Variability of estuarine circulation in a tidally energetic inlet with curvature

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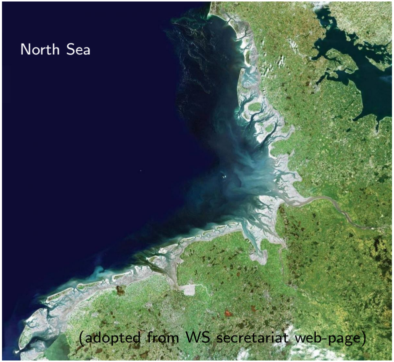
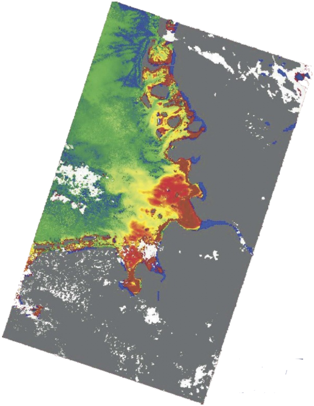
Wadden Sea Features



- The WS is a shallow inter-tidal body of the North Sea,
  - warming, cooling, rain fall and river runoff,
- Horizontal density gradient $(\partial_h \rho)$,
- Highly energetic wind condition,

Wadden Sea Features



Satellite image of suspended sediment

(adopted from Burchard et al. 2008)

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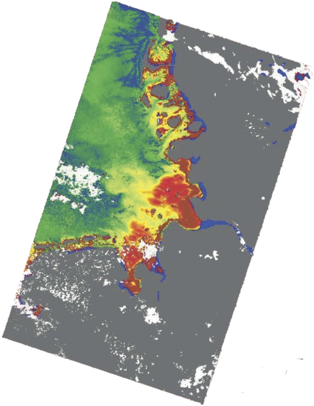

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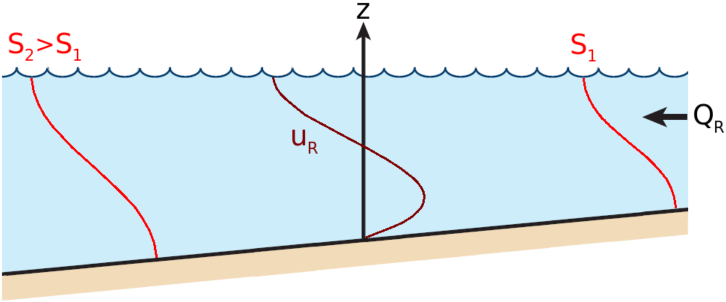
- Higher SSC in the Wadden Sea,
- Pumping mechanism.

Gravitational / density-driven circulation



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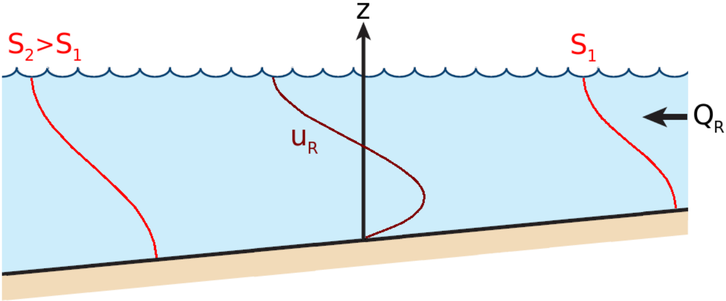
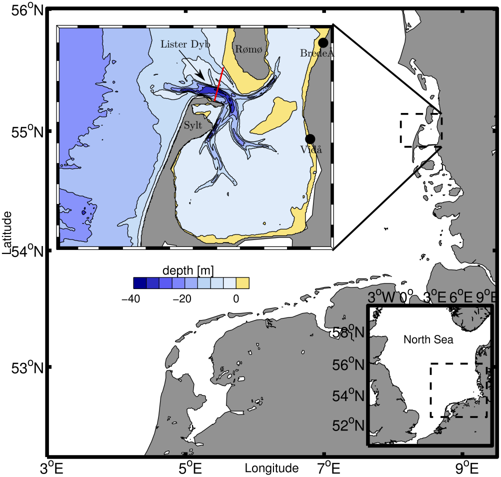


mechanism

- salinity gradient induces a baroclinic pressure gradient,
- saltier water up-estuary at bottom,
- fresher water down-estuary at surface,
- classical estuarine circulation (Pritchard, 1954).



