Is the 100-year Return Value for Significant Wave Height Increasing in the Tasman Sea?

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Motivation

- Climate change is frequently reported to be the cause of an apparent increase in the occurrence and intensity of extreme events
- Recent studies have found that increases can be expected in sea state extremes for some regions of the world's oceans later this century.
- Can the same be expected in the Tasman Sea?
- FIO-ESM v2.0 CMIP6 Earth System Model data include time-series of significant wave height for several Shared Socioeconomic Pathways (SSP) as well as 165-year historical and 700-year pre-industrial realisations.
- Allows estimation of 100-year return values of significant wave height and uncertainties at the end of the 21st century
- Follows approach Ewans & Jonathan (2023)

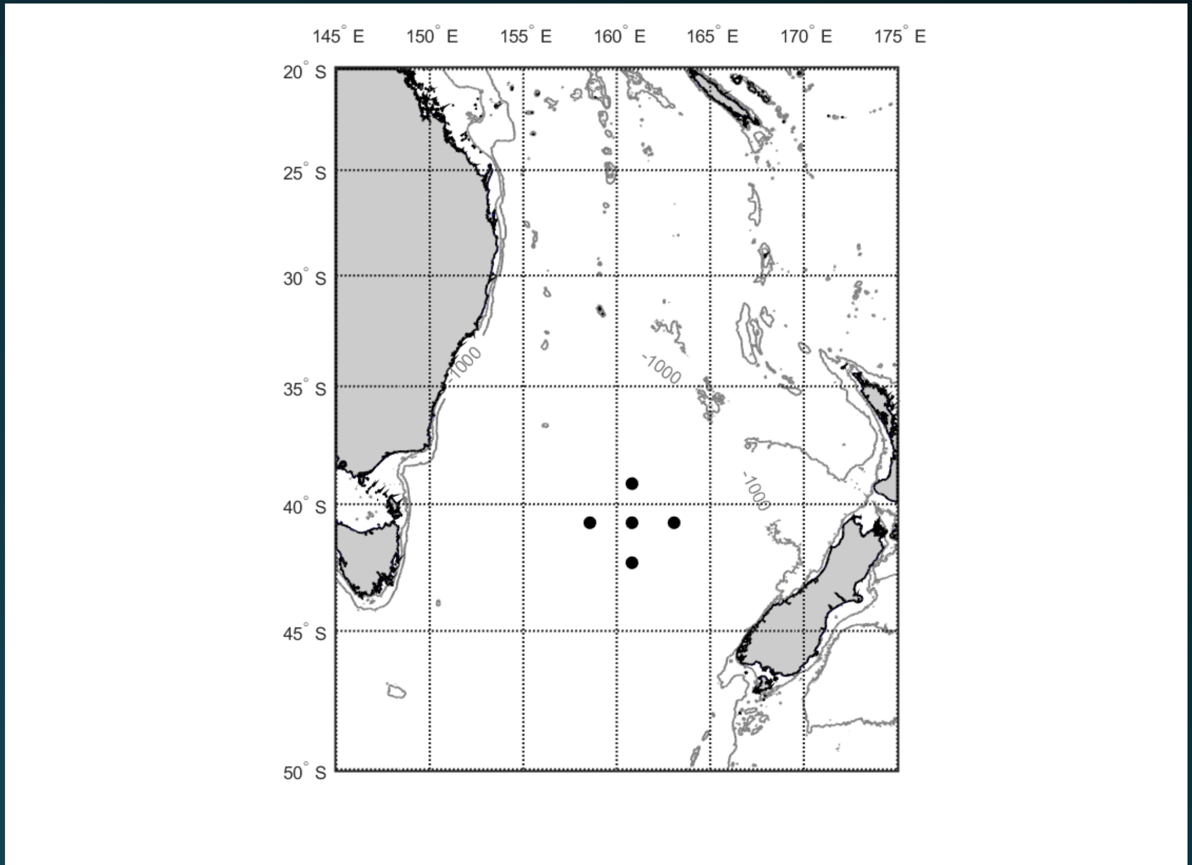
  https://www.sciencedirect.com/science/article/pii/S002980182300224X

Data

- FIO-ESM v2.0 model data (Song et al., 2020)
  - 3-hourly H_s values
  - 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, for radiative forcing of 2.5, 4.5 and 8.5 Wm^{-1} in 2100), all for years 2015-2100)
- Select storm peak H_s values: H_s^{sp}
  - Storm events are identified with peaks over threshold
    - 20 – 25 peaks per annum

Data

- Five locations
- Star configuration
  - Centre (C)
  - North (N)
  - South (S)
  - East (E)
  - West (W)

