Interaction between Eutrophication and Suspended Matter Dynamics in a Shallow Coastal Sea
- Developing Eutrophication Criteria -

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The LOICZ Perspective

- Land-Ocean-Interactions
  - Dams reduce riverine Suspended Matter Loads:
    - Increased erosion (river loads: +2.3 10^9 T/y)
    - Decreased flux to the ocean (-1.4 10^9 T/y)

    (Syvitsky et al., 2005)
  - Increased riverine nutrient fluxes
    (three times since 1970's; Smith et al. 2003)
  - Coastal zones are heterotrophic
    - Focus on riverine OM loads

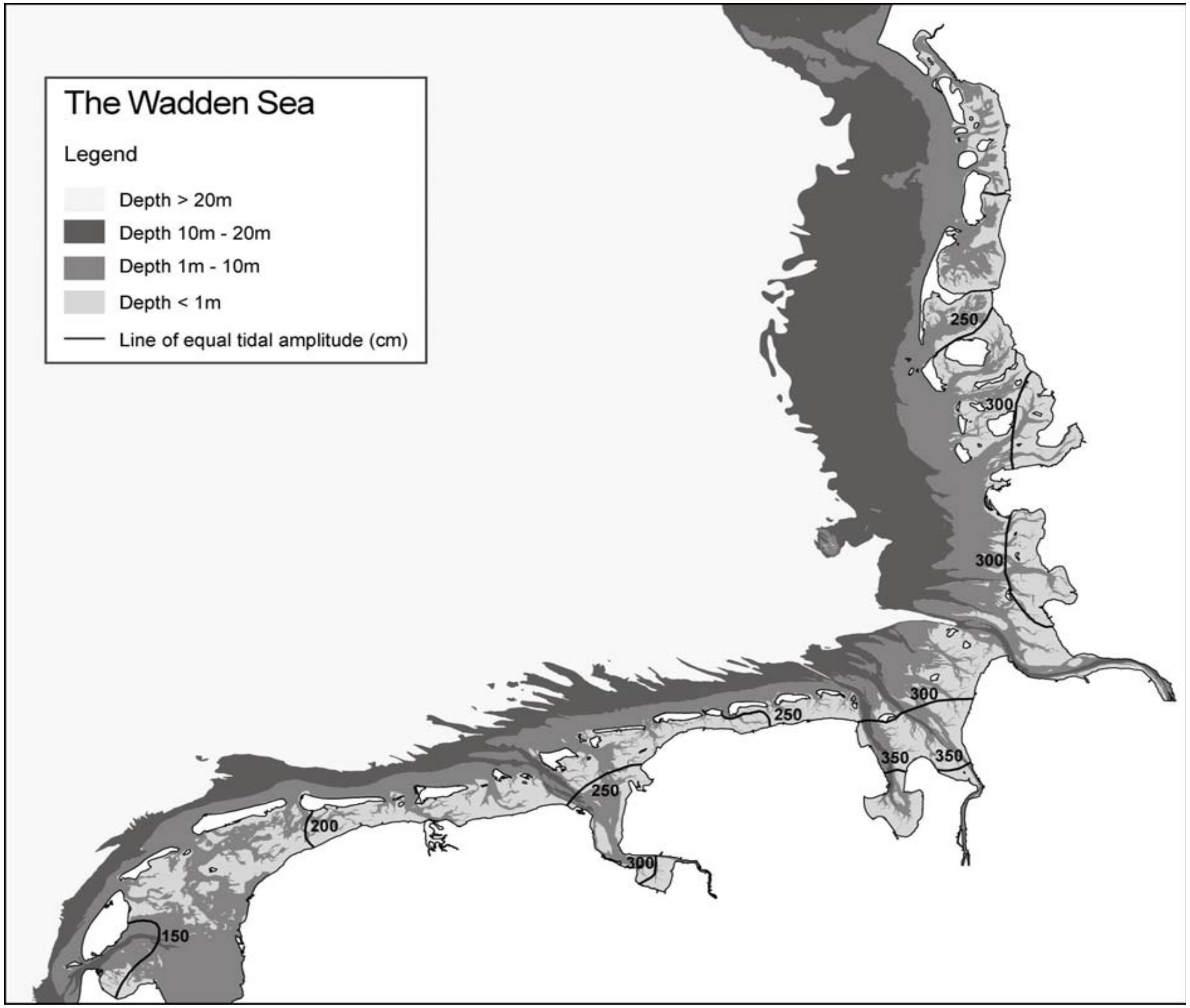
      (Smith & Holibaugh, 1993; Thomas et al., 2005)
- Ocean-"Land" -Interactions

Overview

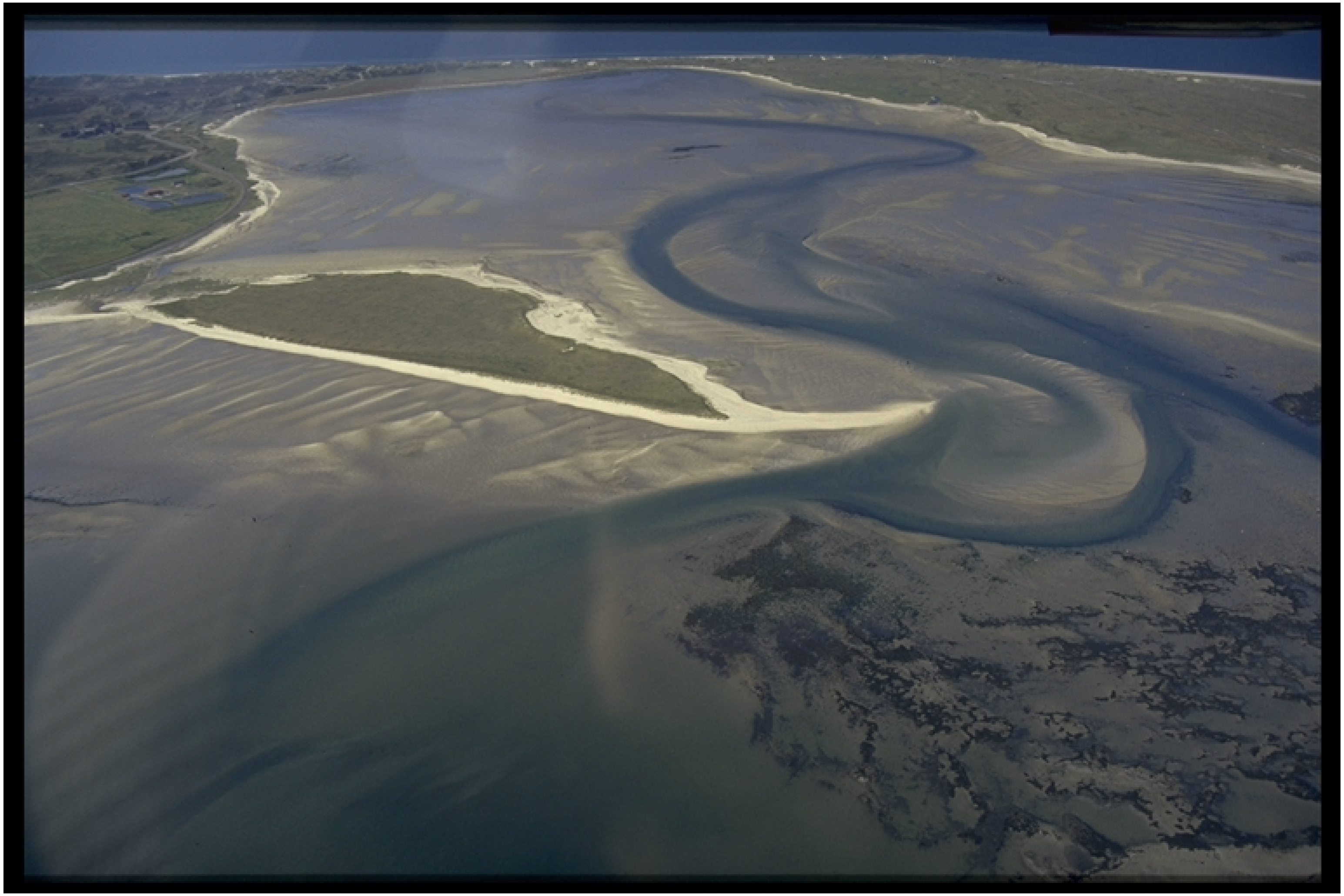
"*..most of the suspended organic matter* [in the Wadden Sea]*…is in the form of organic detritus which forms aggregates with the inorganic particles*… [that are] *transported in a similar manner*."
Postma, 1981

