Estuarine morphodynamics: better be certain about uncertainty

Evaluating 150 years of morphodynamics in San Francisco Bay (USA) and the Western Scheldt estuary (NL)

Gerard Dam (UNESCO-IHE, Svasek Hydraulics)
Mick van der Wegen (UNESCO-IHE, Deltares)
Bruce Jaffe (USGS, Santa Cruz, USA)
Dano Roelvink (UNESCO-IHE, Deltares)

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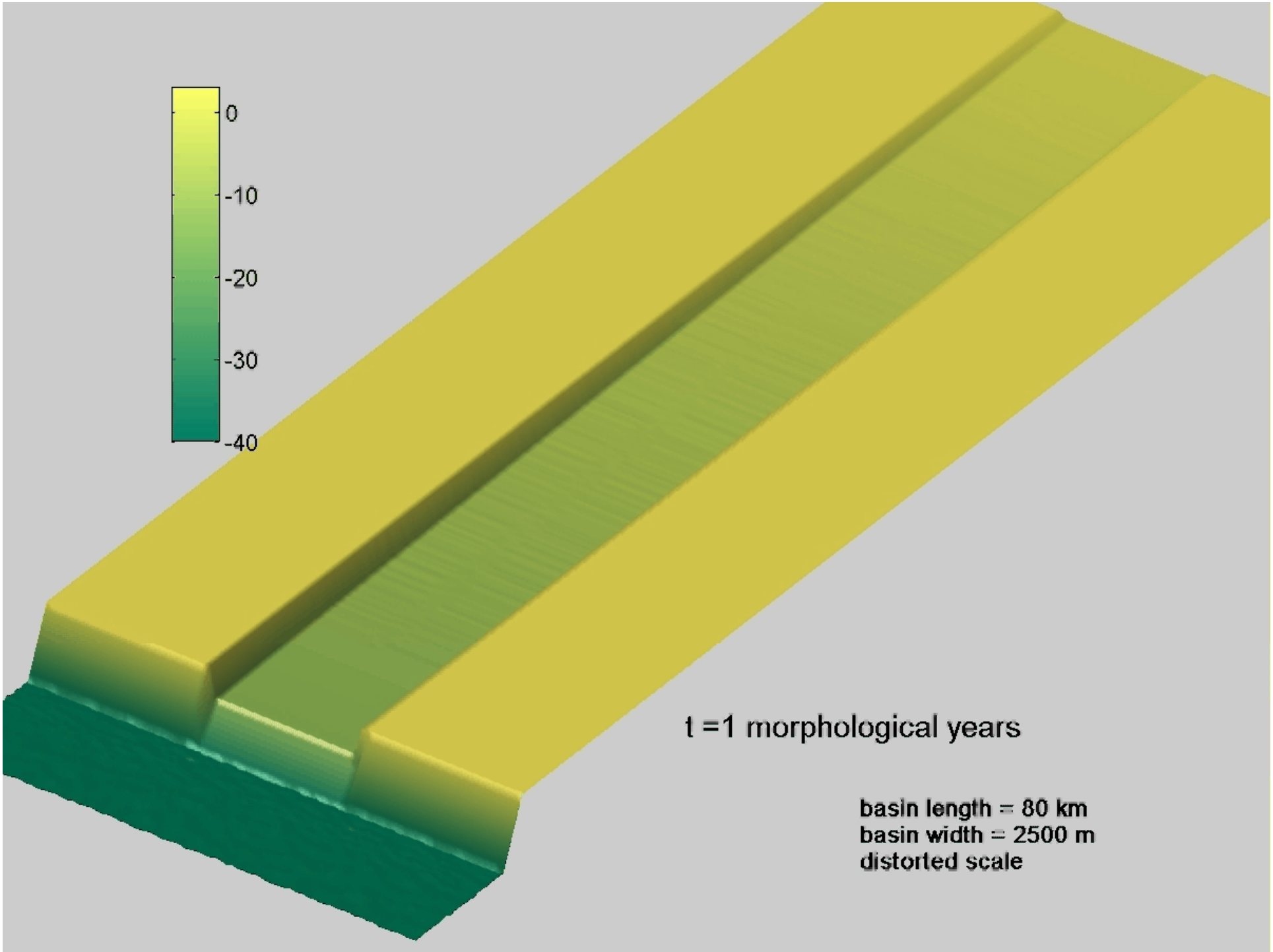
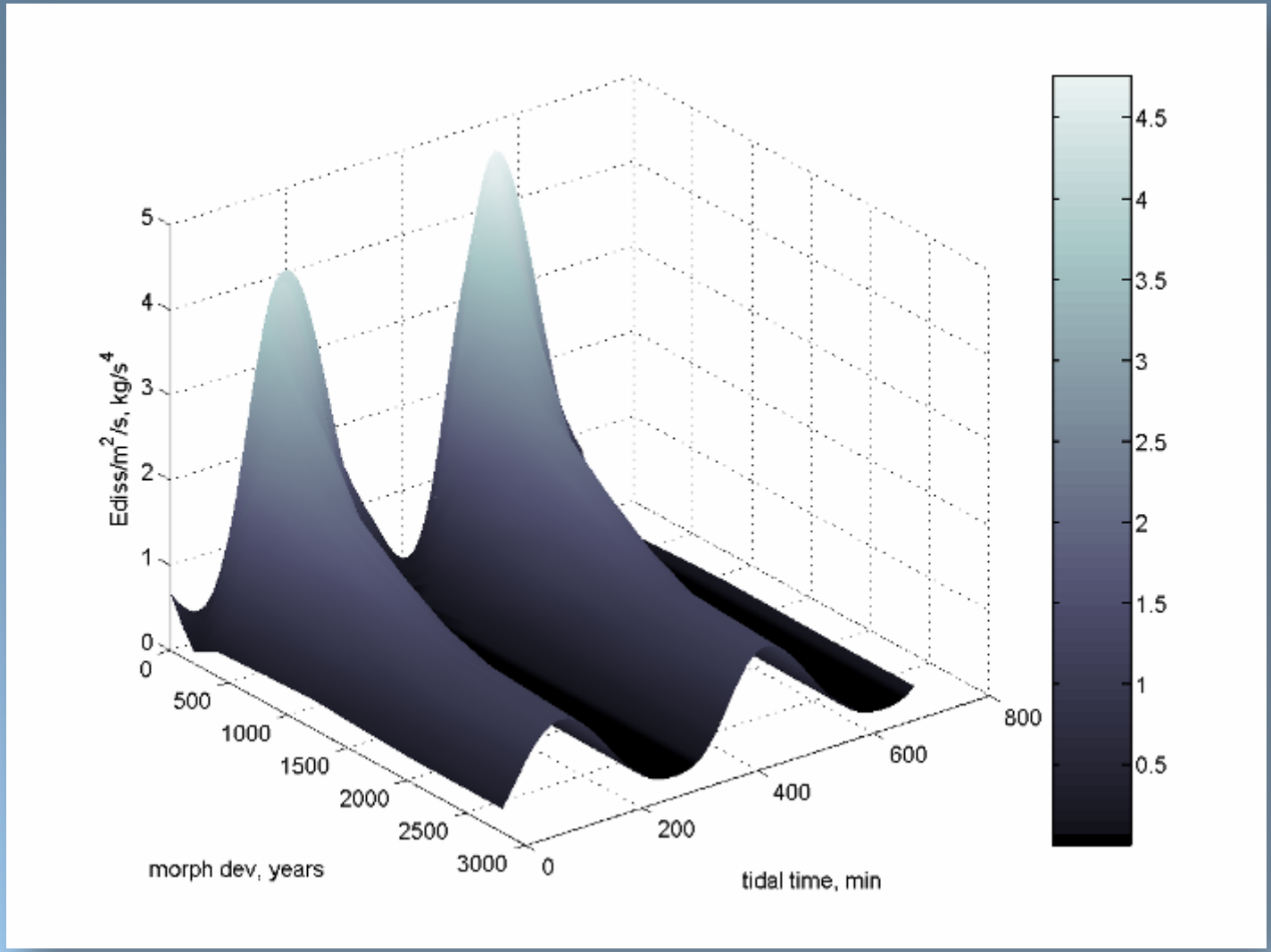

0
-10
-20
-30
-40
t =1 morphological years
basin length = 80 km
basin width = 2500 m
distorted scale

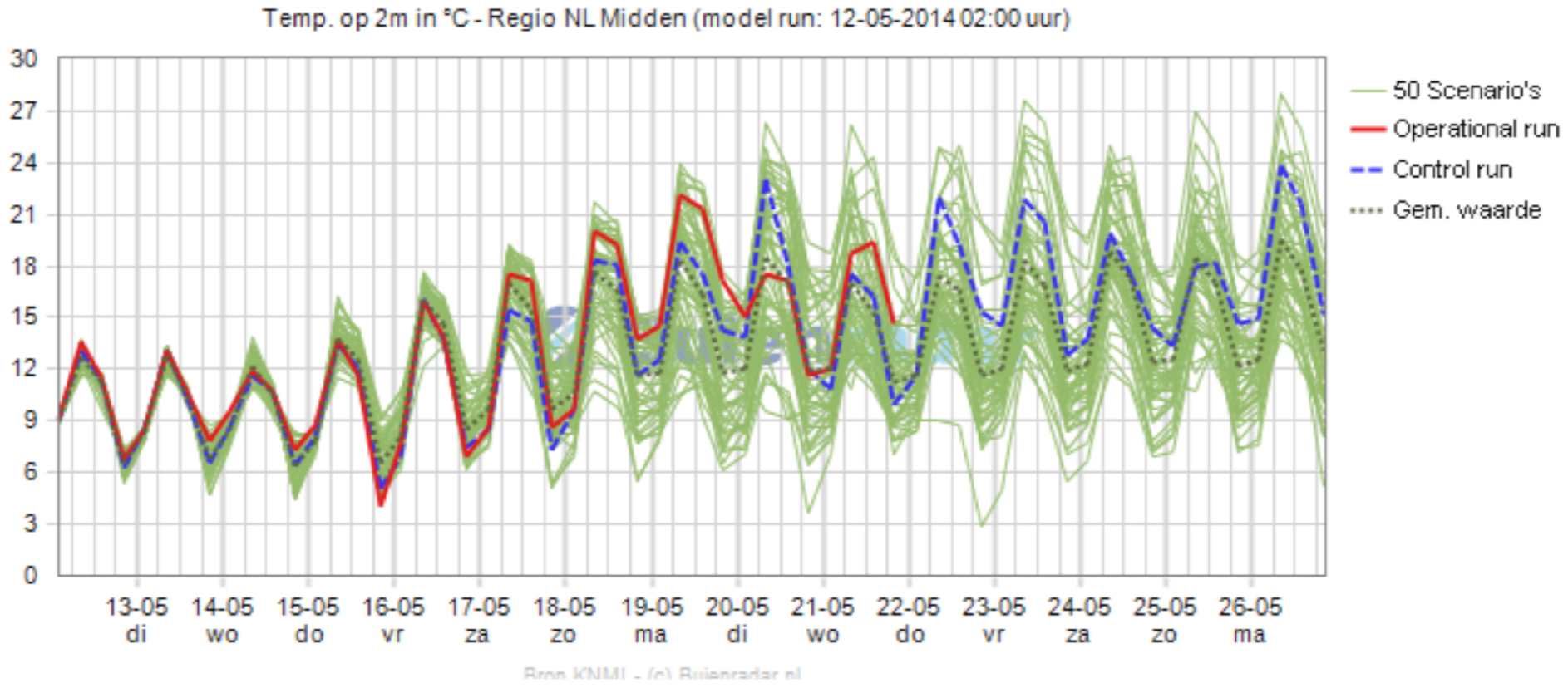
Energy dissipation (Ediss/m^2/s) for fixed banks



Van der Wegen et al. (2008), JGR-ESP

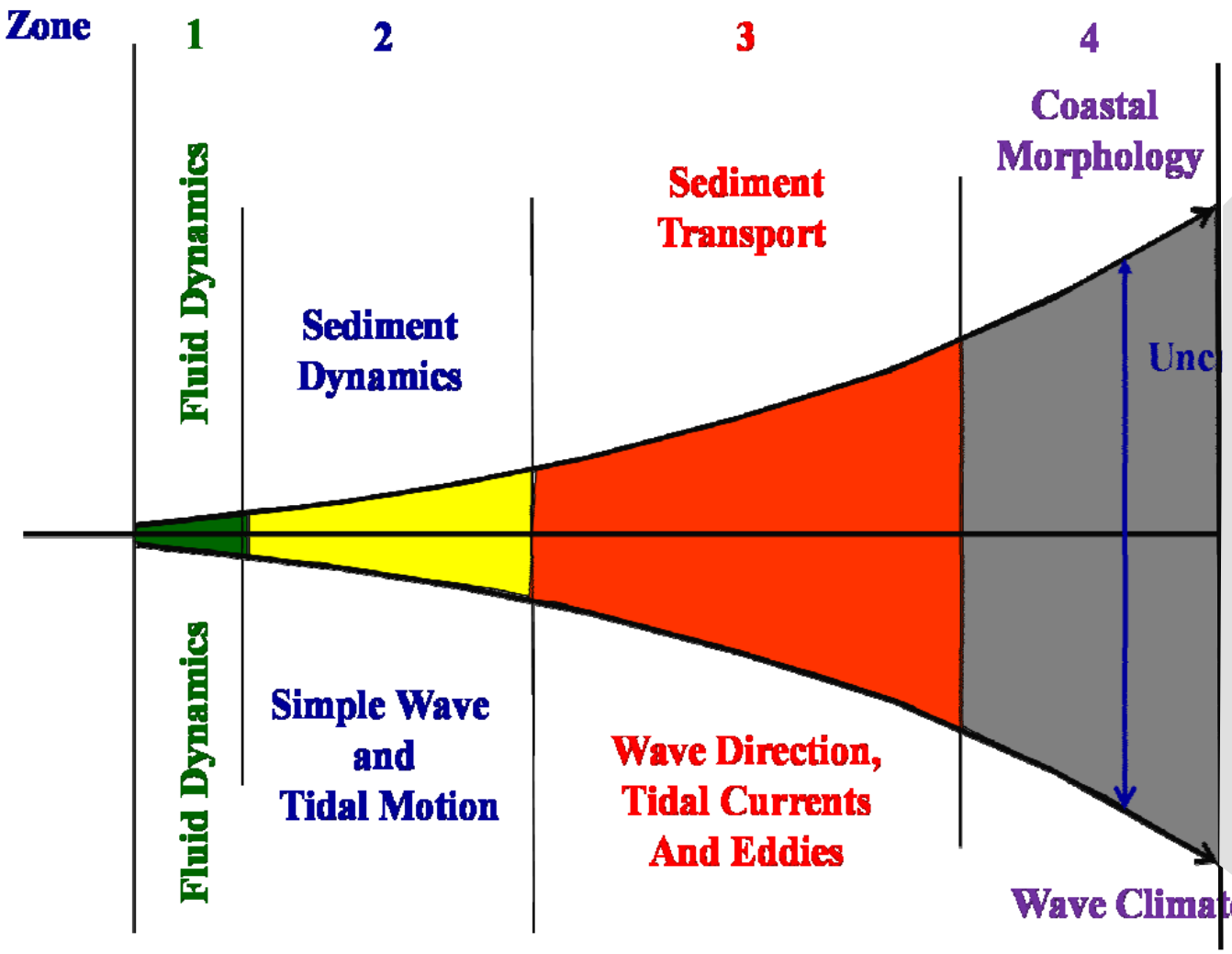
But first…

....the weather forecast for the next days.



(www.buienradar.nl)

Uncertainty trumpet



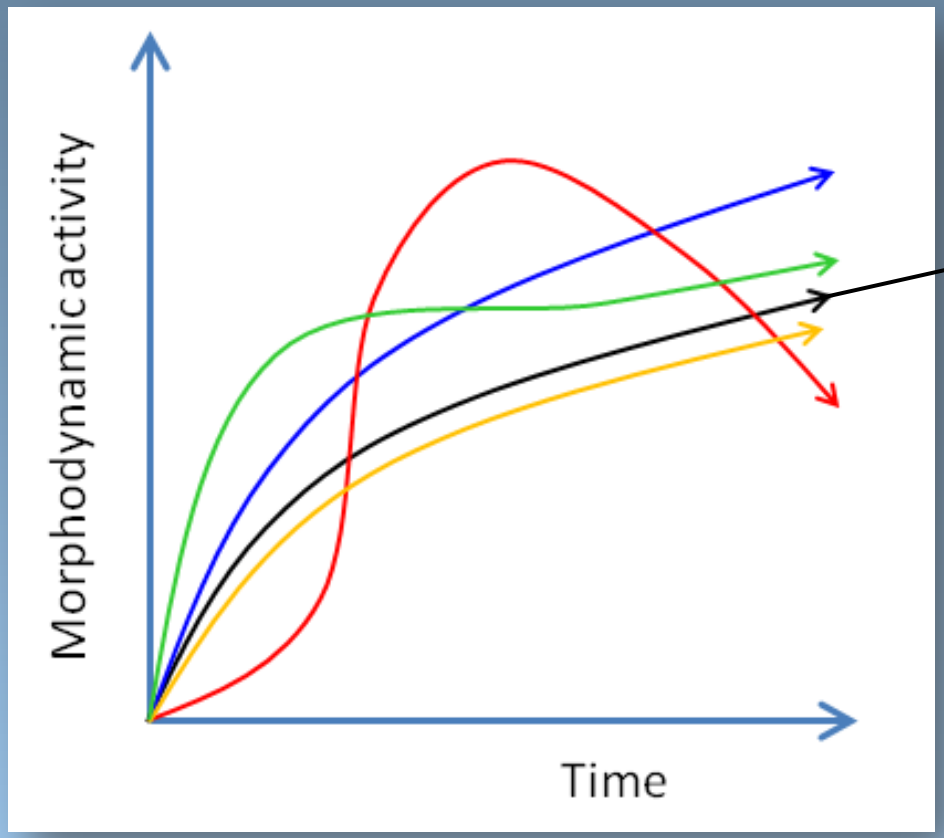
5 Long-term morpho-dynamics

?

- build up of errors
- non-lineair interactions are unpredictable over time
- simplifications of the system

(Kamphuis, 2013)

How do process-based models perform?



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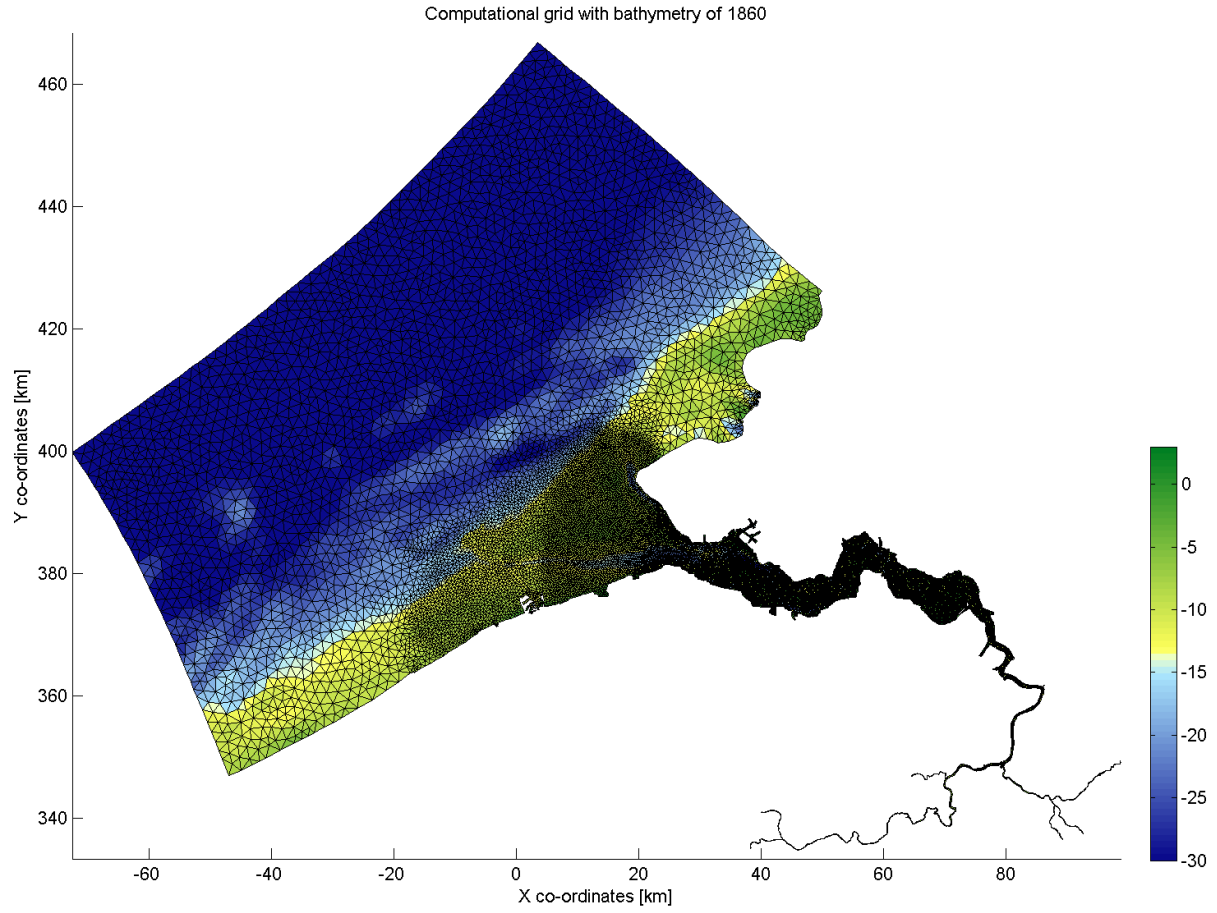
Morphological process-based model:

FINEL2d model (www.finel2d.com):

- 2DH simulation finite elements method;
- Only tidal forcing;
- Engelund-Hansen sediment transport formula
- 1 fraction of sand
- Roughness constant in time and space
- MORFAC: 24.75
- Non-erodable layer
- Parameterisation of spiral flow
- Water motion calibrated



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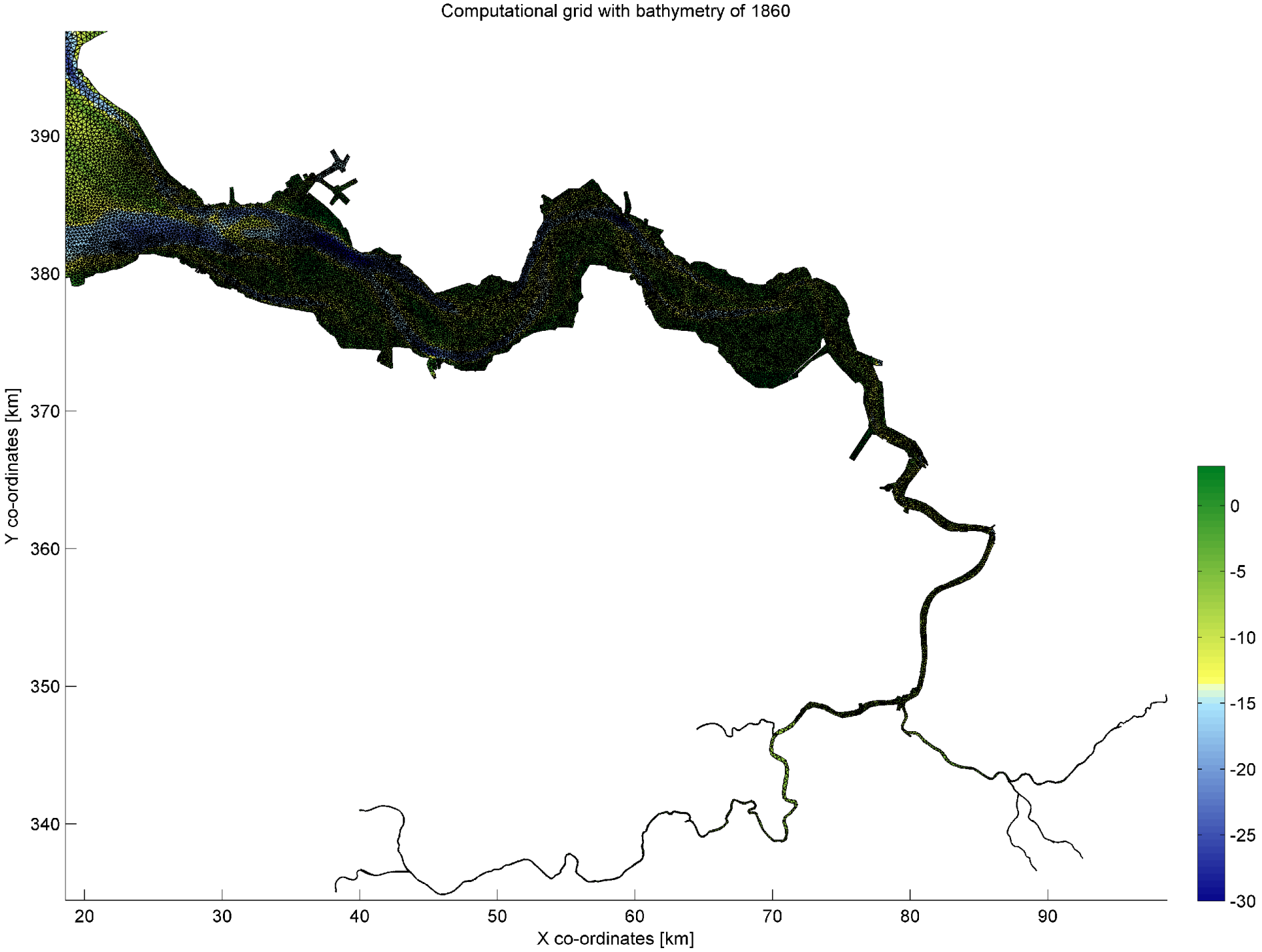
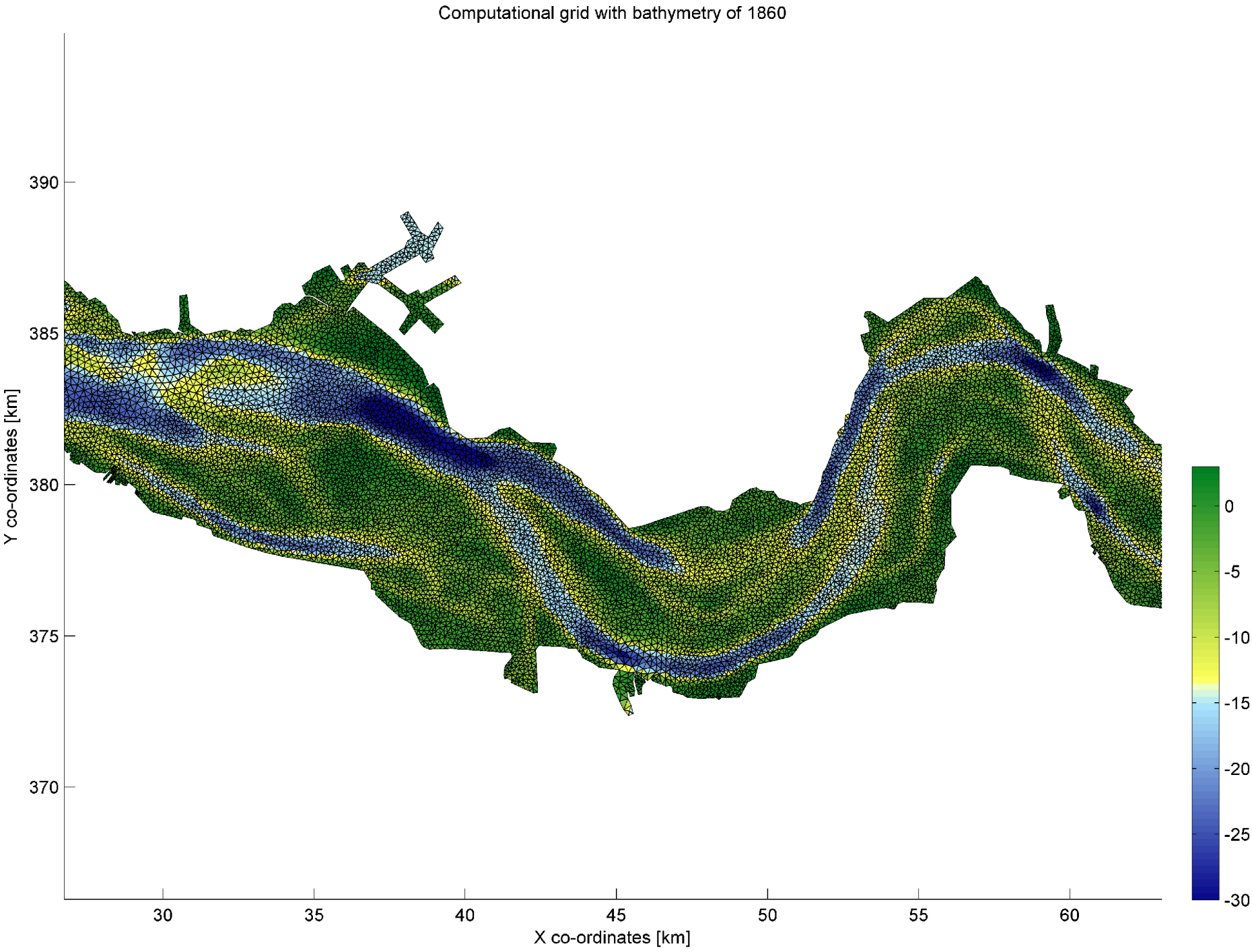

Computational grid with bathymetry of 1860
390
380
370
360
350
340
Y co-ordinates [km]
20
30
40
50
60
70
80
90
X co-ordinates [km]
0
-5
-10
-15
-20
-25
-30

