Future-Ems project - Introduction

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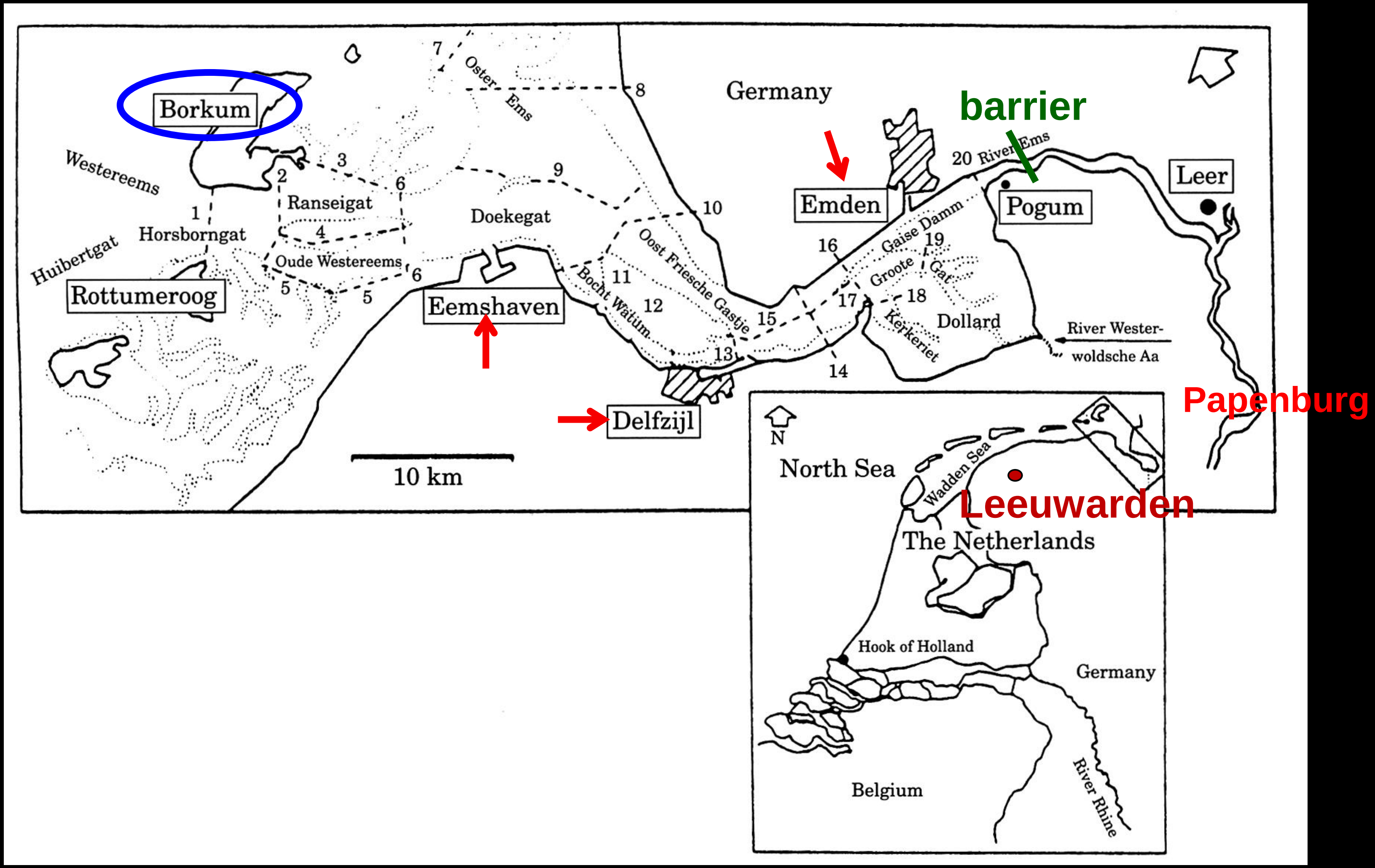
Ems estuary:

Large economic and ecologic importance



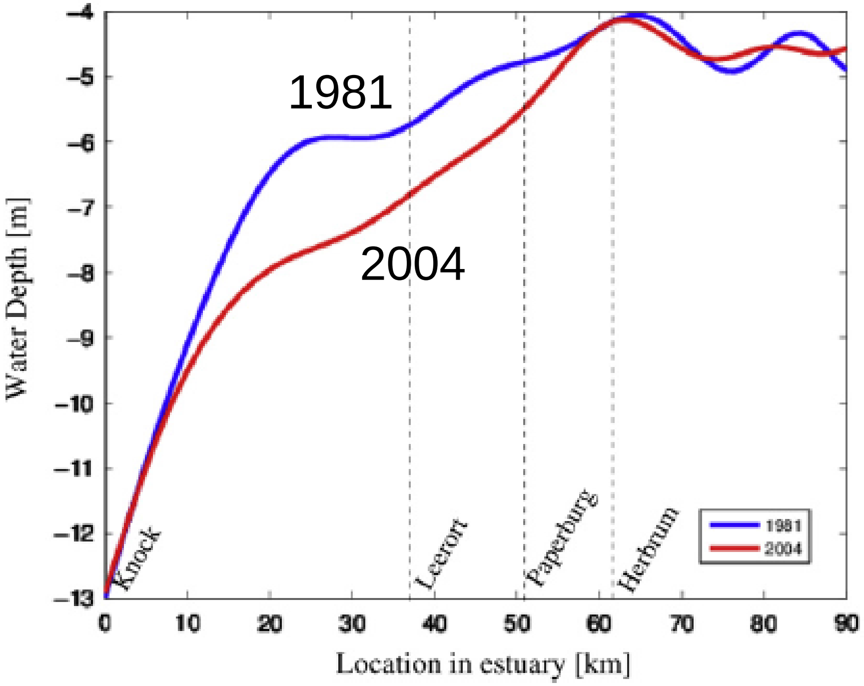
Ems estuary:

Large economic and ecologic importance

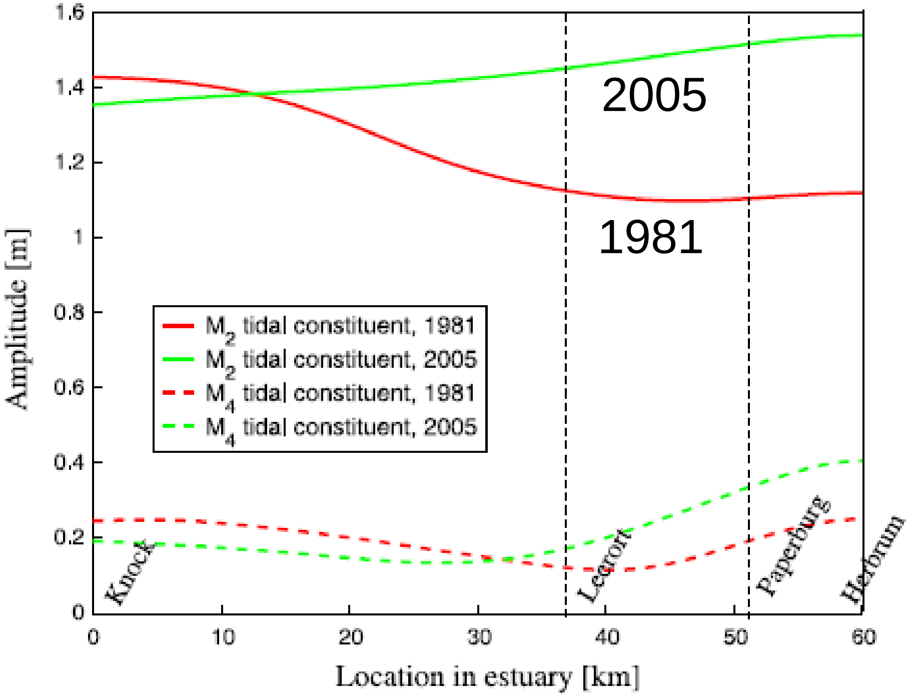
Cruise ship passing the barrier

Large-scale deepening and changes in tides

depth

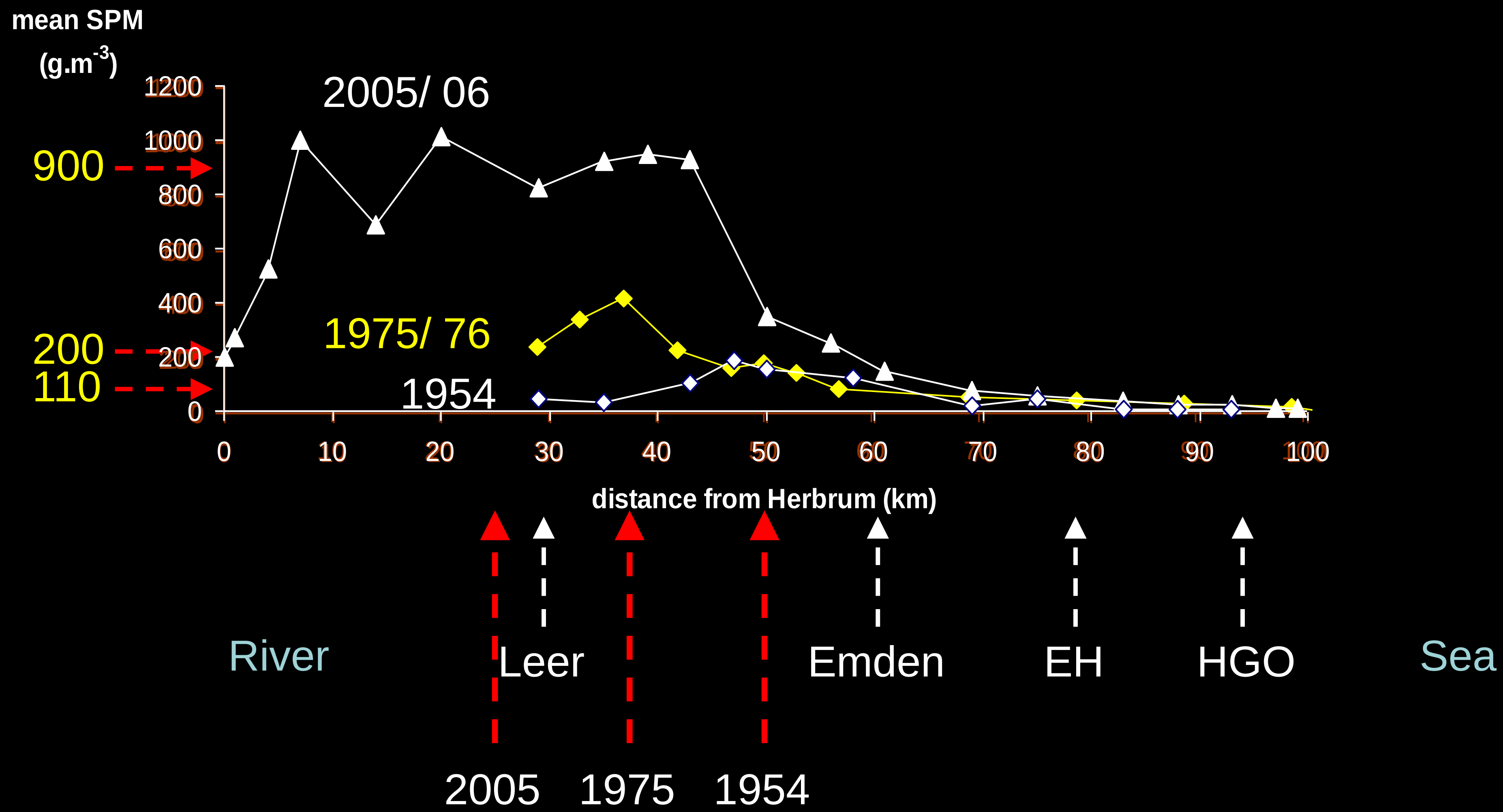


tidal amplitude



(Schuttelaars, de Jonge & Chernetsky, 2013)

mean suspended matter concentration in the Ems estuary

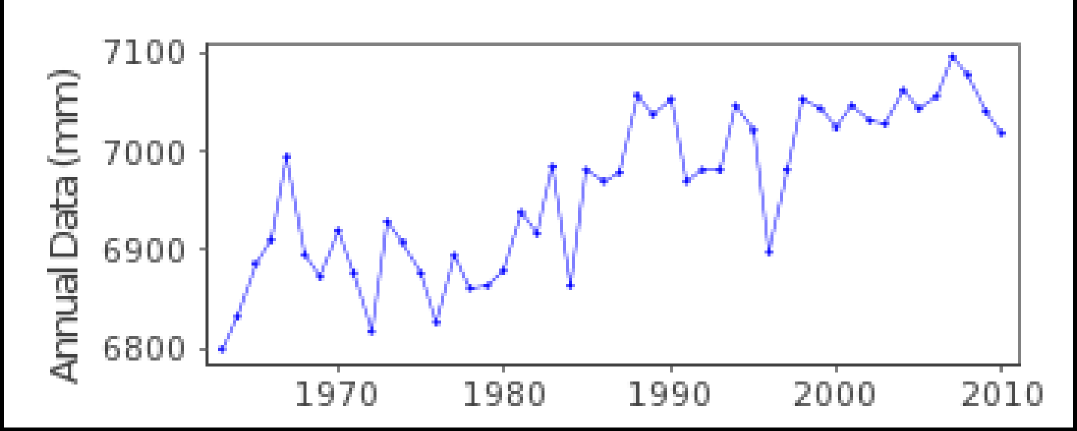


de Jonge *et al.* 2014

Future Ems project addresses the following major questions

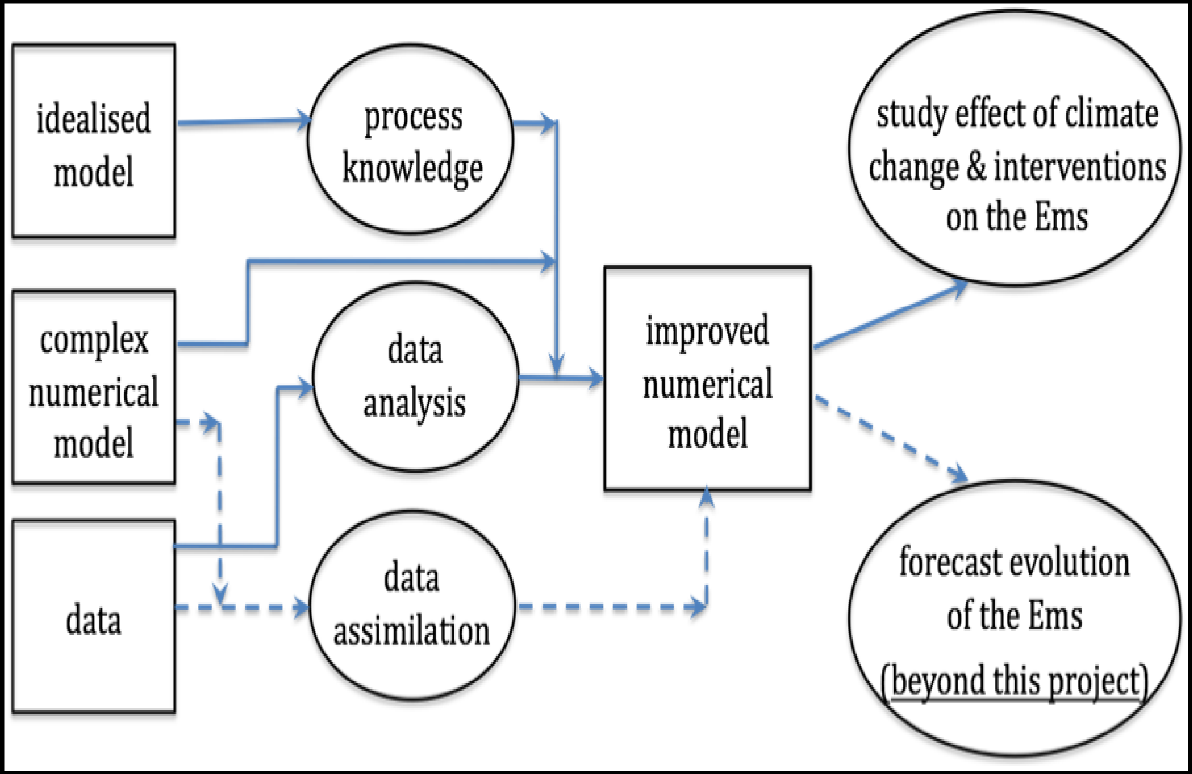
1. Effect of human interventions on tides and turbidity?

2. What is the role of climate change on estuarine functioning (sea level rise, ...)?



Time series of mean sea level (mm/10) at Borkum

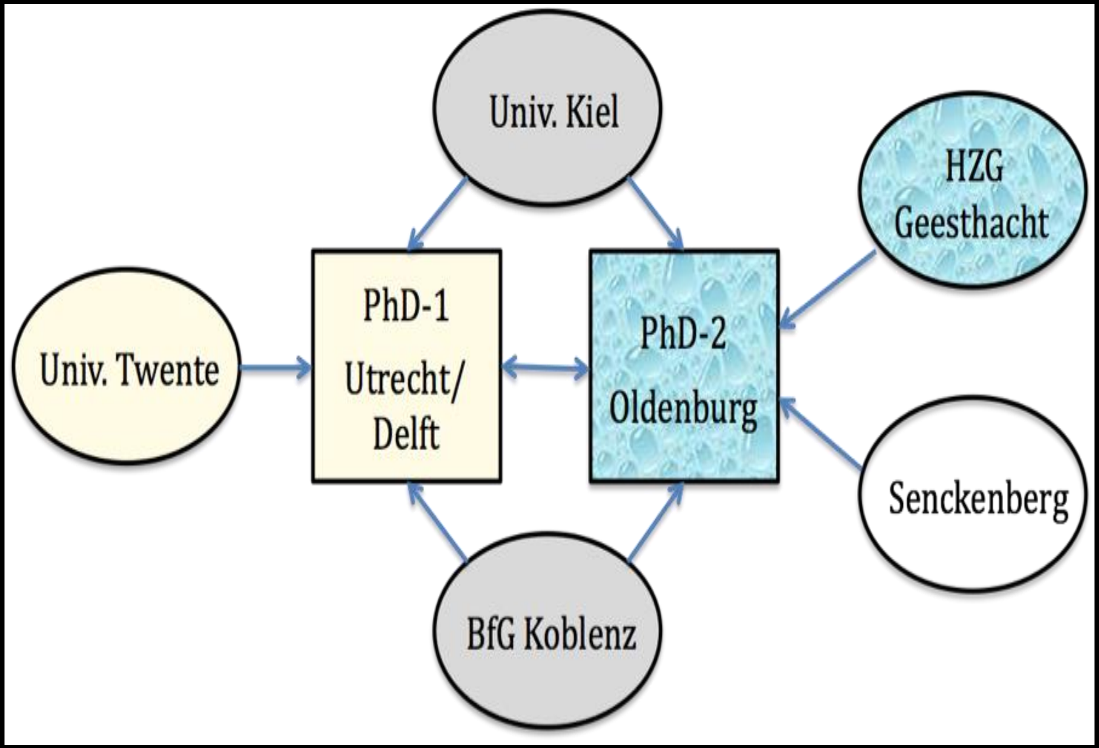
Future-Ems project (2012-2016)



Different model concepts

Models and data

Future-Ems project (2012-2016)



Different countries

Different disciplines

Forthcoming presentations

1. Erik Ensing - Utrecht ($\rightarrow$ Huib de Swart)

   Sensitivity of tidal motion and turbidity to human interventions and climate change