Site description

- Semi-enclosed basin, 190 km^2 tidal flat area,
- Semi-diurnal tide (1.8m range),
- 2 rivers, 0.8 m/yr rainfall, spring condition $(\partial_h \rho)$,

Method and model set up

GETM (numerical coastal ocean model)

- One-way nesting (3-levels) approach is followed (1800m, 600m and 100 m).
- Sea surface elevation, temperature, salinity boundary condition from an operational model for the North Sea.
- Meteorological data provided in 7 km resolution (German Weather Service).
- Riverine outflows (Elbe, Weser, BredeÅ and Vidå).
- 25 sigma layers.

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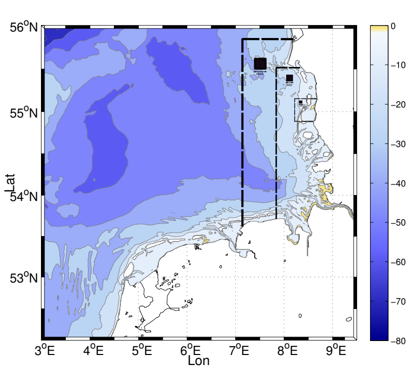
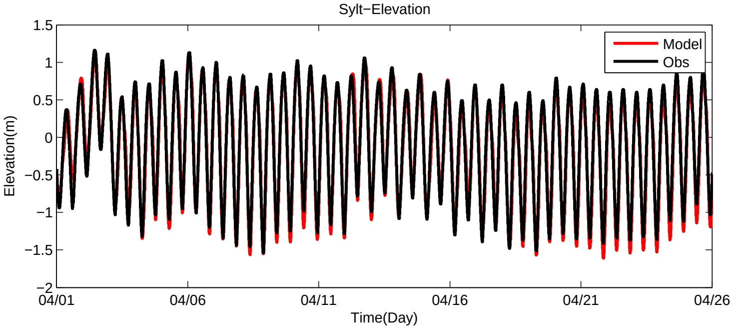
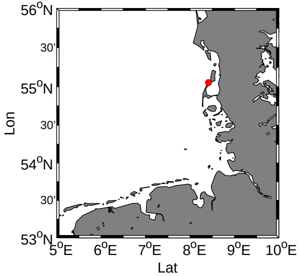
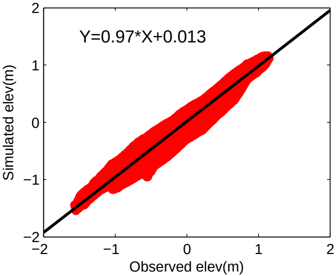


Model validation







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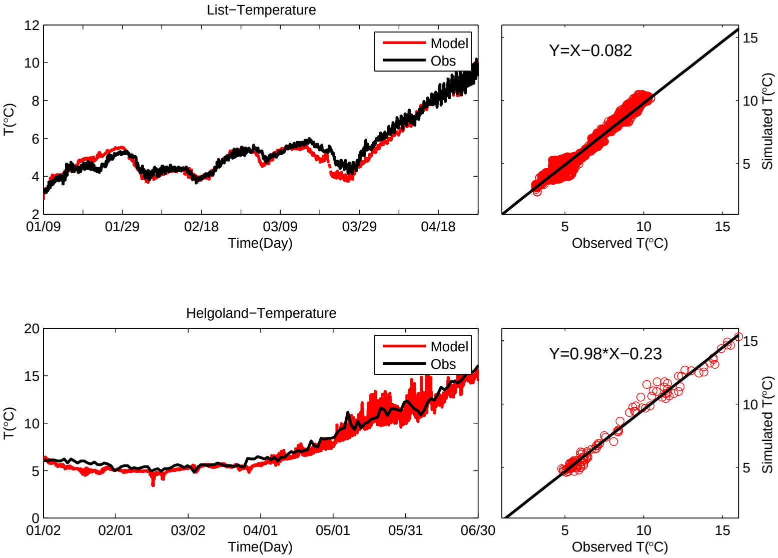
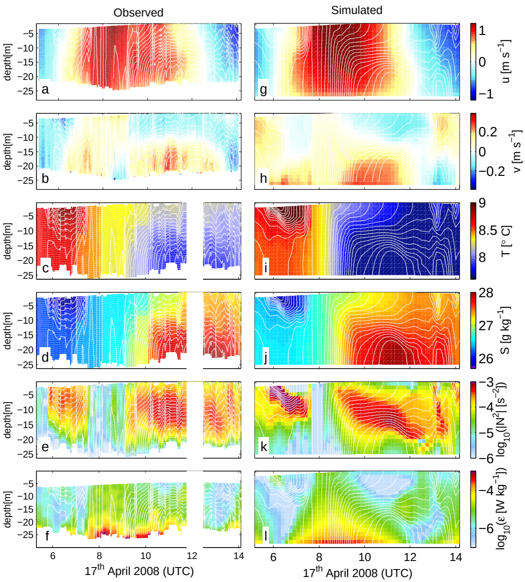




