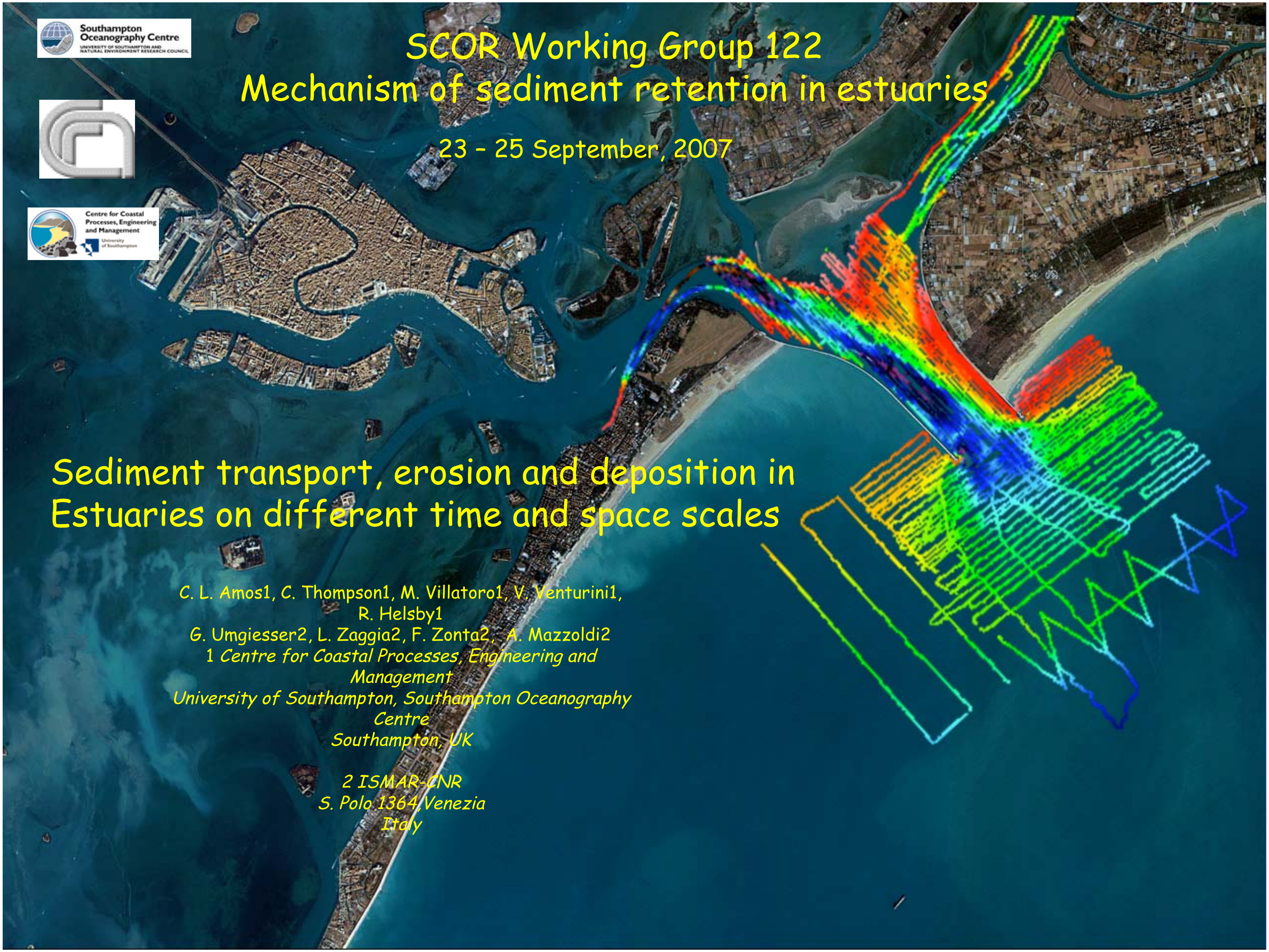


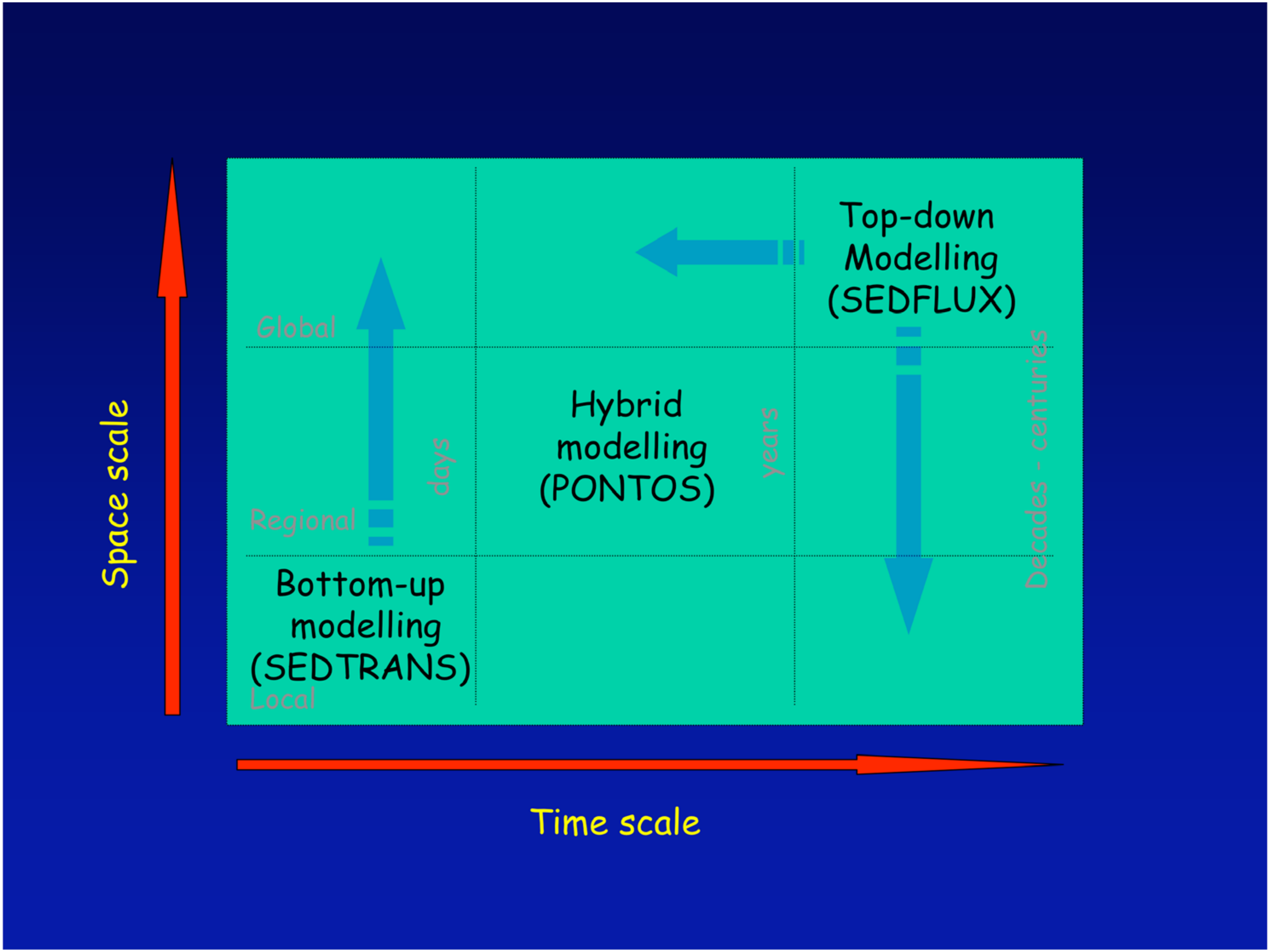
SCOR Working Group 122
Mechanism of sediment retention in estuaries

23 – 25 September, 2007

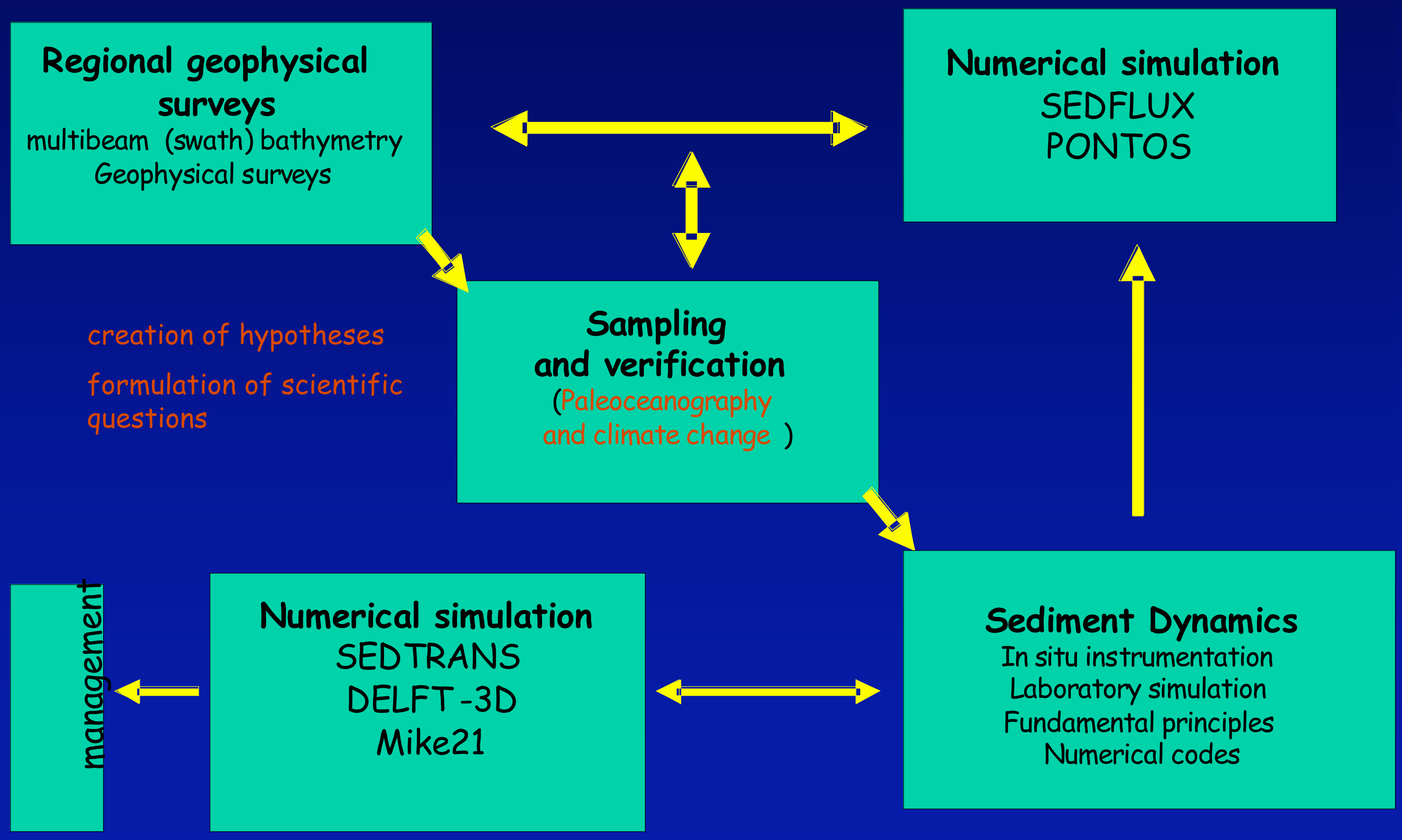
Sediment transport, erosion and deposition in Estuaries on different time and space scales

C. L. Amos1, C. Thompson1, M. Villatoro1, V. Venturini1,
R. Helsby1
G. Umgiesser2, L. Zaggia2, F. Zonta2, A. Mazzoldi2
1 *Centre for Coastal Processes, Engineering and Management*
University of Southampton, Southampton Oceanography Centre
Southampton, UK

2 ISMAR-CNR
S. Polo 1364, Venezia
Italy


Top-down
Modelling
(SEDFLUX)
Global
Hybrid
modelling
(PONTOS)
days
years
Decades - centuries
Regional
Bottom-up
modelling
(SEDTRANS)
Local
Space scale
Time scale

Modelling in sediment dynamics



Bottom-up modelling sediment transport in estuaries

- Types of models
  - box models
  - 1-D models (time, distance)
  - 2-D models (x,y, depth-averaged; time versus x-axis)
  - 3-D models (x,y, time; x,y,z)
  - 4-D models (x,y,z, time)
- Box models - monitor continuity of mass with simple input/output controls
  - simple and effective in sensitivity analyses, can be time-stepped easily
  - no hydrodynamics, spatially-averaging, poor open boundaries
- 1-D models - spatial gradients in sedimentation, concentration
  - easily set up, minimum hydrodynamics, offer practical solutions
  - poor open boundary conditions
- 2-D models - provides links between sedimentation and hydrodynamics
  - valuable insights into fundamental processes, engineering solutions possible
  - labour intensive (99% rule), difficult to calibrate, difficult to programme

Short term estuarine retention

Best method – direct measurements + numerical/physical simulations + “experience”
Next best method – direct measurements + numerical simulations + “experience”
Next best method – direct measurements + “experience”
Next best method – numerical simulation + “experience”
Etc, etc……

“Long term predictions will become within reach when supercomputers are more generally available”

“fundamental problems which remain to be solved are the schematization of the boundary conditions”

“Calibration and verification of mathematical models require a detailed set of synoptic data. Much effort should be put in field surveys to obtain these data.” (van Rijn, 1999)

Fundamental equations

- Sediment continuity equation (3-D):

(Closed system)

$$\frac{\partial S}{\partial t} + U\frac{\partial S}{\partial x} + V\frac{\partial S}{\partial y} + W\frac{\partial S}{\partial z} + \overline{W_s}S = 0$$

- Mass continuity equation (3-D) (Exner):

(Open to the bed)

$$\gamma_b(1-e)\frac{\partial z}{\partial t} = \overline{W_s}S$$

$$\overline{W_s}S = D - E$$

- where D is net deposition, E is net erosion, S is suspended sediment concentration, e is sediment porosity, γ_b is sediment unit weight, h is bed elevation, W_s is mean settling rate, and U,V,W are the three components of mean flow.

University of Southampton

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Instrumentation development to calibrate models - suspension

- benthic landers (RALPH)
- benthic flumes (Sea Carousel)
- remote sensing tools (backscatter)
- self-contained packages (Zedhead)

- acoustical
- optical
- electro-magnetic/peizo-electric
- x-ray

$$\frac{\partial S}{\partial t} + U\frac{\partial S}{\partial x} + V\frac{\partial S}{\partial y} + (W - W_s)\frac{\partial S}{\partial z}$$

$$\frac{\partial S}{\partial t} + \overline{W_s S} + F_1 + F_n = 0$$

time-series, usually from fixed location (1)

Velocity field (3-D) (2)

Mass settling rate (3)

Benthic flux (4)

External sources/sinks (5)

Sediment concentration gradients (3-D) (6)

The sediment continuity equation = sediment budget

Morphological-dynamics and sediment dynamics – suspension and bedload

(1) only possible in closed system !!! (mesocosm)
(2) bottom sampling
(3) acoustic velocity, resistivity, CT scanning
(4) acoustic altimeter, 2-axis sector scanning sonar, repetitive swath bathymetry

(5i) Deposition (D) from cores (Pb_{210} or Cs_{137}) or sediment traps or altimeter measures
(5ii) Erosion (E) (closed systems) or acoustic profiling or long-term swath bathymetry
(6) Sediment traps, geophysical surveys of bedform migration

Benthic flux (1)

Sediment density (2)

Porosity (3)

Time-series of bed level change (4)

$$\overline{W_s}S + F_1 = D - E = \rho(1-e)\frac{\partial h}{\partial t}$$

$$F_1 = \nabla g_s$$

Divergence in bedload transport rate (6)

Deposition(D) Erosion(E) (5)

The Exner equation

AGE

" The time that has elapsed since the water parcels enters an estuary";
Bolin and Rodhe (1973).

TRANSIT TIME

" The period between the times a particle entering and leaving an estuary ";
Bolin and Rodhe (1973).

