over some period of time.
  - Expected size of the change in the return value over time
- "Best overall estimates" - average summary statistics over GCMs

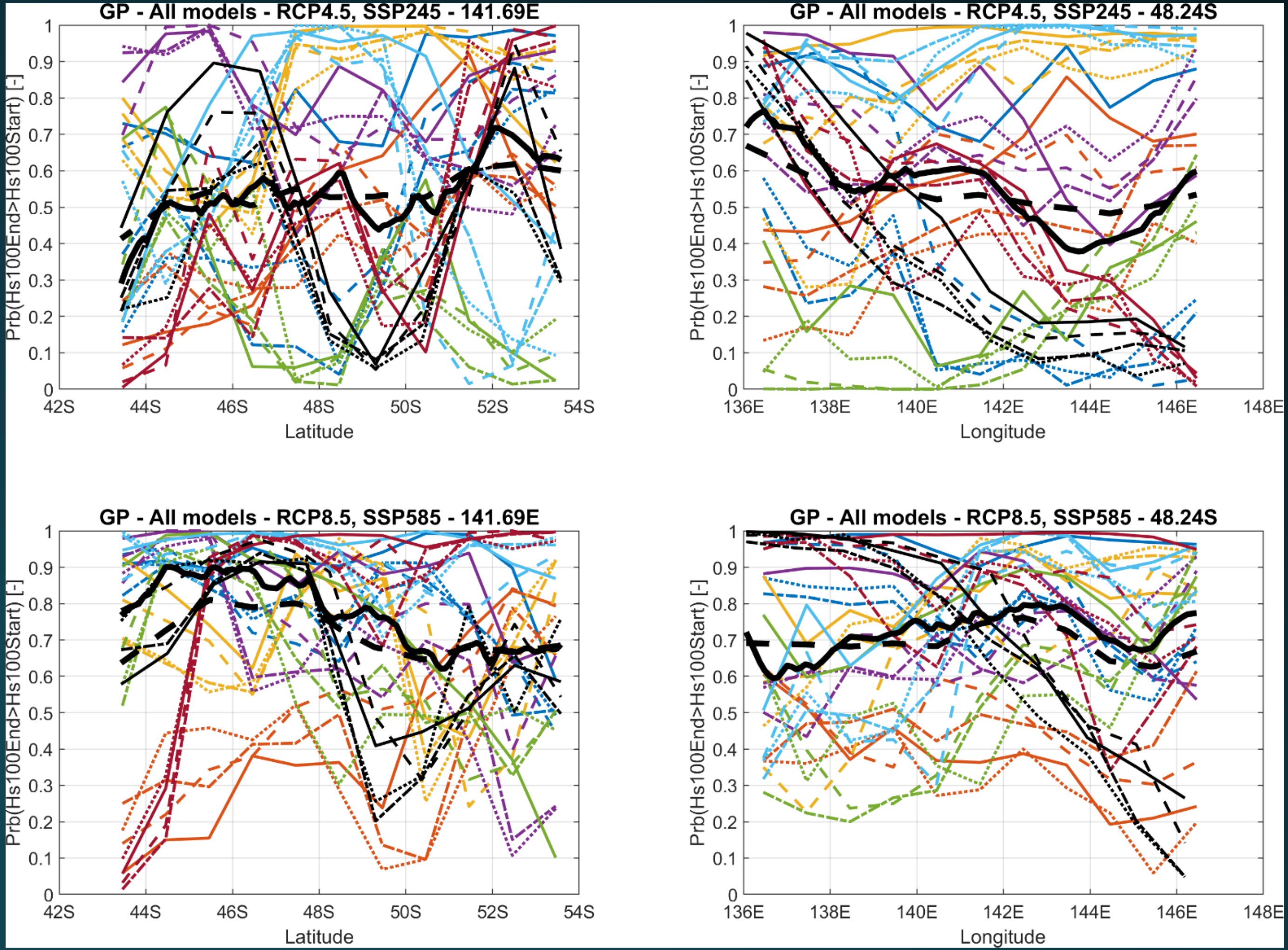
Probability POT Hs100 End > Hs100 Start - all GCMs - EoM

- Thin coloured lines: each GCM
  - Line style: NEP3, NEP4
- Thick black lines:
  - Solid: mean
  - Dashed: median
- Huge variability between models
- Large variability across transects
- Mean, median more consistent
  - Generally less than 0.5
  - Suggest decrease in Hs100.