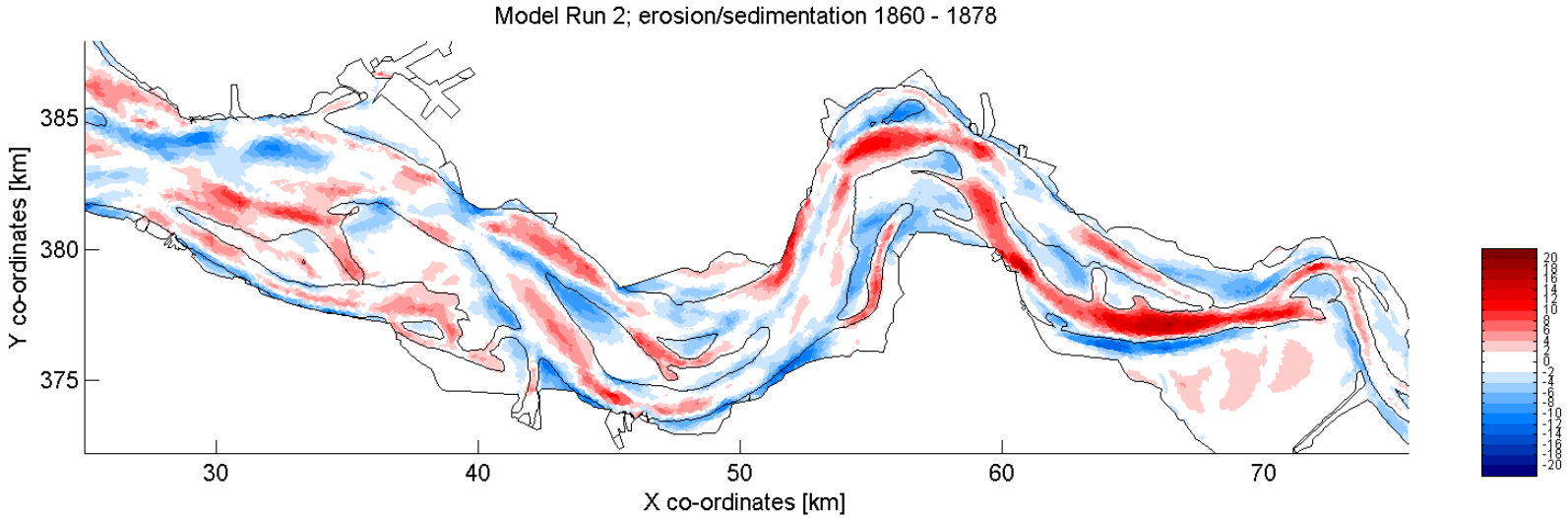

Computational grid with bathymetry of 1860
390
385
380
375
370
Y co-ordinates [km]
30
35
40
45
50
55
60
X co-ordinates [km]
0
-5
-10
-15
-20
-25
-30

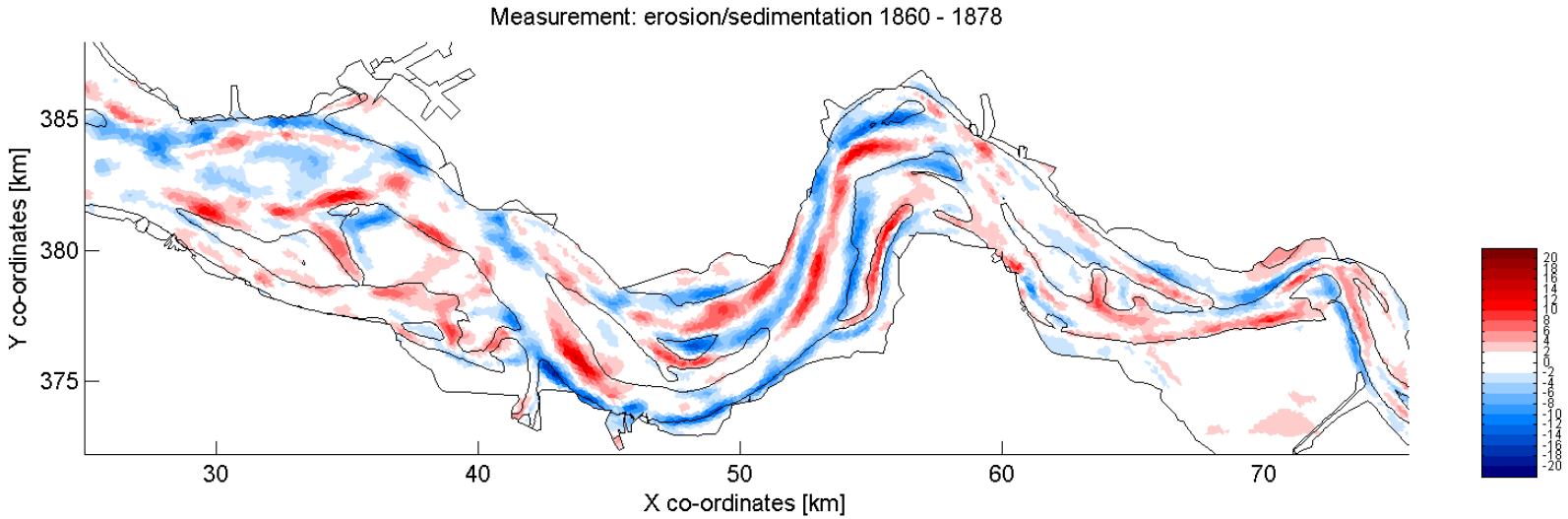
110 years hindcast period 1860 - 1970

Bathymetric recordings in:

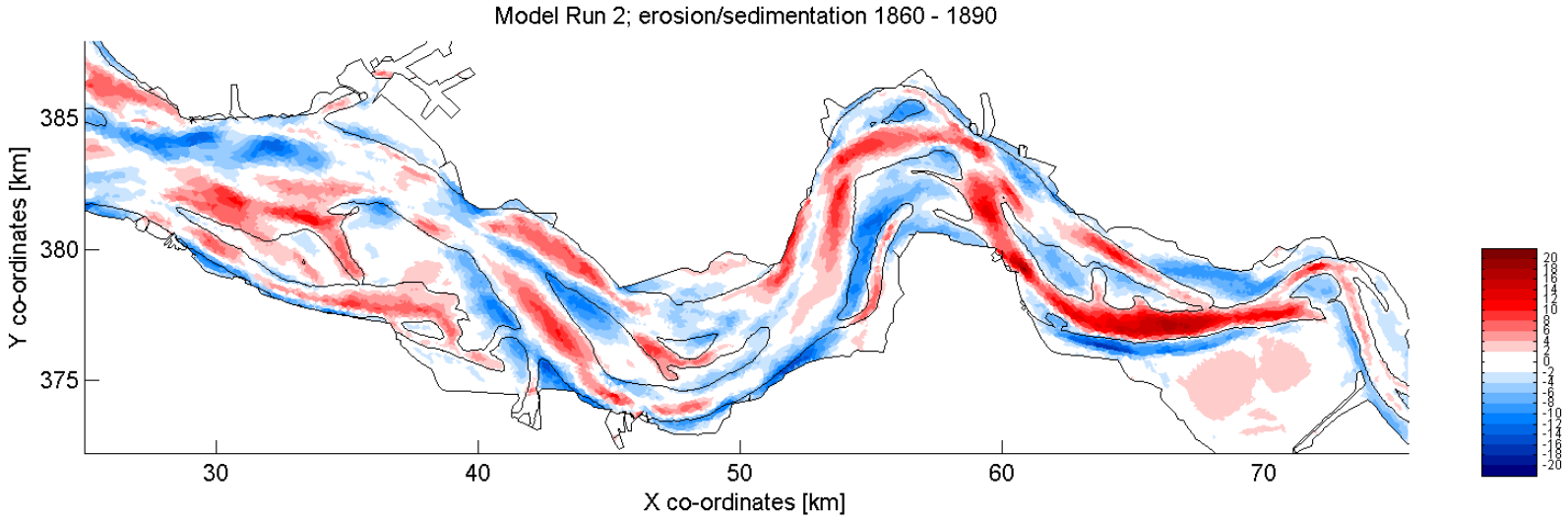
1860- initial bathymetry
1878
1890
1905
1931
After 1955 every 2 years till 1970

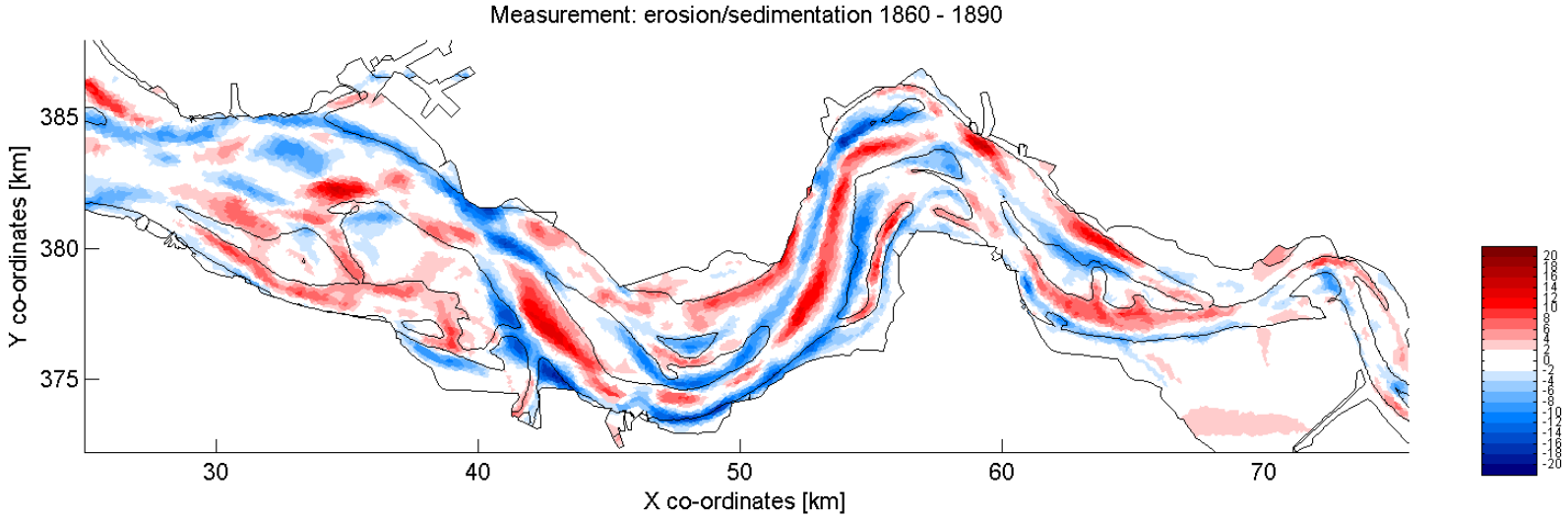
Erosion/sedimentation 1860-1878 (18 years)



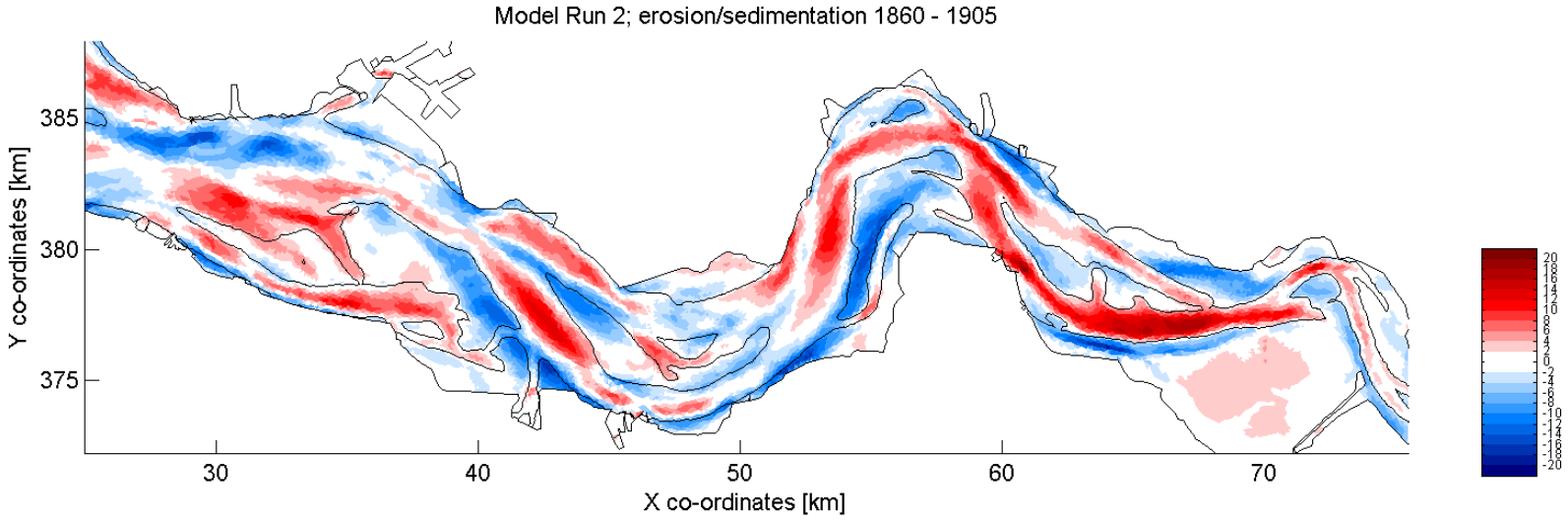


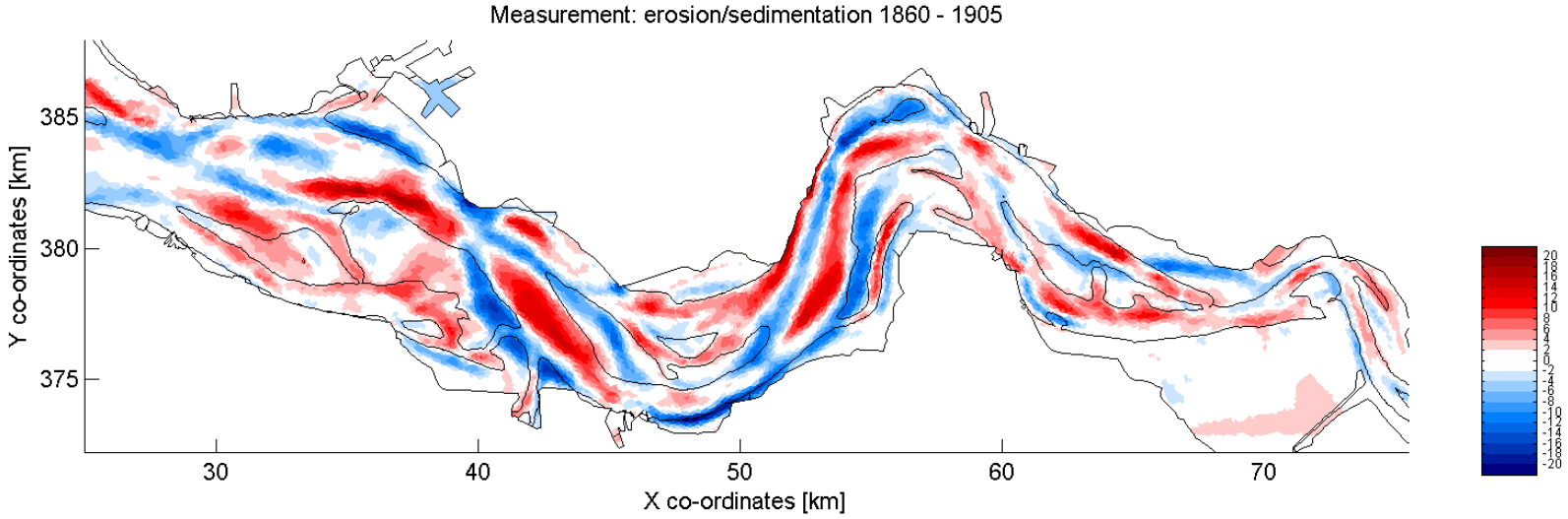
Erosion/sedimentation 1860-1890 (30 years)



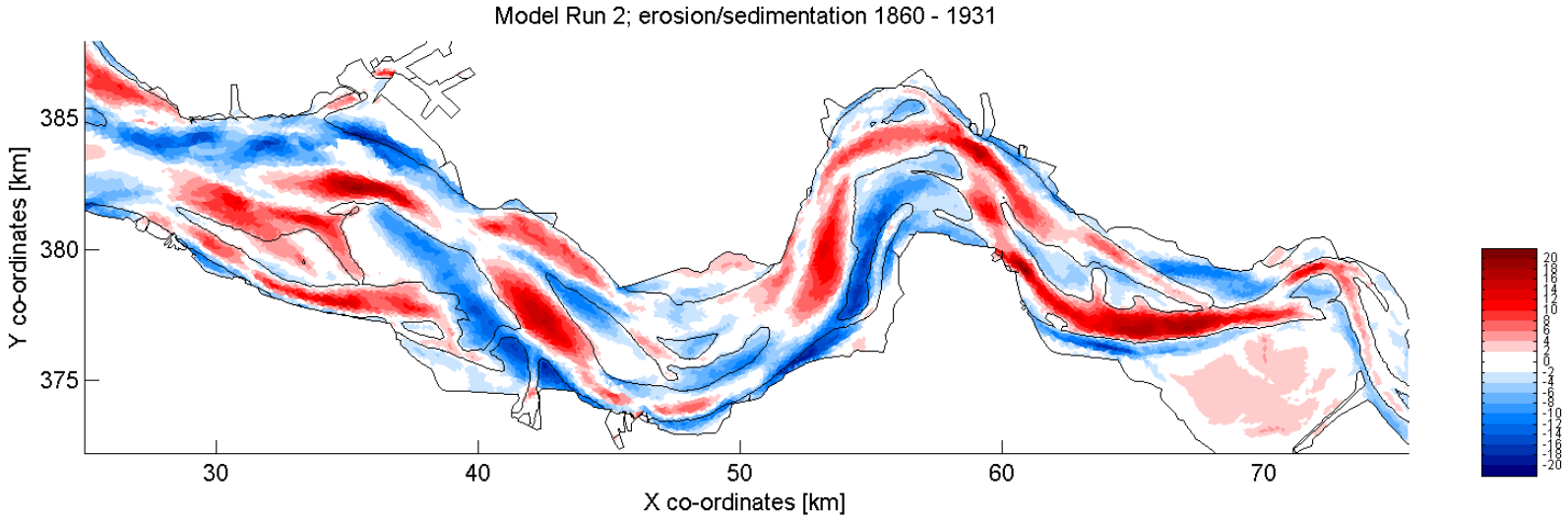


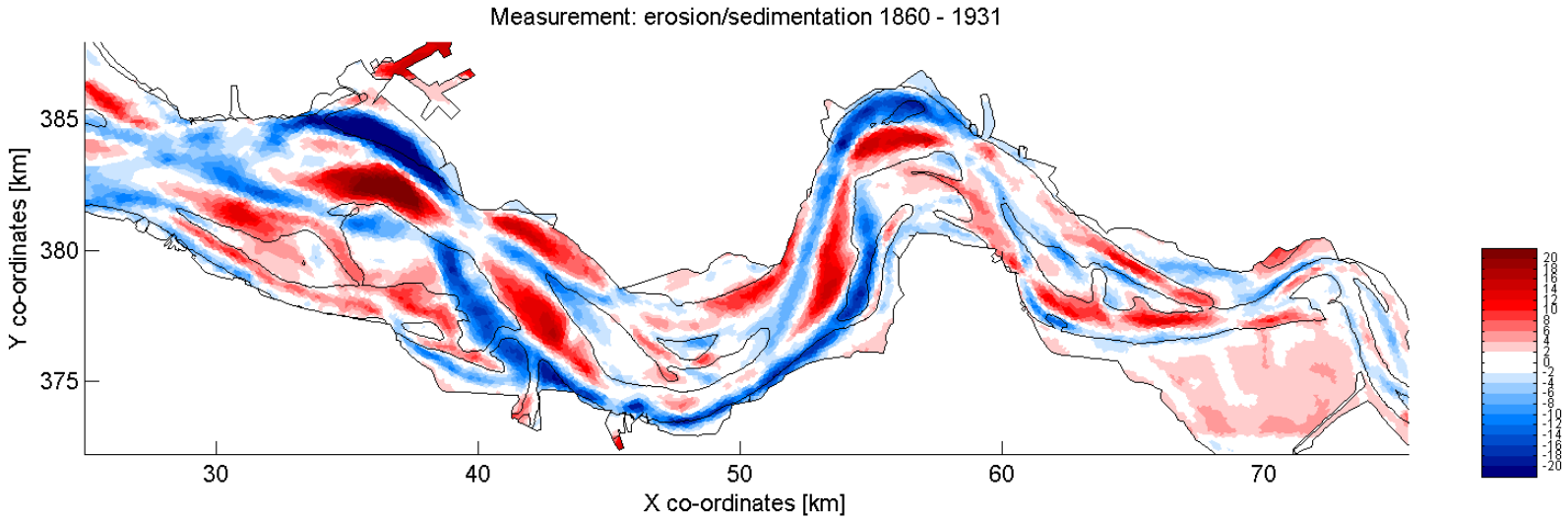
Erosion/sedimentation 1860-1905 (45 years)



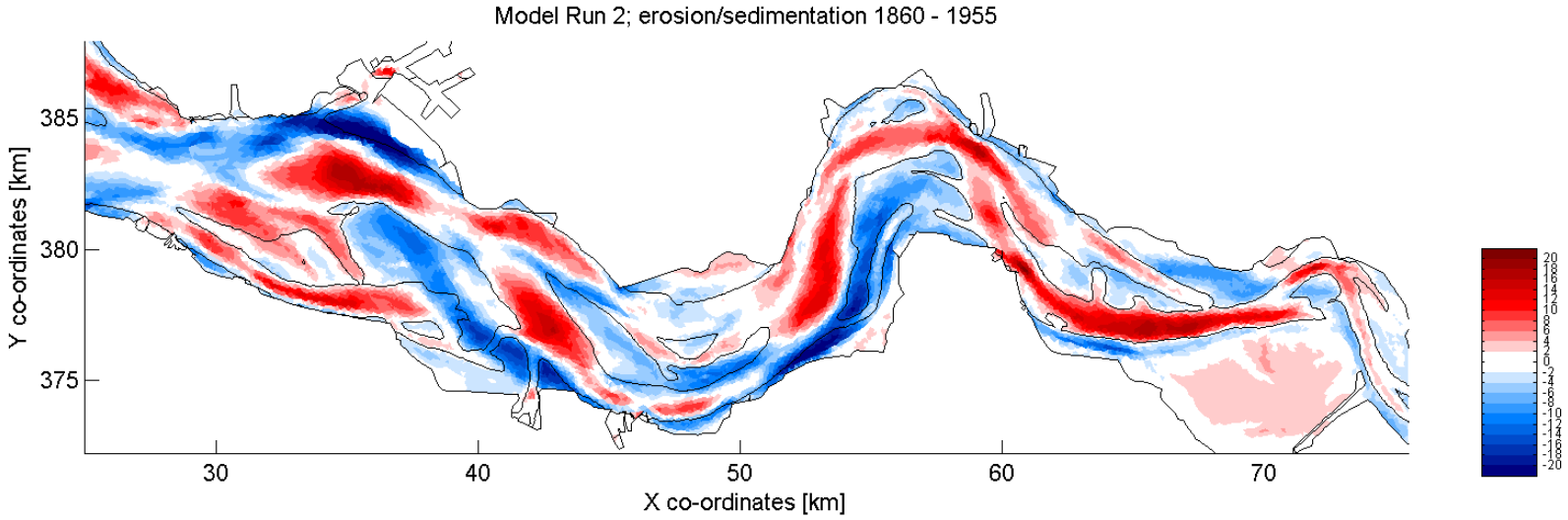


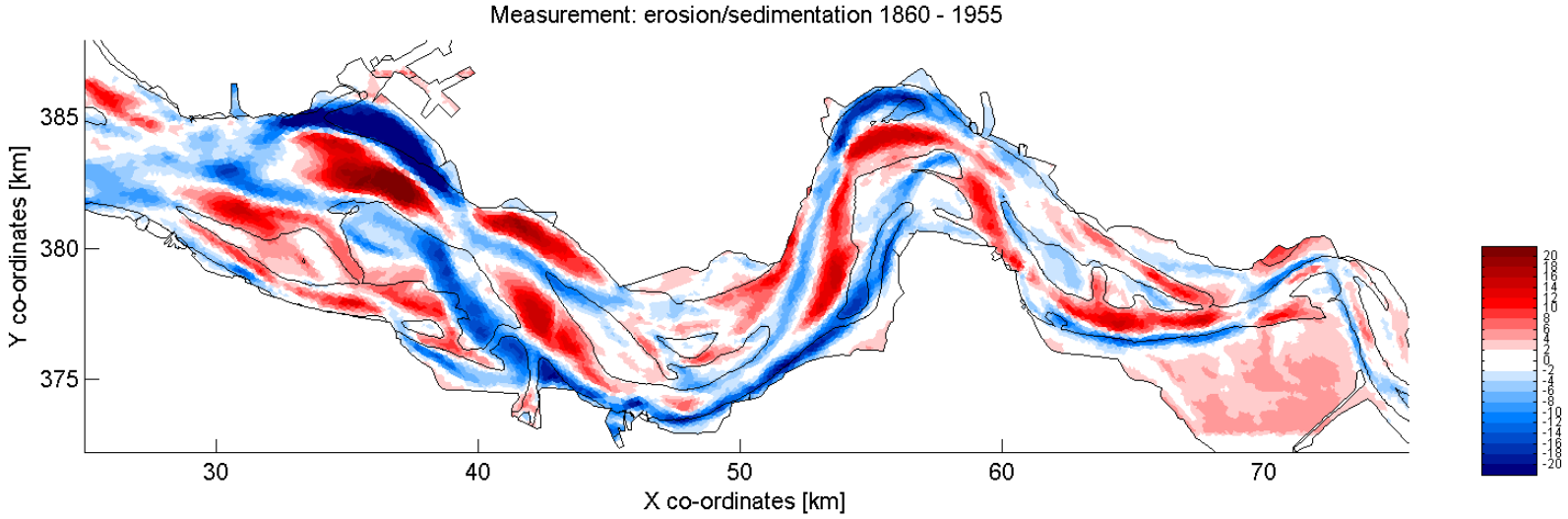
Erosion/sedimentation 1860-1831 (71 years)



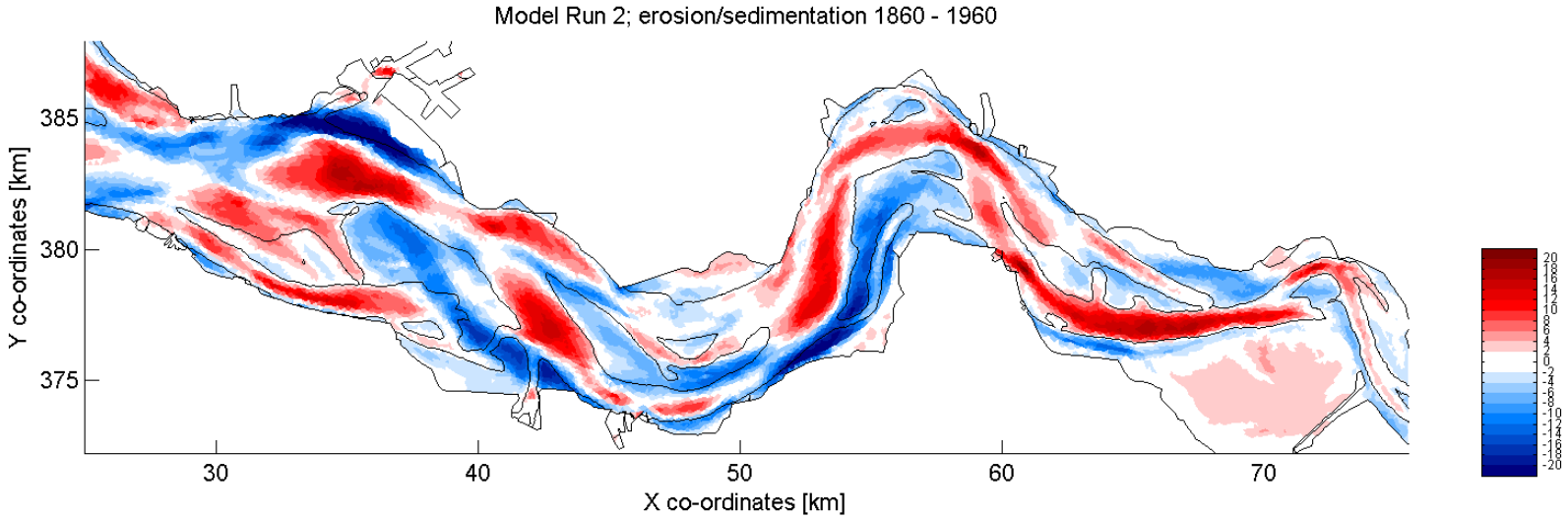


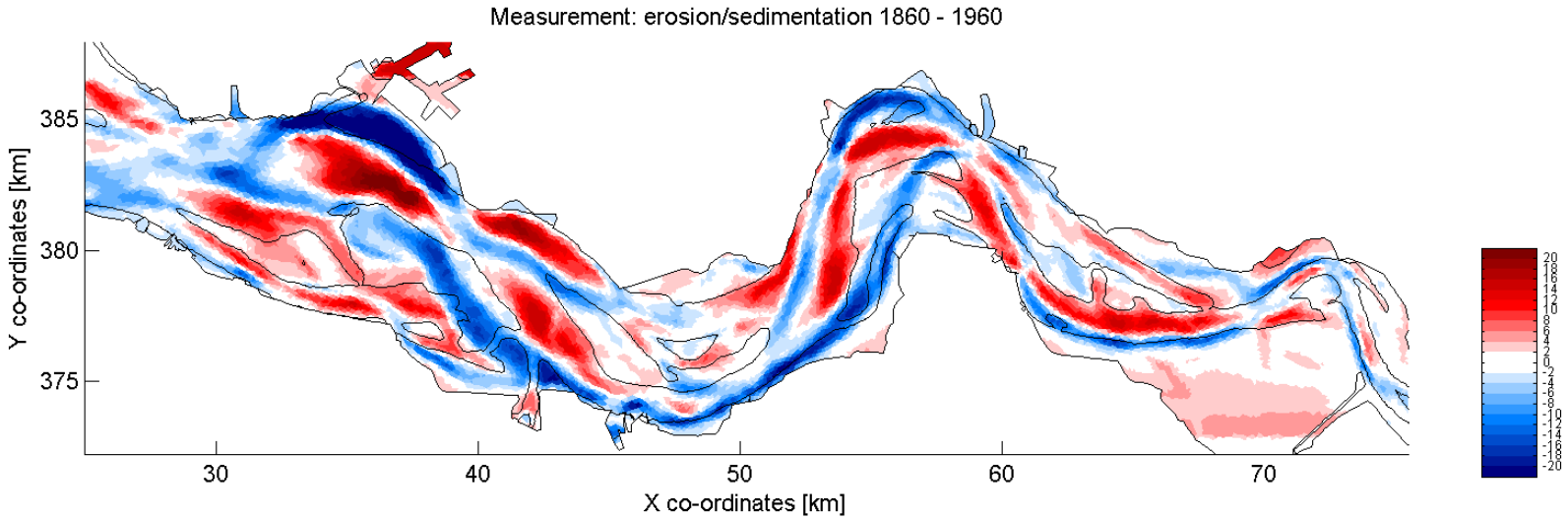
Erosion/sedimentation 1860-1955 (95 years)