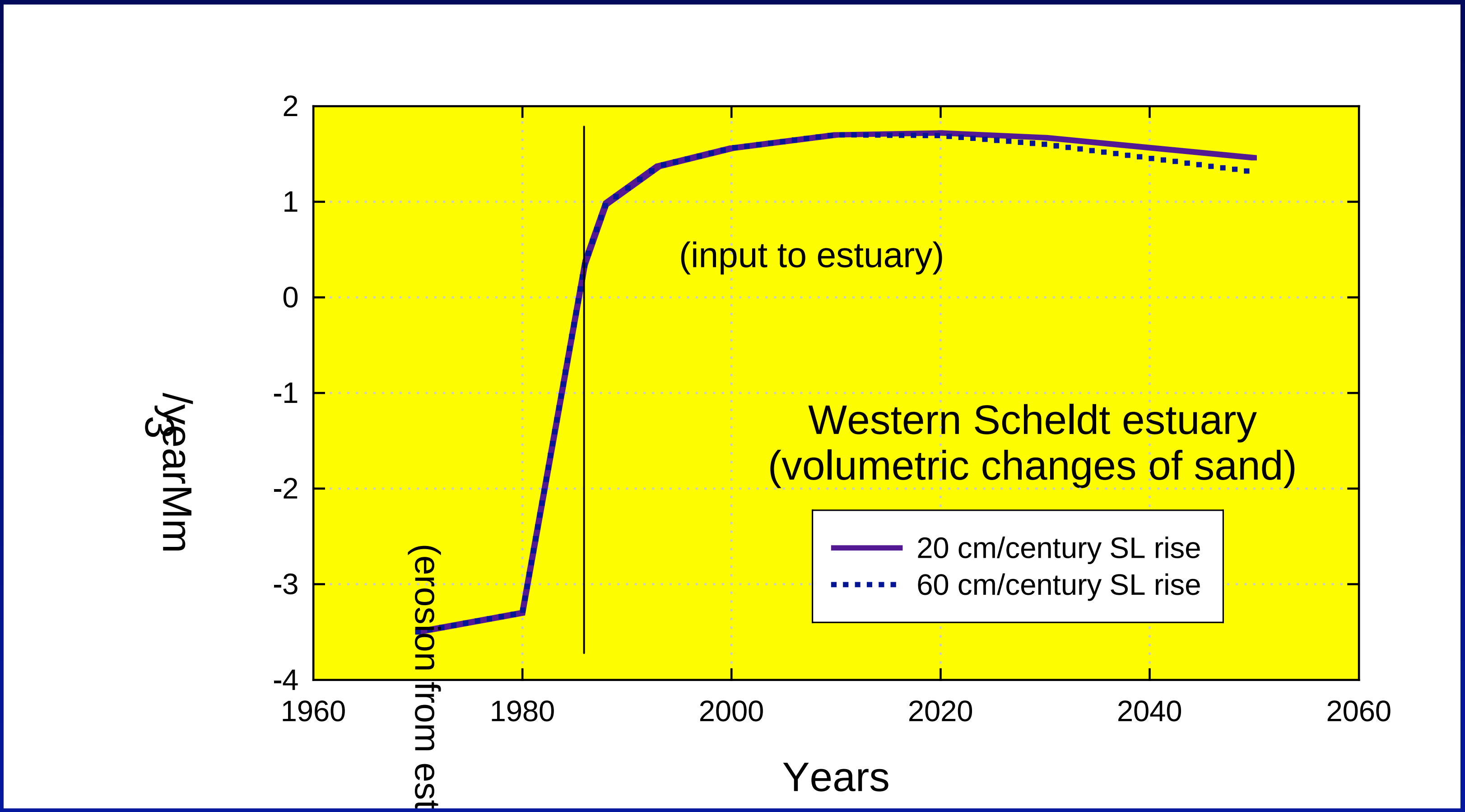
EXPOSURE TIME

" The total amount of time a particle spends in the domain";
Monsen et al. (2002).

RESIDENCE TIME

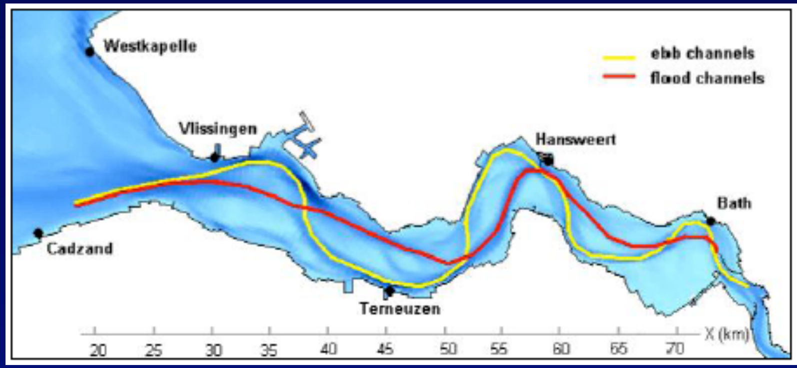
" The time it takes for any water particles of the sample to leave the lagoon through its outlet to the sea "; Dronkers and Zimmerman (1982); Prandle (1984).

" The time required for the total mass of a conservative tracer originally within the whole or a segment of the estuary to be reduced to a factor 1/e ";
Sanford et al. (1992); Luketina, (1998).



Prior to 1986 – export of sand from estuary to ebb tidal delta
After 1986 – import of sand into estuary

