Morphological Development of the German Wadden Sea from 1996 to 2009 determined with the Waterline Method and SAR and Landsat Satellite Images

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Photo:
LKN-SH

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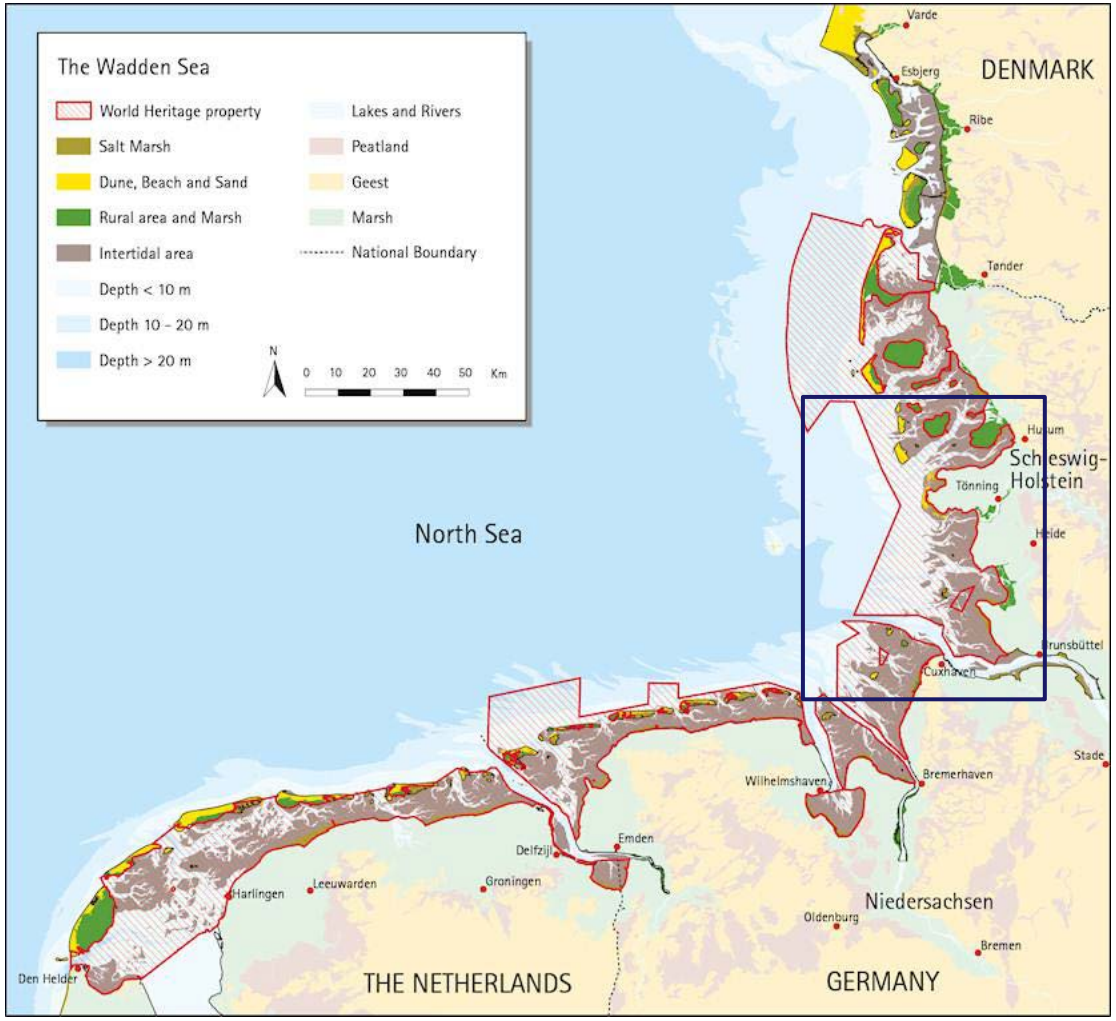
- Turnover height & Net balance height mittl. Absolute Höhenänderung & Höhenänderung mit Vorzeichen
- Sandbars

Introduction

- Motivation
- Investigation Area



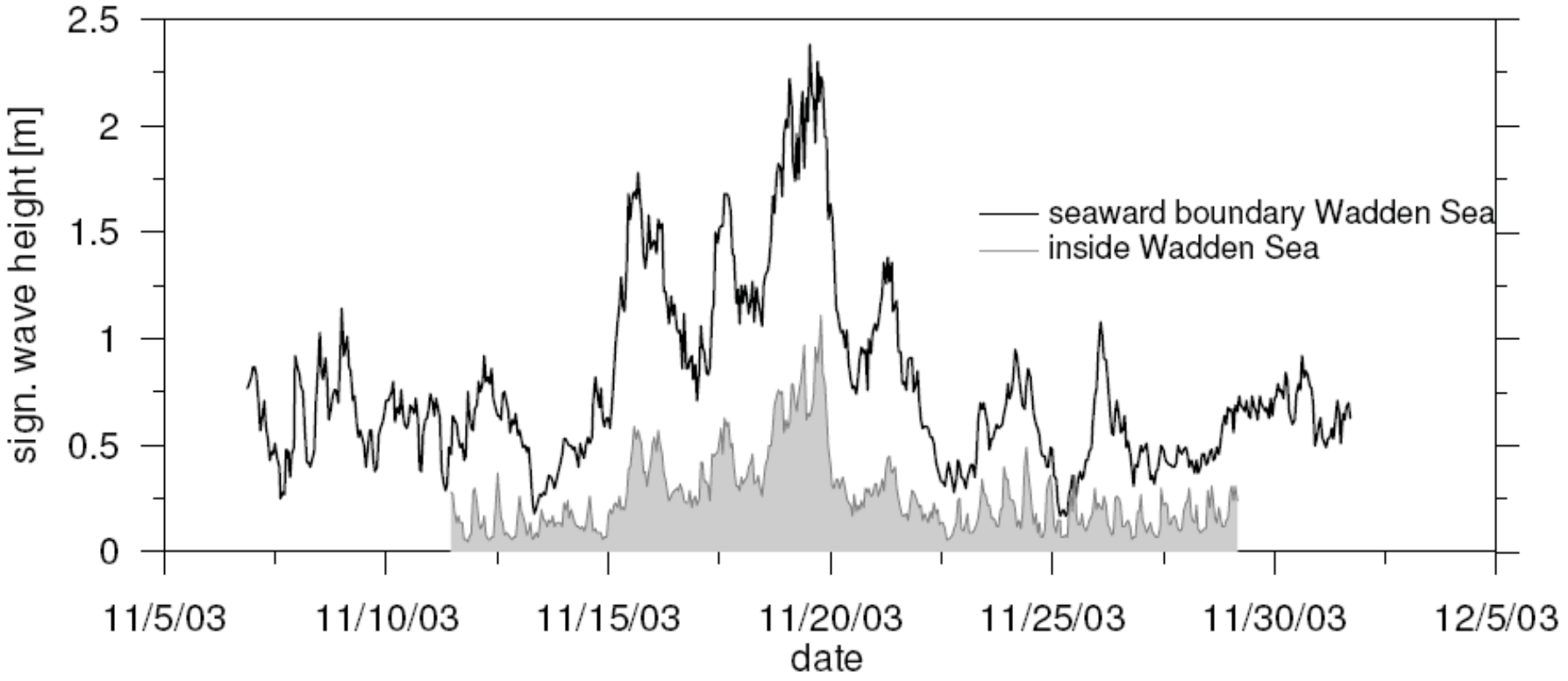
Wadden Sea world heritage site

Introduction

Black arrows
Direction and strength of the tidal currents;
White arrows
direction of sand transport.

Ehlers, 1988

Wave height

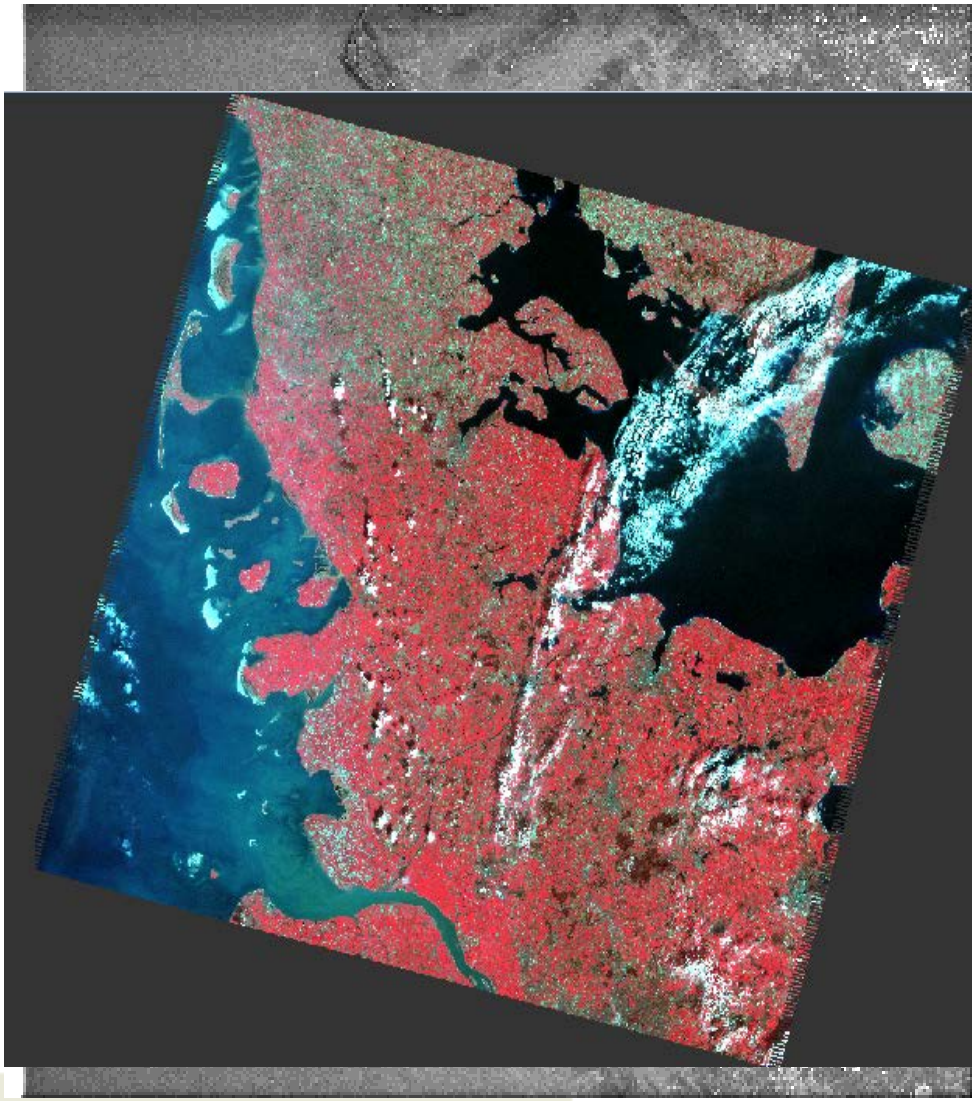


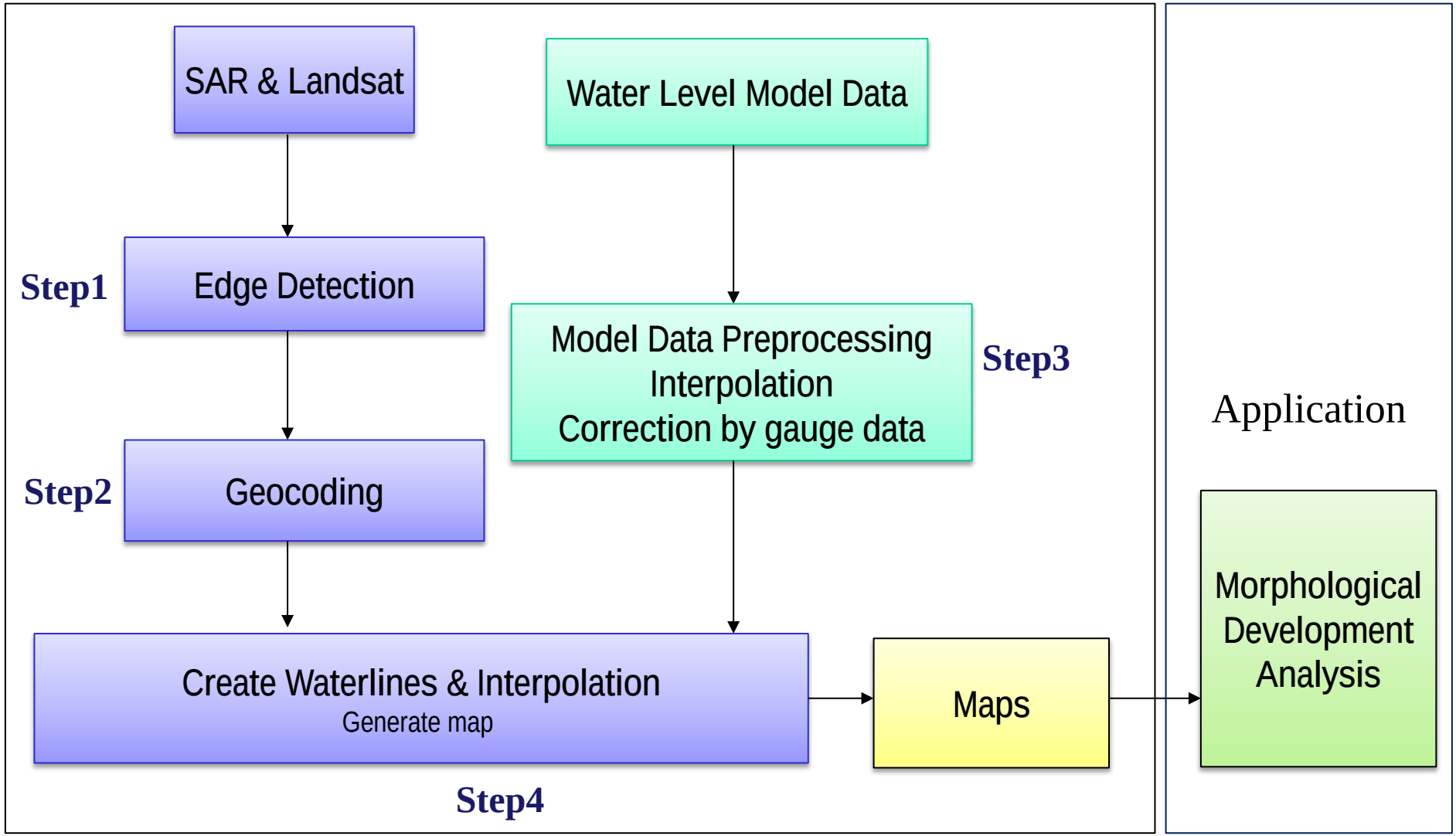
Ricklefs & Neto, 2005

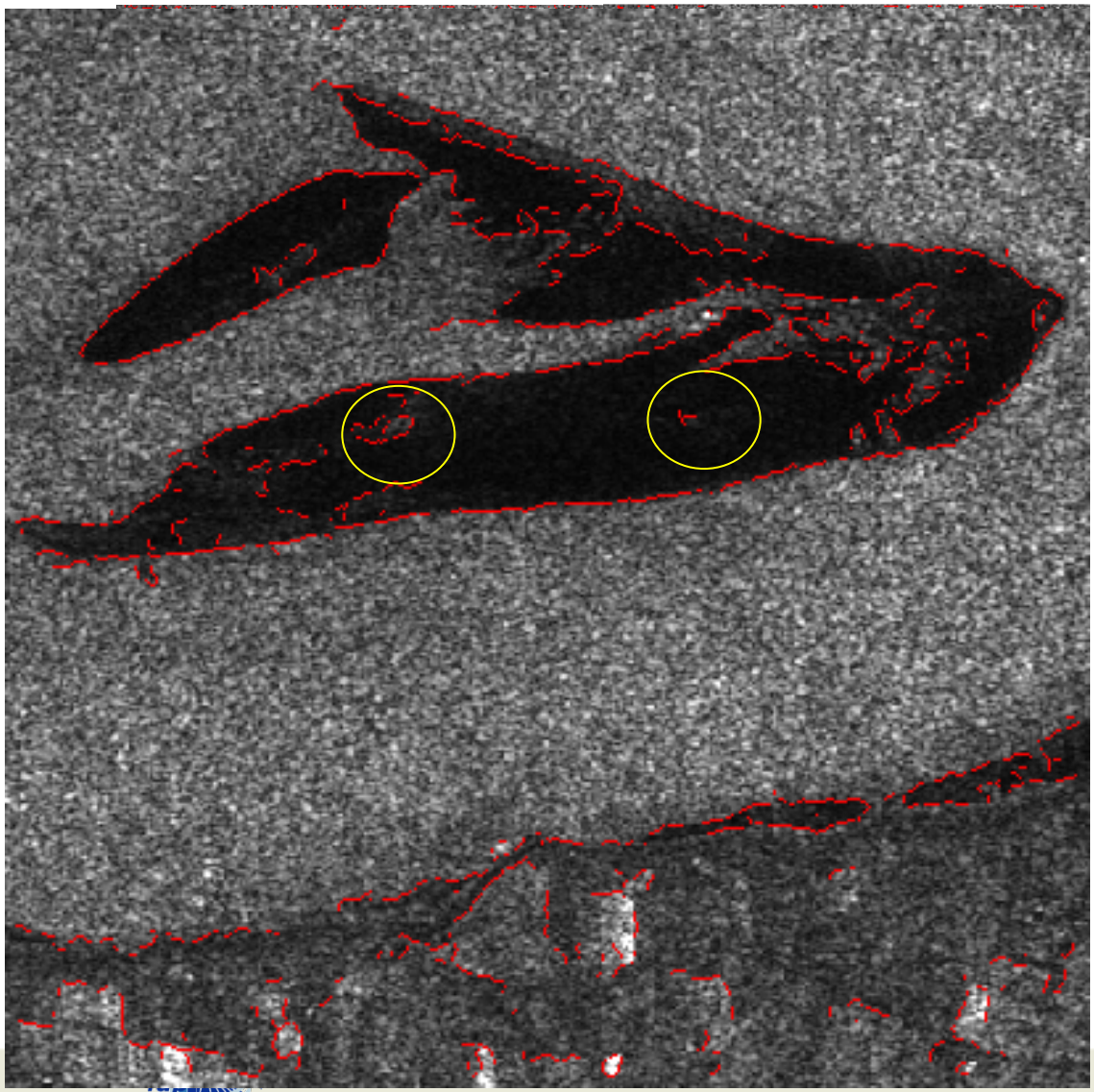
Satellite Image Data Basis

- Synthetic Aperture Radar
  (ERS-2 SAR, ENVISAT ASAR)
- Optical images (Landsat TM 5)

	SAR	Opt	Total
1996	9	2	11
1997	13		13
1998	12	3	15
1999	13		15
2004	18	5	23
2005	20	3	23
2006	16	2	16
2007	15		15
2008	17		17
2009	15	4	19



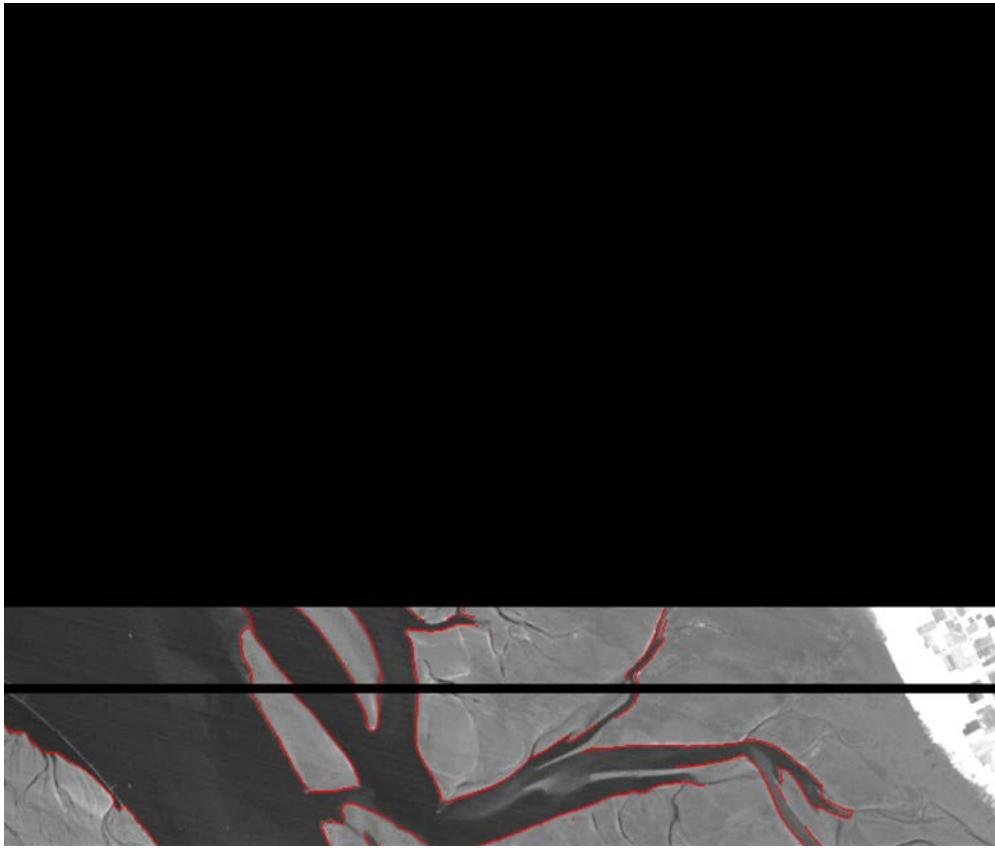

SAR & Landsat
Water Level Model Data
Step1
Edge Detection
Model Data Preprocessing
Interpolation
Correction by gauge data
Step3
Application
Step2
Geocoding
Morphological
Development
Analysis
Create Waterlines & Interpolation
Generate map
Maps
Step4



Edge detection in Landsat image

- Landsat band

Band	Wave length (μm)
near infrared	0.76-0.90



Landsat 5 TM image from 7th Jan, 2004.

- no speckle noise.

Geocoding:

Transform each point of the water lines (edge points) in SAR image into Gauss-Krueger coordinates.

.