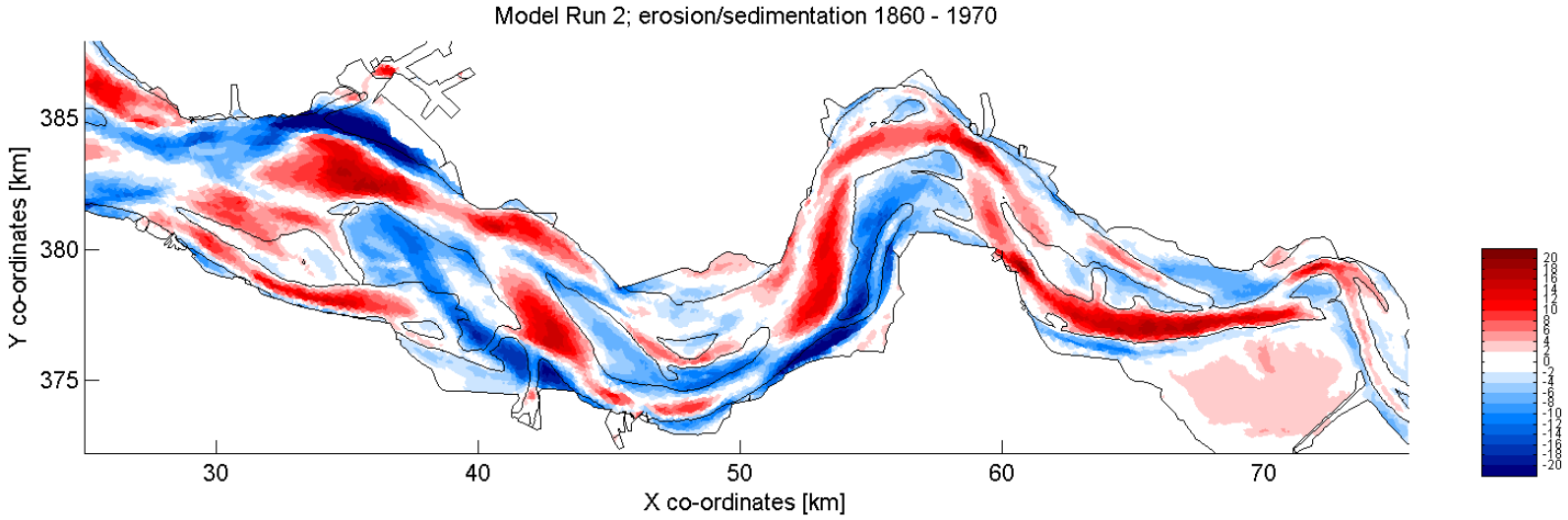


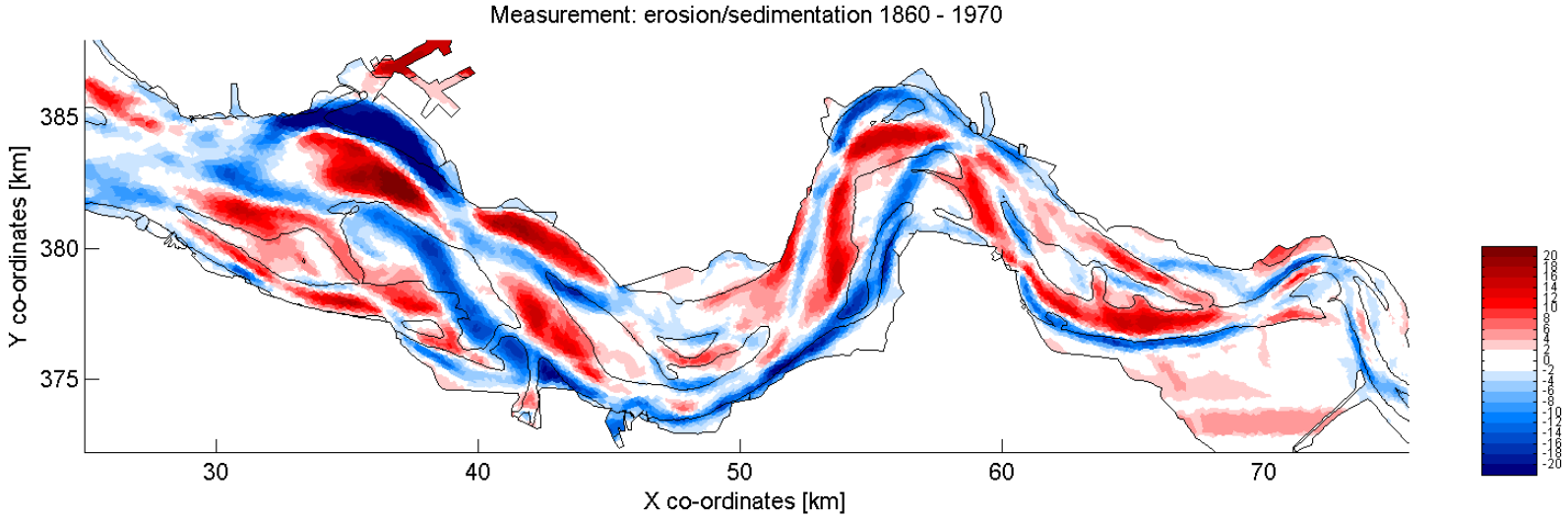
Erosion/sedimentation 1860-1960 (100 years)





Erosion/sedimentation 1860-1970 (110 years)





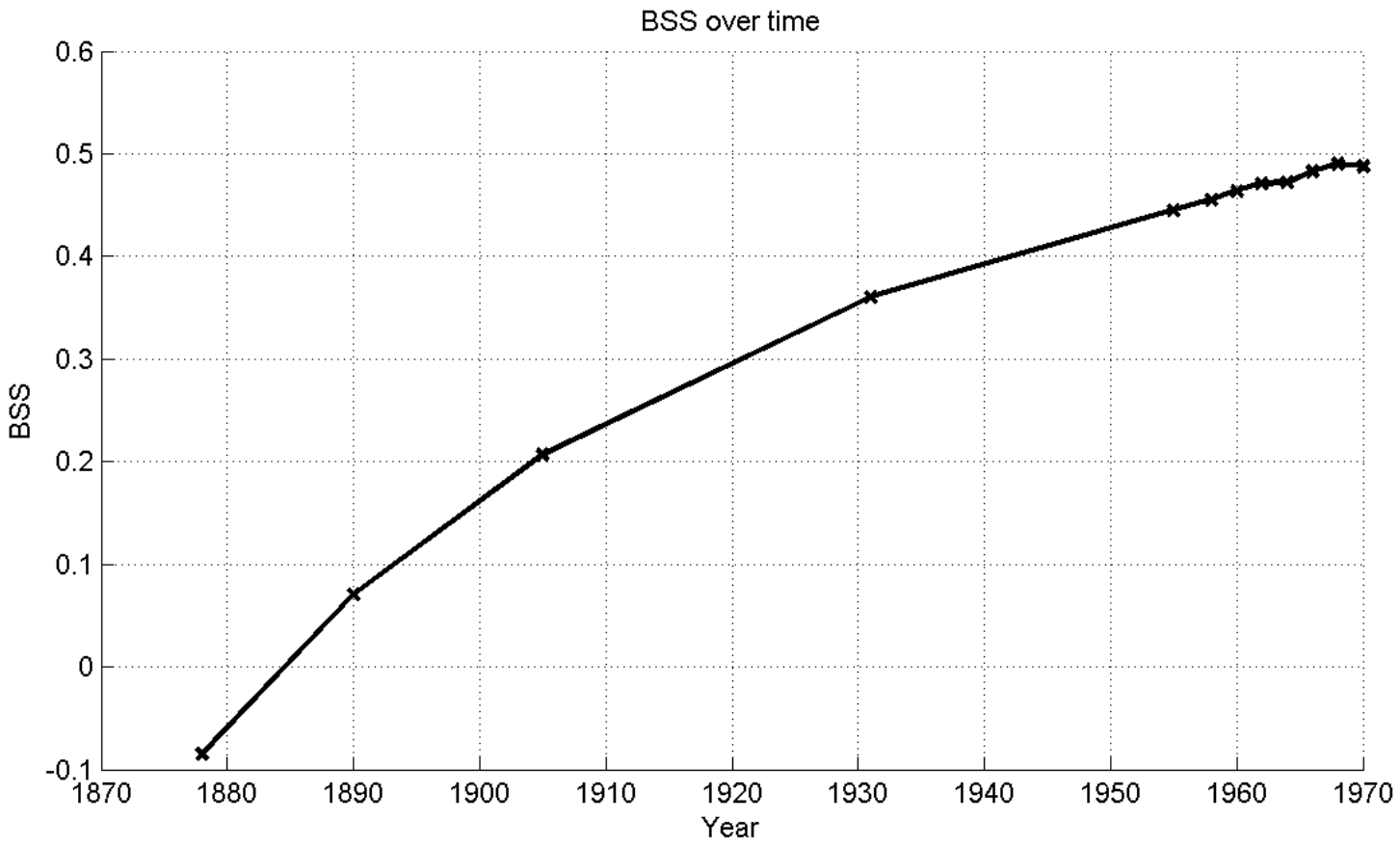
Brier-skill score
(Sutherland et al., 2004)

$$BSS = 1 - \frac{\left\langle (Y - X)^2 \right\rangle}{\left\langle (B - X)^2 \right\rangle} = 1 - \frac{\left\langle error^2 \right\rangle}{\left\langle signal^2 \right\rangle}$$

Where:
Y=Bed level prediction at time T
X=Bed level observation at time T
B=Bed level at t=0
And the <> denote the arithmetic mean.

Rating (van Rijn et al., 2003):
<0 : Bad
0– 0.3 : Poor
0.3- 0.6 : Reasonable/fair
0.6- 0.8 : Good
0.8- 1.0 : Perfect

BSS 1860 – 1970; entire Western Scheldt



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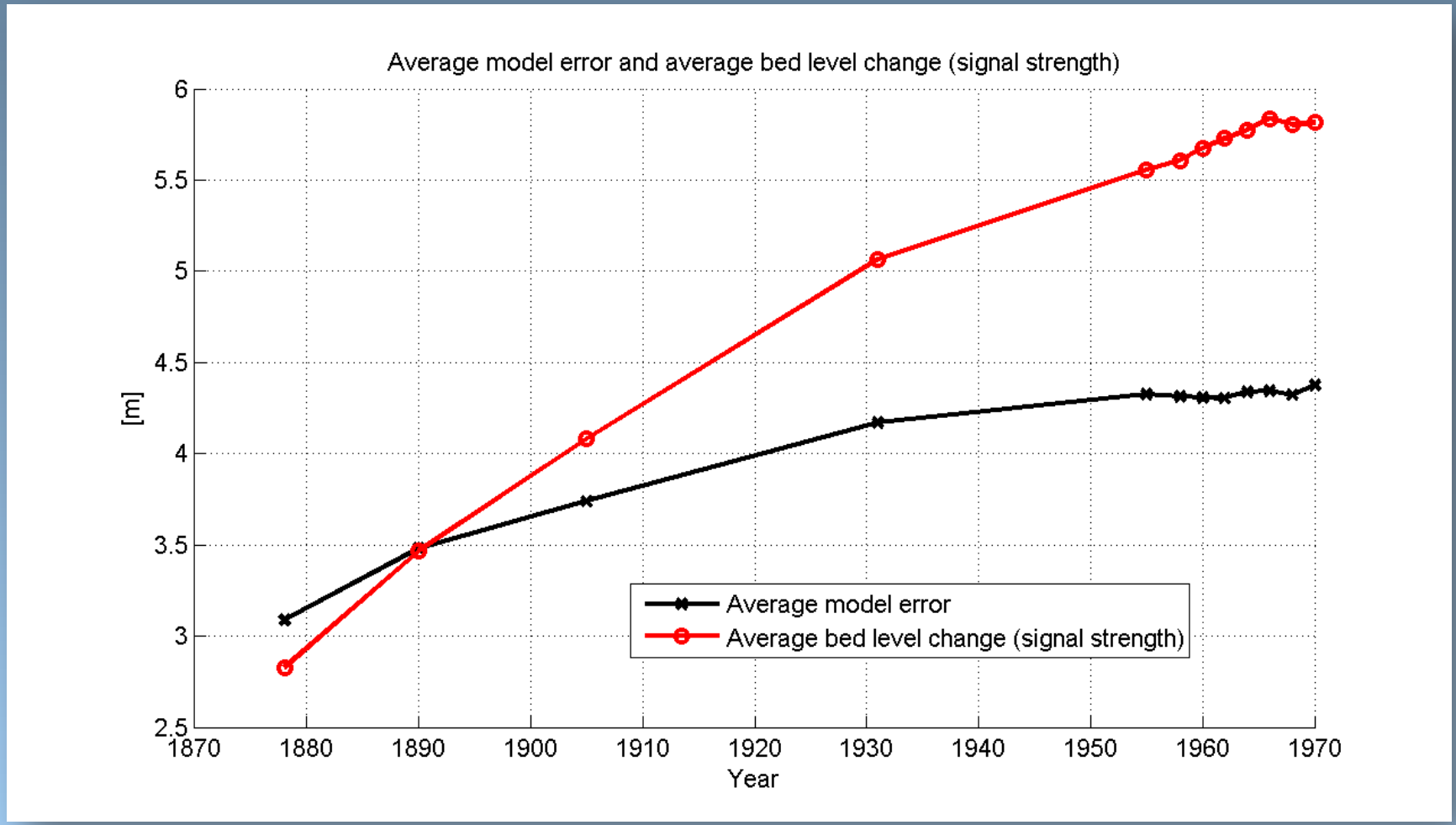
Error and signal 1860 – 1970

$$BSS = 1 - \frac{\left\langle (Y - X)^2 \right\rangle}{\left\langle (B - X)^2 \right\rangle} = 1 - \frac{\left\langle error^2 \right\rangle}{\left\langle signal^2 \right\rangle}$$



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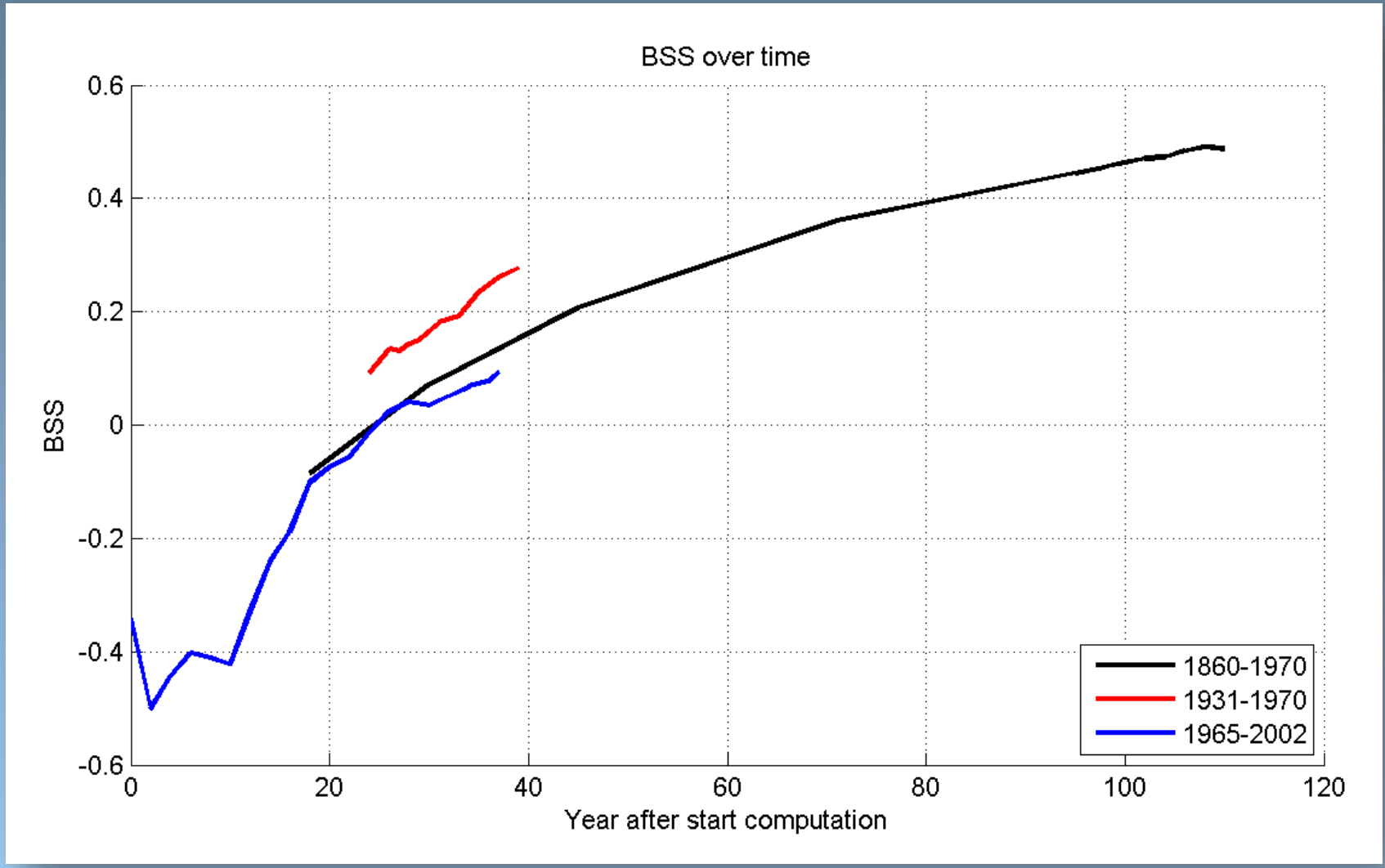
Van der Wegen and Roelvink (2012), Geomorphology

BSS: 3 hindcast periods



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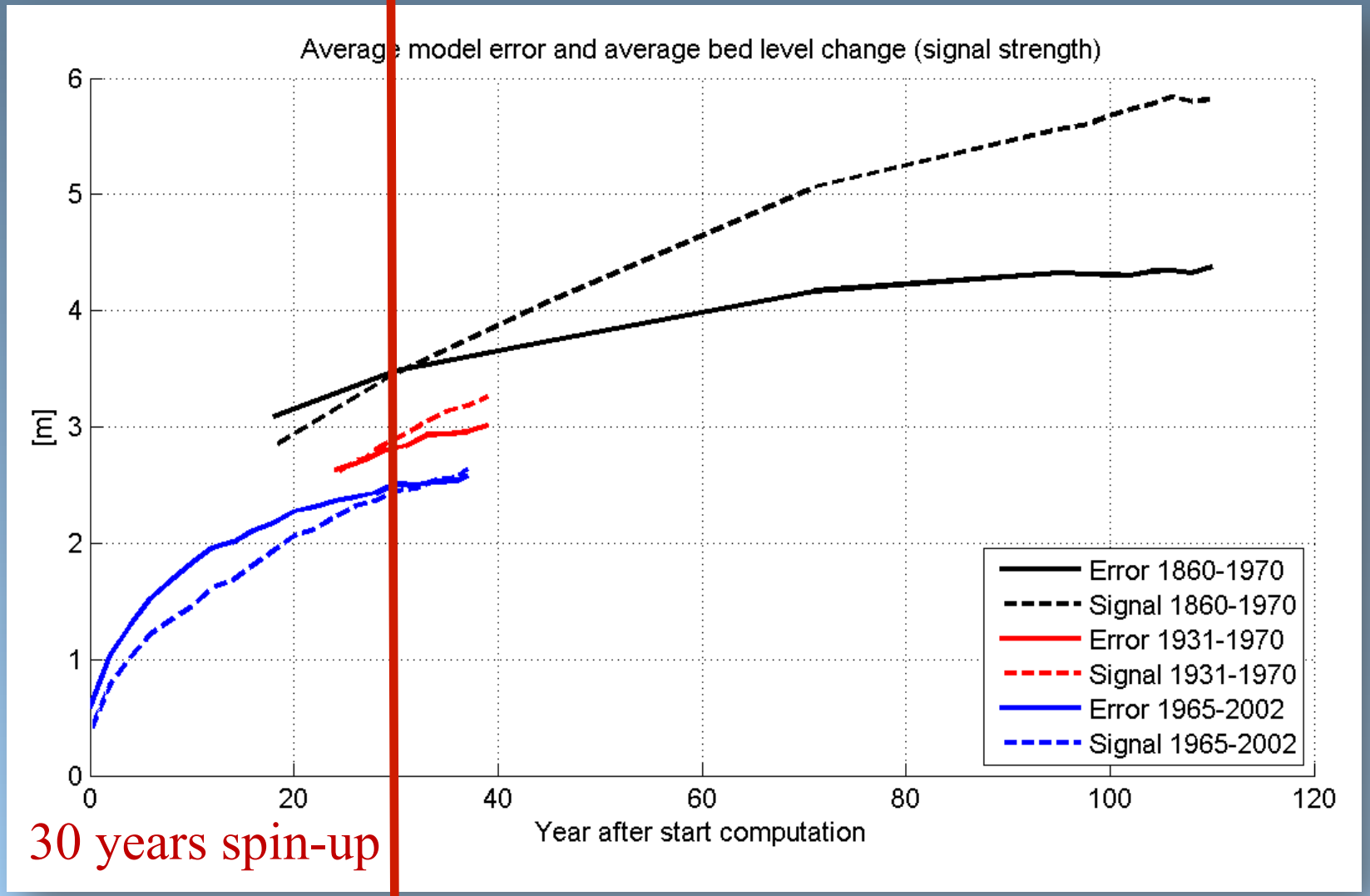
Error and signal; 3 hindcast periods



30 years spin-up

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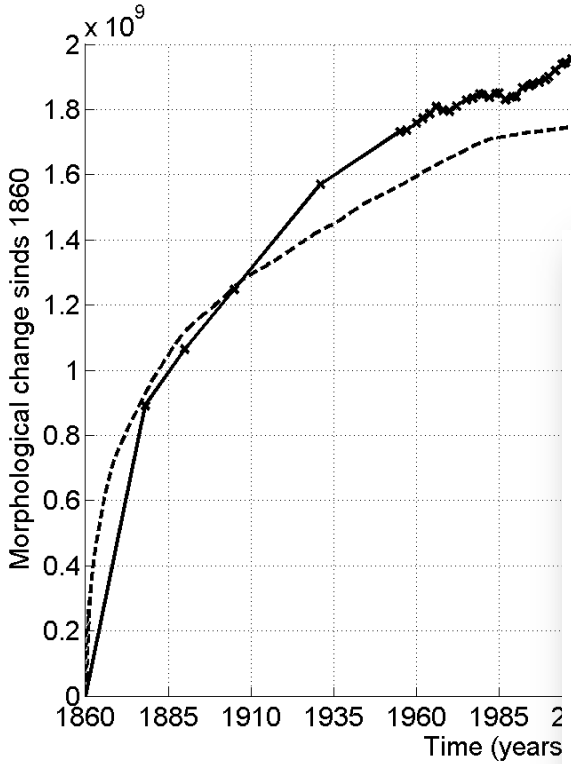
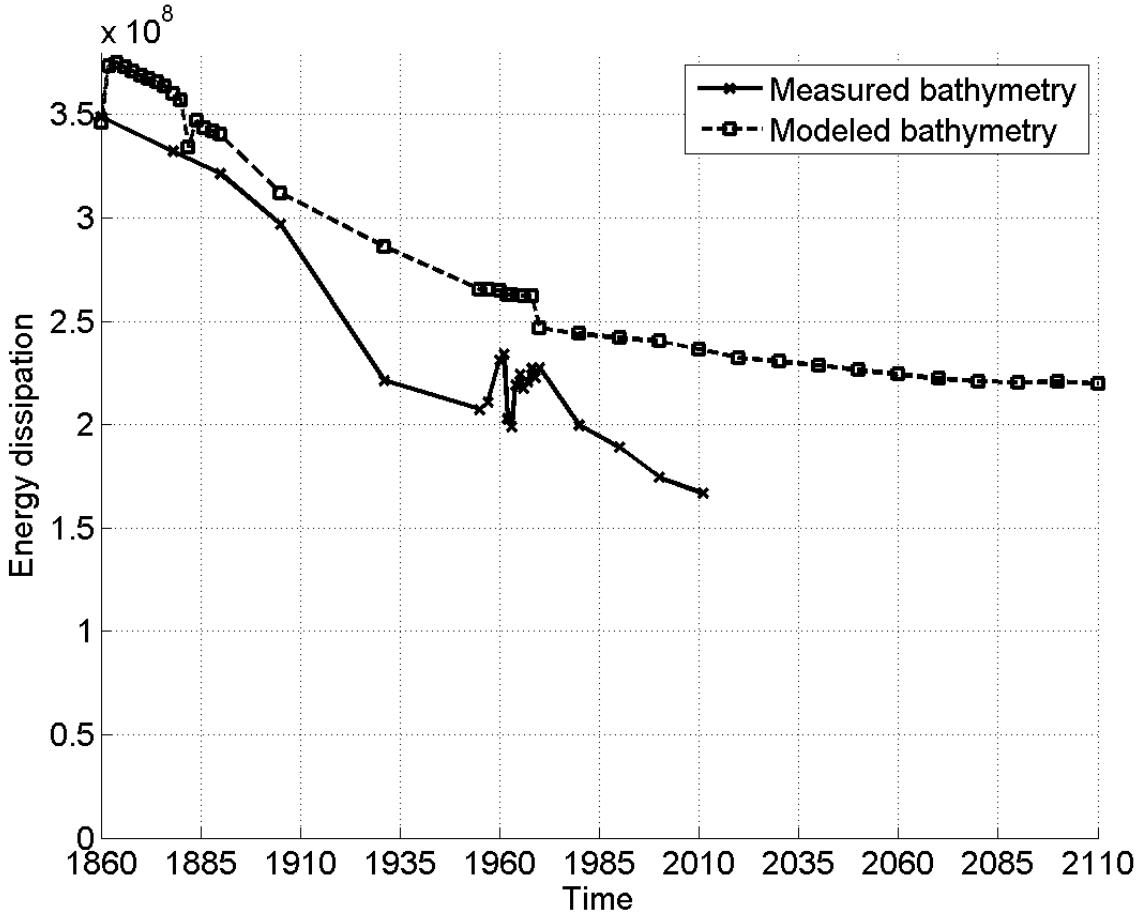
Energy dissipation levels





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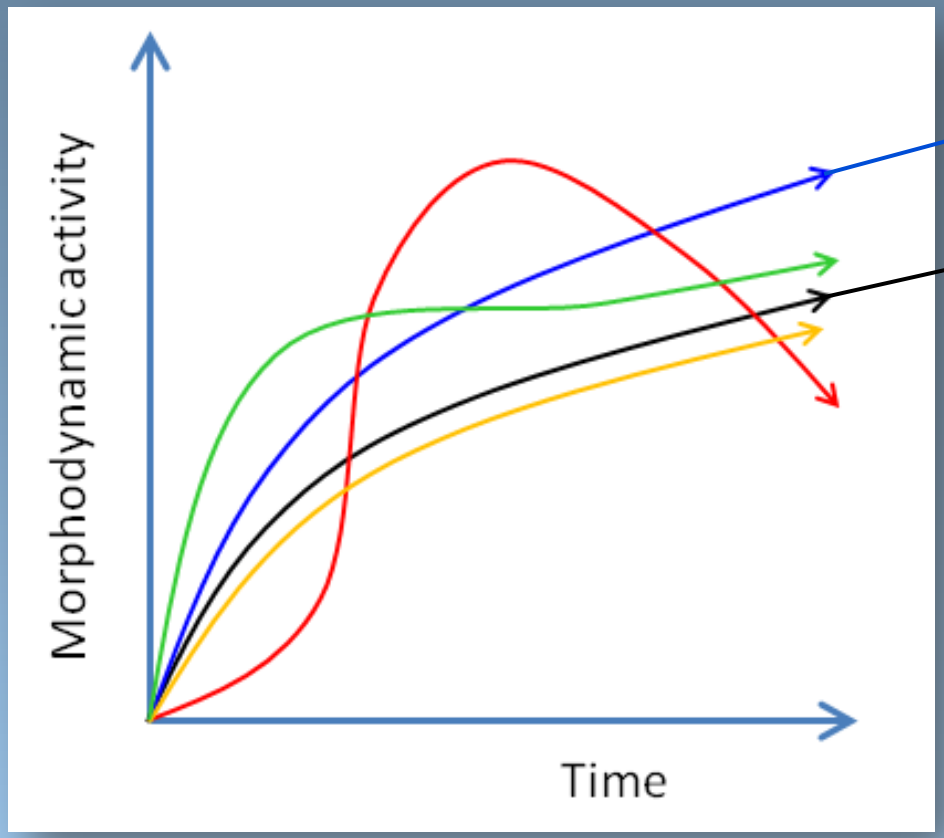
How do process-based models perform?