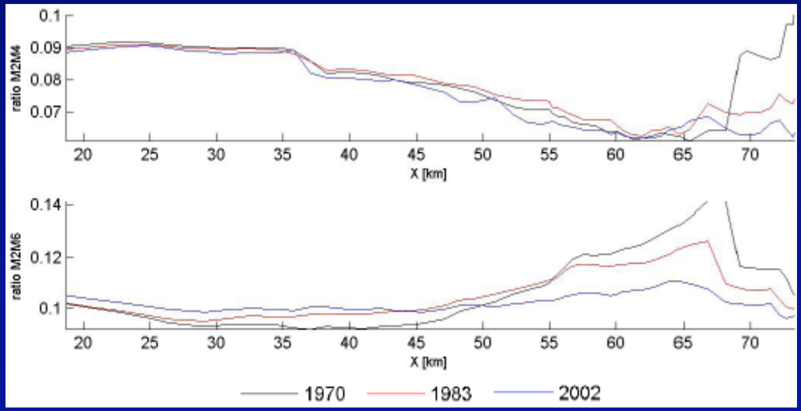
Western Scheldt, Belgium – DELFT-3D



Flood and ebb dominance due to interplay of Semi-diurnal

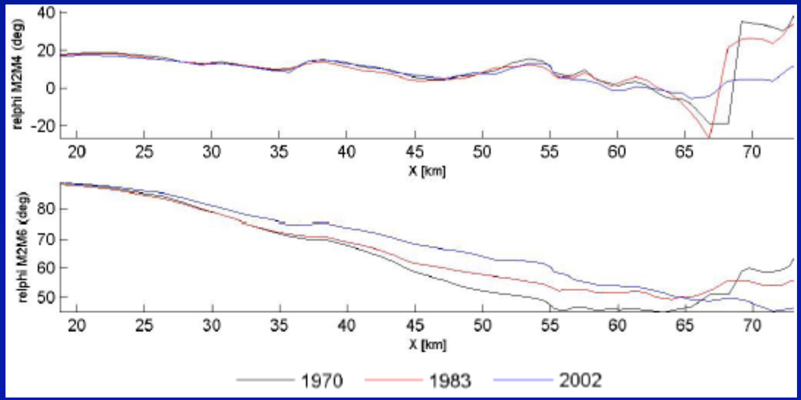
Amplitude ratio: M_2/M_4, M_2/M_6

Phase shift: $2(\varphi_2 - \varphi_4)$, $3(\varphi_2 - \varphi_6)$



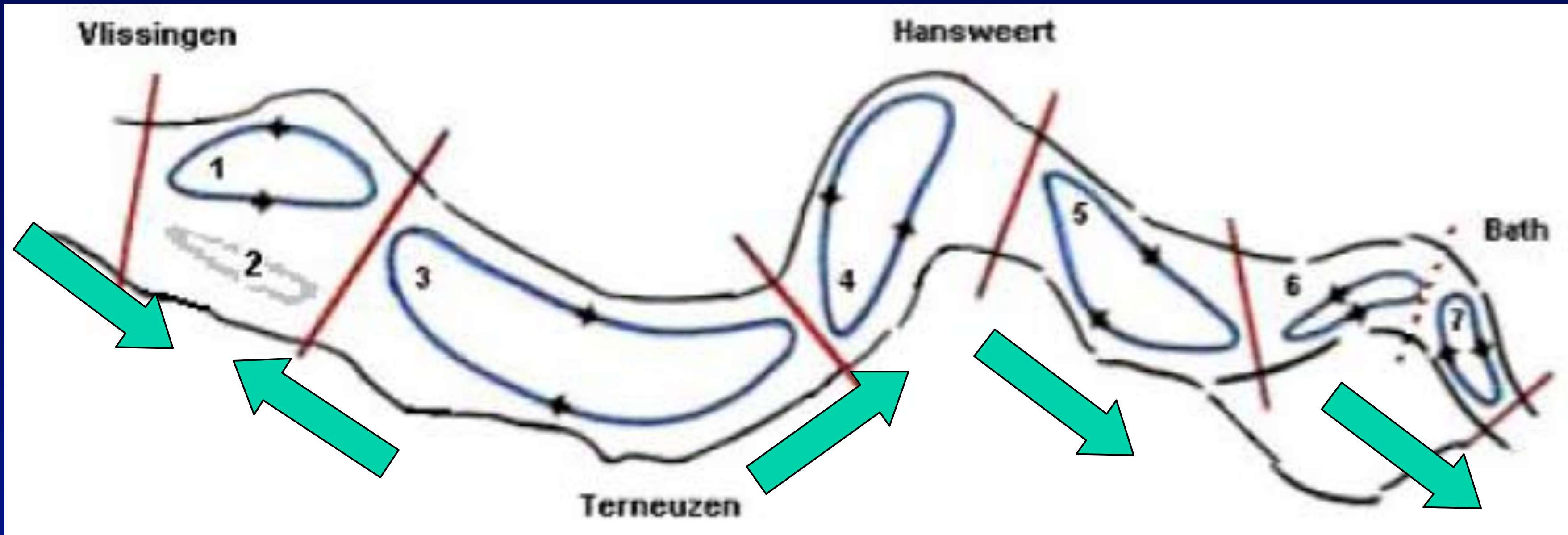
Major change in inner estuary

Major changes on central estuary



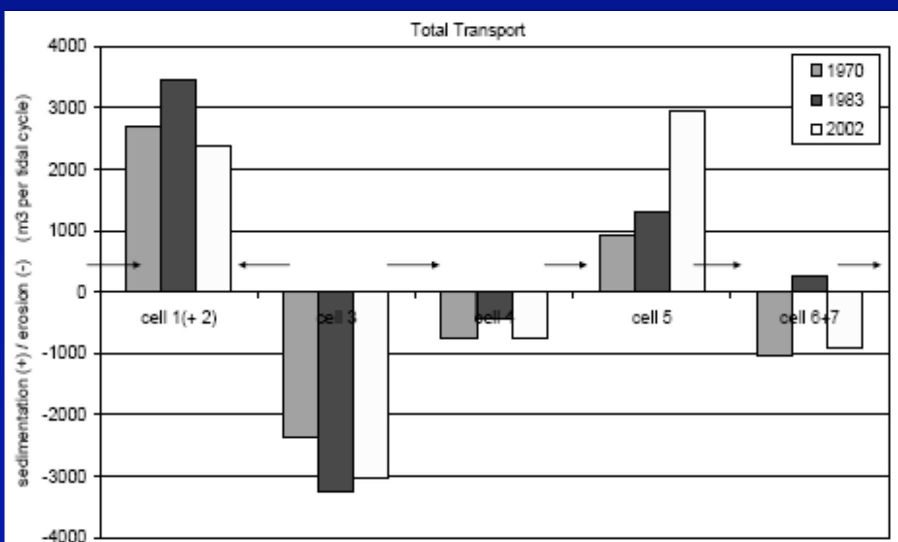
Major changes in inner estuary

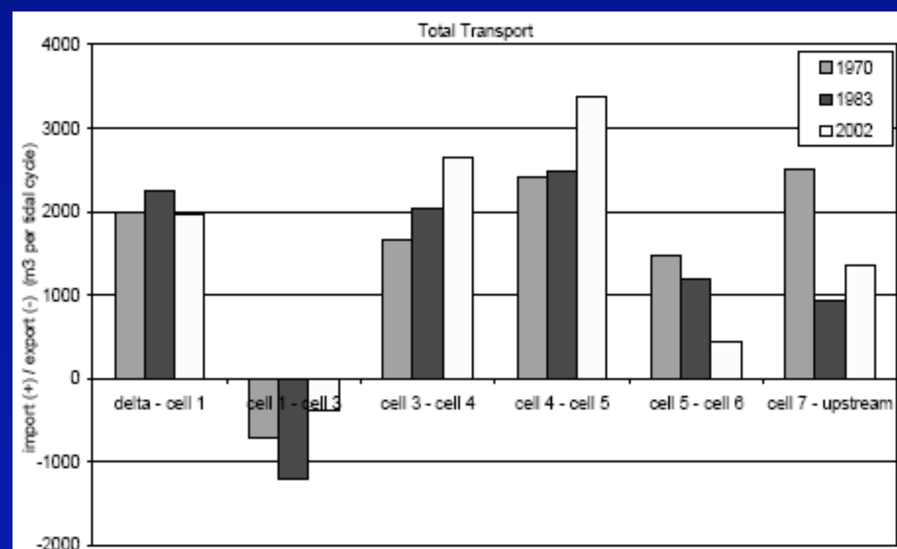
Changes throughout estuary



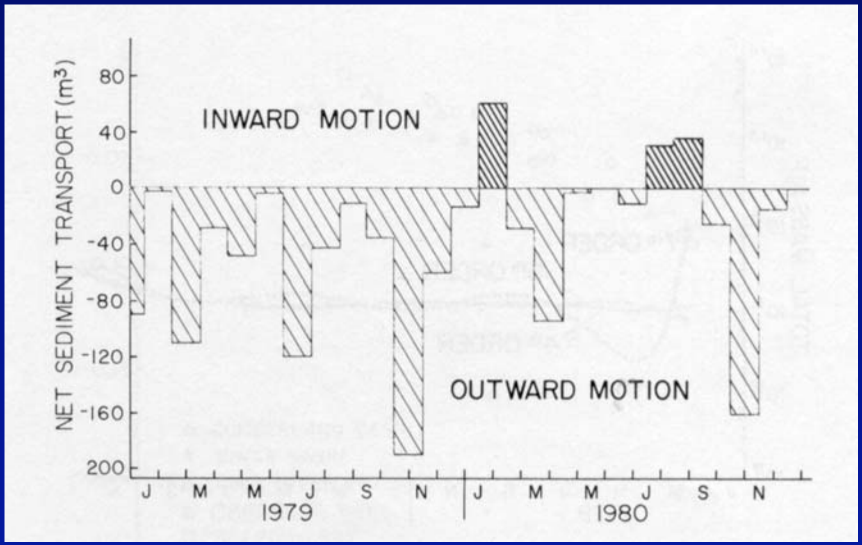
Sedimentation/erosion

import/export



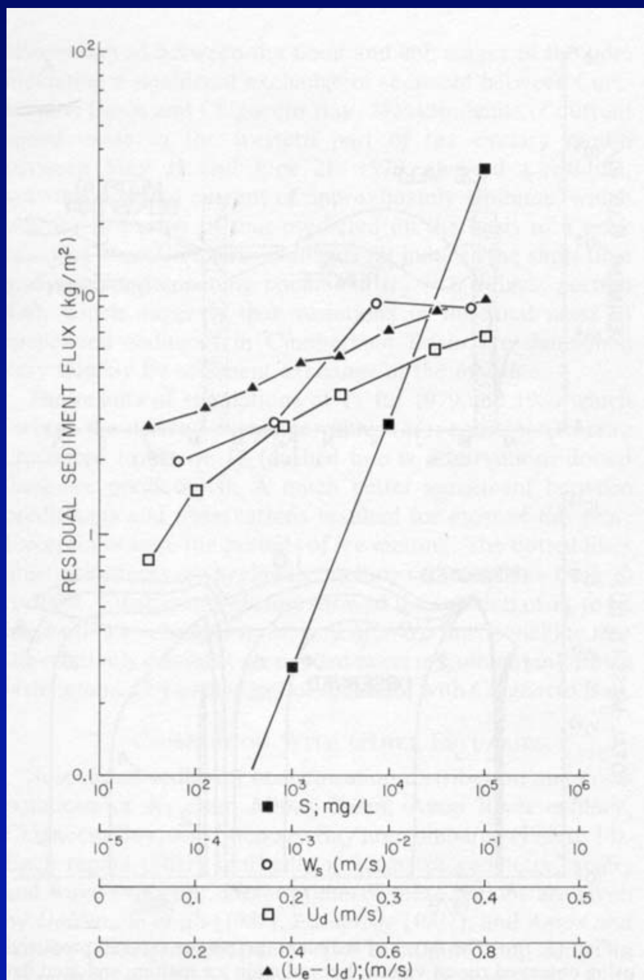


The open boundary problem

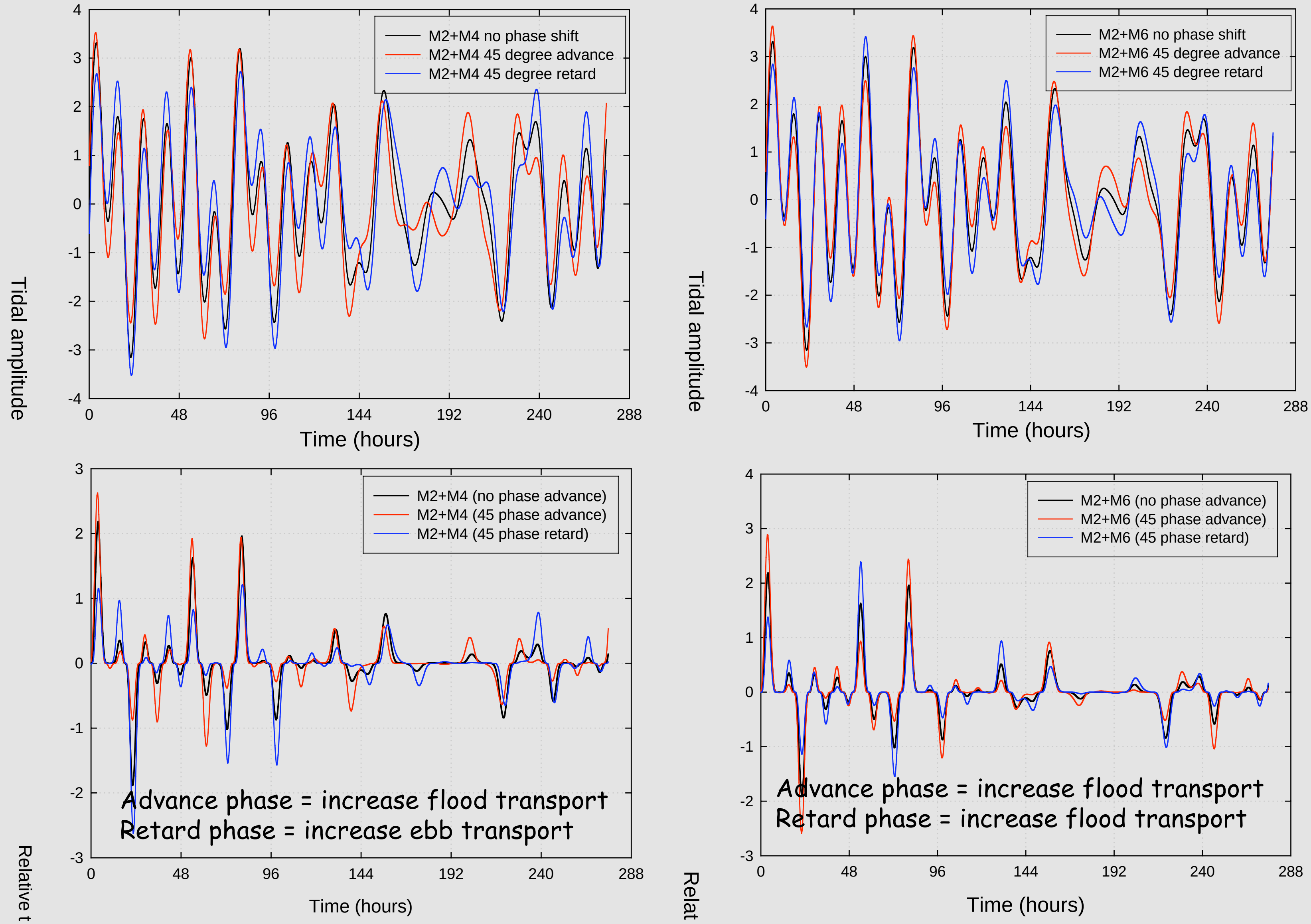


- The open boundary offers the greatest difficulty to measure and to predict accurately
- note the change from importing to exporting with time
- import and export linked to S and more importantly to S(x)
- an estuary can change trapping efficiency depending on S gradient
  - caused by wave resuspension
  - dredging
  - tidal variations
  - construction, etc

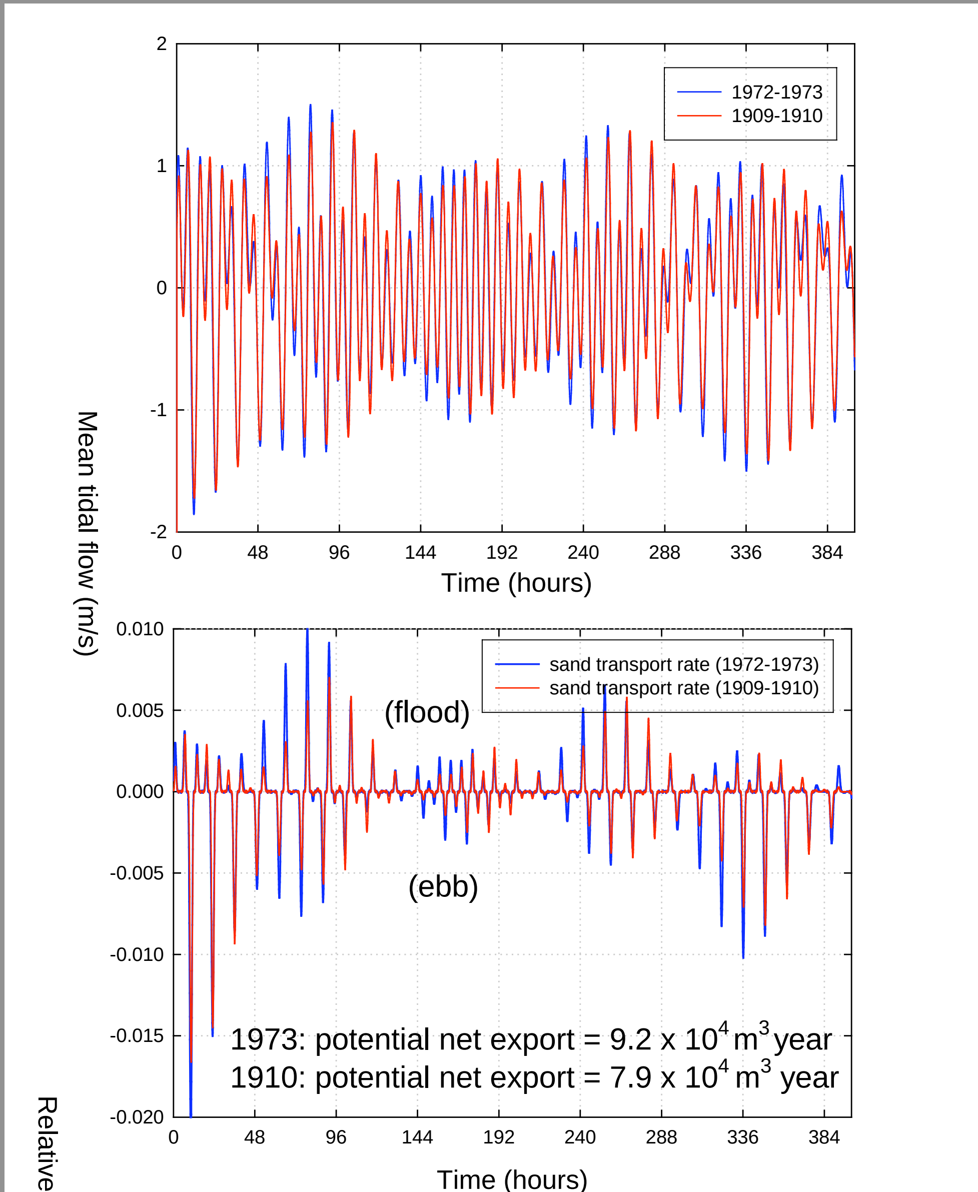
Sensitivity analysis of sediment flux rates at open boundary



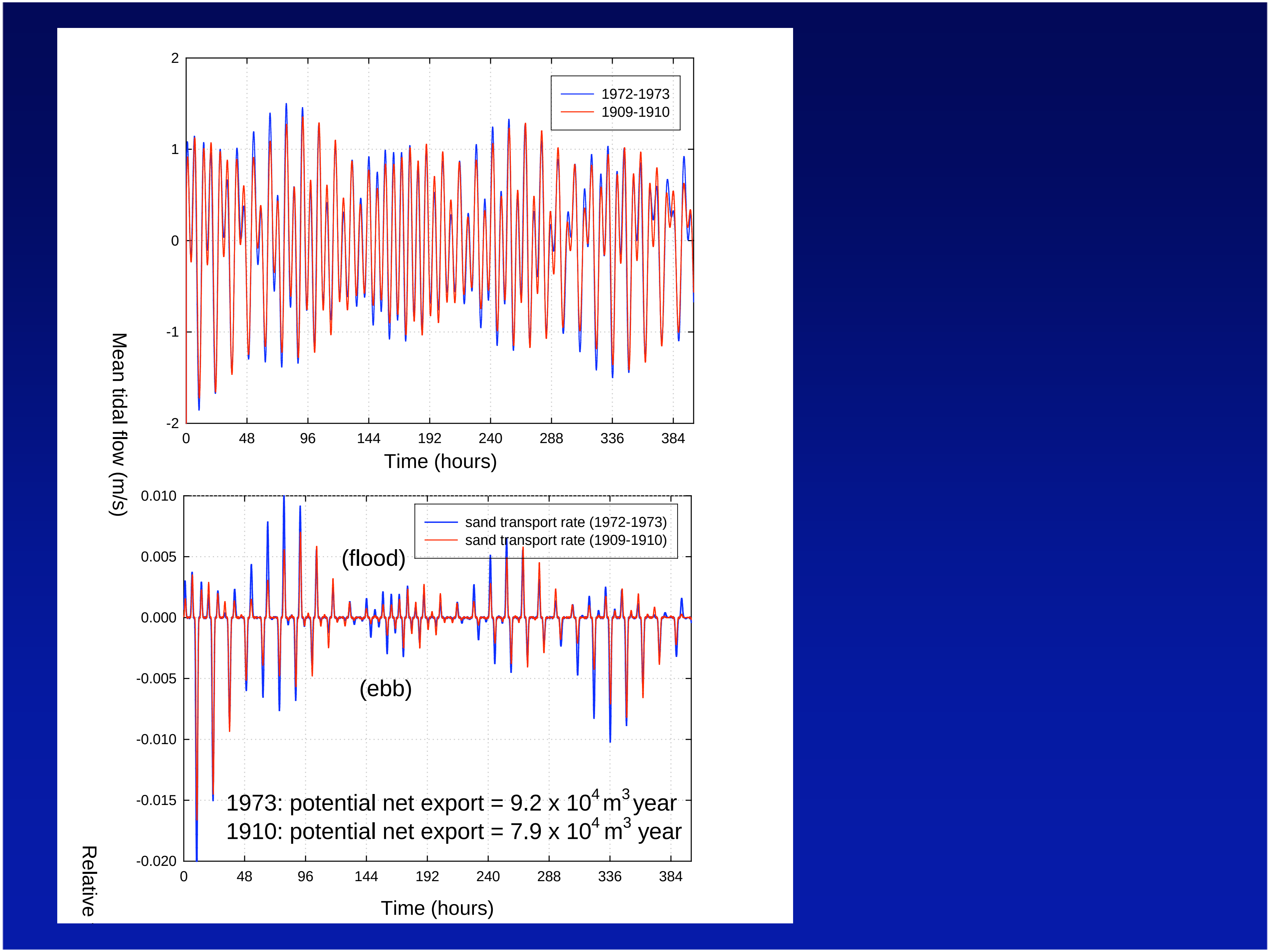
- S - sediment concentration dominates
  - flux increases as S increases
- W_s - flux increases with increased settling rate
- U_d - deposition threshold
  - flux increases as threshold increases
- U_e - erosion threshold
  - flux increases as threshold increases
- NOTE: S dominates the signal so should be the focus of measurement, input and calibration in model


Tidal amplitude
Time (hours)
M2+M4 no phase shift
M2+M4 45 degree advance
M2+M4 45 degree retard
M2+M6 no phase shift
M2+M6 45 degree advance
M2+M6 45 degree retard
Relative t
M2+M4 (no phase advance)
M2+M4 (45 phase advance)
M2+M4 (45 phase retard)
Advance phase = increase flood transport
Retard phase = increase ebb transport
Relat
M2+M6 (no phase advance)
M2+M6 (45 phase advance)
M2+M6 (45 phase retard)
Advance phase = increase flood transport
Retard phase = increase flood transport

tidal constituent	phase	relative transport
M2	--	--
M2+S2	--	--
M2+S2	45(S2)	.00082
M2+S2	-45(S2)	-0.0000942
M2+S2+M4	--	0.0153
M2+S2+M4+M6	--	0.0246
M2+S2+M4+M6	45(S2)	0.0228
M2+S2+M4+M6	-45(S2)	-7.7E-3
M2+S2+M4+M6	45(M4)	0.044
M2+S2+M4+M6	-45(M4)	-0.016
M2+S2+M4+M6	45(M6)	.0241
M2+S2+M4+M6	-45(M6)	0.024

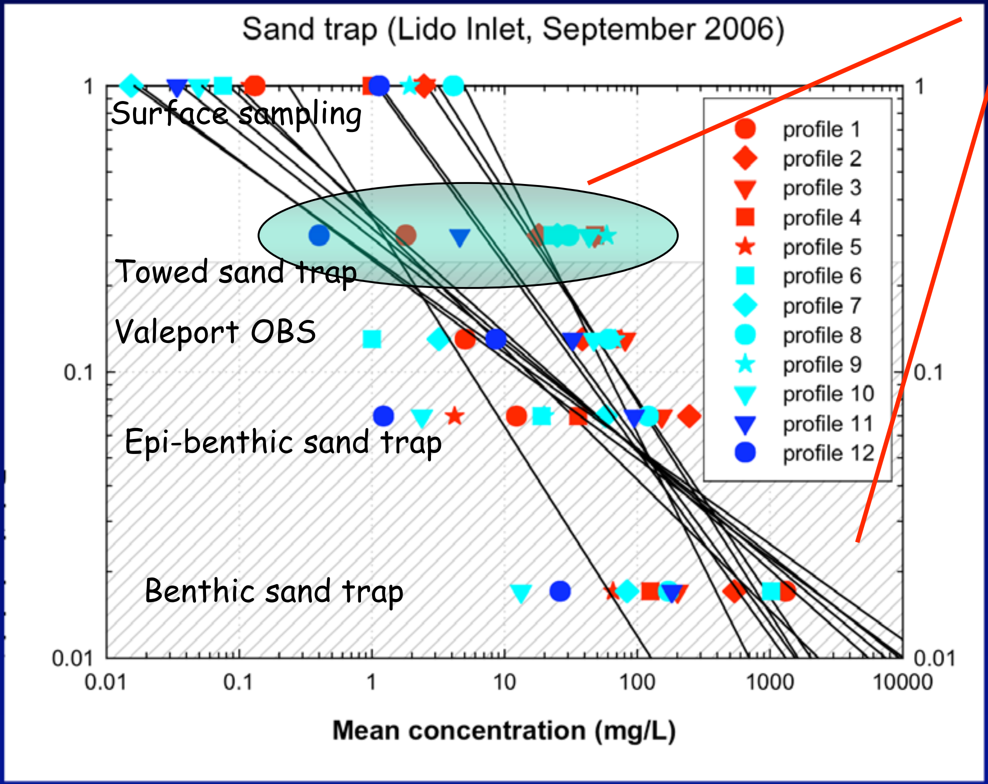


tidal constituent	amplitude(m)	phase	period(hours)
1909-1910			
M2	0.22	305	12.421
S2	0.127	312	12
N2	0.036	301	12.658
K2	0.035	315	11.97
K1	0.169	87	23.934
O1	0.05	67	25.819
P1	0.053	82	24.07
1972-1973			
M2	0.242	310	12.421
S2	0.143	319	12
N2	0.042	310	12.658
K2	0.041	310	11.97
K1	0.175	87	23.934
O1	0.052	79	25.819
P1	0.057	85	24.07



Mean tidal flow (m/s)
1972-1973
1909-1910
Time (hours)
sand transport rate (1972-1973)
sand transport rate (1909-1910)
(flood)
(ebb)
1973: potential net export = 9.2 x 10^4 m^3 year
1910: potential net export = 7.9 x 10^4 m^3 year
Relative
Time (hours)