Pixel location in the map

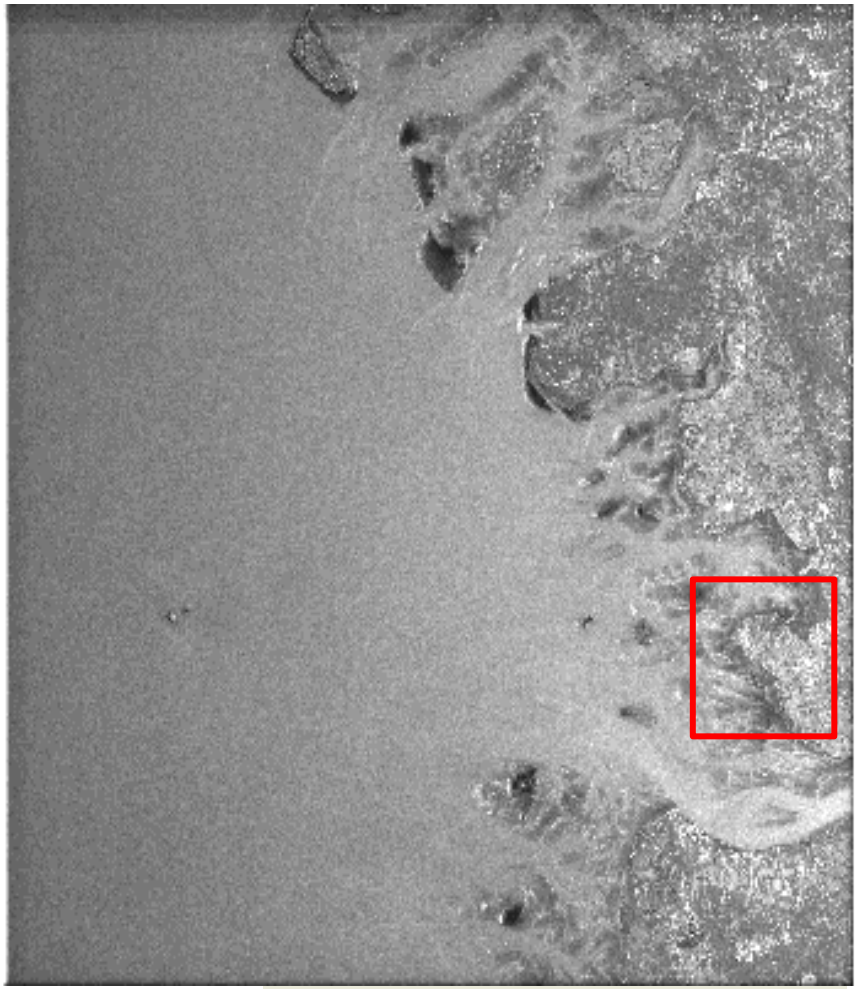
Pixel location in SAR image

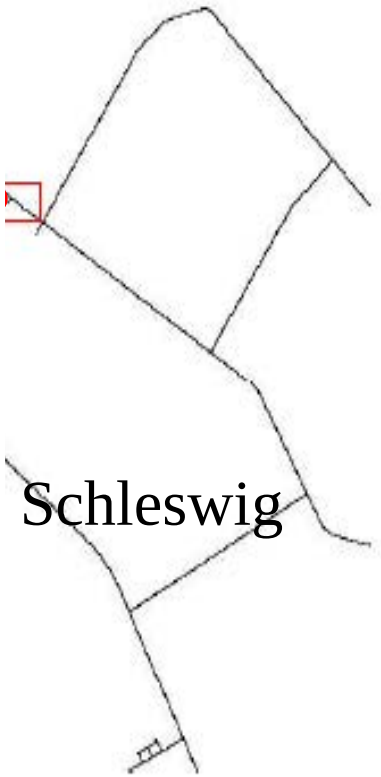
$$x = \sum_{i=0}^{N} \sum_{j=0}^{N-i} a_{ij} x_r^i y_r^j$$

$$y = \sum_{i=0}^{N} \sum_{j=0}^{N-i} b_{ij} x_r^i y_r^j$$

Coefficient	Warp component
a_{00}	shift in x
b_{00}	shift in y
a_{10}	scale in x
b_{01}	scale in y
a_{01}	shear in x
b_{10}	shear in y
a_{11}	y-dependent scale in x
b_{11}	x-dependent scale in y
a_{20}	nonlinear scale in x
b_{02}	nonlinear scale in y

Find the GCPs (Ground Control Points) from the SAR image and the matching map (Atkis dataset).

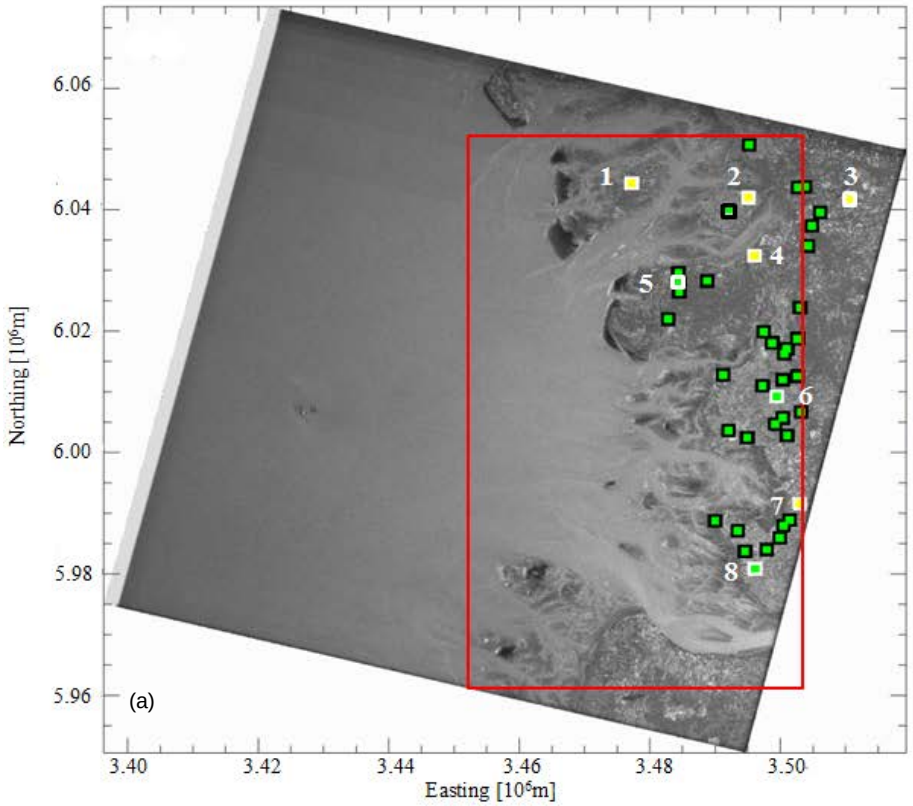




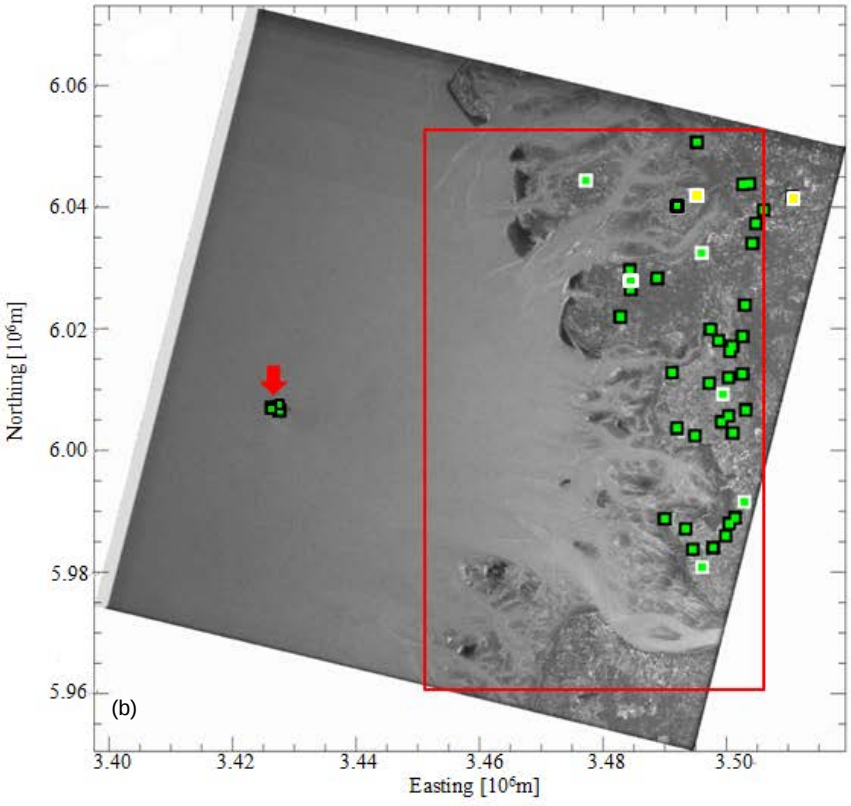
SAR image **map**

Geocoding result (2009)

Without



with Heligoland GCPs



error < 25 m

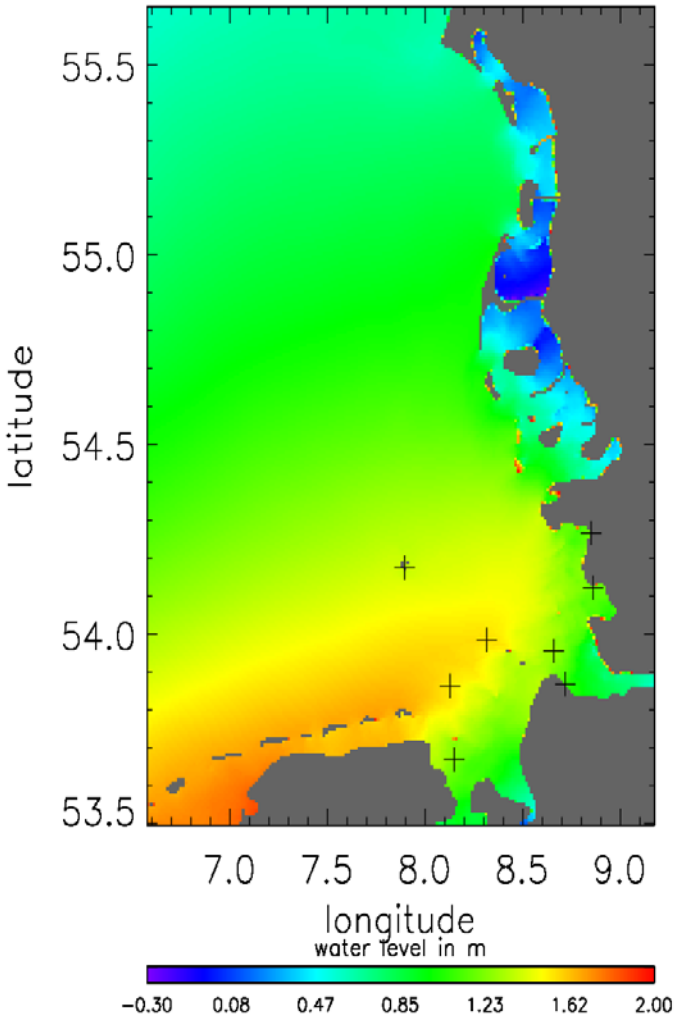
error < 50 m

Number	Error before adding GCPs on Heligoland (m)	Error after adding GCPs on Heligoland (m)
1	44.7	24.2
2	46.2	29.0
3	46.5	45.4
4	42.0	19.7
5	22.1	17.6
6	17.8	17.6
7	41.6	23.7
8	18.7	18.2
Average	35.0	24.4

Step 3: Water level Model data

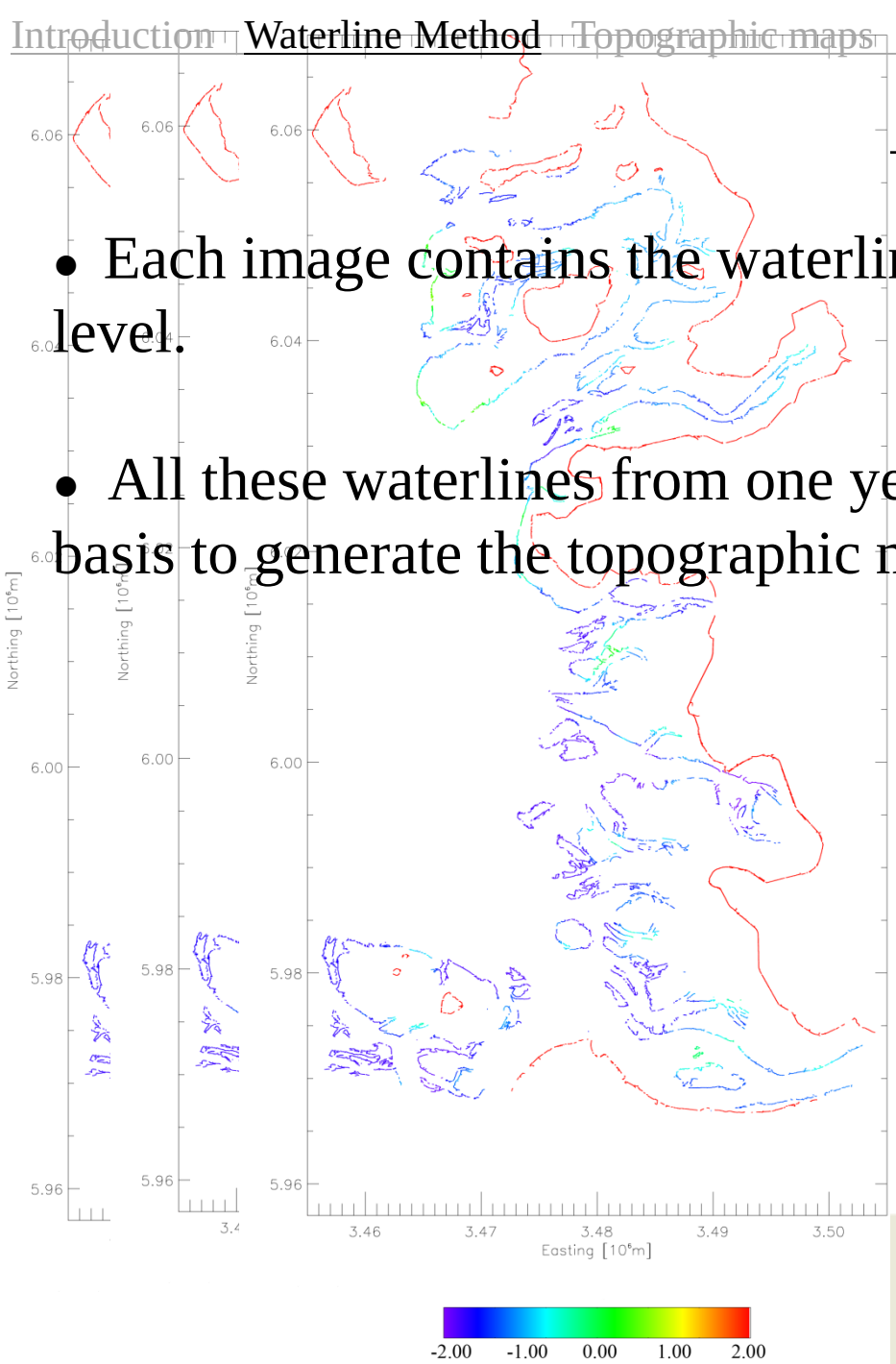
- Operational water level prediction model of BSH (German Federal Maritime and Hydrographic Agency)

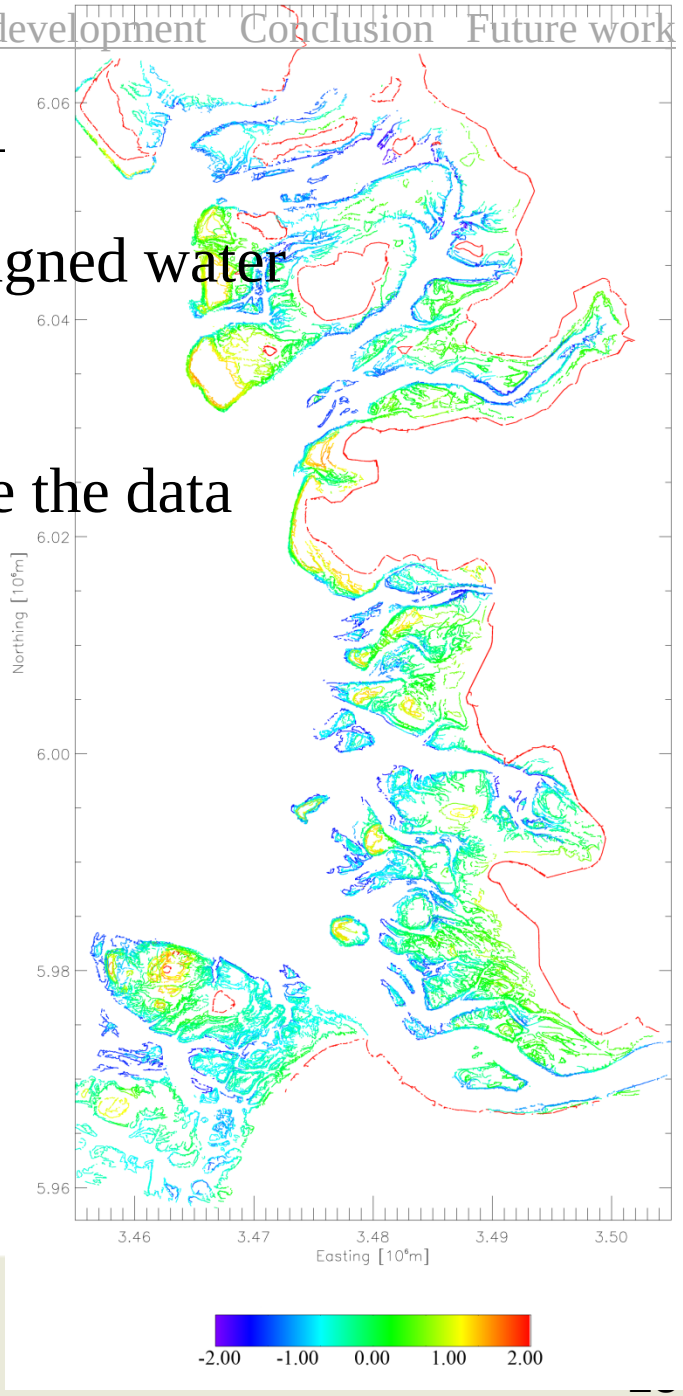
- The gauge data is from WSV (German Federal Water and Shipping Administration Agency).



- Each image contains the waterline with assigned water level.

- All these waterlines from one year compose the data basis to generate the topographic map.