   Tool: available data + idealised model

2. Johannes Pein - Oldenburg

   Hydrodynamics of the Ems estuary: recent observations and 3D modelling

   Material: new field data and numerical model

Sensitivity of tidal motion and turbidity to human interventions and climate change

Idealised model reveals main processes that determine 3D flow / sediment trapping in a tidal estuary

E. Ensing

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Universiteit Utrecht

Contents

1. **Introduction**

   Ems, problems, relevance, objectives

2. **Tool: idealised model**

   tides, residual flow, sediment transport

3. **Response of tides to changes in depth/forcing: Ems**

   deepening, weir, sea-level rise, changes in tidal forcing

4. **Net sediment transport patterns and turbidity maxima**

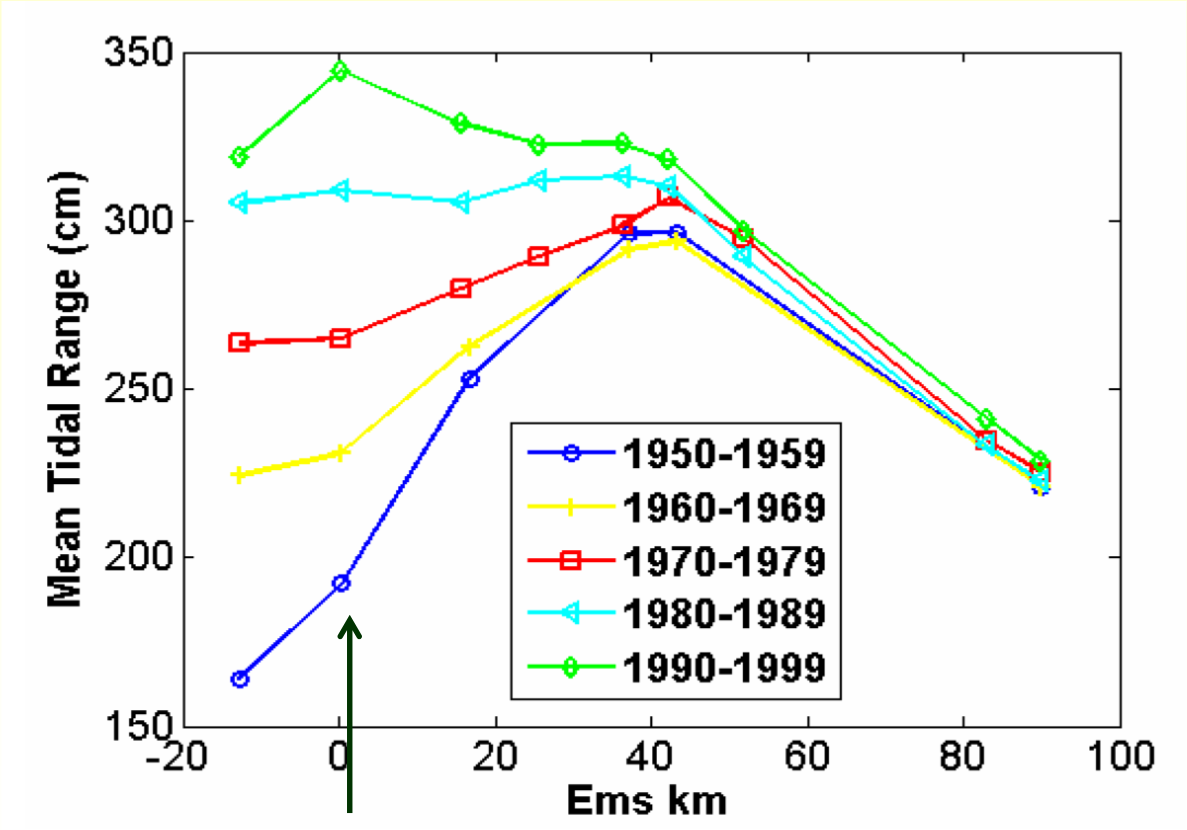
Ems estuary


ÄUßERE EMSMÜNDUNG
BORKUM
OSTEREMS
ROTTUMER-PLAAT
ROTTUMER OOG
AUßENEMS
KNOCK
EMDEN
EMDER FAHRWASSER
POGUM
DOLLART
UNTER-EMS
LEER
LEDA
DORTMUND-EMS-KANAL
PAPENBURG

Problems

Increase of tidal range

(cf. Schuttelaars *et al.*, 2013; data provided by NLKWN)



Herbrum (land)

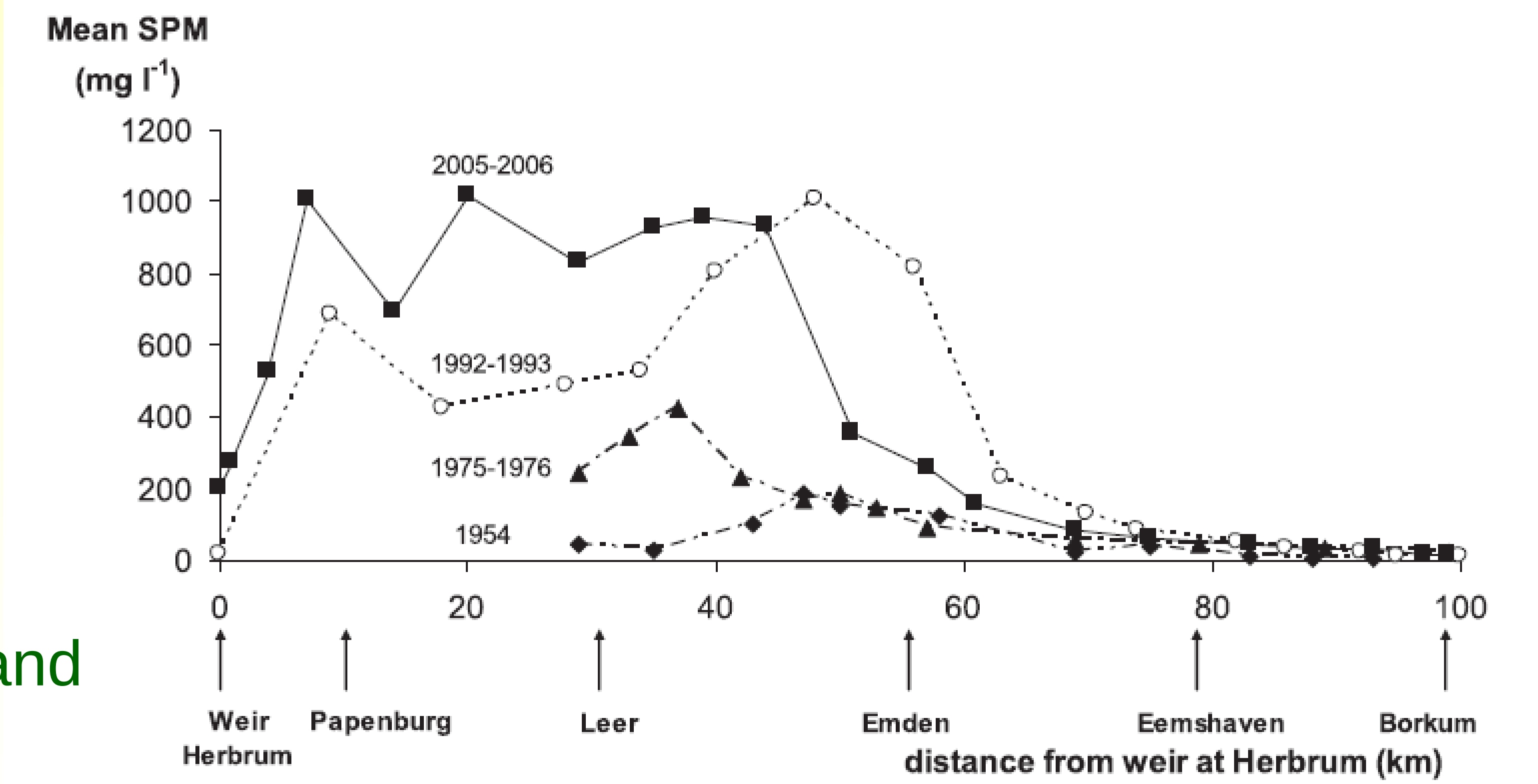
sea

Problems

Increase + landward shift of turbidity maximum

(de Jonge *et al.*, 2014)

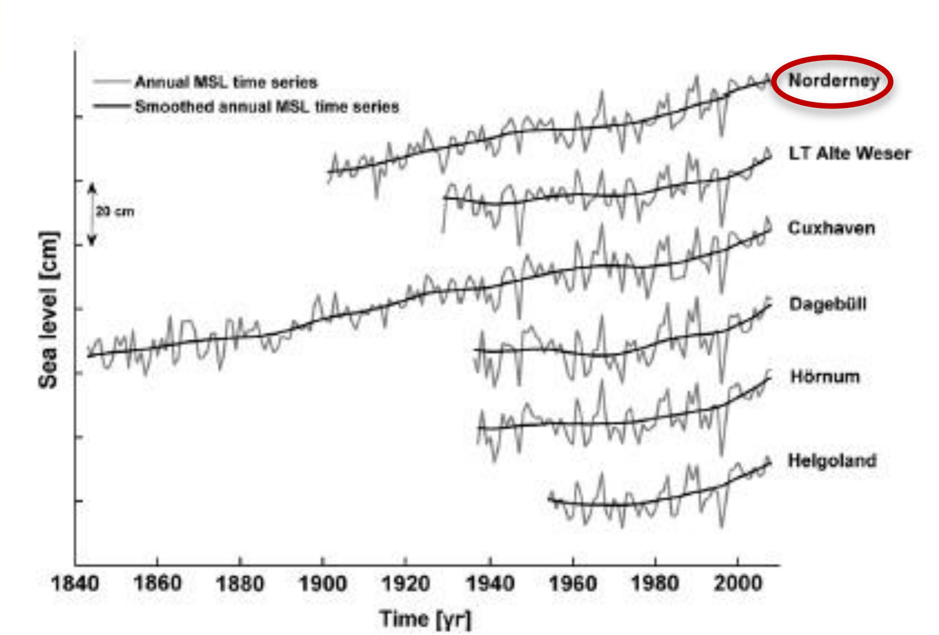
land



sea

Aims

1. Effect of <u>human interventions</u>
   (here: fairway deepening, location of the weir)
   on tidal motion and turbidity



(Wahl *et al.*'11)

2. Effect of <u>climate change</u>
   (here: sea level rise)
   on tidal motion in Ems

Methodology

Idealised three-dimensional (3D) model that governs

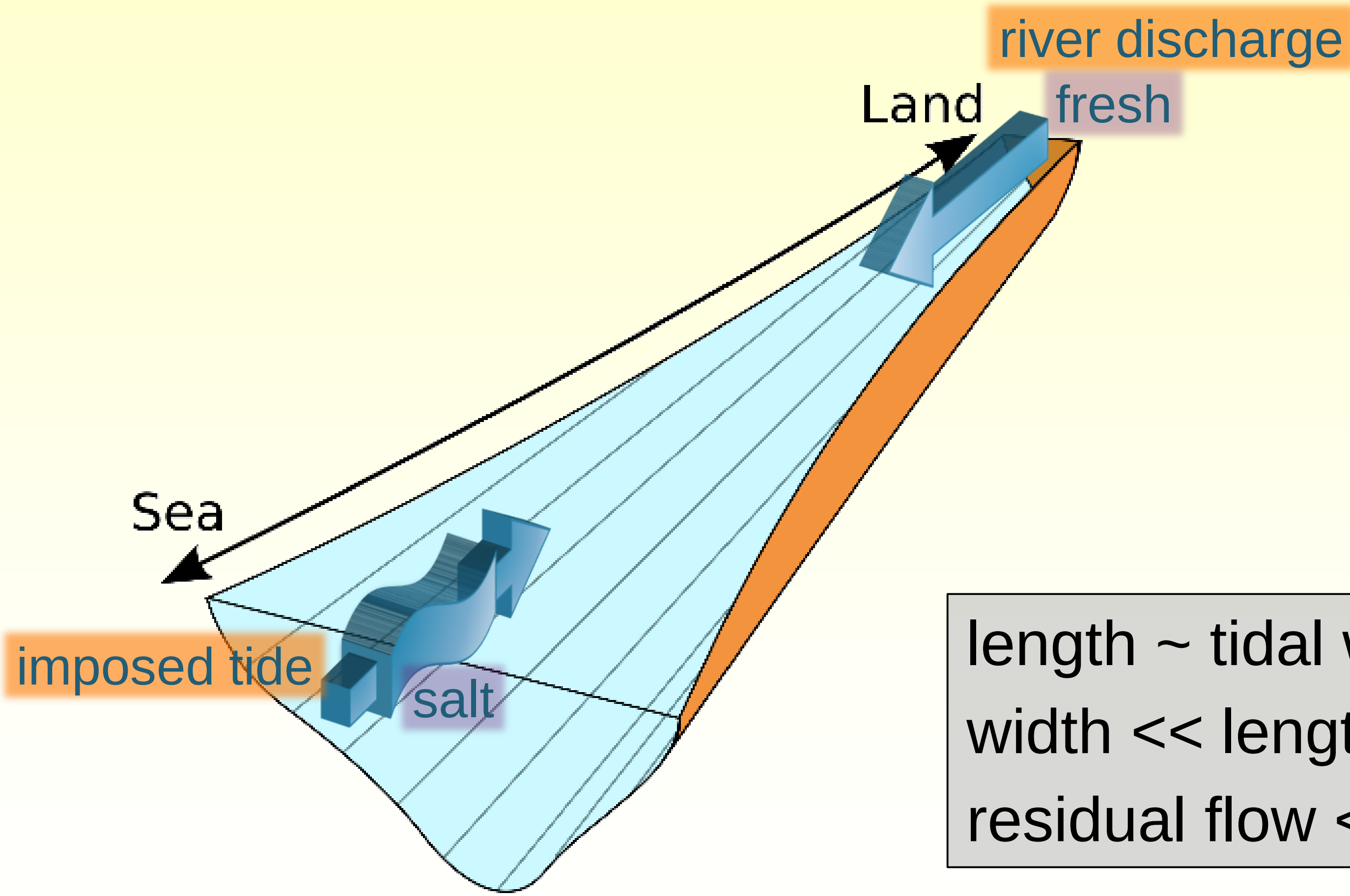
1) flow (tidal and residual components)
2) sediment transport

Why idealised?

- Allows assessment of role of individual mechanisms on the computed flow and sediment transport
- Fast and flexible
- Complementary to numerical models

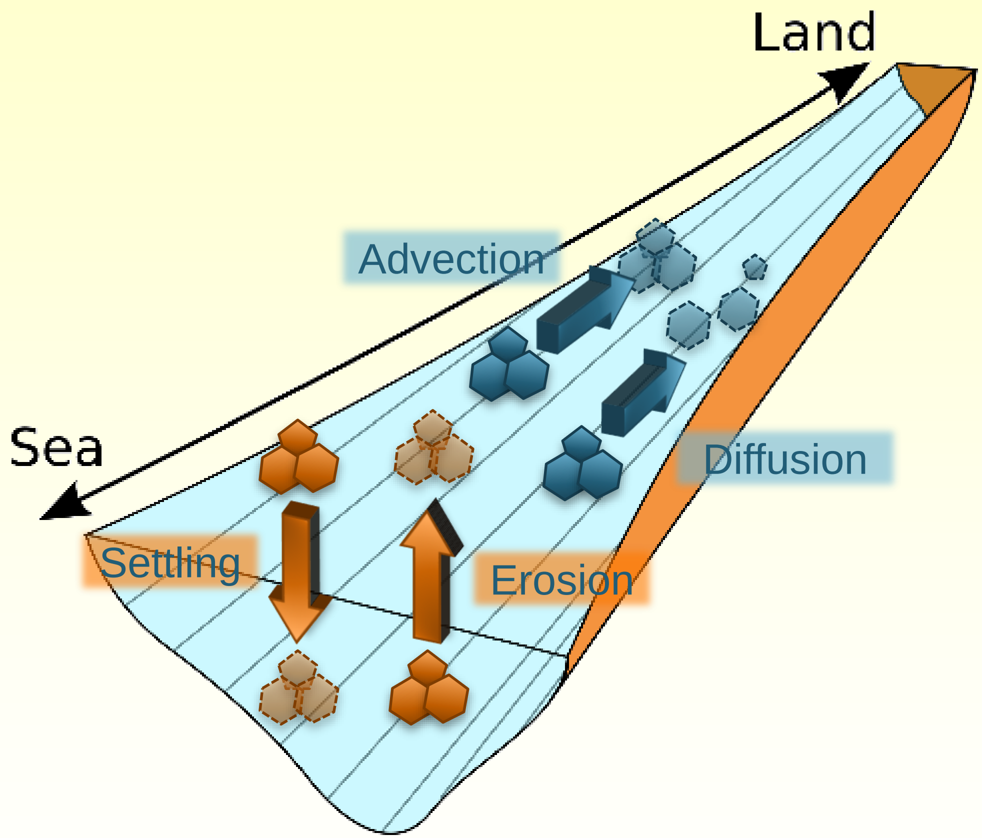
Model: domain and forcing

Estuary with exponentially decreasing width



length ~ tidal wavelength
width << length
residual flow << tidal flow

Sediment mass balance

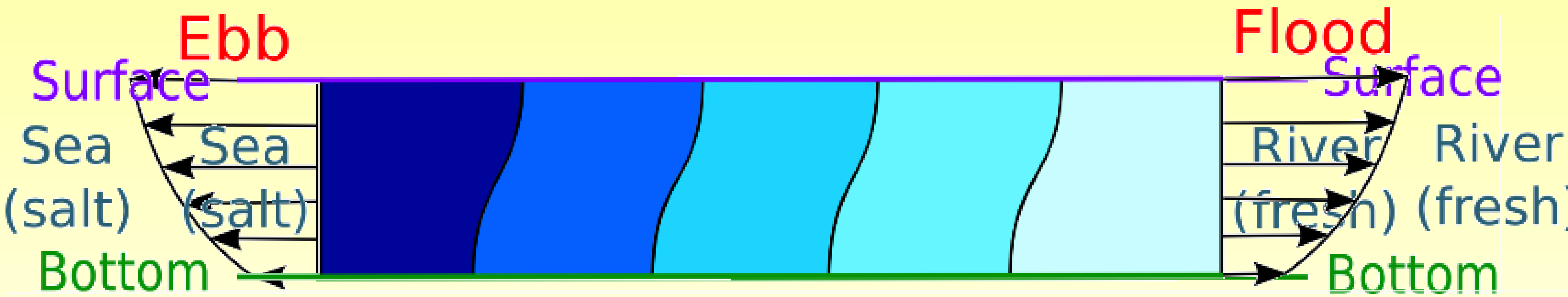


Role of lateral depth variations on dynamics

Lateral flow (due to Coriolis, differential salt advection)

Model accounts for time-varying mixing due to tidal straining of density field

(Simpson *et al*., 1990; Jay & Musiak, 1994; Stacey *et al*., 2008, Burchard *et al.*, 2013)