Data comparison

- Horizontal current velocity ✓
- Stratification in T and S ✓
- General features of N^2 and ε ✓

Intensity of residual circulation

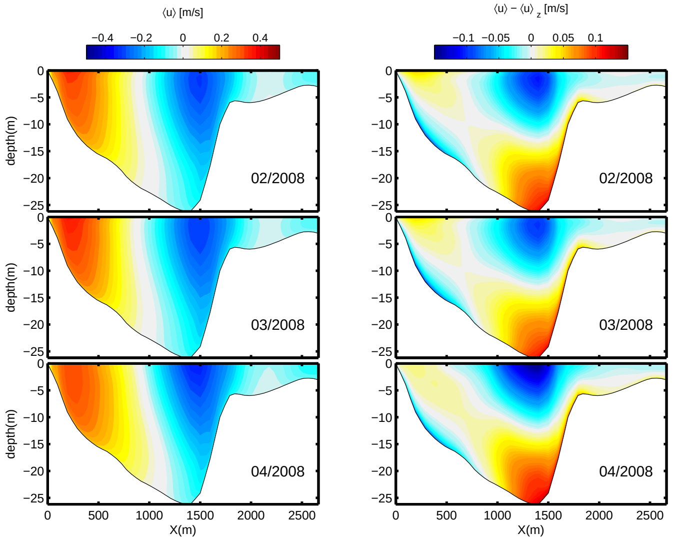
Measure of exchange flow intensity (Burchard et al, 2011)

$$[\mathcal{M}_x, \mathcal{M}_y] = -\frac{1}{W}\int_0^W \frac{4}{\langle D\rangle^2}\int_{-H}^{\langle\eta\rangle}[\langle u\rangle, \langle v\rangle]\{z + \frac{\langle D\rangle}{2}\}dz\,dy. \tag{1}$$

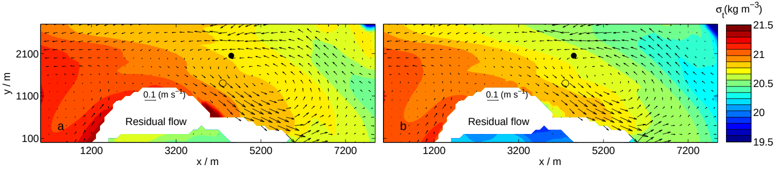
$$\langle\partial_x b\rangle_{\langle A\rangle} = \frac{1}{\langle A\rangle}\int_0^W \int_{-H(y)}^{\langle\eta\rangle}\langle\partial_x b\rangle dz\,dy \tag{2}$$

- $\mathcal{M}(u) > 0$, classical estuarine circulation.
- $\mathcal{M}(u) < 0$, non-classical estuarine circulation.