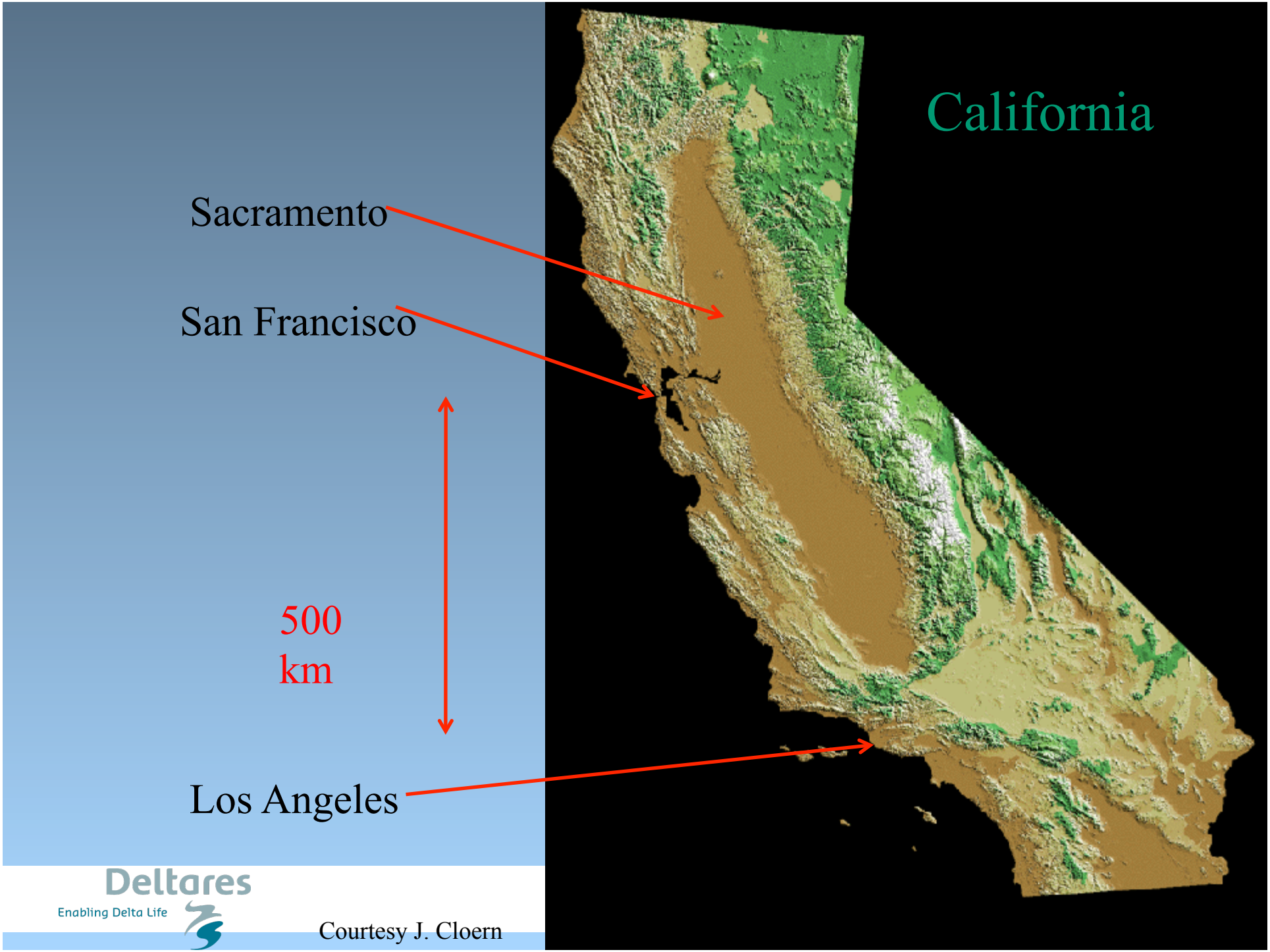
Modeled reality

Measured reality

Remarks

- Performance of process-based model is weak in the first decades, but increases significantly on the longer run
- Model and measurements show decreasing energy dissipation levels and rates
- Application of long-term developments (eg. Sea level rise) seems more valuable than decadal predictions
- How to decrease morphodynamic spin-up time?

Dam et al. (2014), submitted



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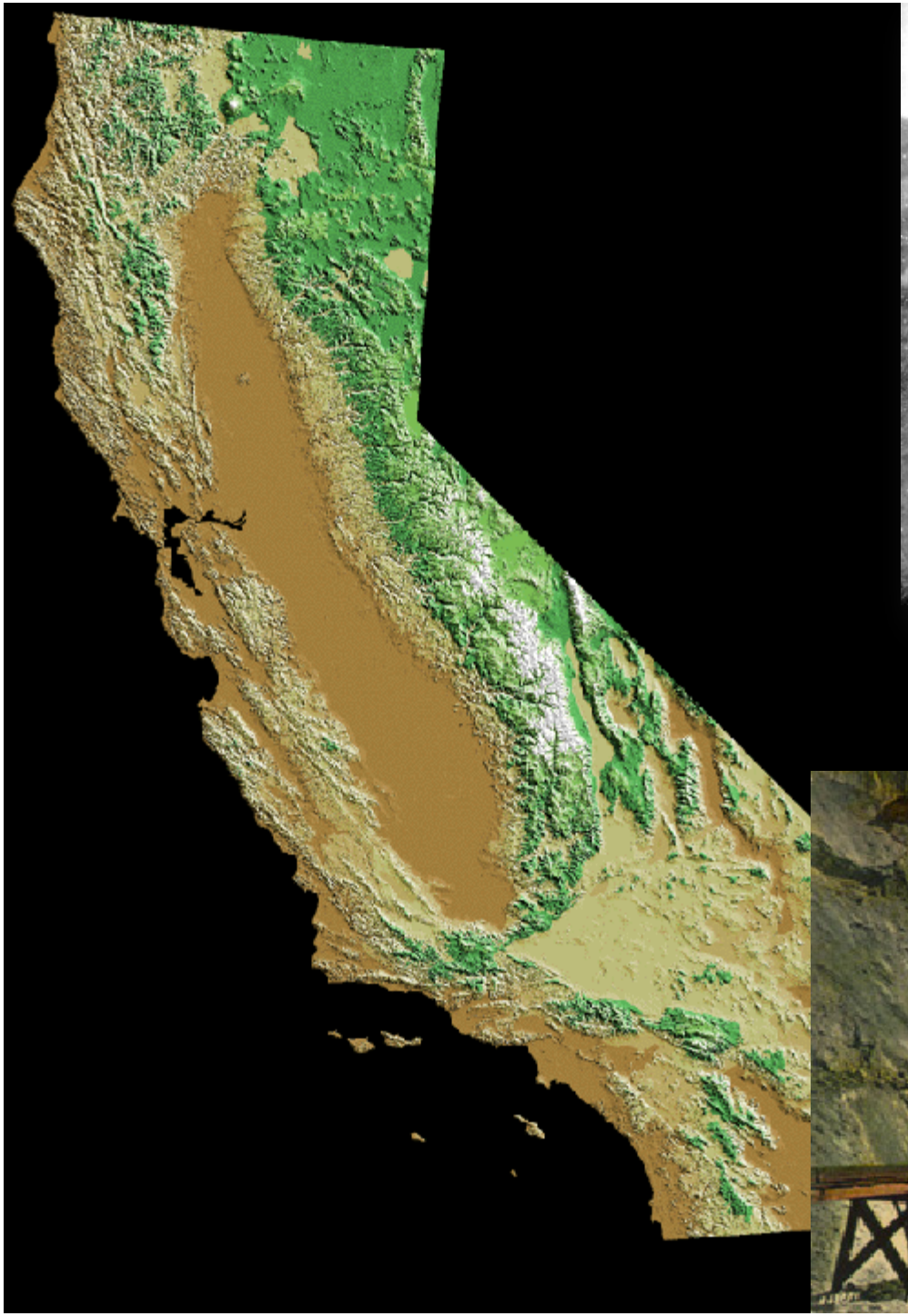
Courtesy J. Cloern


Sierra Nevada
Sacramento R.
San Joaquin R.
Delta
San Francisco Bay
Pacific Ocean
Courtesy J. Cloern

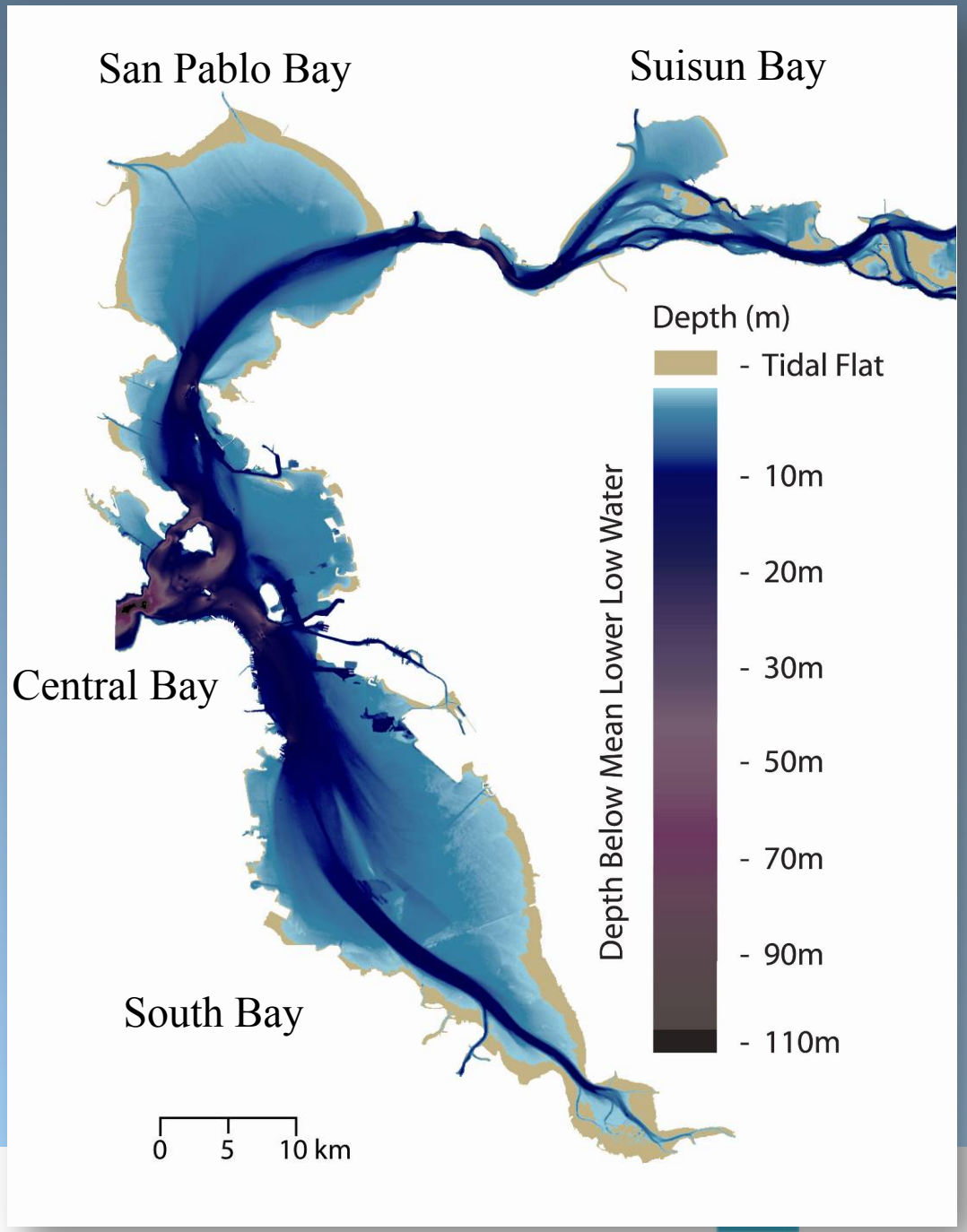


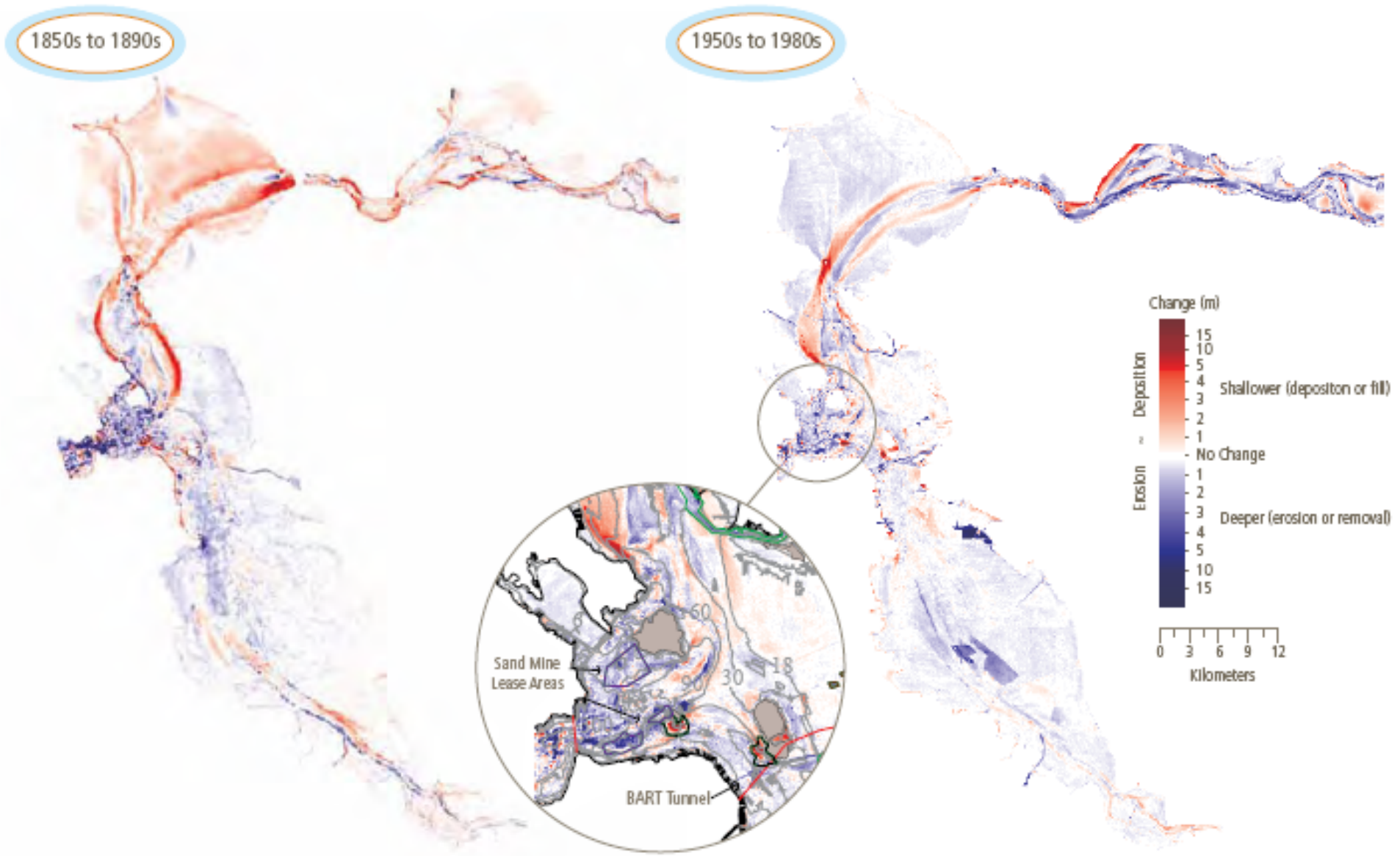
Hydraulic mining

San Francisco Estuary in the 1980s

- Area: ~1200 km^2
- Average depth: 7 m
- Median depth: 3 - 4 m
- Deepest point: ~120 m (Golden Gate)

Jaffe 2009





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The Data

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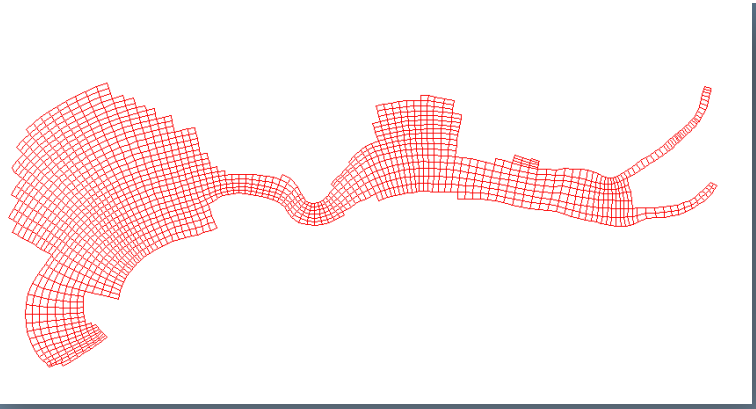
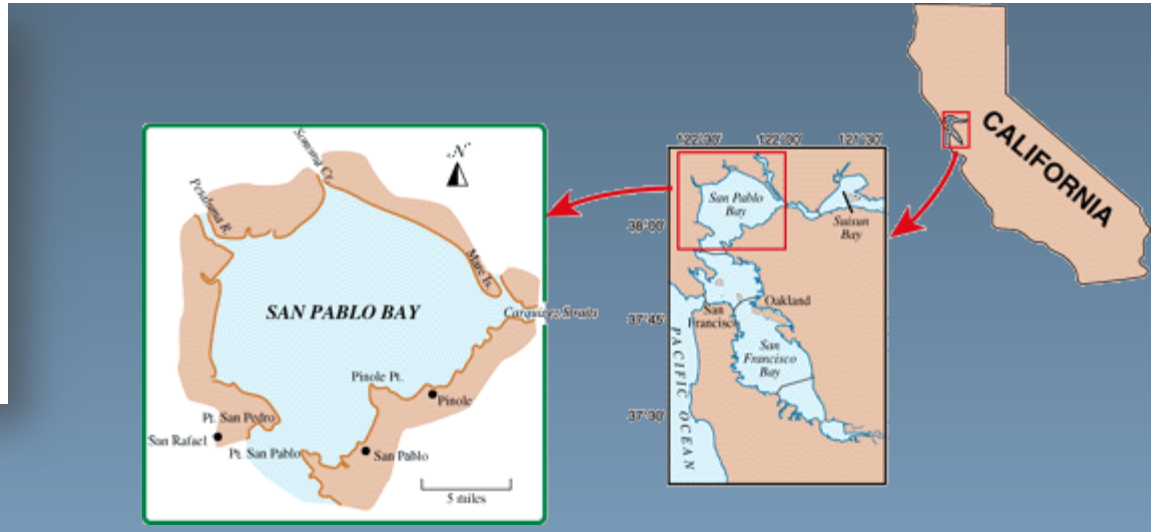
Image obtained from NOAA photo library (www.photolib.noaa.gov)

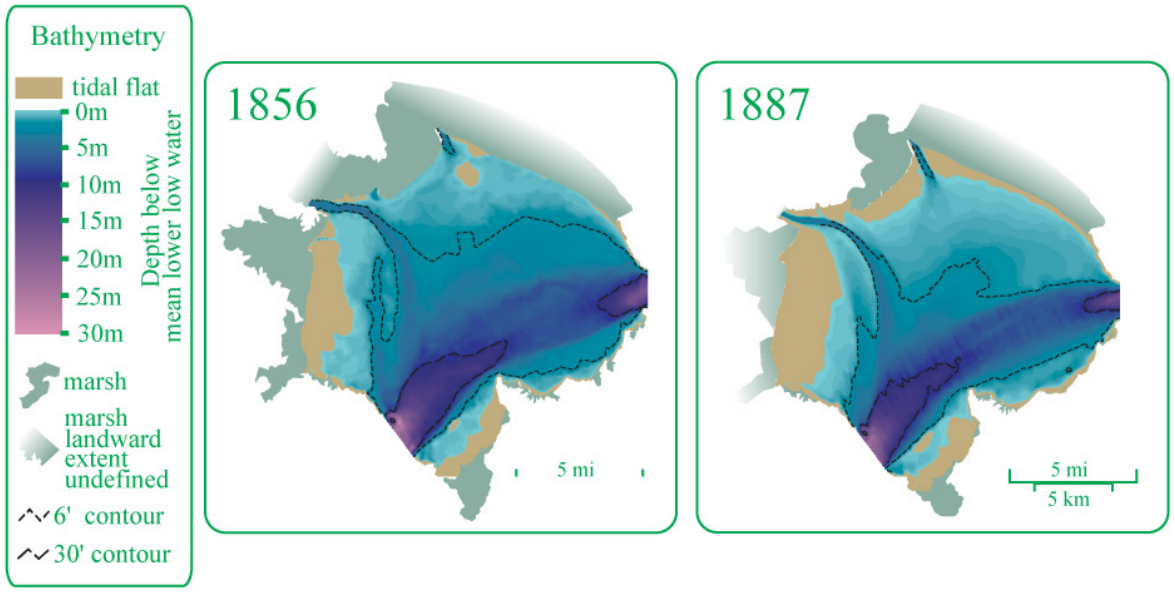


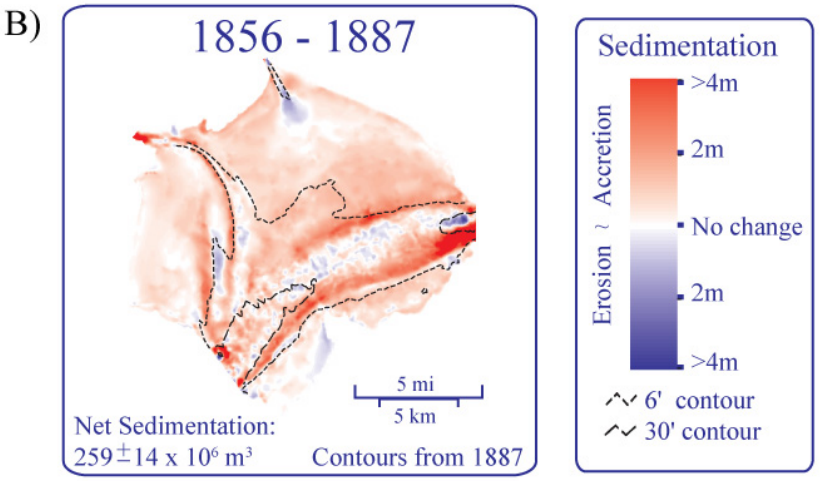


Three characteristic periods

1. Excess sediment supply due to ***hydraulic mining*** about 150 years ago – *measured deposition*.
2. Dramatic decrease in sediment supply after stop in hydraulic mining and ***dam construction*** in the last century – *measured erosion*.
3. ***Climate change*** will further perturb the morphodynamics as sea level rises and the river discharge regimes are altered by warming and precipitation changes – further erosion?

Deposition in San Pablo Bay 1856 to 1887





Jaffe et al. (2007)

Average net **deposition** was

~ 8 million m3/ yr

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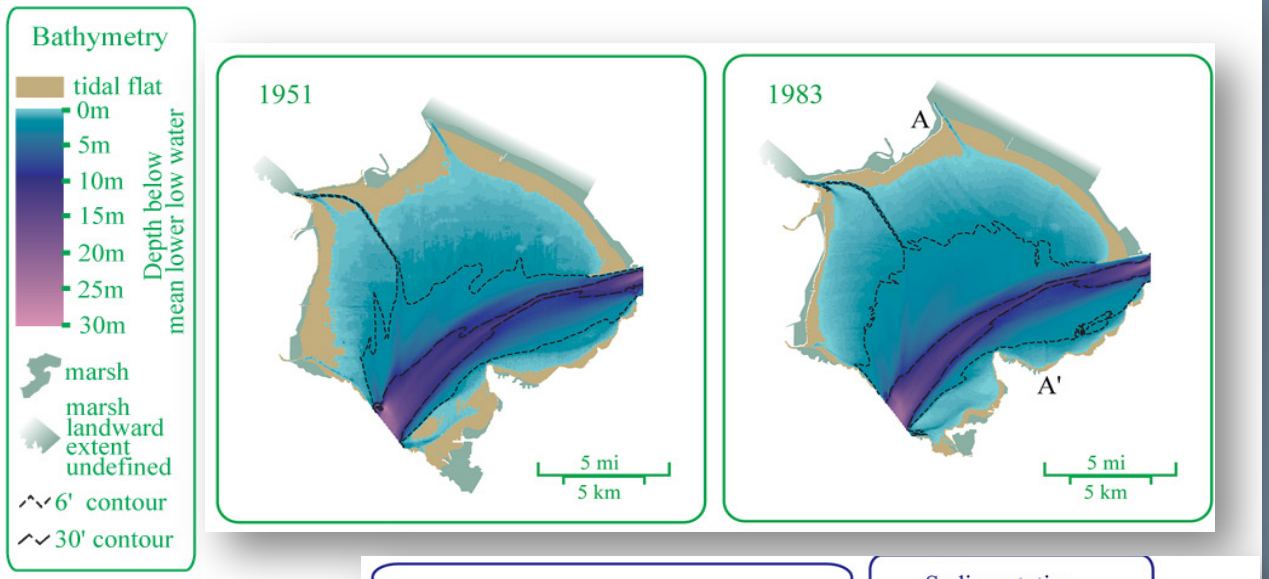
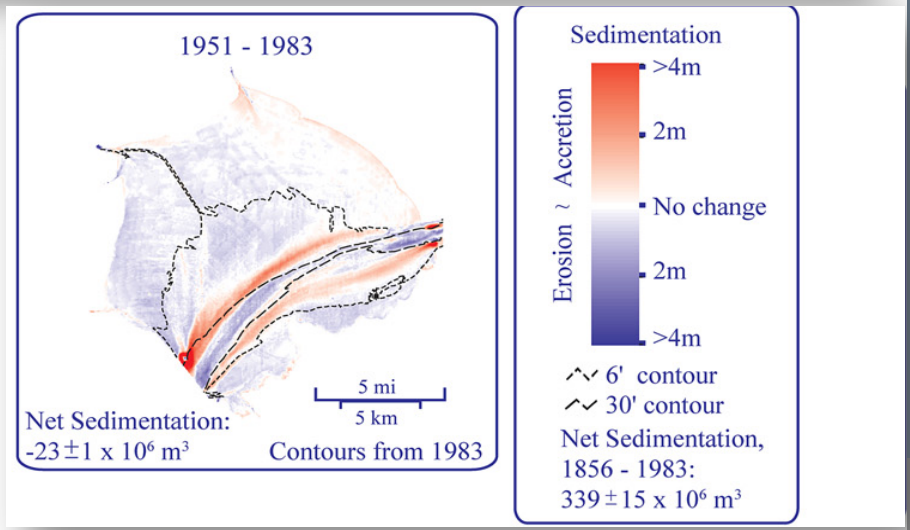
Erosion in San Pablo Bay 1951 to 1983





Jaffe et al. (2007)

Average net **erosion** was

~ 0.8 million m3/yr

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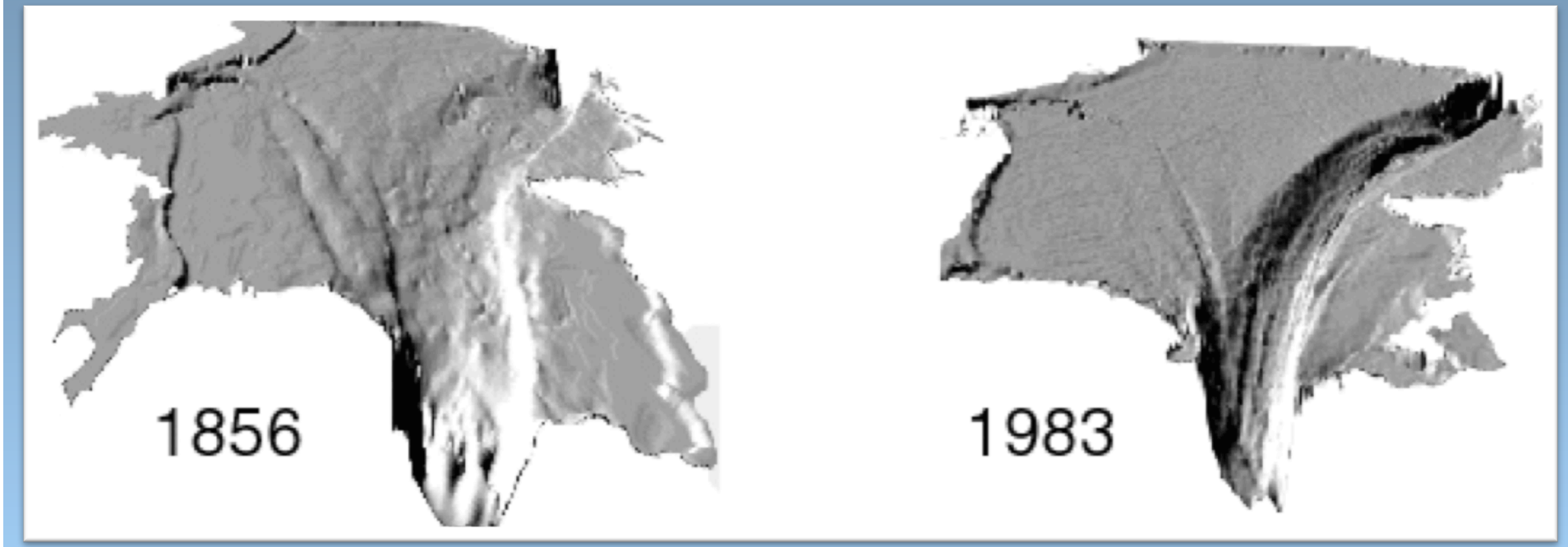

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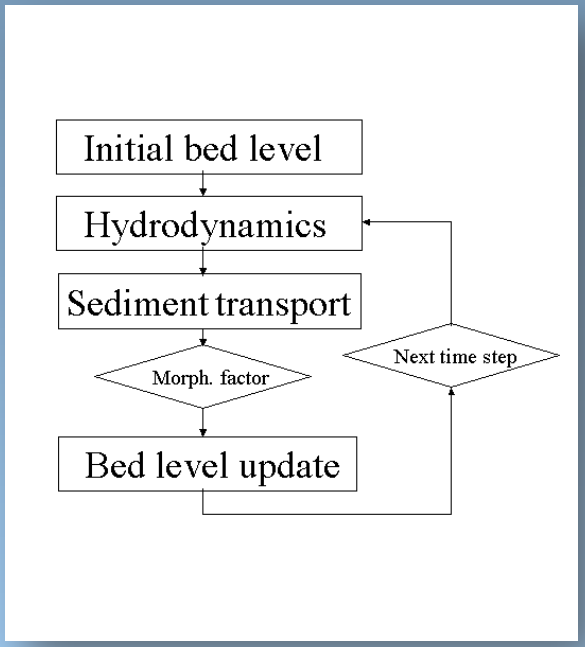
Aim of the study

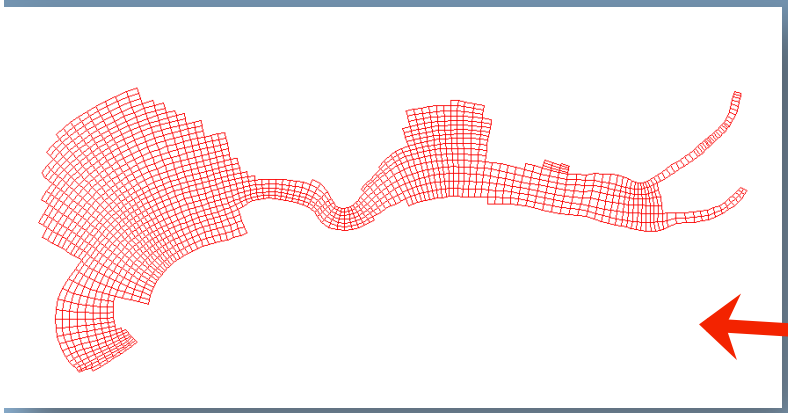
1) To hindcast bathymetric changes in San Pablo Bay with a process-based morphodynamic model.
2) To assess uncertainty levels.
3) To eventually predict future development under climate change scenarios.