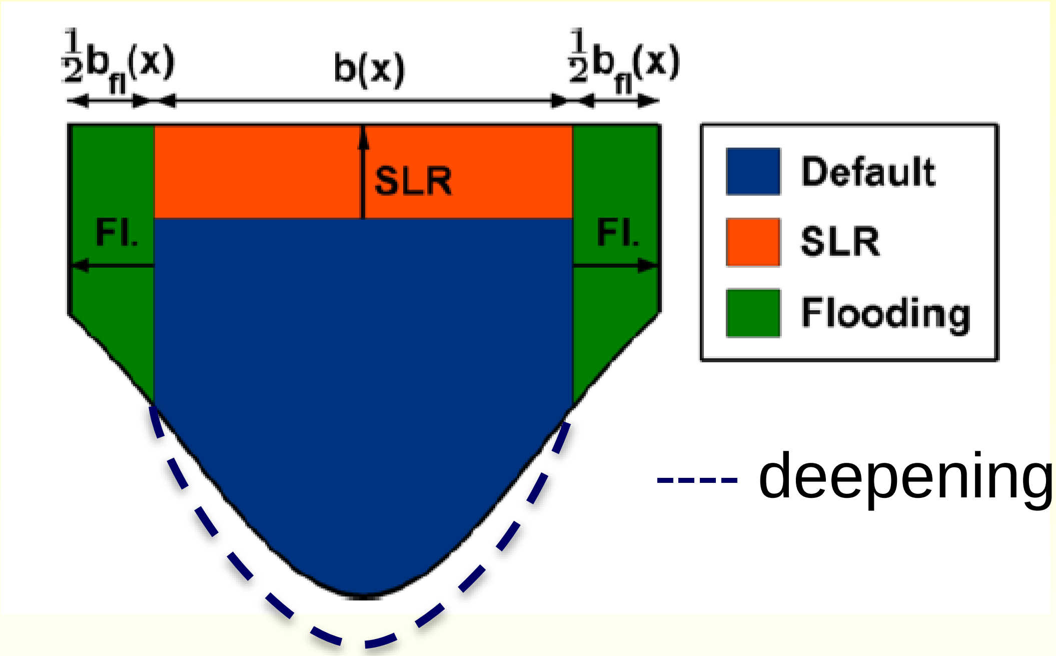
During ebb: fresh water strained over salt water → low mixing

During flood: salt water strained over fresh water → high mixing

⇒ Generation of residual flow, M4 tidal flow

⇒ Affects erosion and vertical mixing of SSC

Methodology: deepening and sea level rise

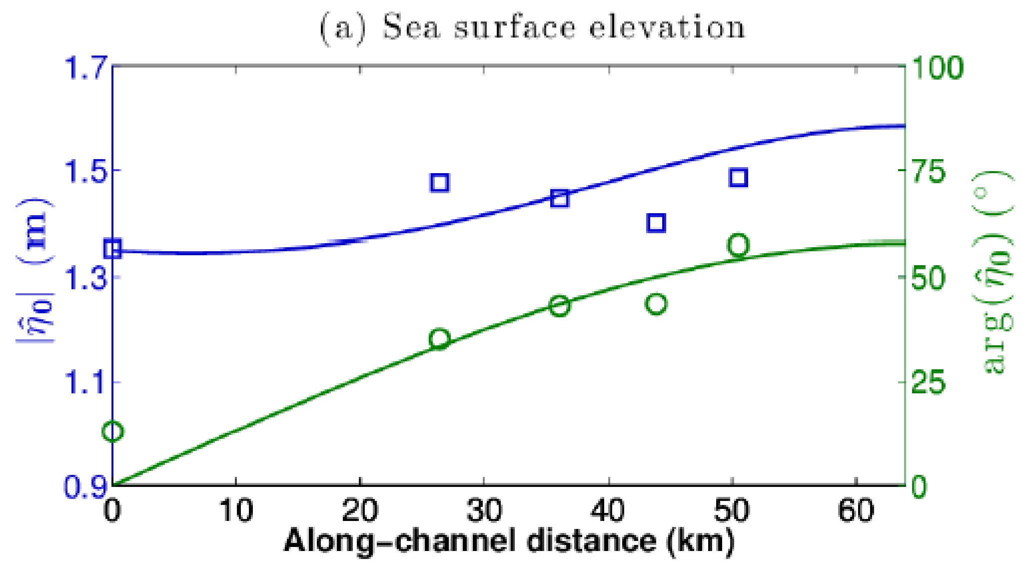


Parameter	Value
Estuary length	65 km
Convergence e-folding length	30 km
Maximum depth	8.5 m
Amplitude of tidal forcing (M2/M4)	1.4 m/0.3 m
Width at seaward end	750 m
River discharge	60 m^3/s

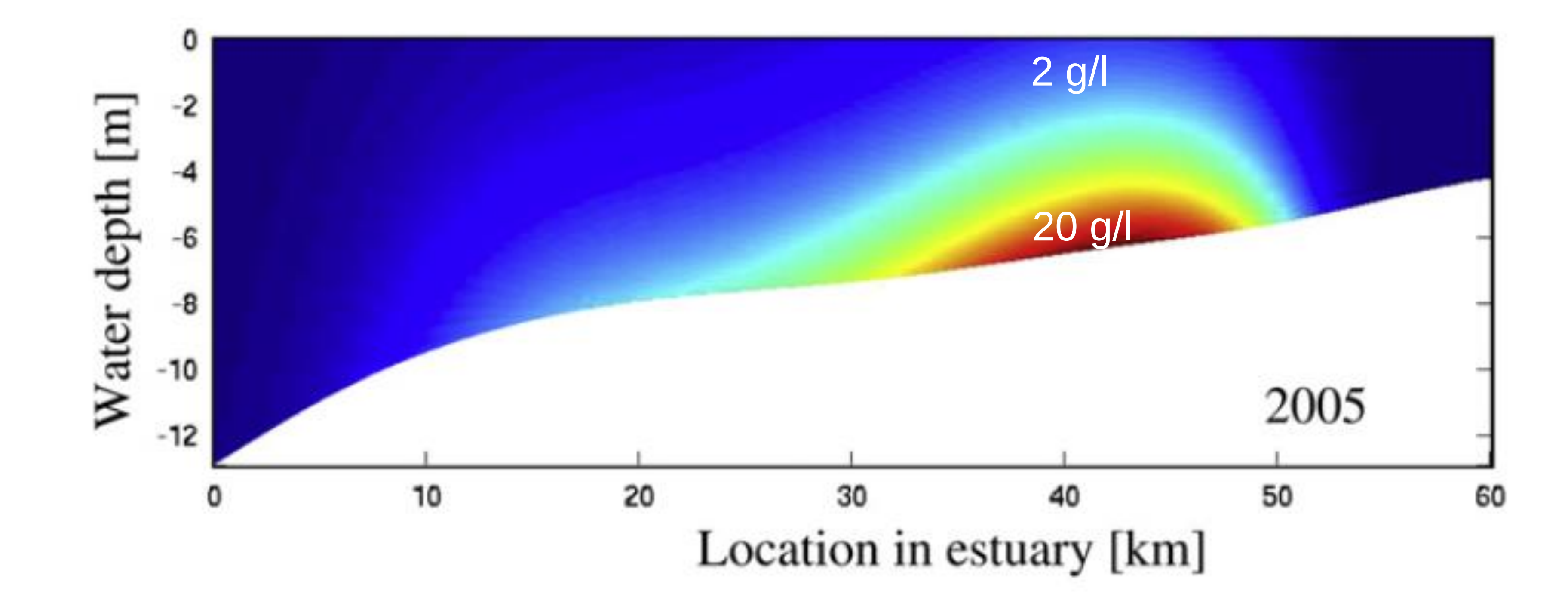
Semi-diurnal lunar (M2) tide 2005

(Ensing *et al.*, subm.)

Blue: amplitude
Green: phase
Symbols: data



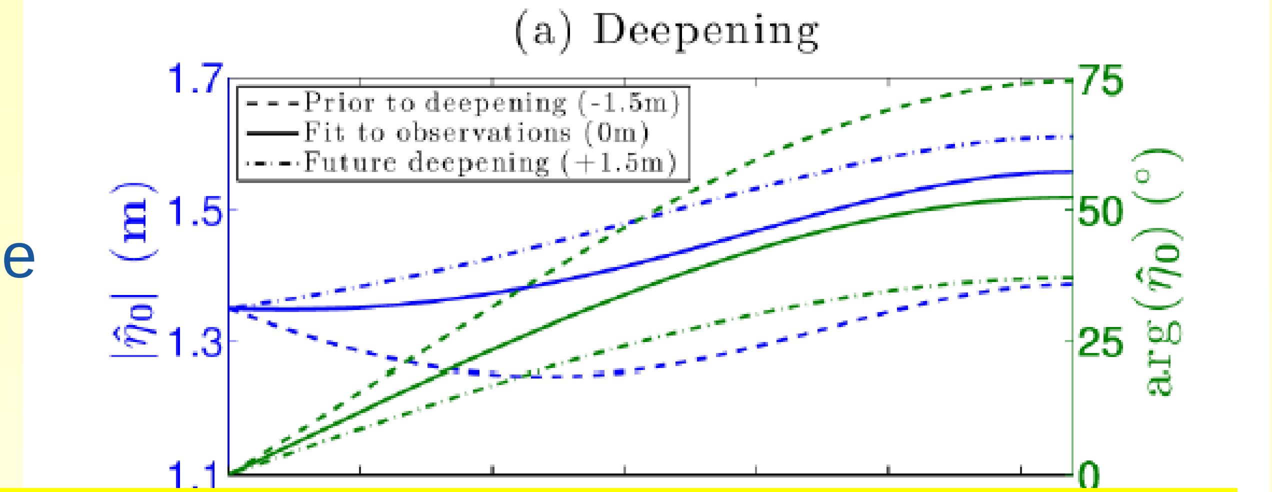
Suspended Sediment Concentration (SSC)



Pronounced estuarine turbidity maximum

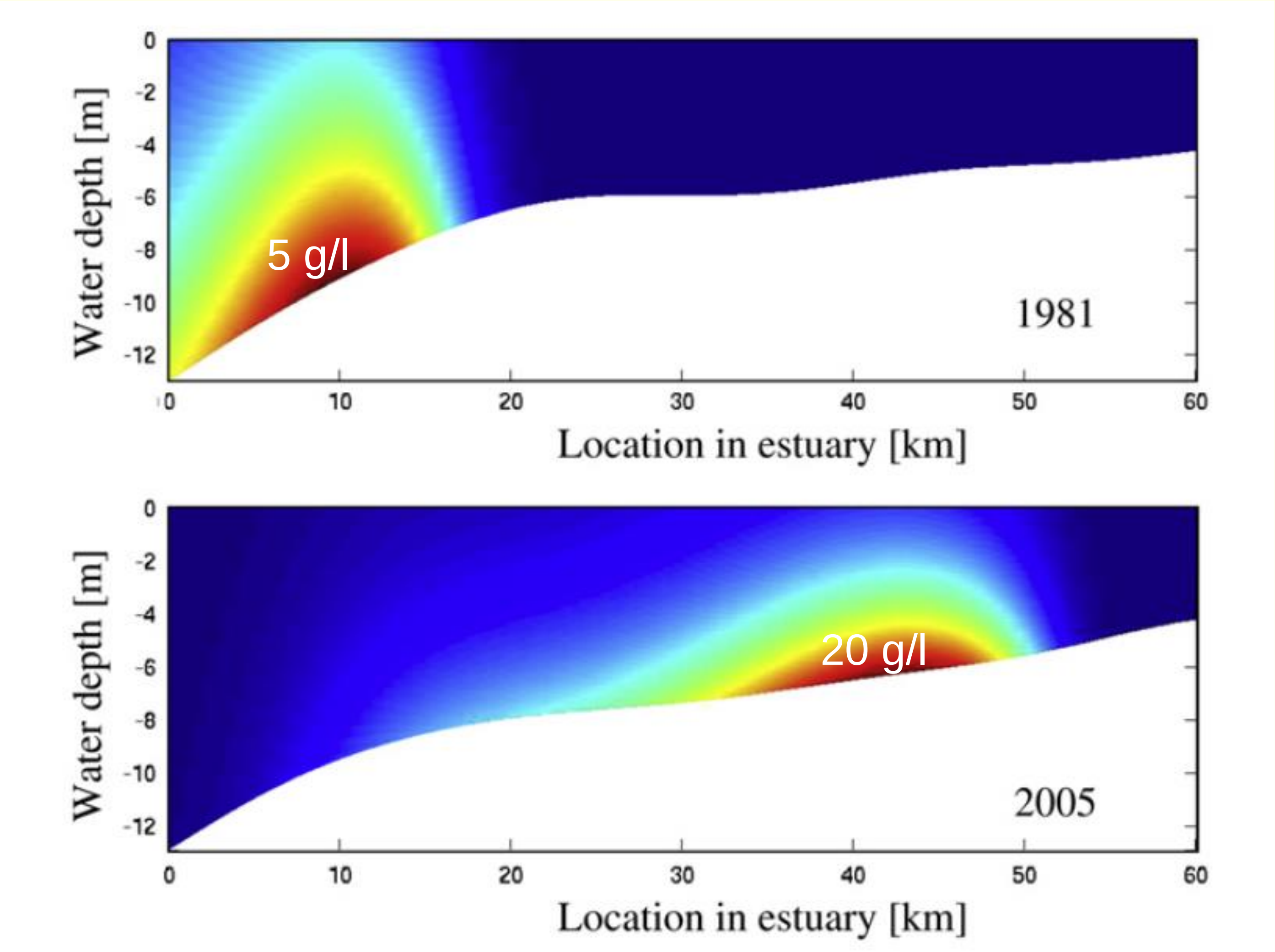
Effect of deepening and sea level rise on M2 tide

Blue: amplitude
Green: phase



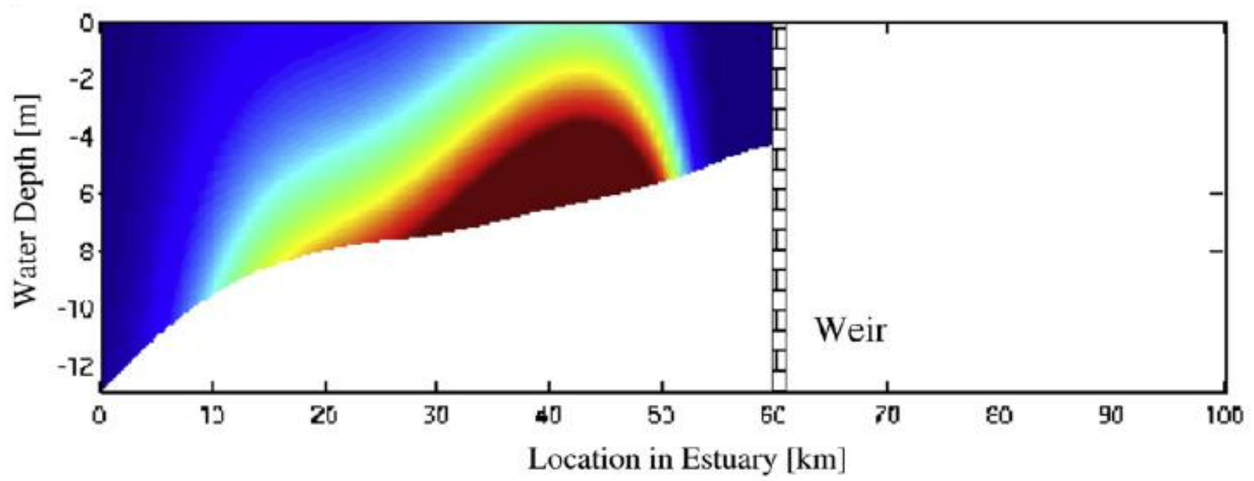
Deepening/sea level rise:
Amplification of the tide + faster propagation speed

Effect of deepening on turbidity



Increase + landward shift of turbidity maximum, due to changes in tidal asymmetry and residual flow

Distribution of turbidity for different locations of the weir

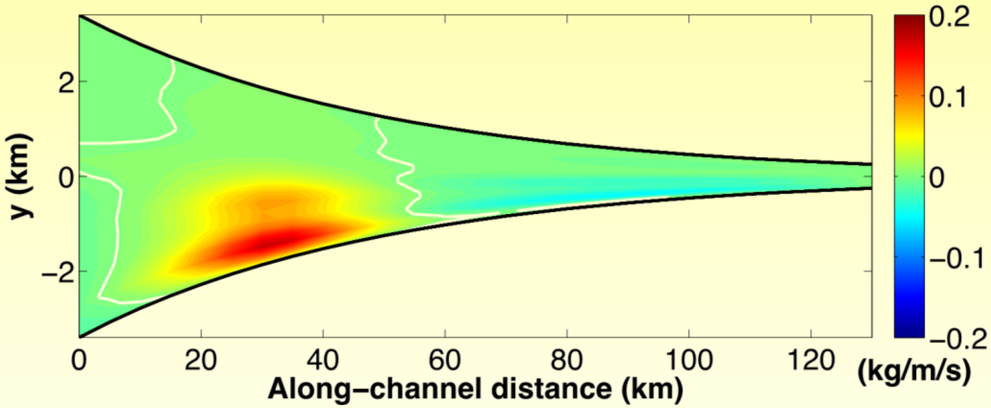


(Schuttelaars, de Jonge & Chernetsky, 2013)

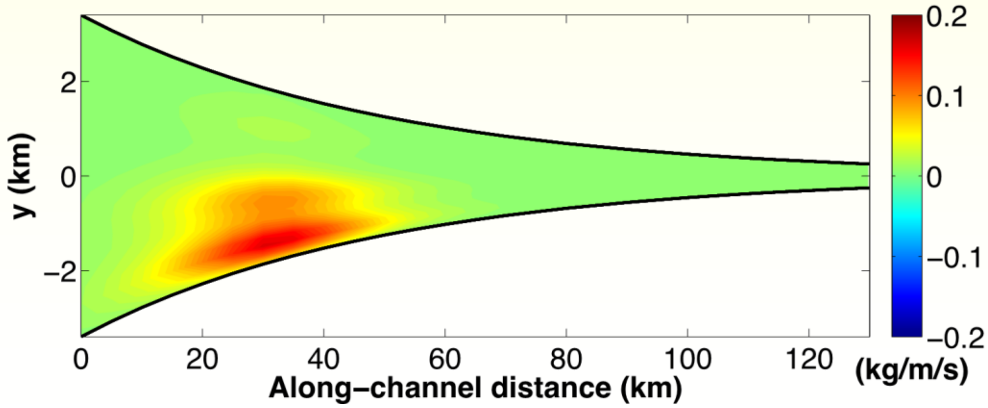
Discussion: importance of time-varying mixing on turbidity dynamics

