

Best practice for extreme sea level estimations

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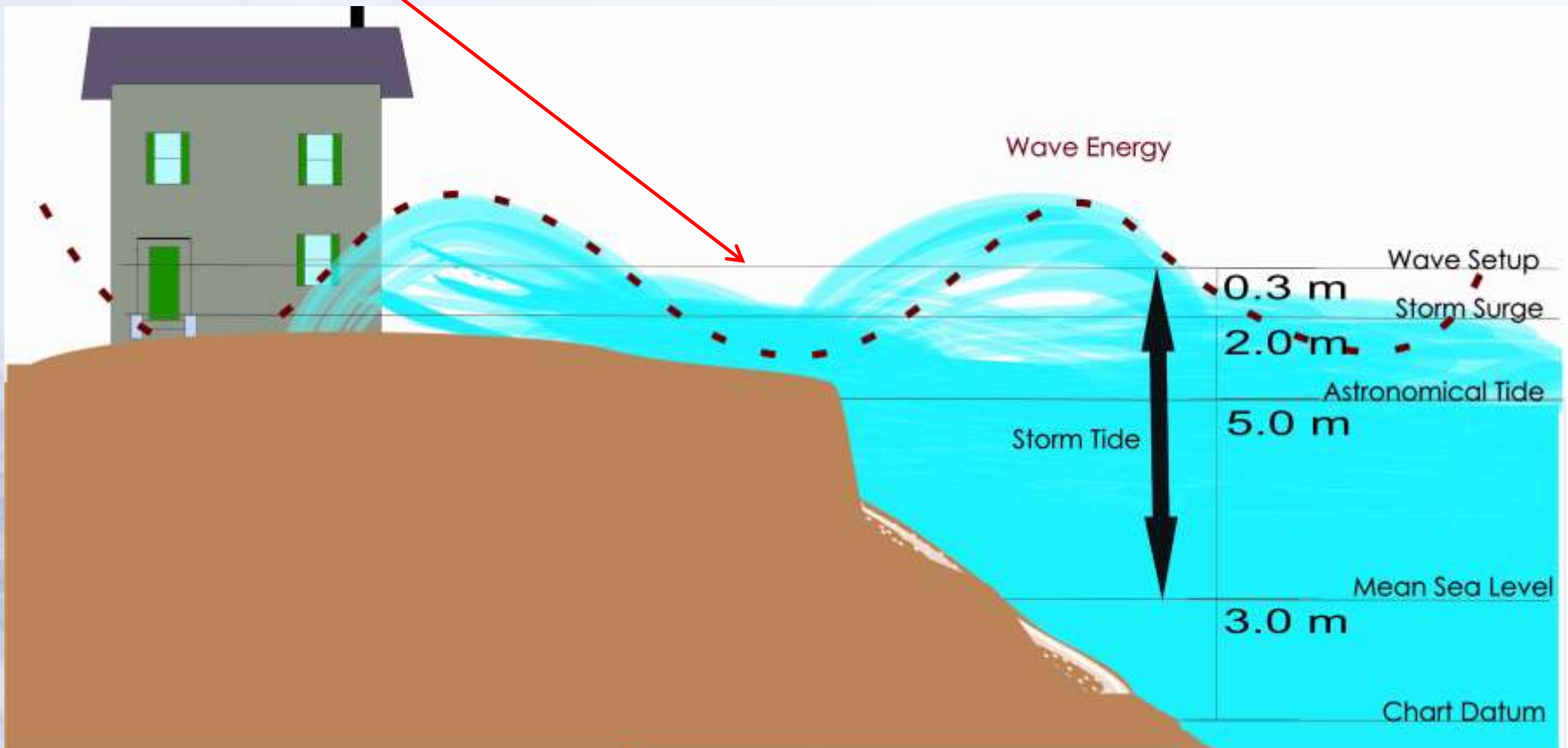
Coastal defences

- Insured annual losses due to coastal flooding in the UK are about £1 billion
- Without sea defences this figure would rise to about £3.5 billion
- Typical sea wall: £20m per km
- Coastal planners require accurate estimates of flood risk for defence design purposes
- This work was funded by the EA/Defra FCRM R&D programme SC0600694 and the Scottish government under the Coastal Extremes programme
- Our aim - a consistent spatial statistical method to deliver reliable estimates of extreme sea level around the UK coast