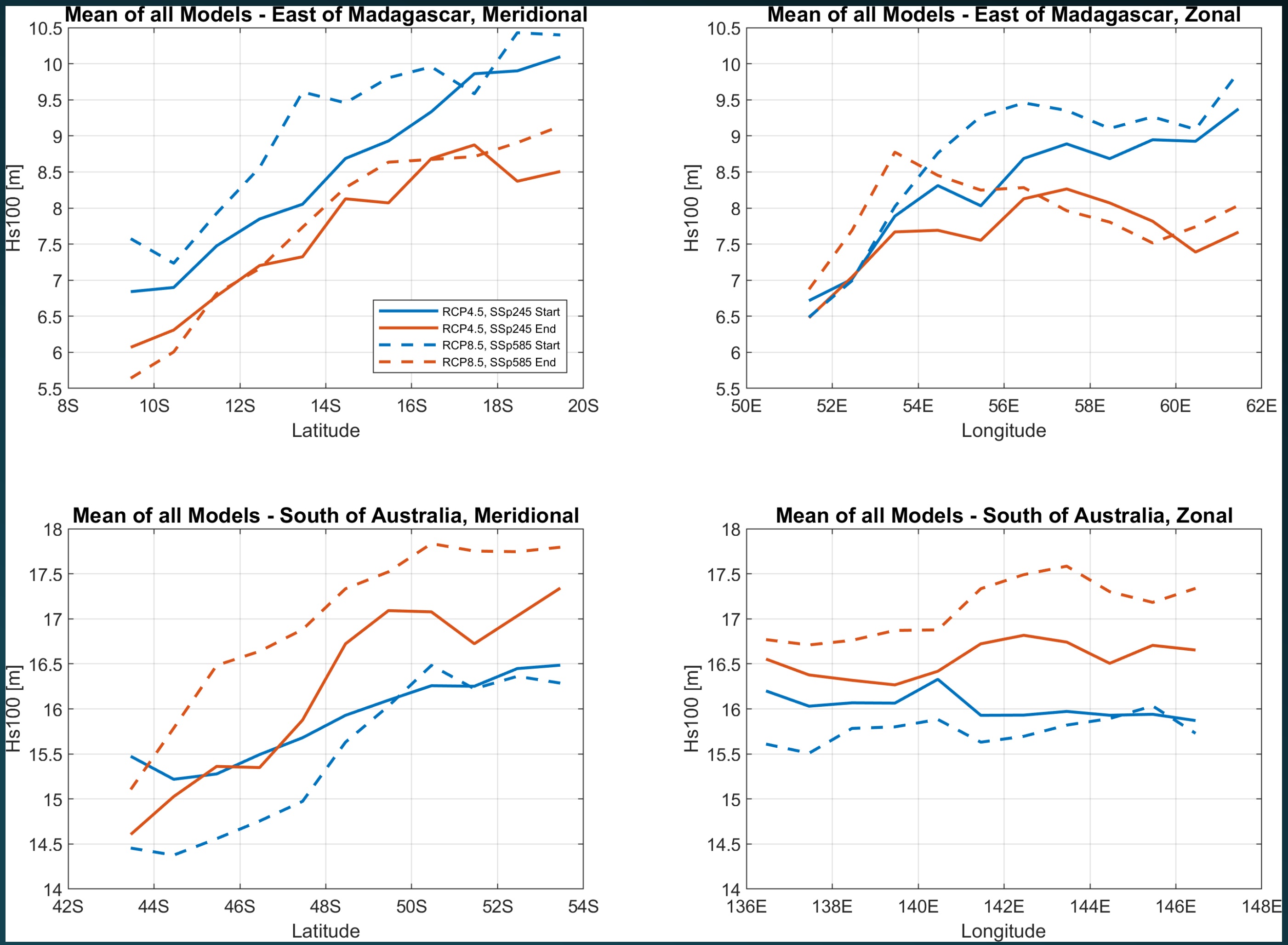
Probability POT Hs100 End > Hs100 Start - all GCMs - SoA

- Huge variability between models
- Large variability across transects
- Mean, median more consistent
  - Generally greater than 0.5
  - Suggest increase in Hs100.



Mean Hs100 - Start (1979) & End (2100)

- Hs100 increases with increasing latitude
- Little zonal variation
- EoM Hs100 decreases
  - Both RCPs ≈ 0.5 m
- SoA Hs100 increases
  - RCP4.5: ≈ 0.5 m
  - RCP8.5: ≈ 1.0 m
- Individual estimates
  - Large variability
  - Little evidence for change



Conclusions

- Considerable variability in predictions of changes in storm severity at any of a number of locations
- Specific inferences may be considerably biased compared to more general inferences
- Non-stationary EVA with linear trends in parameters appropriate
  - Data unlikely to provide evidence in favour of more complex models.

Conclusions

- EoM: Relatively large thresholds (POT, or block lengths for BM) are necessary
    - Avoid bias in return values caused by mixed population of extratropical storm and occasional tropical cyclones
- NSEVA GP modelling of POT and GEV modelling of BM generally agree very well
    - thresholds and block lengths must be set sensibly
- Estimated Hs100 and ΔHs100 less sensitive to threshold (or block length) than to choice of GCM, or arbitrary choice of location within a geographic neighbourhood