Here results for James River estuary

Total net sediment transport

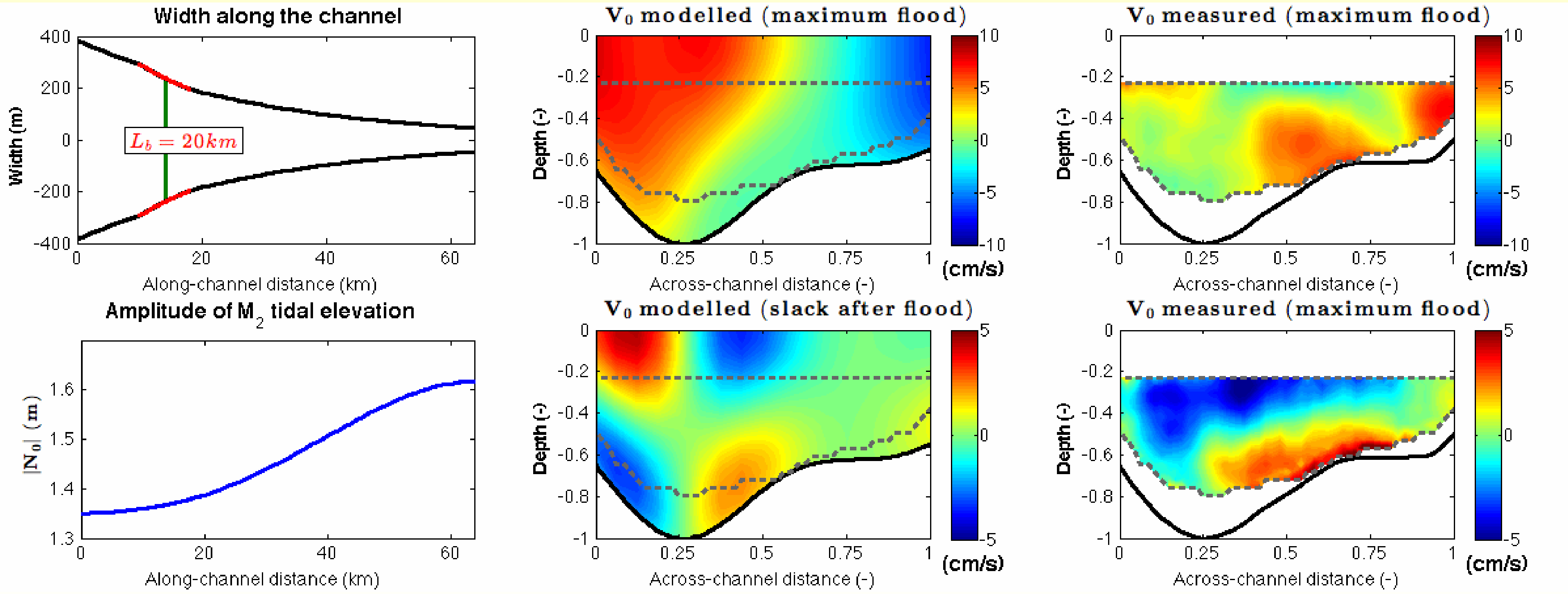


Net sediment transport due to time-varying mixing:



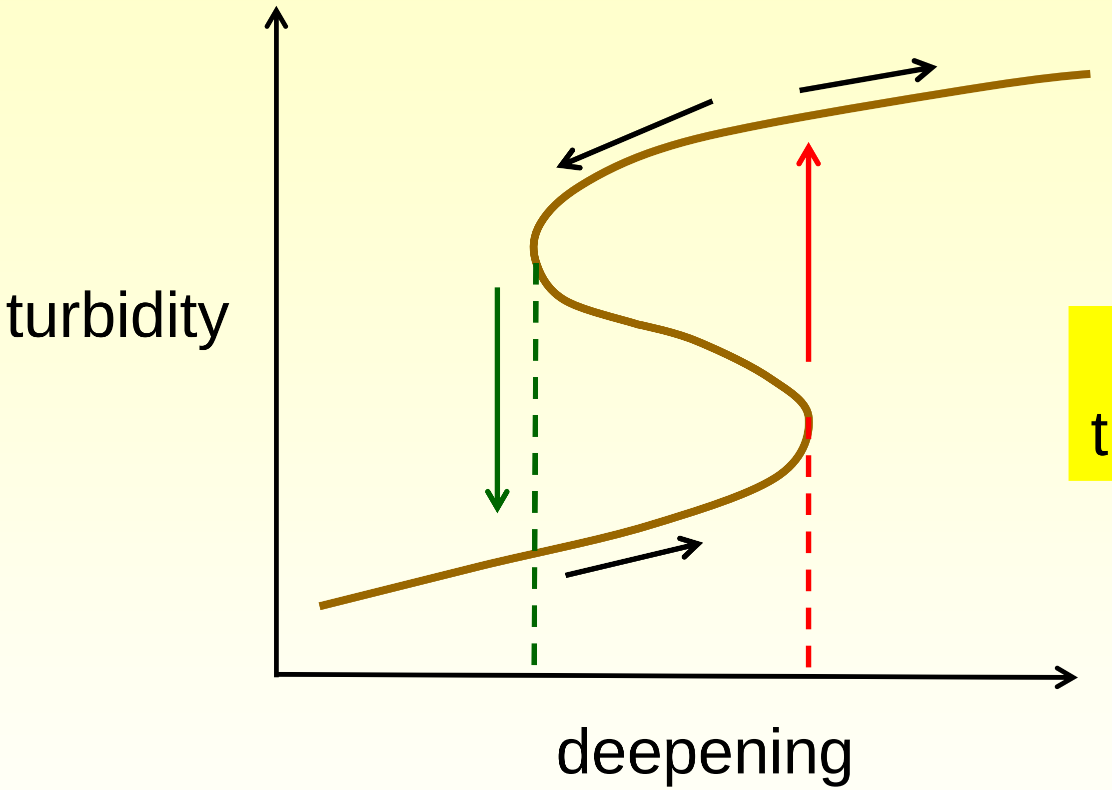
Discussion/Outlook

Distribution of lateral tidal flow over an estuarine cross-section at a specific location



Structure lateral flow is strongly affected by geometric parameters

Discussion/Outlook



Existence of tipping points?

Feedback mechanism (Winterwerp *et al.*, 2014):

deepening: more sediment → smoother bottom → damping of turbulence → stronger tidal asymmetry → larger transport → ETM intensifies

Conclusions

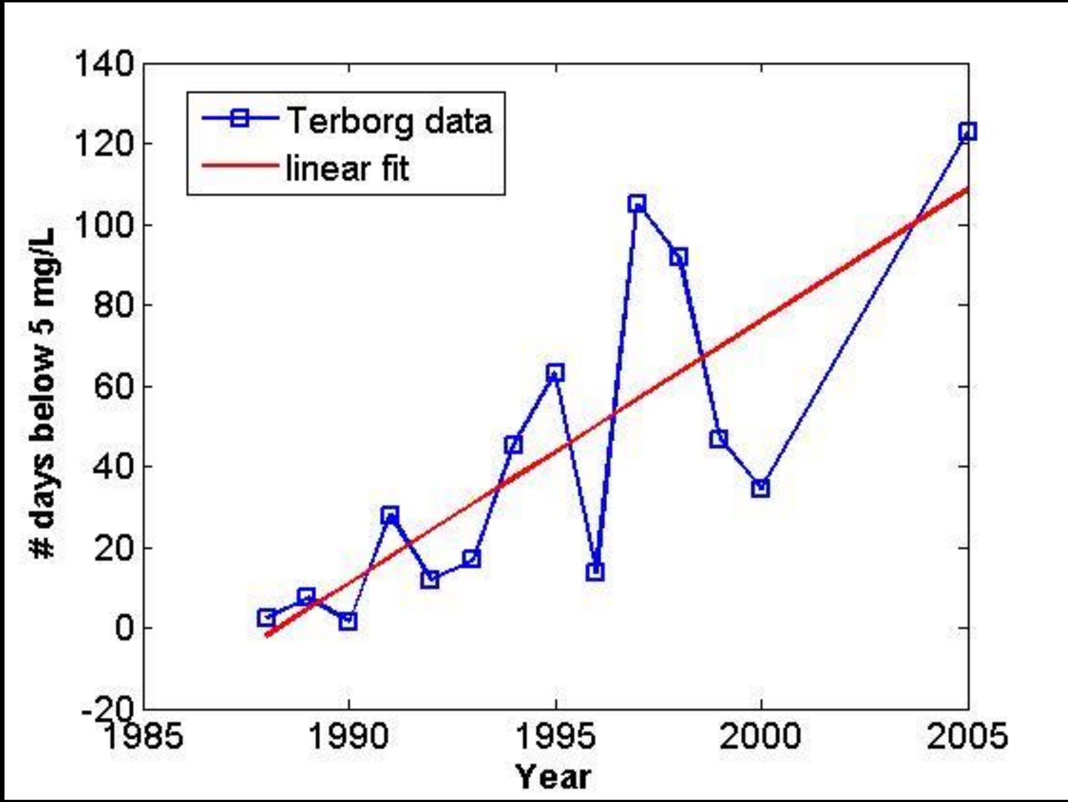
1. Both deepening and sea level rise for Ems setting: amplification of the tide + faster propagation speed

2. Idealised model is able to simulate and explain the **landward shift of the turbidity maximum**

3. **Asymmetry in mixing** is important agent in driving net sediment transport

4. **Idealised models** useful for gaining fundamental knowledge + for sensitivity studies

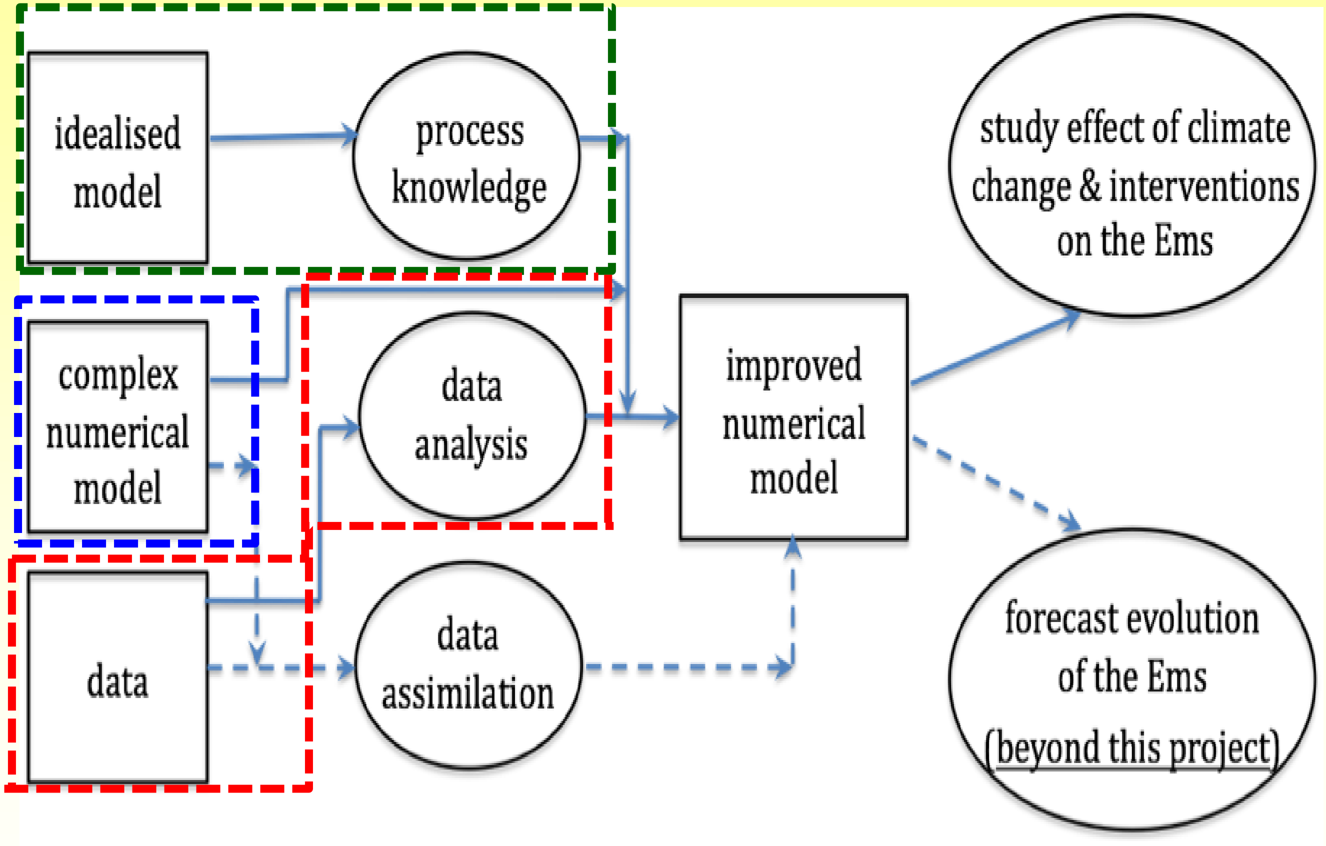
Large-scale deepening and changes in ecology



Number of days with oxygen concentraties < 2 mg/l

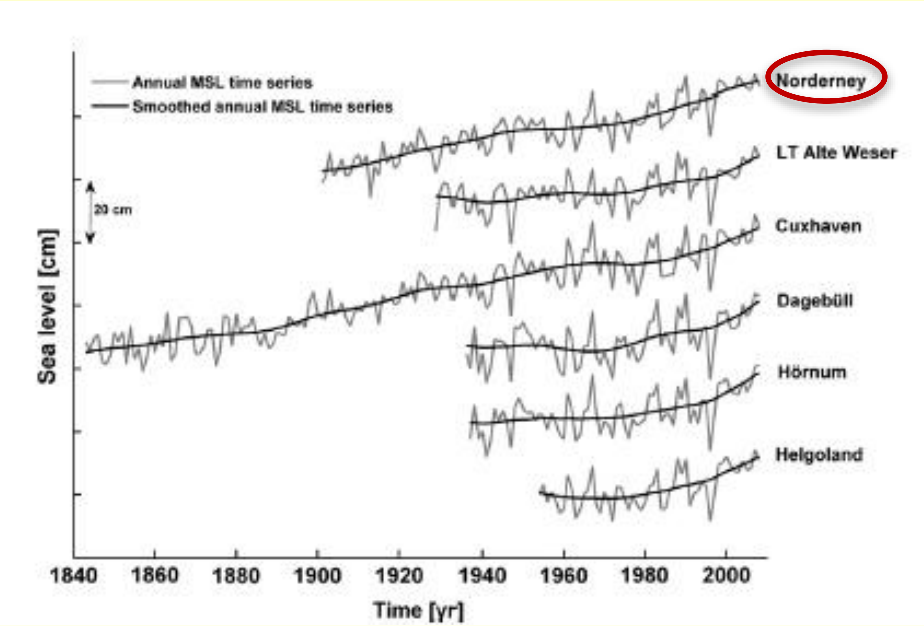
Increase in hypoxia

State of the art

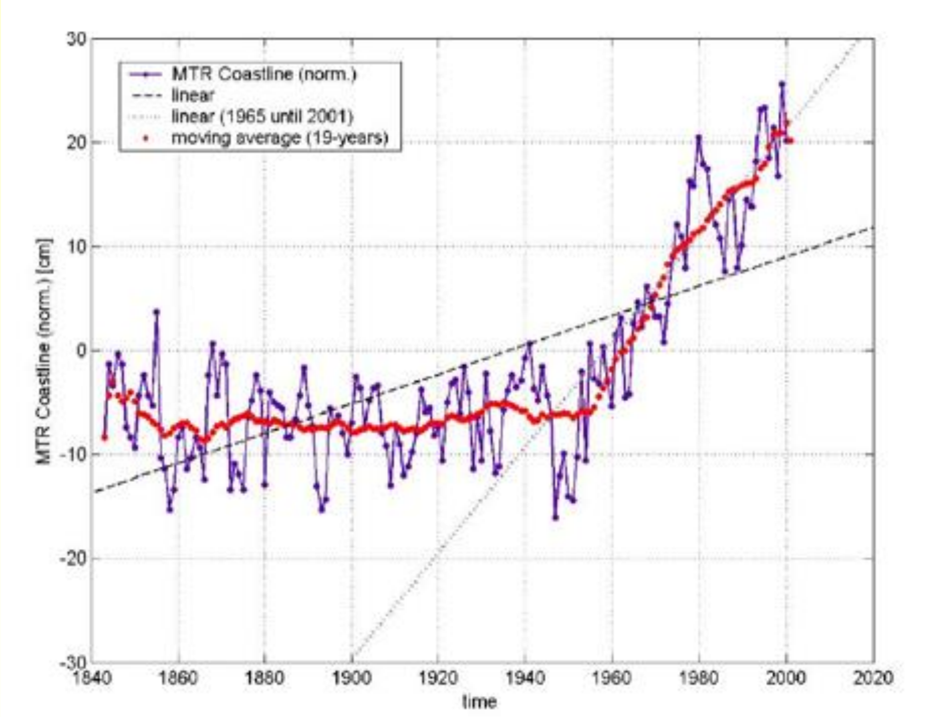


Feedback end users is essential

Note: sea level rise also affects external tidal forcing

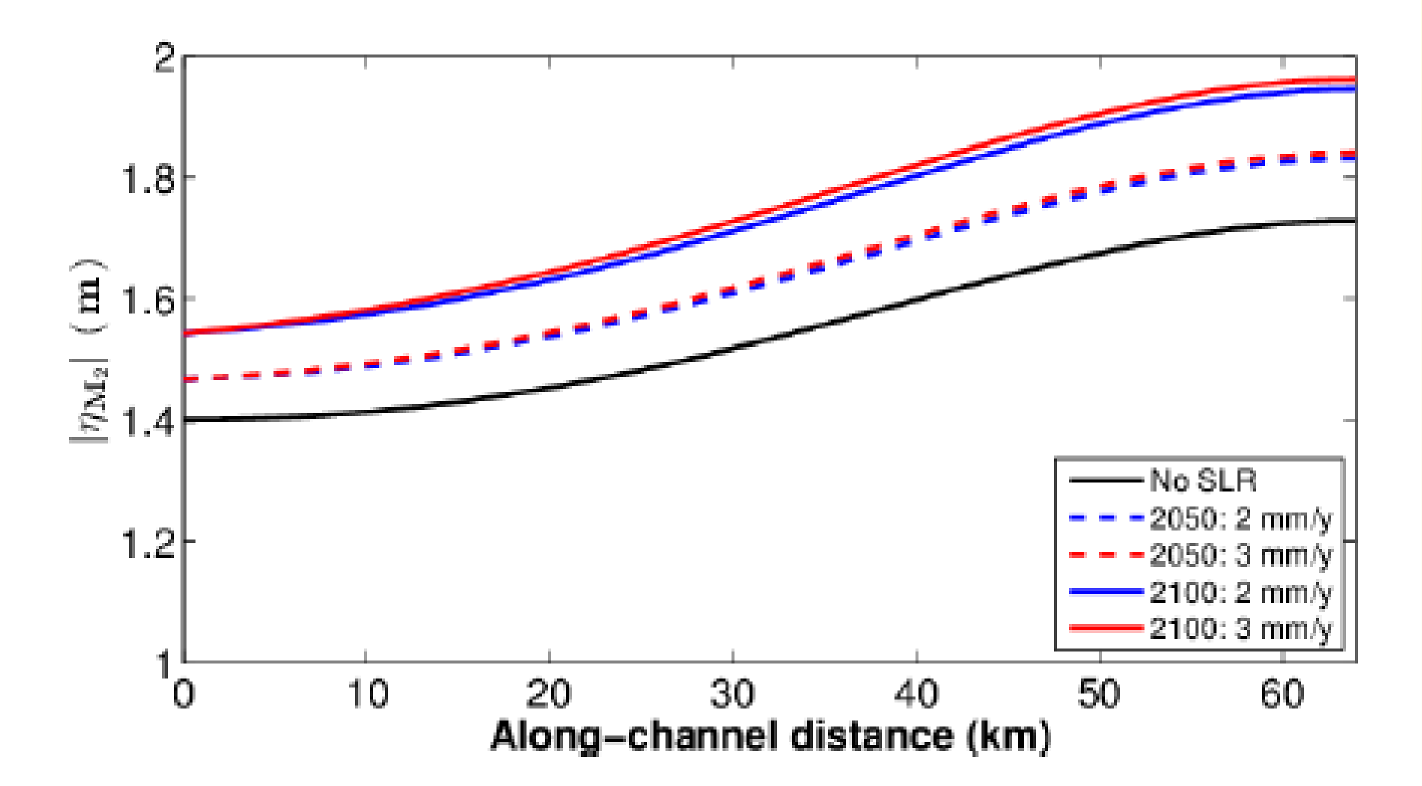


Time series mean sea level
German coast (Wahl et al'11)