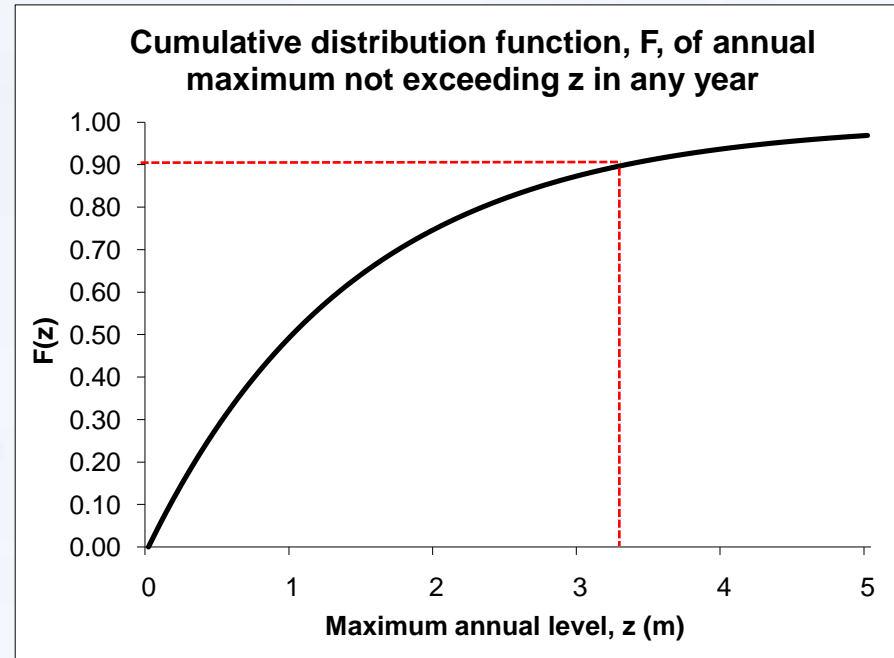
Components of “still water level”

- Coastal defences are designed based on the probability of exceeding certain still water levels
- Extreme SWL = MSL + high spring tide + storm surge + wave set up



Return period (RP)

- Many applications of extreme values theory (Gumbel, 1958) precede modern instrumentation, so early work (and terminology) was based on annual maxima
- If some level, z , is exceeded in one year with probability p then its return period is said to be $1/p$
- If $z_{0.1}$ is that level whose probability of annual exceedance is 0.1, then it is said to have a 10 year return period
- Probabilistic measures are NOT predictions: a level with 5 year return period may occur twice in 5 years