- Suspended Matter Accumulation in the Wadden Sea
- Role of Particulate Organic Matter in the Eutrophication "History" of the Wadden Sea
- Long-Term SPM Dynamics in the Wadden Sea
  - Dutch Wadden Sea: The Inorganic View
  - Northern Wadden Sea: The Organic View

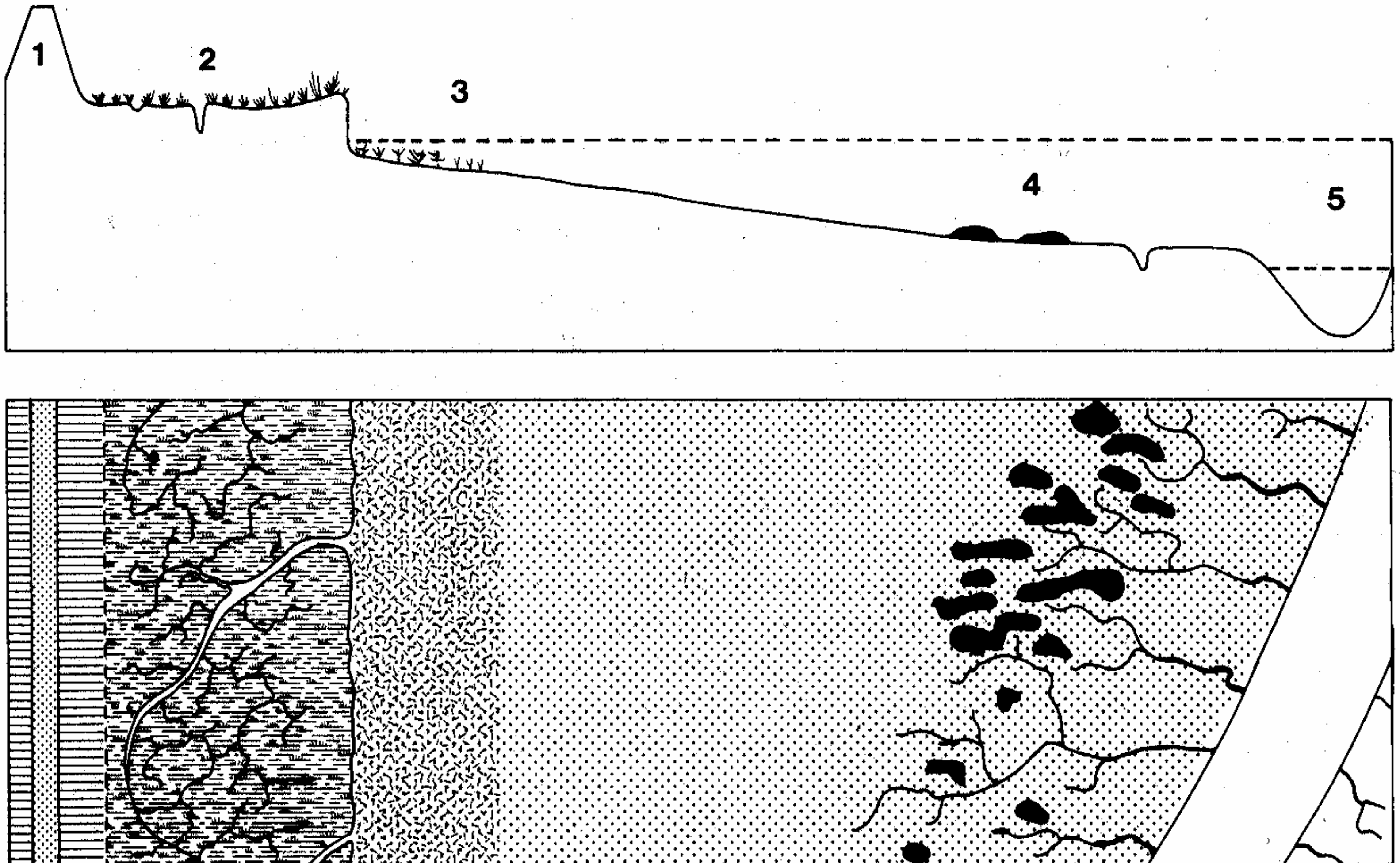
Map: www.waddensea-secretariat.org



Source: Wadden Sea Quality Status Report 1999



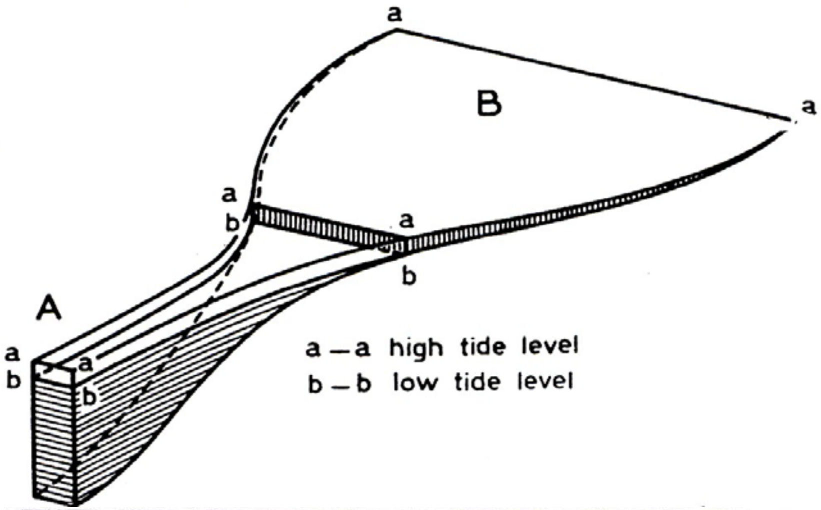
Königshafen, Northern Wadden Sea
Photo: Karsten Reise