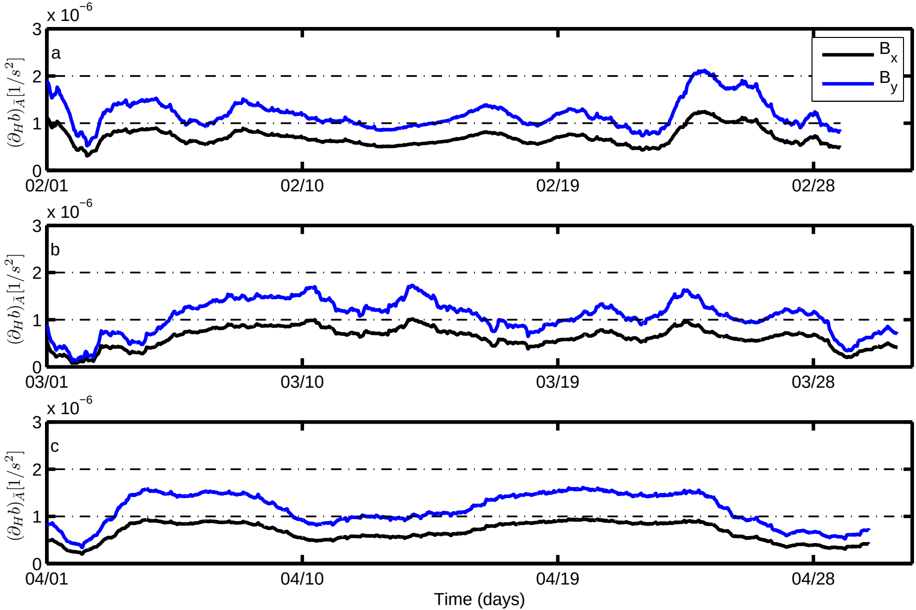
Monthly mean residual circulation



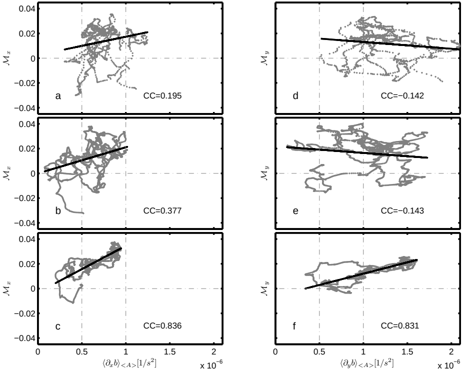
Residual eddy generated by curvature



Cross sectionally averaged buoyancy gradient



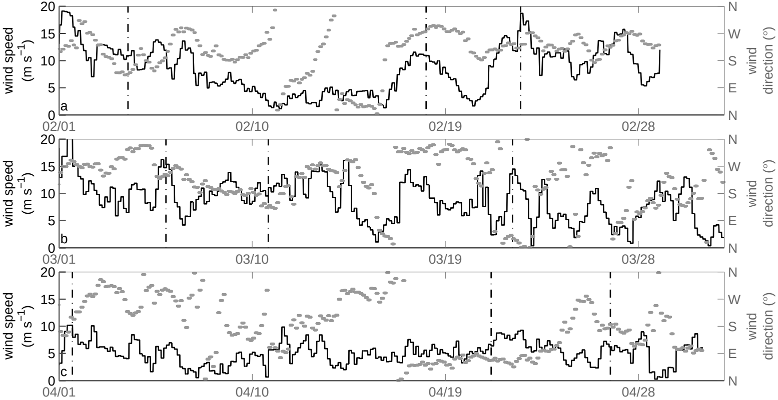
Variability of residual circulation



Mechanism: density gradient

- Weak correlation at February and March.
- Correlation increases from Feb to April.

Wind forcing



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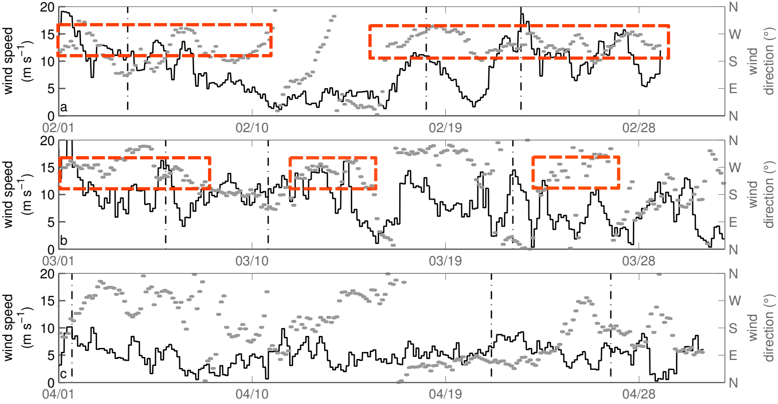
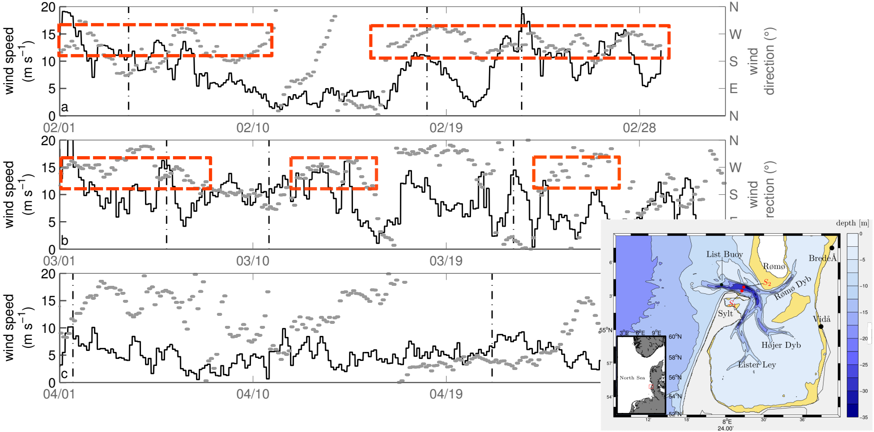