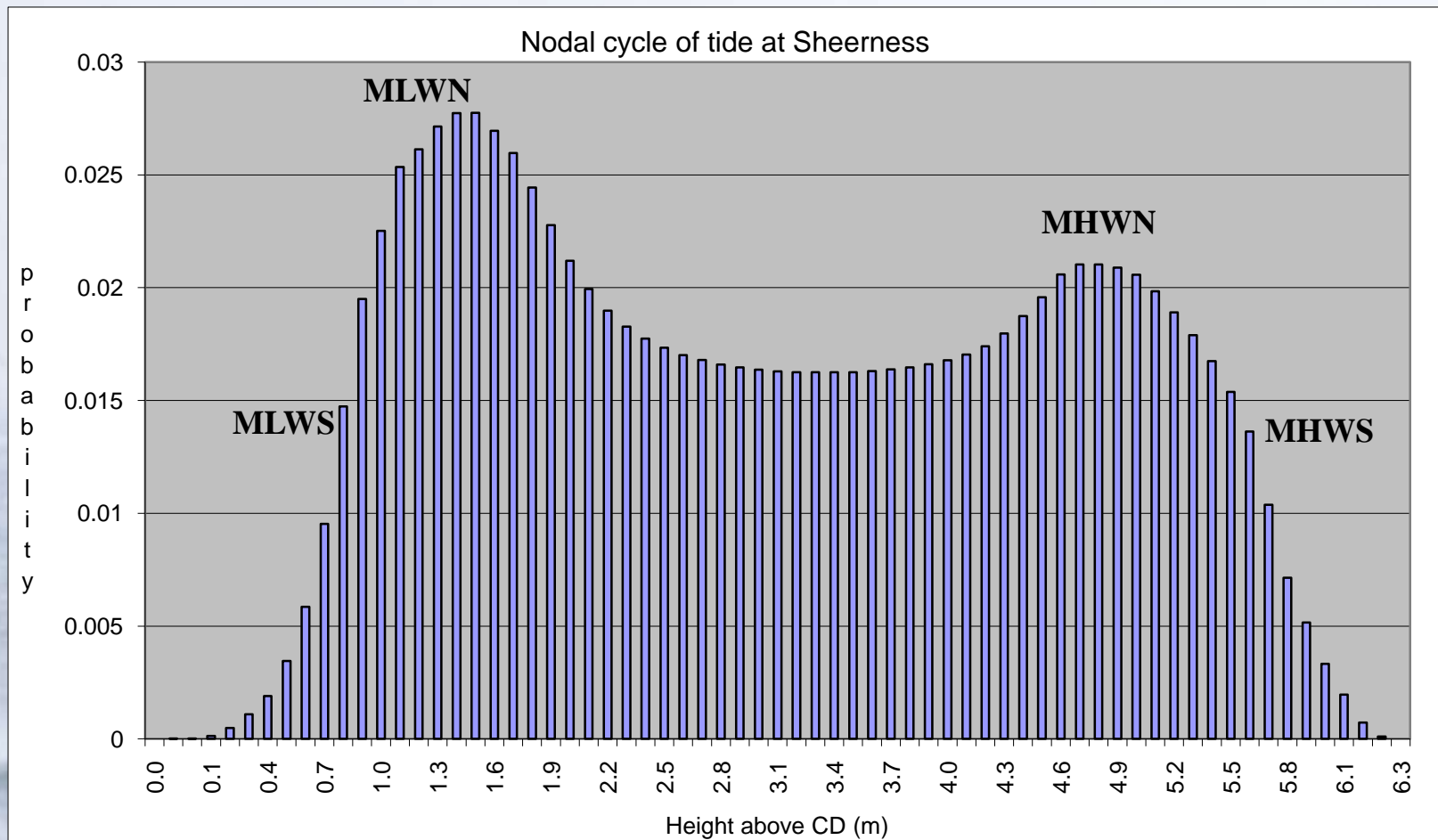
3.2 m has a return period of 10 years

$$F(z) = \int_{-\infty}^z p(x) dx$$

$$P(>z) = 1 - F(z)$$

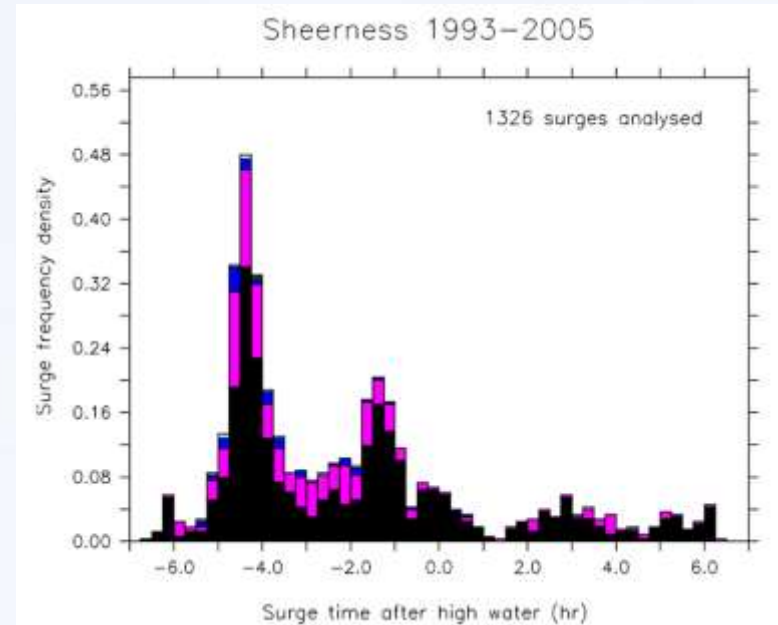
Probability distribution function of tides

- Tides are, of course, deterministic. The only reason we calculate the PDF is so that it can be combined with storm surge heights (otherwise we would just build sea walls to highest astronomical tide)

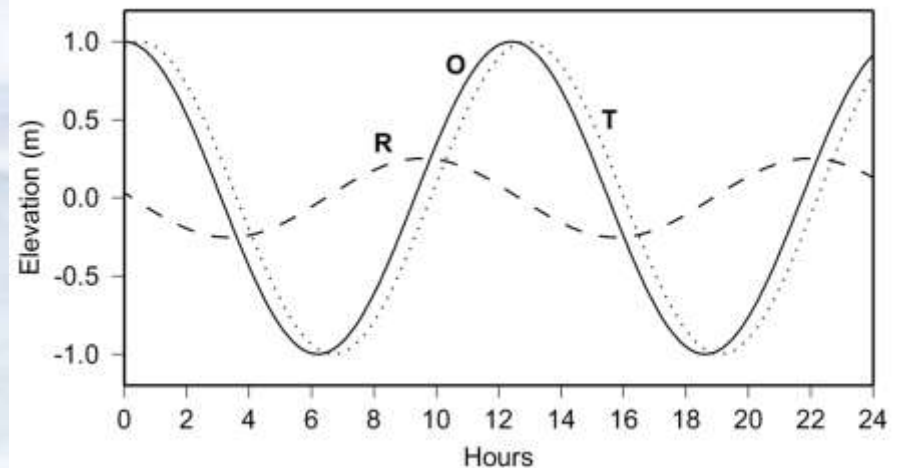


Tide-surge dependence

- At many tide gauges peak non-tidal residuals (observations – predictions) are consistently obtained 3-5 hours before tidal high water
- It is mathematically simple to show that for an idealised phase shifted wave, the residual peak occurs at exactly mid-tide
- In practice, local effects cause peak residual to typically occur nearer low water
- This link between the residual and the state of the tide led to a series of joint probabilities methods (JPM) for extreme sea levels