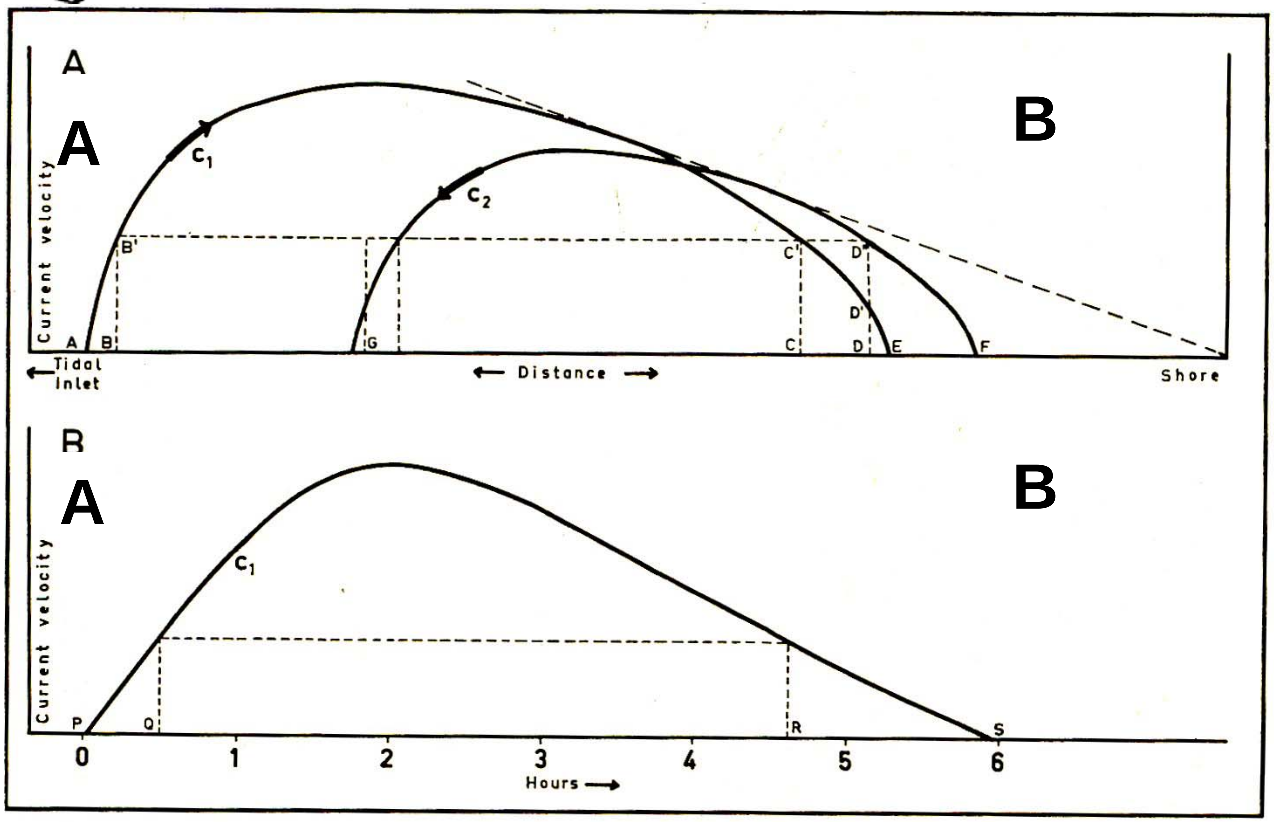
Van Straaten & Kuenen, 1957

Suspended Matter Accumulation in the Wadden Sea: -the classical view-

- Verwey (1952):
  - High bivalve biomass explained by OM import from North Sea
- Postma (1954); Van Straaten & Kuenen (1957):
  - Inorganic (clay) particles: marine origin
  - SPM gradient towards coast implies active accumulation
    - Scour-Lag
    - Settling Lag
    - Depth gradient
    - Asymmetry of the tides