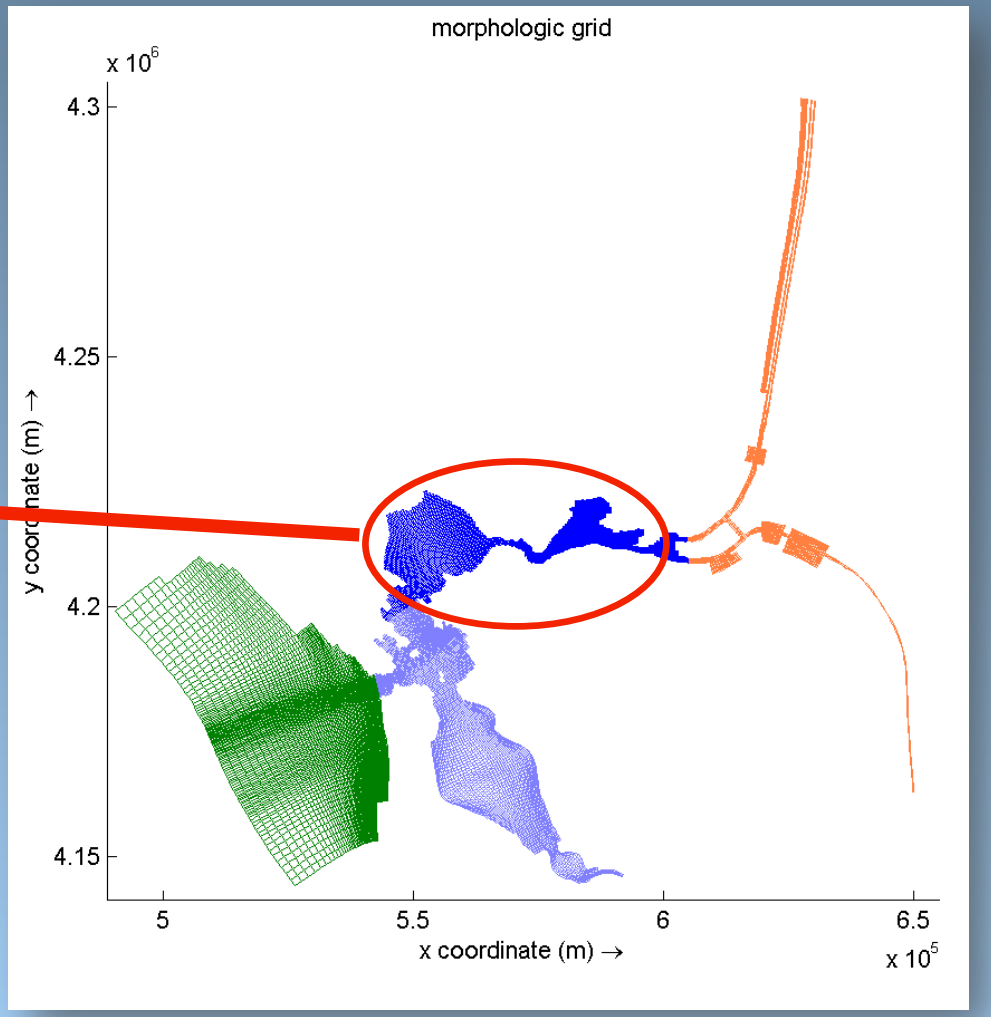
Delft 3D

- Process-based 3D numerical model
- Shallow water equations
- Multiple transport formulations
- Multiple sediment fractions
- Bed slope effects
- Bed level update every time step
- Waves, density currents



Boundary conditions





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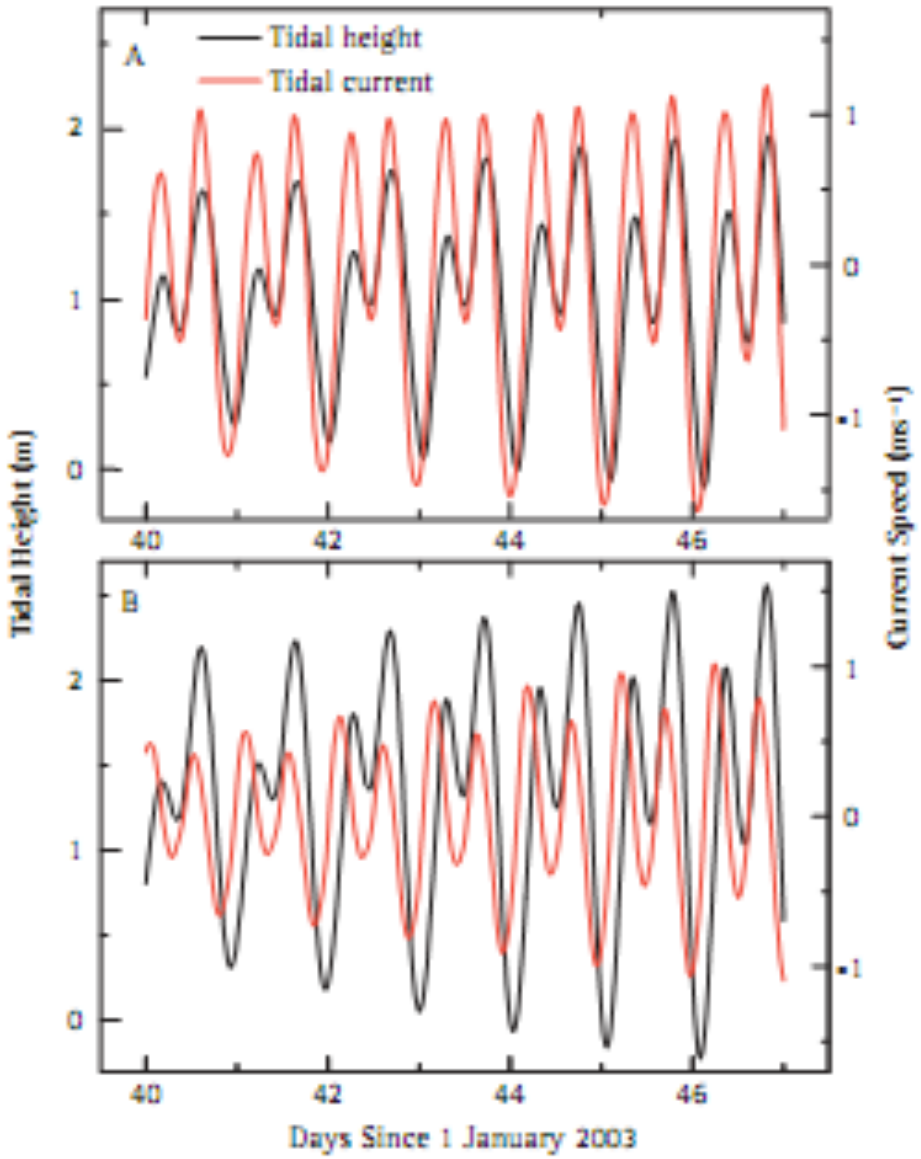
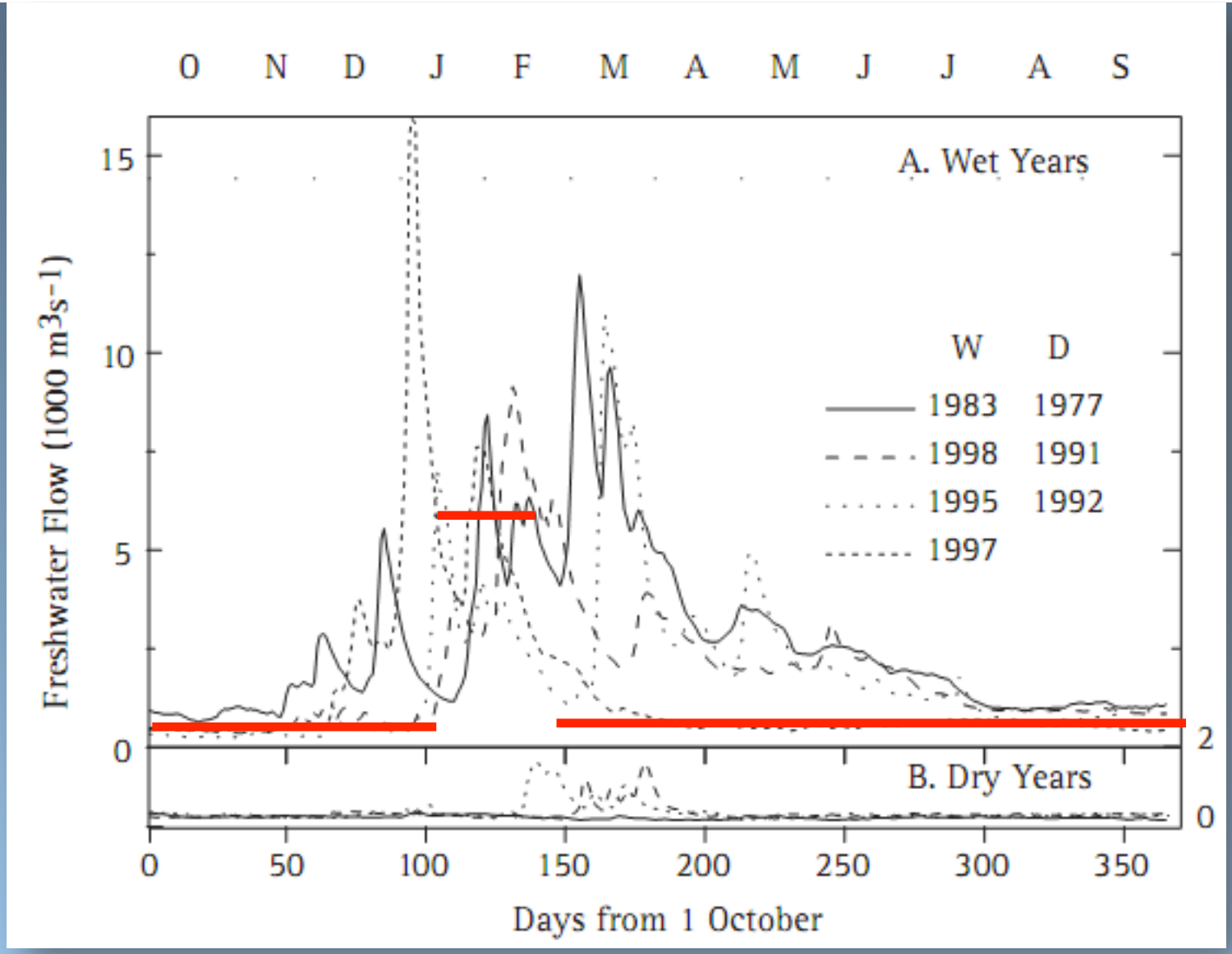


Figure 9. Example of tidal height (black lines, left axis) and tidal currents (red, right axis) for a single week. A., Carquinez Strait in the northern estuary; B., San Mateo Bridge in South Bay.

Schematization by applying only M2, M4, K1 and O1 at the boundaries



Sediment supply via $Qs = \alpha Qr^{\beta}$ (historic proxy by Ganju et al (2008))

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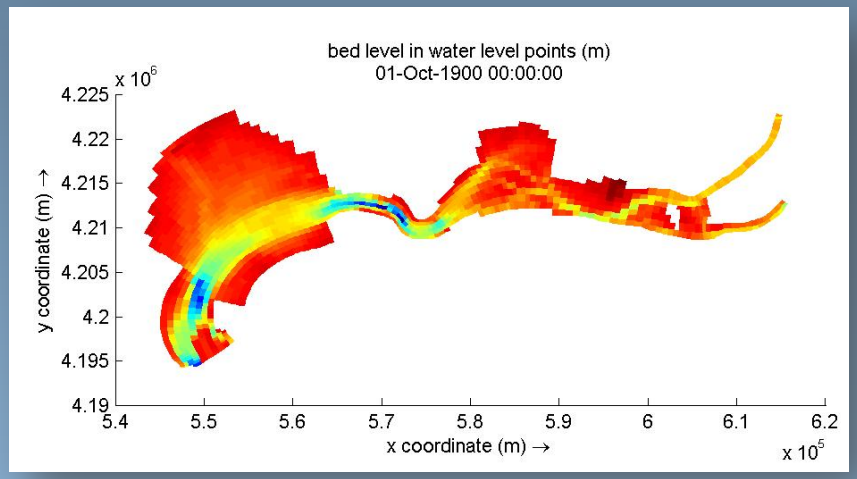
Model schematization

- Wind diurnal with 7 m/s around noon
  - 6 months from the west
  - 5 months from south east
- Sediment transport formulae
  - Van Rijn for sand, 3 fractions
  - Krone/Partheniades for mud, 5 fractions

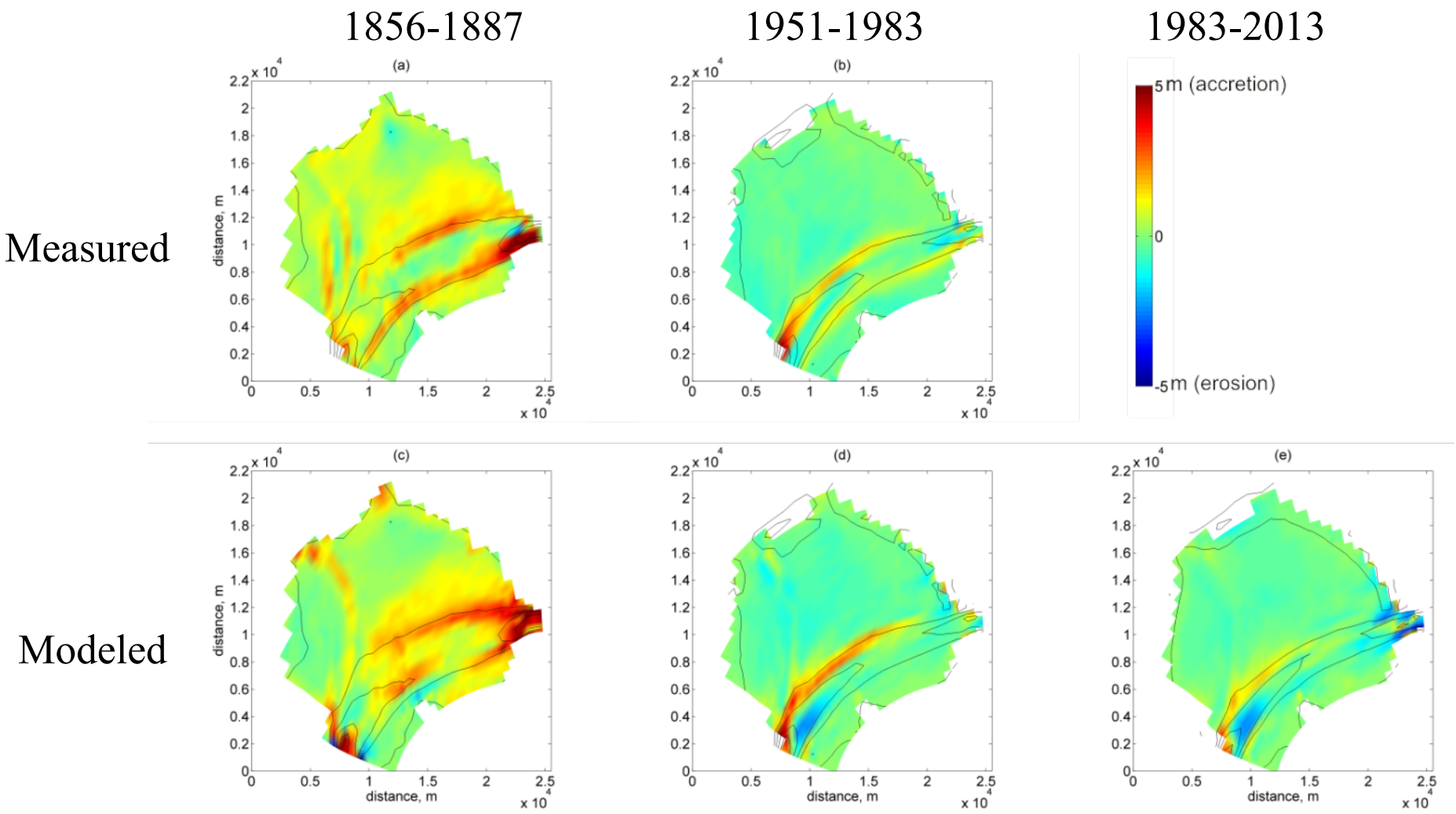


Unknown parameters

Sand fractions	9
Mud fractions	20
Wind	4
Flow	10
Wave	10
Total	**53 !!**

Some physically unknown (not measured)
Some introduced by schematization (time-saving)

Can a process-based model (like Delft3D) reproduce decadal morphodynamics?



Van der Wegen et al. (2011), OD and JGR

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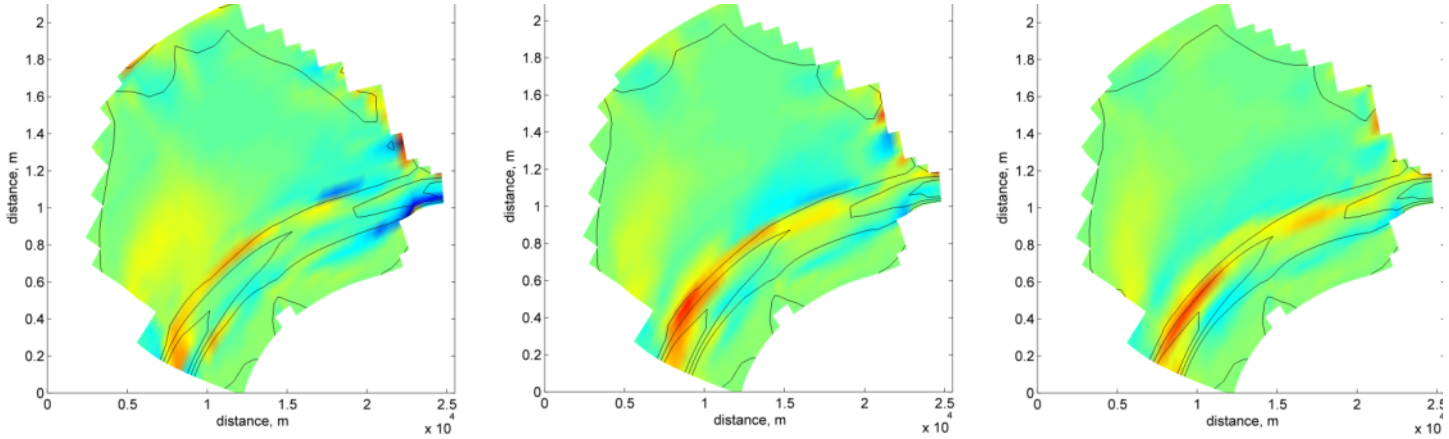
Constant mean sea level

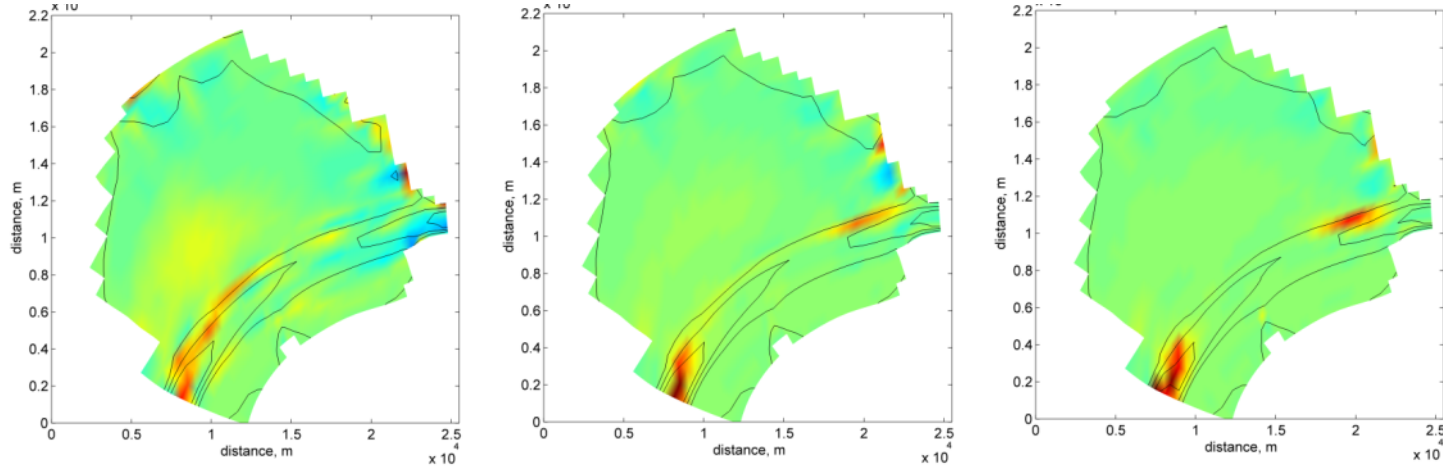
2013-2046 2046-2067 2067-2100



With sea level rise

+ 0.2 m + 0.5 m + 1 m

2013-2046 2046-2067 2067-2100



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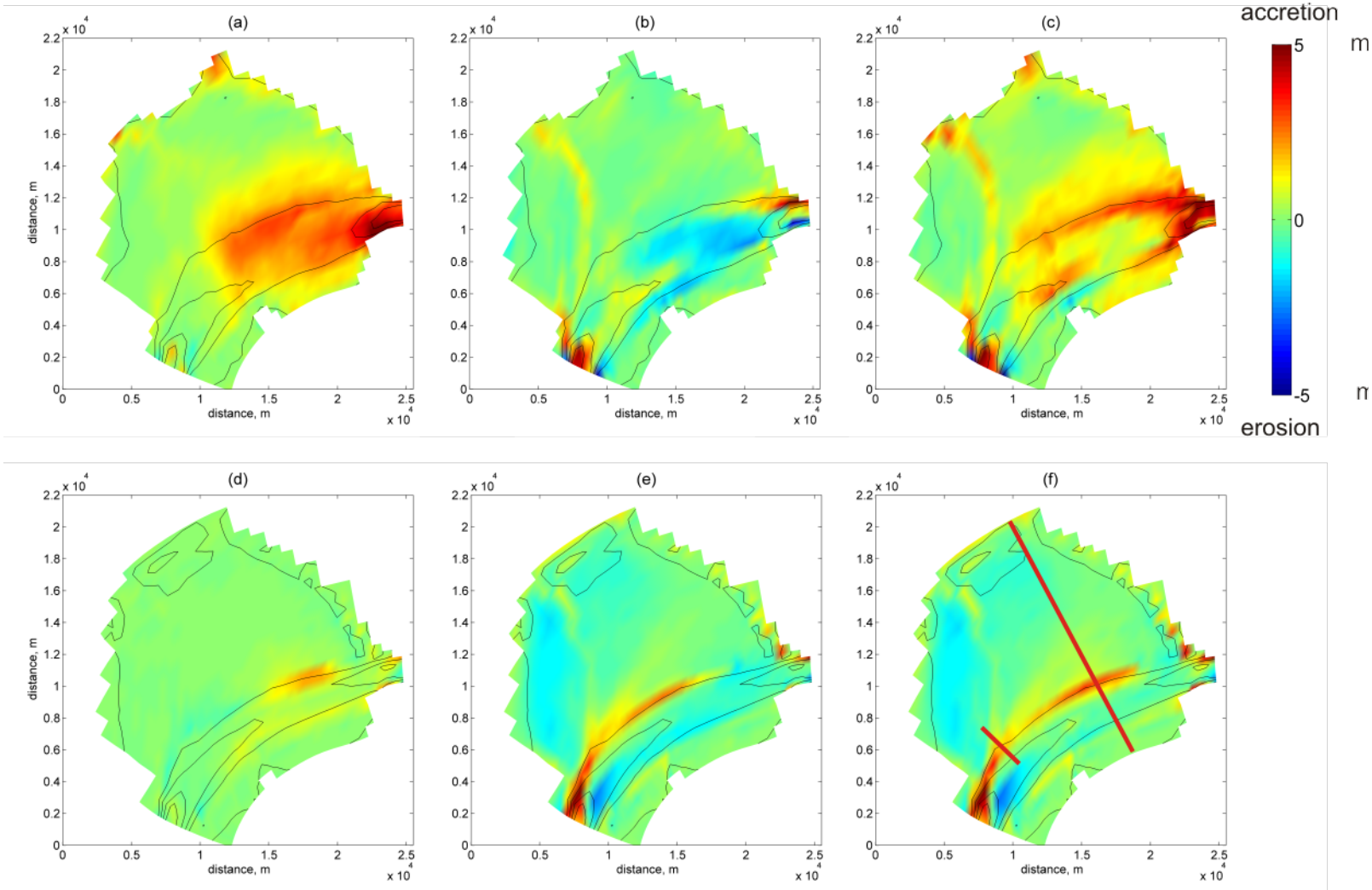
Seasonal fluctuations (modeled)

high river flow | low river flow | total

1856-1887

1951-1983



Van der Wegen et al. (2013)

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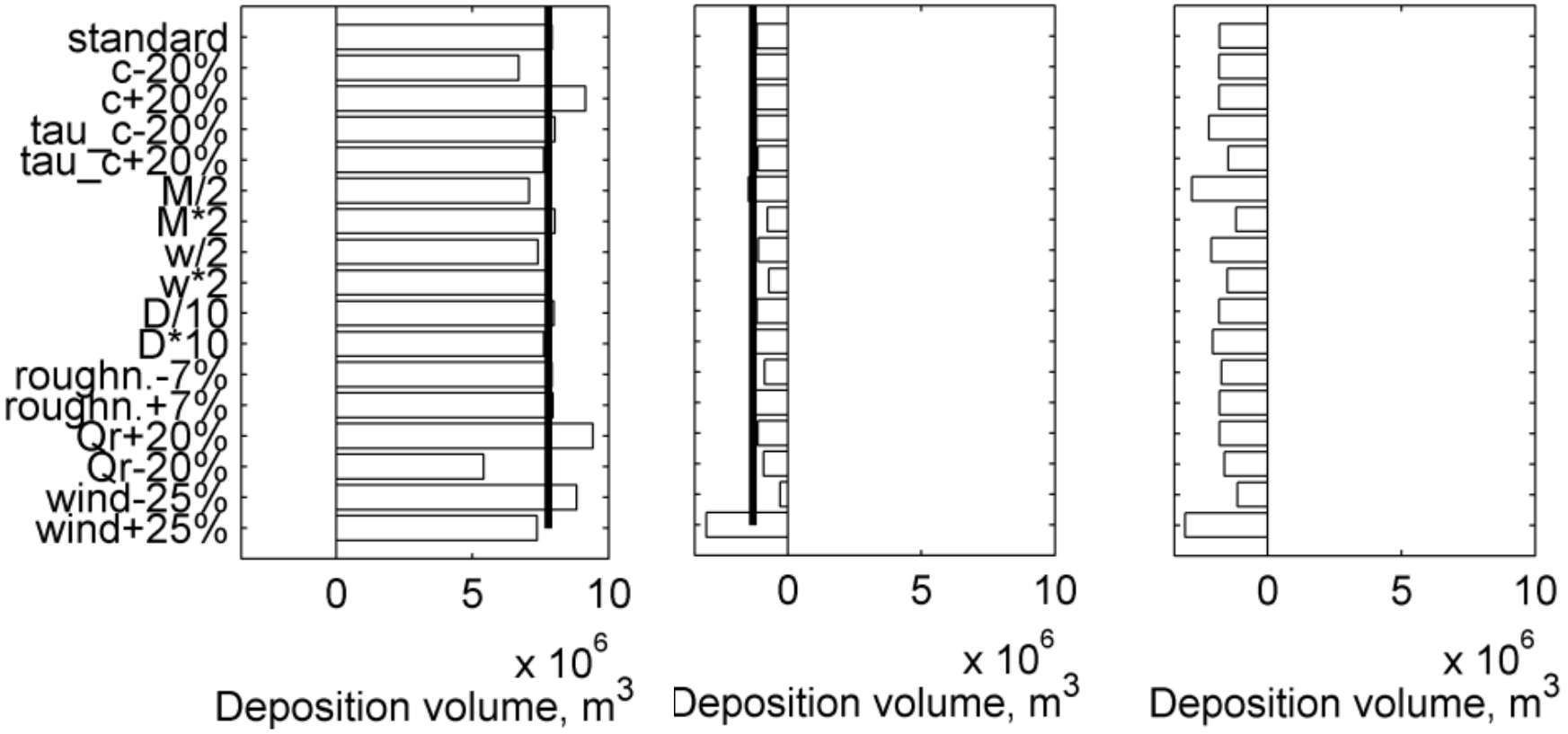
nett volume change per year



1856-1887 1951-1983 1983-2013

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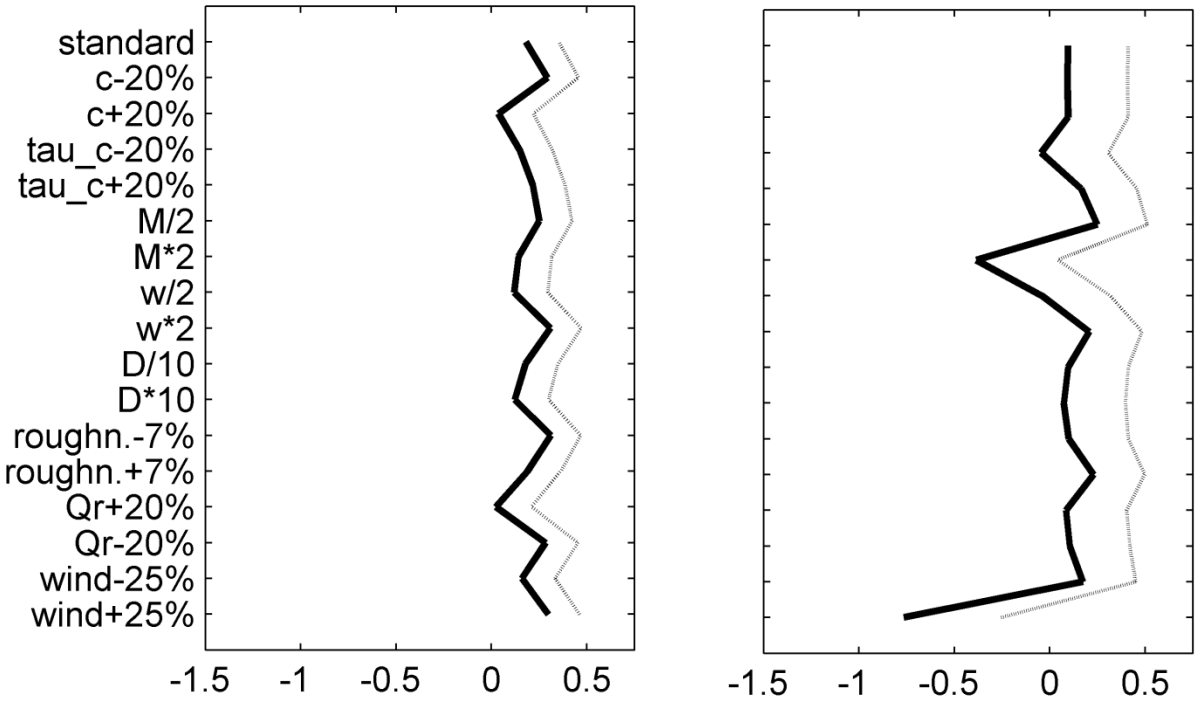
BSS



1856-1887 1951-1983

Subquestion:

How much percent of the modeled erosion/deposition volume skill?