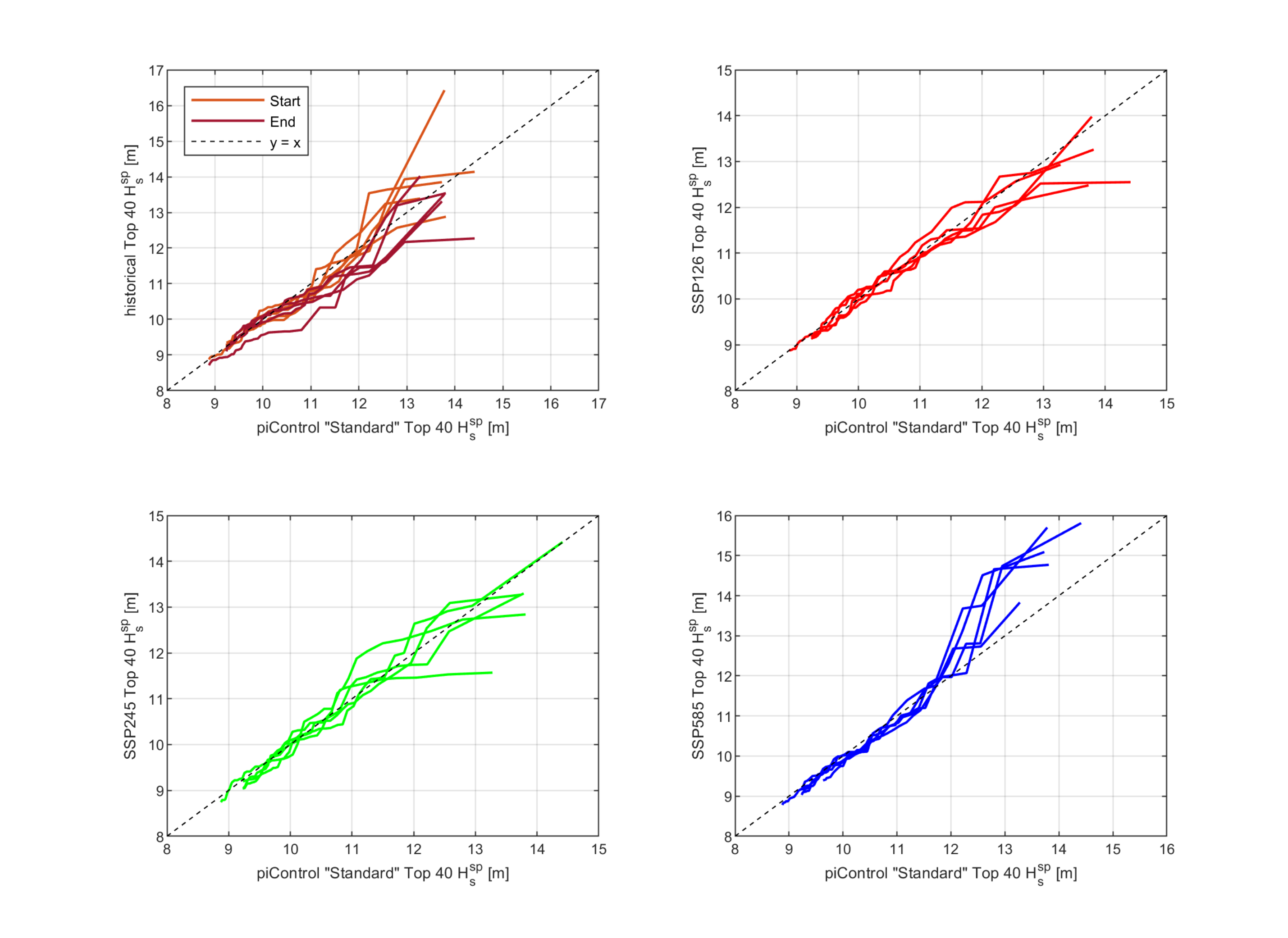


Approach

- Standard Period 86 years
  - the longest period of data available for all future projection scenarios
- piControl to investigate inherent steady-state conditions
  - 25 representative 86-year subintervals, with starting years approximately uniformly distributed over the 700 years
- Historical to investigate changes over the last 165 years
  - Start and End 86-year periods: first and last 86 years (some overlap)
- Future Scenarios to investigate predictions

Data Tail Characteristics – 40 largest H_s^{sp}

- piControl "Standard"
  - Mean ordered sequence of 25 subintervals
- considerable variability for different locations
- Historical Start > piControl
- Historical End < piControl
- SSP126, SSP245 ≈ piControl
- SSP585 > piControl



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

$$F_{\mathrm{GP}}(x | X_t > \psi_t, \psi_t, \sigma_t, \xi_t) = 1 - \left[1 + \frac{\xi_t}{\sigma_t}(1 - \psi_t)\right]^{-1/\xi_t} \qquad \xi_t \neq 0$$

$$= 1 - \exp\left(-(x - \mu_t / \sigma_t)\right) \qquad \xi_t = 0$$

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

- Assume any parameter, η, 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, referred to as NEP1-NEP4, based on 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 is then estimated using a quantile regression for specified τ
- Annual rate of occurrence, ρ_t, of threshold exceedances in time for given τ, is determined with Poisson regression with density

$$f(\{c_t\}|\rho_t) = \exp\left(-\sum_{t=1}^{P} \rho_t\right) \prod_{t=1}^{P} \rho_t^{c_t}$$

Where $\{c_t\}_{t=1}^{P}$ are empirical annual counts of threshold exceedances, and

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

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:

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

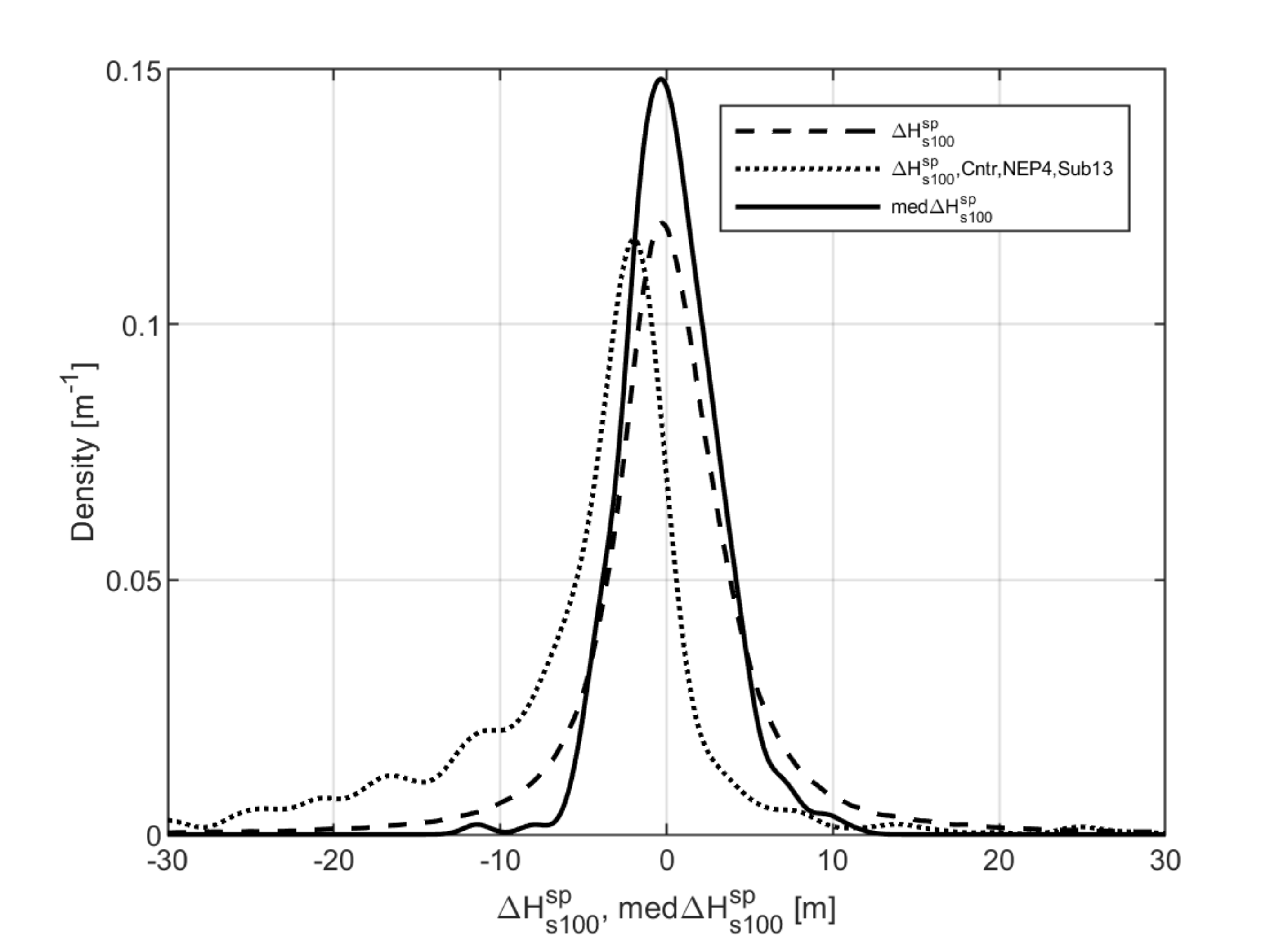
- Parameter estimation using Bayesian inference, with MCMC algorithm; generate 10000 100-year return values, last 1000 used
- Compare Q_1 and Q_{86} 100-year H_s for Start and End of the 86-year period.

Analysis

- **First** compare two quantities, for given location, EV threshold level, climate scenario, and potential subinterval.
  - ΔH_{s100}^{sp} difference between the estimates of 100-year return value at the end (Q_P) and the start (Q_1) of each sample of $P = 86$ years of data.
  - $\mathrm{med}\Delta H_{s100}^{sp}$ median of the 1000 estimates.
- **Then** average ΔH_{s100}^{sp} and $\mathrm{med}\Delta H_{s100}^{sp}$ over locations and threshold values
  - Final estimates will therefore be model averages over five locations, and four EV thresholds and potentially 25 subintervals of the piControl output.