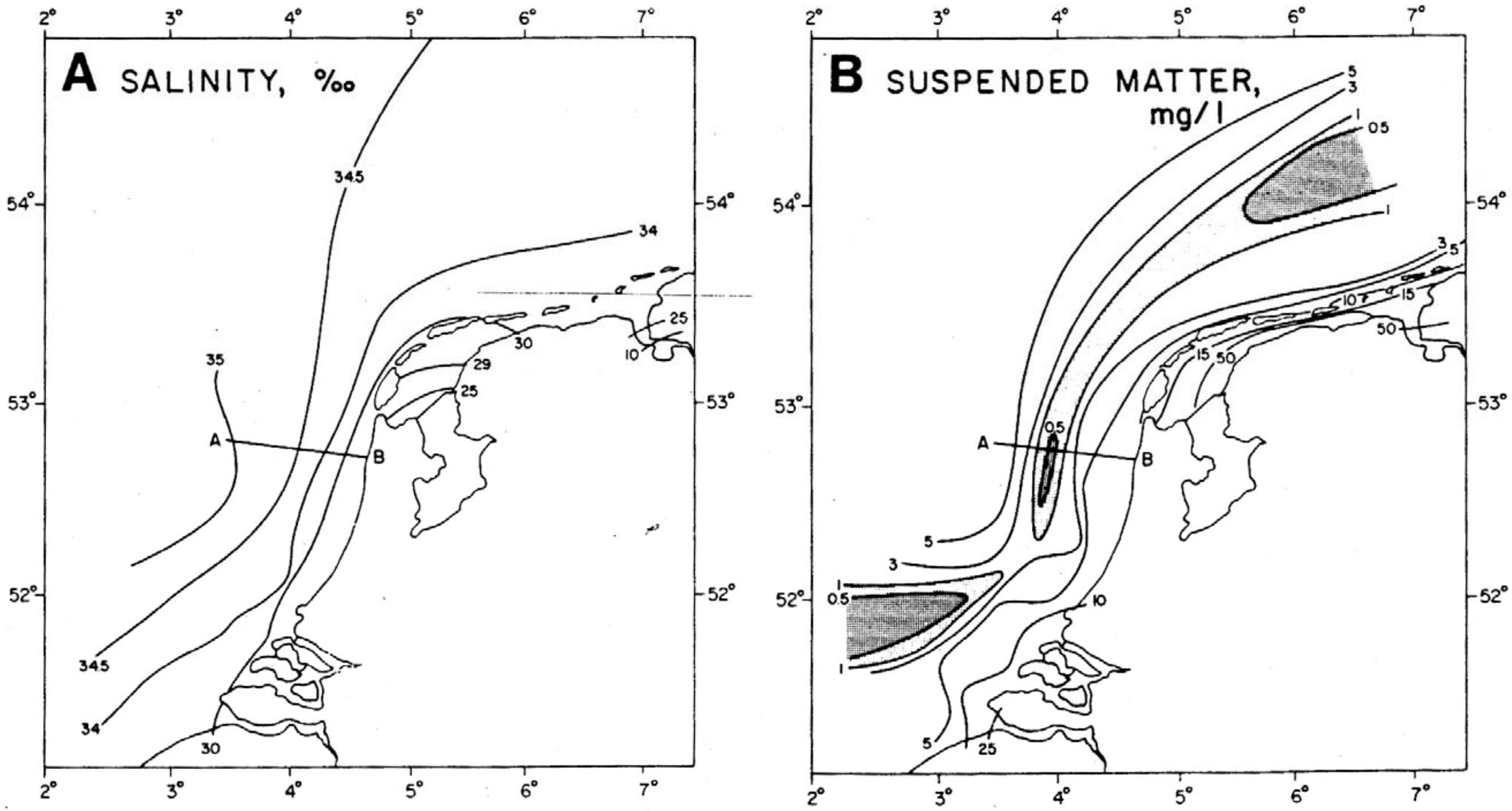


- Shallow Tidal Flats
- Deep Channels
- Settling Lag
- Scour Lag
- Asymmetry of Tides



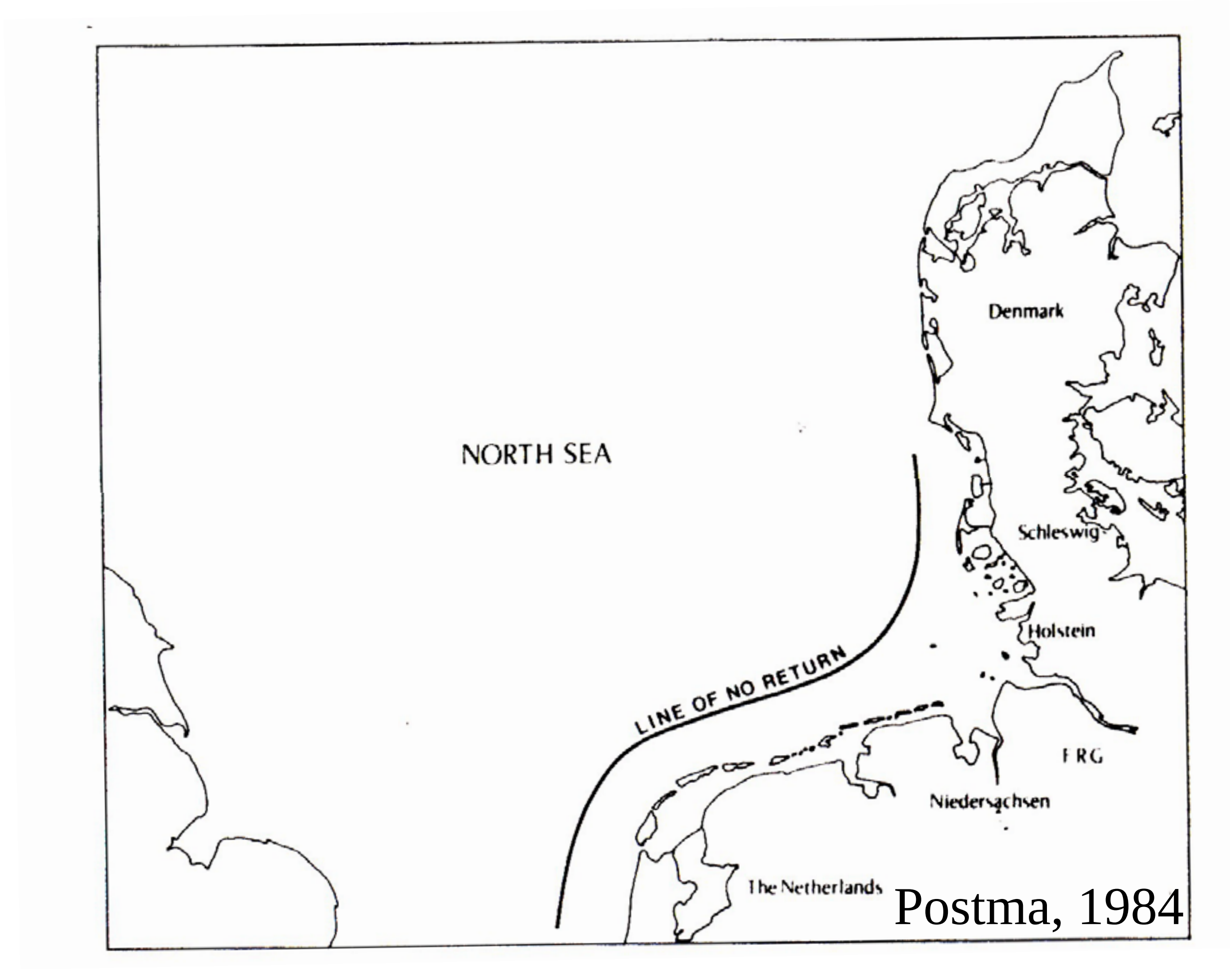
Van Straaten & Kuenen, 1957, Postma 1961

Accumulation along the North Sea Coast toward the Wadden Sea (Postma,1981)



Line of "No Return":