Horsburgh and Wilson (2007), JGR

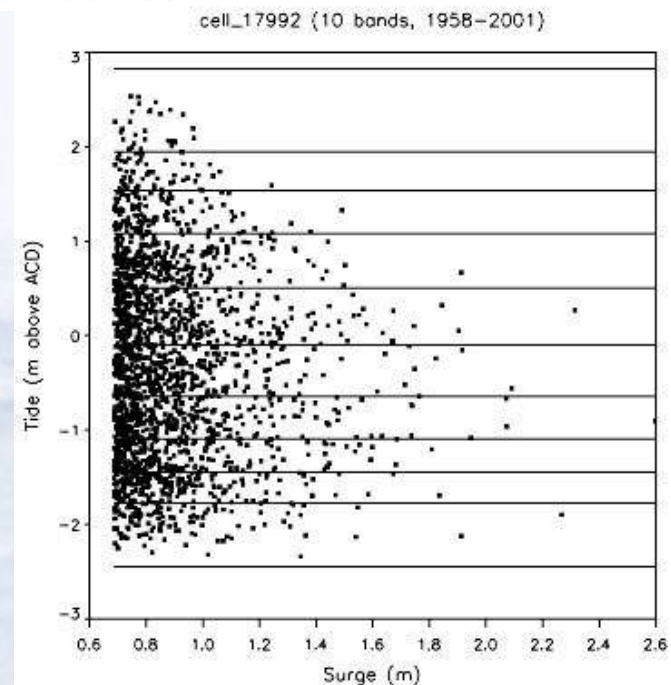


Joint probabilities methods for sea level

Tidal HW level (m)	Normalised frequency	Non-tidal residual (m)				
		-0.2	-0.1	0.0	0.1	0.2
3.2	0.1	0.01	0.02	0.04	0.02	0.01
3.1	0.2	0.02	0.04	0.08	0.04	0.02
3.0	0.3	0.03	0.06	0.12	0.06	0.03
2.9	0.3	0.03	0.06	0.12	0.06	0.03
2.8	0.1	0.01	0.02	0.04	0.02	0.01

From Pugh (2004)

- In JPM, separate distribution functions are calculated from hourly sea level observations
- Pugh and Vassie (1980) used simple empirical calculations of residual PDFs, based on finite windows of the full tidal range
- Largest deficiency is that the observed distribution of residuals (“surges”) is not a true estimate of the real distribution

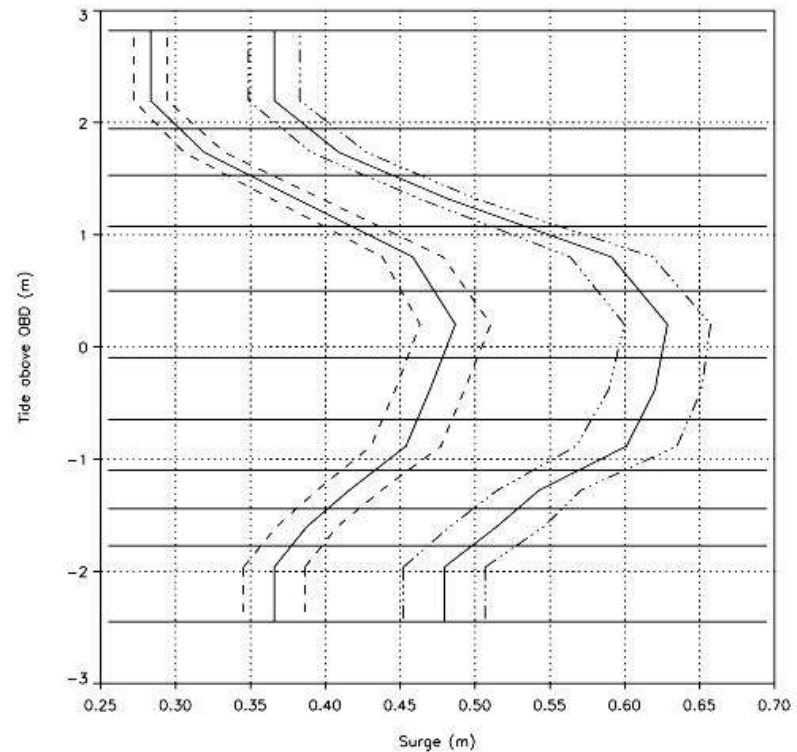


Revised Joint Probabilities Methods (RJPM)

- Tawn and Vassie (1989) & Tawn (1992) made two significant improvements:
- Extreme end of the residual distribution was modelled using a Generalised Extreme Value (GEV) distribution function
- Dependence of successive hourly values was addressed via an extremal index, θ , that represents the clustering of extremes
- A transformed residual is calculated based on non-dimensional tide-surge interaction functions:

$$S_t^* = [S_t - a(X_t^*)]/b(X_t^*)$$

- GEV parameters obtained by maximum likelihood in a point process method

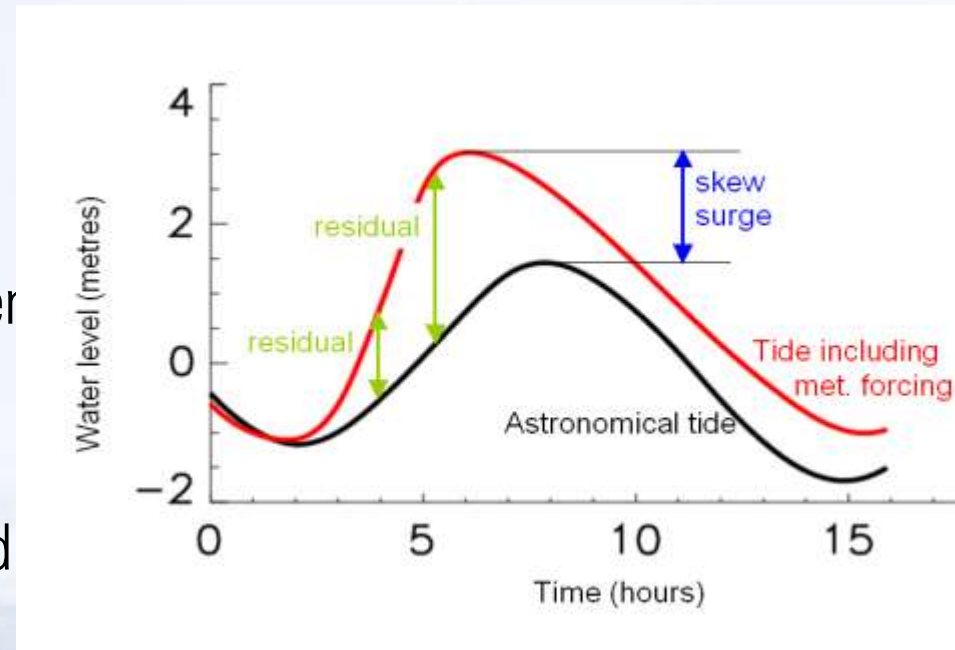


cell_17992 (10 bands, 1958-2001)
Interaction functions a1(x) and a2(x)