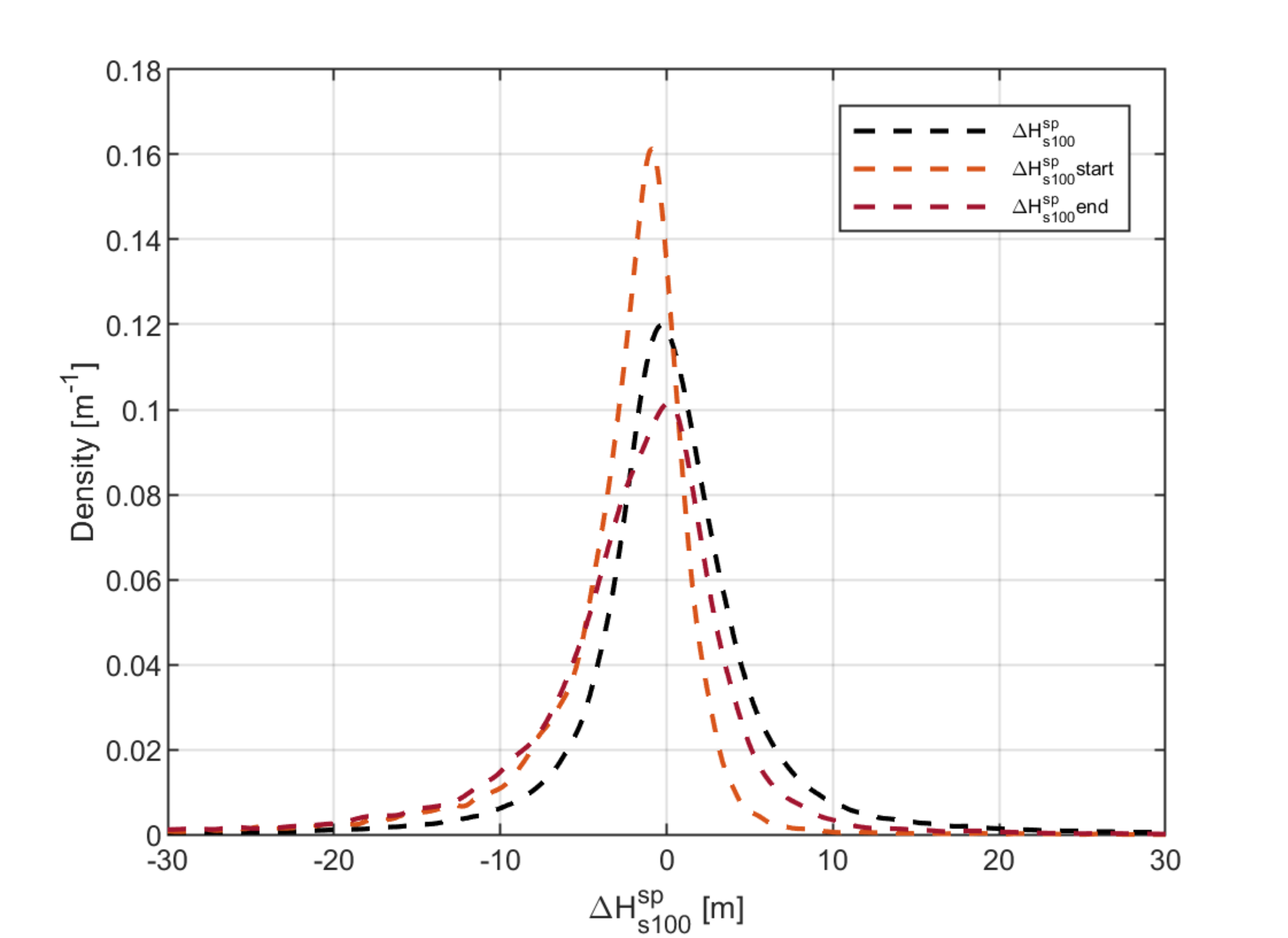
Inherent variability in return value over 86 years

- ΔH^{sp}_{s100}
  - 5×4×25×1000 = 500,000 values
  - MPV ≈ 0
  - Range ± 5m
- $\text{med}\Delta H^{sp}_{s100}$
  - 5×4×25 = 500 values
  - MPV ≈ -2 m
- ΔH^{sp}_{s100}, Cntr, NEP4, Sub13
  - 1000 values, around year 650
  - MPV ≈ 0
  - Range ± 5m
- SSP $\text{med}\Delta H^{sp}_{s100}$ up to 5m consistent with piControl