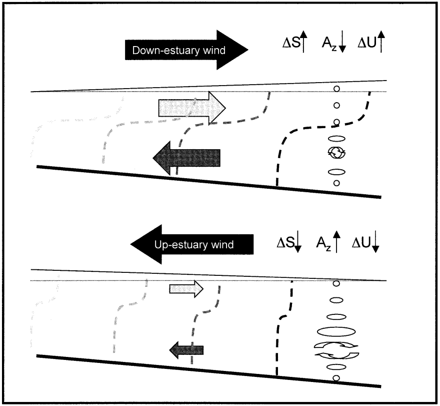


wind speed (m s−1)
wind direction (°)
N
W
S
E
a
b
c
02/01
02/10
02/19
02/28
03/01
03/10
03/19
04/01
04/10
04/19
depth [m]
List Buoy
Rømø
BredeÅ
Rømø Dyb
Sylt
Vidå
Højer Dyb
Lister Ley
North Sea

Wind induced circulation

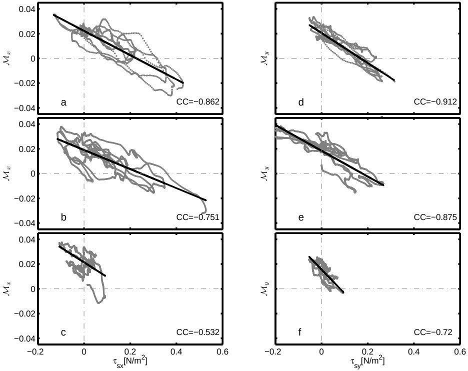
Wind induced circulation

- Down-estuary wind
  - vertical shear increases,
  - vertical viscosity decreases,
  - stratification increases,
  - estuarine exchange flow increases.
- Up-estuary wind
  - vertical shear is suppressed,
  - vertical viscosity increases,
  - stratification decreases,
  - estuarine exchange flow decreases.



Conceptual model of wind-driven circulation and responding exchange flow

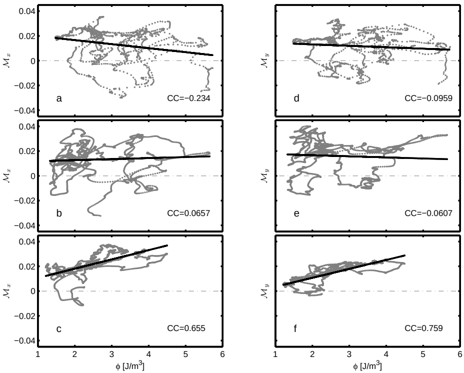
Variability of residual circulation



Mechanism: surface wind stress

- Correlation decreases from Feb to April.
- Up-estuary wind, decreases the R-C.
- Down-estuary wind, increases the R-C.
- $\tau_{\rm sx} > 0.15\mathrm{Nm}^{-2}$, induces non-classical R-C.

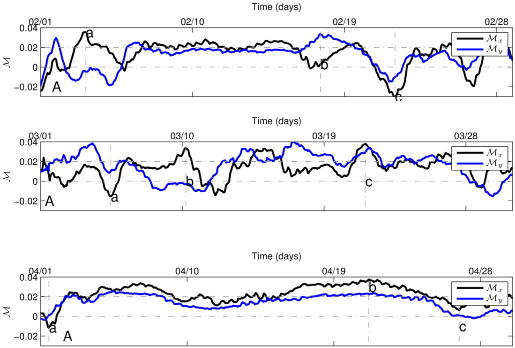
Variability of residual circulation



Mechanism: stratification

- $$\phi = \frac{1}{D}\int_{-H}^{\eta} gz(\bar{\rho}-\rho)\mathrm{d}z \quad (3)$$
- No correlation at Feb and March.
- Strong correlation during calm month.

Episodic variation of estuarine circulation



Conclusions

- Buoyancy gradient determines dynamics only during calm weather condition.
- Estuarine circulation is strongly correlated with wind straining.
- Strong wind towards the inner shoal can revert the classical residual circulation.