$$G(S^*, \mu, \sigma, k) = \exp \left\{ - \left[1 - k_{S^*} \left(\frac{S^* - \mu_{S^*}}{\sigma_{S^*}} \right) \right]^{-\frac{1}{k_{S^*}}} \right\}$$

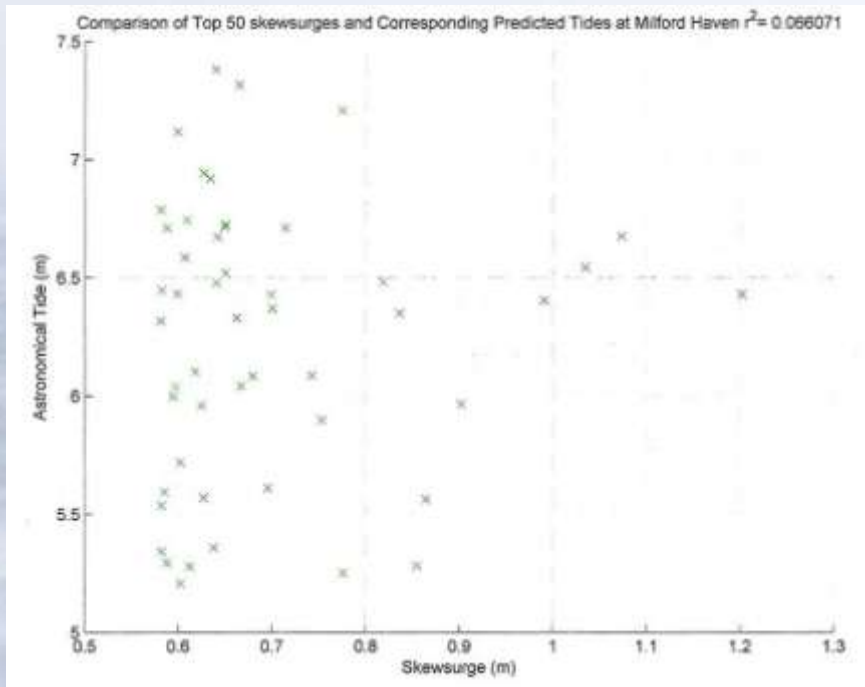
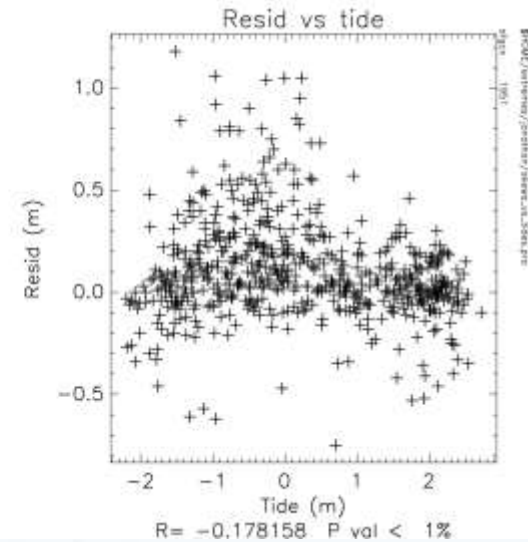
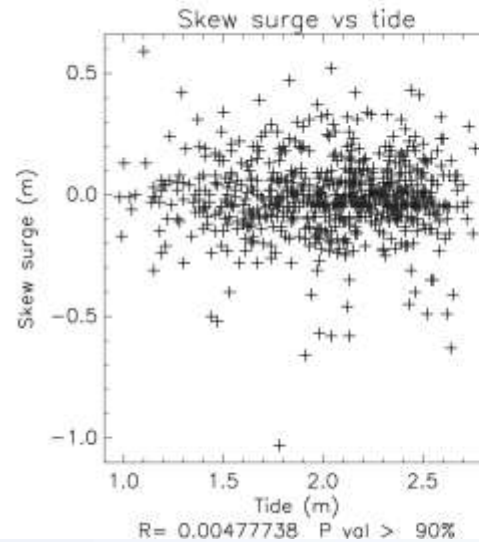
The skew surge – a proper measure of surge

- The skew surge is defined as the difference between the predicted astronomical high tide and the nearest experienced high water
- It is the preferred diagnostic for the UK and Dutch operational surge modelling systems, and is of greater practical significance than the non-tidal residual
- It can be thought of as the time and basin-integrated effect of the weather on sea level at some location over a tidal cycle
- **It is statistically independent of tidal state**