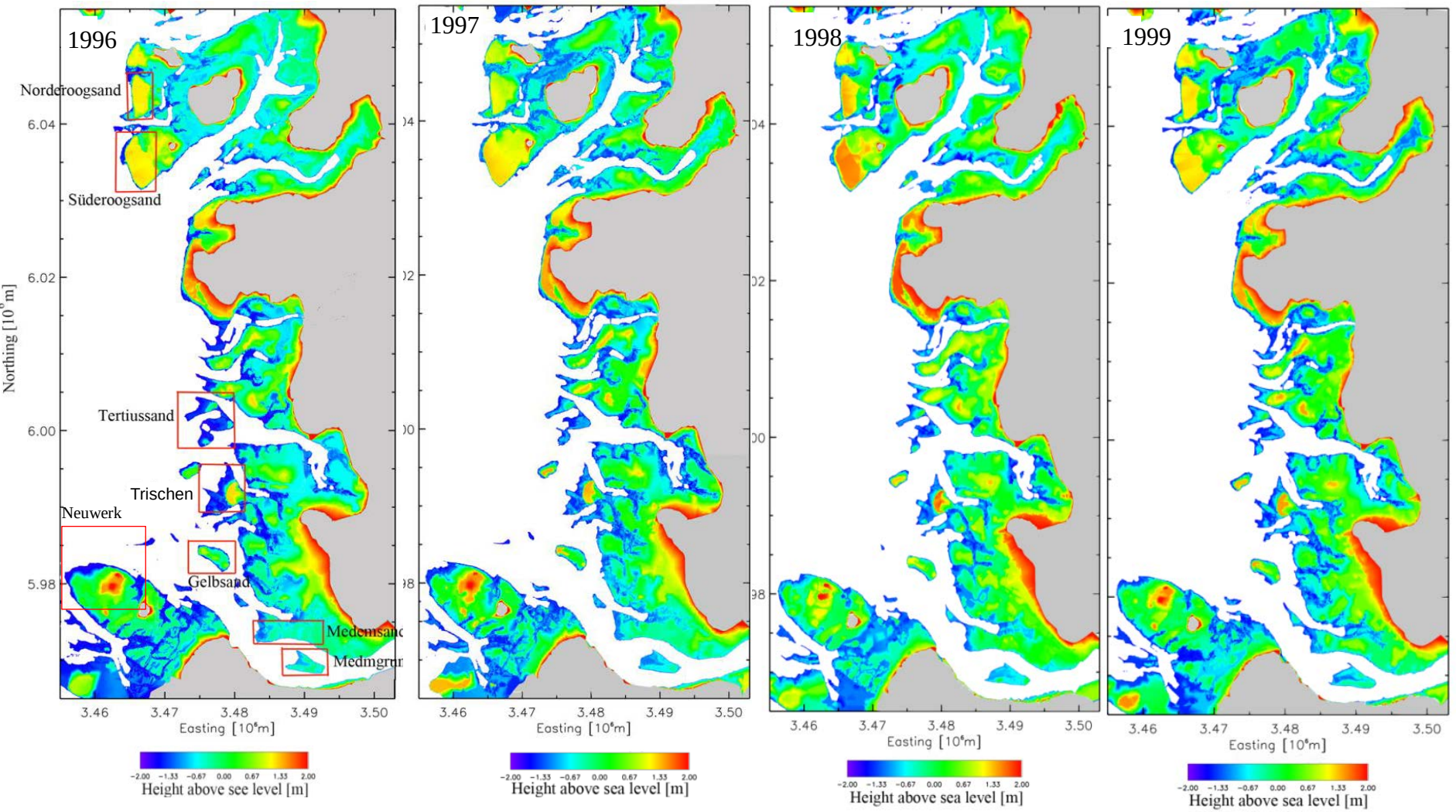


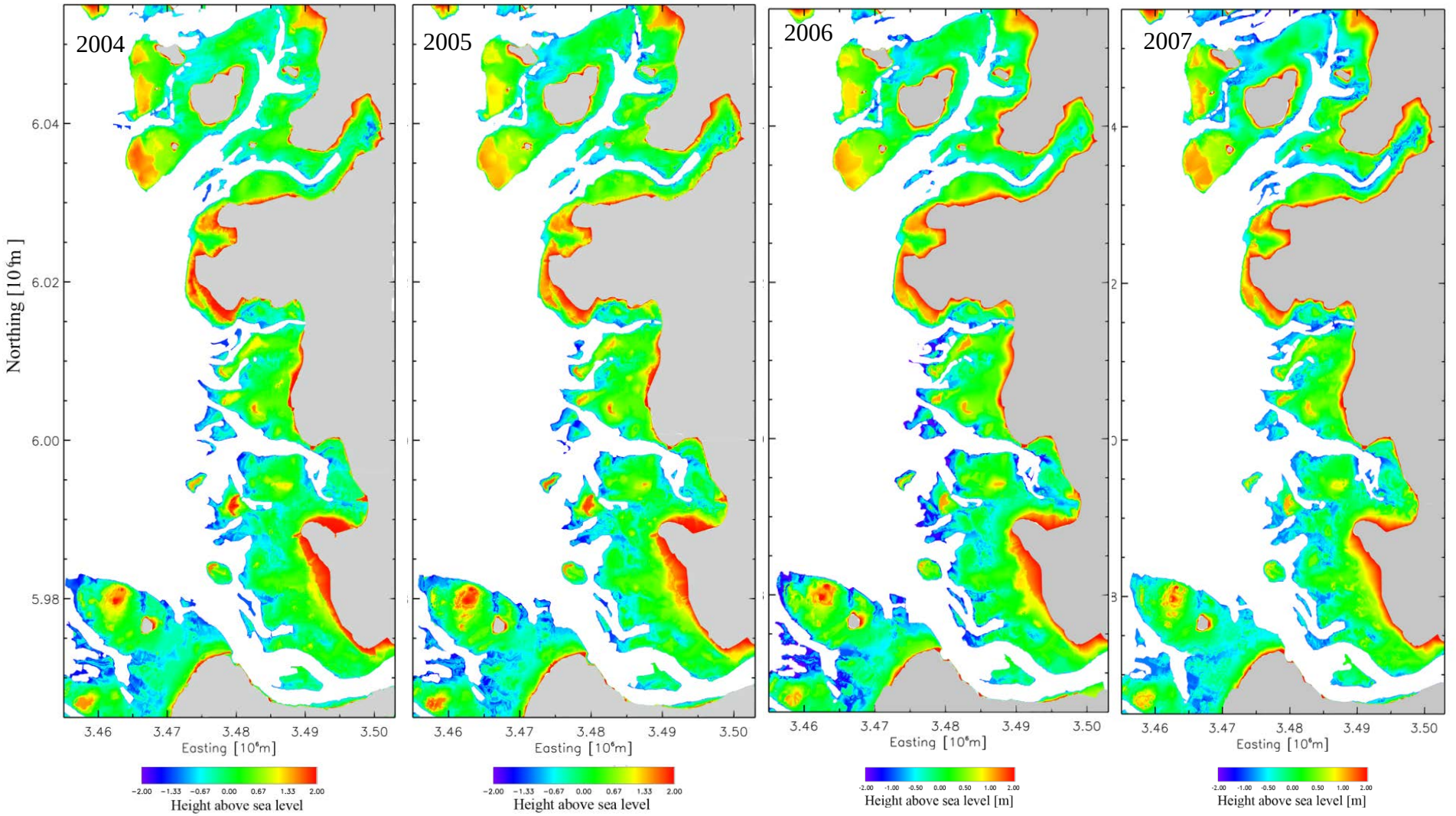


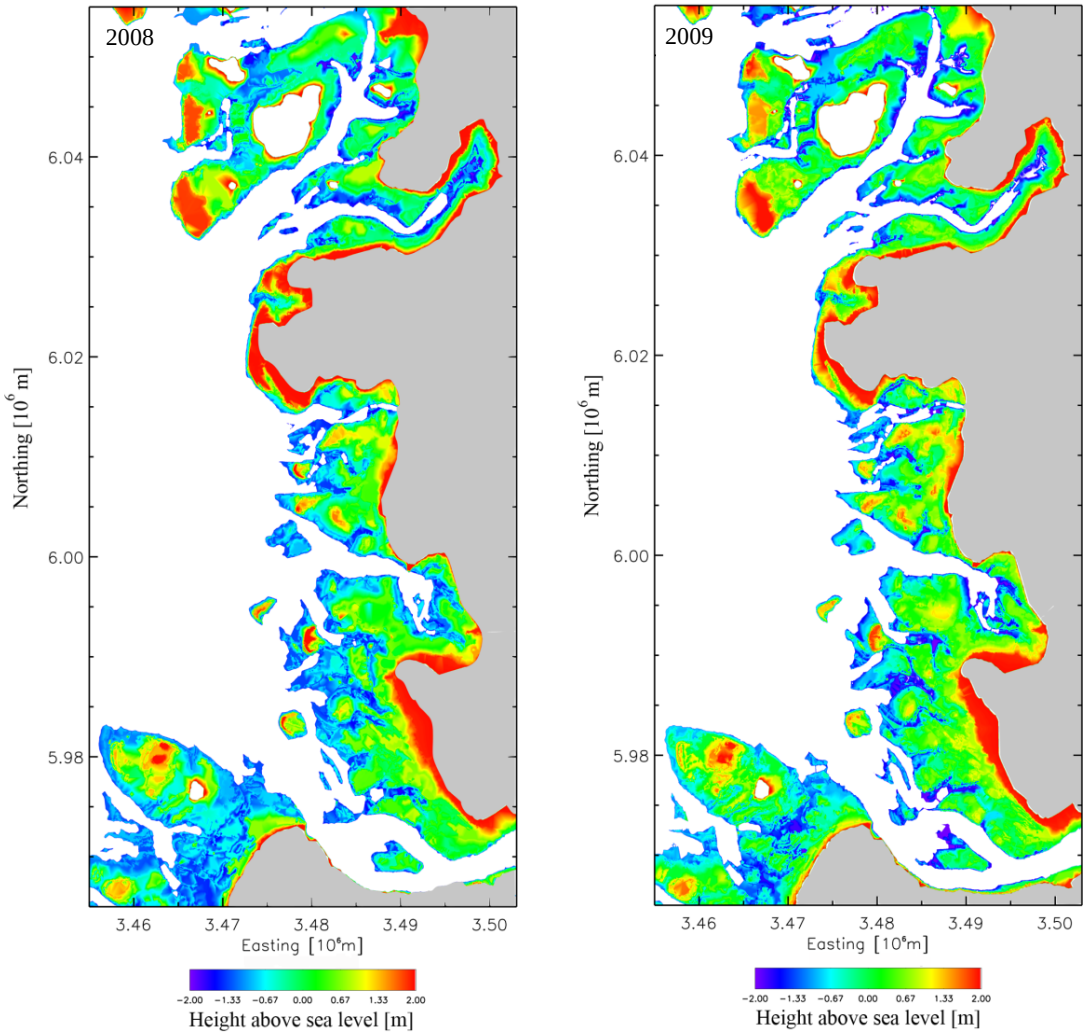
Step 4: Interpolation and map generation

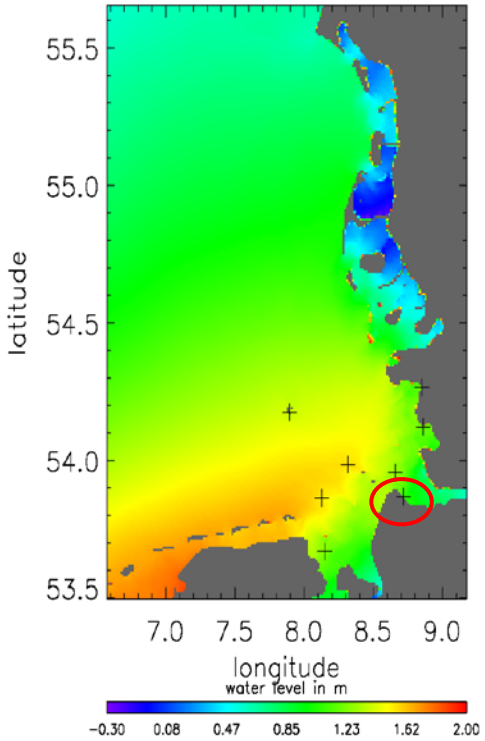
- Tool: **TASH** software
  (**T**opographisches **A**uswerte **S**ystem **H**annover, Institute für Kartographie Universitaet Hannover)

- Interpolate into 20m grid (Delaunay-Triangulation)


1996
1997
1998
1999
Nordcroogsand
Süderoogsand
Tertiussand
Trischen
Neuwerk
Gelbsand
Medemsand
Medmgrnd
Northing [10⁶m]
6.04
6.02
6.00
5.98
3.46
3.47
3.48
3.49
3.50
Easting [10⁶m]
−2.00 −1.33 −0.67 0.00 0.67 1.33 2.00
Height above see level [m]
Height above sea level [m]


2004
2005
2006
2007
Northing [10⁶m]
6.04
6.02
6.00
5.98
3.46
3.47
3.48
3.49
3.50
Easting [10⁶m]
−2.00 −1.33 −0.67 0.00 0.67 1.33 2.00
Height above sea level
Height above sea level [m]

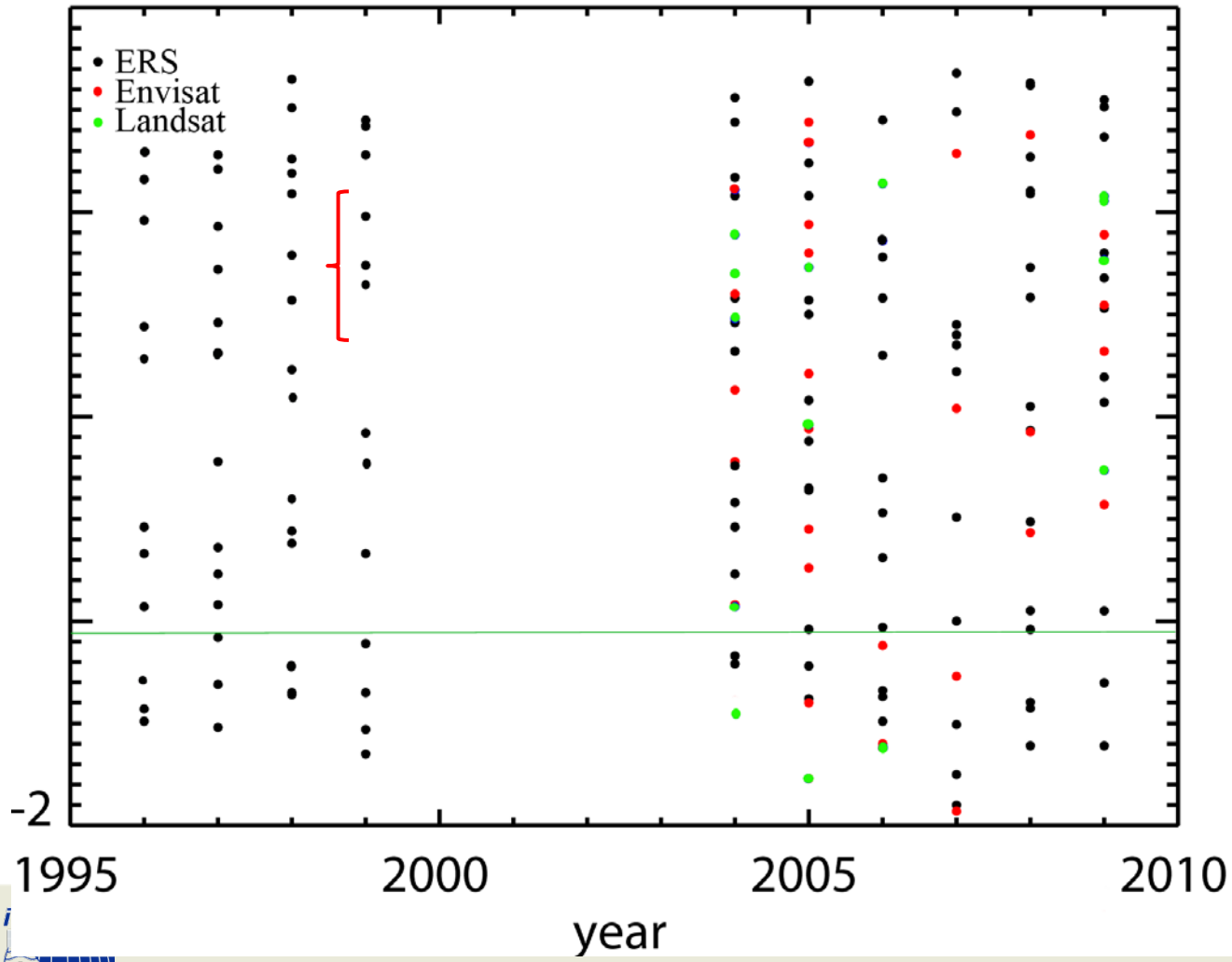

2008
2009
6.04
6.02
6.00
5.98
Northing [10^6 m]
3.46
3.47
3.48
3.49
3.50
Easting [10^6m]
−2.00 −1.33 −0.67 0.00 0.67 1.33 2.00
Height above sea level [m]



- ERS 1/2 SAR
- Envisat ASAR
- Landsat

Year group A: 1996-1999

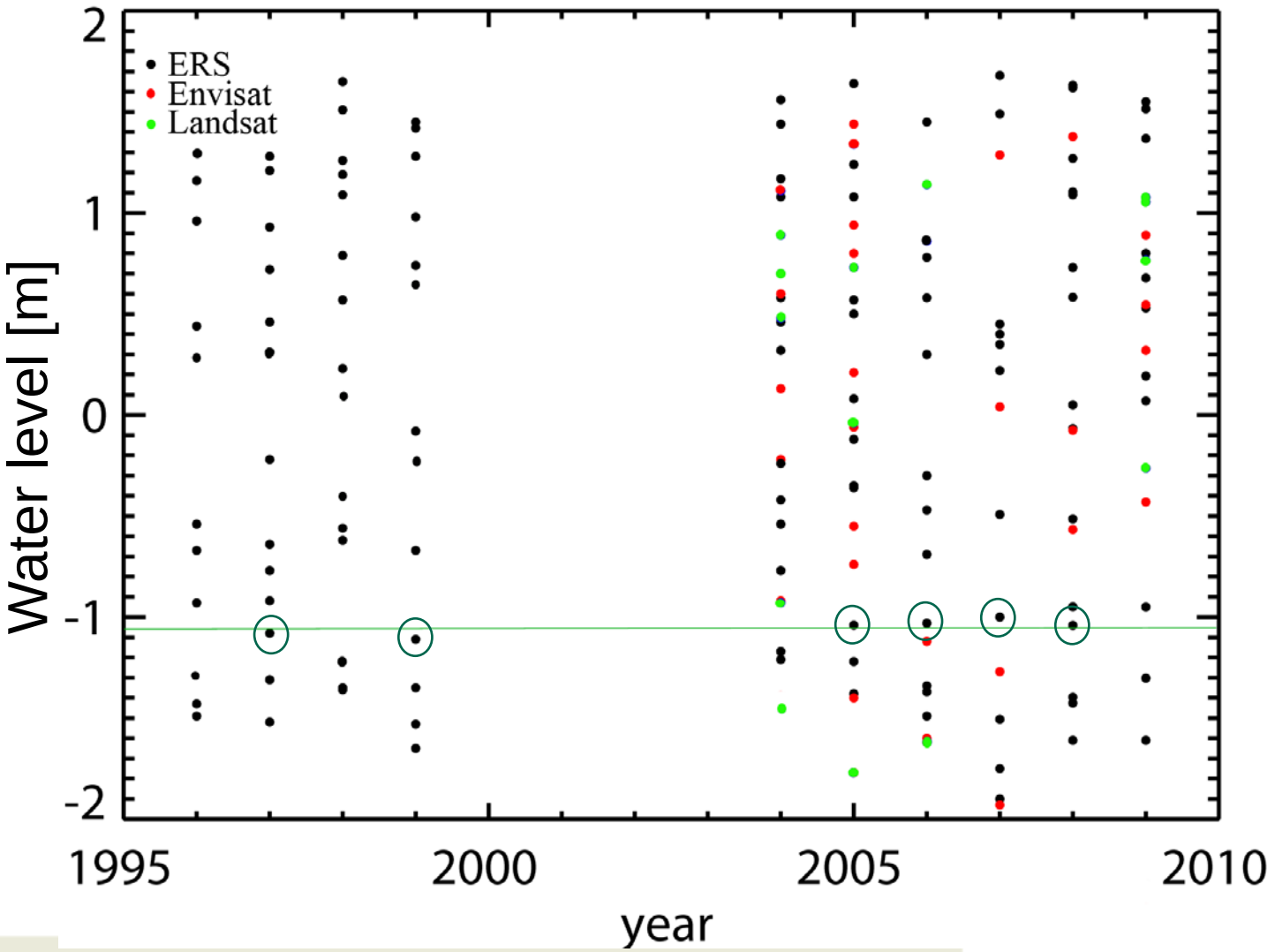
Year group B: 2004-2009

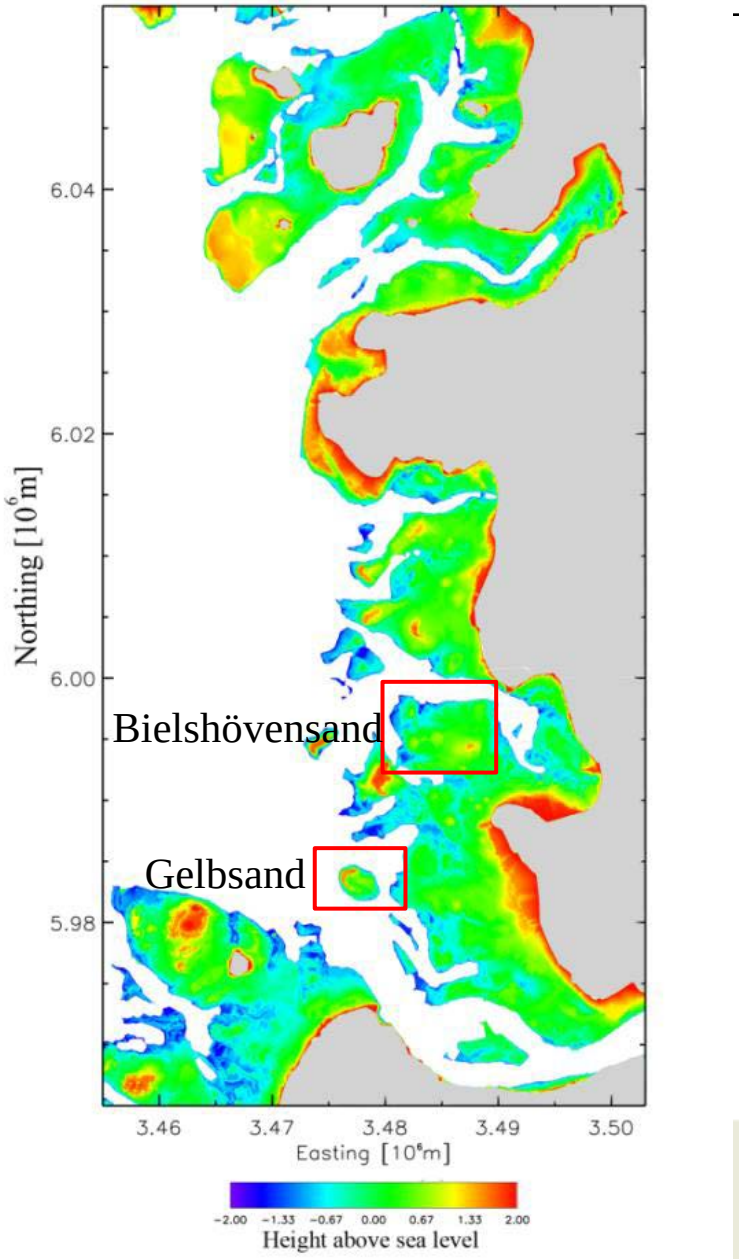


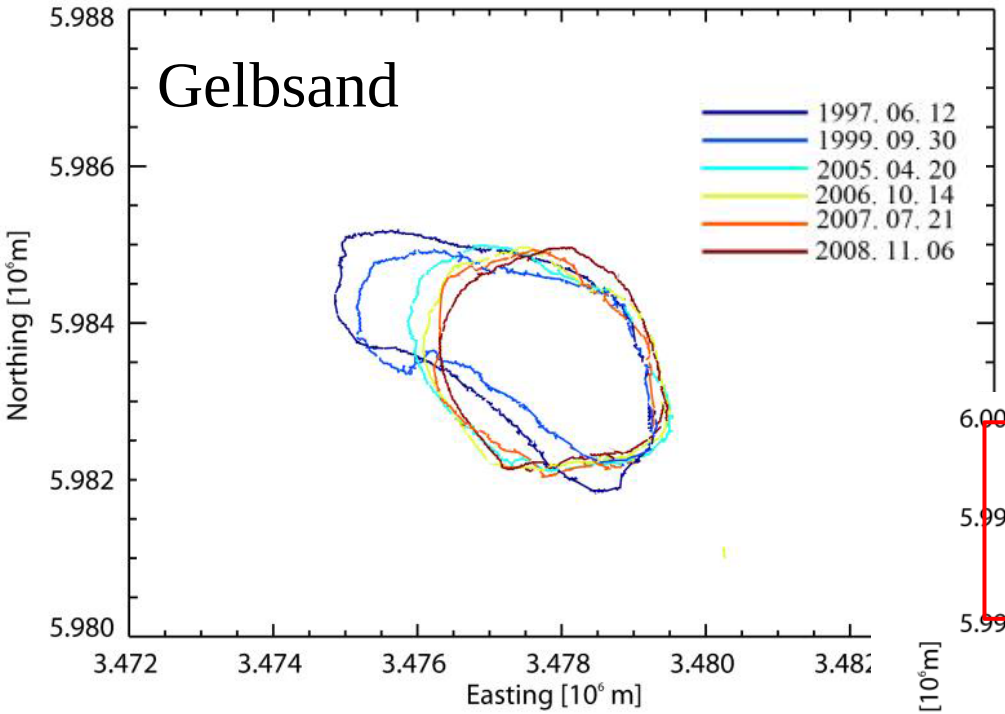
Year (group A)	Number of involved scenes	Max height difference between two scenes (m)
Average 1996-1999	13	0.67

Year （group B）	Number of involved scenes	Max height difference between two scenes (m)
Average 2004-2009	17	0.51

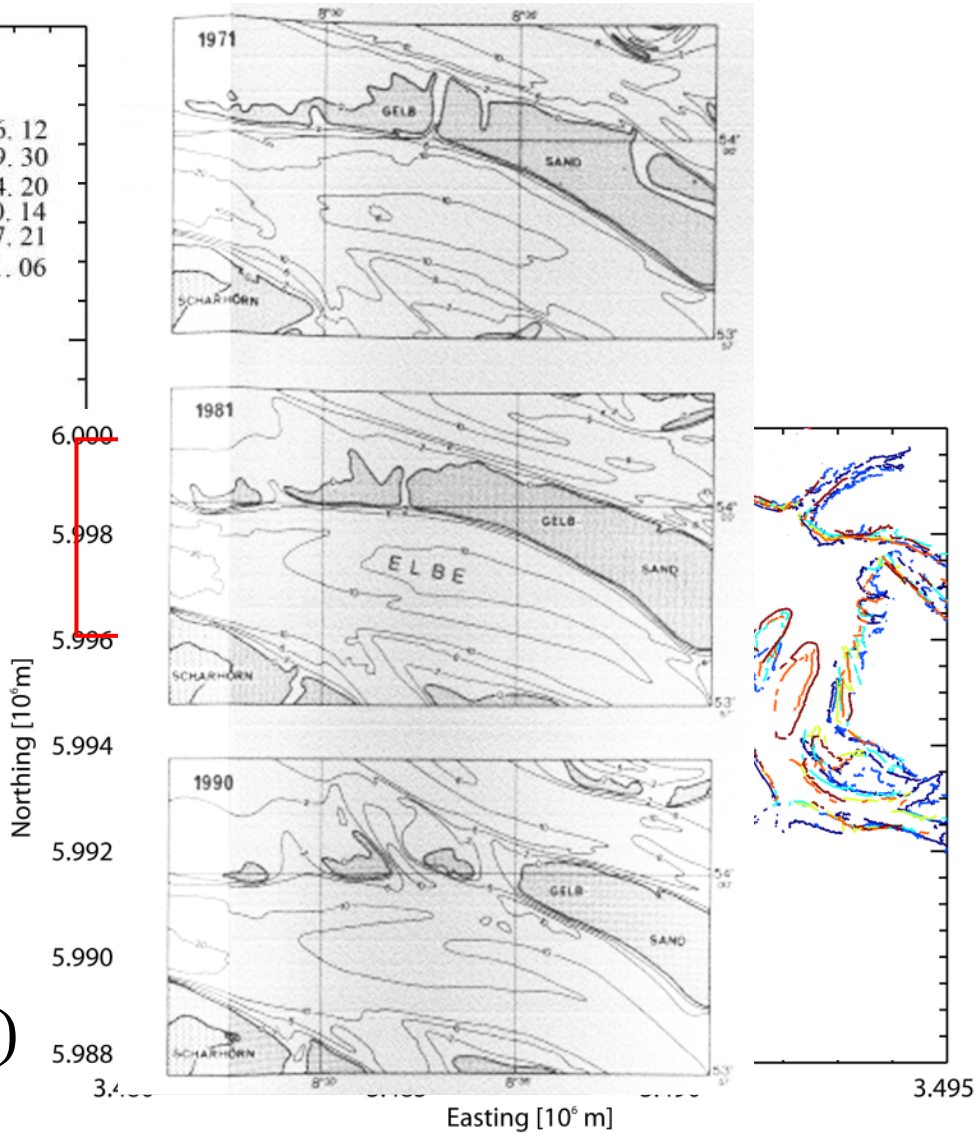
Validation


ERS
Envisat
Landsat
Water level [m]
2
1
0
-1
-2
1995
2000
2005
2010
year


6.04
6.02
6.00
5.98
Northing [10⁶m]
Bielshövensand
Gelbsand
3.46
3.47
3.48
3.49
3.50
Easting [10⁶m]
−2.00 −1.33 −0.67 0.00 0.67 1.33 2.00
Height above sea level