Lido Sud (fixed ADCP site)
Shaded region is the shadow zone of ADCP



PROFILE #	R-squared	1/m	b
1	0.91	1.45	0.2
2	0.98	0.89	-0.16
3	0.82	0.79	-0.49
4	0.65	0.94	-0.51
5	0.47	1.45	-0.59
6	0.77	1.59	-0.15
7	0.66	1.79	-0.71
8	0.26	1.02	-1.1
9	0.99	0.26	-0.01
10	0.26	2.08	-1
11	0.89	1.49	-0.38
12	0.55	0.86	-0.02

$$\log_{10}(z) = m\log(C) + b$$

$$C = (z)^{\frac{1}{m}} 10^{\frac{-b}{m}}$$

$$z = \frac{h}{H - a}$$

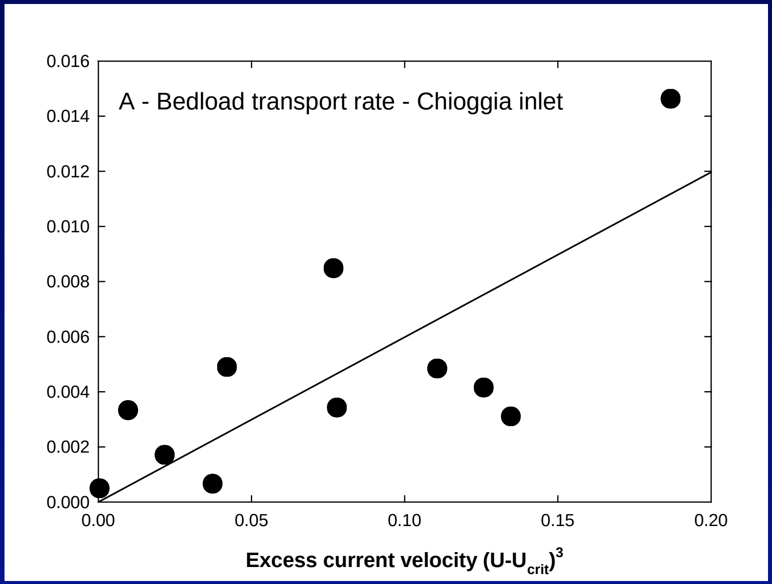
Suspension number
Our results 1/m = -0.93

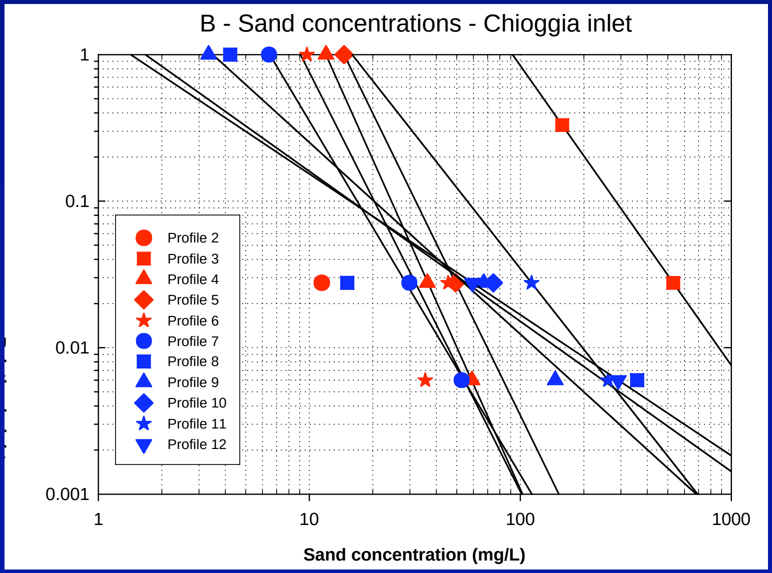
C = concentration (sand)
Z = relative height
h = sample height
H = water depth
a = reference conc. height

$$\frac{1}{m} = \left(\frac{W_s}{\beta\kappa U_*}\right) \approx 0.93$$

$$\left|\frac{W_s}{U_*}\right| = 0.93\beta\kappa \approx 0.38$$

$$k = 0.4; \beta = 1$$





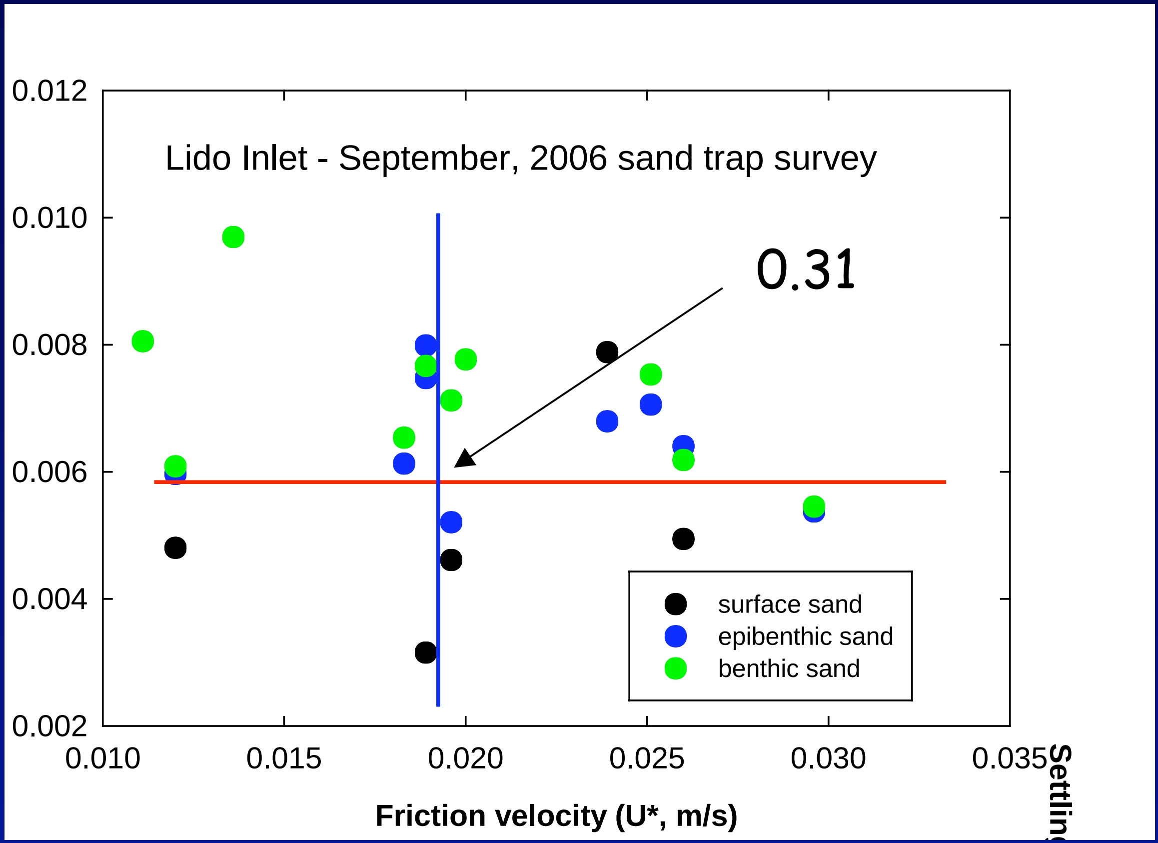
$$G_s = 0.06(\overline{U} - U_{crit})^3 kg/m/s(Chioggia)$$

$$G_s = 0.52(\overline{U} - U_{crit})^3 kg/m/s(Lido)$$

Gadd *et al.* (1976) relationship for fine sand coefficient from 1.73 to 7.33 (wave-dominated shelf)

Ws/U* is evaluated as 0.4*m = 0.23

PROFILE	U (m/s)	STAGE OF TIDE	1/m
3	0.77	EBB	-0.49
4	0.71	FLOOD	-0.31
5	0.7	FLOOD	-0.34
6	0.63	FLOOD	0.35
7	0.48	FLOOD	-0.41
8	0.27	EBB	-0.97
9	0.42	EBB	-0.76
11	0.62	EBB	-0.54
12	0.68	EBB	-1.04



Settling rate measured in NOC sedimentation column (1.8 m)

U_* derived from TKE method on ADV (25 Hz) time-series (7500 data points)

Linear (inverse) relationship between friction velocity (U_*) and settling rate (W_s)

Inverse relationship i.e. Faster flows have finer grains !!!

Ws/U_* given by van Rijn et al. (1997) as 2.5 (turbulent rough)

Ws/U* given by Bagnold (1966) as 1.25 (turbulent rough)

Using measured values from Lido yields a value of 0.38 (turbulent smooth)

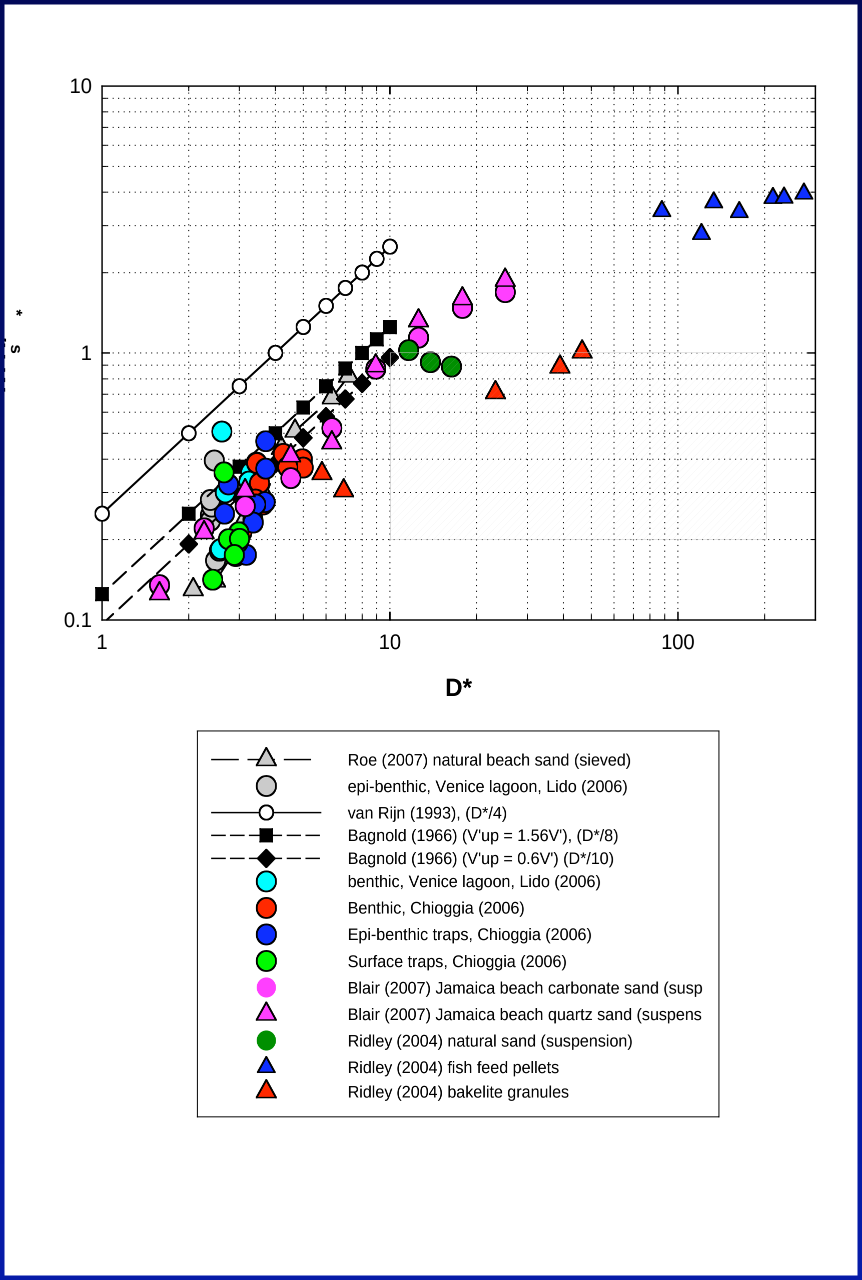
Using measured values from Chioggia yields a value of 0.29 (turbulent smooth)

$$\frac{W_s}{U_*} = 0.38\,(\text{Lido})$$

$$\frac{W_s}{U_*} = 0.29\,(\text{Chioggia})$$

Summary of results (Ws/U*) – Venice lagoon, 2006

	Lido Inlet	Chioggia Inlet
Measured from SSC profiles	0.38	0.29
Measured from samples	0.31	0.23
D* = 10	1.0	1.0



D* is dimensionless grain diameter
Ws = still water fall velocity
U* = critical friction velocity

$$D_* = \left| \frac{(\frac{\rho_s - \rho}{\rho})g}{\upsilon^2} \right|^{0.333} d_{50}$$

$$\frac{W_s}{U_*} = \frac{\chi}{D_*}, D_* < 10$$

$$\frac{W_s}{U_*} = const., D_* > 10$$

$$\theta_{crit,susp} = \frac{\chi^2}{D_*^2}\left[\frac{\rho}{\rho_s - \rho}\right]\frac{W_s^2}{gd_{50}}, D_* < 10$$

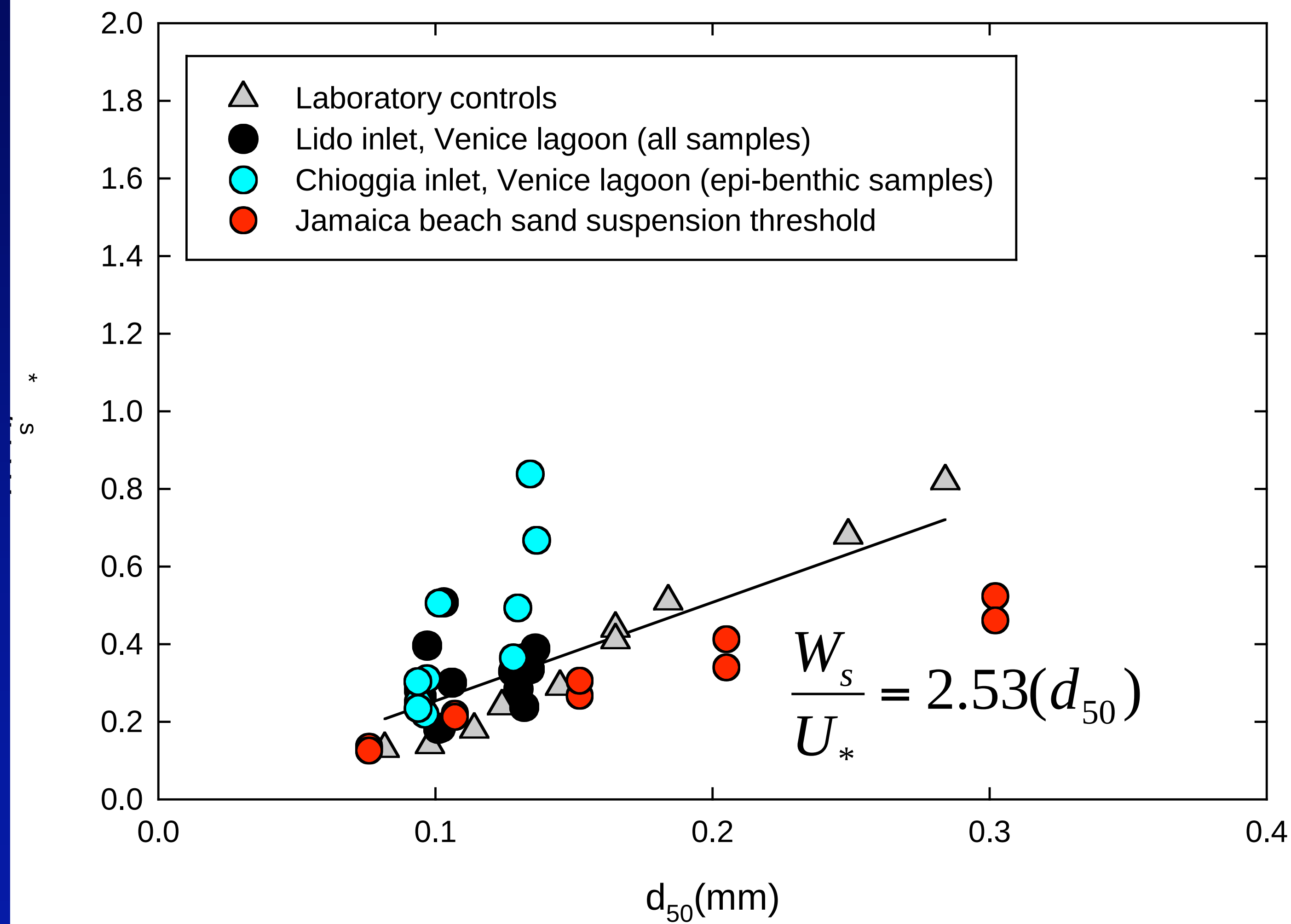
$$\theta_{crit,susp} = const.\left[\frac{\rho}{\rho_s - \rho}\right]\frac{W_s^2}{gd_{50}}, D_* > 10$$