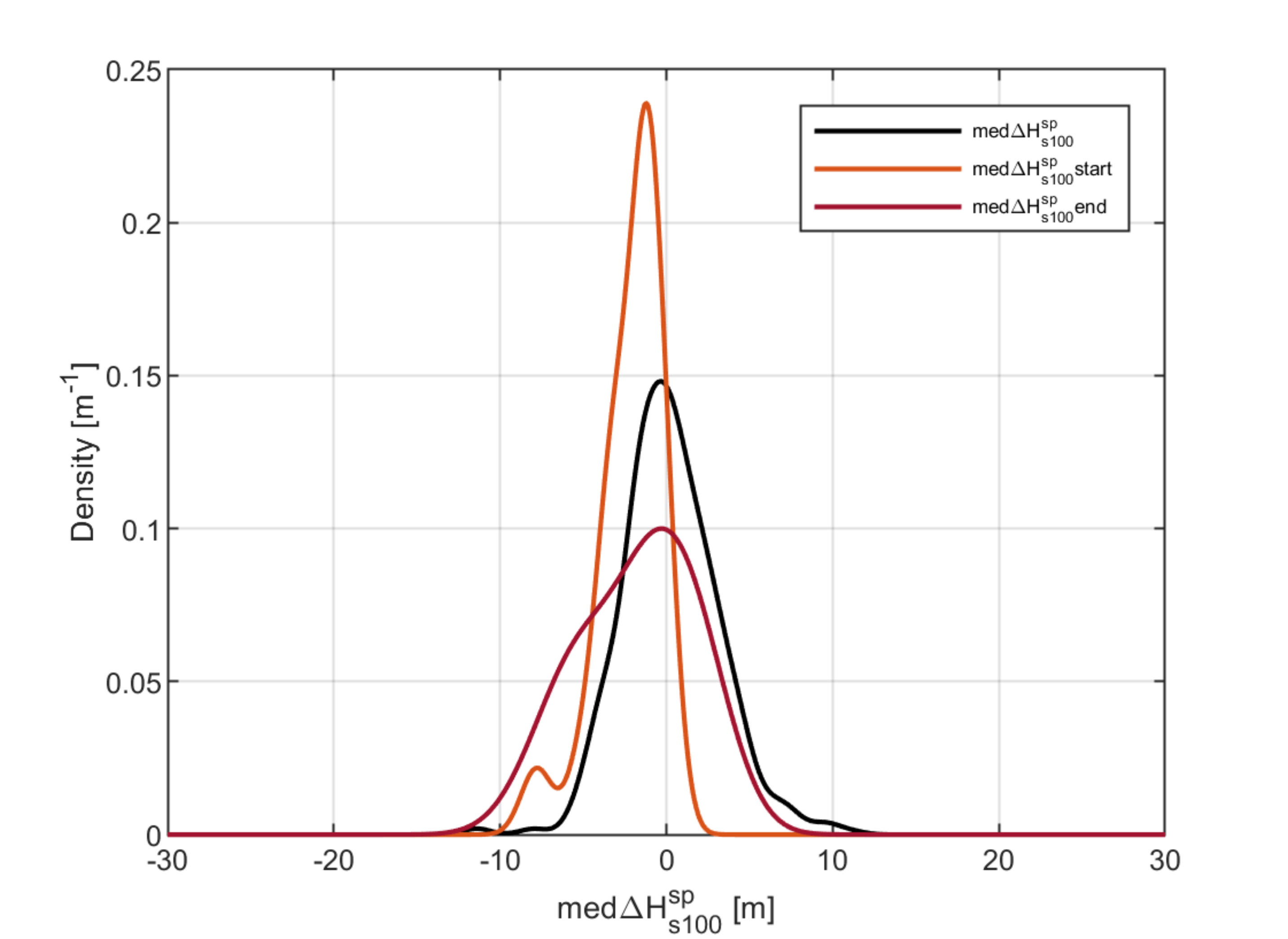
Variability in return value over **early and late historical periods** of 86 years - ΔH^{sp}_{s100}

- ΔH^{sp}_{s100} piControl
  - 500,000 values
  - MPV ≈ 0
- ΔH^{sp}_{s100} Start
  - 1000 values
  - MPV ≈ -1m
  - Similar to piControl
- ΔH^{sp}_{s100} End
  - 1000 values
  - MPV ≈ 0m
  - Similar to piControl



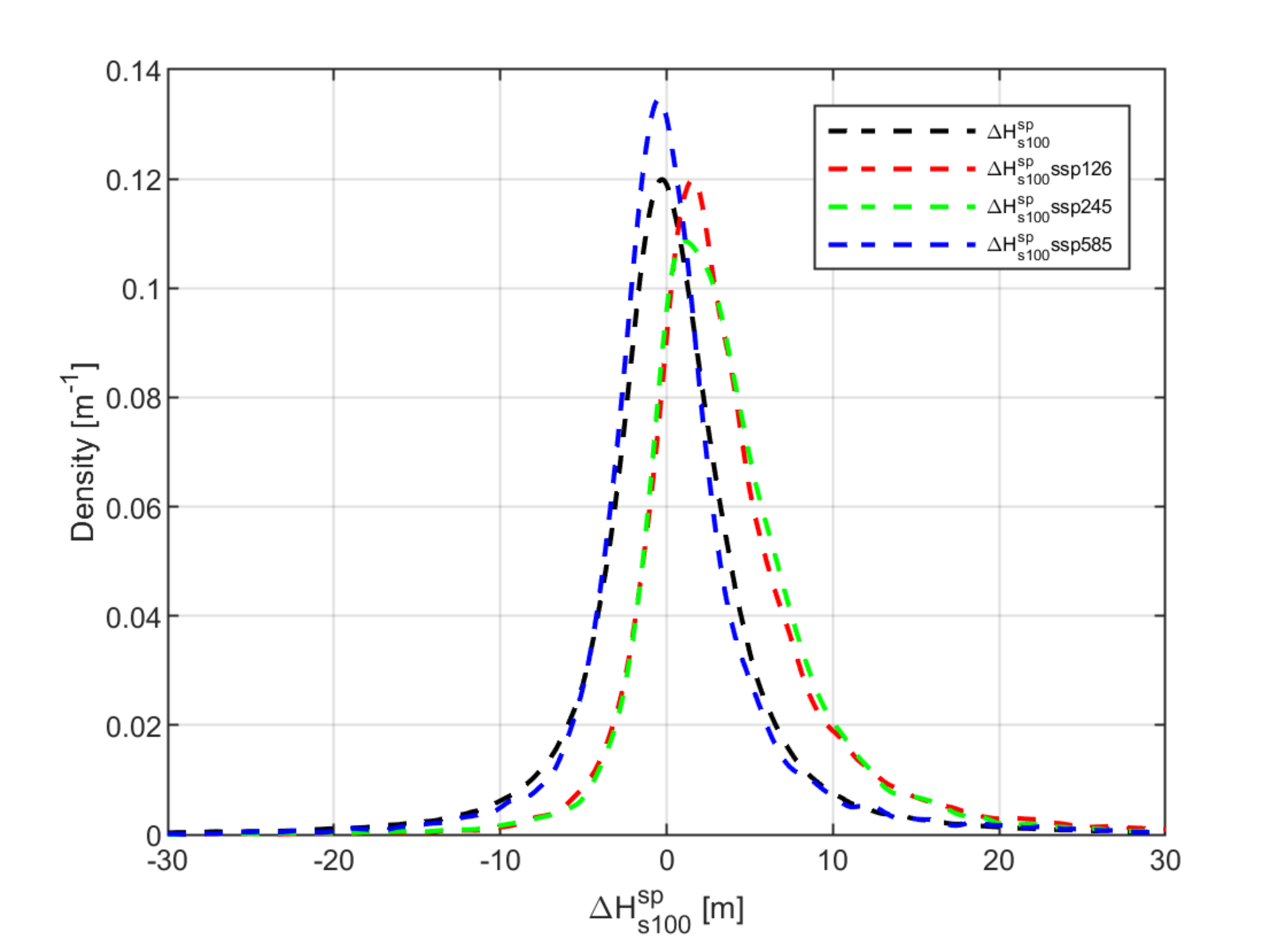
Variability in return value over **early and late historical periods** of 86 years - $\mathrm{med}\Delta H_{s100}^{sp}$