Independence of skew surge and tide

Skew surge vs. predicted high water at Sheerness.
 $r^2 = 0$

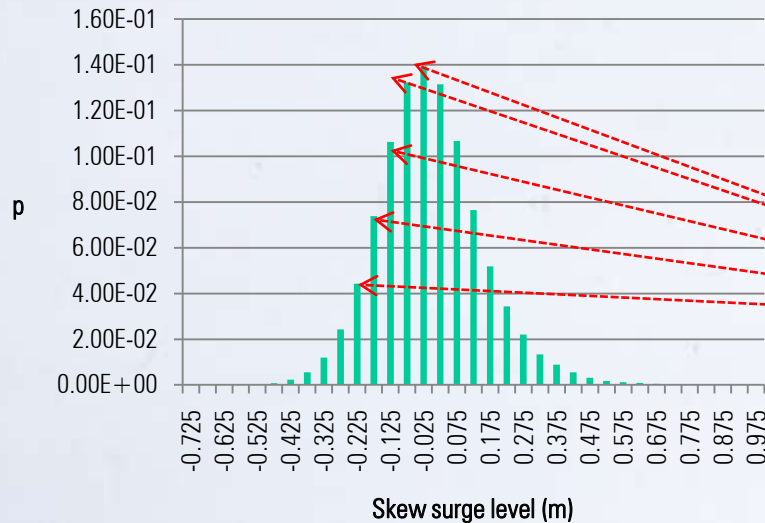


Howard et al., submitted

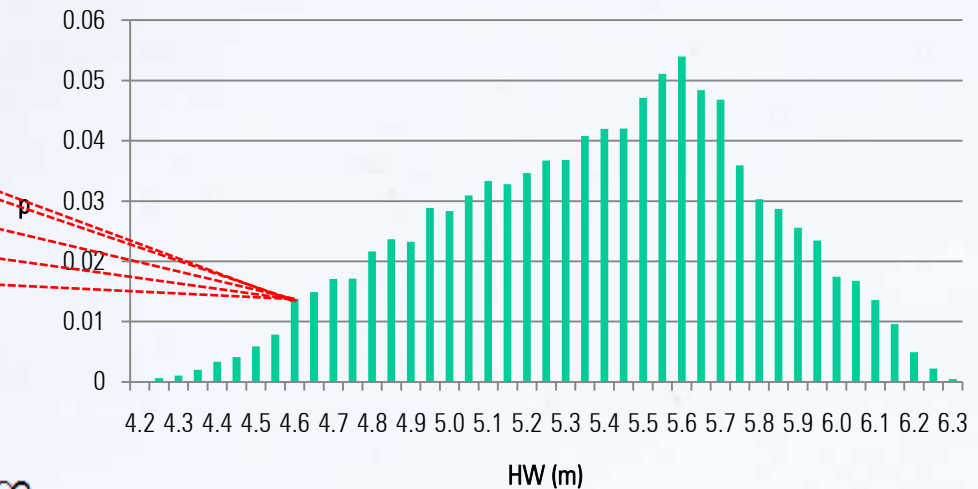
Skew surge vs. predicted high water at Milford Haven. $r^2 = 0.066$

Combining tidal and skew surge probabilities

Skew surge distribution at Sheerness



High Water PDF at Sheerness over 18.6 yrs



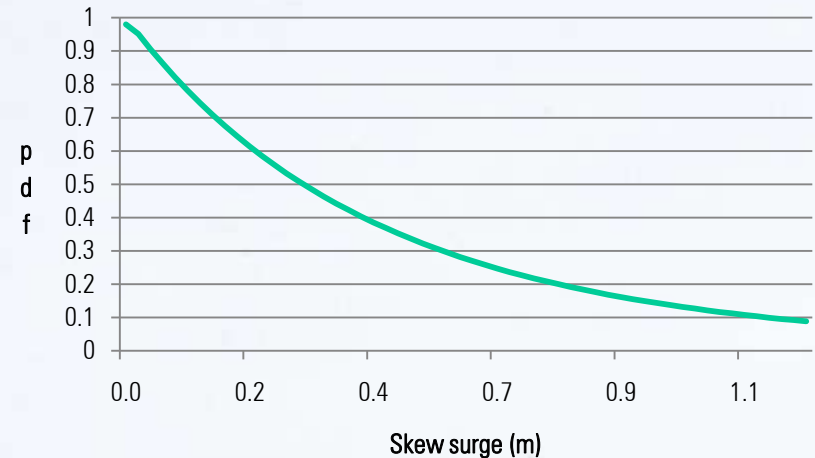
$$p(z) = \int_{-\infty}^{\infty} p_T(z - s) \cdot p_{SS}(s) ds$$

- Skew surge distribution is combined simply with the nodal tidal distribution. Any skew surge may be added to any tidal high water, and their probabilities multiplied
- Total levels thus obtained can be integrated into narrow bins ($\sim 5\text{cm}$) and those probabilities summed to give $p(\text{any level})$

Remaining statistical assumptions

- Because the observed data cannot fully sample the skew surge distribution then a generalised pareto distribution (GPD) is fitted to the tail of the data
- Because exceedances of extreme thresholds may cluster, an extremal index is applied in the calculation of return period
- $RP_z = 1/[705 \times \theta(z) \times p(> z)]$
- If a certain level has a probability of 1/705 then naively one would expect to wait 705 tides to see it
- In practice, that level will occur less when observed over a short span