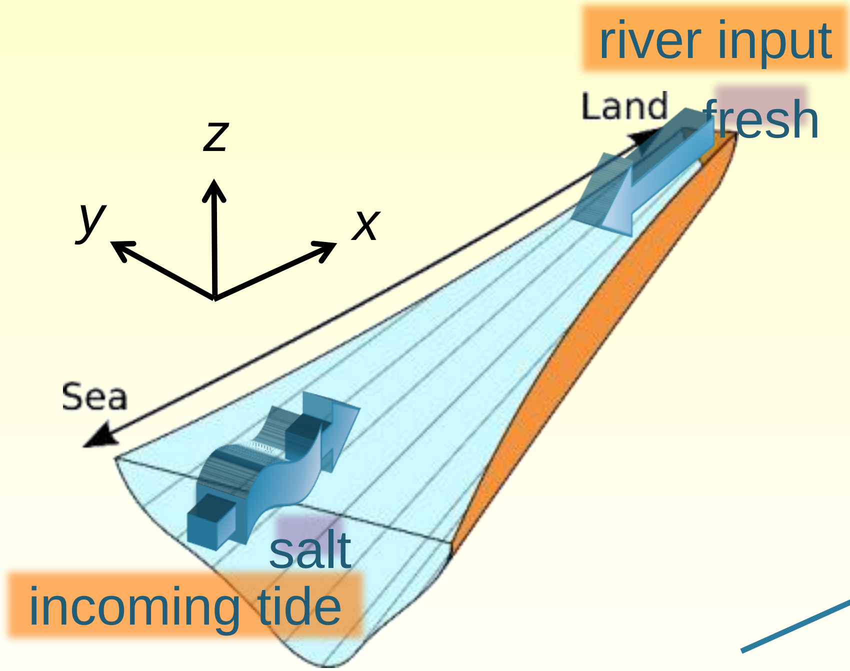
Time series changes in tidal range
(German coast; Jensen&Mudersbach'04)

Effect of sea level rise and changing external tides on M2 sea surface amplitude



Changes in external tides on time scale ~ century have an effect that is comparable to deepening

Equations of motion



Warner & Geijer'05

- 3D shallow water equations
  (inertia, advection, Coriolis, pressure gradient, friction)

- <u>semi-diagnostic</u> in salinity:

  $$s = S(x) + s'(x,y,z,t)$$

  where

  $$S(x) = \frac{S_0}{2}\left[1 - \tanh\left(\frac{x - x_c}{x_L}\right)\right]$$

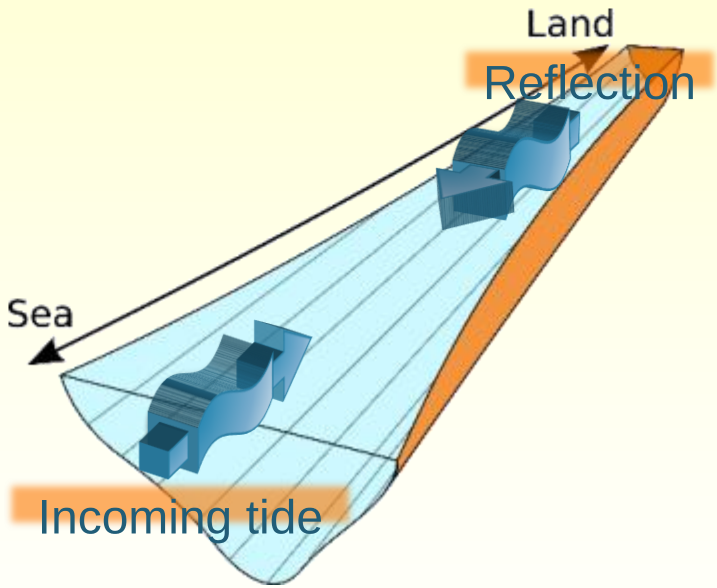
  $$\frac{\partial s'}{\partial t} + u'\frac{dS}{dx} = \frac{\partial}{\partial z}\left(\kappa_v \frac{\partial s'}{\partial z}\right)$$

- sediment transport

  $$Q = \iint u\, c\, dydz$$

Equations for tidal flow

- Tides >> residual flow
- Small Froude number (weakly nonlinear)
- Along-channel tidal flow >> across-channel tidal flow



$$\frac{\partial u'}{\partial t} = -g\frac{\partial \eta'}{\partial x} + \frac{\partial}{\partial z}\left(\bar{A}_z \frac{\partial u'}{\partial z}\right)$$

$$fu' = -g\frac{\partial \eta'}{\partial y} + \frac{g\beta}{\rho_0}\int_{\eta}^{z}\frac{\partial s'}{\partial y}dz + \frac{\partial}{\partial z}\left(\bar{A}_z \frac{\partial v'}{\partial z}\right)$$

$$\frac{\partial \eta'}{\partial t} + \frac{\partial}{\partial x}\int_{-b/2}^{b/2}\int_{-H(y)}^{0} u' dz dy = 0$$

β : saline contraction coefficient
b : local width
η' : tidal sea surface

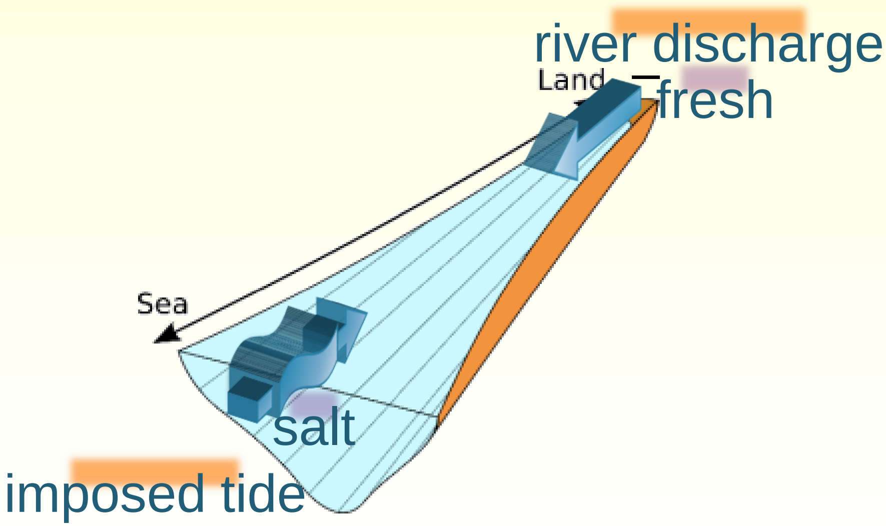
Along-channel residual flow

$$\overline{u'\frac{\partial u'}{\partial x}+v'\frac{\partial u'}{\partial y}+w'\frac{\partial u'}{\partial z}} = -g\frac{\partial \bar{\eta}}{\partial x}+\frac{g\beta}{\rho_0}\int_{\eta}^{z}\frac{\partial \bar{s}}{\partial x}\,dz+\frac{\partial}{\partial z}\left(\overline{A_z'\frac{\partial u'}{\partial z}}\right)+\frac{\partial}{\partial z}\left(\bar{A}_z\frac{\partial \bar{u}}{\partial z}\right)$$

tidal rectification

density driven

asymmetric mixing



$$\int_{-b/2}^{b/2}\int_{-H(y)}^{0}\bar{u}\,dz\,dy+\int_{-b/2}^{b/2}\overline{u'(z=0)\eta'}\,dy=Q$$

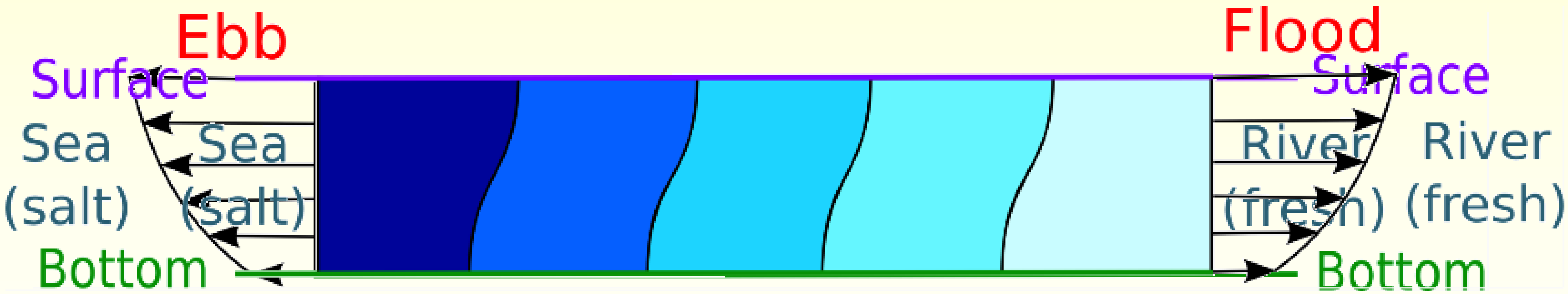
Stokes transport

river

Assumptions

1. Partial slip condition at the bottom
2. Eddy viscosity/diffusivity independent of *z*
3. Mixing varies during tidal cycle

(~straining of density: Simpson *et al.*'90, Jay'91 a.o.)



During ebb: fresh water strained over salt water → low mixing

During flood: salt water strained over fresh water → high mixing

Correlation mixing-flow shear: source of residual flow

Along-channel residual flow

Solution for residual flow

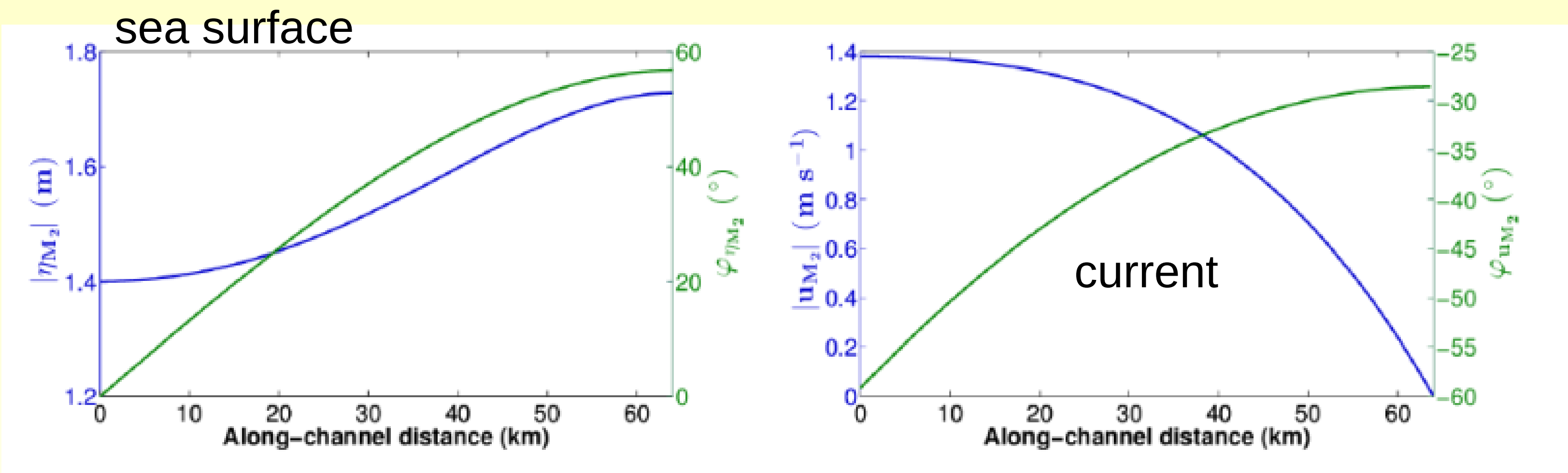
$$\overline{u} = \overline{u}_D + \overline{u}_R + \overline{u}_s + \overline{u}_N + \overline{u}_A$$

Density gradient | **R**iver | **S**tokes return flow | **N**onlinear advection | **A**symmetric mixing

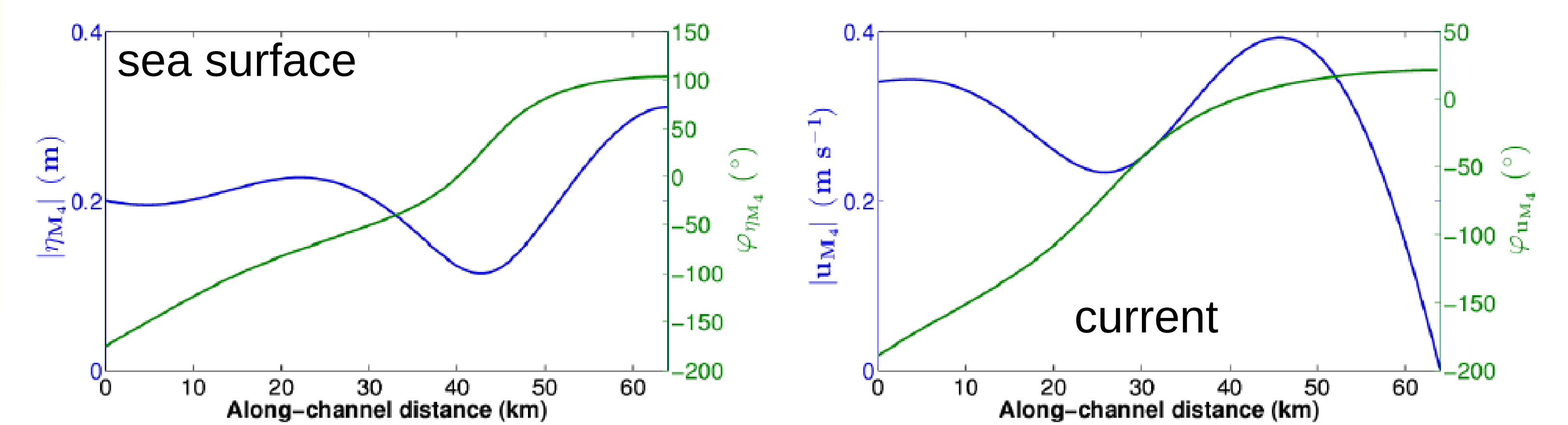
and analytic expressions for each of the 5 components

M2 tide 2005

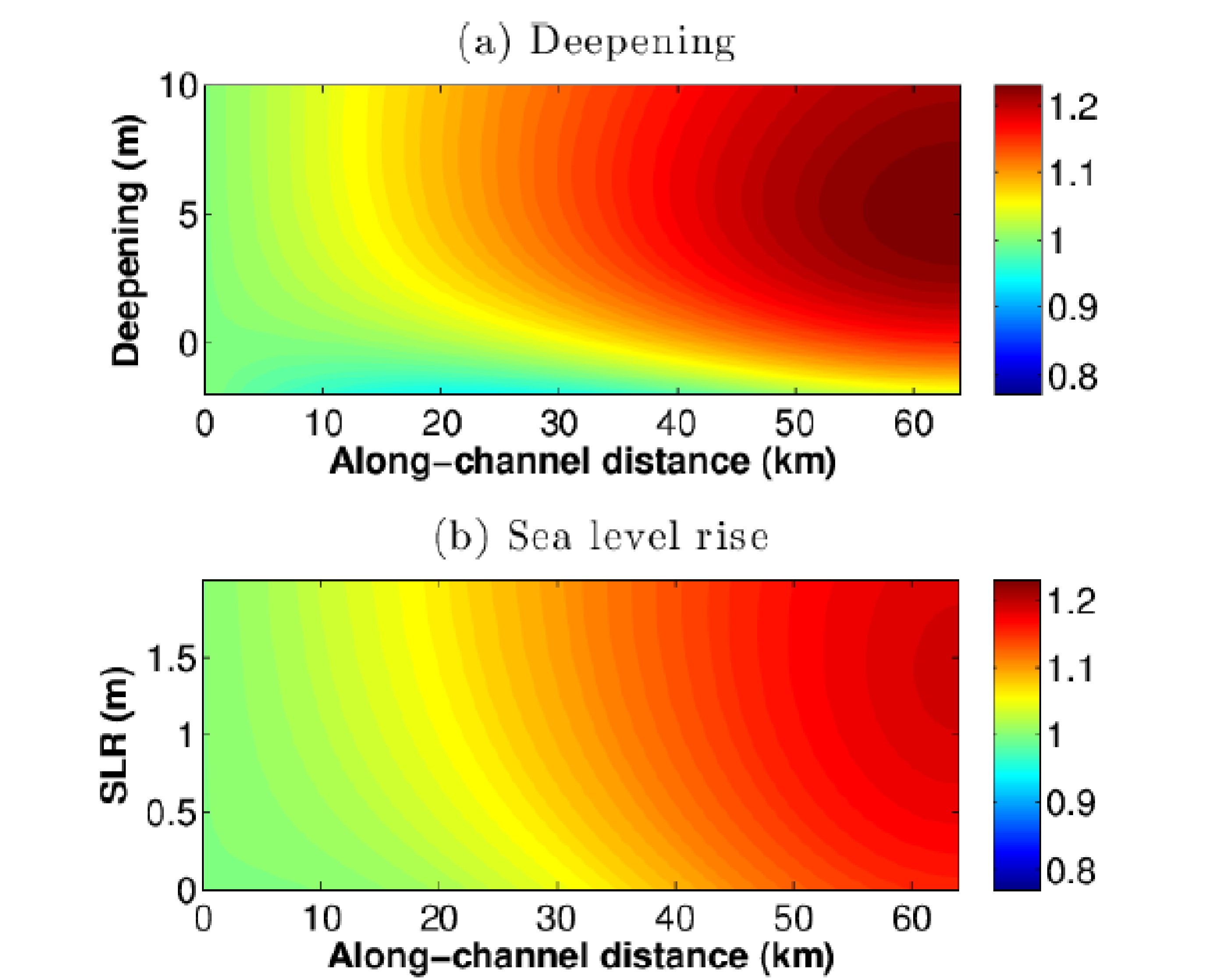
(Ensing *et al.*, subm.)