- $\mathrm{med}\Delta H_{s100}^{sp}$ piControl
  - 500 values
  - MPV ≈ 0
- $\mathrm{med}\Delta H_{s100}^{sp}$ Start
  - 20 values
  - MPV ≈ -1.5m
  - Similar to piControl
- $\mathrm{med}\Delta H_{s100}^{sp}$ End
  - 20 values
  - MPV ≈ 0m
  - Similar to piControl



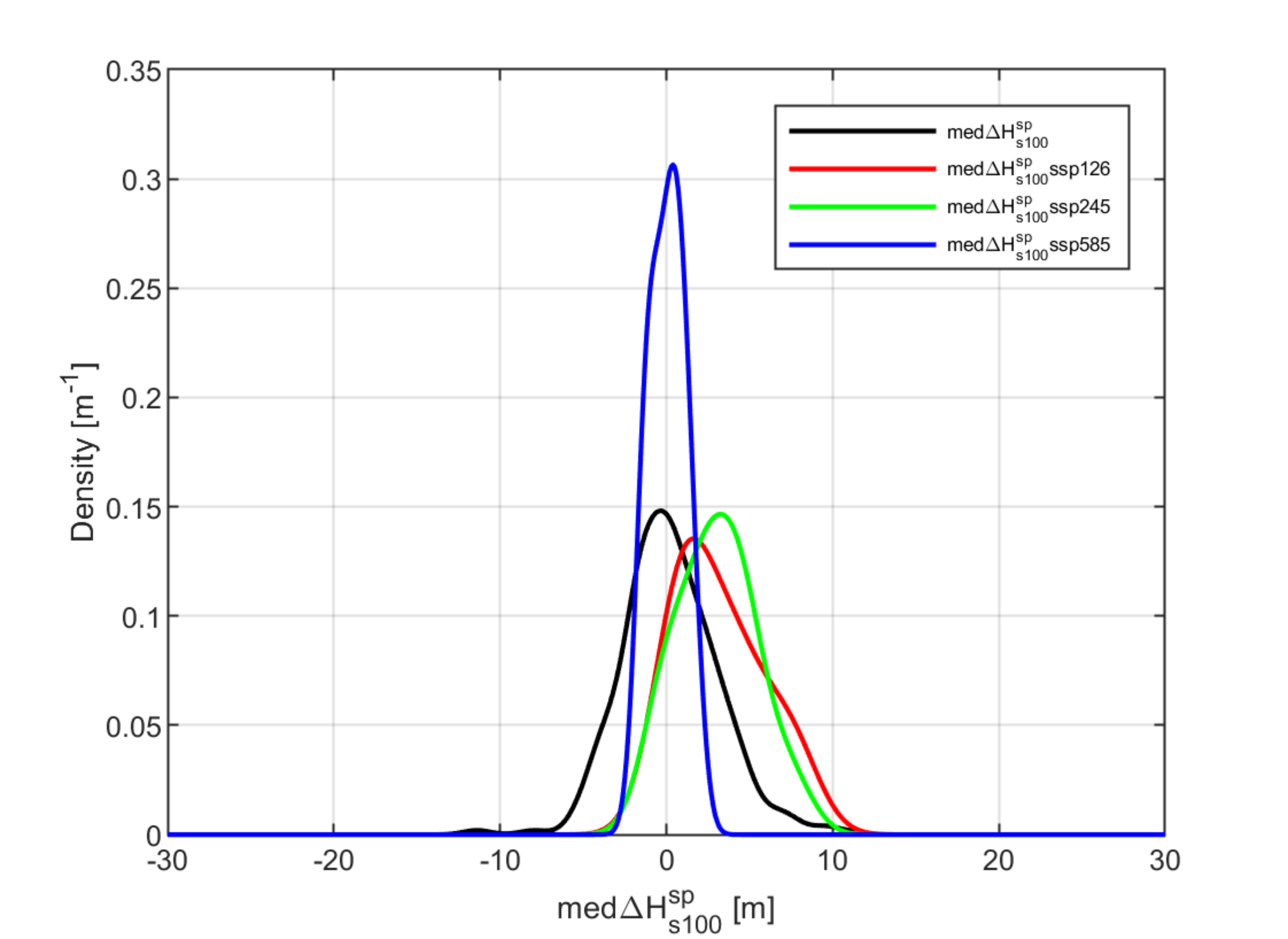
Variability in return value over 86 years under **SSP climate scenarios**