GPD of skew surge at Sheerness



Sheerness

YEARS 2008 TO 2026

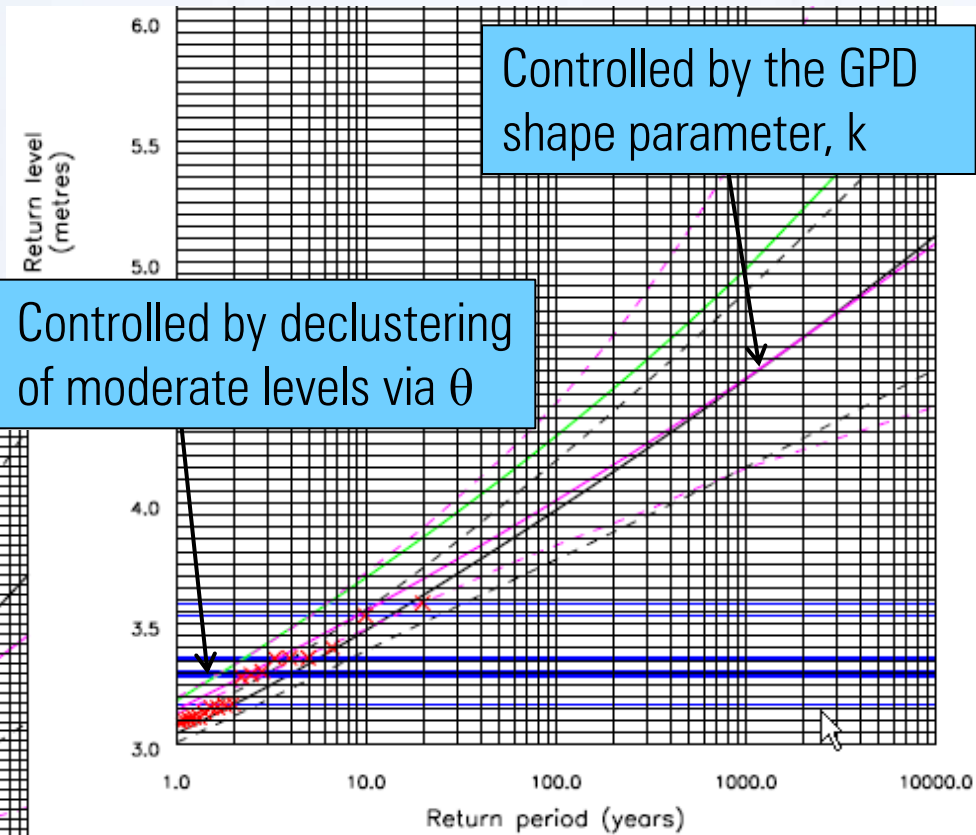
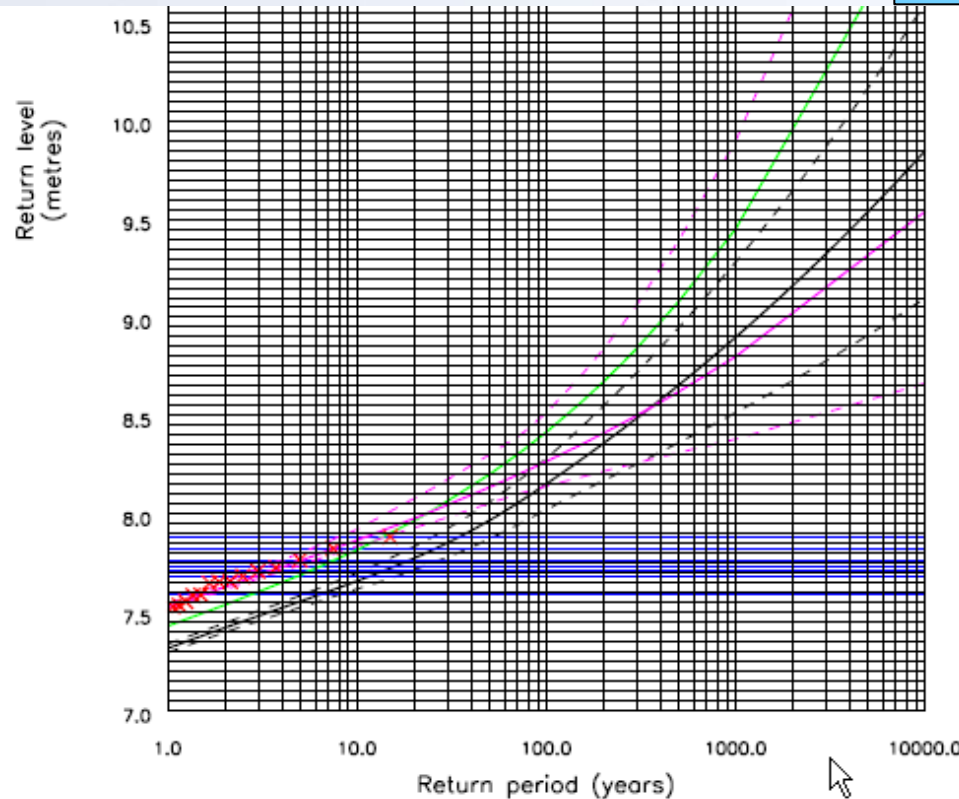
HIGHEST ASTRONOMICAL TIDE 6.34 m
MEAN HIGH WATER SPRINGS 5.86 m
MEAN HIGH WATER NEAPS 4.81 m
MEAN LOW WATER NEAPS 1.55 m
MEAN LOW WATER SPRINGS 0.65 m
LOWEST ASTRONOMICAL TIDE 0.04