Wadden Sea traps Organic Matter from a larger area than the off-shore equivalent



Postma, 1984

Driver: along-shore estuarine circulation

Suspended Matter Accumulation in the Wadden Sea:
-the classical view-

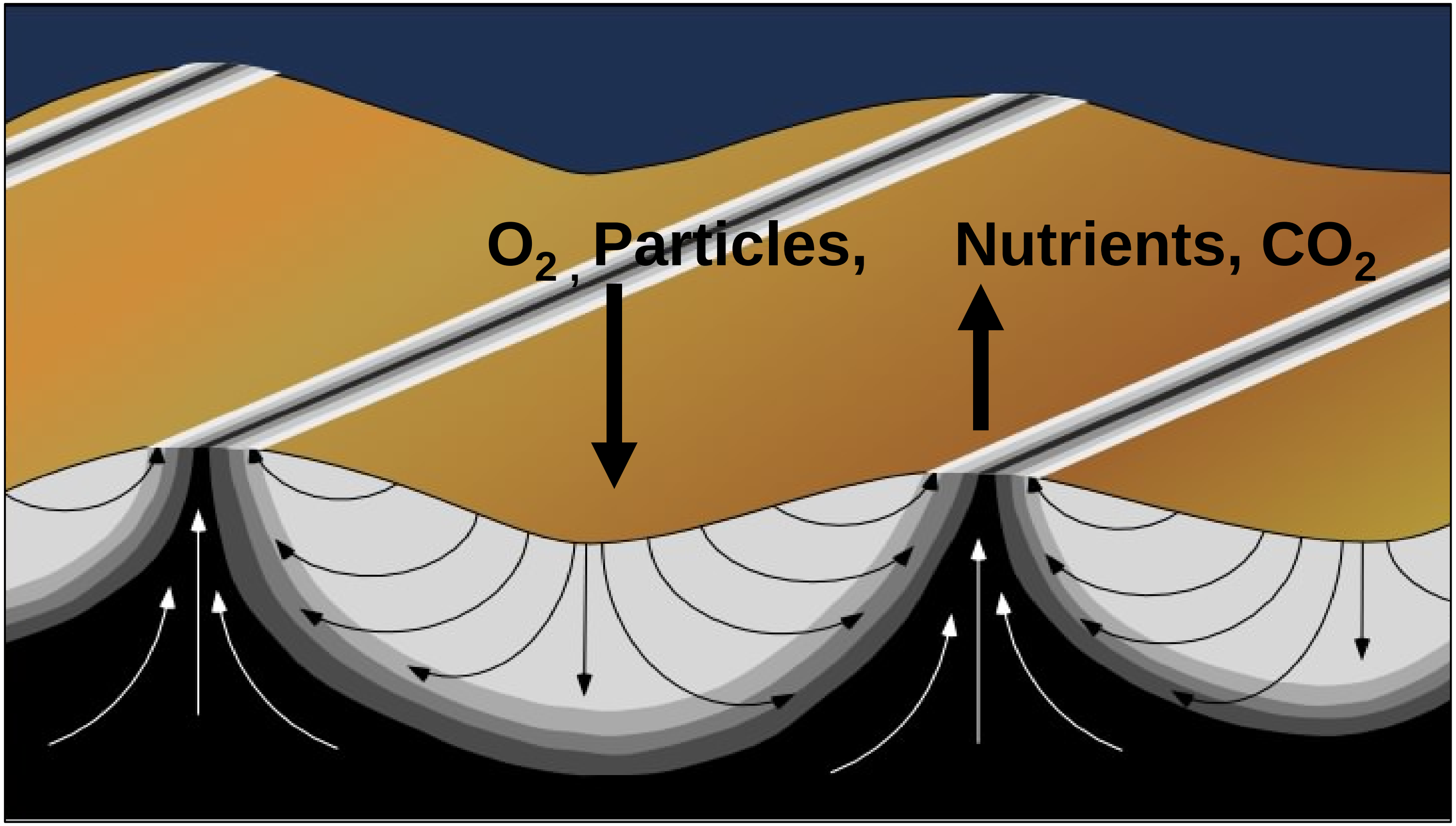
Sediments viewed upon as being cohesive

- Accumulation from the North Sea
- Physical Factors
  - Scour – Lag
  - Settling - Lag
  - Asymmetry of the tide
- Biological Factors
  - Filter Feeders
  - Benthic Diatoms

Suspended Matter Accumulation in the Wadden Sea:
- the role of permeable sands -

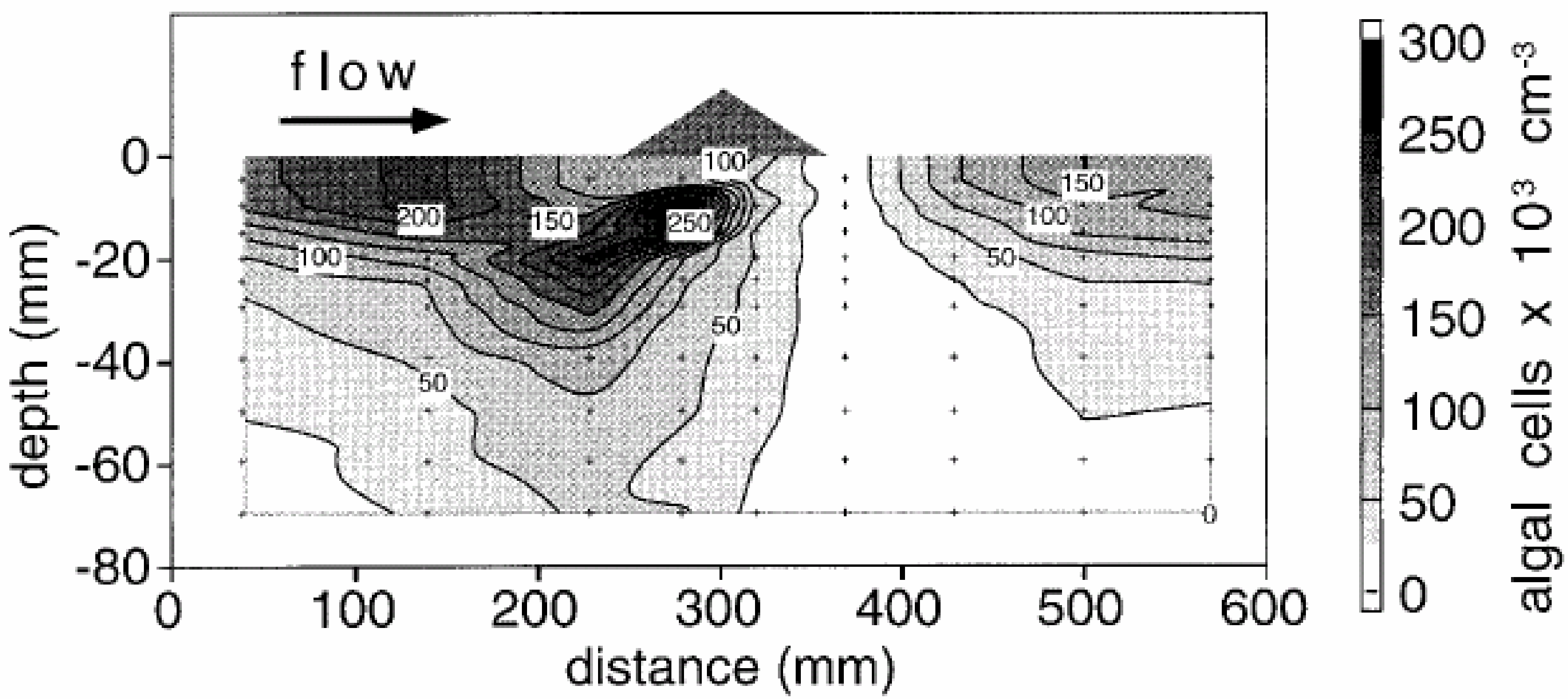
Ripple formation

- leads to complex patterns of water inflow and outflow
- Filtering of particles
- Rapid transport of solutes in and out of these sediments