Bielshövensand

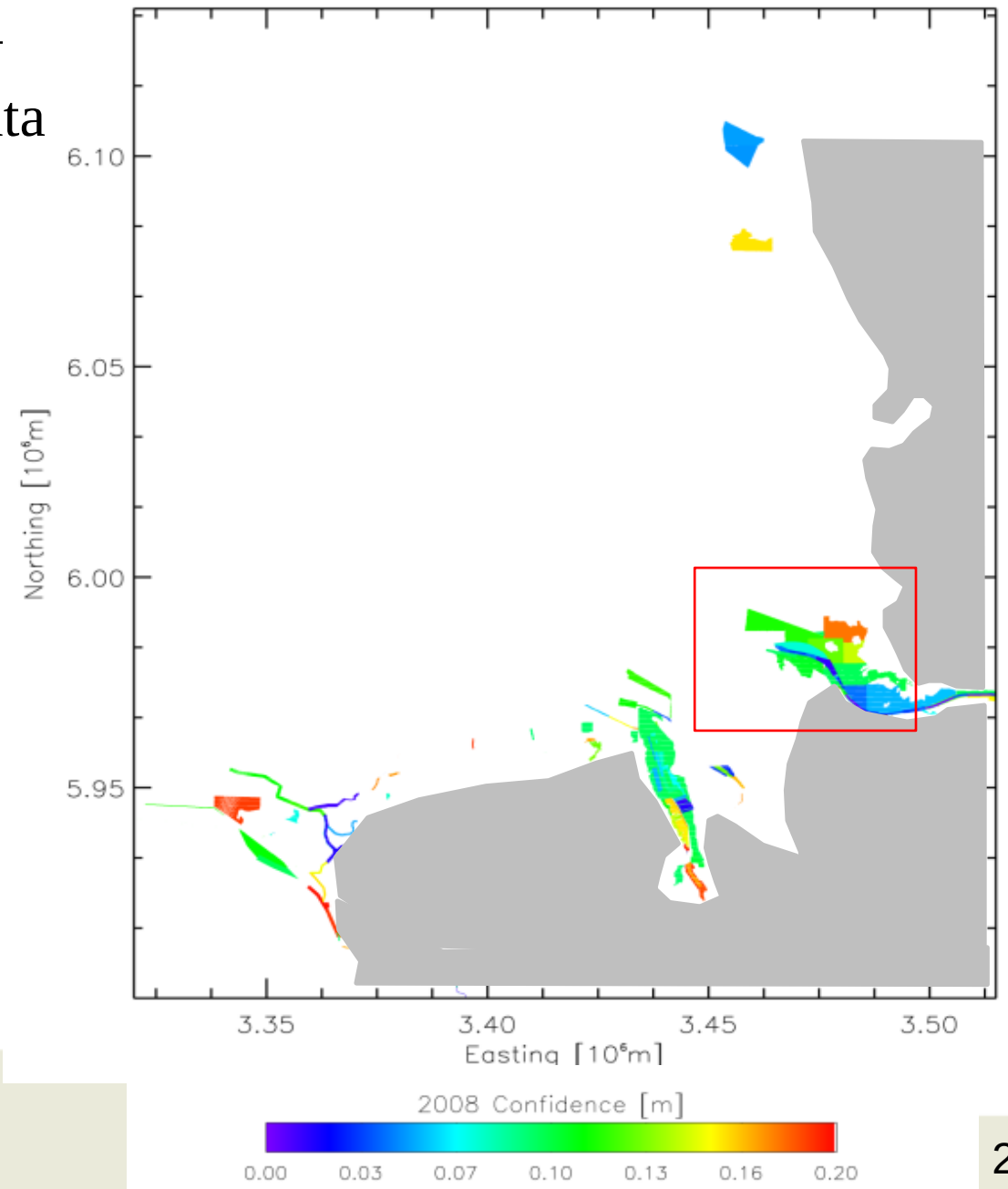


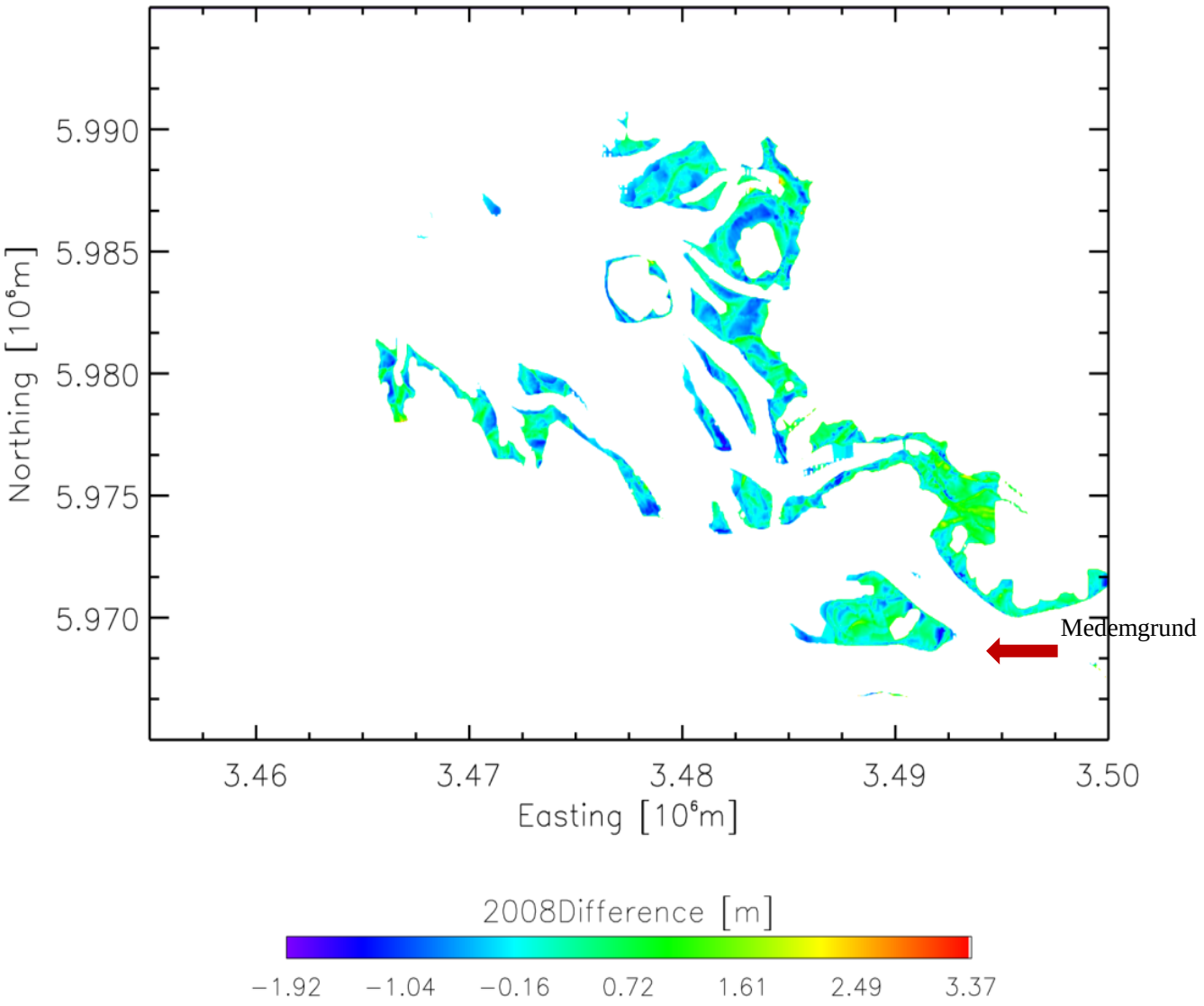
Ricklefs and Neto (2005)

Ulrich, 1991

Validation by bathymetric data (AufMod, BSH)

Confidence Parameter
((0-0.12m))




5.990
5.985
5.980
5.975
5.970
Northing [10⁶m]
3.46
3.47
3.48
3.49
3.50
Easting [10⁶m]
Medemgrund
2008Difference [m]
−1.92
−1.04
−0.16
0.72
1.61
2.49
3.37

Validation Results

Year（group B）	The averaged difference (m)	Standard deviation (m)
2004	0.020	0.15
2005	0.119	0.34
2006	0.013	0.13
2007	0.061	0.27
2008	0.006	0.14
2009	0.011	0.13
average	**0.04**	**0.19**

Morphodynamic study of the Wadden Sea

- Based on field data:

  Ehlers, 1988; Aps, 2004; Alberts and von Lieberman, 2010; Winter, 2011; van Dijk et al., 2012; Vonhögen et al., 2013;

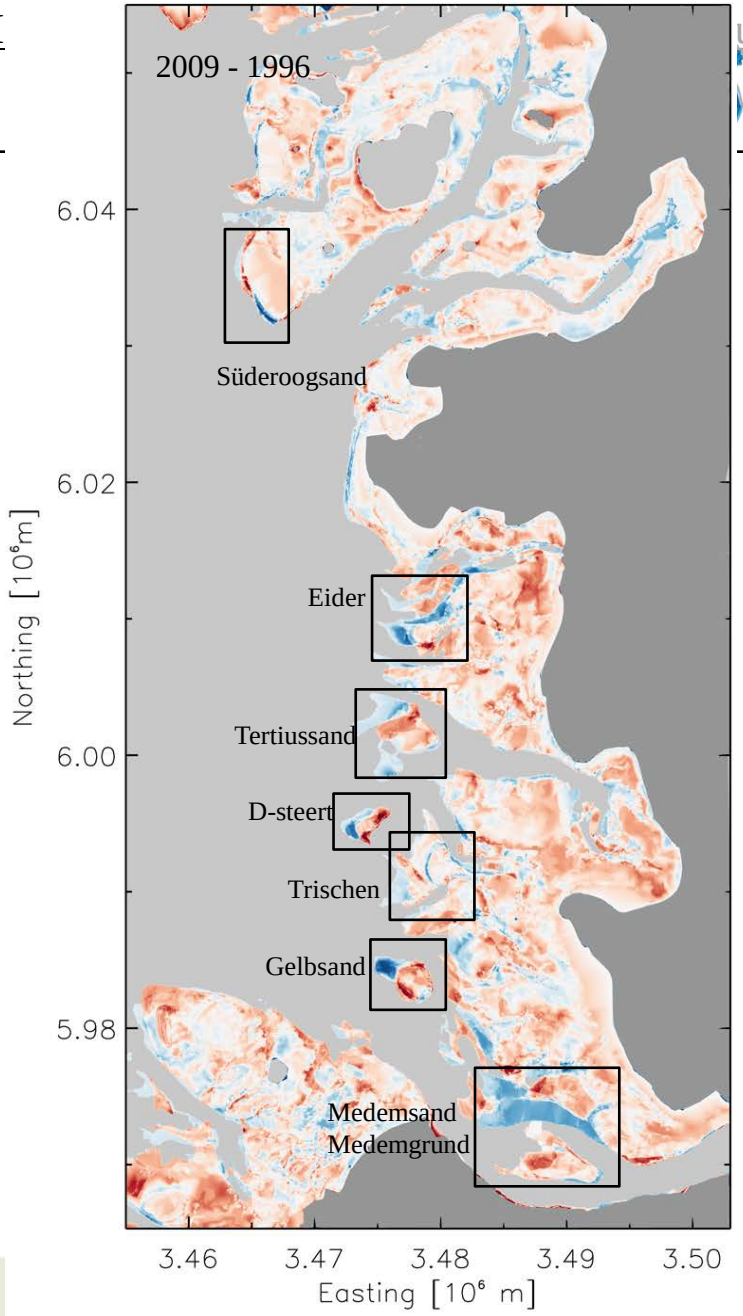
- Based on model data:

  Flemming and Bartholomä, 1997; van der Molen, 2002; Winter, 2006; Chu et al., 2013;

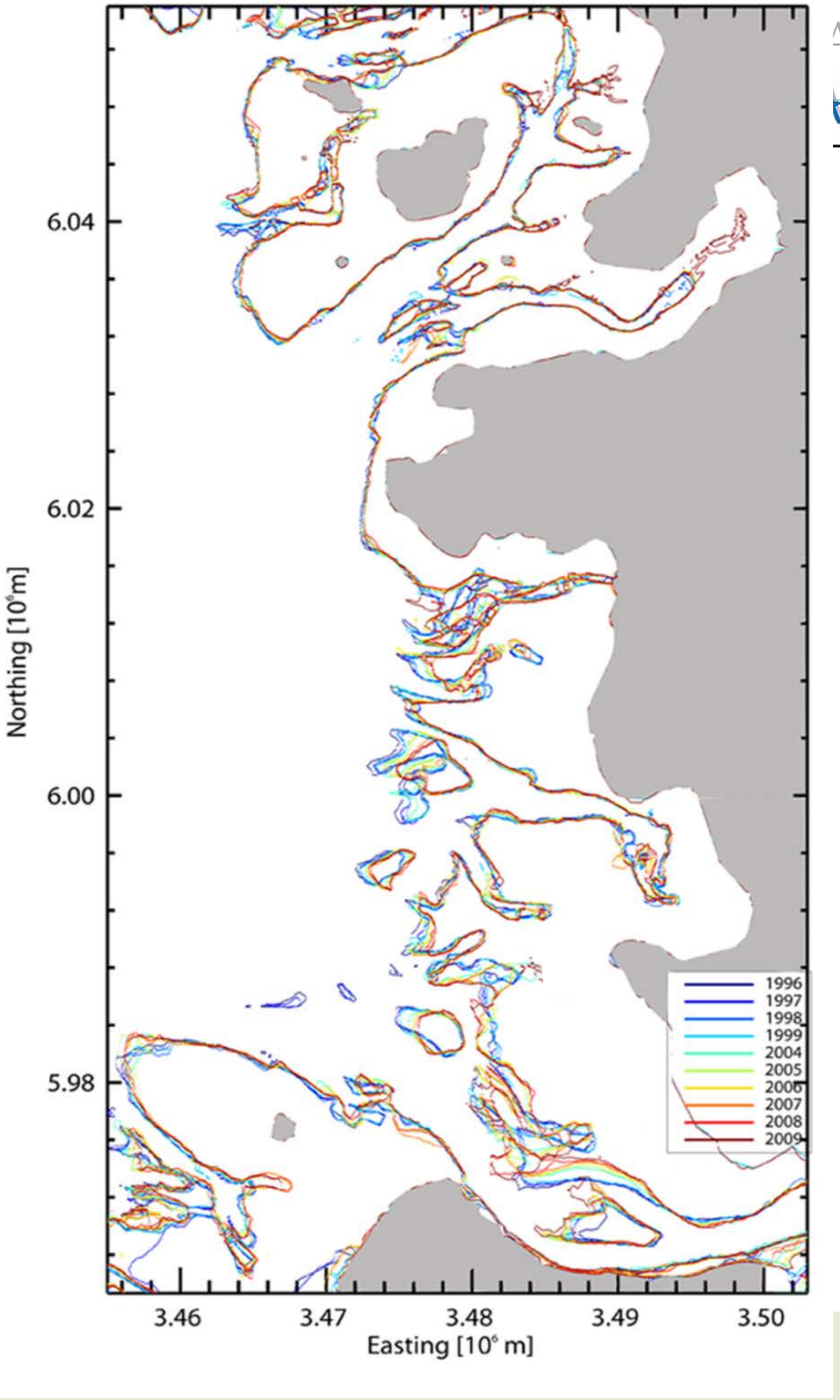
- Based on remote sensing data:

  Wang, 1995; Zeug, 2000; Niedermeier et al., 2005; Recklefs et al., 2005; Brzank et al., 2008; Heygster et al., 2010; Li et al., 2014;

Topographic difference map between 2009 and 1996



-2 m isobaths


6.04
6.02
6.00
5.98
Northing [10⁶m]
3.46
3.47
3.48
3.49
3.50
Easting [10⁶ m]
1996
1997
1998
1999
2004
2005
2006
2007
2008
2009

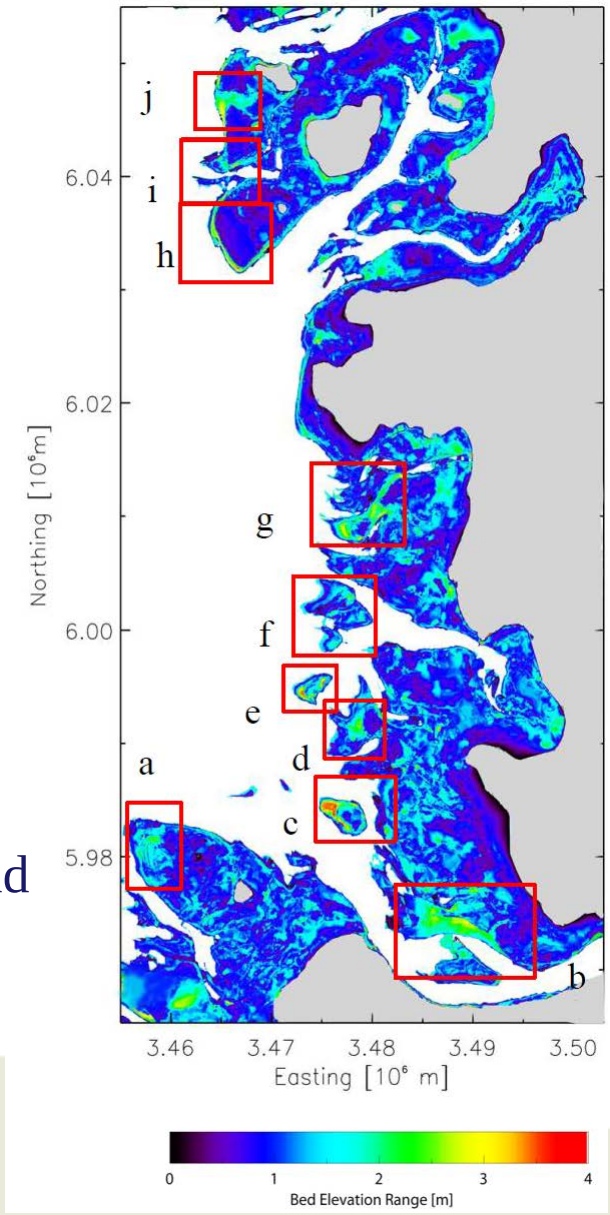
Bed Elevation Range / Vertikaler morphologischer Raum

- Is the difference between the maximum and the minimum of the bed elevation within the observation time frame.

- $BER_{ij} = Max(z_{ij}(t)) - Min(z_{ij}(t))$

BER captures regions of intensive morphological activities and stable ones

BER > 2m:
j Noderoogsand
i Süderoogsand
h Hever
g Eider
f Tertiussand
e D-Steert
d Trischen
c Gelbsand
b Medemgrund/-sand
a Scharhörn



Vertical nodal linear regression / linearer vertikaler Trend

- Is defined as the slope of the linear regression of all the bed elevation in the stacked time series (1996 to 1999, and 2004 to 2009) at each grid node.
- Quantifies the speed and the trend of the morphology evolution.
- Here is the first time to analyze the vertical trend in the German Wadden Sea at 90 km scale.

Vertical linear regression rate

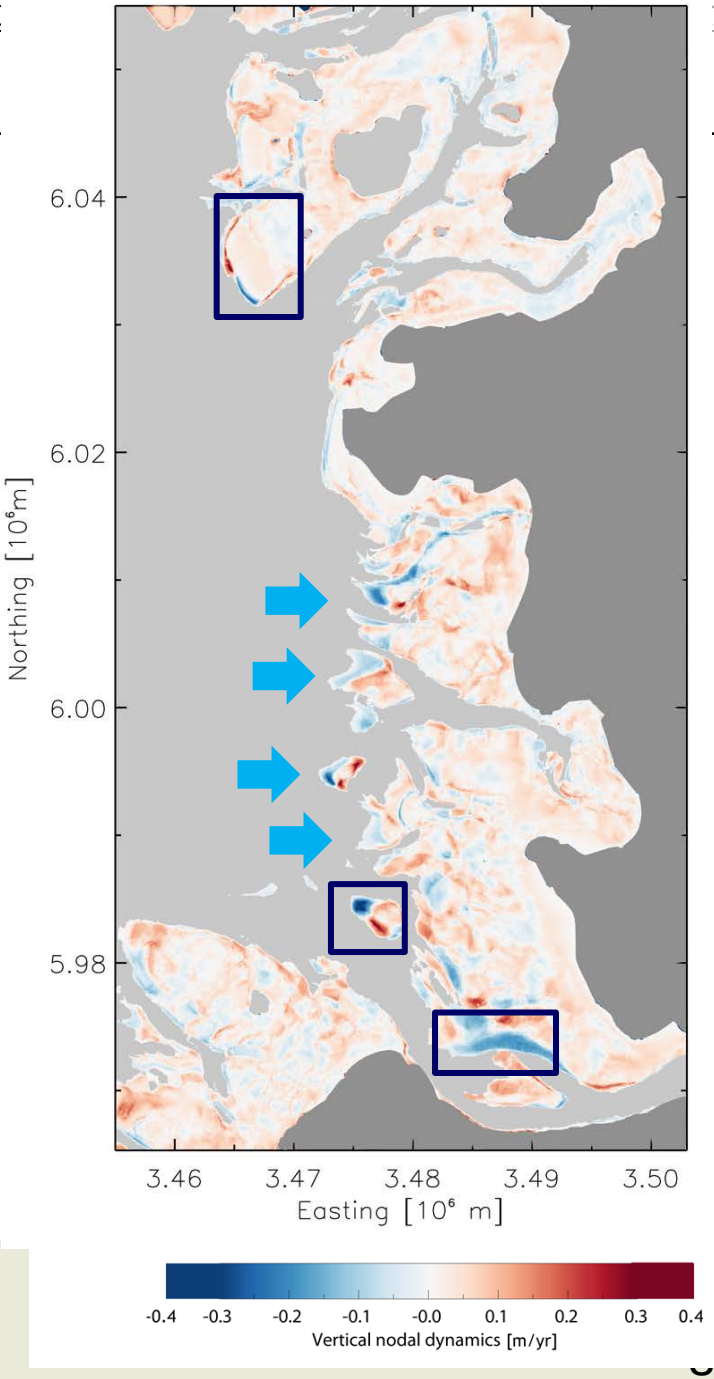
- Typical rate is -0.1 to 0.1 m/yr;
- Erosion occurs at the west side of the tidal flat;
- Süderoogsand,

  northern part sedimentation,

  southern part erosion;
- Medemsand, 0.2 m/yr toward the north;
- Gelbsand exhibits highest rate,

  erosion over -0.3 m/yr;

  sedimentation up to 0.36 m/yr.