HIGHEST SPRING AND AUTUMN TIDES

6.06m	9/Apr/2008
6.06m	11/Feb/2009
6.17m	2/Mar/2010
6.23m	22/Mar/2011
6.18m	9/Apr/2012
6.16m	26/Jun/2013
6.22m	2/Feb/2014
6.26m	23/Mar/2015
6.26m	10/Apr/2016
6.18m	29/Apr/2017

Results from the skew surge JP method

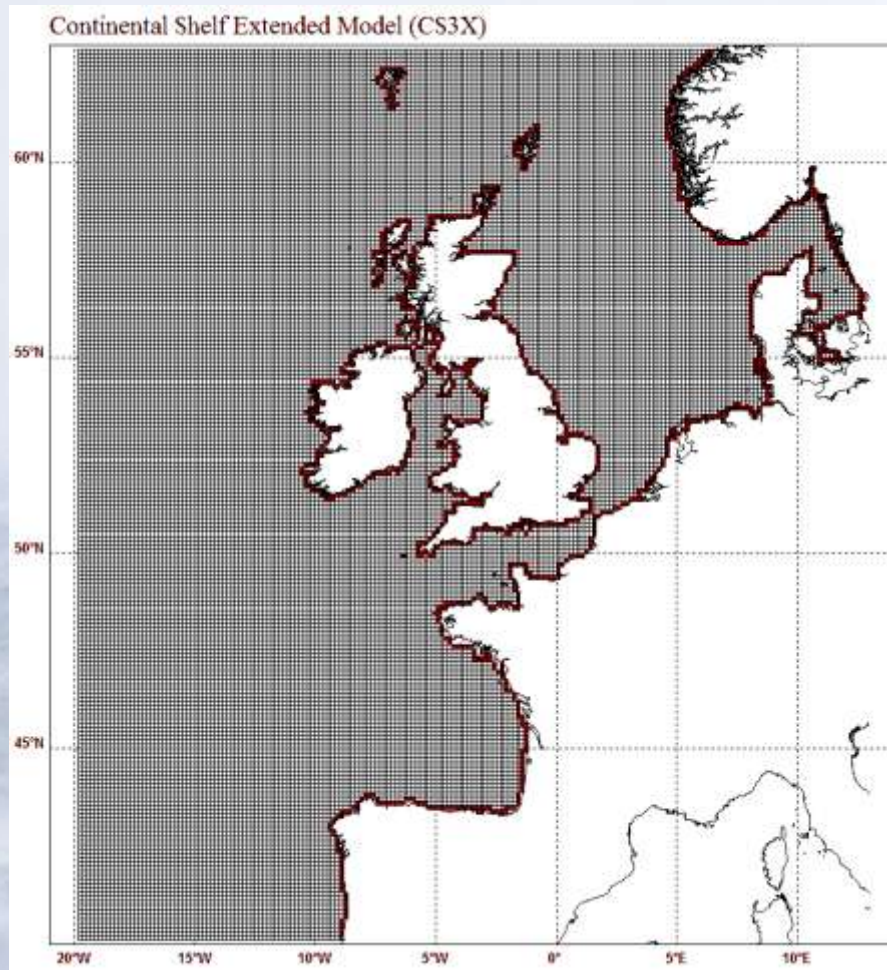
- Pink: skew surge JP; Black: RJPM
- Across the 44 national tide gauge sites the results were consistent at 38 locations (ensemble check)



- Red crosses mark actual observed top sea levels, placed in rank order and then assigned an RP based on length of data

Interpolating to coastal sites between gauges

- We used the POL operational tide-surge model at 12 km resolution, forced by the ECMWF ERA40 meteorological reanalysis (1°) to interpolate between the estimates of extreme water levels at tide gauge sites



Concluding remarks

- We have developed a consistent spatial method to deliver reliable estimates of extreme sea level around the UK coastline
- The results are directly applicable to Flood and Coastal Risk Management
- The use of skew surges in joint probability calculations with the nodal tide is an order of magnitude simpler than previous methods
- The only parametrical statistical assumption is the GPD fit to the tail of the skew surge distribution
- The quality of the skew surge distribution is dependent on data length and quality
- The shape parameter is very sensitive to record length: for short time series it can be smoothed using neighbouring sites appealing to spatial smoothness
- A physical meaning can be assigned to the extremal index: it is the average number of sequential high waters that exceed each level

Concluding remarks

- The accuracy of any joint probabilities method is basically the confidence in the calculation of very small probabilities – and this is quantifiable via the confidence limits
- Our interpolated model results are being validated against independent tide gauge data supplied by the Environment Agency
- The results from this exercise will be quality reviewed and made available to the scientific and engineering community in summer 2010



Thank you for your attention

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