What is the confidence level given input parameter uncertainty?

Skill score (BSS) and Confidence index (CI)

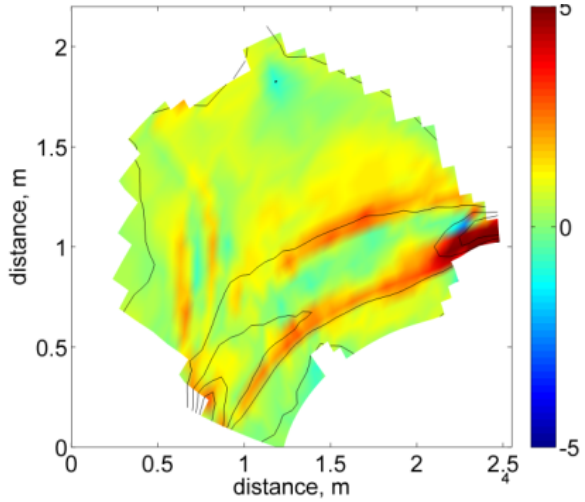
$$BSS = 1 - \frac{\left\langle (Y - X)^2 \right\rangle}{\left\langle (B - X)^2 \right\rangle} = 1 - \frac{\left\langle error^2 \right\rangle}{\left\langle signal^2 \right\rangle}$$

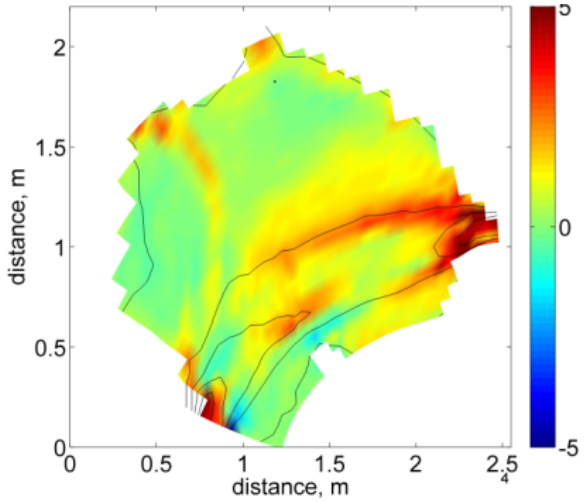
$$CI = 1 - \frac{\left\langle \sigma^2_{\mathrm{mod}} \right\rangle}{\left\langle \mu^2_{\mathrm{mod}\,abs} \right\rangle}$$

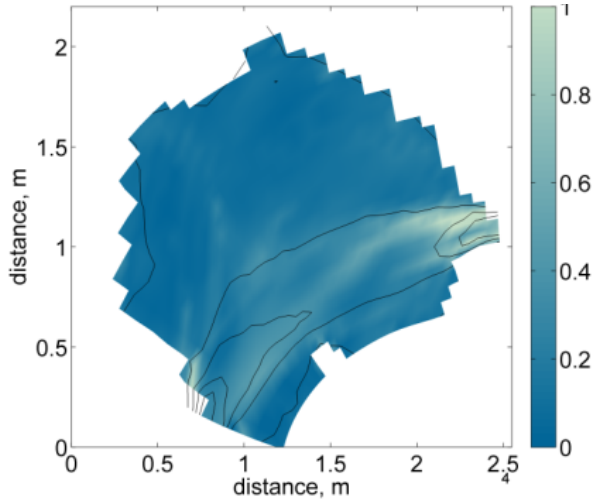
measured

μ modeled
(ensemble averaged)

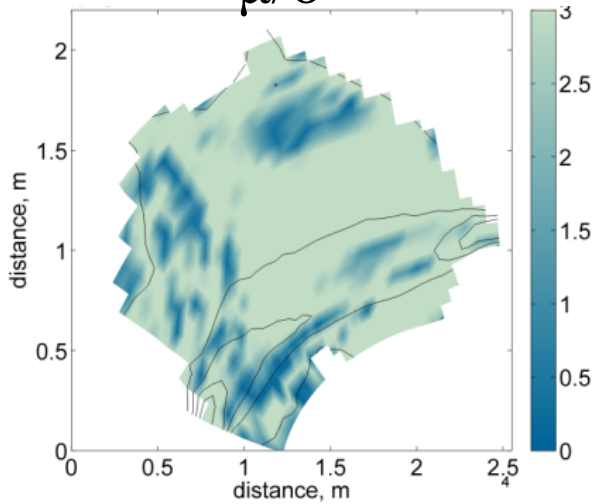
σ



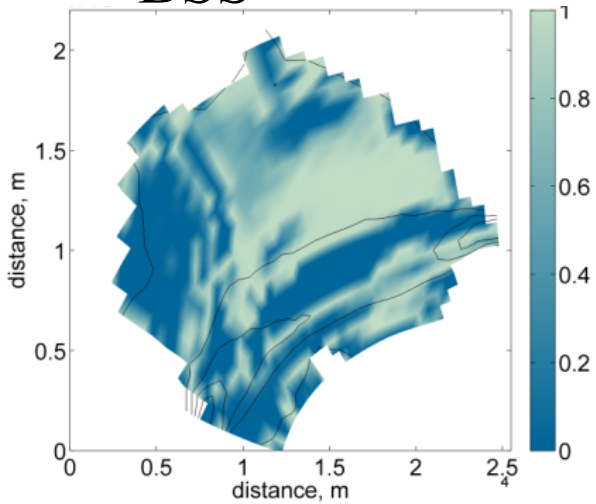




μ/σ

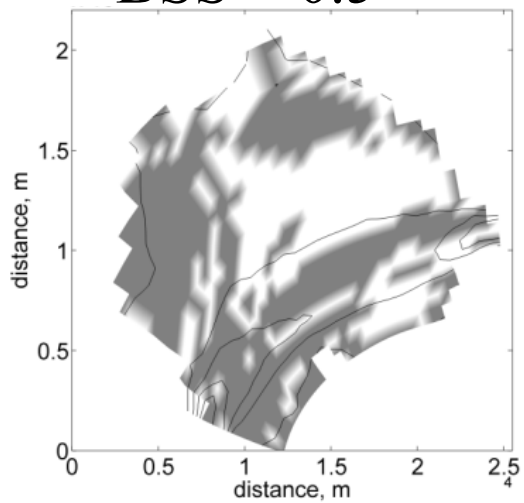


BSS



CI > 0.3

BSS > 0.5



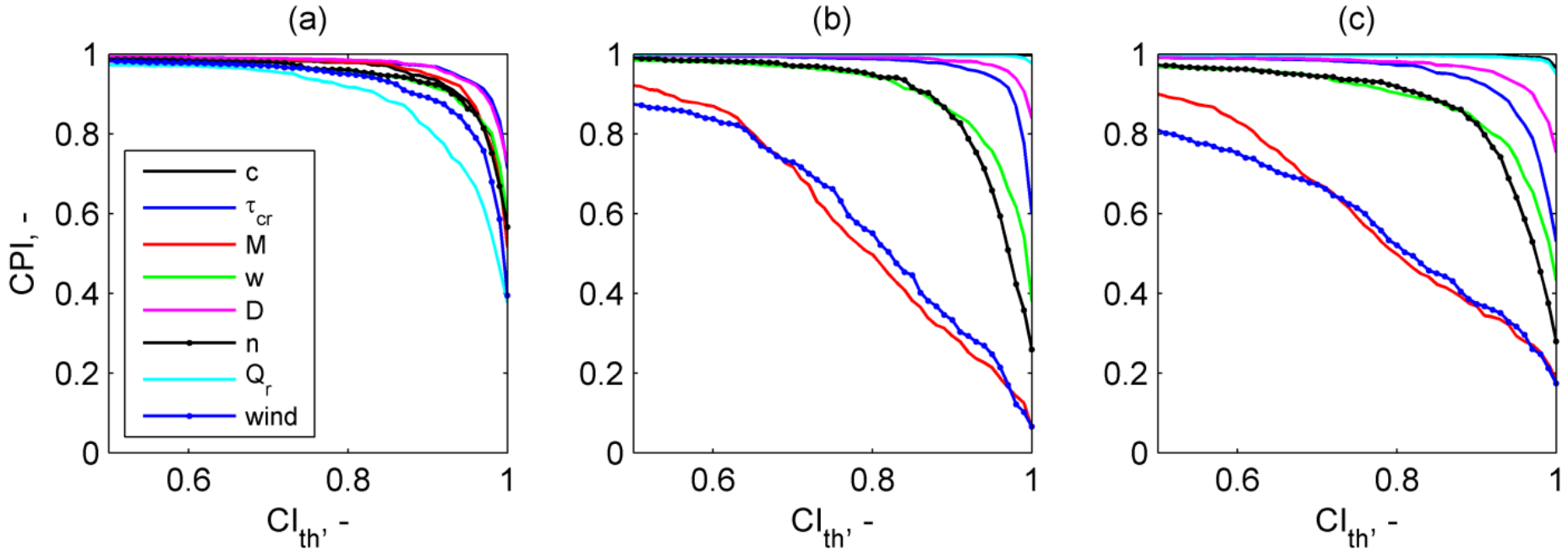
Model performance indicator (MPI)

combination of uncertainty and skill

indicator	criterion	1856-1887	1951-1983	1983-2013
Confidence	CI > 0.3	90%	68%	60%
Skill	BSS > 0.5	57%	19%	
MPI	CI > 0.3 BSS > 0.5	53%	9%	

xx % of the modeled erosion and sedimentation volume fulfils the criterion

CPI : Volumetric percentage fulfilling confidence criterion (CI_{th})



1856-1887 1951-1983 1983-2013

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Concluding remarks

- Estuarine morphodynamic development is better predictable at longer (> decades) time scales
- After decades the model skill score becomes significant even in complex environments
- Uncertainty levels by uncertain model input parameter settings remain limited
- Plan form plays a governing role in the morphodynamic development of confined systems such as estuaries.

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https://beeldbank.rws.nl, Rijkswaterstaat

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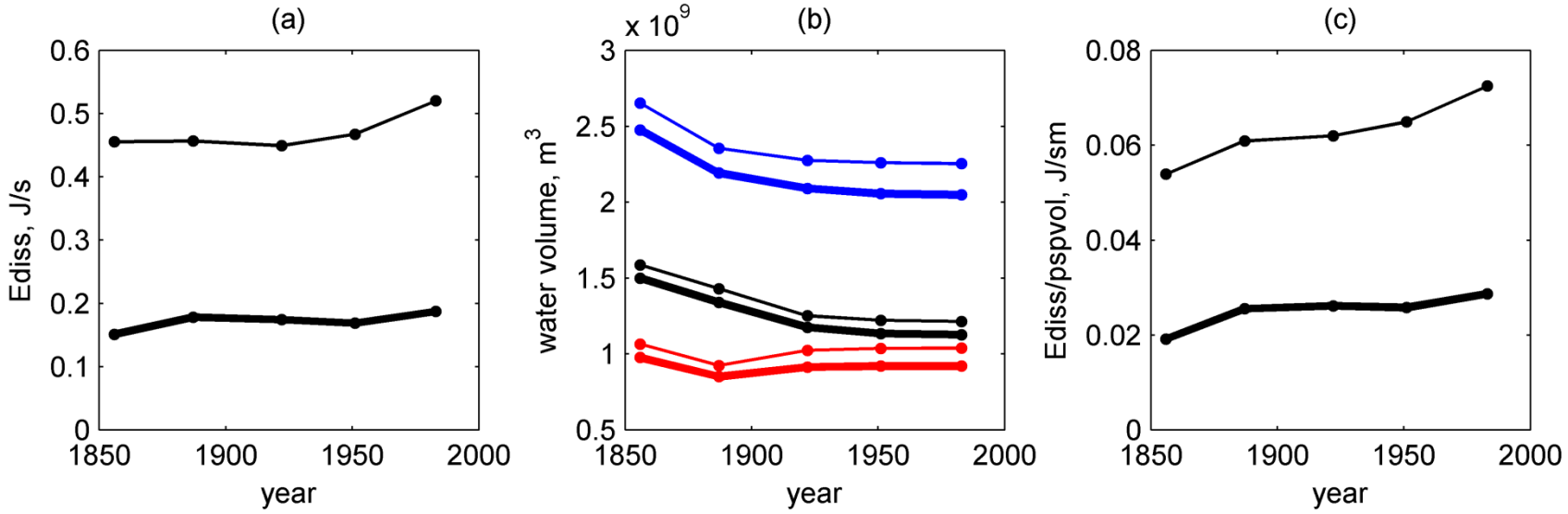
Energy dissipation and tidal prism in San Pablo Bay



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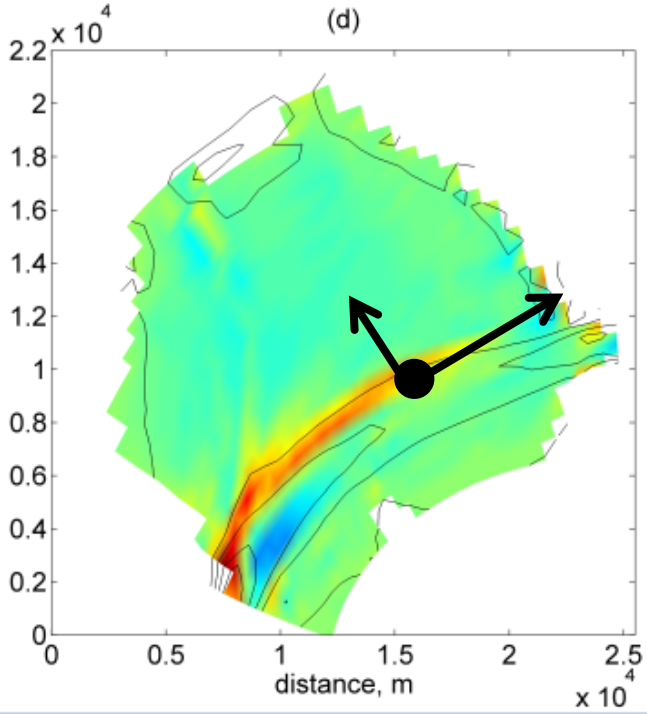
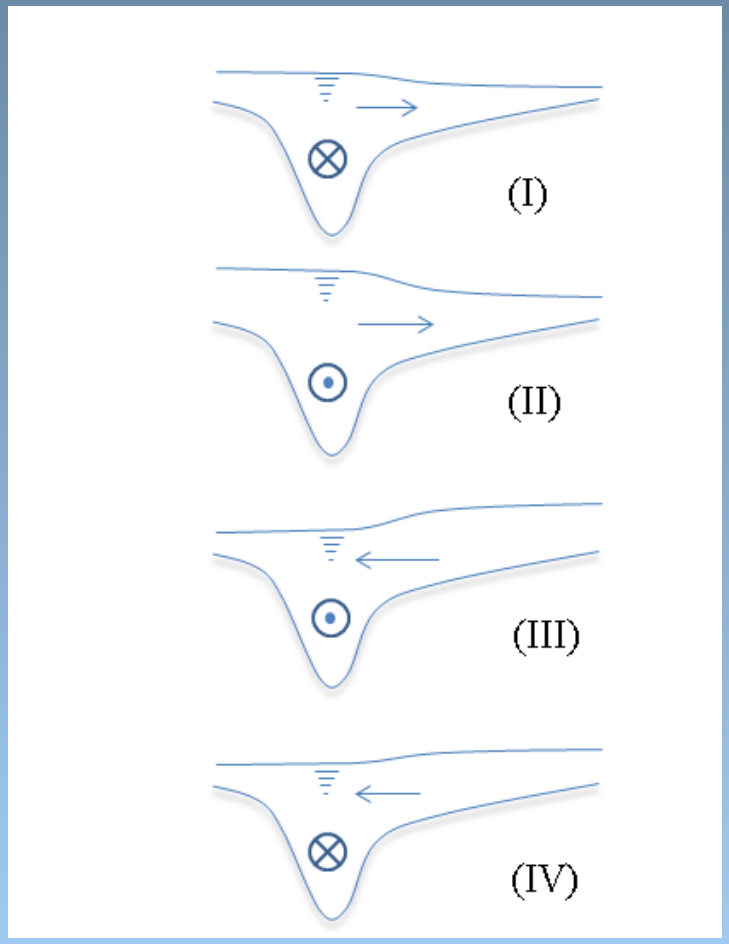


What are governing tidal conditions?



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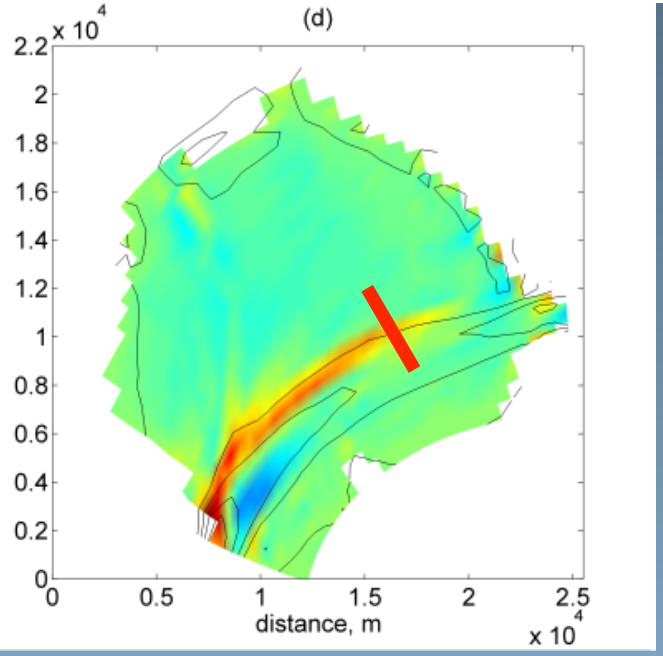
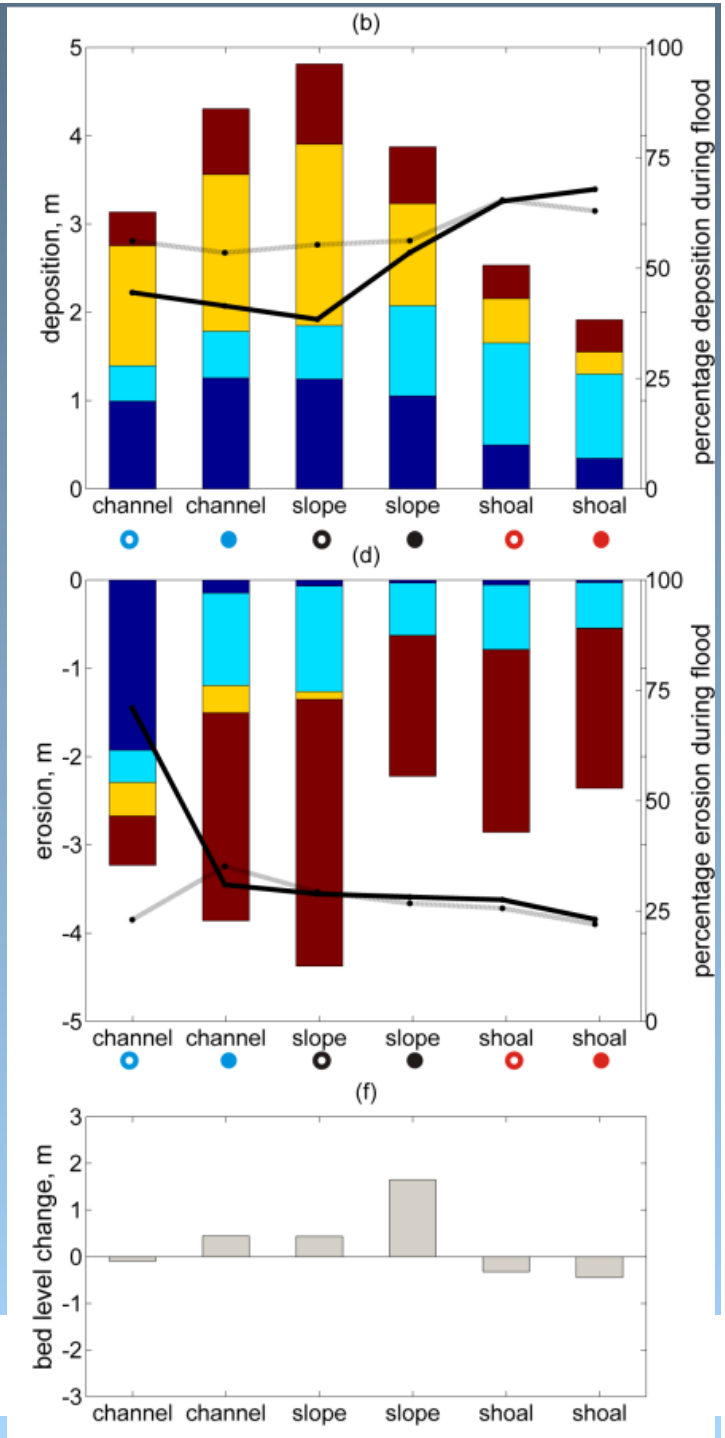
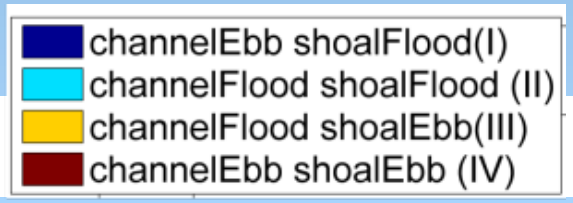


- 60% of the slope *deposition* occurs during flooding of the shoals;
- 75 % of the slope *erosion* occurs during ebbing of the shoals;





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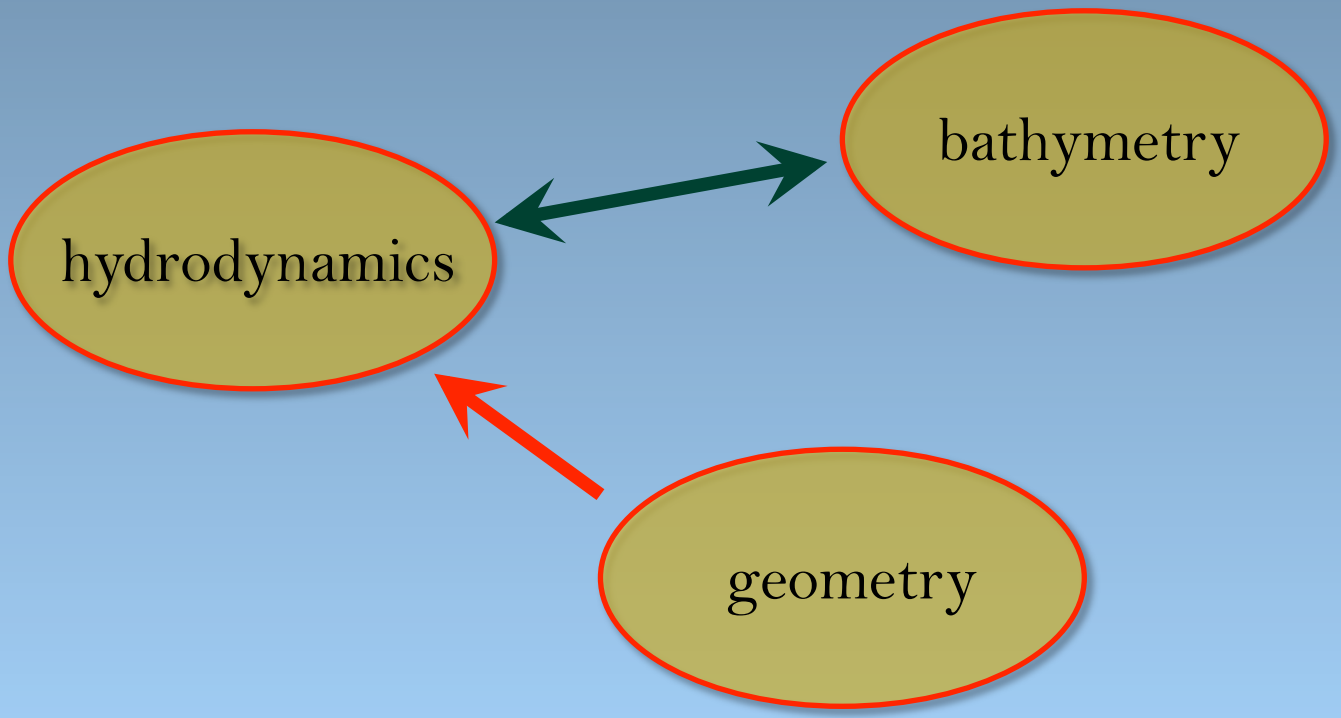
Question :

- What is the impact of the geometry on the location of the patterns?



Reproduction of the Western Scheldt bathymetry by means of a process-based, morphodynamic model

or:

What are the main driving forces that determine the morphological patterns in a tidal embayment?