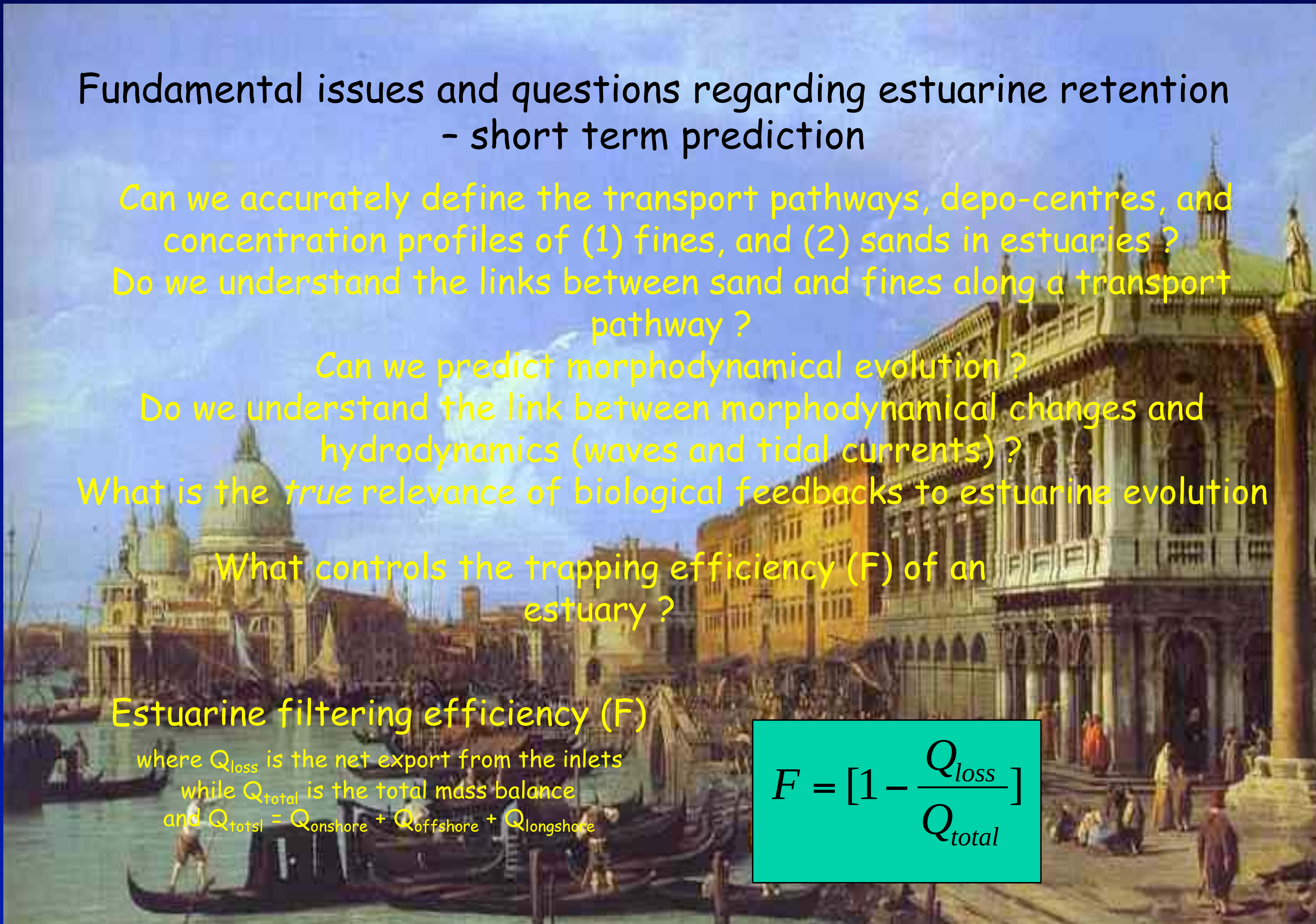
Ws/U* = 10/D*
Lower than van Rijn (4/D*)

Critical Shields parameter for suspension lower than Bagnold (1966)

Yields good separation between bedload and suspended load samples from Lido inlet.

$$\Theta_{crit,susp} = 0.043 D_*^{1.152}, D_* < 10$$


Laboratory controls
Lido inlet, Venice lagoon (all samples)
Chioggia inlet, Venice lagoon (epi-benthic samples)
Jamaica beach sand suspension threshold
$\frac{W_s}{U_*} = 2.53(d_{50})$
d_{50}(mm)
0.0
0.1
0.2
0.3
0.4
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0



Fundamental issues and questions regarding estuarine retention – short term prediction

Can we accurately define the transport pathways, depo-centres, and concentration profiles of (1) fines, and (2) sands in estuaries ?

Do we understand the links between sand and fines along a transport pathway ?

Can we predict morphodynamical evolution ?

Do we understand the link between morphodynamical changes and hydrodynamics (waves and tidal currents) ?

What is the *true* relevance of biological feedbacks to estuarine evolution

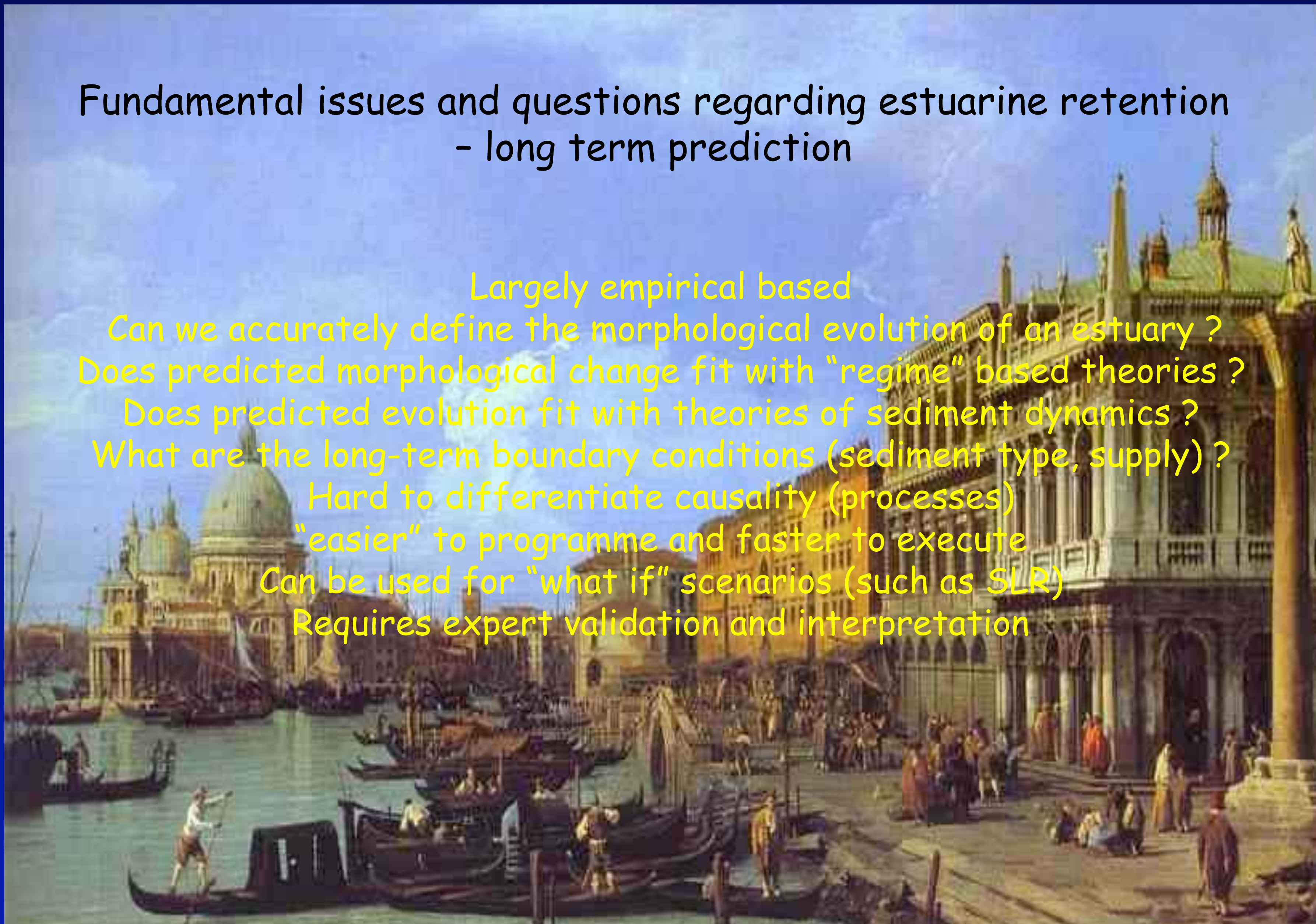
What controls the trapping efficiency (F) of an estuary ?

Estuarine filtering efficiency (F)

where Q_{loss} is the net export from the inlets
while Q_{total} is the total mass balance
and $Q_{totsl} = Q_{onshore} + Q_{offshore} + Q_{longshore}$

$$F = [1 - \frac{Q_{loss}}{Q_{total}}]$$

Fundamental issues and questions regarding estuarine retention – long term prediction



Largely empirical based
Can we accurately define the morphological evolution of an estuary ?
Does predicted morphological change fit with “regime” based theories ?
Does predicted evolution fit with theories of sediment dynamics ?
What are the long-term boundary conditions (sediment type, supply) ?
Hard to differentiate causality (processes)
“easier” to programme and faster to execute
Can be used for “what if” scenarios (such as SLR)
Requires expert validation and interpretation

THE NUMERICAL MODEL

- **Shallow Water Finite Element Model (SHYFEM)**

$$\frac{\partial U}{\partial t} - fV + gH\frac{\partial \varsigma}{\partial x} + RU + F_x = 0$$

$$\frac{\partial V}{\partial t} + fU + gH\frac{\partial \varsigma}{\partial y} + RV + F_y = 0$$

$$\frac{\partial \varsigma}{\partial t} + \frac{\partial U}{\partial t} + \frac{\partial V}{\partial t} = 0$$

$$U = \int_{-h}^{\varsigma} u\,\partial z$$

$$V = \int_{-h}^{\varsigma} v\,\partial z$$

Barotropic transport

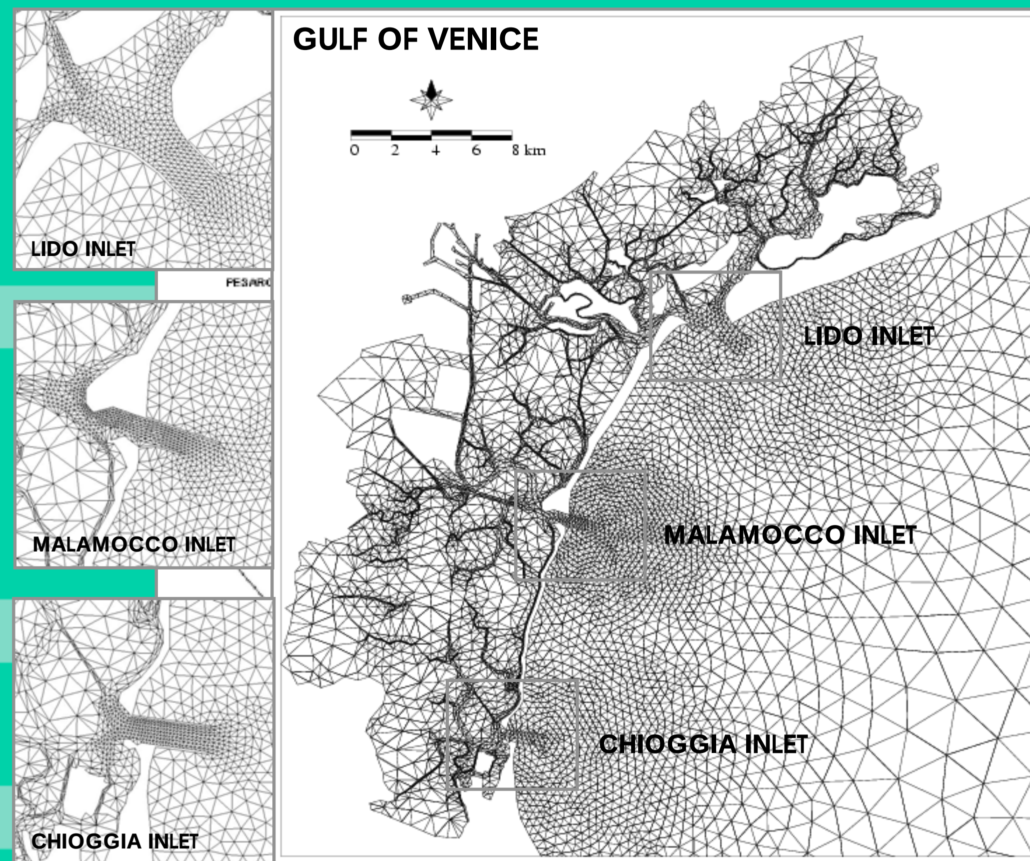
$$R = \frac{c_b}{H}\sqrt{u^2 + v^2}$$

Friction term

$$F_x = \int_{-h}^{\xi}\left[\frac{\partial p_H}{\rho_0 \partial x} + \hat{f}_x\right]dz + \frac{1}{\rho_0}\left(\tau_x^B - \tau_x^W\right)$$

$$p_H = p_S + \int_{z}^{\xi} g\rho^{1}(z)\,dz$$

Wind stress, non-linear advective terms ...



MODEL DOMAIN F.E. grid of the Adriatic Sea and Venice Lagoon (8072 nodes, 15269 elements, spatial resolution varying from 30 Km to 50 m)

THE TRANSPORT TIME SCALES

RESIDENCE TIME (Eulerian approach)

" THE TIME REQUIRED FOR EACH ELEMENT OF THE DOMAIN TO REPLACE THE MASS OF A CONSERVATIVE TRACER, ORIGINALLY RELEASED, WITH NEW WATER "

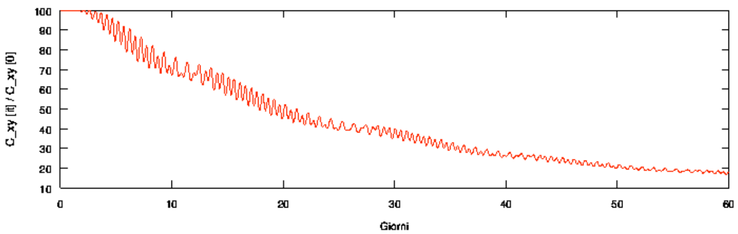
- TRACER [C] IN THE LAGOON = 100 %

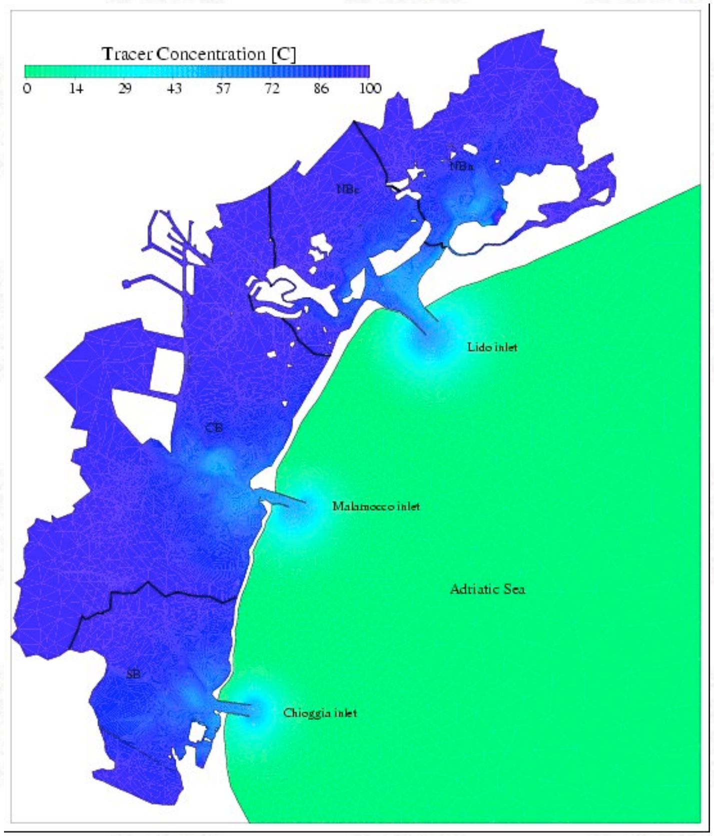
$$S_0 = S(t=0)$$

- TIDE AND WIND ACTION DRIVES IT OUT THE BASIN

$$\frac{\partial S}{\partial t} + \frac{\partial uS}{\partial x} + \frac{\partial vS}{\partial y} = K_H \left(\frac{\partial^2 S}{\partial x^2} + \frac{\partial^2 S}{\partial y^2} \right)$$