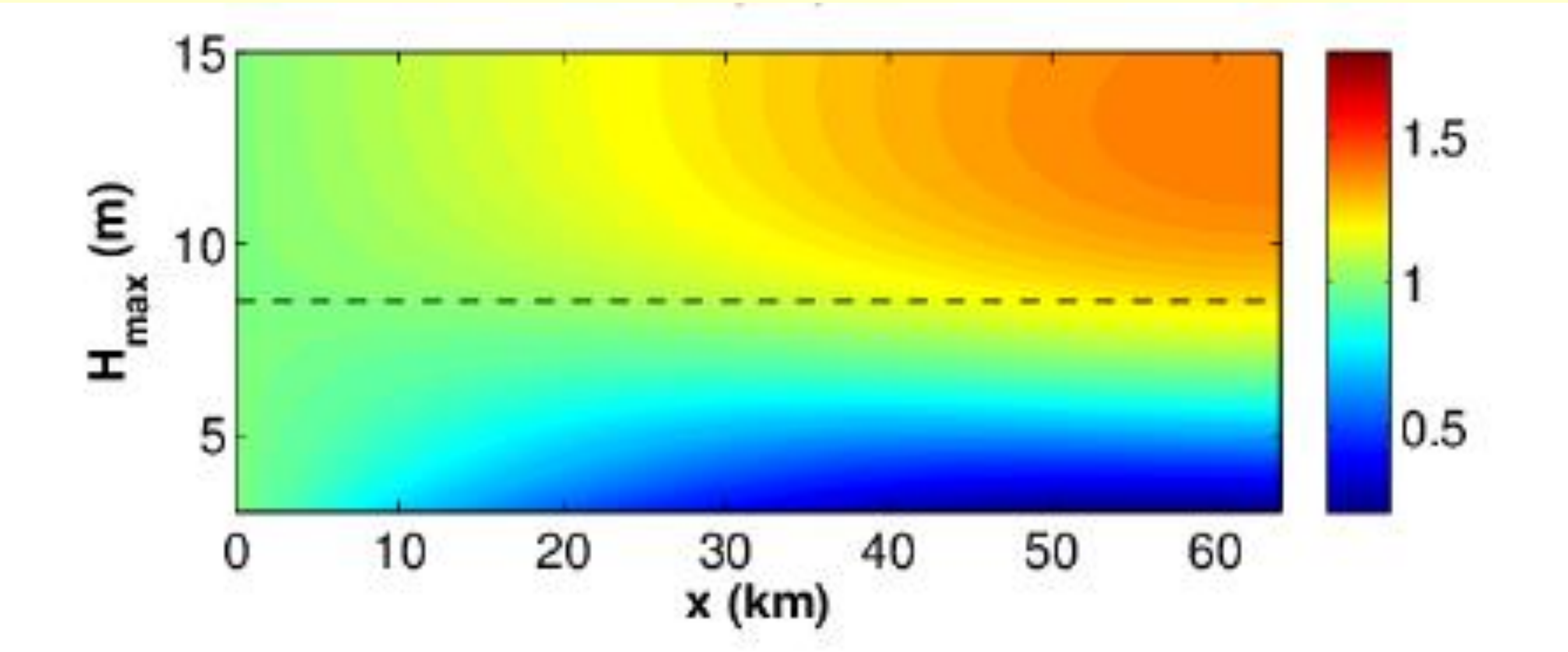
M4 tide 2005



Effect of deepening and sea level rise on M2 tide



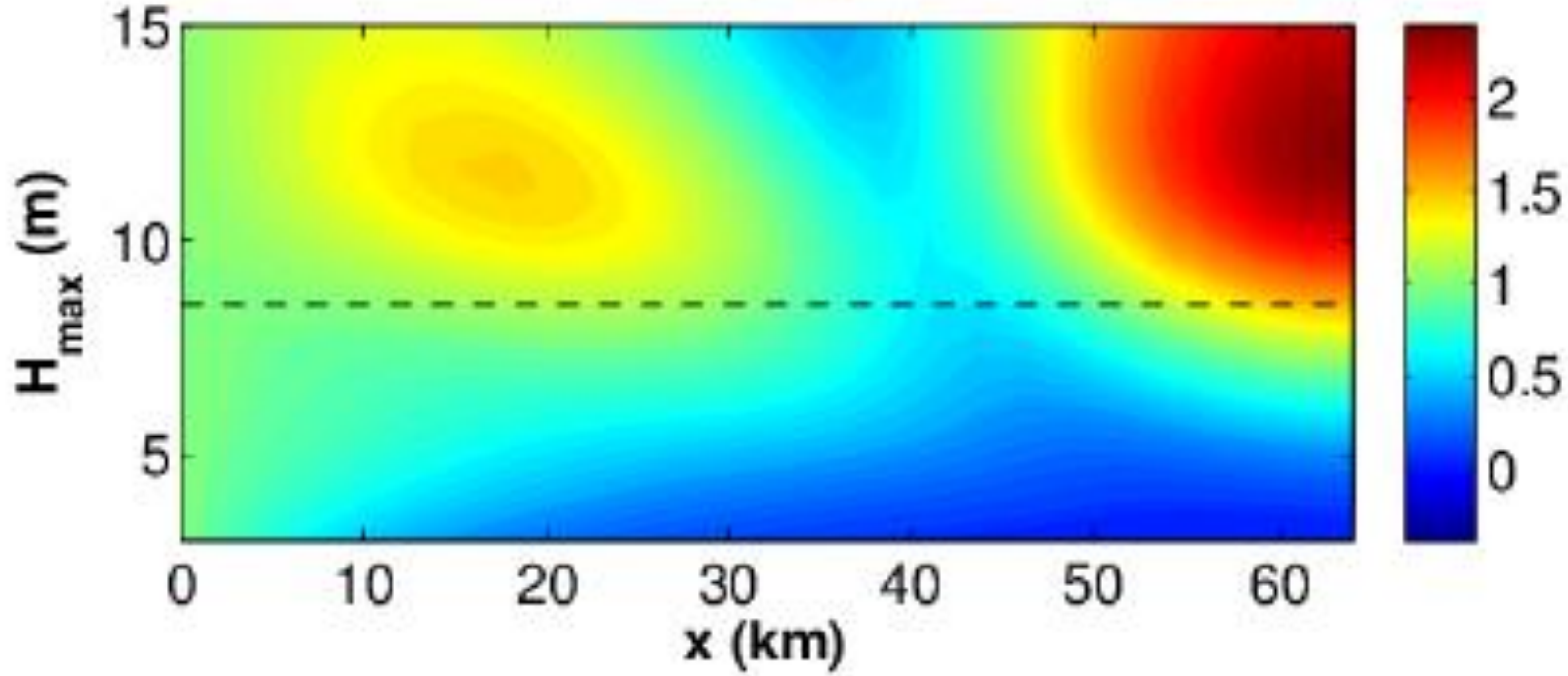
Effect of deepening on M2 sea surface amplitude



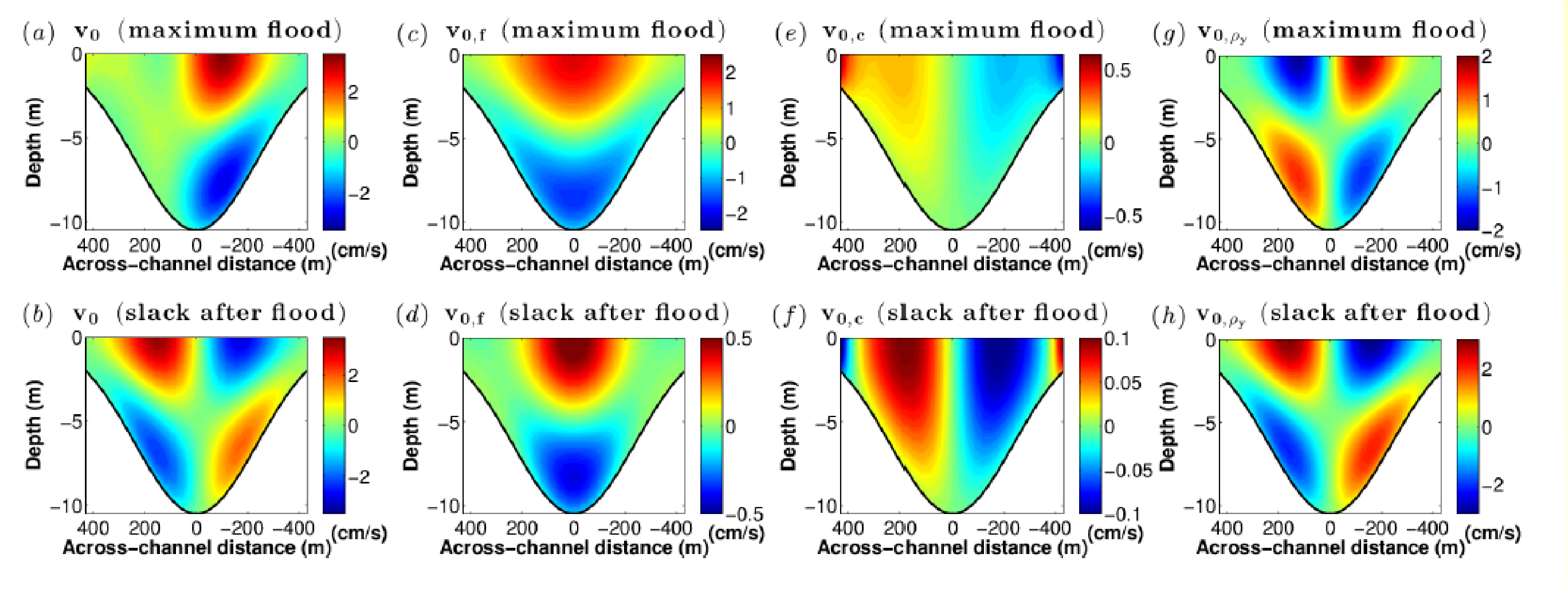
Deepening: increase of tidal range, followed by decrease

Reason: resonance characteristics of the tidal wave

Effect of deepening on M4 sea surface amplitude



Mechanism that determine lateral tidal flow



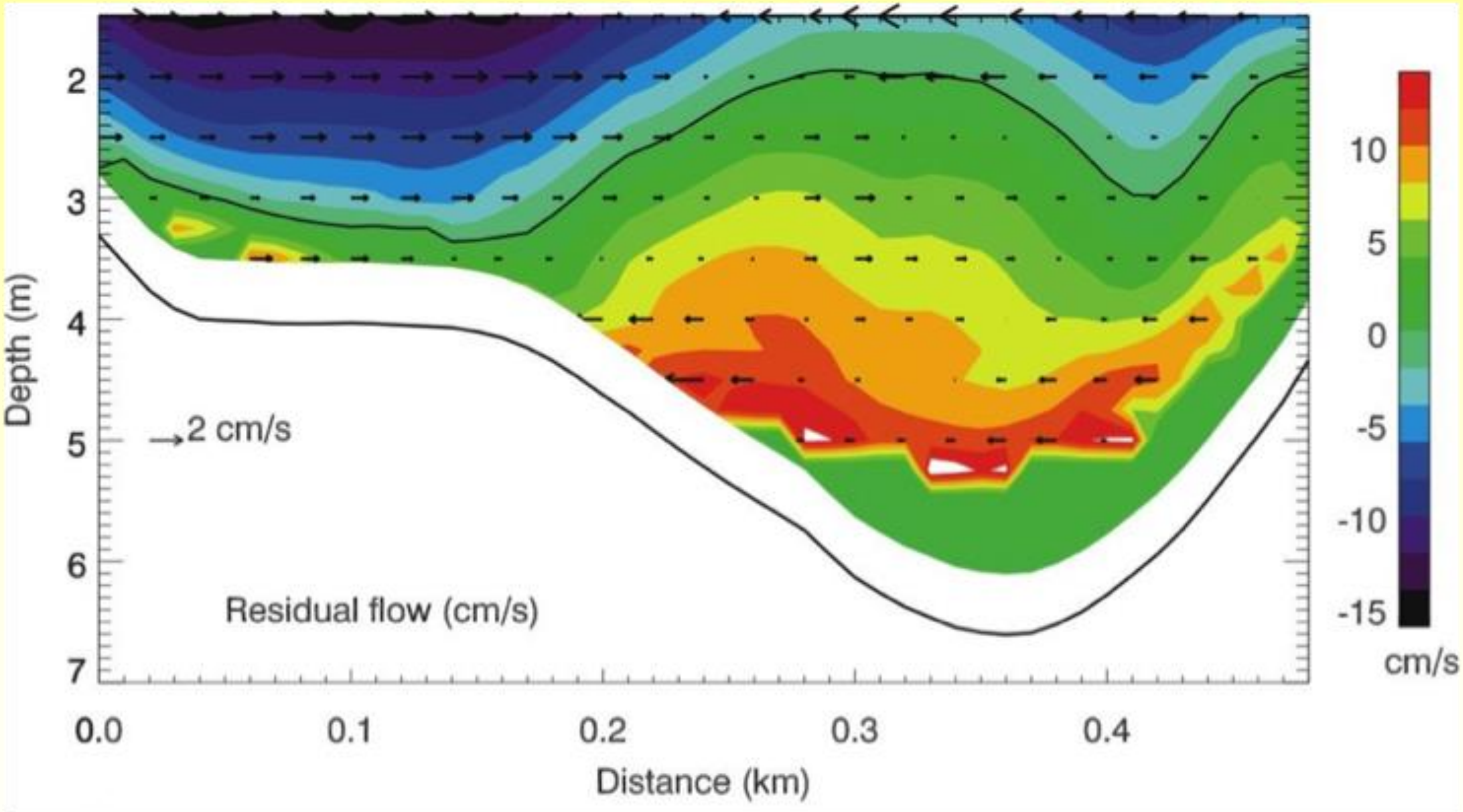
Total

Coriolis

continuity

lateral density gradient

New 13h mesaurements in the Ems

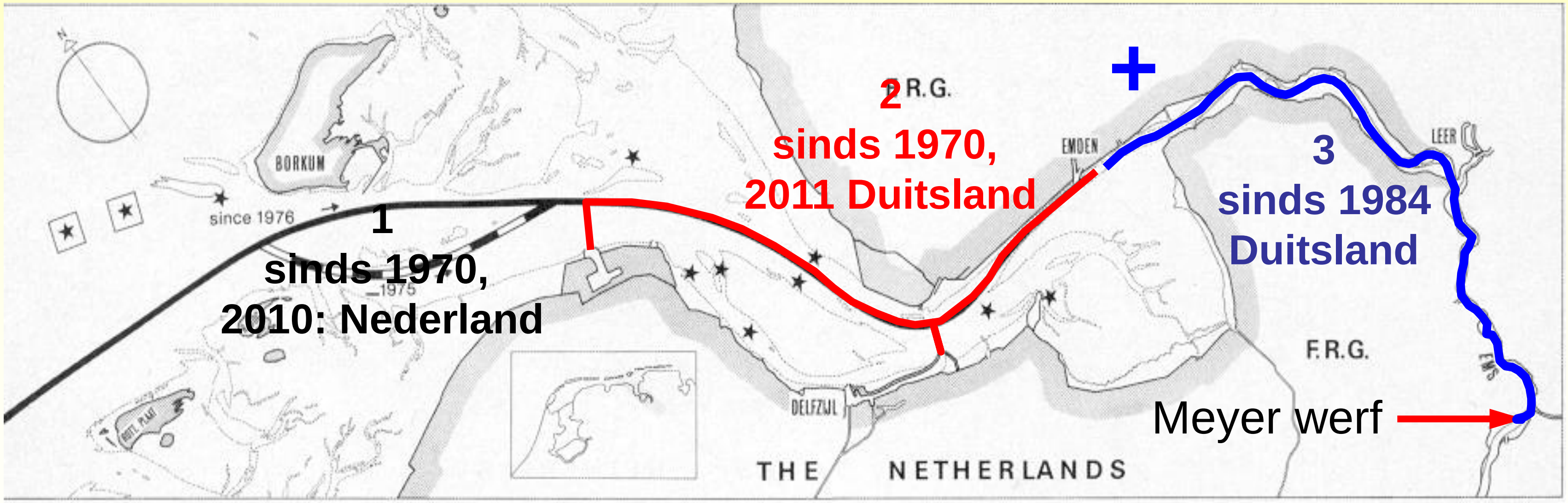


Residual velocities in cross-section near Pogum

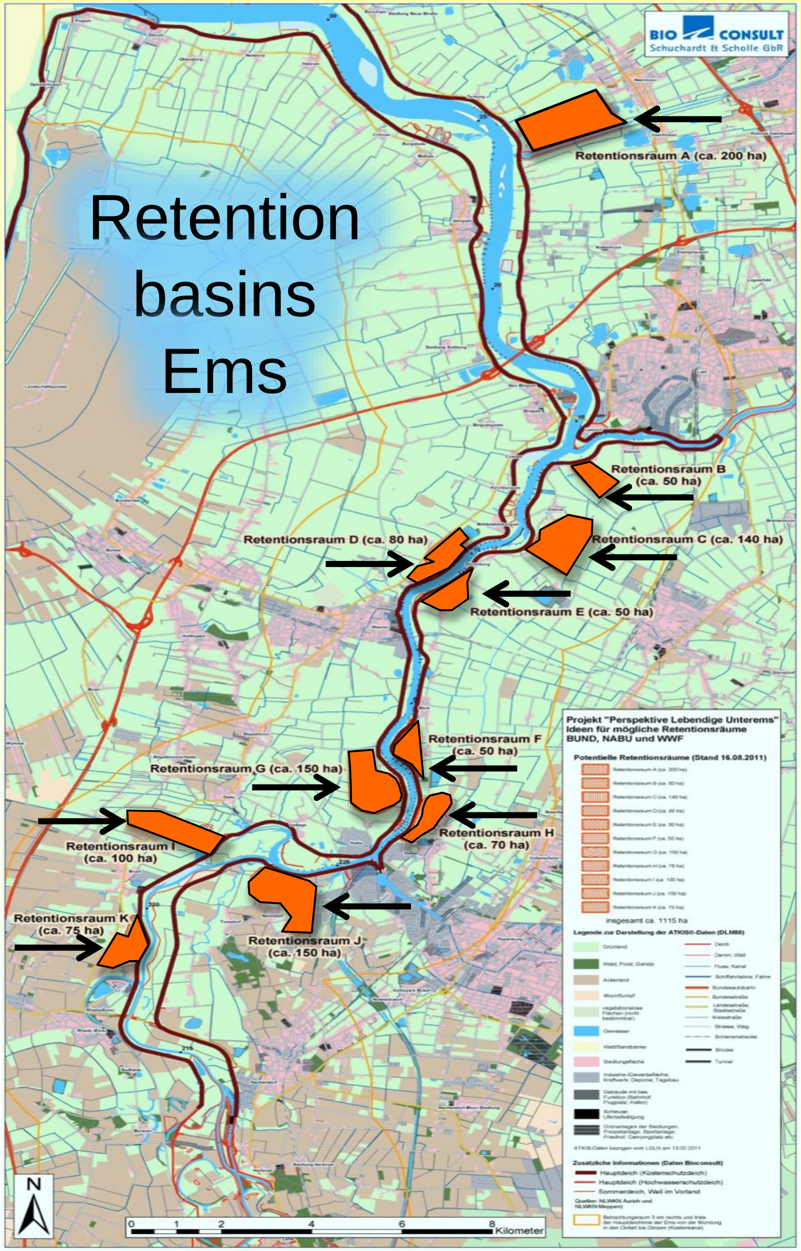
(Badewien *et al*.)