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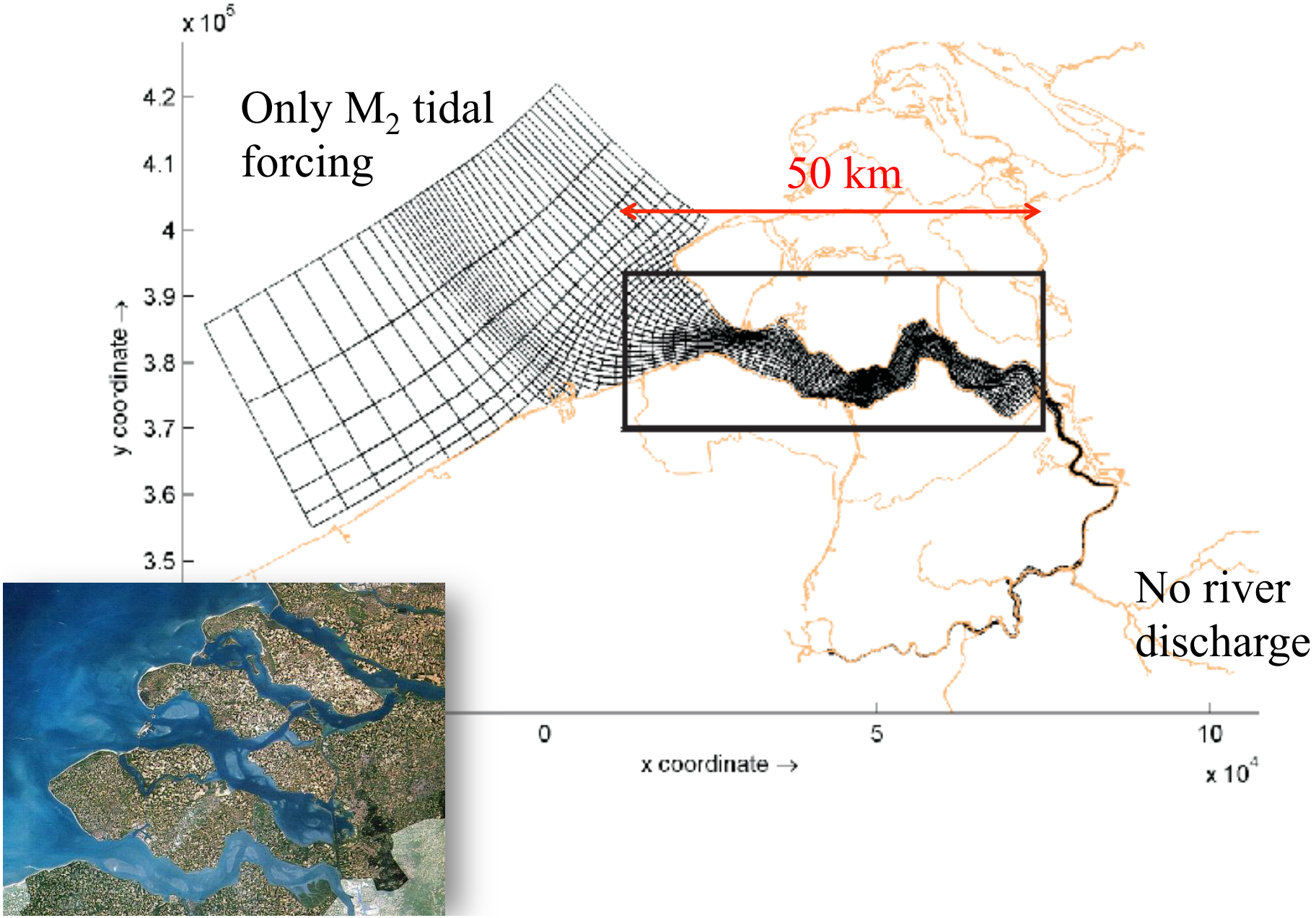
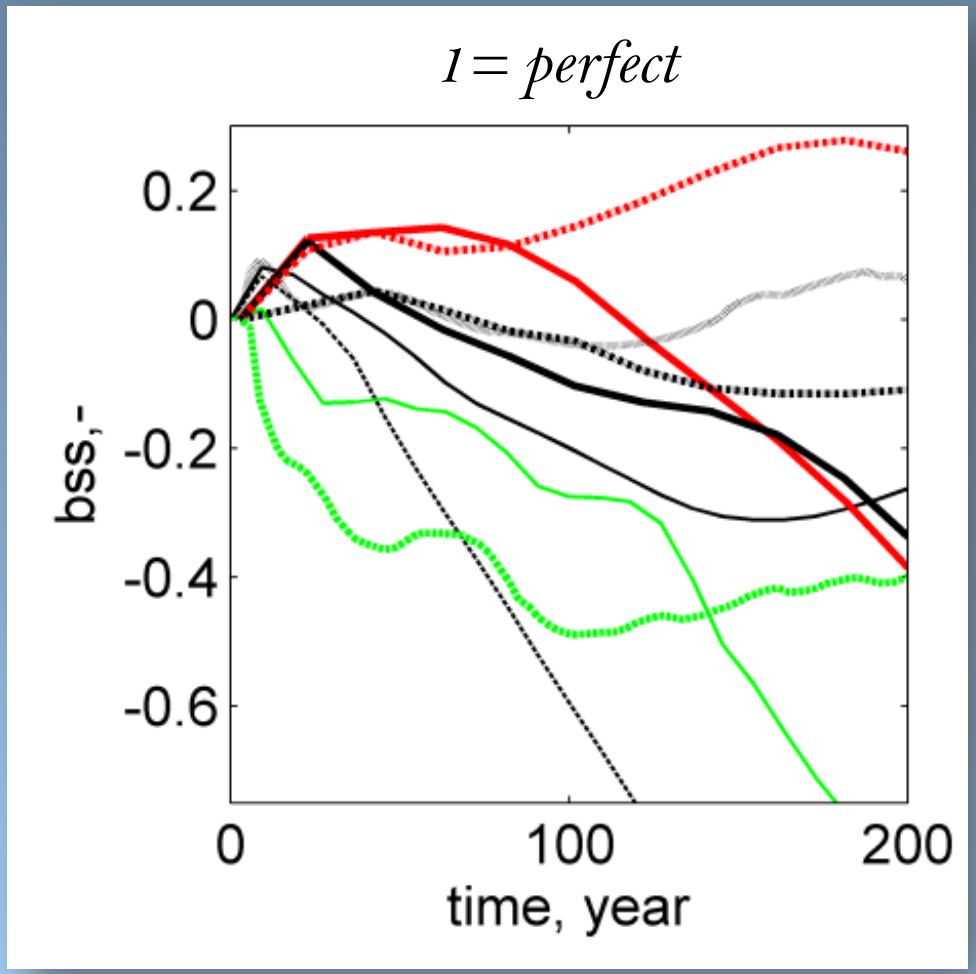
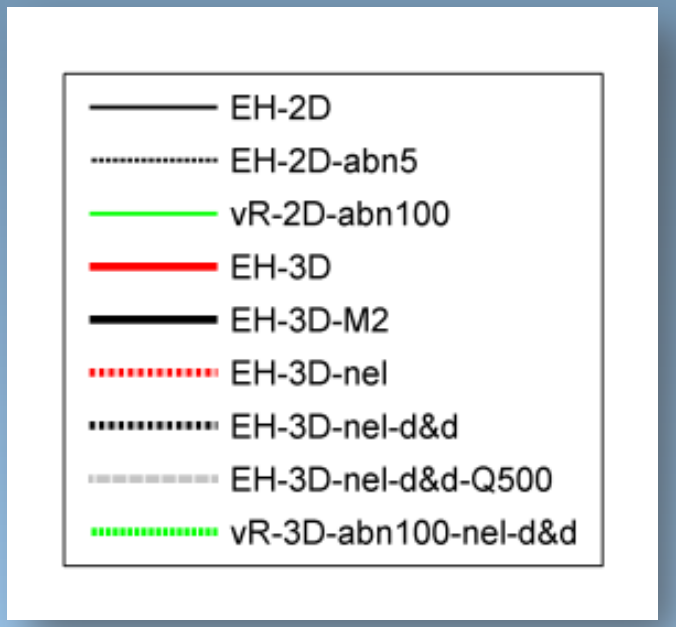

x 10^5
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
y coordinate →
Only M2 tidal forcing
50 km
No river discharge
0
5
10
x coordinate →
x 10^4

Brier Skill Score

$$BSS = 1 - \frac{\left\langle (\Delta vol_{\mathrm{mod}} - \Delta vol_{\mathrm{meas}})^2 \right\rangle}{\left\langle \Delta vol_{\mathrm{meas}}{}^2 \right\rangle}$$

1 = perfect





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Conclusions

- Modeling approach reproduces realistic and characteristic patterns in the Western Scheldt tidal basin.
- Major tidal forcing shows significant skill in reproducing the bathymetry, even for variations in model parameter settings.
- Model performance varies over 200 years due to continuous pattern formation and deepening of the basin

Process-based models

- Based on physical principles like mass conservation.
- Use mathematical equations for water motion, sediment transport and bottom change
- Uses an empirical formula for sediment transport derived in a laboratorium (timescale of seconds).
- General view: Long-term morphological changes are not possible to model using process-based models!

General view on performance of long-term morphology of process-based models

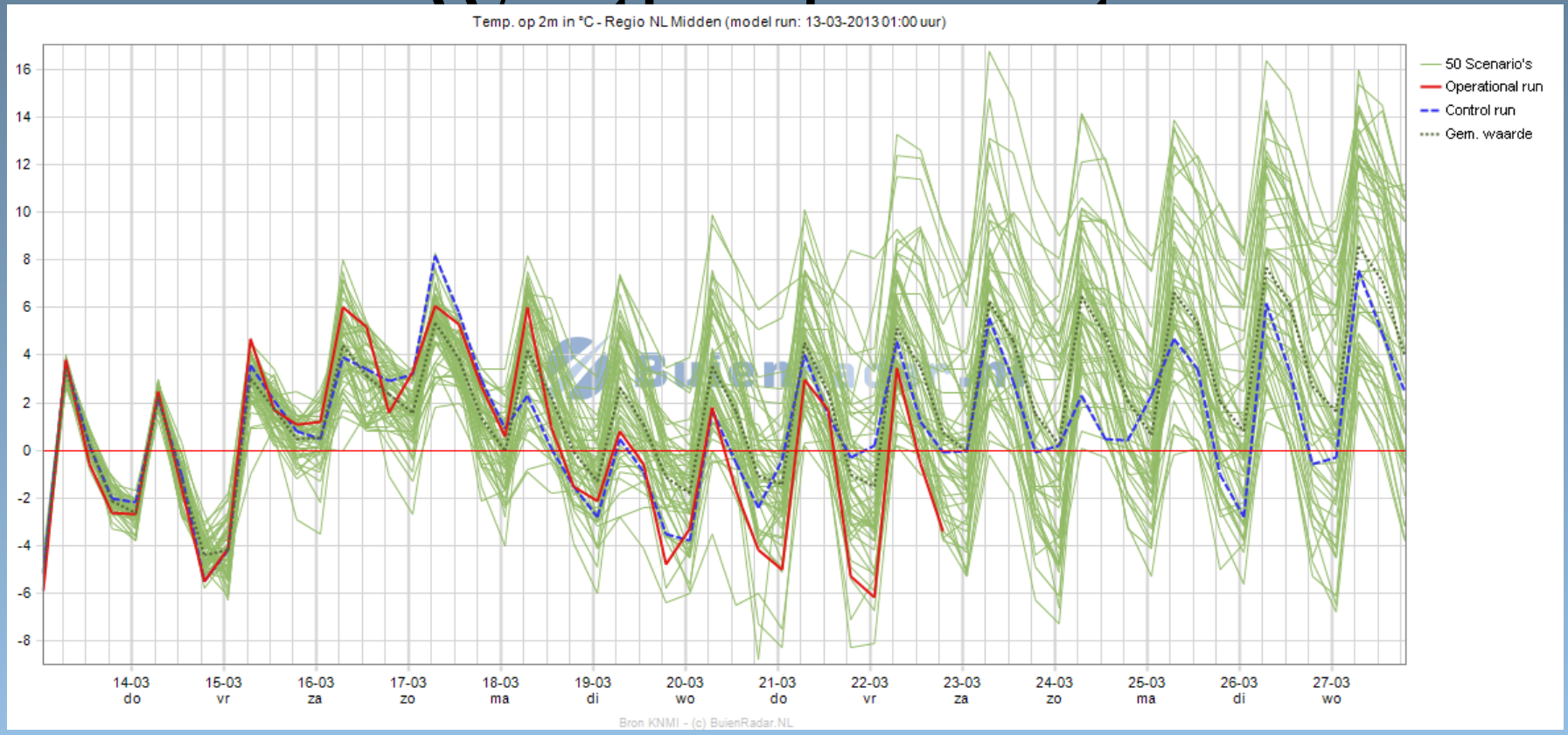
Morphological models drift away from reality over time due to:

-Build up of errors;

-Non-lineair interactions that are unpredictable over time;

-Processes are missing (simplification of system).

Weather forecast



(www.buienradar.nl)

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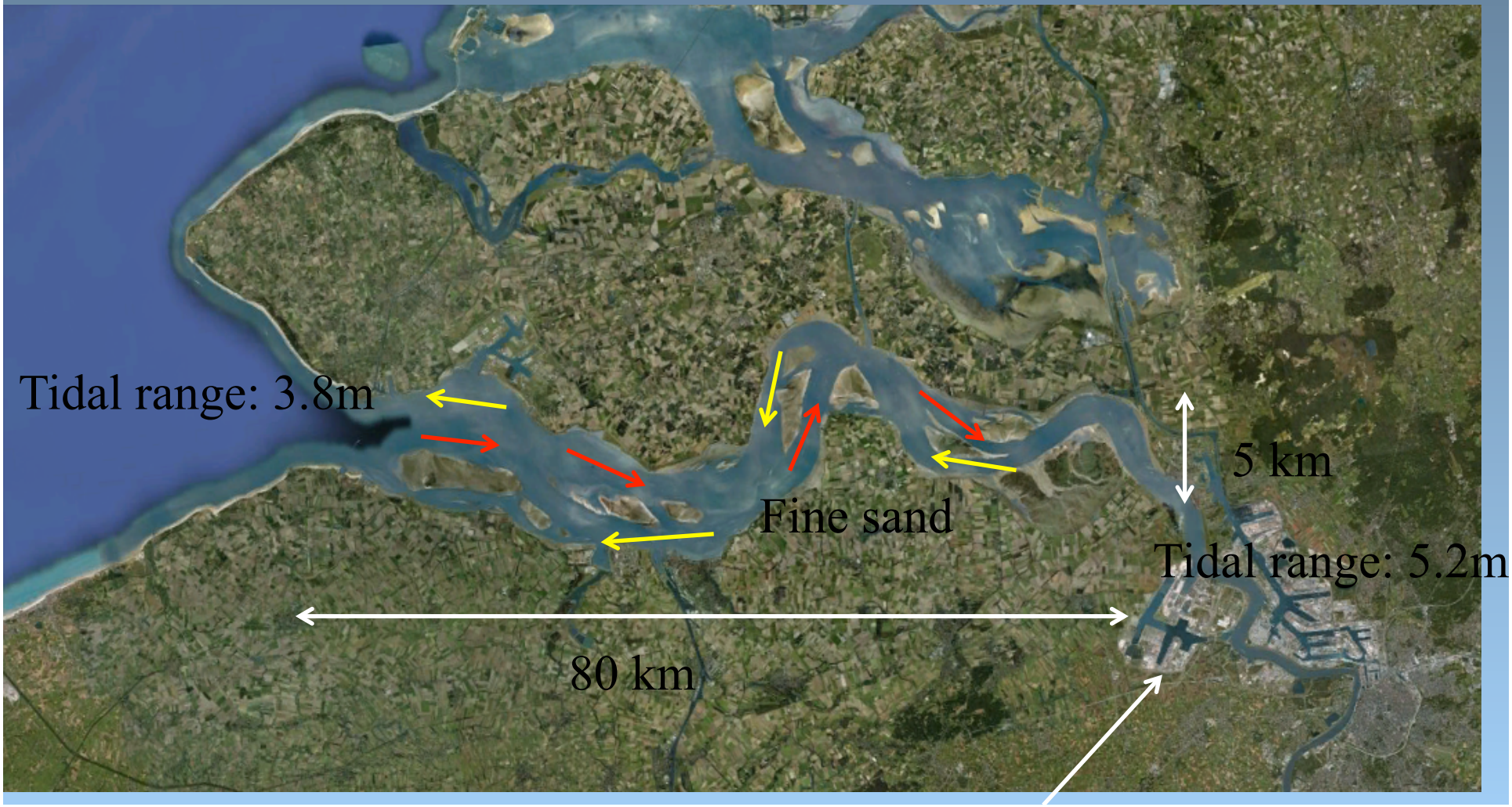
Research question

What is the value of long-term morphological modelling in estuaries using a process-based model?

(long-term = decades – century timescale)

Case study: Western Scheldt estuary, The Netherlands



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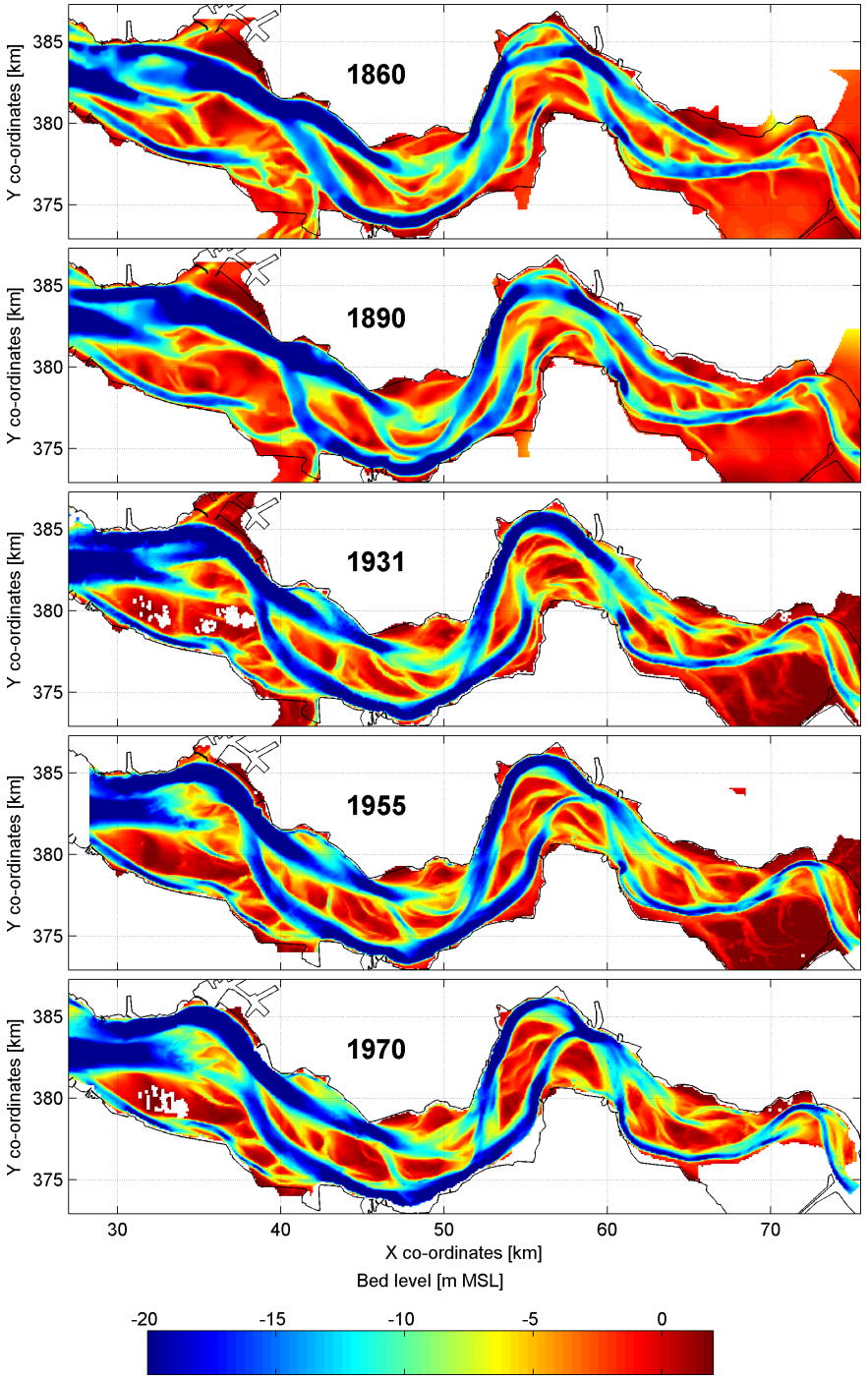
Hindcast of 1860-1970 period:
(110 years)



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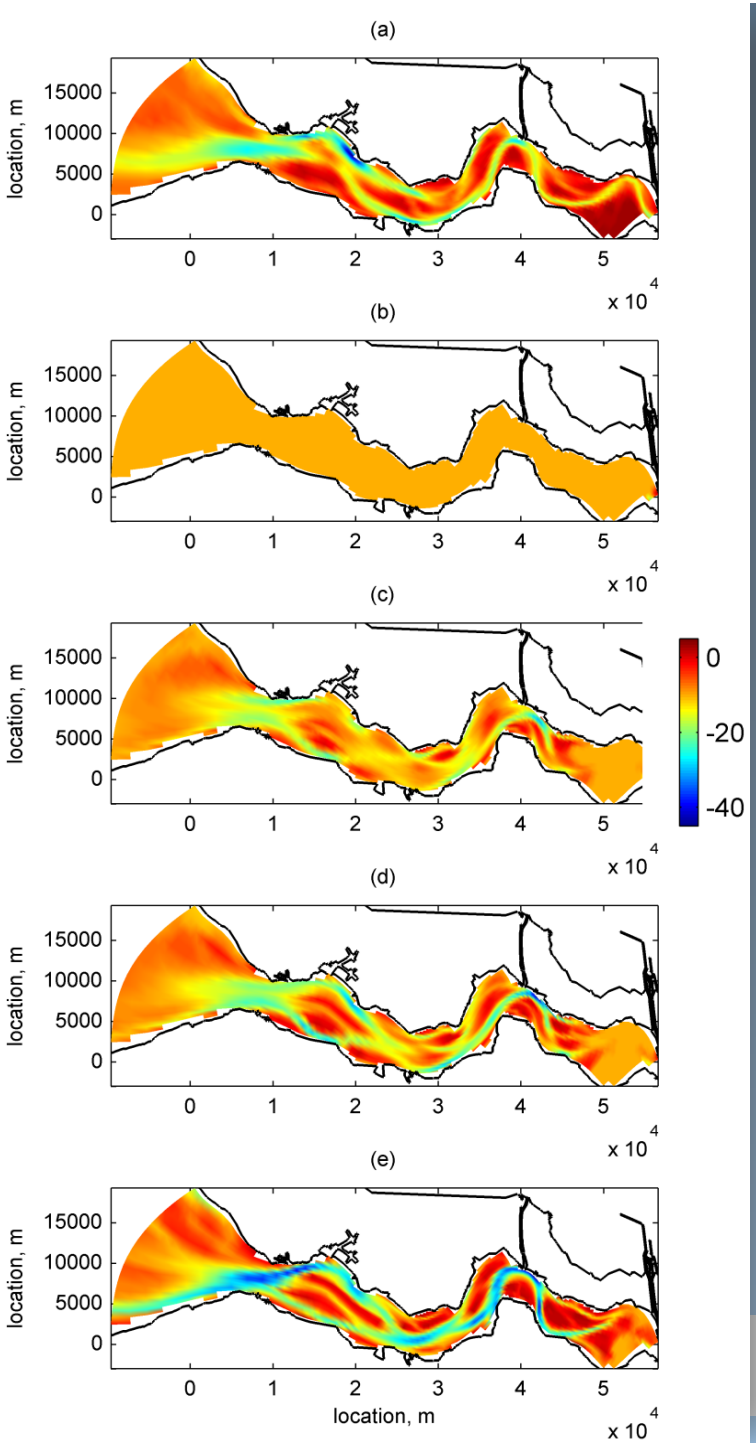

1998 bathymetry

Flattened bathymetry

After 15 years

After 30 years

After 200 years

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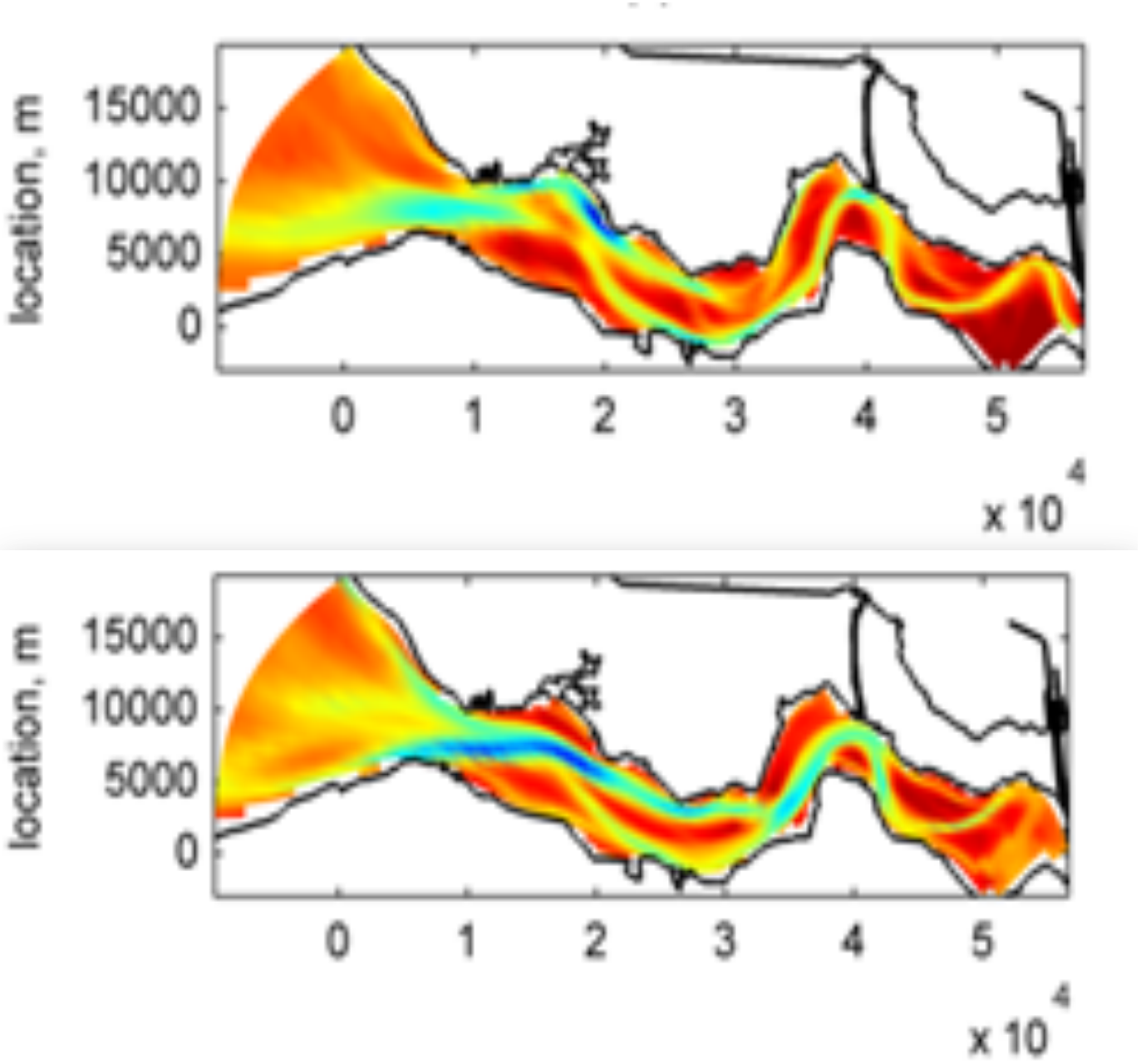
Variations:

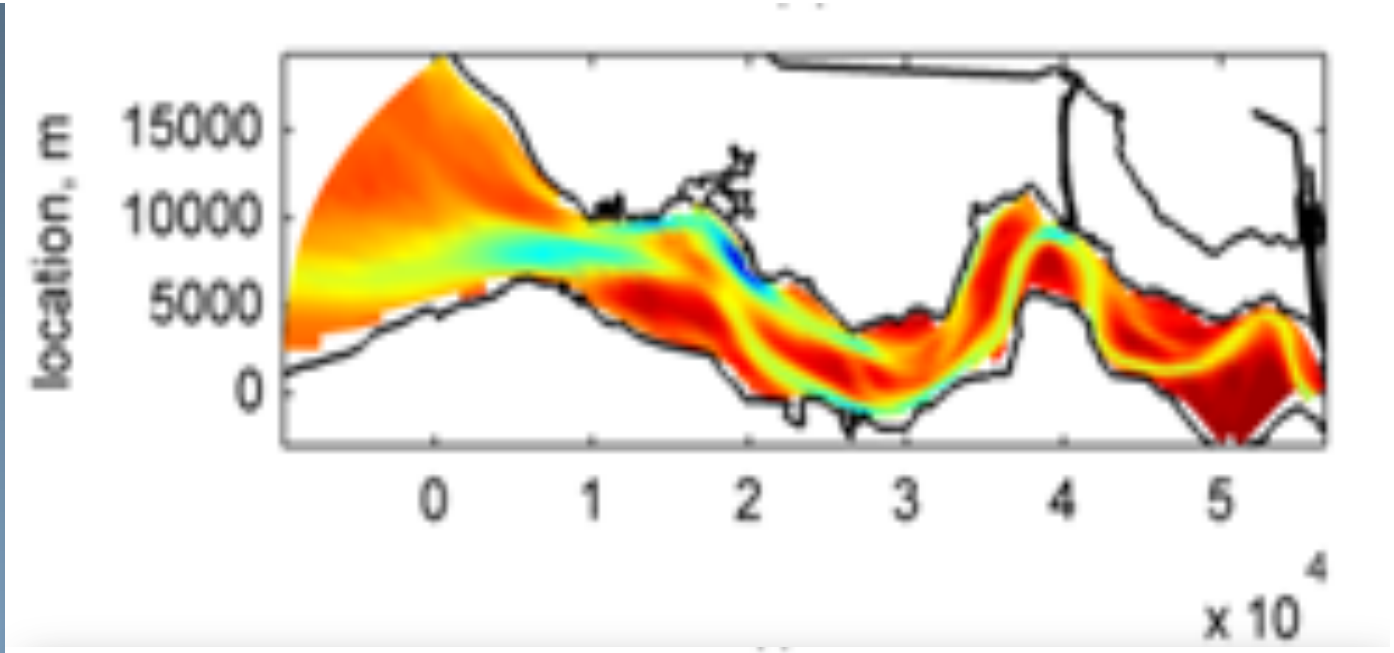
- Tidal Forcing M2, M4, M6
- Transport formulation Engelund Hansen, Van Rijn
- Bed slope parameter
- 2D, 3D
- Inclusion/exclusion :
  - Dredging and dumping actvities
  - River discharge (500 m3/s)
  - Non-erodible substrate
- Sediment grain size

measured 1998

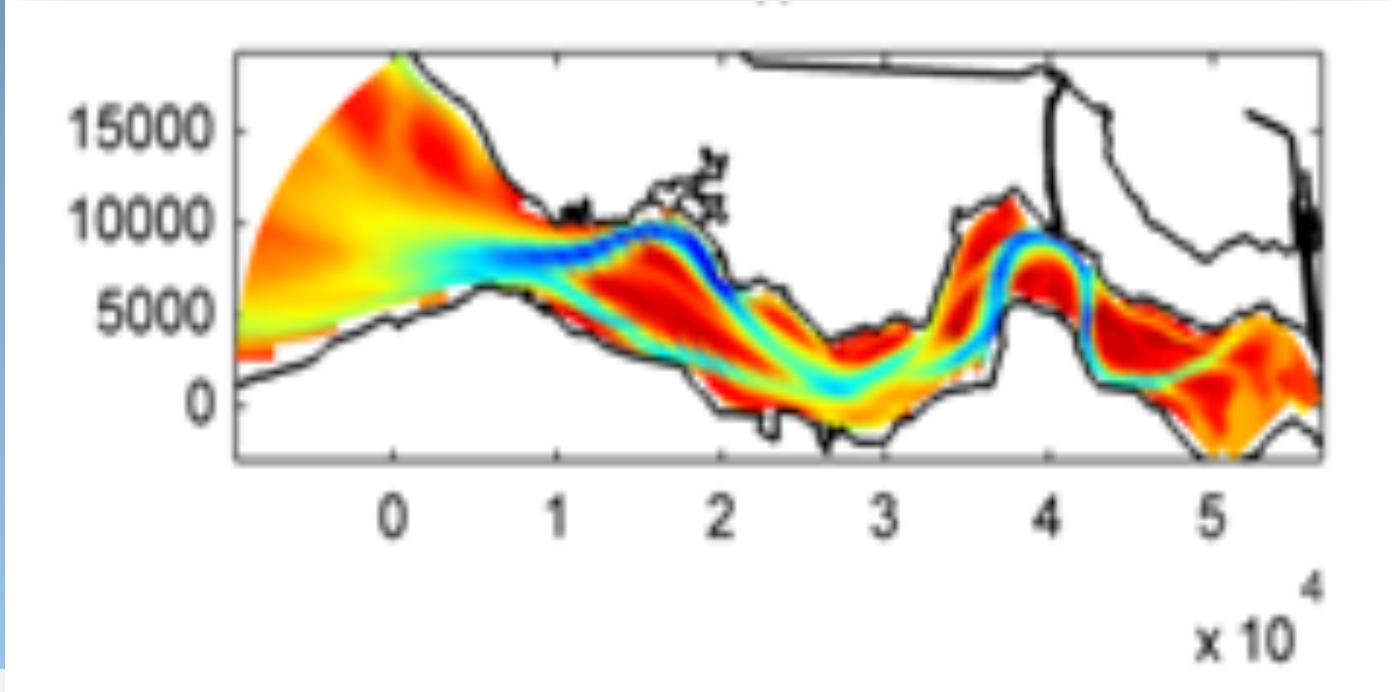
EH-2D



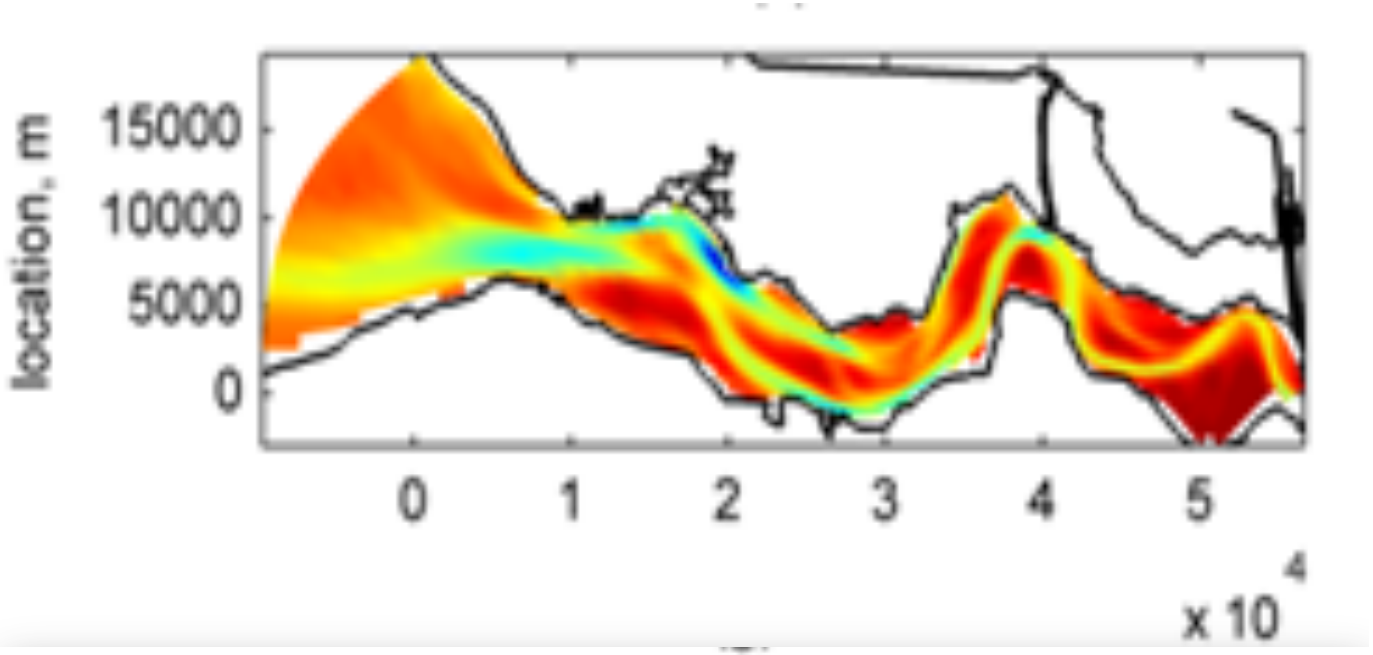
measured 1998



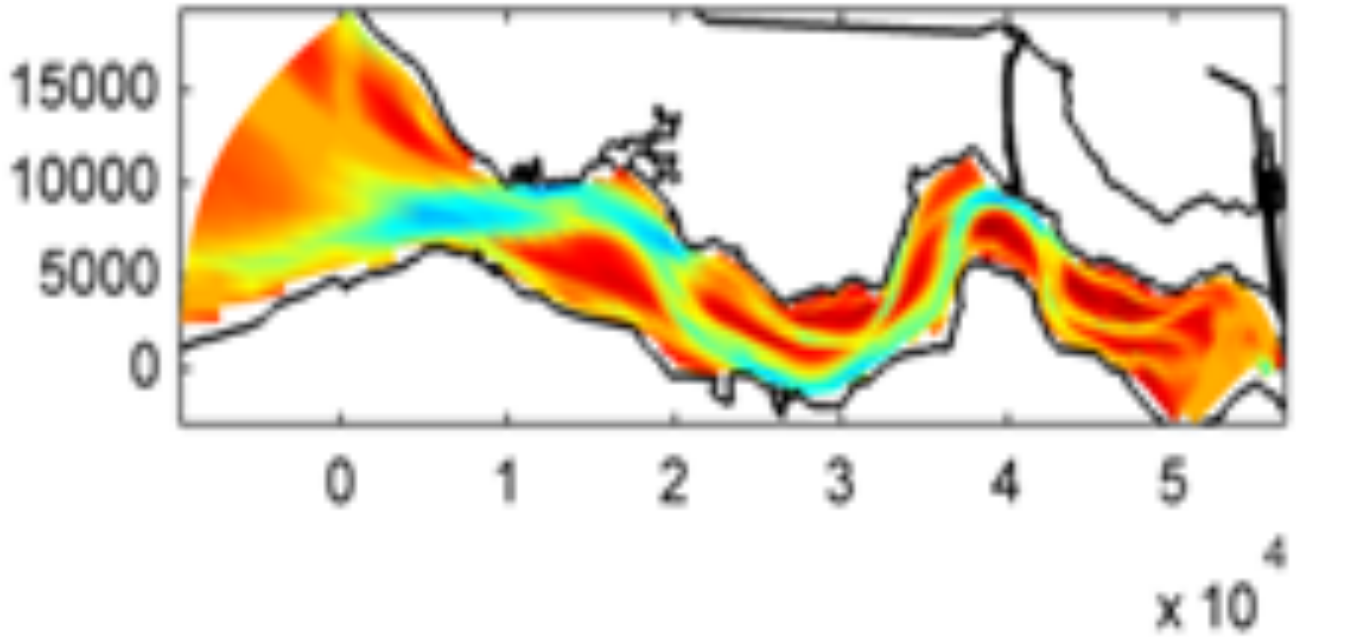
EH-3D-M2



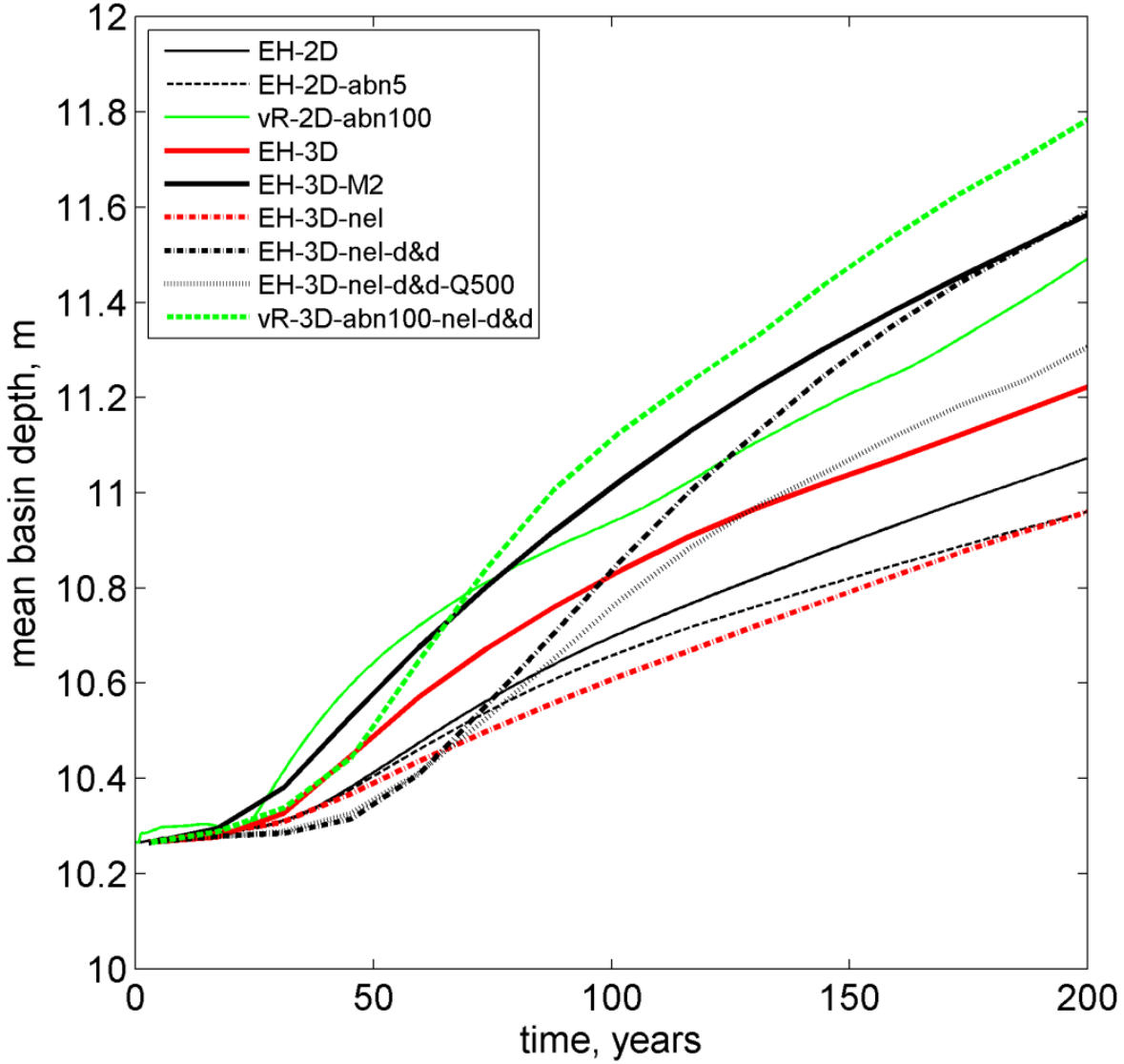
measured 1998



EH-3D-nel



Mean depth



Exporting basin:

About 1m deepening over 200 years

~100 Mm^3/200 years

~500,000 m^3/year

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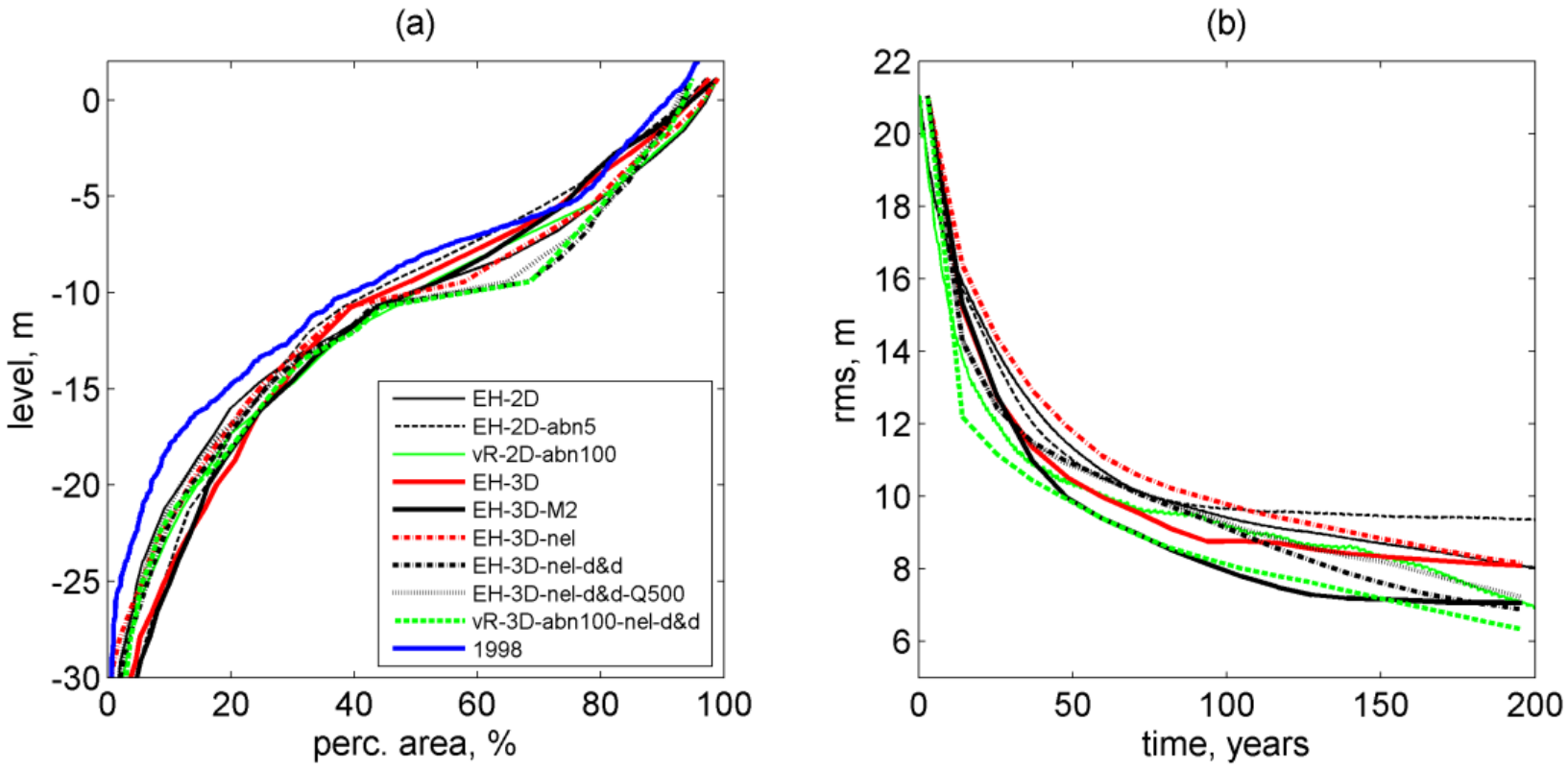
Hypsometry after 200 years



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Brier Skill Score

$$BSS = 1 - \frac{\left\langle (\Delta vol_{\mathrm{mod}} - \Delta vol_{\mathrm{meas}})^2 \right\rangle}{\left\langle \Delta vol_{\mathrm{meas}}{}^2 \right\rangle}$$

- *Δvol* - volumetric change compared to the initial flat bed, (m^3)
- *mod* - modeled quantity,
- *meas* - measured quantity
- =1 is perfect model
- <0 is worse than a flat bed

BSS

- 1
- 0.75
- 0.75
- 0.76
- 0.83

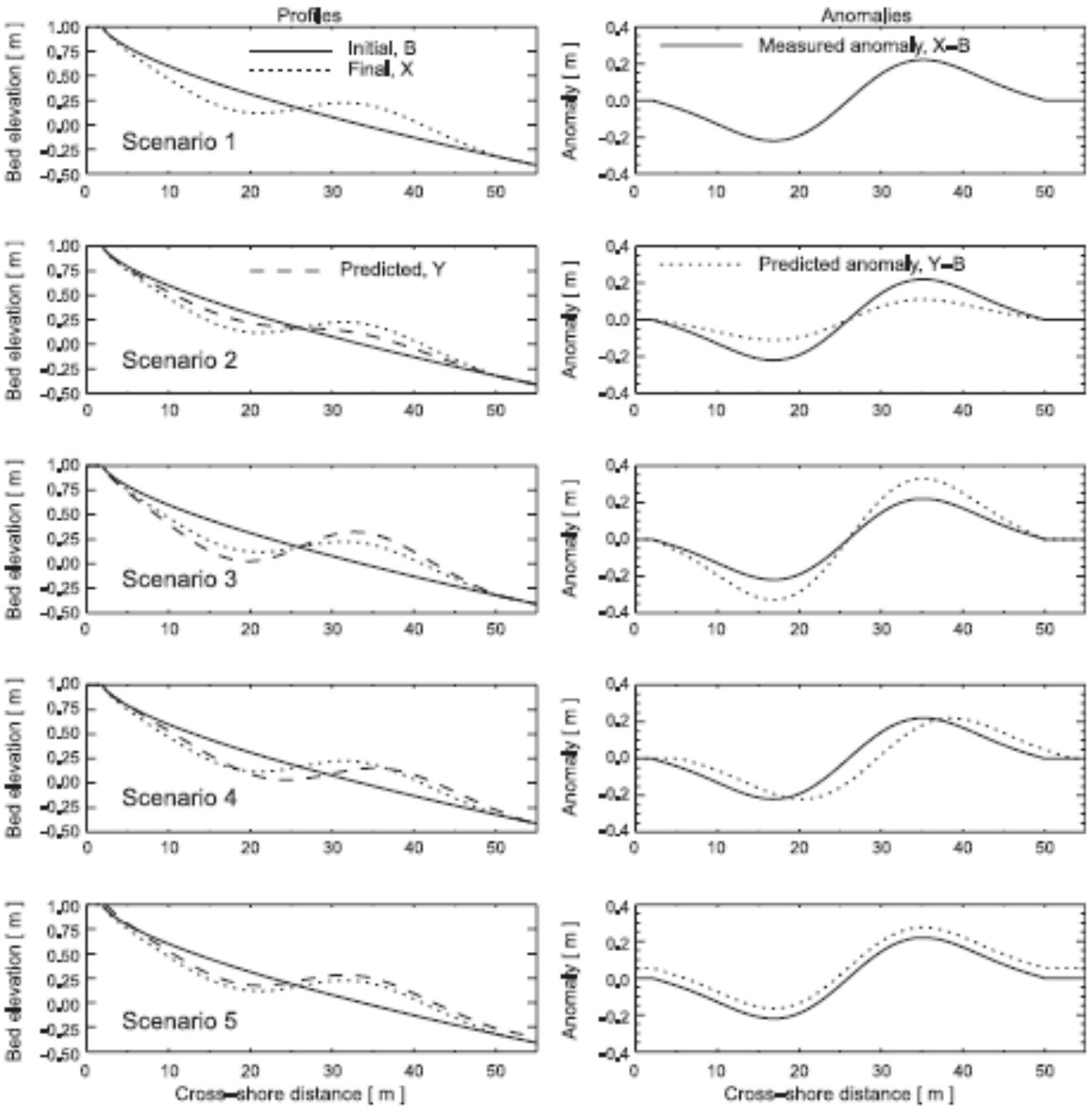

Fig. 1. Cross-shore profiles and predicted anomalies for idealized Scenarios 1 to 5.

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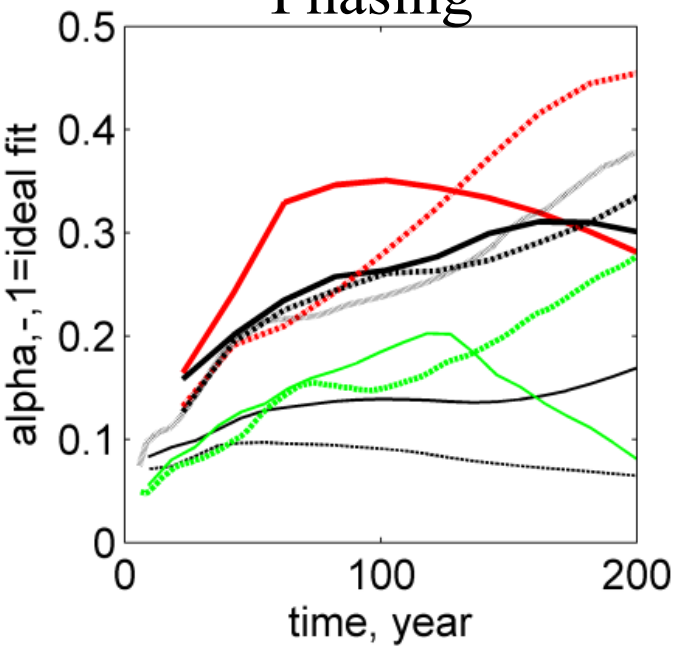
What determines the BSS?

$$BSS = 1 - \frac{\left\langle (\Delta vol_{\mathrm{mod}} - \Delta vol_{\mathrm{meas}})^2 \right\rangle}{\left\langle \Delta vol_{\mathrm{meas}}{}^2 \right\rangle} \qquad BSS = \frac{\alpha - \beta - \gamma + \varepsilon}{1 + \varepsilon}$$

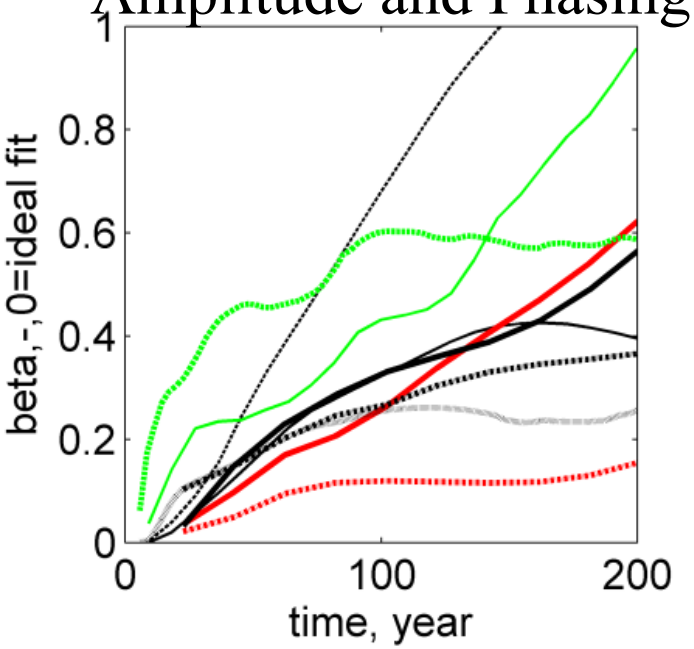
(Sutherland et al. 2004)

- Amplitude (α) — Pattern formation
  (size of the patterns)
- Phase (β) — Pattern formation
  (location)
- Mean level (γ) — Longitudinal profile

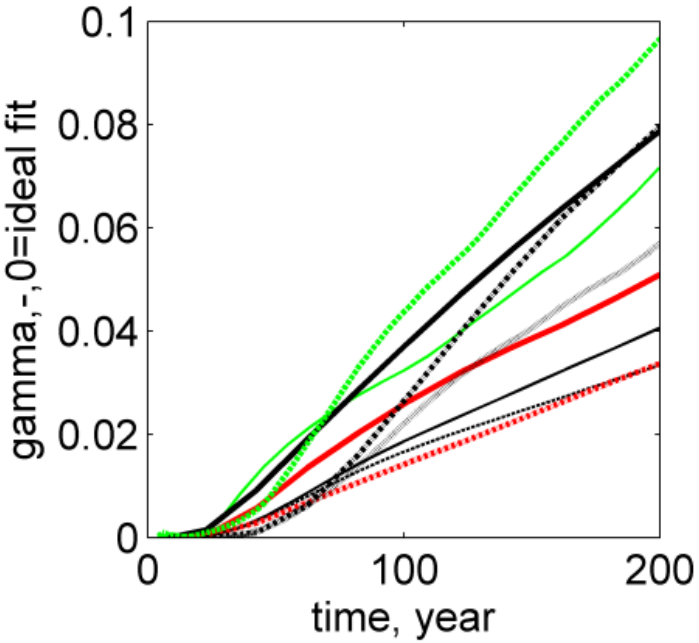
Phasing

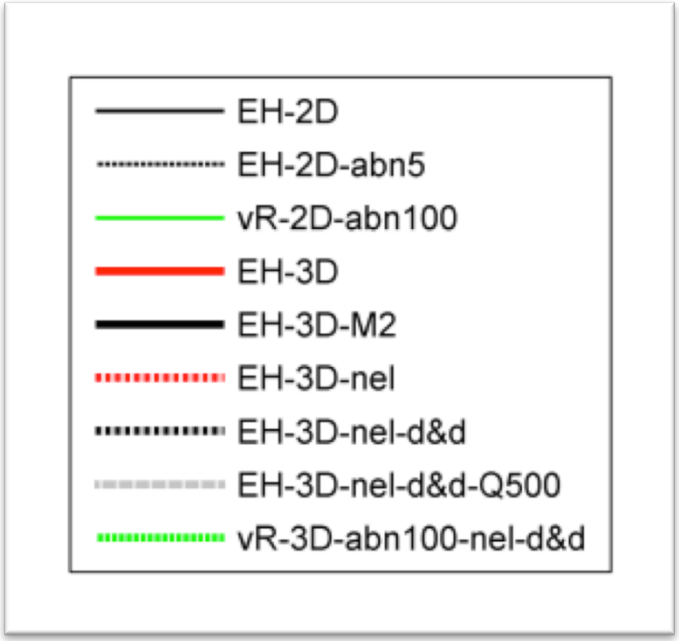


Amplitude and Phasing



Mean level



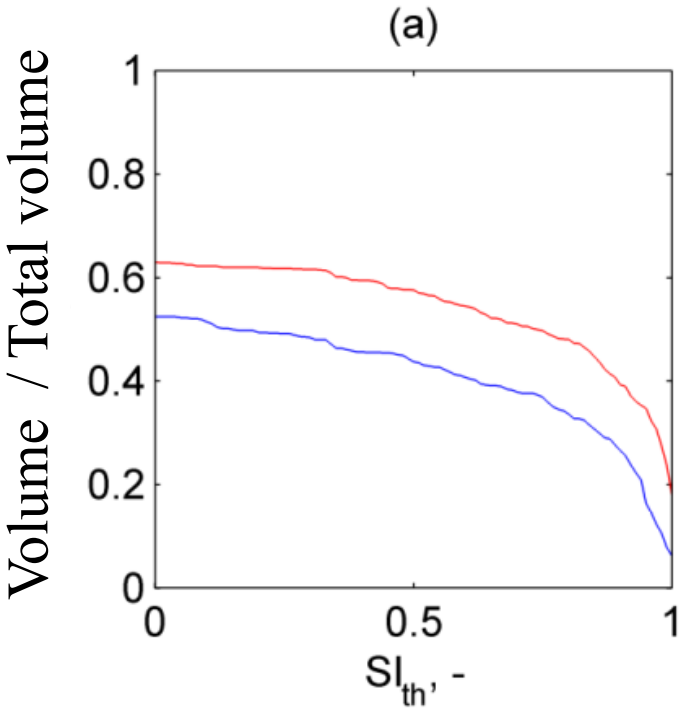


Confidence index

$$CI = 1 - \frac{\sigma^2_{\mathrm{mod}}}{\mu^2_{\mathrm{mod}\,abs}}$$

1856-1887 period
1951-1983 period
1983-2013 period

Skill performance



Accuracy performance