- TIME DECAY OF THE TRACER CONCENTRATION



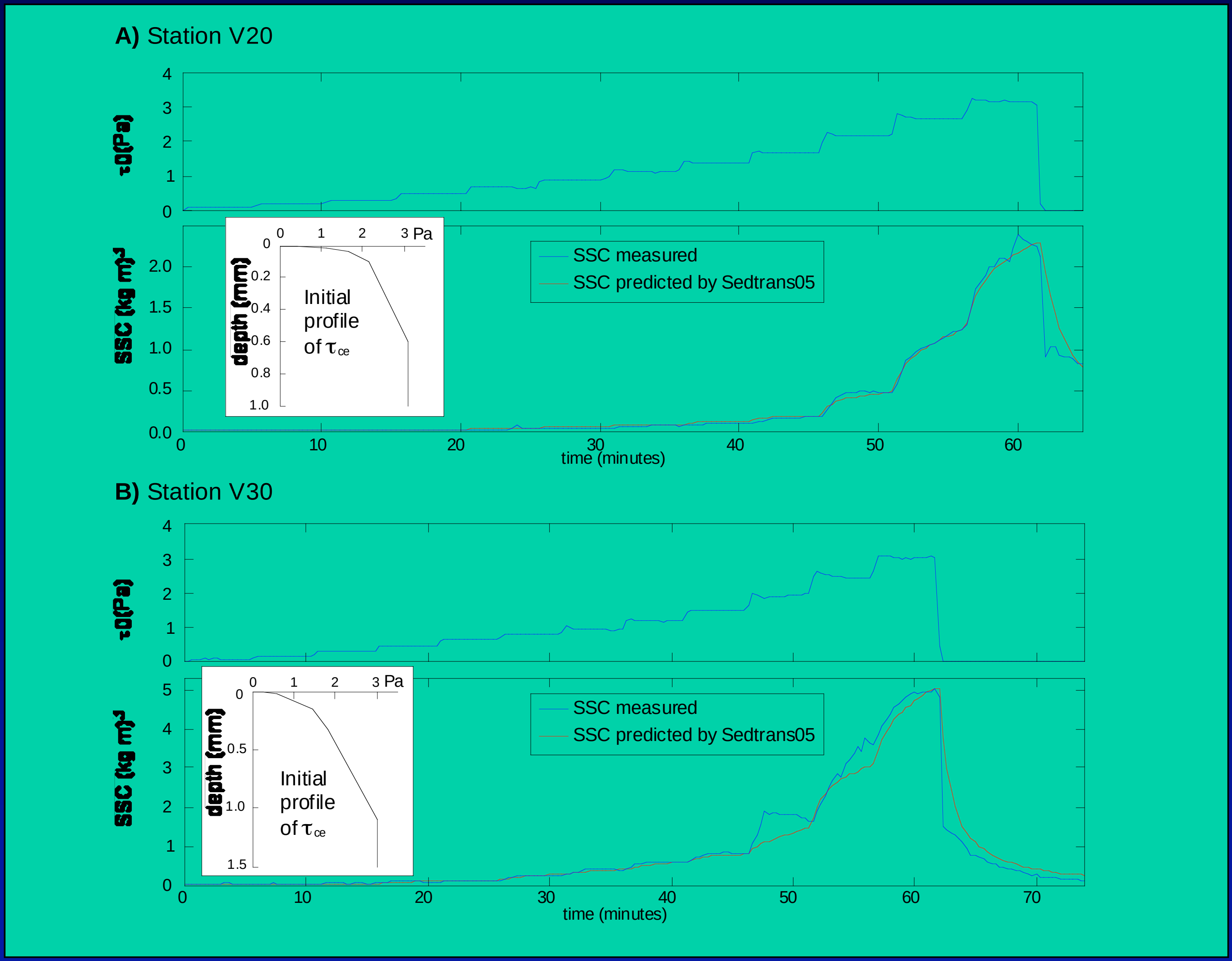


- DEFINITION OF THE REMNANT FUNCTION (Takeoka, 1984 a,b)

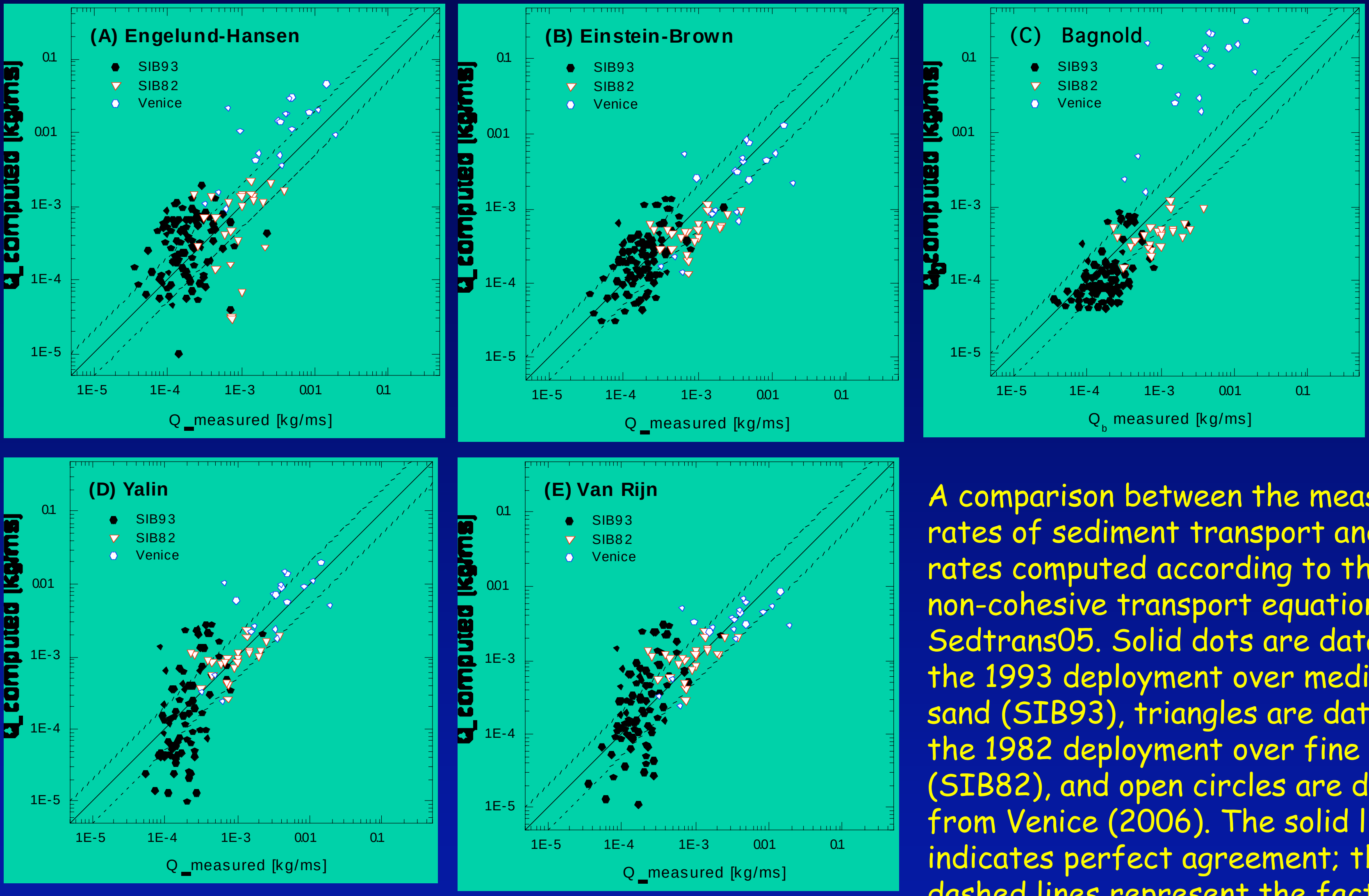
$$r(x,y,t) = S(x,y,t)/S_0$$

- DEFINITION OF THE WATER RESIDENCE TIME

$$\tau(x,y) = \int_0^{\infty} r(x,y,t)\,dt$$



A comparison of the cohesive sediment algorithm with field data collected with the Sea Carousel in Venice lagoon (Stations 20 and 30, February 1999). The initial profile of critical erosion threshold t_{ce}, and the time-series of applied bed shear stress t_0, measured SSC, and SSC predicted by Sedtrans05 are shown.



A comparison between the measured rates of sediment transport and the rates computed according to the five non-cohesive transport equations in Sedtrans05. Solid dots are data from the 1993 deployment over medium sand (SIB93), triangles are data from the 1982 deployment over fine sand (SIB82), and open circles are data from Venice (2006). The solid line indicates perfect agreement; the dashed lines represent the factors 0.5 and 2.

THE TRANSPORT TIME SCALES

THE RETURN FLOW FACTOR (b)

FROM TIDAL PRISM METHOD:
THE AVERAGE WATER RESIDENCE TIME IS DEFINED AS:

$$\tau_{av} = \frac{TV_{av}}{(1-b)P}$$

b IS THE RETURN FLOW FACTOR. IT EXPRESSES THE FATE OF THE WATER ONCE IT IS OUTSIDE THE EMBAYMENT

•DEFINITON OF THE RFF (b)

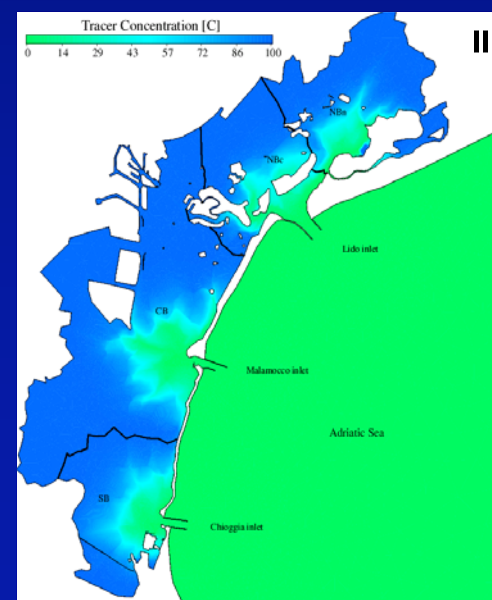
SIMULATION I, THE MASS OF THE TRACER EXITED THE LAGOON CAN RETURN TO THE EMBAYMENT. τ_{Av} IS COMPUTED

SIMULATION II, THE MASS OF THE TRACER EXITED THE LAGOON IS SET TO ZERO, (b=0). τ_0 IS COMPUTED

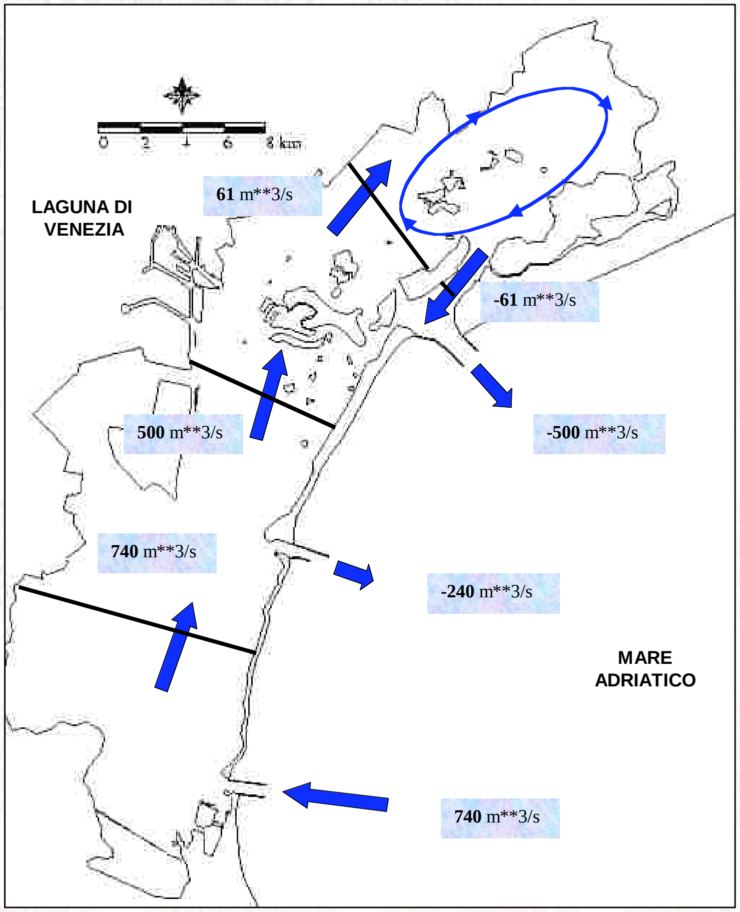
$$\tau_0 = \frac{TV_{av}}{P} \longrightarrow \tau_{av} = \frac{\tau_0}{1-b}$$

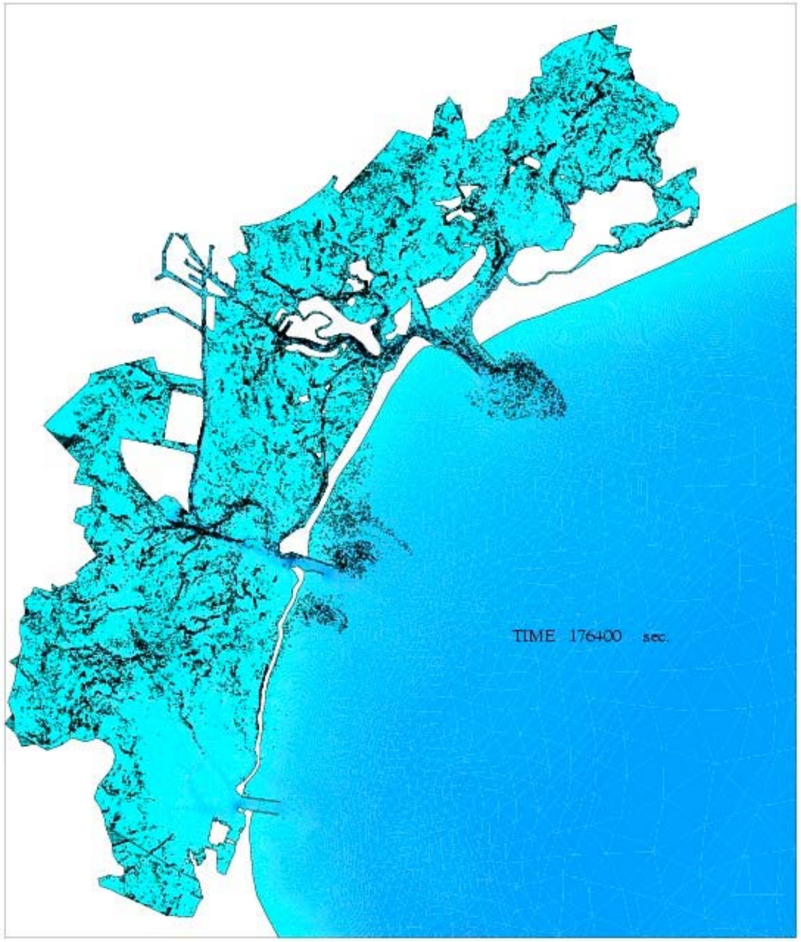
THE RFF IS DEFINED AS:

$$b(x,y) = \frac{\tau(x,y) - \tau_0(x,y)}{\tau(x,y)}$$



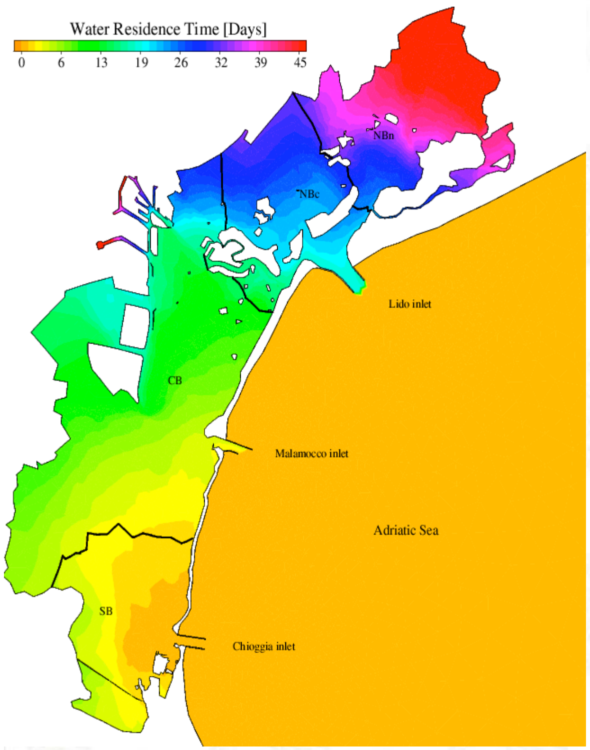
SCENARIO: TIDE AND SIROCCO WIND (7 m/s)