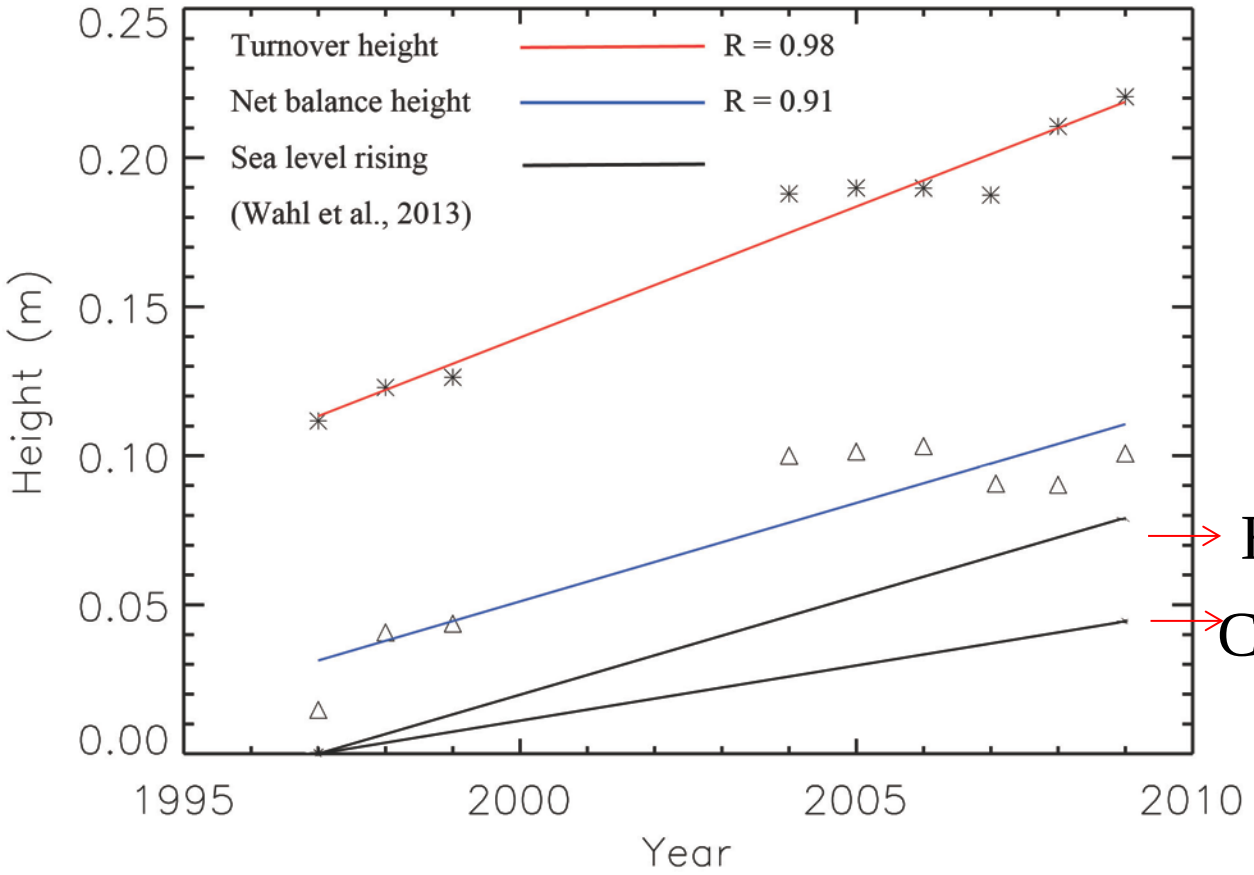


Turnover height / Mittlere absolute Höhenänderung

- Indicate morphological acitivity

Net balance height / mittlere Höhenänderung mit Vorzeichen

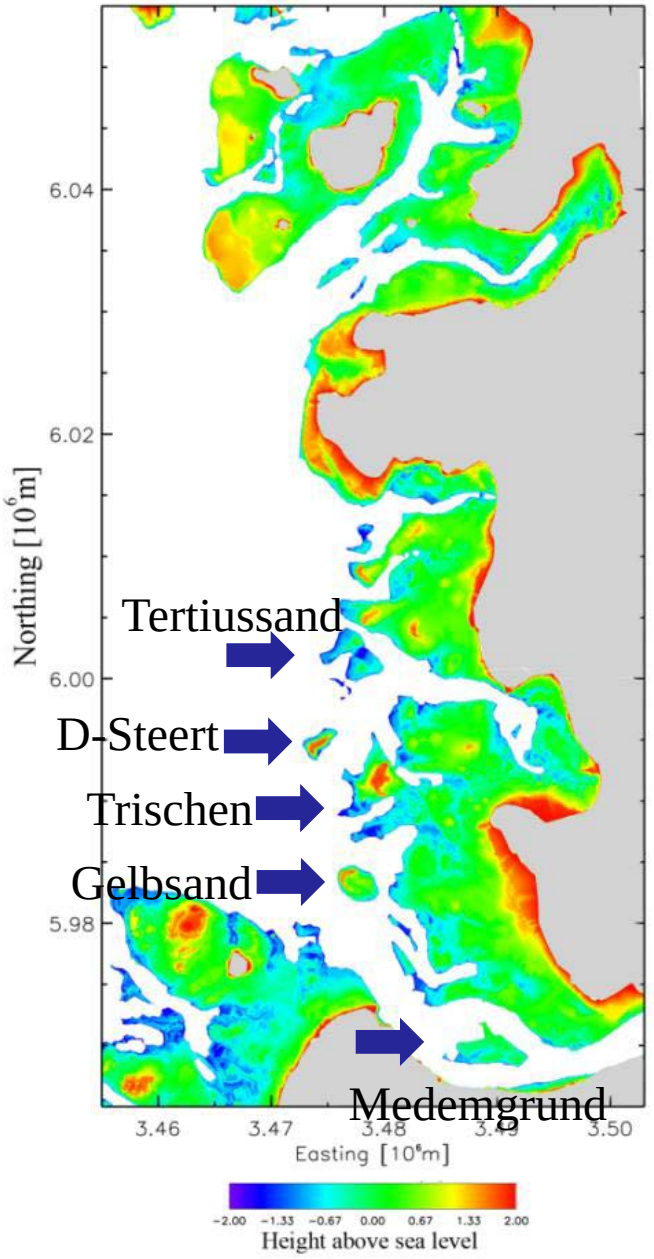
- The net balance height is the mean of topographical height change (negative: erosion; positive: sedimentation)

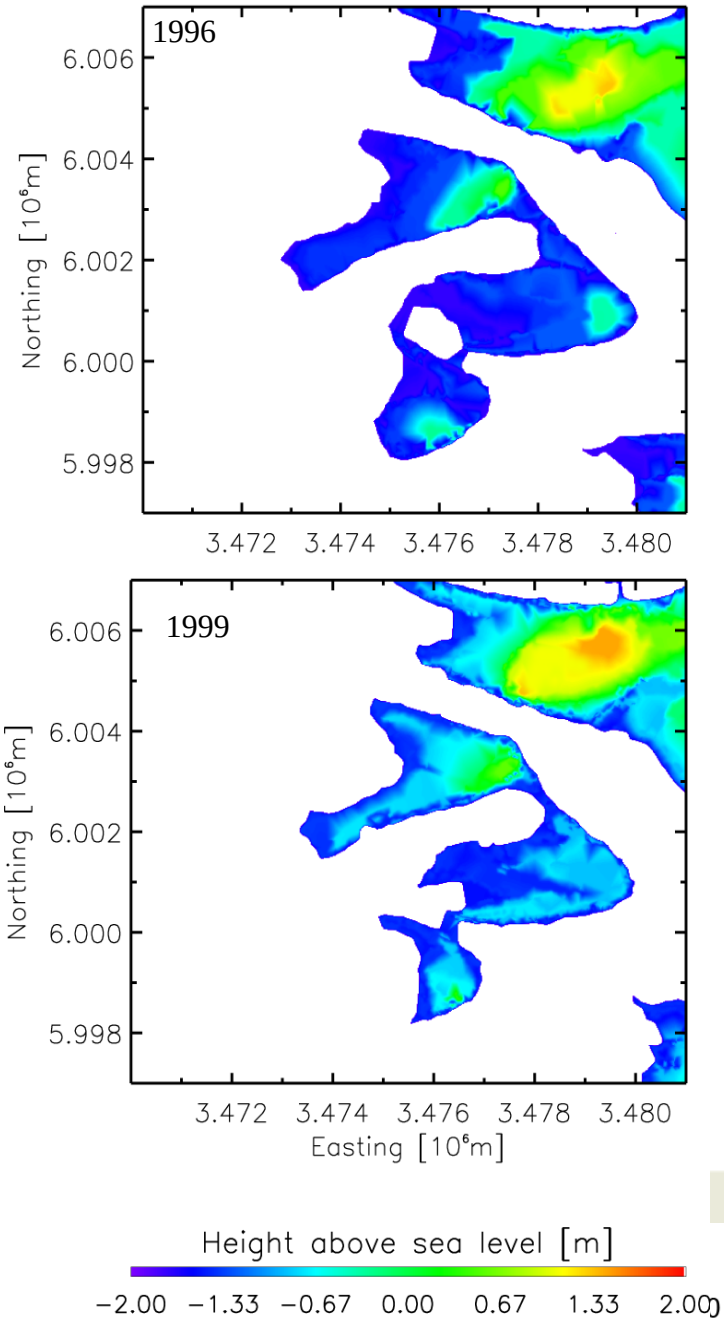


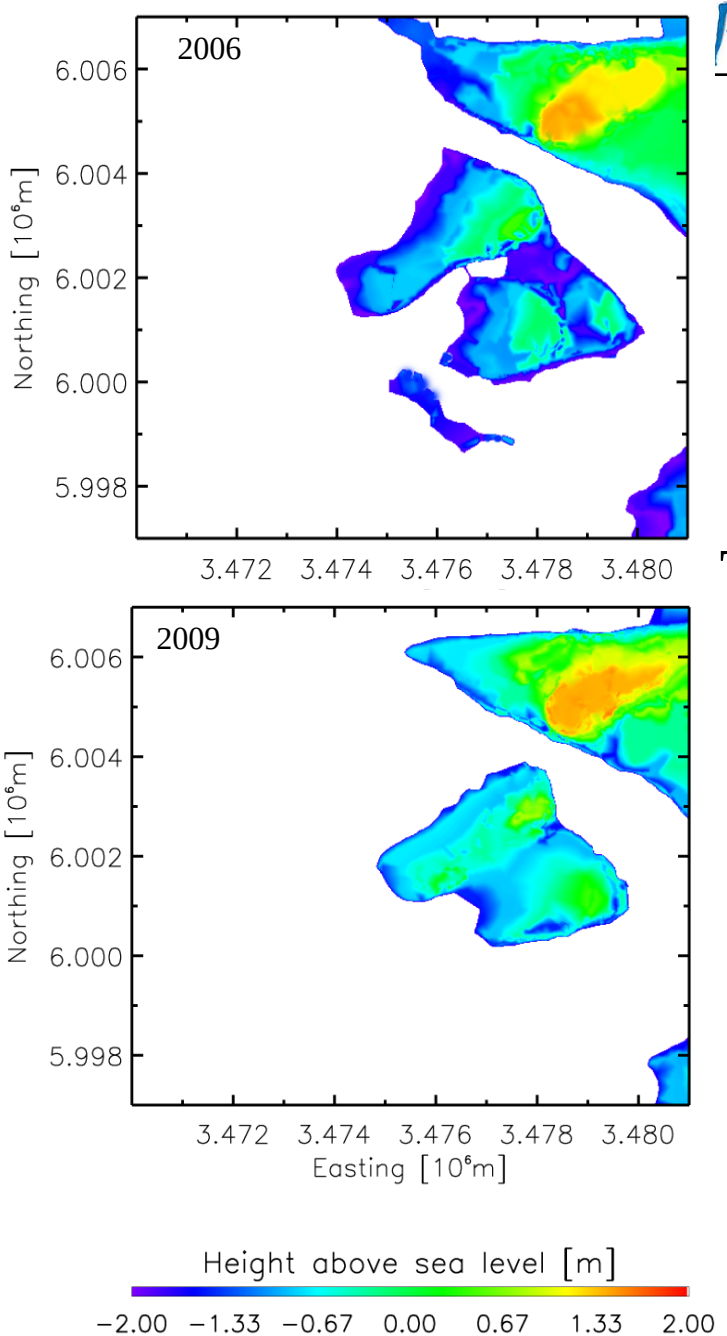
Turnover height, 8.2±0.7 mm/y
Net balance height, 6.8±1.2 mm/yr
Sea level rising, 3.7±3.5 mm/yr, Cuxhaven
6.6±3.2 mm/yr, Hörnum from 1993 to 2011
(Wahl et al., 2013)

Sandbars

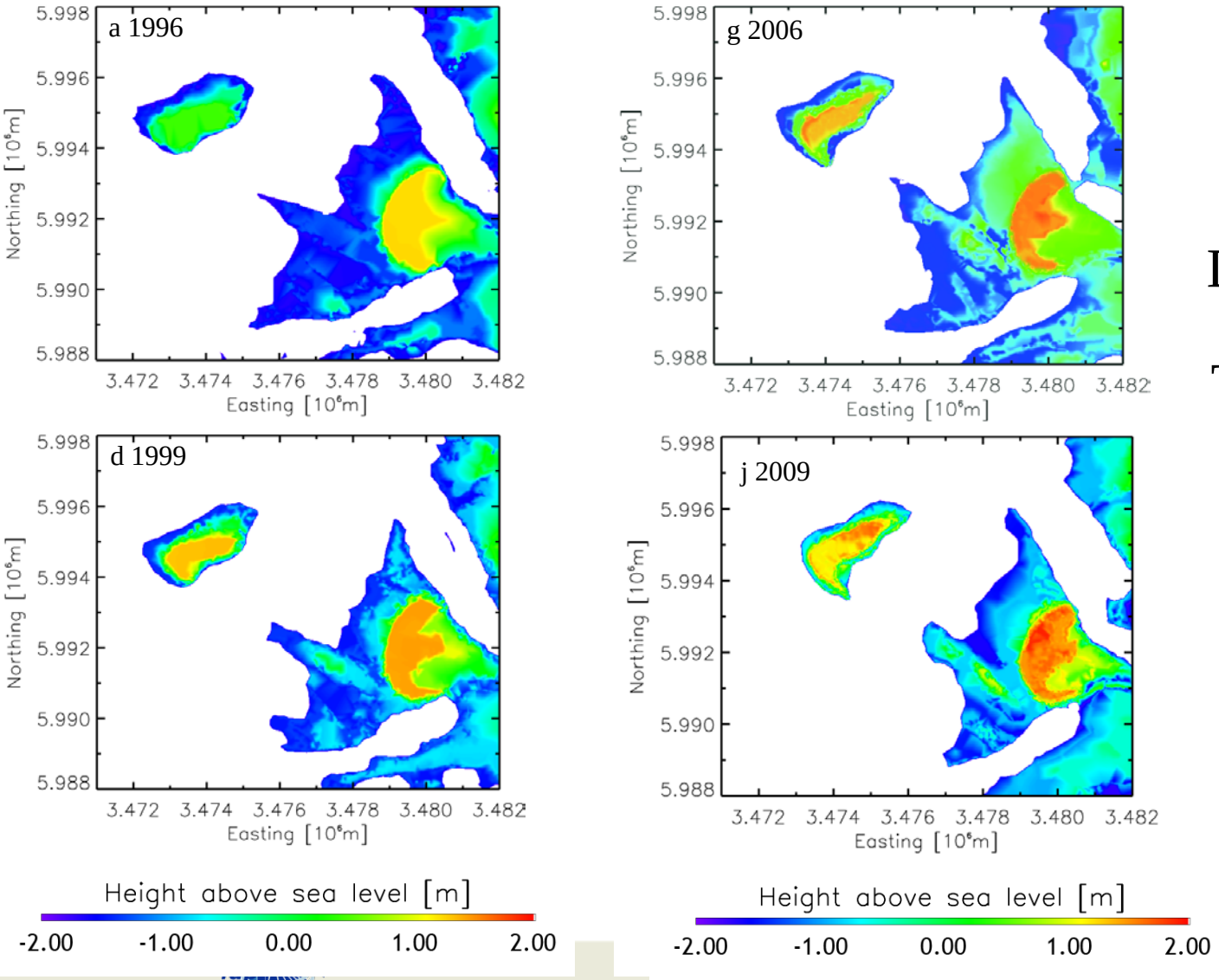
- development strongly influenced by sediment transport, tide, waves, wind, extreme events, human intervention, and the interaction with other tidal flat areas.





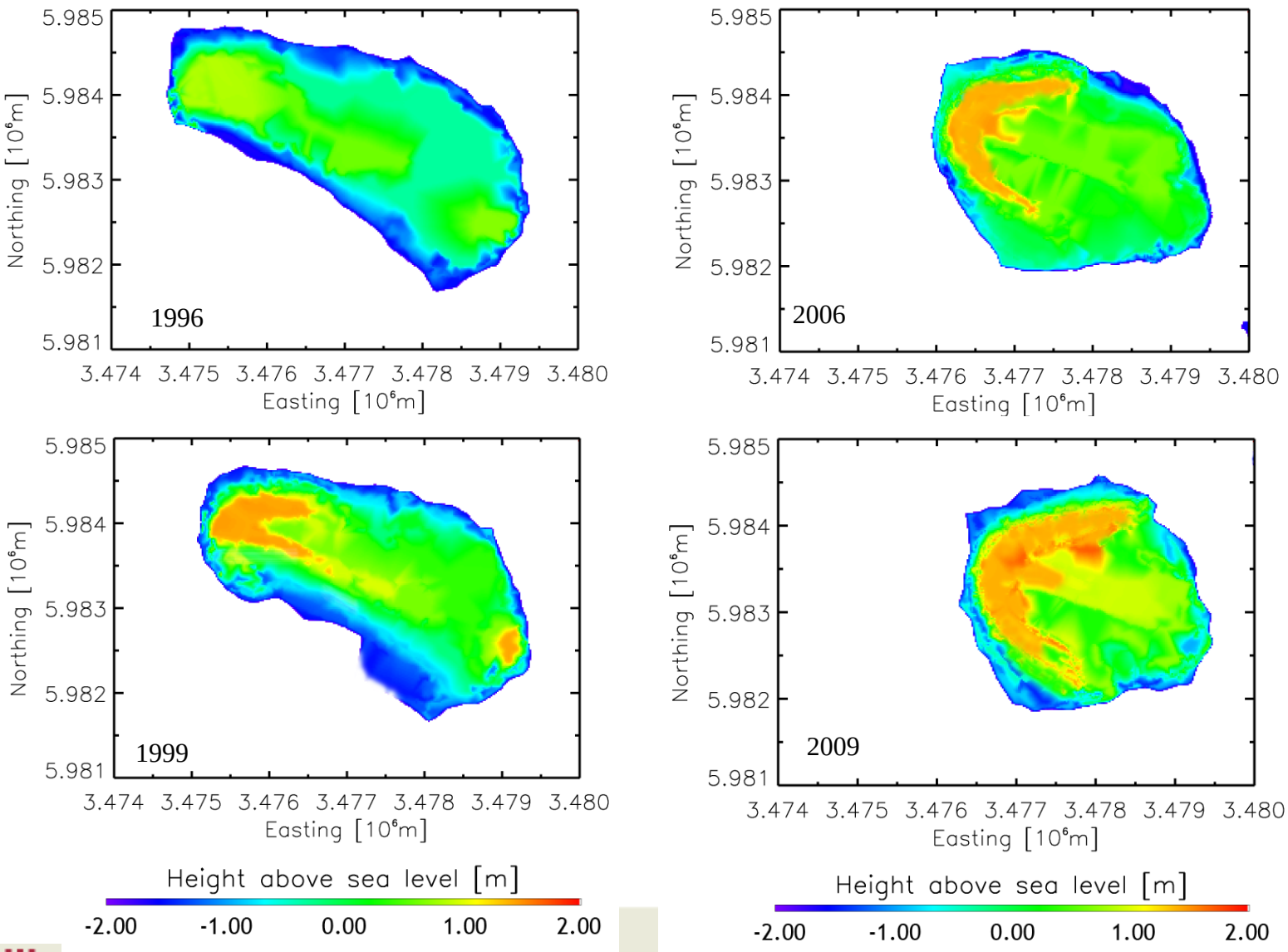


Tertiussand

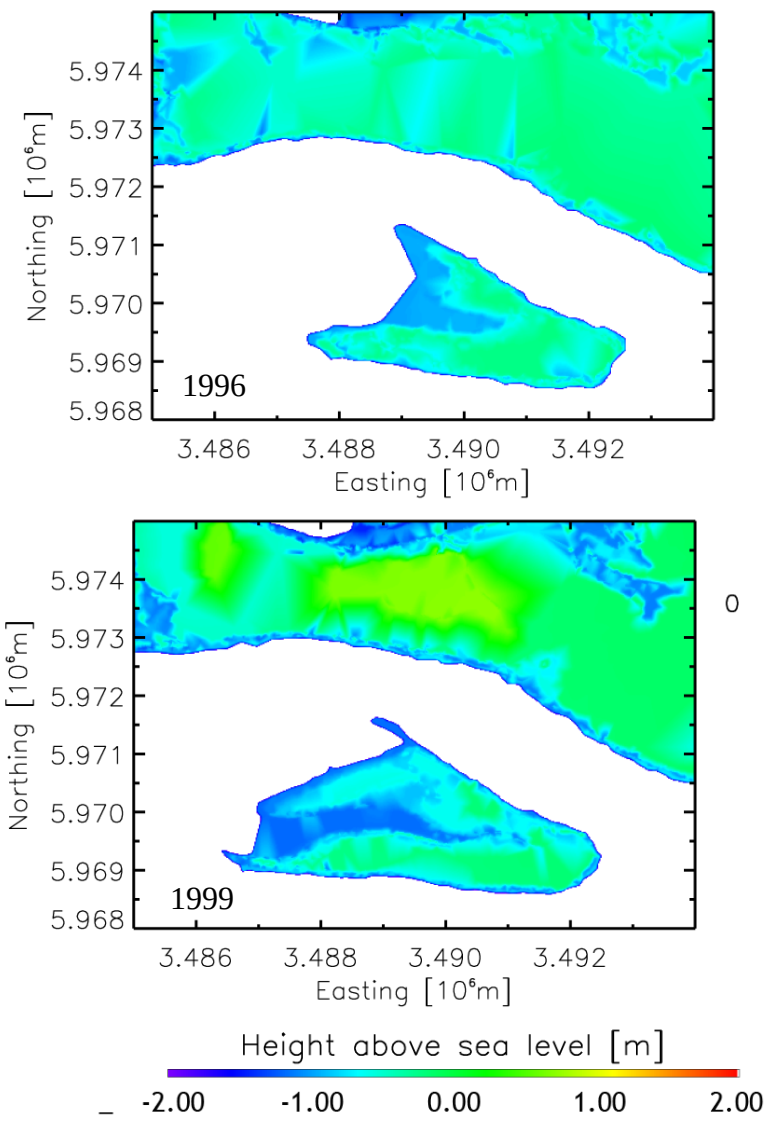


D-Steert

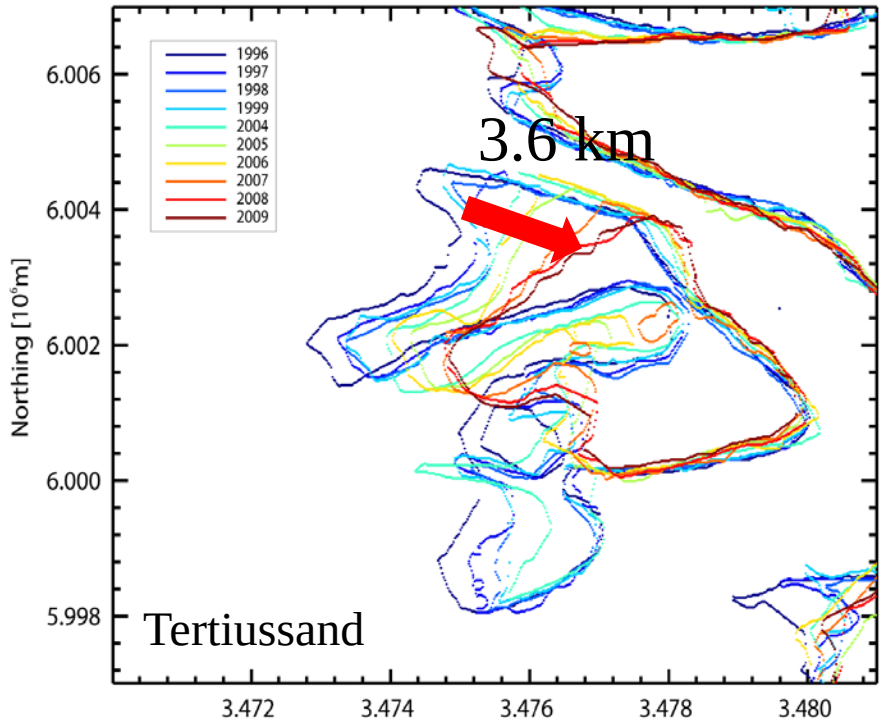
Trischen

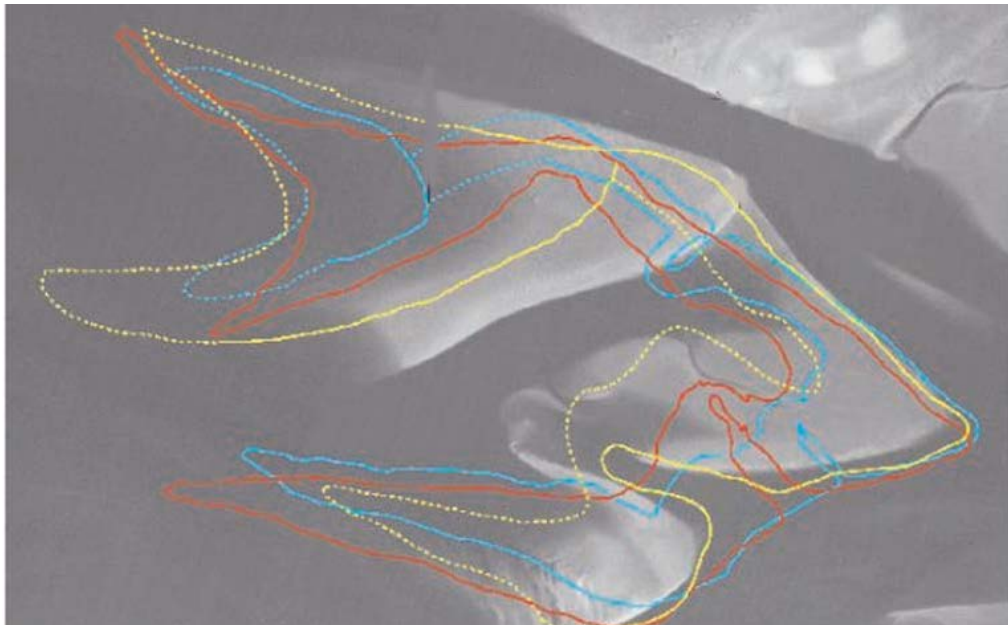

5.985
5.984
5.983
5.982
5.981
Northing [10⁶m]
1996
2006
1999
2009
3.474 3.475 3.476 3.477 3.478 3.479 3.480
Easting [10⁶m]
Height above sea level [m]
-2.00 -1.00 0.00 1.00 2.00