- ΔH_{s100}^{sp} piControl
  - 500,000 values
  - MPV ≈ 0
- ΔH_{s100}^{sp} SSP126, SSP245
  - 1000 values
  - MPV ≈ +2m
  - Similar to piControl
- ΔH_{s100}^{sp} SSP585
  - 1000 values
  - |MPV| < 0.5m
  - Similar to piControl



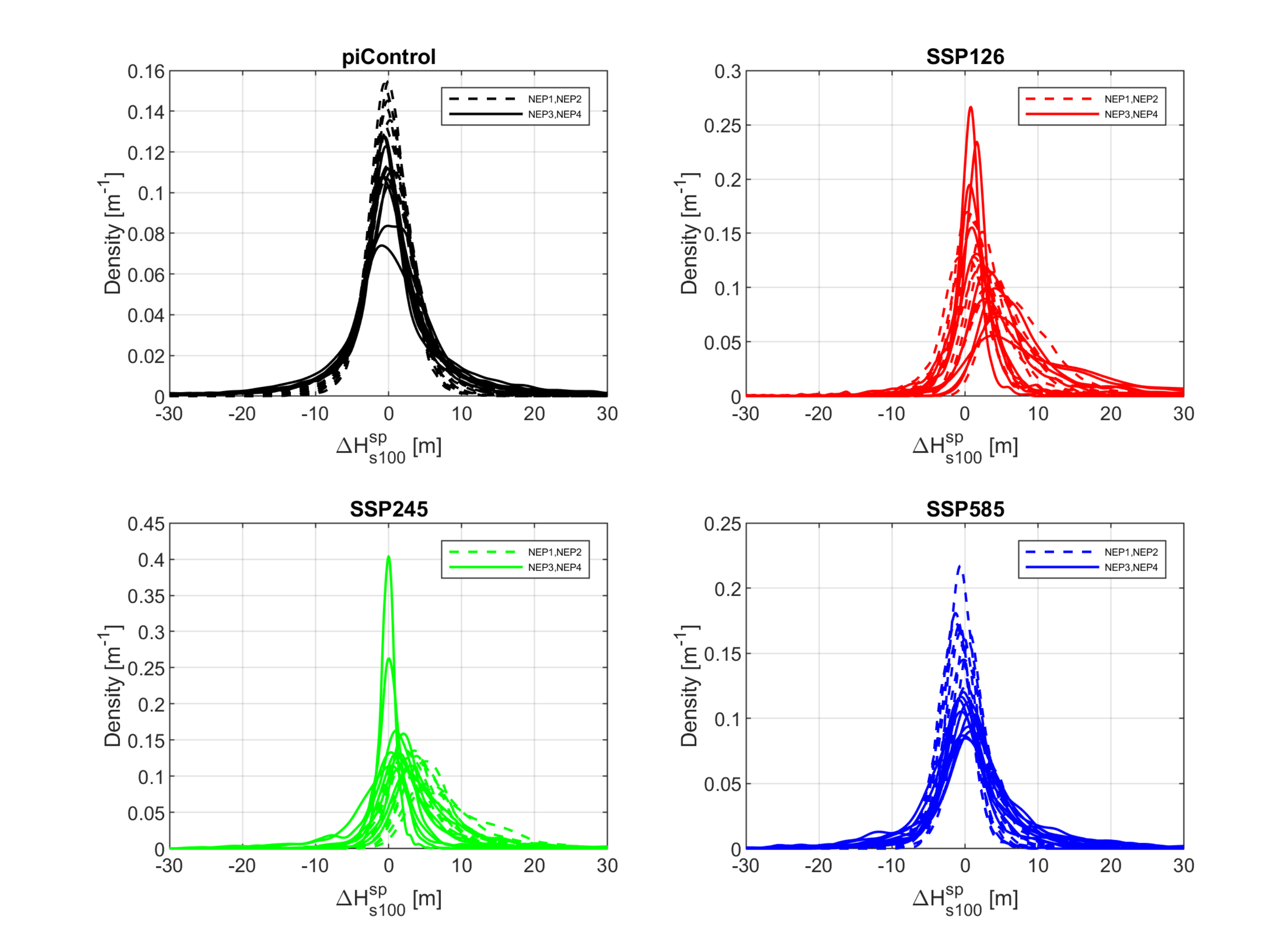
Variability in return value over 86 years under **SSP climate scenarios**

- $\mathrm{med}\Delta H_{s100}^{sp}$piControl
  - 500,000 values
  - MPV ≈ 0
- $\mathrm{med}\Delta H_{s100}^{sp}$ SSP126
  - 1000 values
  - MPV ≈ +1.5m
- $\mathrm{med}\Delta H_{s100}^{sp}$ SSP245
  - 1000 values
  - MPV ≈ +3m
- $\mathrm{med}\Delta H_{s100}^{sp}$SSP585
  - 1000 values
  - |MPV| < 0.5m
  - Density narrower