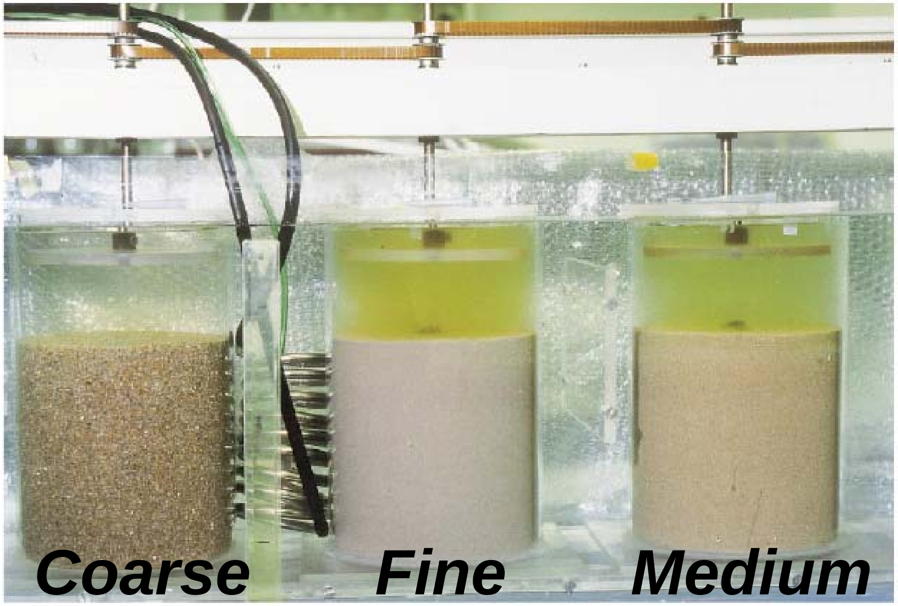


After Precht et al. 2004

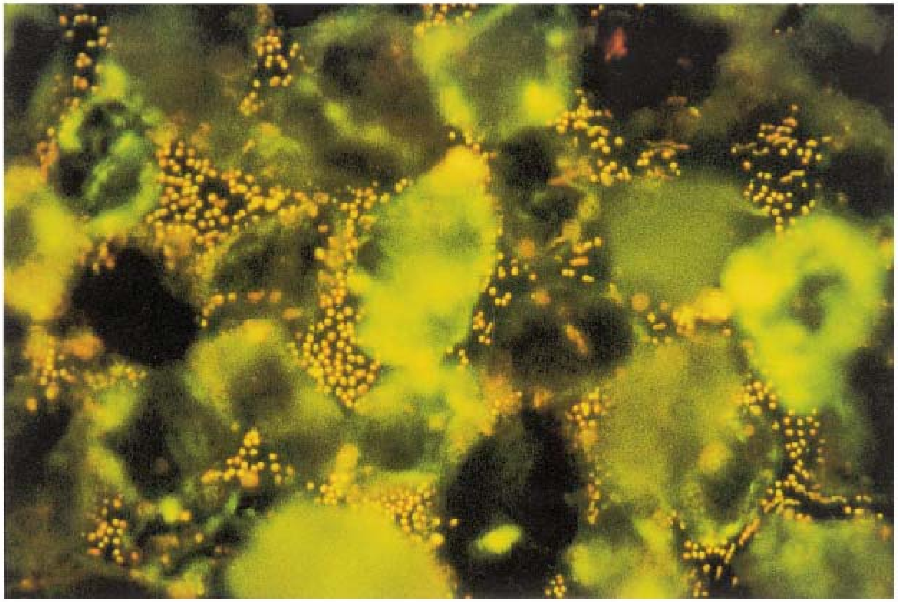
Algae are transported deep into permeable sands



From Huettel & Rusch, 2000



Coarse sands filter faster

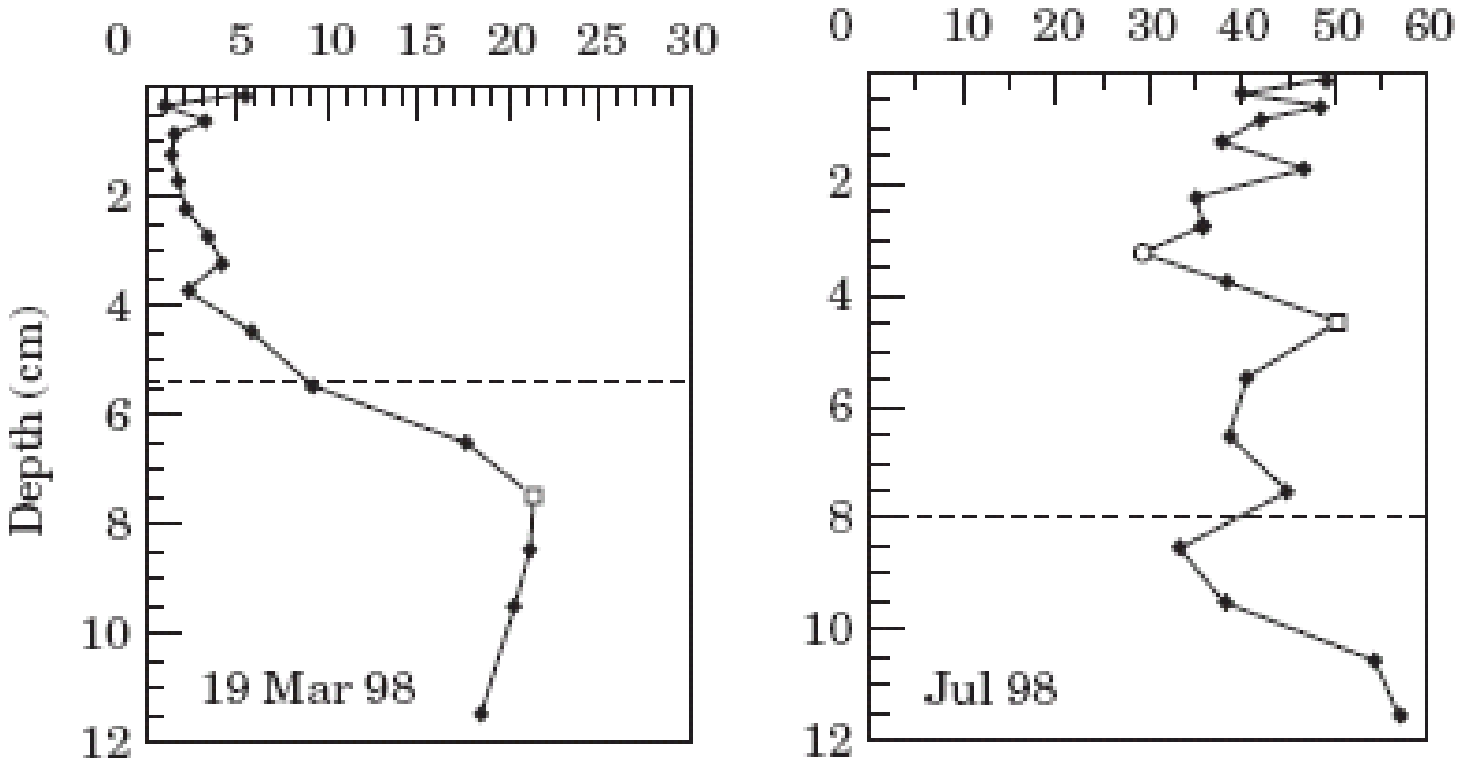


Much space between the sand grains

From Huettel & Rusch, 2000

Sandy Sediments accumulate fines during Summer (exposed tidal flat, Sylt)

fraction of fines in sediment (mg/g)