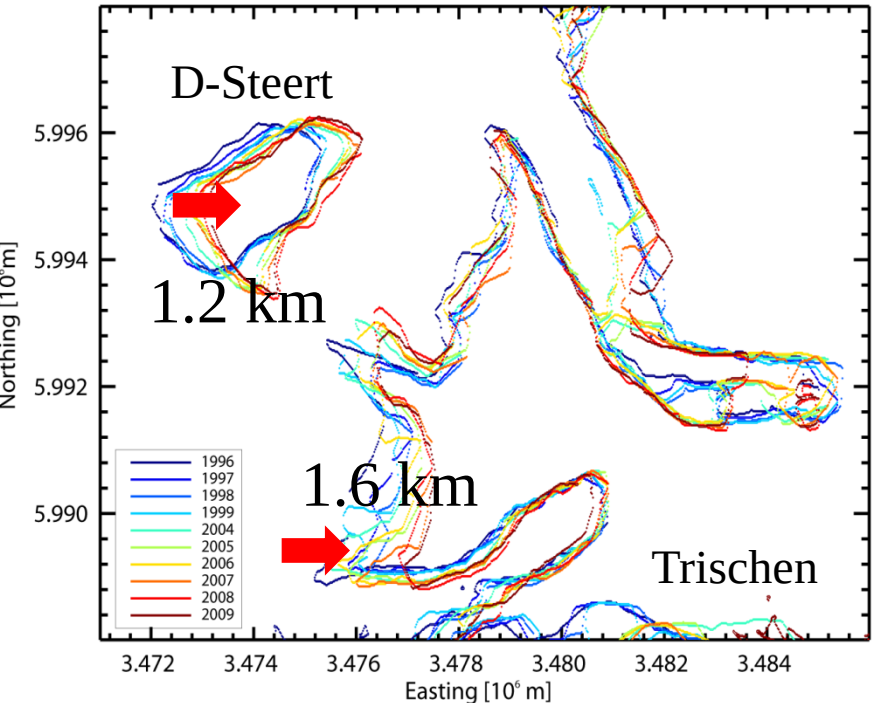
Gelbsand

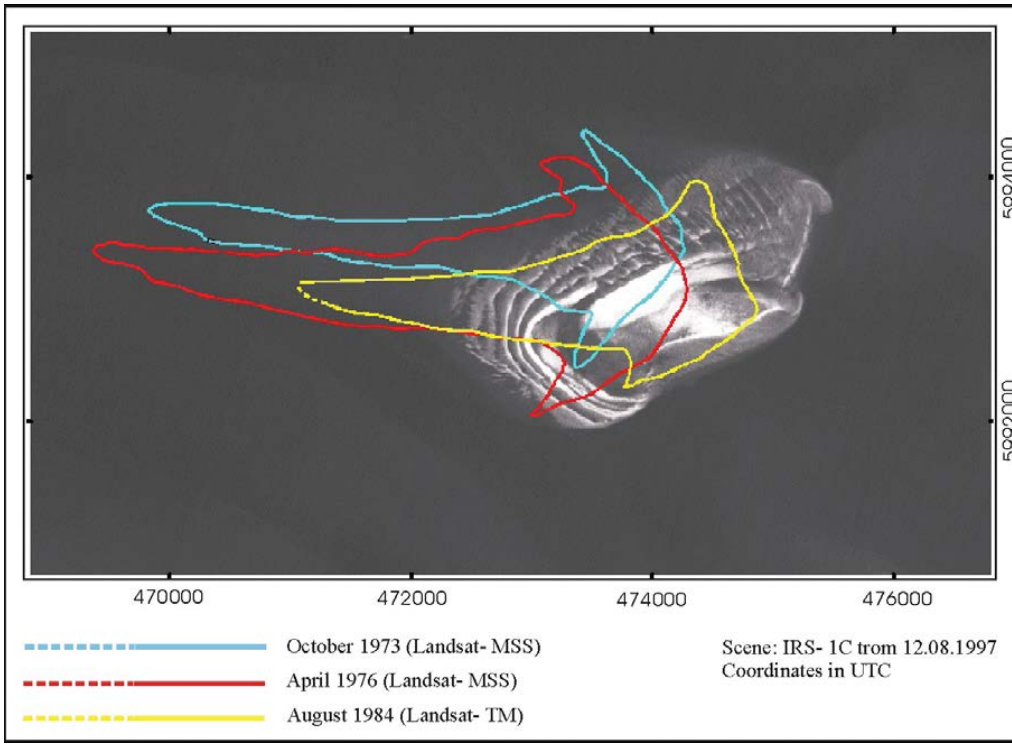

1996
1999
2006
2009
Northing [10⁶m]
Easting [10⁶m]
5.974
5.973
5.972
5.971
5.970
5.969
5.968
3.486
3.488
3.490
3.492
Height above sea level [m]
-2.00
-1.00
0.00
1.00
2.00

Medemgrund

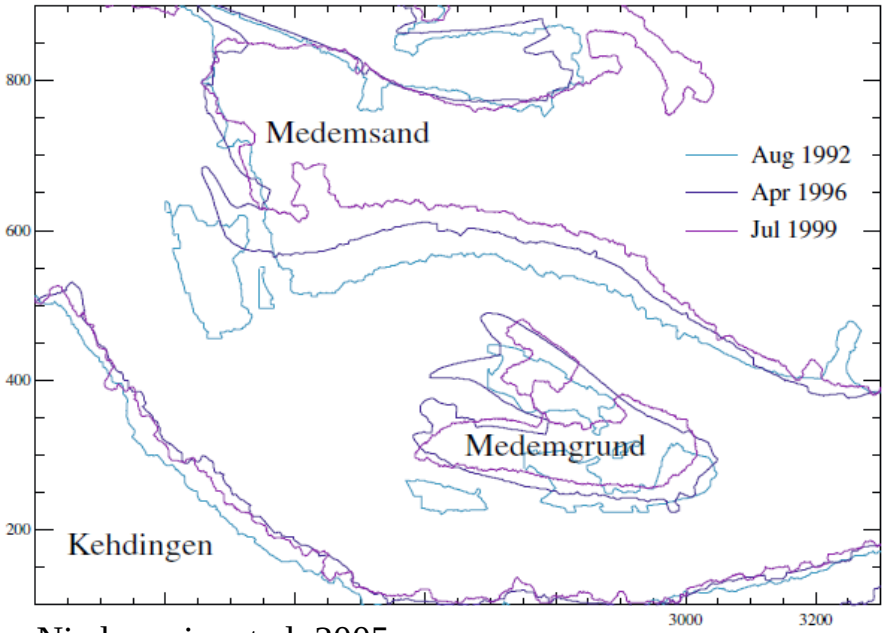




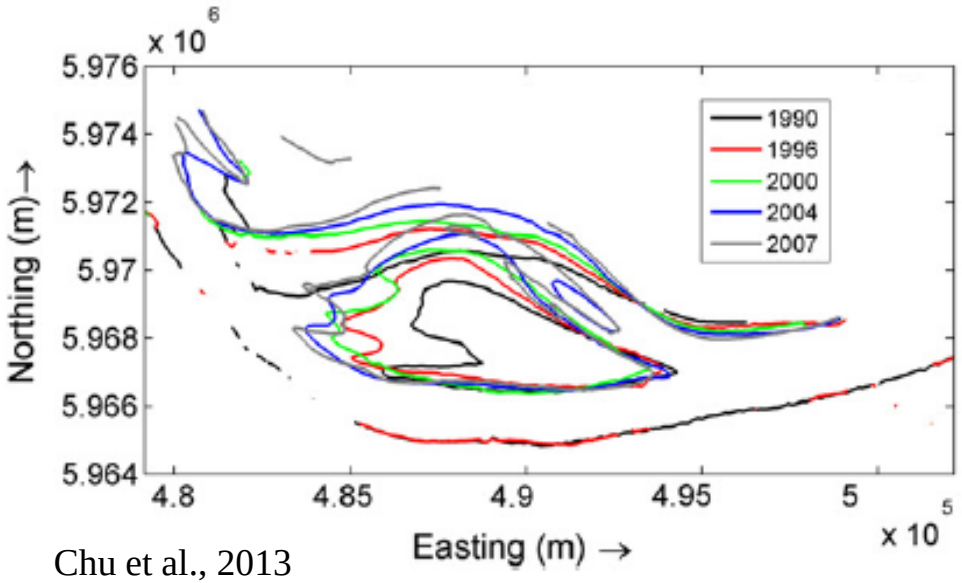




Ricklefs et al, 2005



Niedermeier et al. 2005



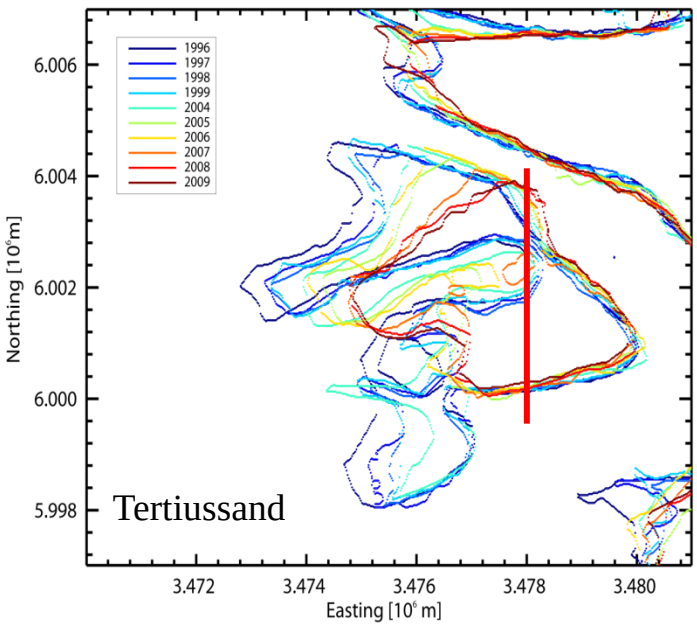
Chu et al., 2013

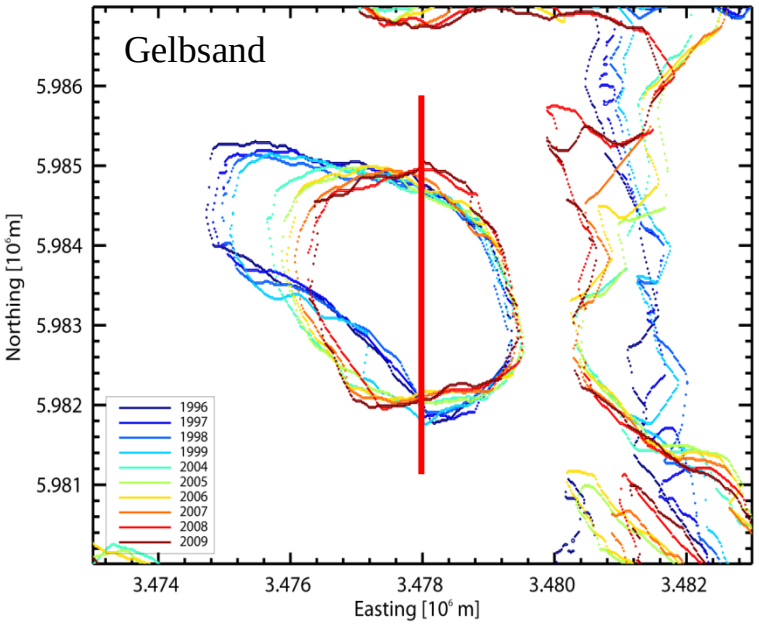
1990 1995 2000 2005 2010

0.85 km, 0.12 km/yr — Niedermeier et al., 2005

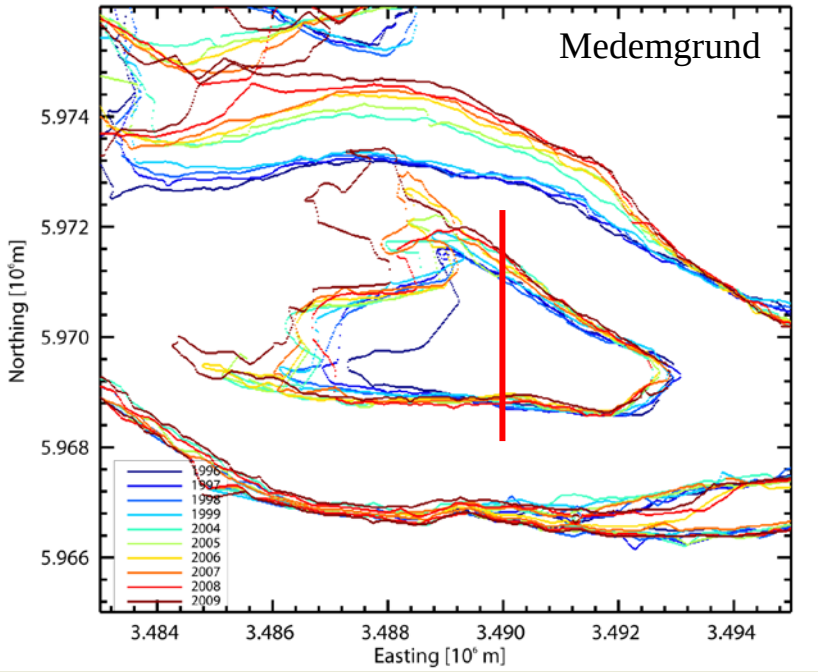
1.7 km, 0.24 km/yr — Chu et al., 2013

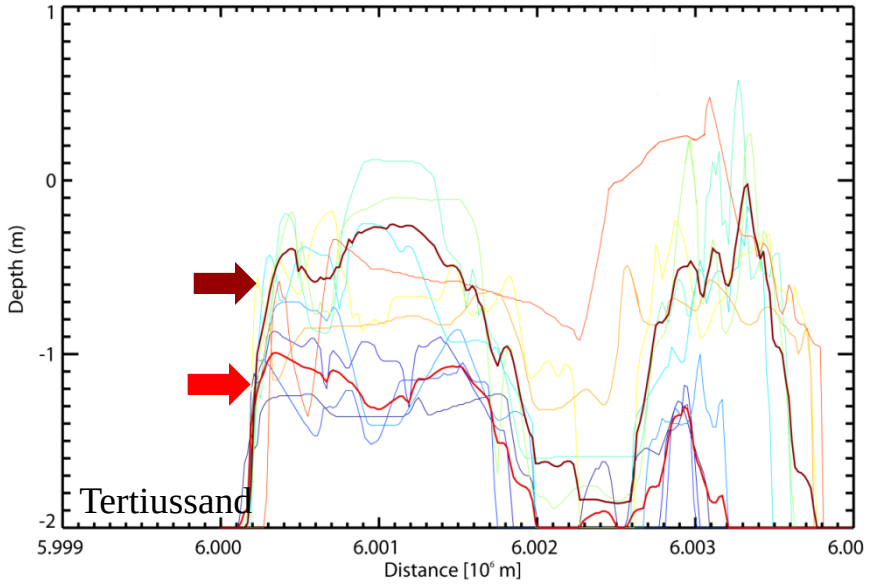
2.2 km, 0.17 km/yr — This study

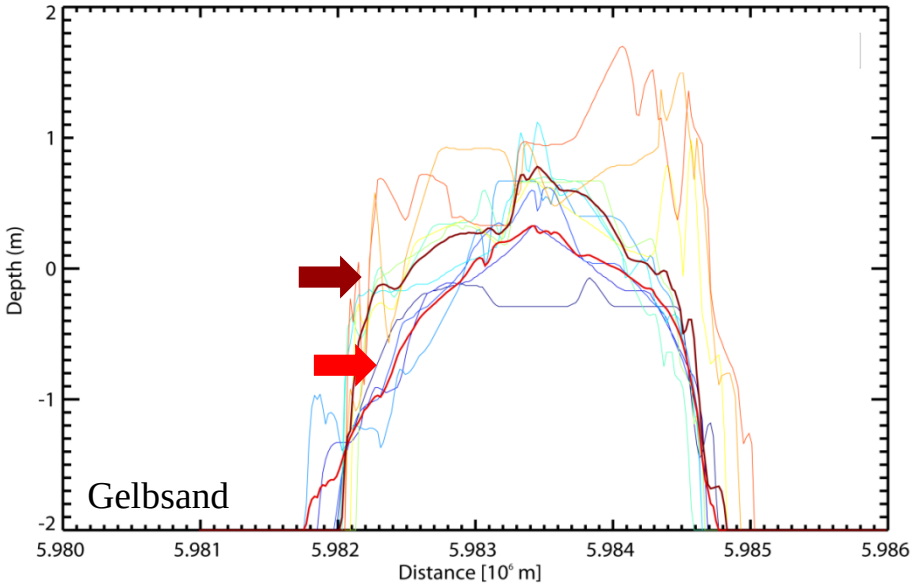


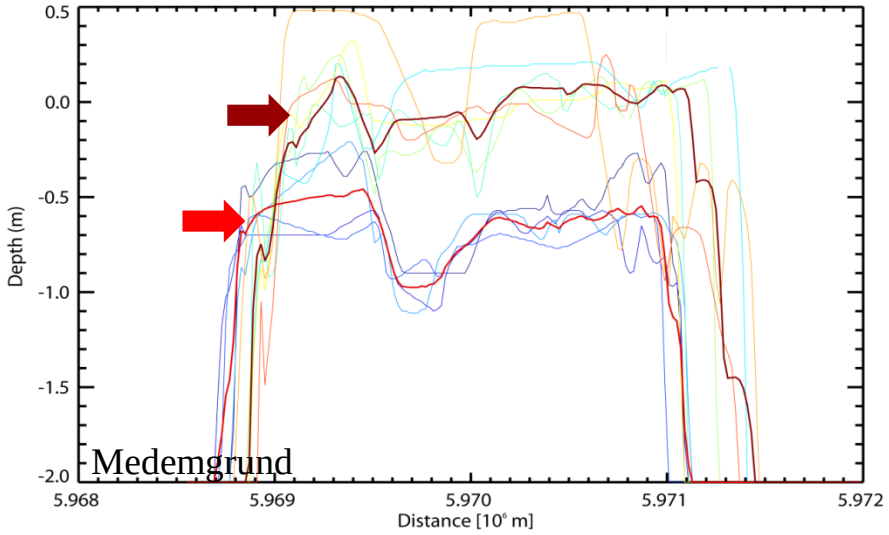


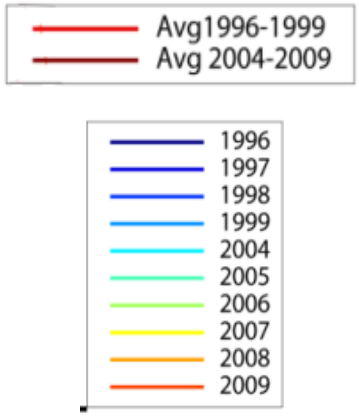
Cross Sections




Tertiussand
Depth (m)
Distance [10⁶ m]

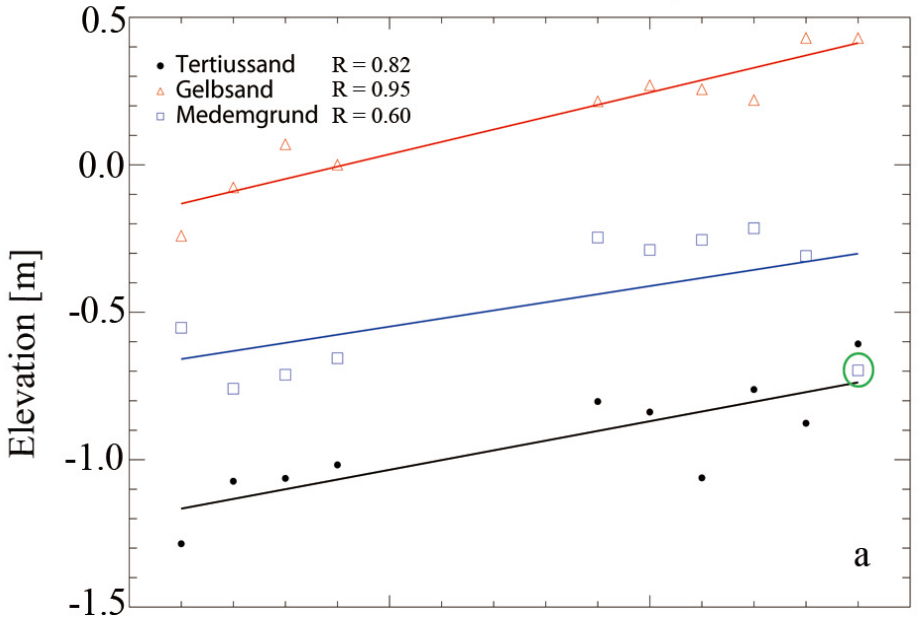

Gelbsand
Depth (m)
Distance [10⁶ m]