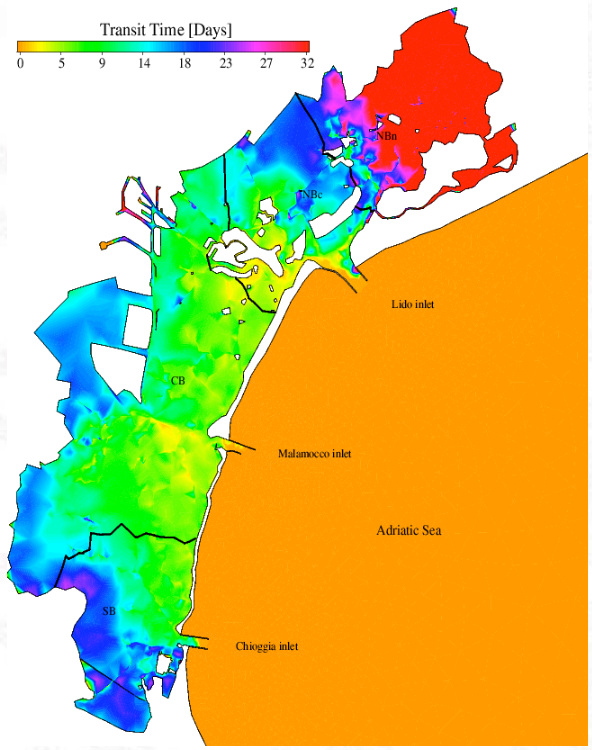


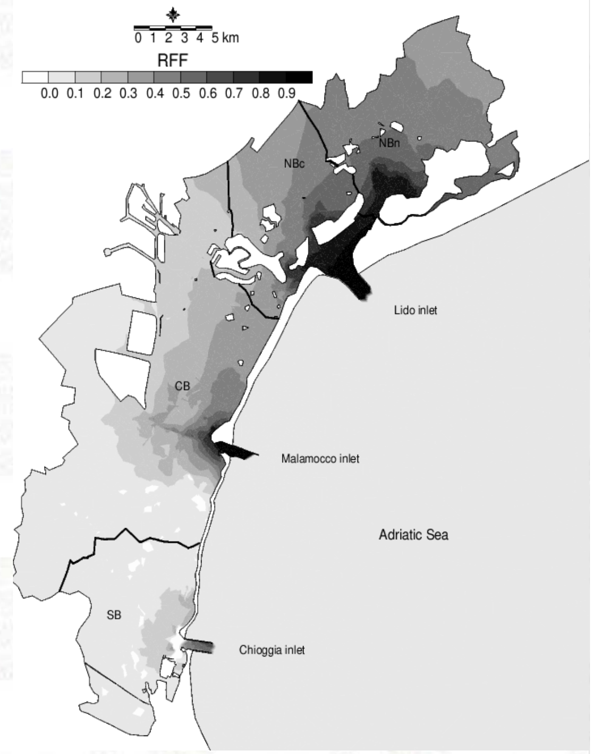


SCENARIO: TIDE AND SIROCCO WIND (7 m/s)

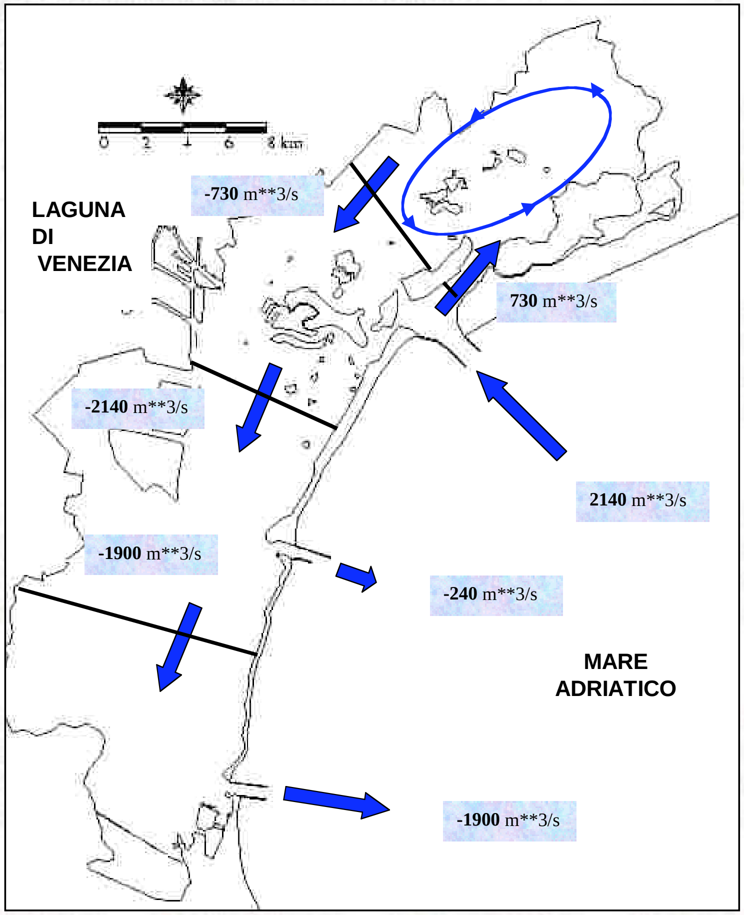
TRANSPORT TIME SCALE	Total	NBn	NBc	CB	SB
WRT	16 ± 8	38 ± 9	23 ± 6	10 ± 6	2 ± 1
		32 ± 10		8 ± 6	
WTT	18 ± 9	37 ± 14	11 ± 6	10 ± 5	13 ± 6
		26 ± 17		11 ± 5	
RFF	0.3	0	0	0	0

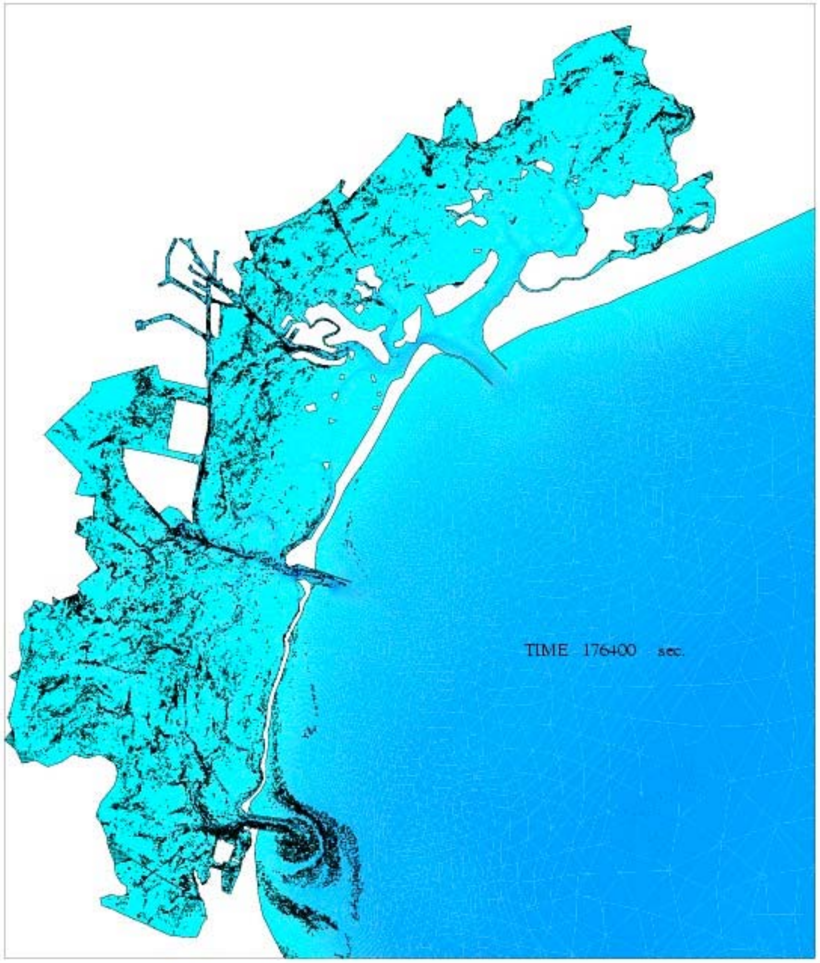






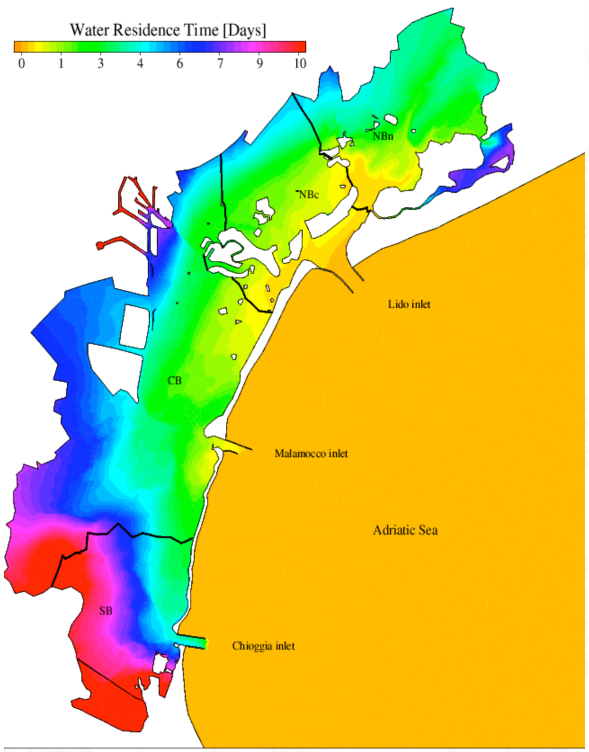
SCENARIO: TIDE AND BORA WIND (10 m/s) ↙

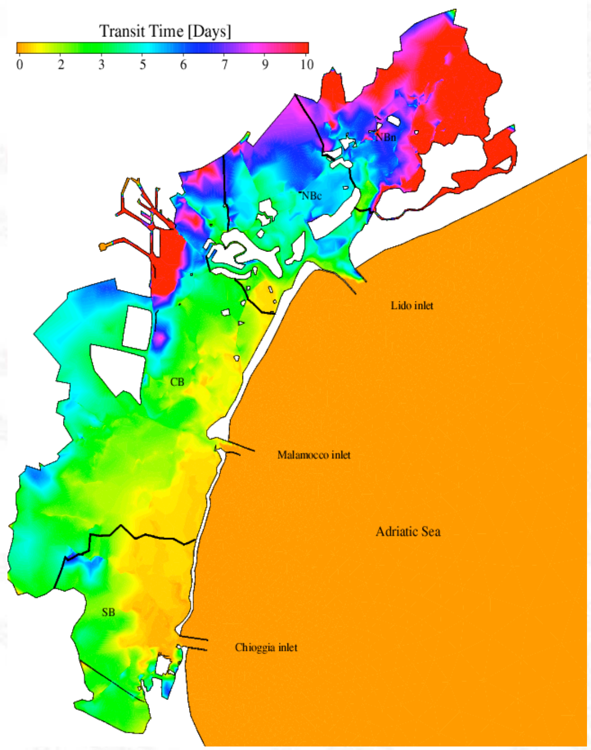


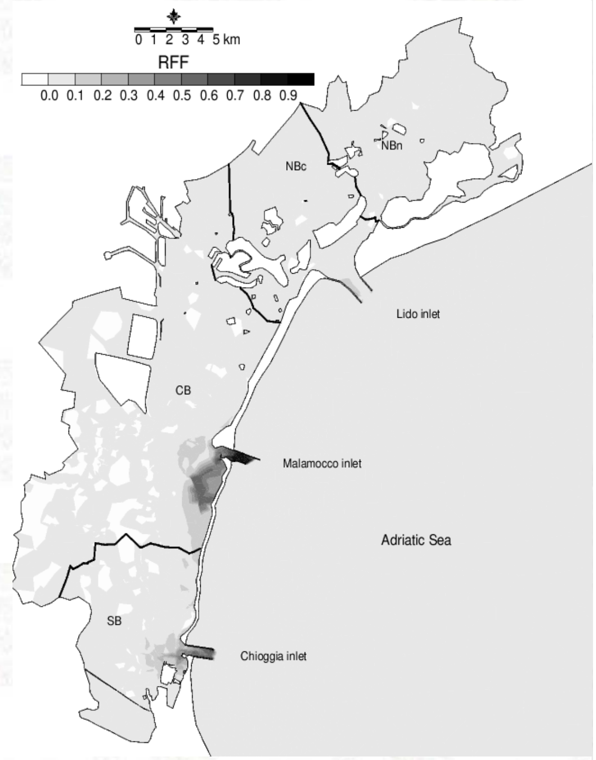


SCENARIO: TIDE AND BORA WIND (10 m/s) ↙

TRANSPORT TIME SCALE	Total	NBn	NBc	CB	SB
WRT	4 ± 4	3 ± 1	2 ± 1	5 ± 3	7 ± 3
WTT	4 ± 2	9 ± 4	4 ± 1	3 ± 2	2 ± 1
RFF	0	0	0	0	0





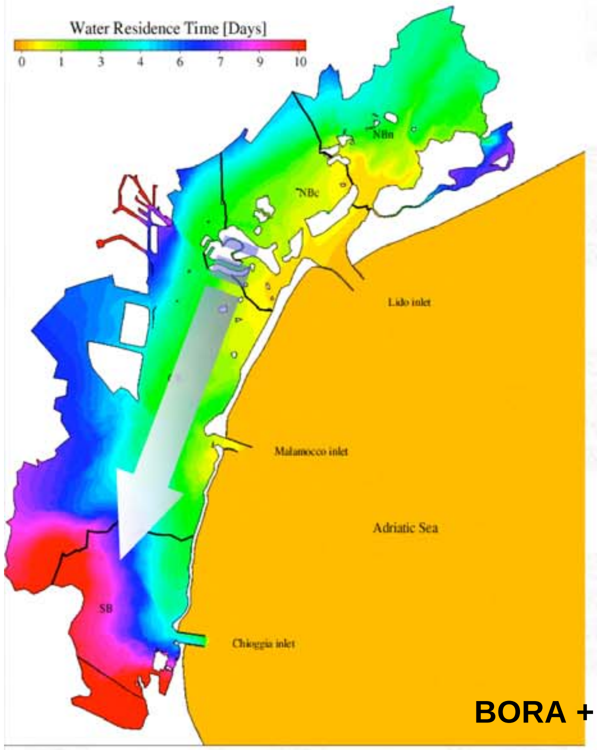


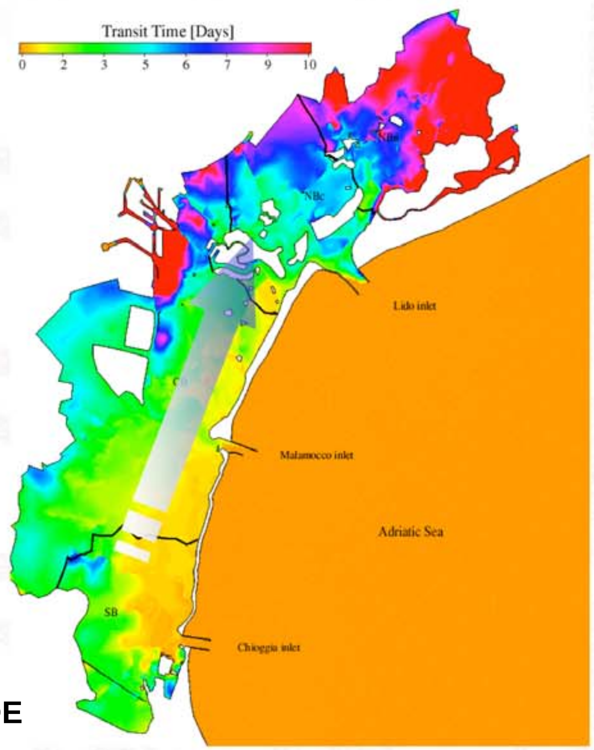
RESIDENCE TIME VS TRANSIT TIME

TRAPPING FACTOR

SIROCCO + TIDE	Total	NBn	NBc	CB	SB
WRT	16 ± 8	38 ± 9	23 ± 6	10 ± 6	2 ± 1
WTT	18 ± 9	37 ± 14	11 ± 6	10 ± 5	13 ± 6

BORA +TIDE	Total	NBn	NBc	CB	SB
WRT	4 ± 4	3 ± 1	2 ± 1	5 ± 3	7 ± 3
WTT	4 ± 2	9 ± 4	4 ± 1	3 ± 2	2 ± 1