Rusch et al, 2000

Filtration Rates in Wadden Sea Sands

- Permeable sands: ~100 l m^{-2} day^{-1}
  e.g. de Beer *et al.* (2005); COSA Results
- Water is passed at least every 20 days through sediment
- Comparable to (Basin-averaged):
  - Filtration by Lugworms (*Arenicola*) ~100 l m^{-2} day^{-1}
  - Filtration by Bivalves~ 200 l m^{-2} day^{-1}

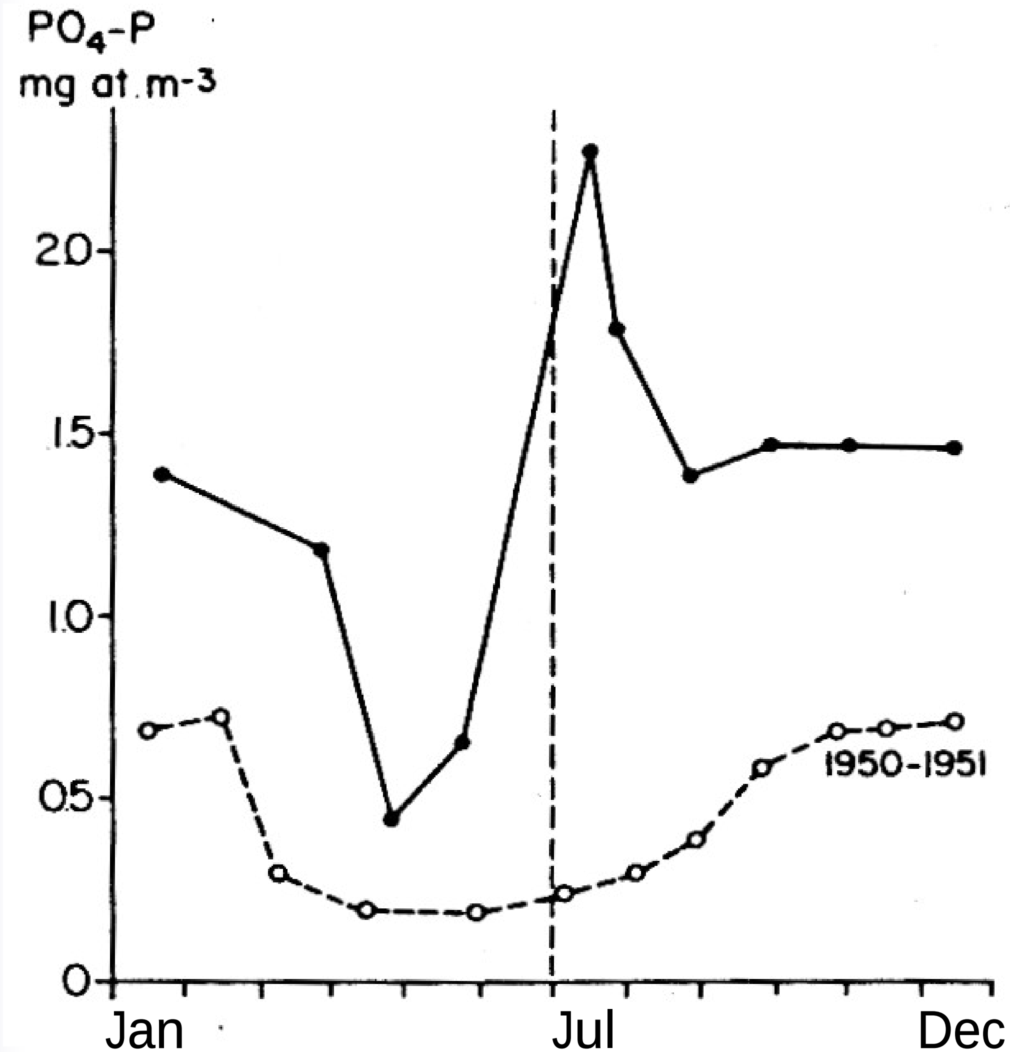
Suspended Matter Accumulation Summary

- SPM: inorganic and organic components
- Physical Factors
  - Settling Lag
  - Scour Lag
- Biological Factors
  - Filter Feeders
  - Benthic Diatoms
- Permeable Sediments as Filters

Role of Organic Matter in the Eutrophication "History" of the Wadden Sea

- Postma (1954):
  - Estimated Particulate Organic Matter import from the North Sea: ~80 gC m^{-2} y^{-1}
    based on PO_4 gradients between North Sea and Wadden Sea
- De Jonge & Postma (1974):
  - Compared PO_4 Dynamics between 1950 and 1970
  - Concluded a 3-fold increase of OM import to ~240 gC m^{-2} y^{-1}