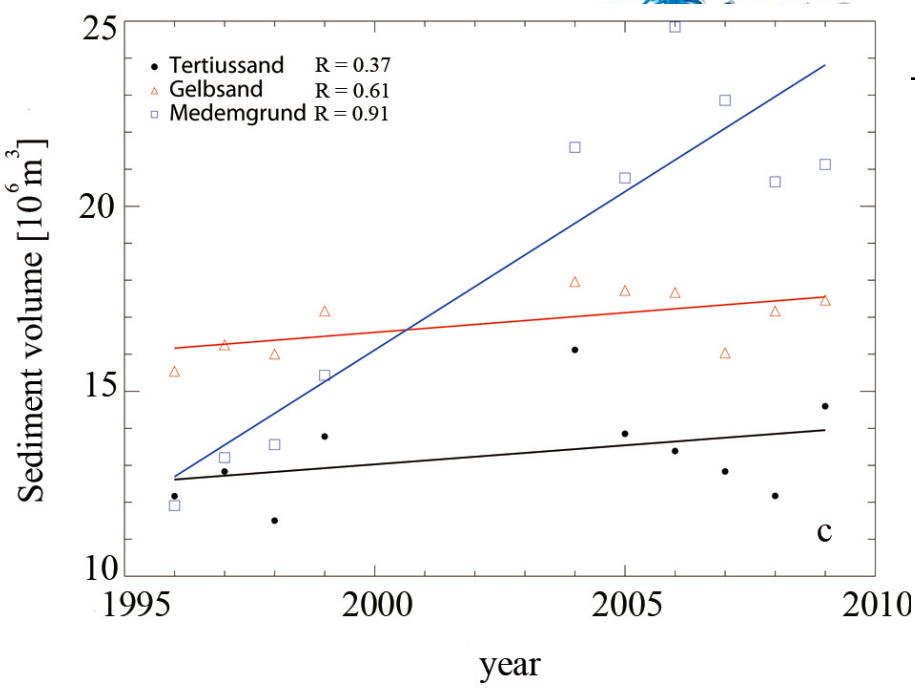

Medemgrund
Depth (m)
Distance [10⁶ m]

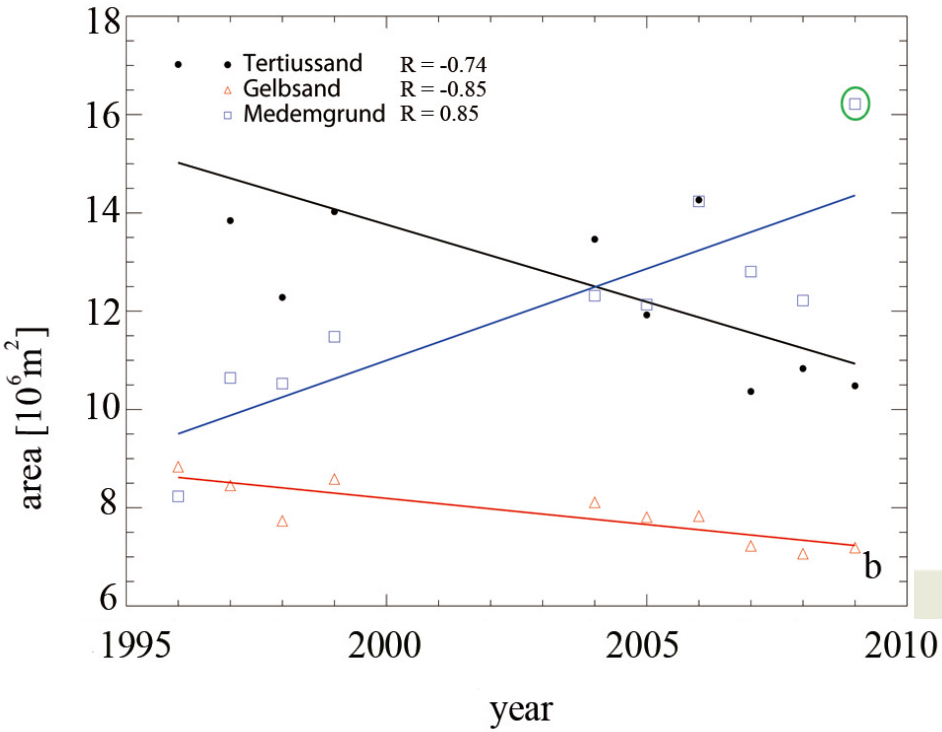

Avg1996-1999
Avg 2004-2009
1996
1997
1998
1999
2004
2005
2006
2007
2008
2009

Averaged elevation for the sandbars

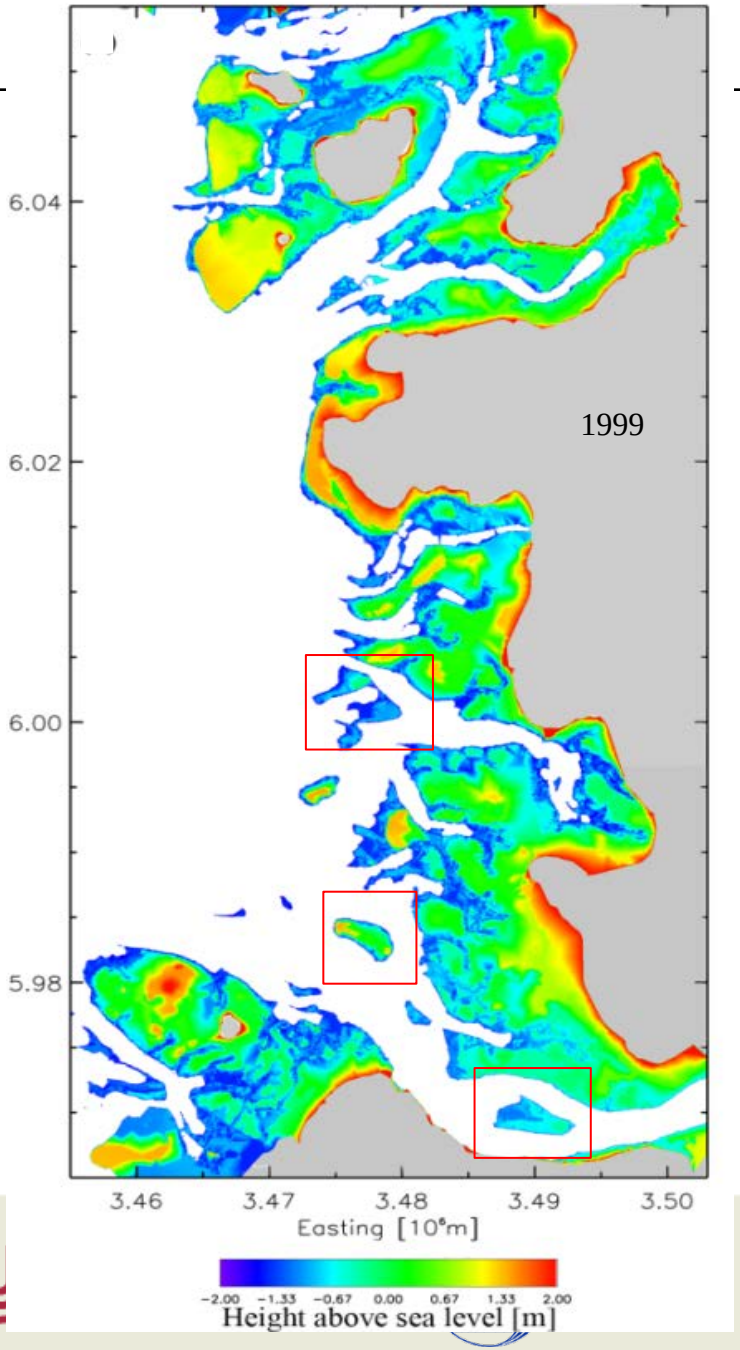
Sandbars	Average elevation (m)		Elevation difference (m)	Averaged increasing per year (m/yr)
	year group A (1996-1999)	year group B (2004-2009)		
Tertiussand	-1.09	-0.84	0.25	0.03
Gelbsand	-0.16	0.28	0.44	0.05
Medemgrund	-0.48	-0.35	0.13	0.01







	Area	Elevation	Sediment
Tertius-sand	↓	↑	Internal redistrib.
Gelbsand	↓	↑	Internal redistrib.
Medem-grund	↑	↑	External compens.



	Area	Elevation	Sediment
Tertius-sand	↓	↑	Internal redistrib.
Gelbsand	↓	↑	Internal redistrib.
Medem-grund	↑	↑	External compens.

Conclusion

- Waterline method with SAR and optical images suitable to document development of Wadden sea
- on scales from 20 m to 90 km and years to decades, here from 1996 to 2009
- Average sea floor in similar range as sea level rise, *but unevenly distributed*

Future Plans

- using TanDEM-X Science Mission (April-Aug. 2015) with extended baseline, estimated rmse: 10 cm to
- generate standard of the Wadden Sea floor as reference for future changes induced by water construction activities and sea level rise
- Challenges:
  - meet overflights at low water level
  - vertical resolution improvement by nonlinear filtering and generating multilook images from Single Look Complex (SLC) data.


Thank you for your attention

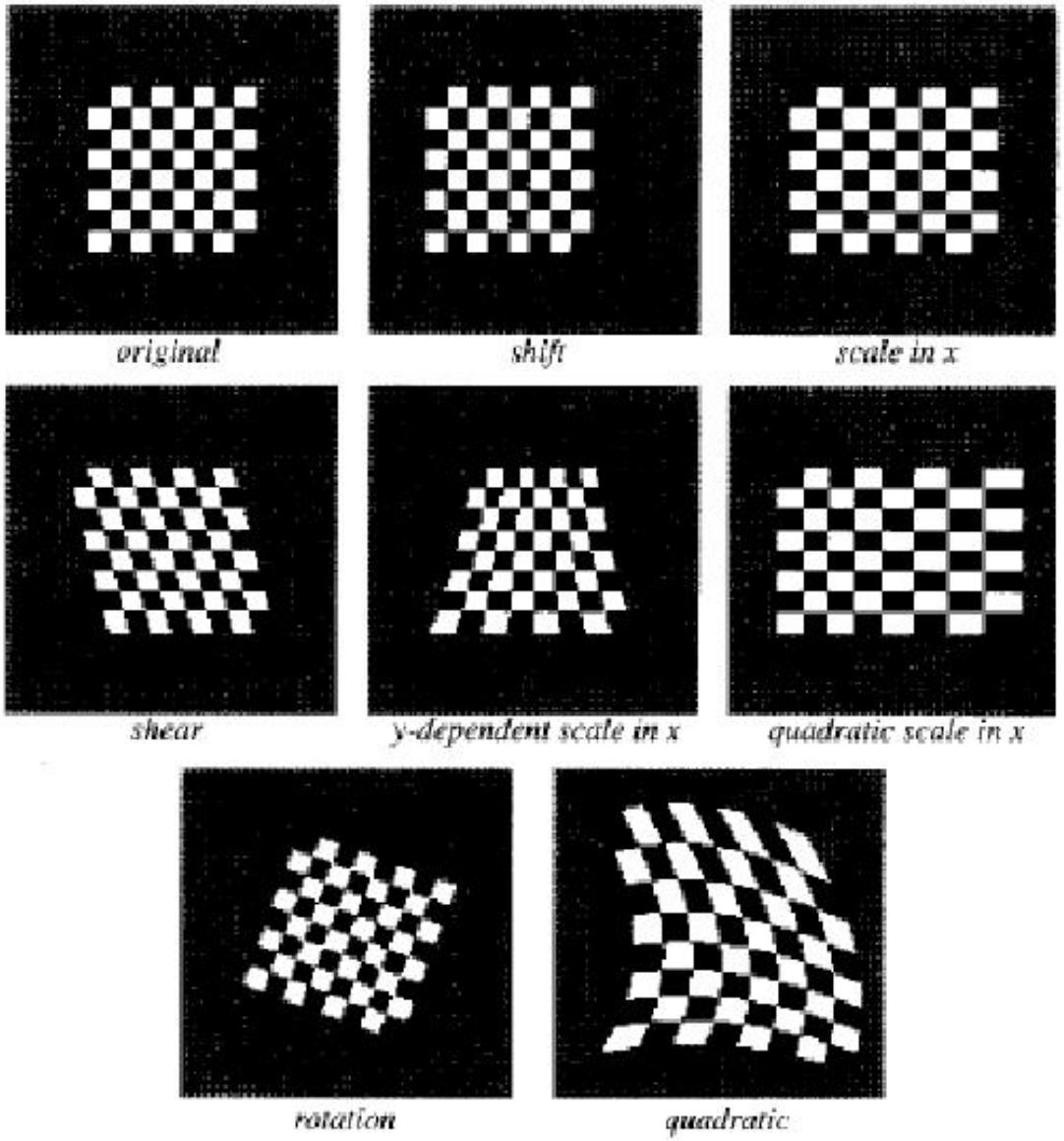
Step 3: Preprocessing of Water level Model data

1. The two model states available each 15 mins nearest to the time of the SAR scene are interpolated linearly in time.
2. Interpolate model data into a finer grid (from grid width 100m to 20m).
3. Correct model data with water gauge data.
4. Attach waterlevel data to the waterlines.

a_{00}, b_{00}

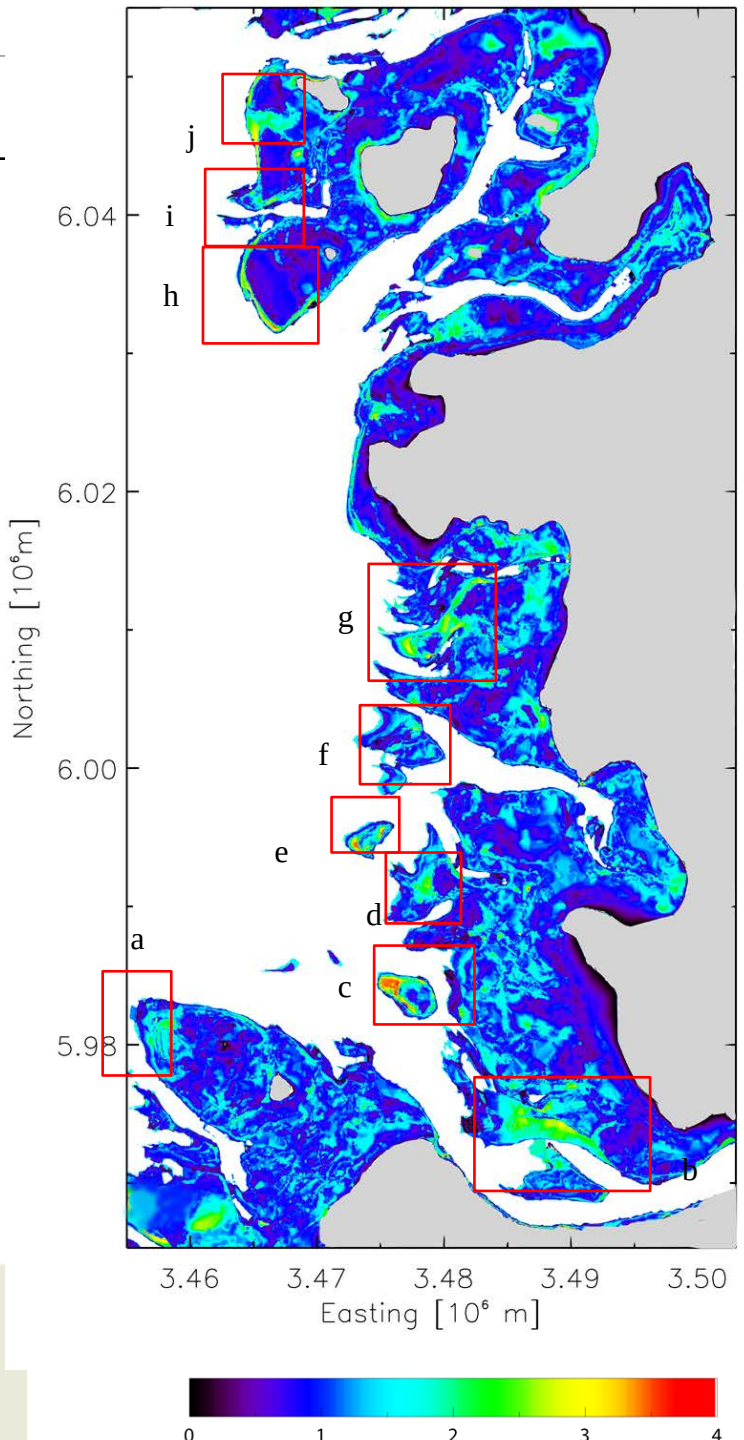
a_{10}

a_{01}, b_{10}



Regions of high BER

(a)Outer part of Scharhörn;
(b) Medemsand and Medemgrund;
(c) Gelbsand;
(d) Trischen;
(e) D-Steert;
(f) Tertiussand;
(g) Eider;
(h) Süderoogsand;
(i)Norderoogsand;
(j)Japsand.



Step 4: Interpolation and map generation

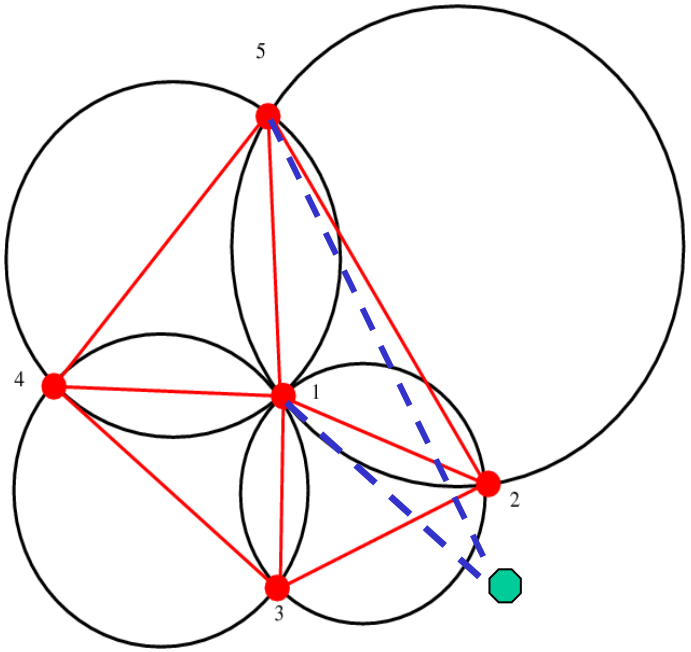
- Tool: TASH software

  (**T**opographisches **A**uswerte **S**ystem **H**annover, Institute fuer Kartographie Universitaet Hannover)

- Method: Delaunay-Triangulation

  1. no other sample points are located within the triangle circumcircle.
  2. select for each side of a triangle the third point with the largest crown angle.

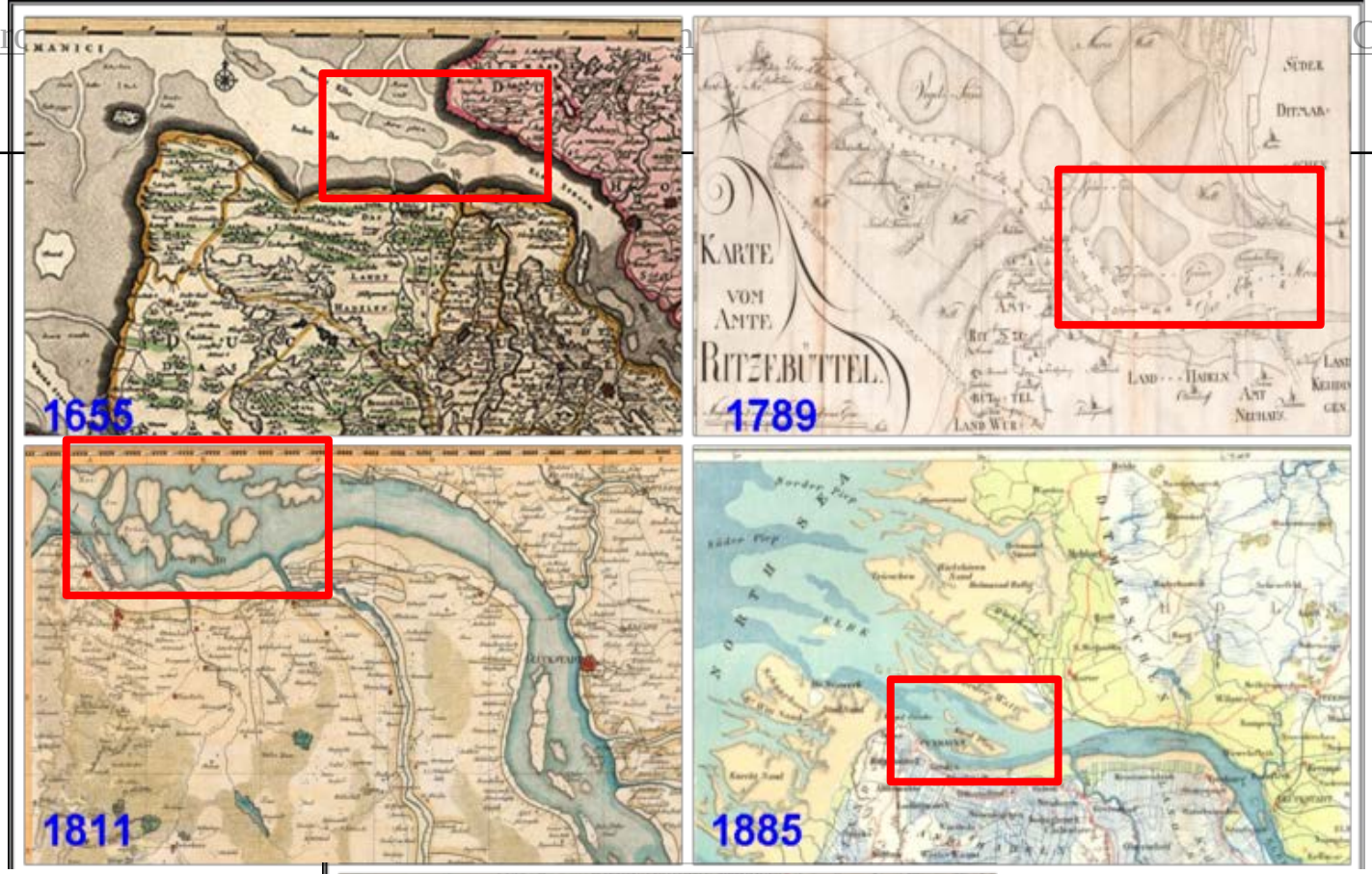
- Interpolate into regular grid (grid width=20m)



- MSL is defined as the zero elevation for a local area. The zero surface referenced by elevation is called a vertical datum.