Model studies (Ems estuarium)

Veranderingen in getijden, troebelheid, zuurstof
te verklaren als respons op
grootschalige verdieping

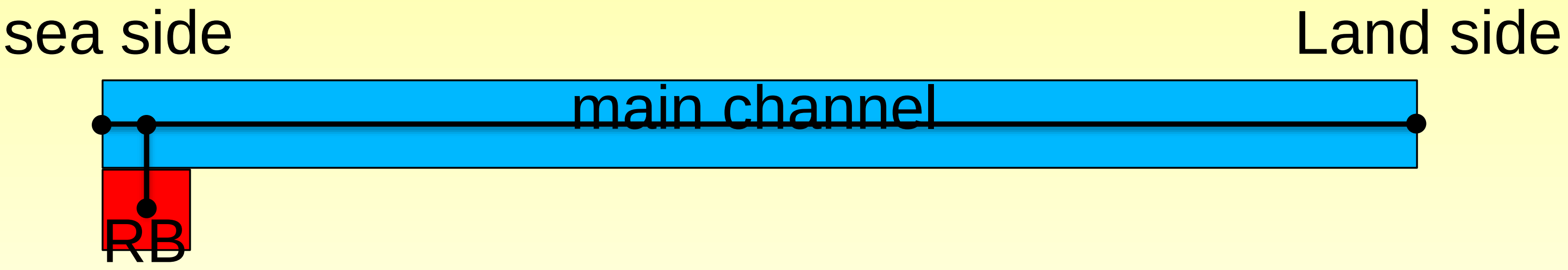


Retention basins Ems



Experiments with an idealised model

RB: retentiebekken

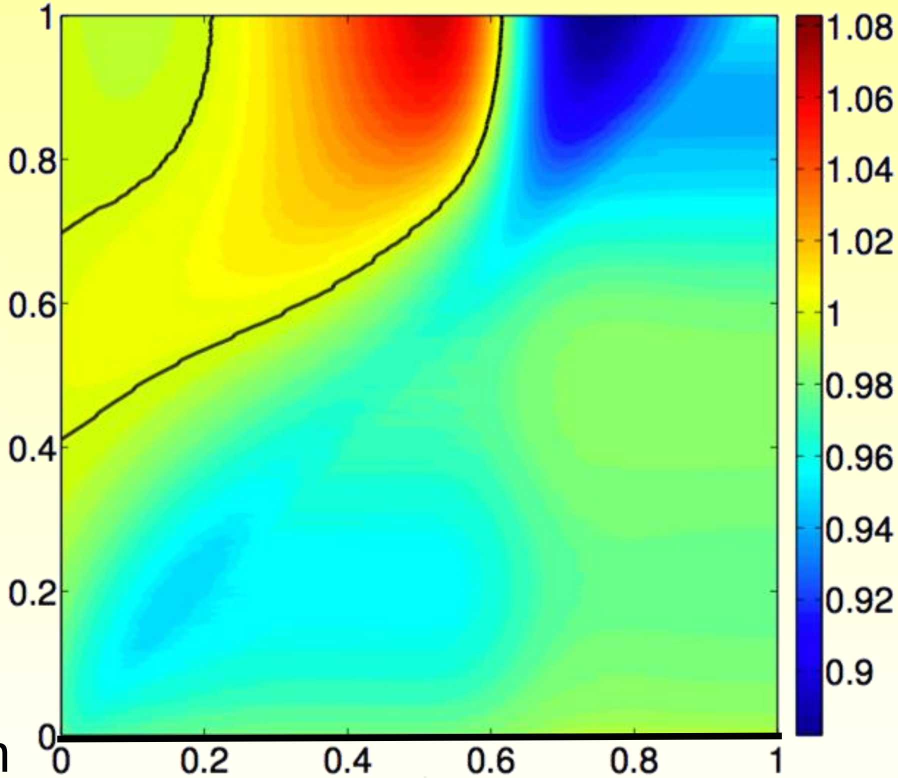


In next slide: ratio

$$\frac{\text{tidal range (with RB)}}{\text{tidal range (without RB)}}$$

Experiments with an idealised model

RB: retentiebekken



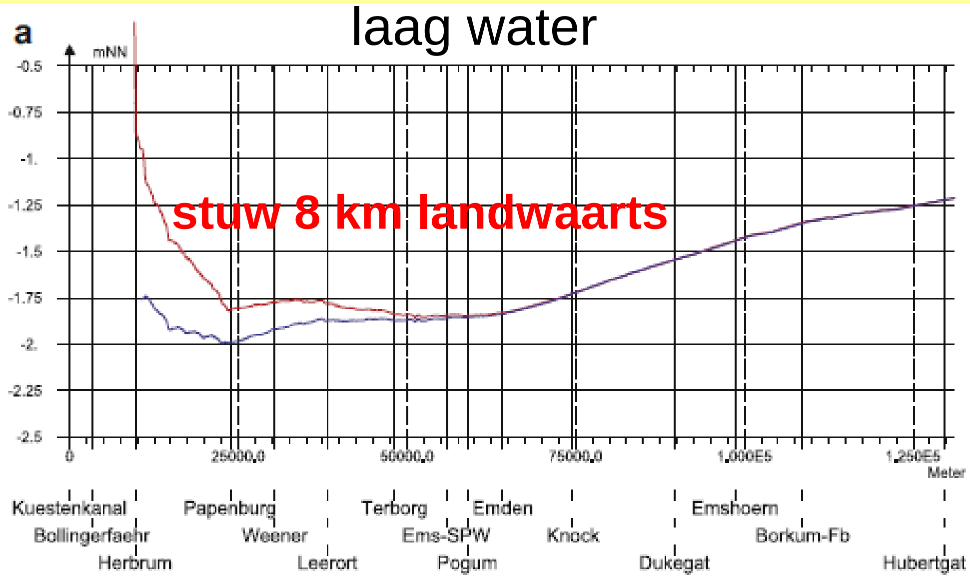
Location
5etention basin

distance to sea

Alebregtse et al.'13

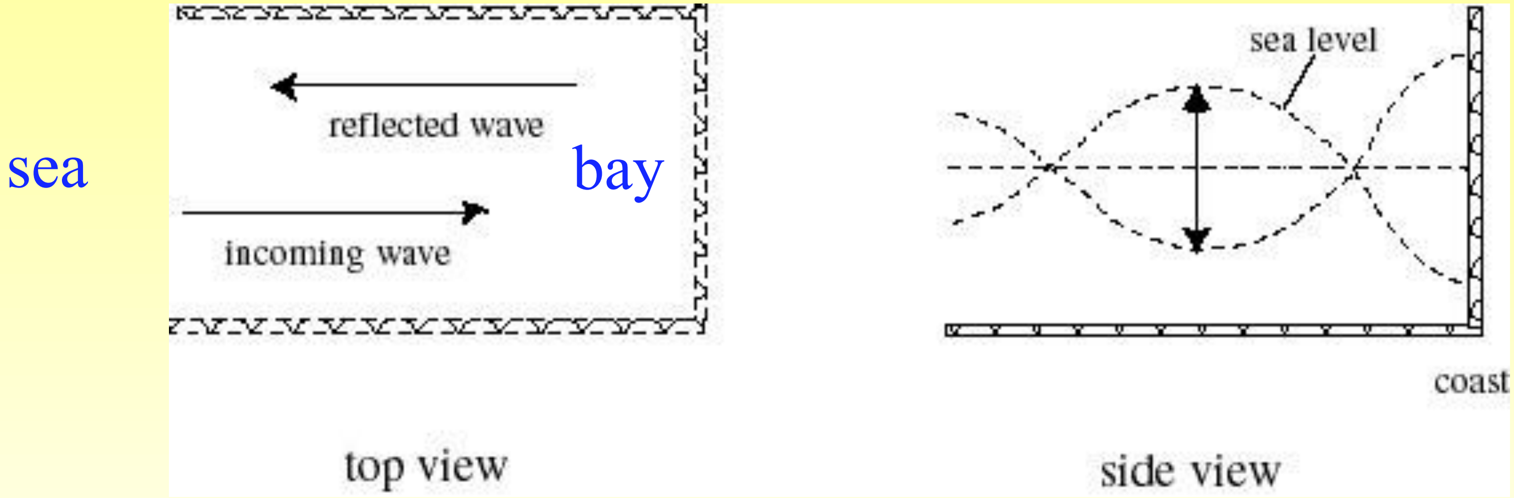
Amplification/reduction, depending on location RB and position in the channel

Resultaten BAW model (H. Heyer)



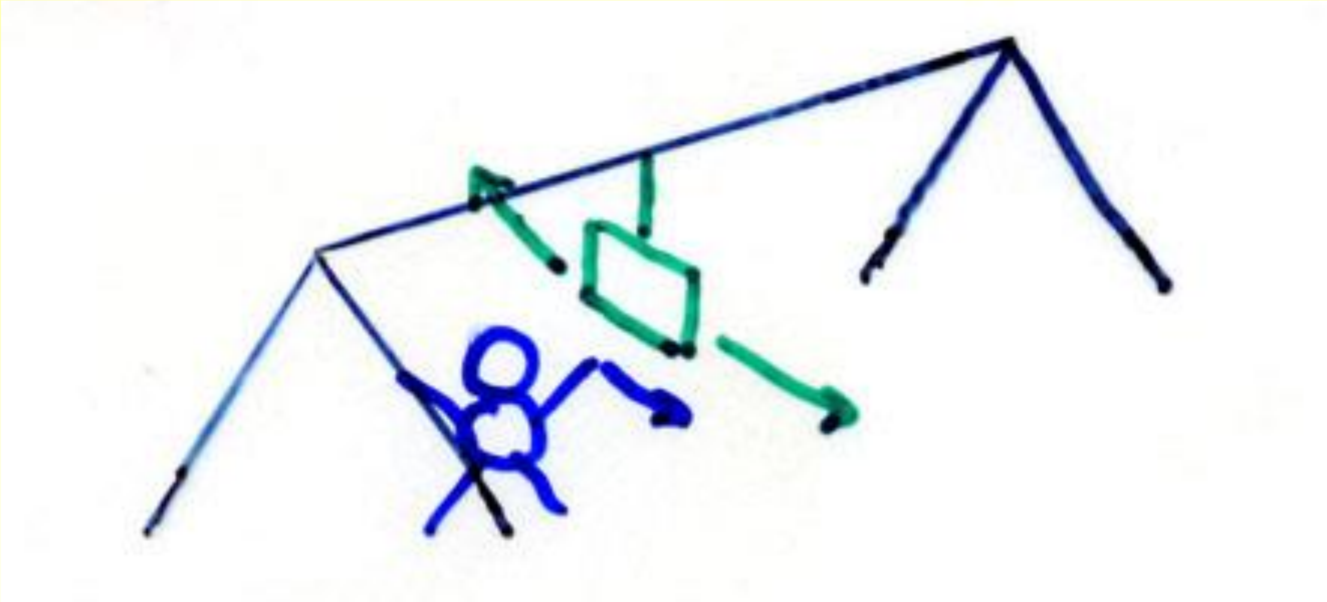
(Schuttelaars et al. 2013)

Tides in estuaries: **co-oscillation / tidal resonance**



- water in embayment co-oscillates with that in adjacent sea
- at open boundary: wave is generated
- wave reflects at the coast
- if forcing frequency = eigenfrequency: **resonance**

Analogy between tidal resonance in a bay and a forced pendulum:

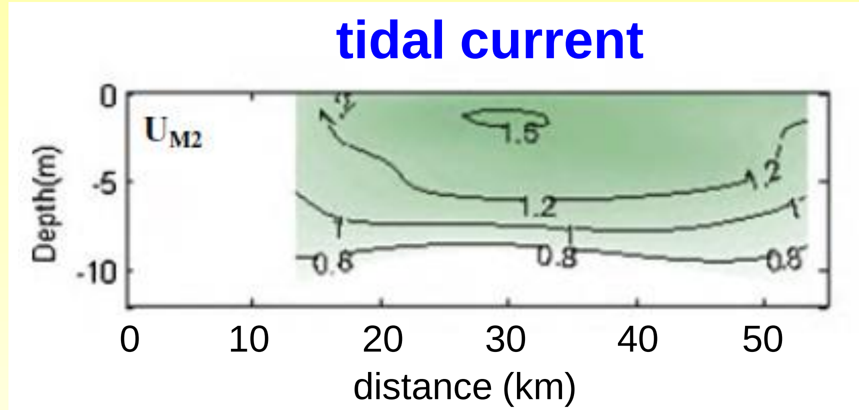


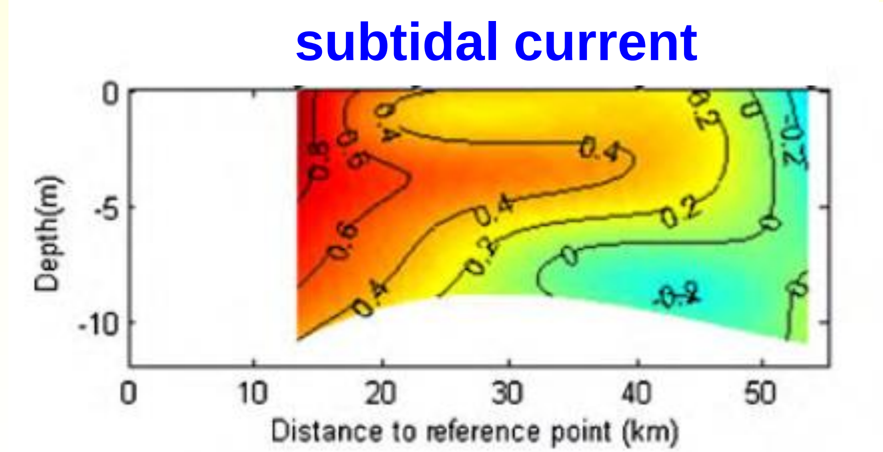
Model results: deepening of fairway caused tides in Ems (and WS) to become more resonant

Water motion, main constituents

Yangtze estuary

from Jiang et al.’13

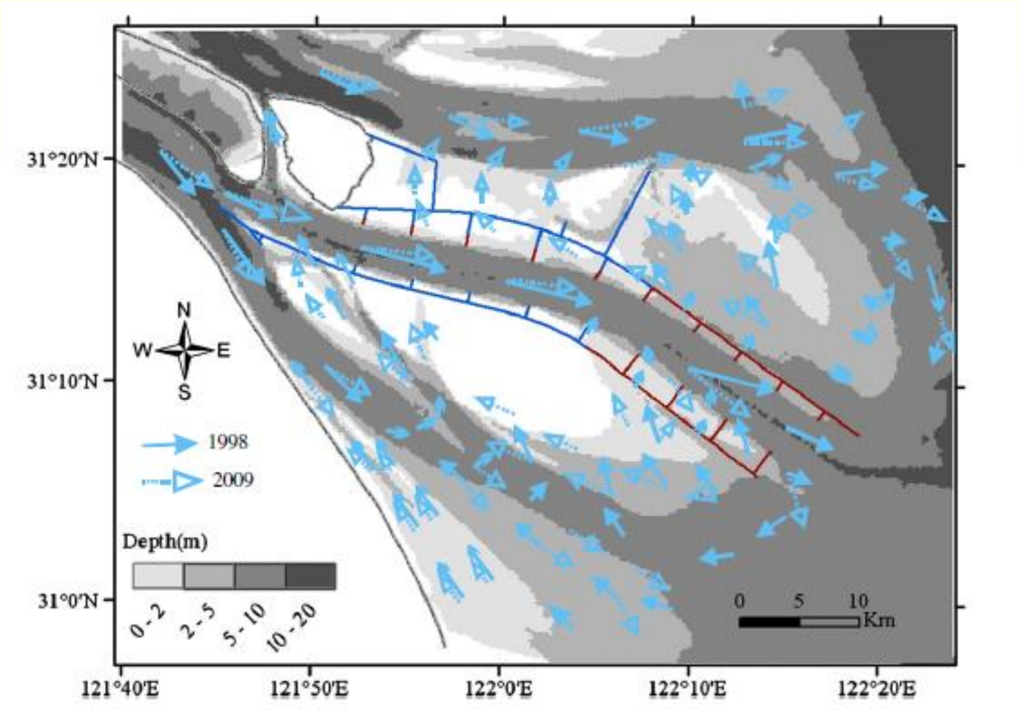




Sources of subtidal flow in estuaries

- fresh water flow / horizontal density gradient
- wind
- **tides** (through rectification)

Residual transport in the Yangtze estuary (data + model)



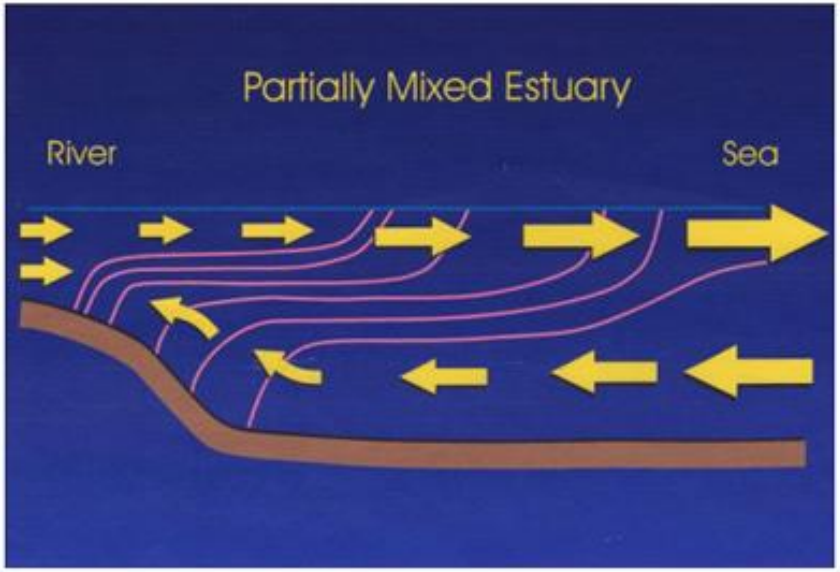
Classic view on subtidal flow in estuaries

(cf. Hansen & Rattray'65)

Subtidal flow mainly due to

- fresh water flow
- horizontal density gradient

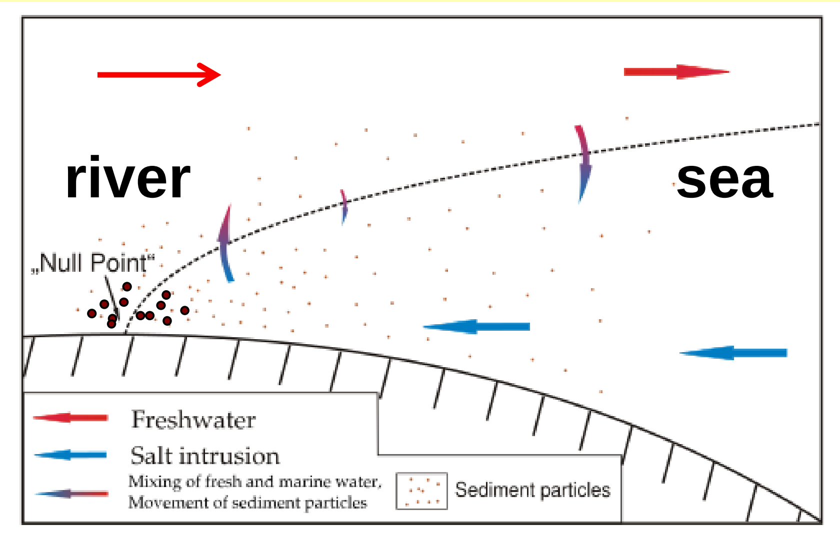
=> **gravitational circulation**



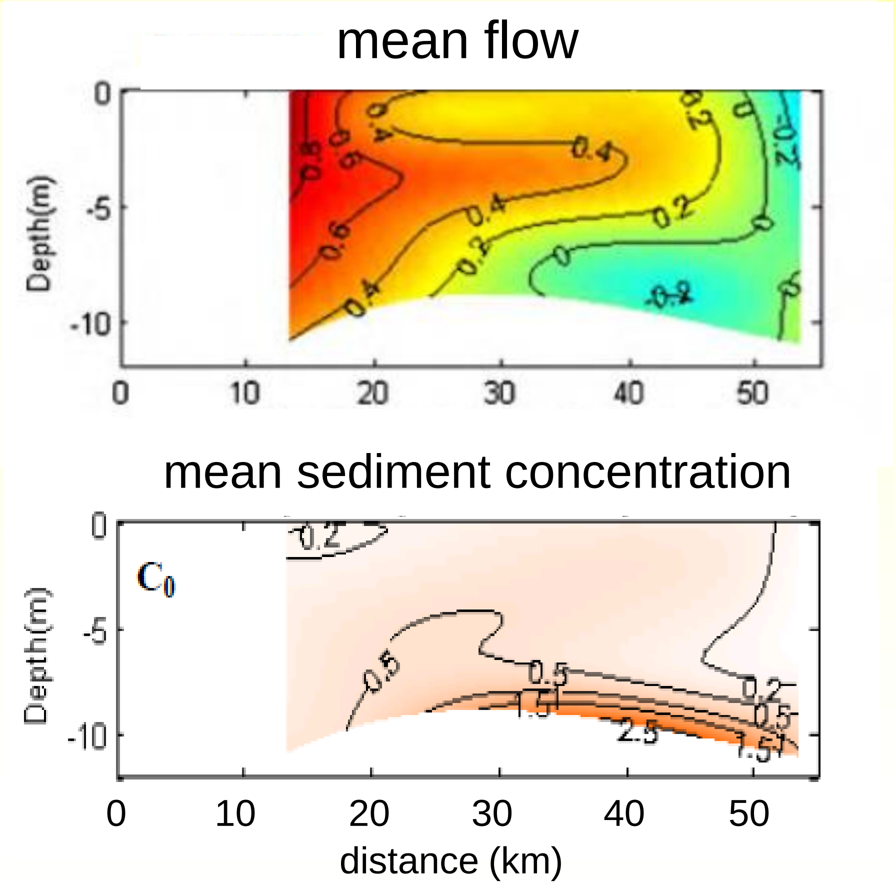
c. L. Zhong

Gravitational circulation causes formation of estuarine turbidity maximum

(cf. Postma’67)