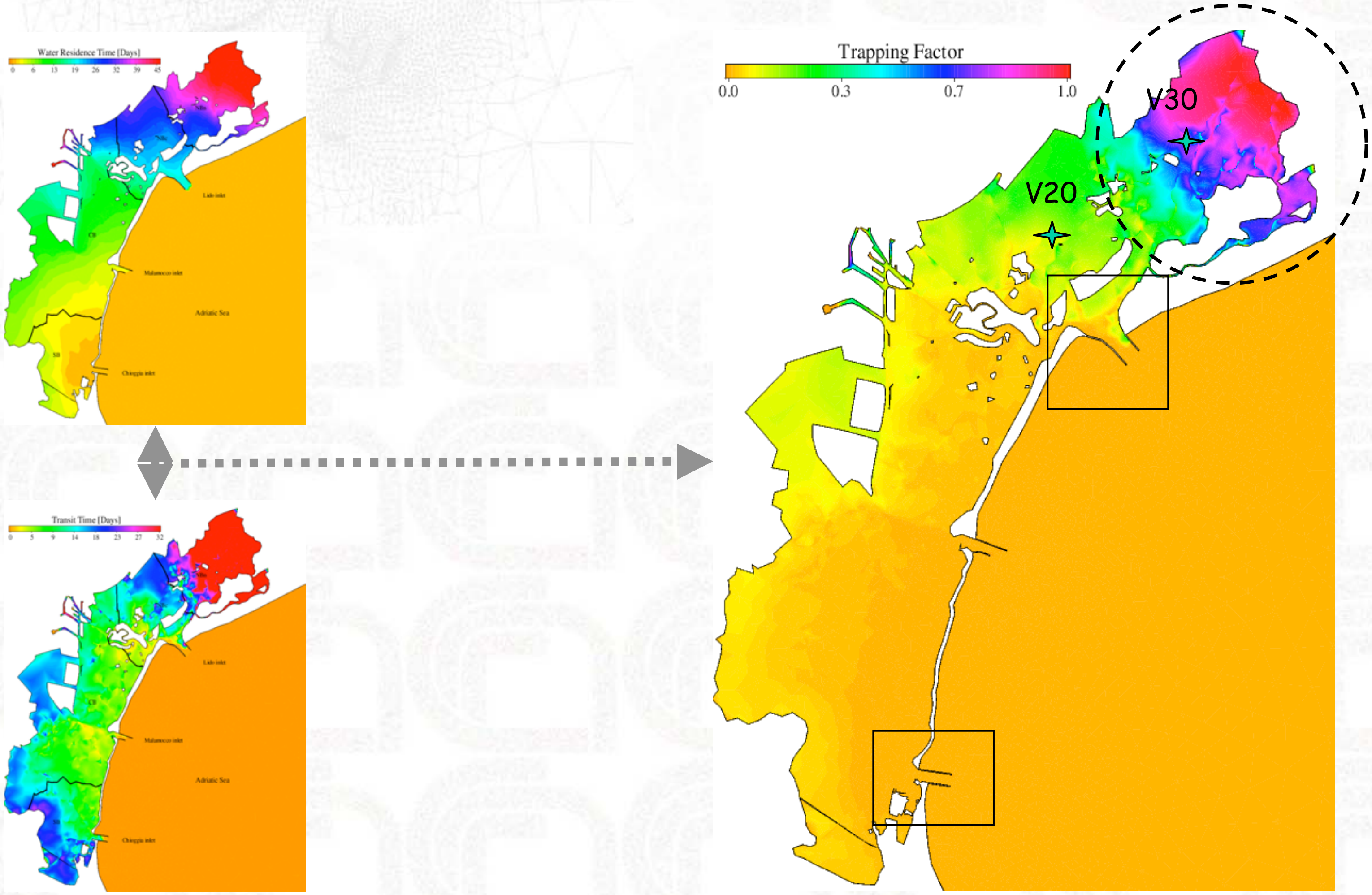
BORA + TIDE

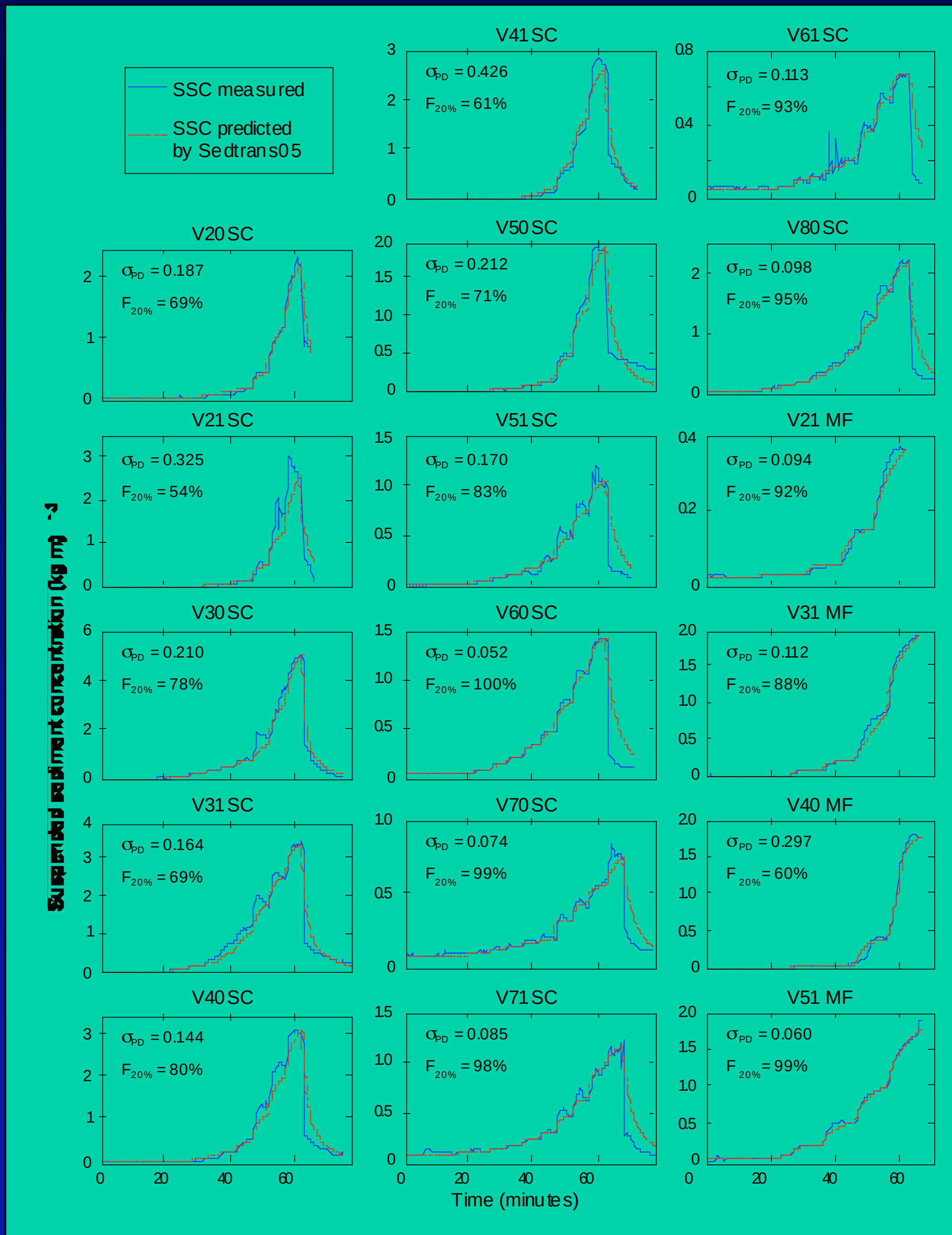
THEY SEEM TO BE CORRELATED !

SCENARIO: TIDE AND SIROCCO WIND (7 m/s)

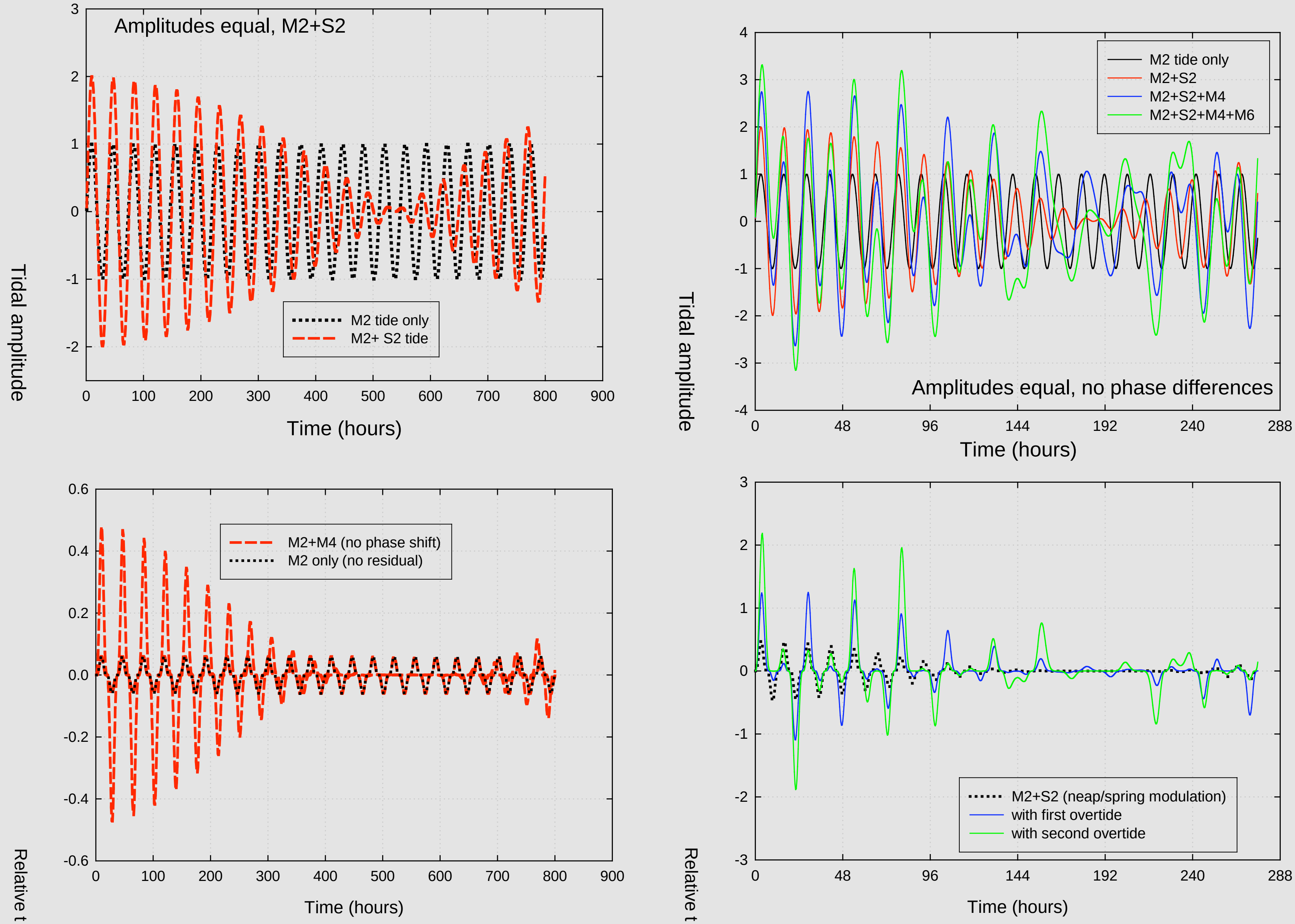
SIROCCO + TIDE	Total	NBn	NBc	CB	SB
WRT	16 ± 8	38 ± 9	23 ± 6	10 ± 6	2 ± 1
WTT	18 ± 9	37 ± 14	11 ± 6	10 ± 5	13 ± 6

CF = 0.09



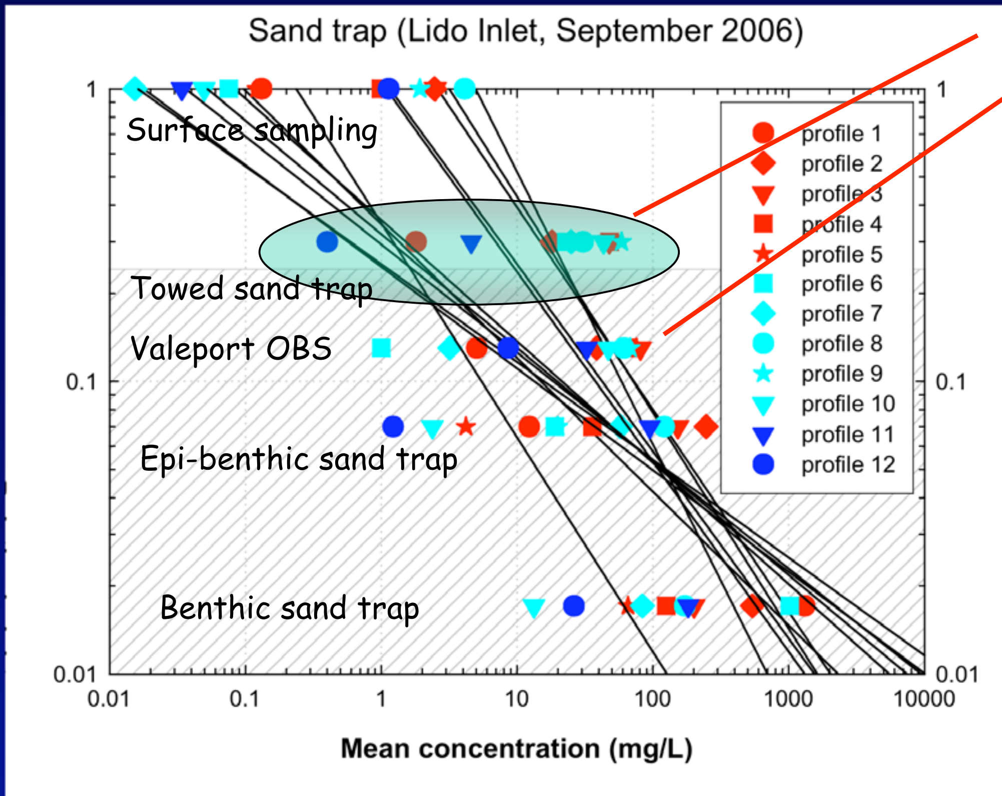


A comparison of the cohesive sediment algorithm with field data collected with the Sea Carousel (SC) and the field MiniFlume (MF) at different stations in Venice lagoon, February 1999. For each experiment, the time-series of SSC measured and predicted by Sedtrans05, the standard deviation of the proportional difference (s_{PD}), and the time percentage when the difference is less than 20% ($F_{20\%}$) are shown.



Amplitudes equal, M2+S2
M2 tide only
M2+ S2 tide
Tidal amplitude
Time (hours)
M2 tide only
M2+S2
M2+S2+M4
M2+S2+M4+M6
Amplitudes equal, no phase differences
Tidal amplitude
Time (hours)
M2+M4 (no phase shift)
M2 only (no residual)
Relative t
Time (hours)
M2+S2 (neap/spring modulation)
with first overtide
with second overtide
Relative t
Time (hours)

Lido Sud (fixed ADCP site)
Shaded region is the shadow zone of ADCP



PROFILE	R-squared	offset	1/m
1	0.97	-0.46	-2.17
2	0.96	0.29	-1.64
3	0.85	0.37	-1.35
4	0.76	0.04	-1.56
5	0.61	-0.04	-2.44
6	0.75	-0.53	-2.70
7	0.76	-0.61	-2.86
8	0.91	0.64	-1.08
9	0.43	0.02	-1.54
10	0.44		-3.03
11	0.89	-0.50	-2.56
12	0.51	-0.05	-1.37

$$\log_{10}(z) = m\log(C) + b$$

$$C = (z)^{\frac{1}{m}} 10^{\frac{-b}{m}}$$

Suspension number
Our results 1/m = -1.77

Suspension throughout water column at peak flows

Stratification at Ht and LT

$$\frac{1}{m} = \left(\frac{W_s}{\beta \kappa U_*}\right) \approx -1.77$$

$$\left|\frac{W_s}{U_*}\right| = \beta m \kappa \approx 0.71$$

$$m = 0.56; k = 0.4; \beta = 1$$