- The mean sea level used here is the reference height from Amsterdam. The level network name is DHHN12 (Meter über Normalnull, m. Ü. NN)

- https://www.pegelonline.wsv.de/gast/hilfe#hilfe_hoehensystem
- http://www.bsh.de/en/Marine_data/Forecasts/Prediction_models/index.jsp

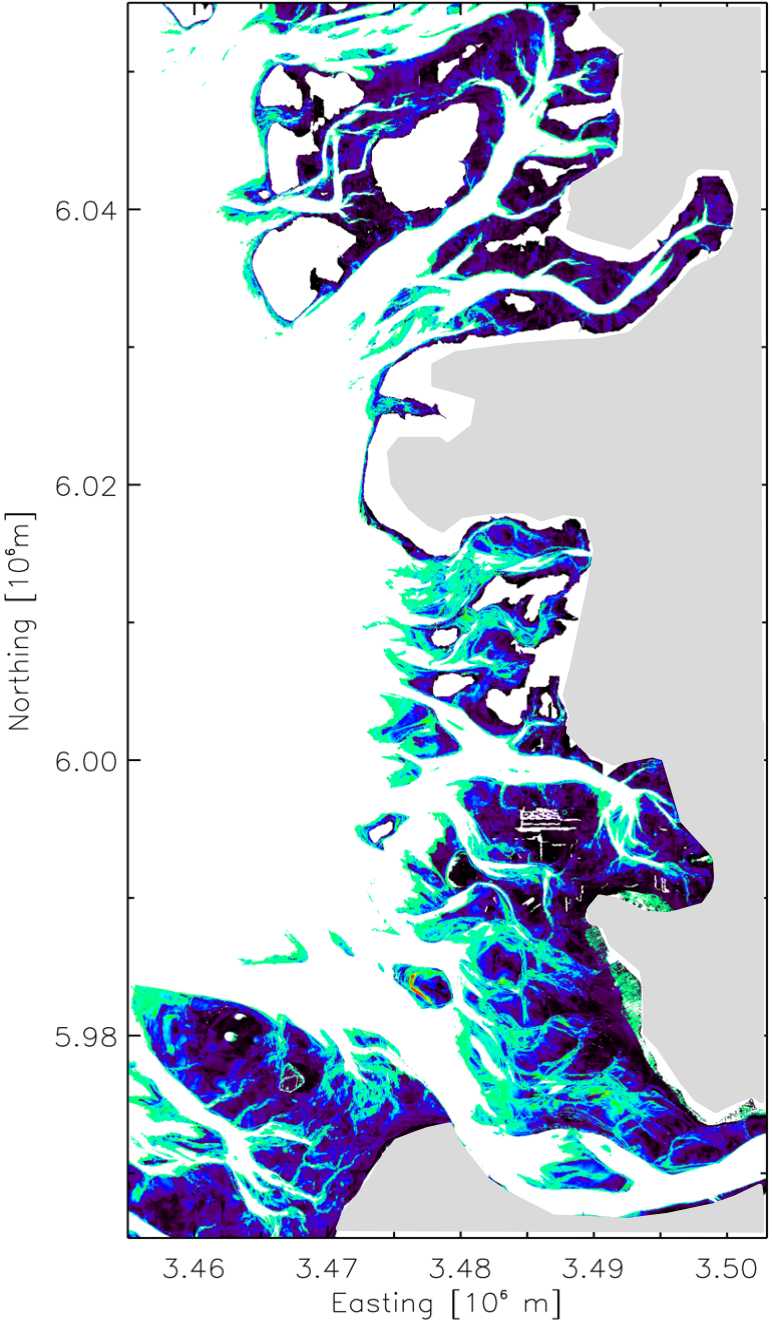


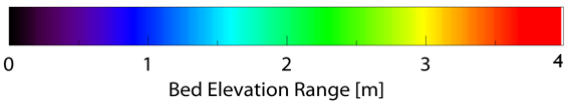
Medem-sand

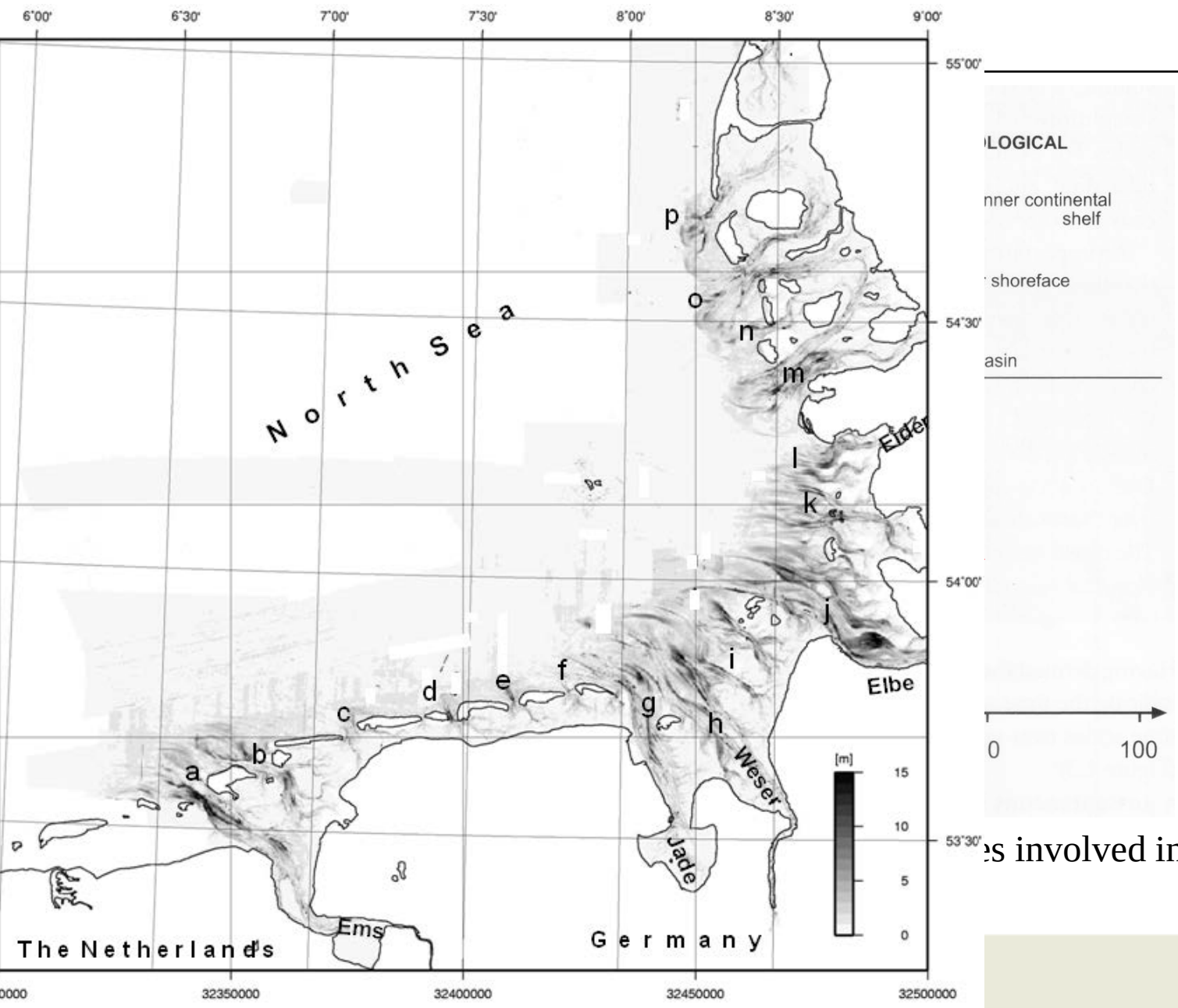
de Wit, 1665;
von Hess, 1789;
Streit, 1811;
Vuillemin 1885;
Wagner and Debes, 1910


7°
Esbjerg
NORTH SEA
Flensburg
Husum
54°
Cuxhaven
Emden
Groningen
BREMEN
0
50 km

Ehlers, 1988


6.04
6.02
6.00
5.98
Northing [10⁶m]
3.46
3.47
3.48
3.49
3.50
Easting [10⁶ m]


0
1
2
3
4
Bed Elevation Range [m]

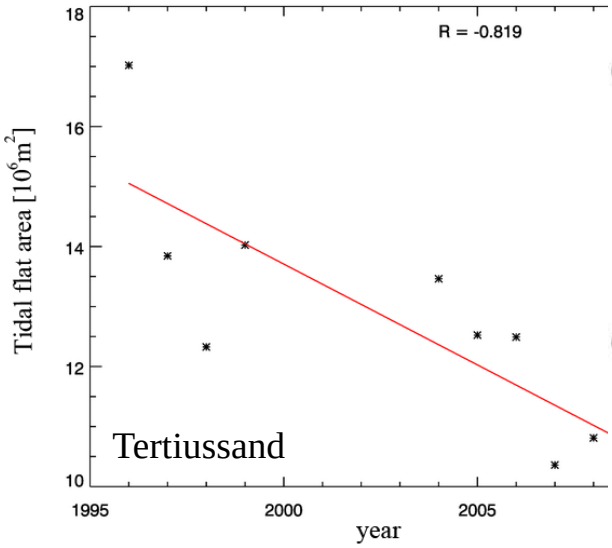


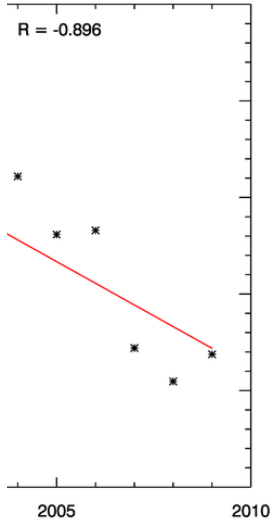
s involved in coastal evolution

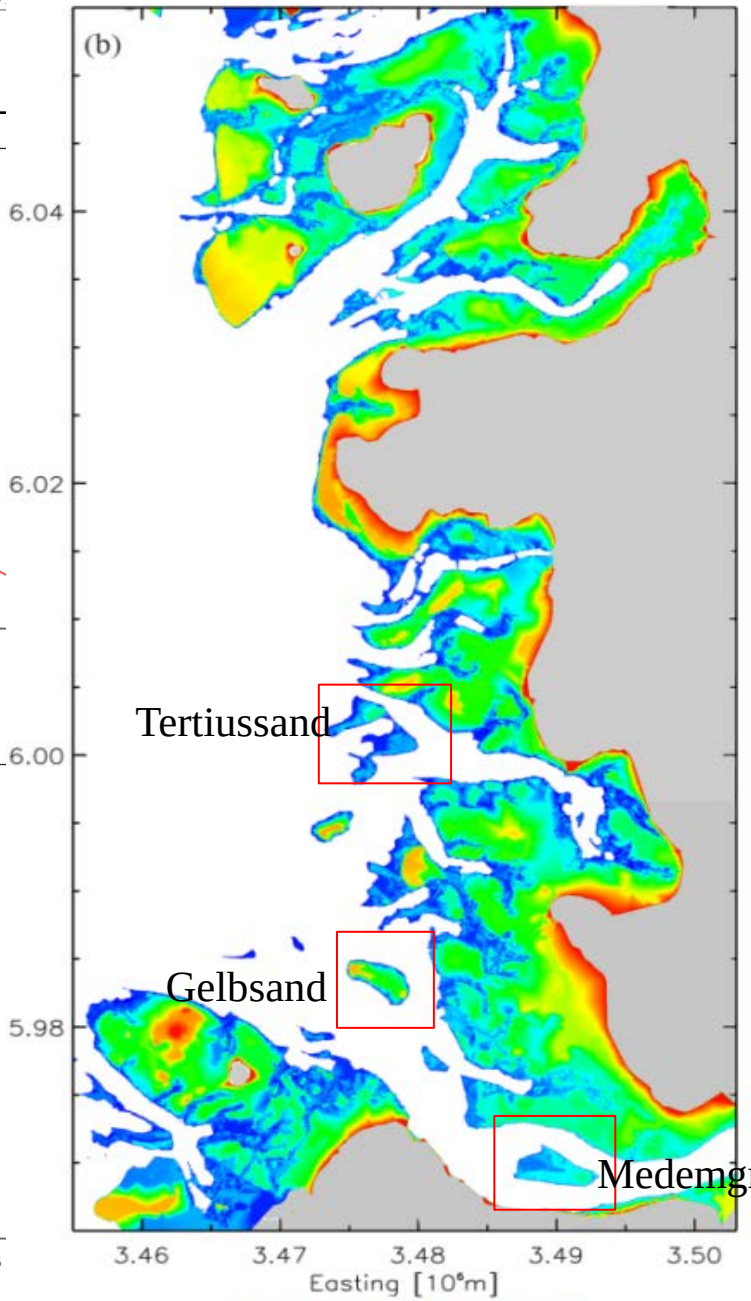
Tidal flat types

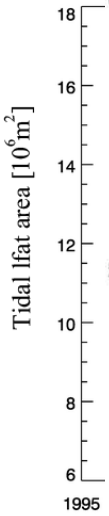
Type	Example
An area linked to a river or its neighboring delta	*The Yangtze river delta in China*
The inner part of a bay	*The Wash in England*
An area surrounded by mountains	*Gros Morne National Park in Canada*
A lagoon without waves because of the barrier islands	*East Coast of USA*
An inland sea where sand tidal flats formed under the high influence of waves despite the presence of barrier islands	*The Wadden Sea*

UNESCO http://whc.unesco.org/en/tentativelists/5482/

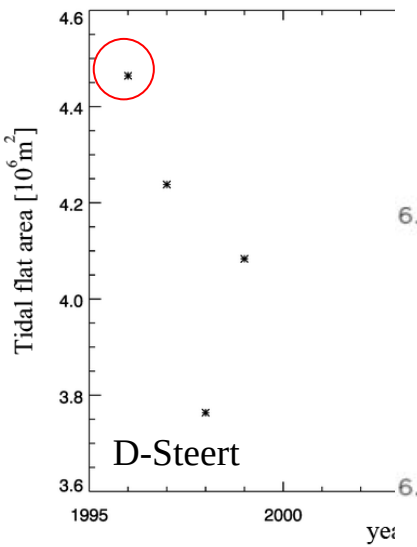


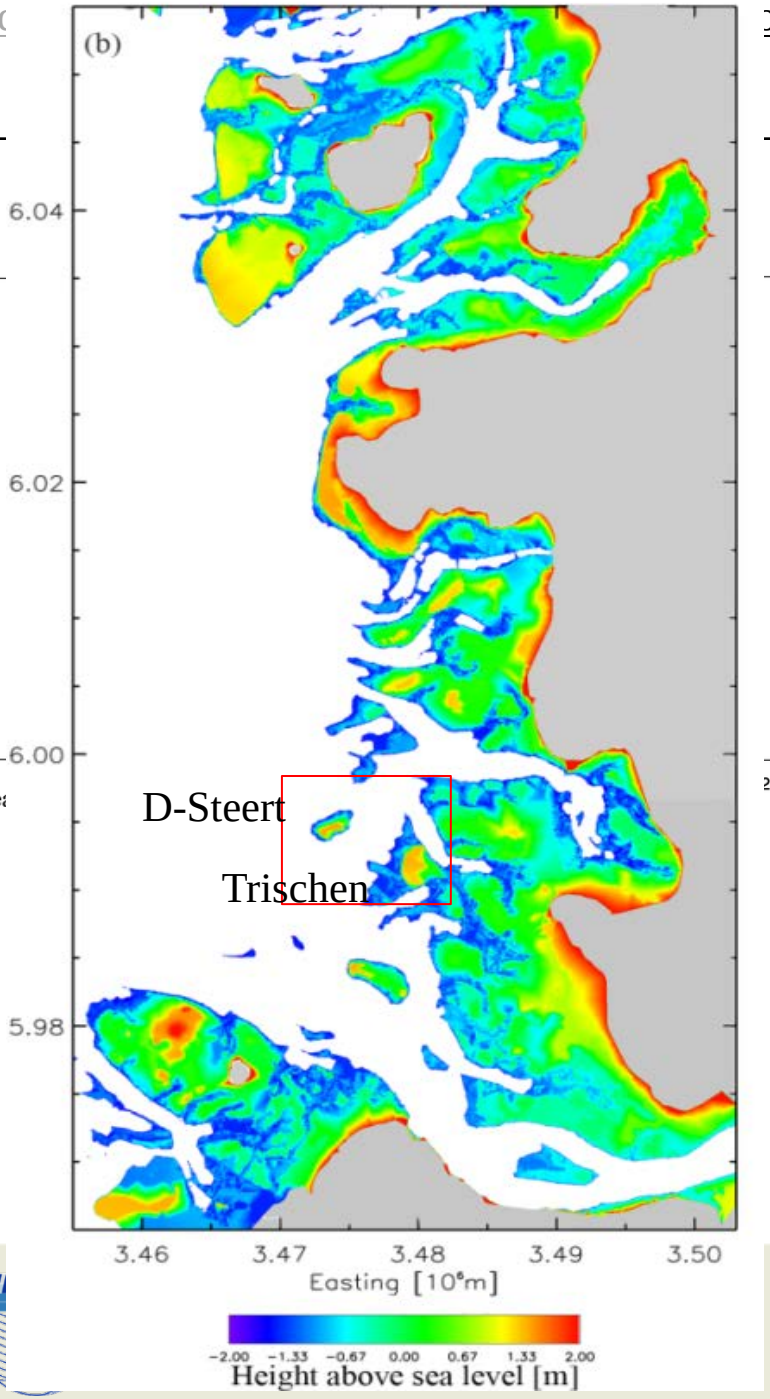


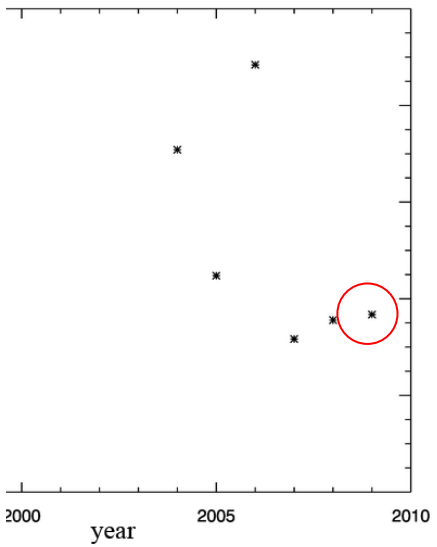




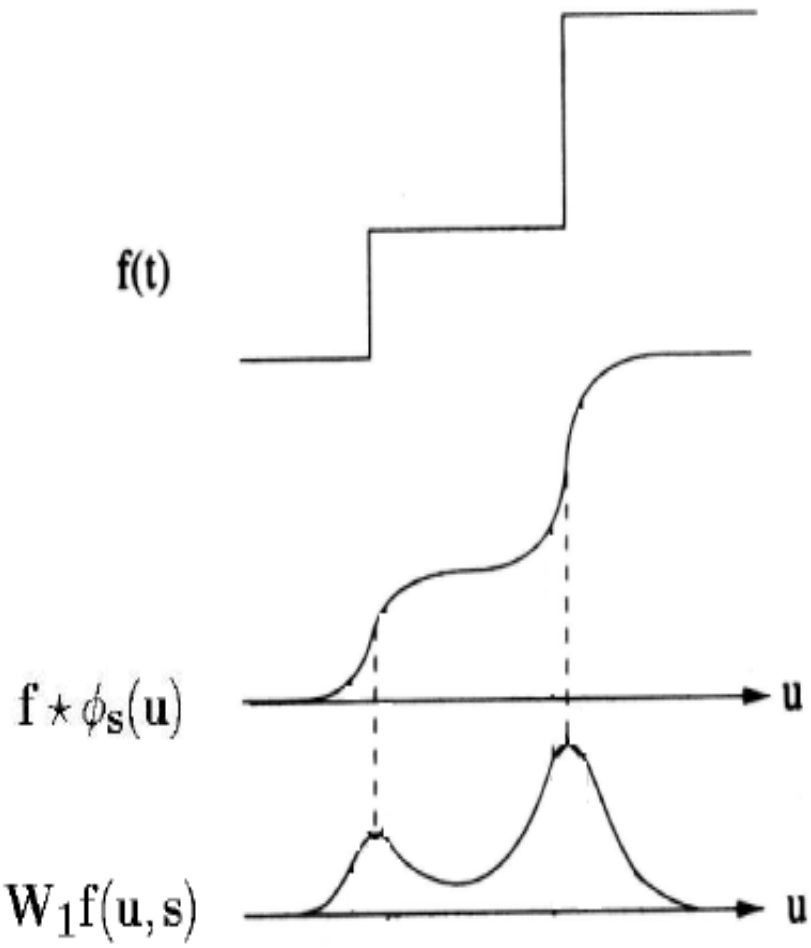
Area of the sandbars


Tidal flat area [10^6 m^2]
4.6
4.4
4.2
4.0
3.8
3.6
1995
2000
D-Steert


(b)
6.04
6.02
6.00
5.98
D-Steert
Trischen
3.46
3.47
3.48
3.49
3.50
Easting [10^6 m]
−2.00 −1.33 −0.67 0.00 0.67 1.33 2.00
Height above sea level [m]


2000
2005
2010
year

Step 1: Multi scale edge detection (based on wavelet transform)



Mallat 1997

Wavelet transform can be written with multi-scale differential operator:

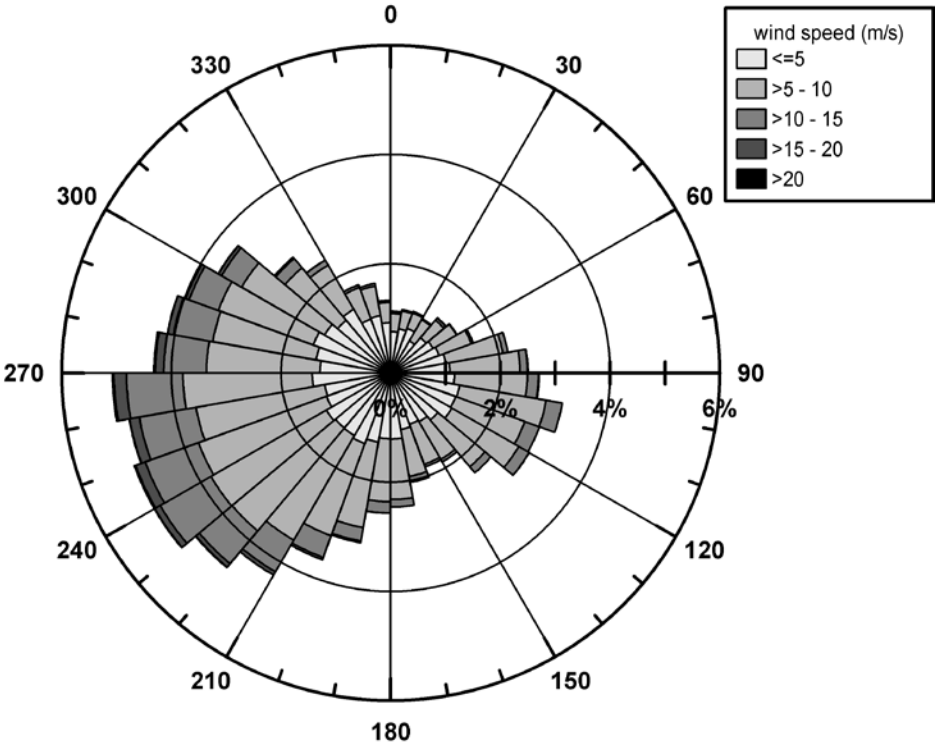
$$W_n f(u,s) = s^n \frac{d^n}{du^n}(f * \phi_s)(u)$$

ϕ_s is the scaling function

The location u_0 of an edge in the image is given by →

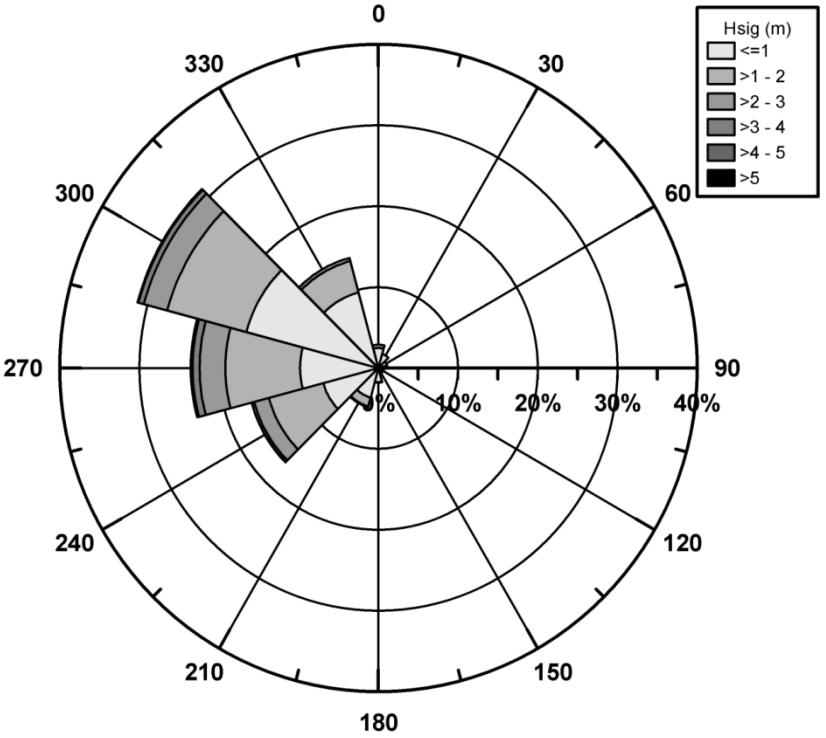
$$\frac{\partial W_n f(u_0,s)}{\partial u} = 0$$

Wind rose (1989-2000)



Wilkens, 2004

Wave rose (1986-1993)



Froehle & Kohlhase, 1995