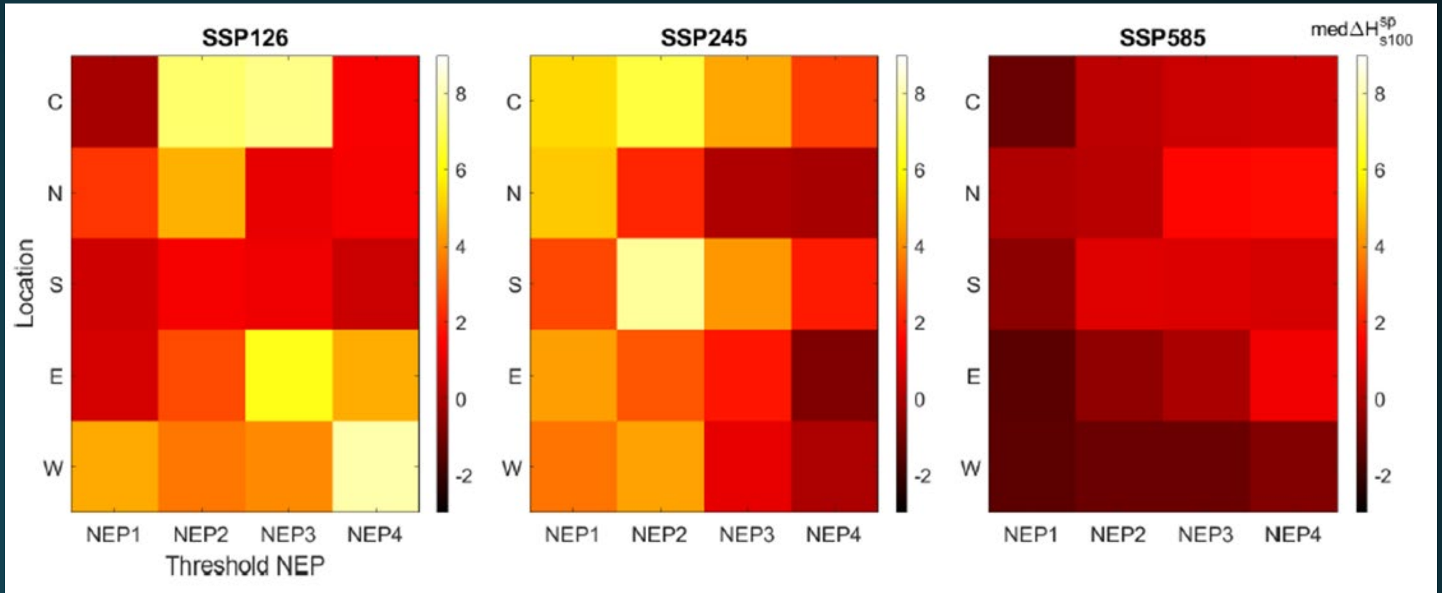
Variability in ΔH_{s100}^{sp} by **threshold & location**

- Dashed NEP1 & NEP2
- Continuous NEP3 & NEP4
- Line for each location
- piControl & SSP585 consistent
- SSP126 & SSP245 right-shoulder
  - Zonal variation for SSP126
  - Meridional variation for SP245
  - Perhaps arbitrary GCM-wave model run effects



Variability in $\mathrm{med}H_{s100}^{sp}$ with **location & threshold**

- Some evidence for systematic effects
  - higher values across NEPs for location C and SSP245
  - lower values across NEPs for location W and SSP585
  - lower values across locations for NEP1 and SSP585
- Warning against over-interpretation of specific EV analyses
  - sensitive to arbitrary modelling effects
- Advantageous to model average over output from multiple GCM-wave models, and ensembles from given GCM-wave model.



Conclusions

<u>PiControl</u>

- Most probable value of ΔH_{s100}^{sp} and $\mathrm{med}\Delta H_{s100}^{sp}$ over a period of 86 years is approximately zero
- Empirical densities of ΔH_{s100}^{sp} and $\mathrm{med}\Delta H_{s100}^{sp}$ are broad
- Change in H_{s100}^{sp} and $\mathrm{med}\Delta H_{s100}^{sp}$ of ±5m not surprising

<u>Historical</u>

- Weak evidence for reduction in ΔH_{s100}^{sp} (1m) and $\mathrm{med}\Delta H_{s100}^{sp}$ (1.5m) for Start 86-yr period
- Weak evidence for some reduction H_{s100}^{sp} in the End 86-yr period
- Effects are small relative to the inherent uncertainty in H_{s100}^{sp} (±5m) observed in the piControl output

Conclusions

<u>Future Projections</u>

- SSP126: Results suggest H_{s100}^{sp} increases
  - Distribution modes of ΔH_{s100}^{sp} and $\mathrm{med}\Delta H_{s100}^{sp}$ are +2m and +1.5m respectively
- SSP245: Results suggest H_{s100}^{sp} increases
  - Distribution modes of ΔH_{s100}^{sp} and $\mathrm{med}\Delta H_{s100}^{sp}$ are +2m and +3m respectively
- SSP585: Results more inconclusive
  - Distribution modes -0.5m < of ΔH_{s100}^{sp} < 0 < $\mathrm{med}\Delta H_{s100}^{sp}$ < +0.5m

<u>Historical</u>

- Weak evidence for ~1 m reduction in H_{s100}^{sp} over Historical period, but small relative to the inherent piControl uncertainty observed (±5m).

Is H_{s100}^{sp} increasing the Tasman Sea?

- From a design perspective for year 2100 at this location, it would be wise to plan for an increase of H_{s100}^{sp} of around 2m relative to 2015
- But the evidence in favour of a climate-driven change in H_s^{sp} is weak