Yangtze estuary

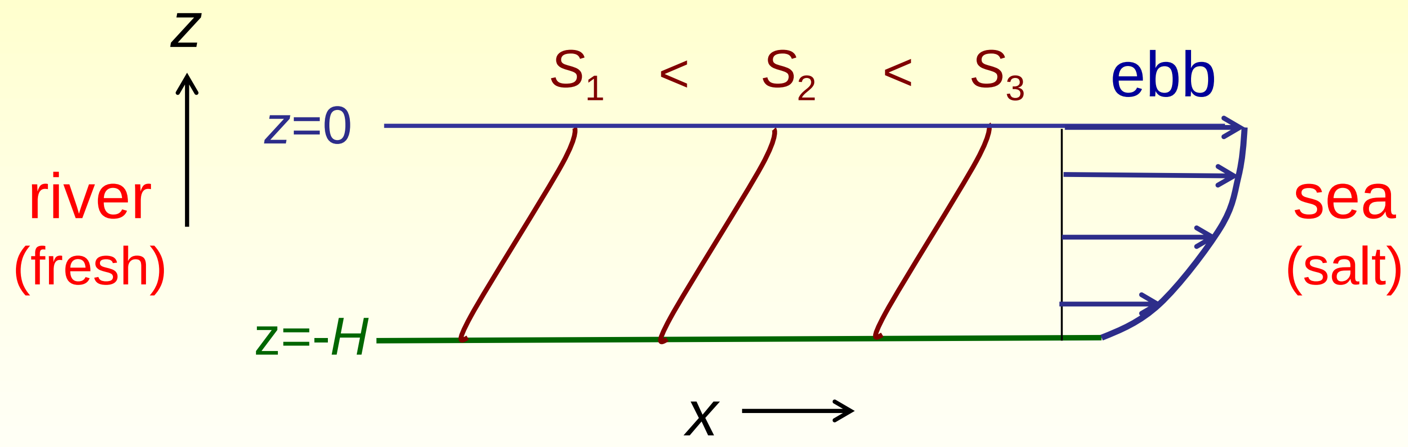


Focus of this presentation:

Subtidal flow due to asymmetric mixing caused by tidal straining

The mechanism

(after Simpson *et al*.'90, Jay'91,..)



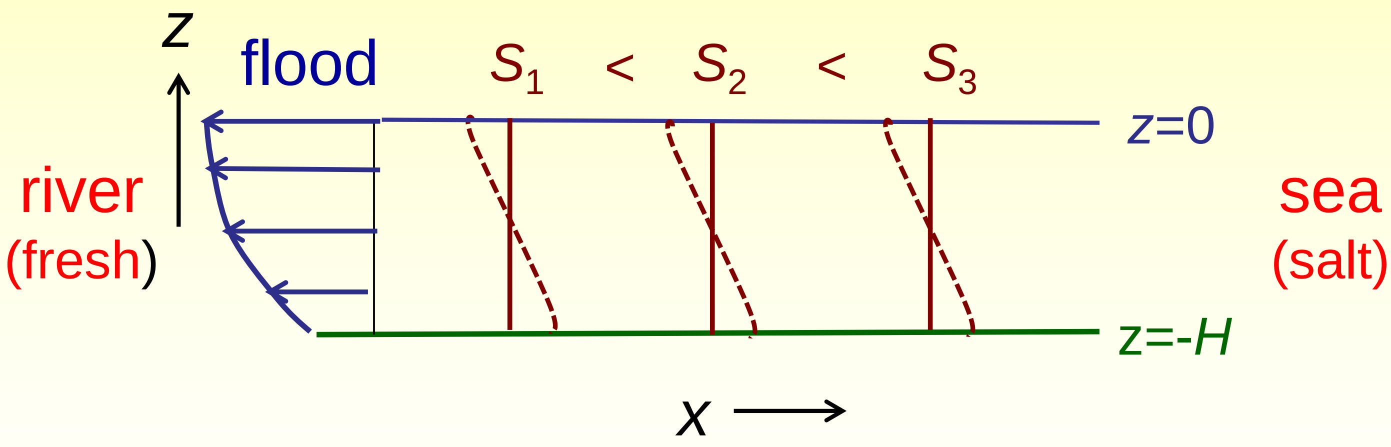
During ebb: fresh water strained over salt water
=> mixing will be lower than average

Focus of this presentation:

Subtidal flow due to asymmetric mixing caused by tidal straining

The mechanism

(after Simpson *et al*.'90, Jay'91,..)



During flood: salt water strained over fresh water
=> mixing will be high

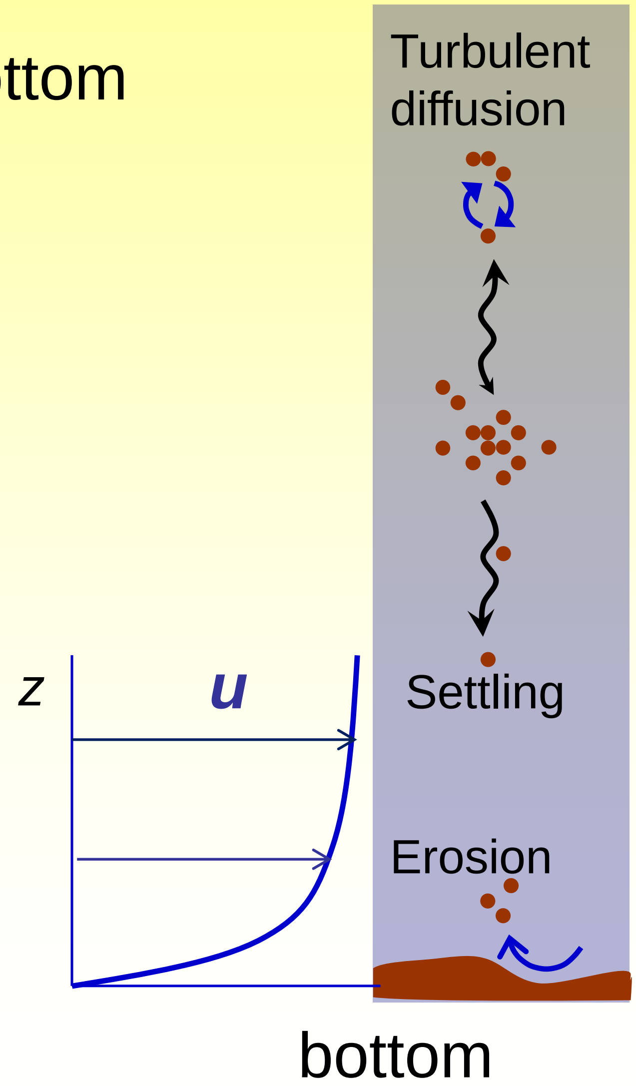
ETM dynamics – basic concepts

- Flow *u* exerts stress at the bottom
  => erosion of sediment,
  concentration *c*

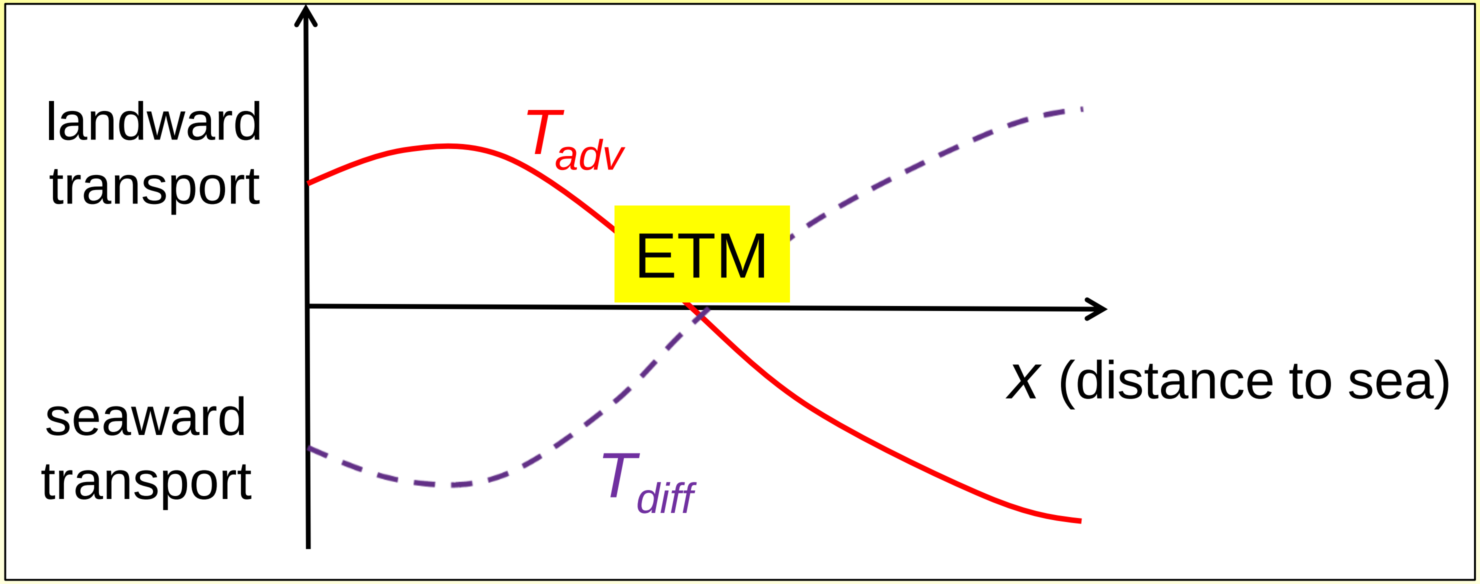
- Net <u>advective</u> transport of sediment by flow:

$$T_{adv} = \overline{\iint_{\text{cross-section}} u\, c\, dA}$$

(bar is tidal average)



Now assume the following situation:



If system in morphodynamic equilbrium:

Advective transport T_{adv} balanced by diffusive transport T_{diff}

$T_{diff} \sim -\partial c/\partial x$, so c has extremum where T_{adv}=0

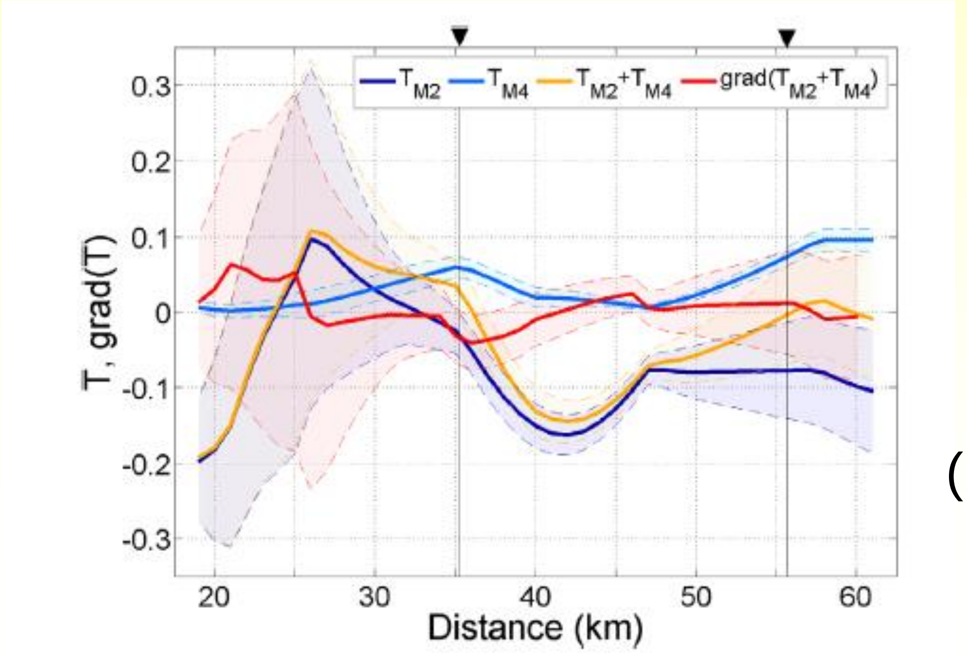
In situation above: turbidity maximum (ETM)

Recall,

$$T_{adv} = \overline{\iint_{\text{cross-section}} u\, c\, dA}$$

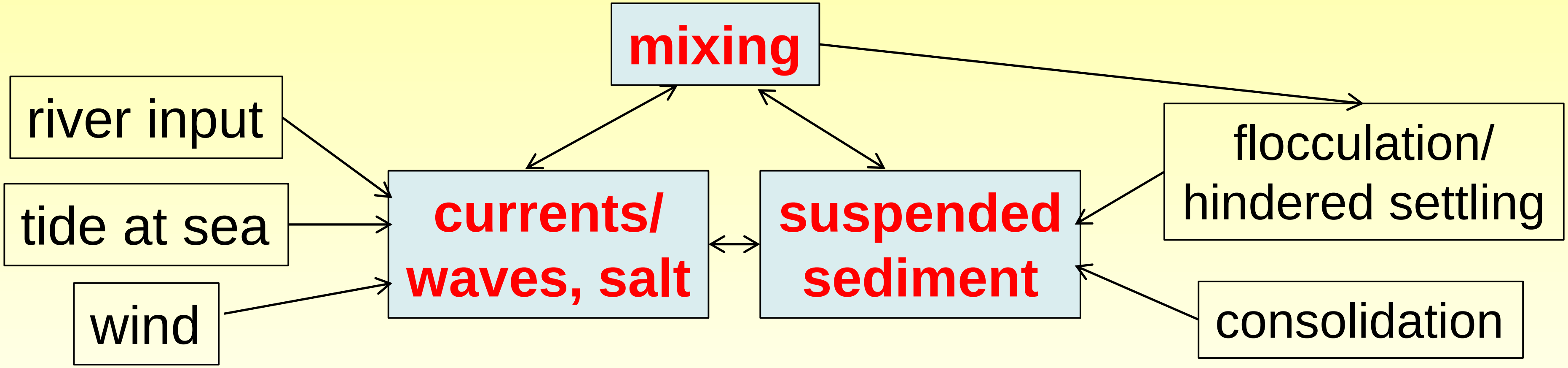
So net transport due to

- mean current * mean concentration
- correlations between *u*', *c*' and variation in cross-section
  (primes: departure from means)



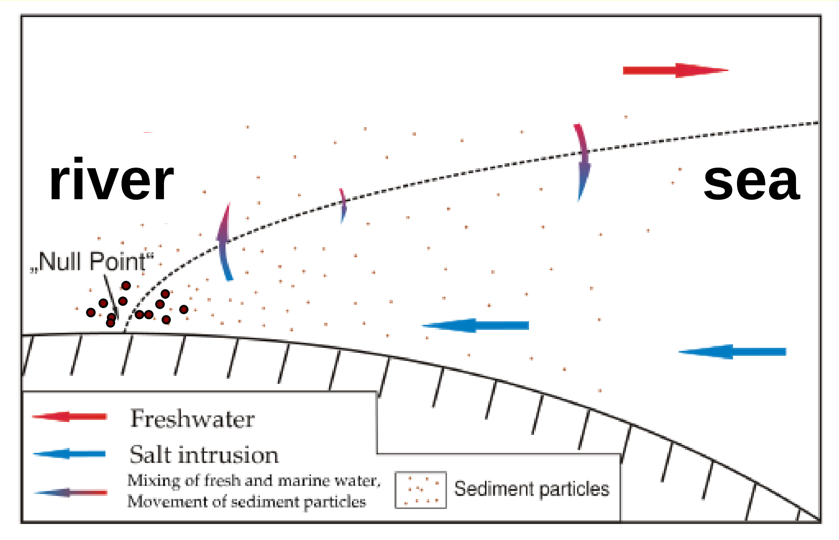
Guadalquivir, observed transports (Diez-Minguito *et al*.'14)

The complexity of the system

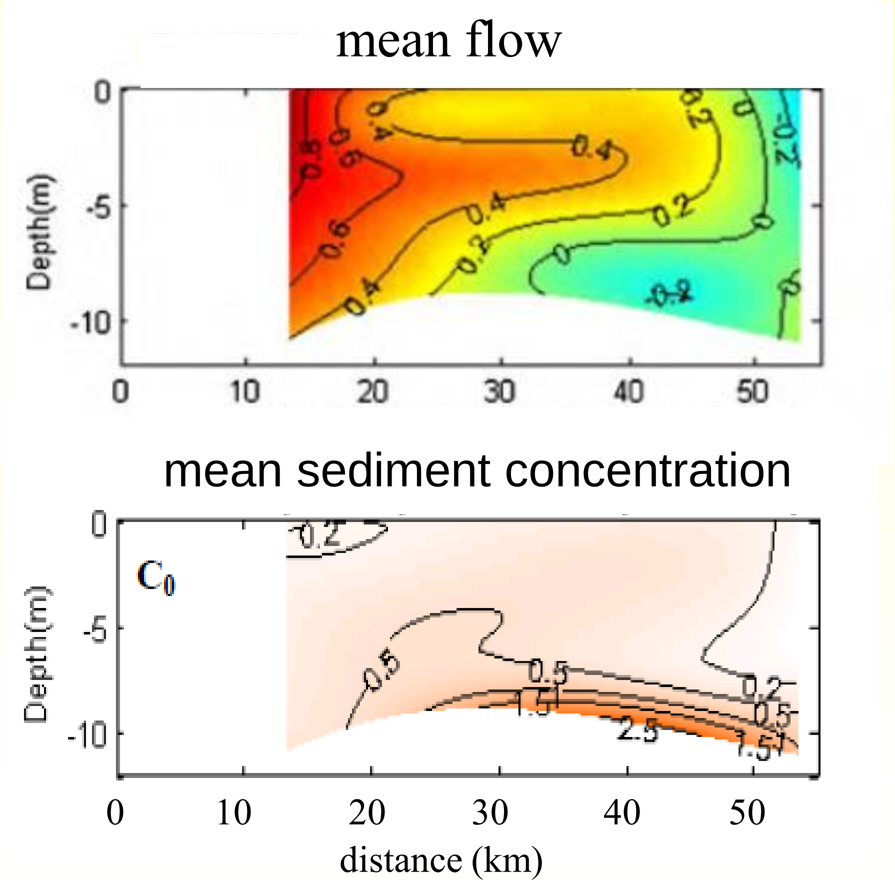


Concept by Postma'67:

Gravitational circulation causes formation of estuarine turbidity maximum



Yangtze estuary



Types of models:

conceptual
process-based numerical
process-based semi-analytical

What models are used and why?

Choice depends on

- specific question that one wishes to address
- knowledge available
- technical opportunities (e.g. hardware)

Also important:

- for public services predictions are needed
- scientists (also) want understanding, improve options, increase level of knowledge