PO_4 cycle in the Wadden sea intensified by increased riverine P load



1970-1972

Rhine P Load: ~16 Mol s^{-1}

C-Import: 240 gC m^{-2} y^{-1}

1950-1951

Rhine P Load: ~5 Mol s^{-1}

C-Import: 80 gC m^{-2} y^{-1}

Postma, 1981

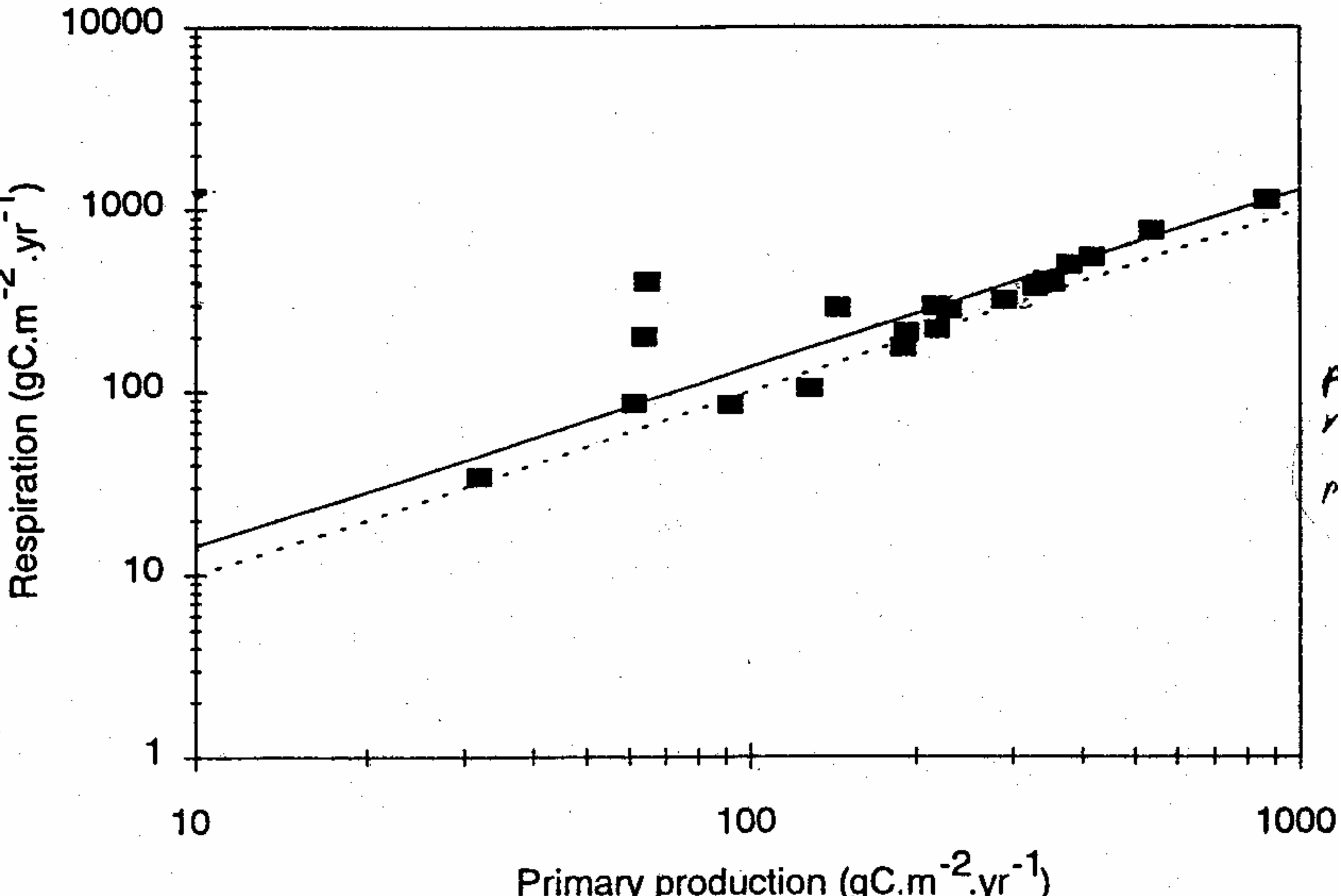
de Jonge & Postma, 1974

Carbon Budgets from the Wadden Sea ~1975-1995

Area	Production (g/m^2•a)	Remineralisation (g/m^2•a)	Nett. Import (g/m^2•a)
W. Dutch Wadden Sea	**298**	**450**	**152**
Ems Estuary	**210**	**280**	**80**
Sylt Romo Basin	**309**	**419**	**110**

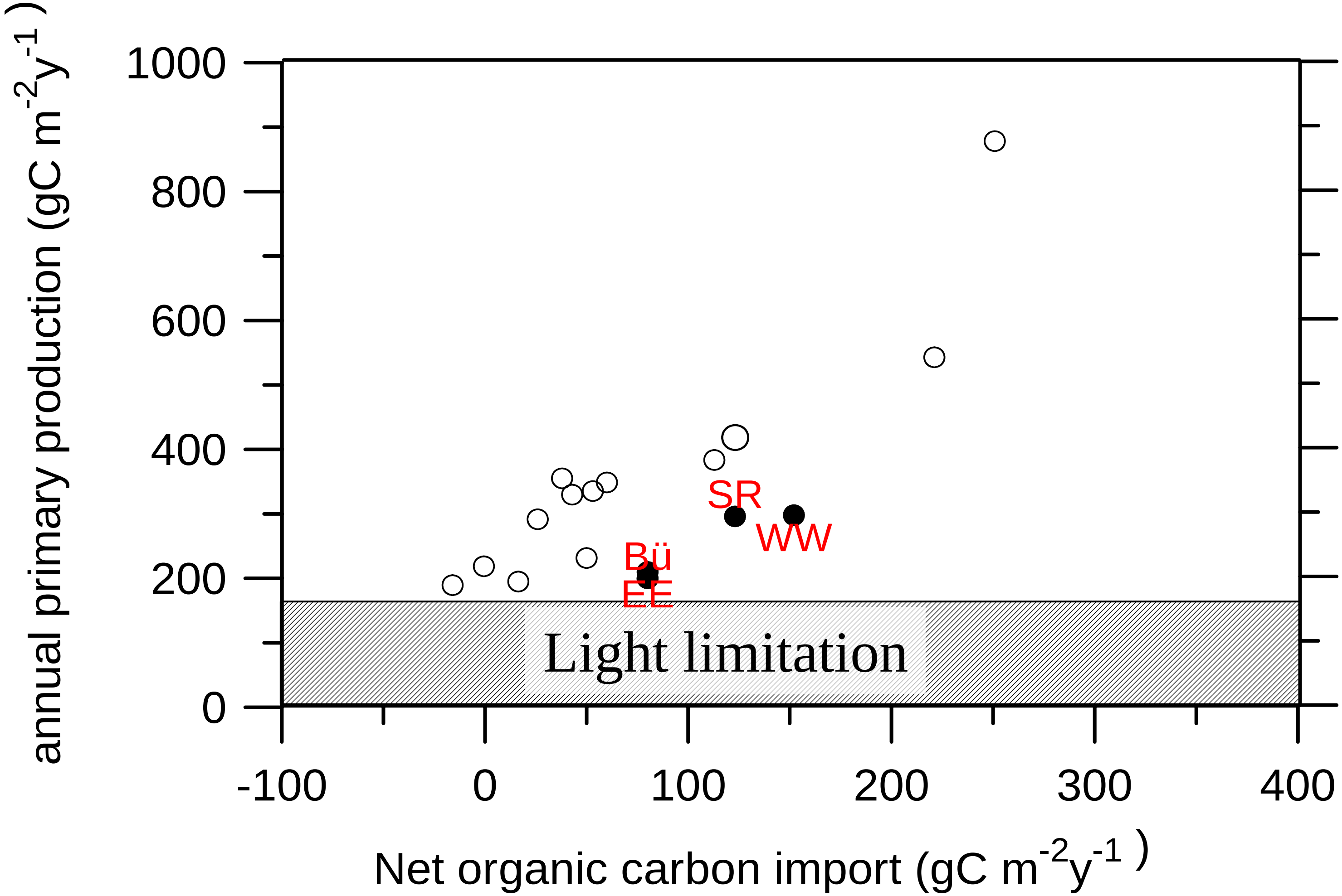
Adapted from van Beusekom et al., 1999

Temperate Tidal Estuaries are Heterotrophic



Heip et al., 1995

Import of Organic Matter Stimulates Productivity



after Heip et al., 1995

Role of Organic Matter in the Eutrophication "History" of the Wadden Sea
- Summary-

- Wadden Sea is heterotrophic
- Source: North Sea
- Increased Import since ~1950's
- At present about 100 gC m^{-2} y^{-1} are imported

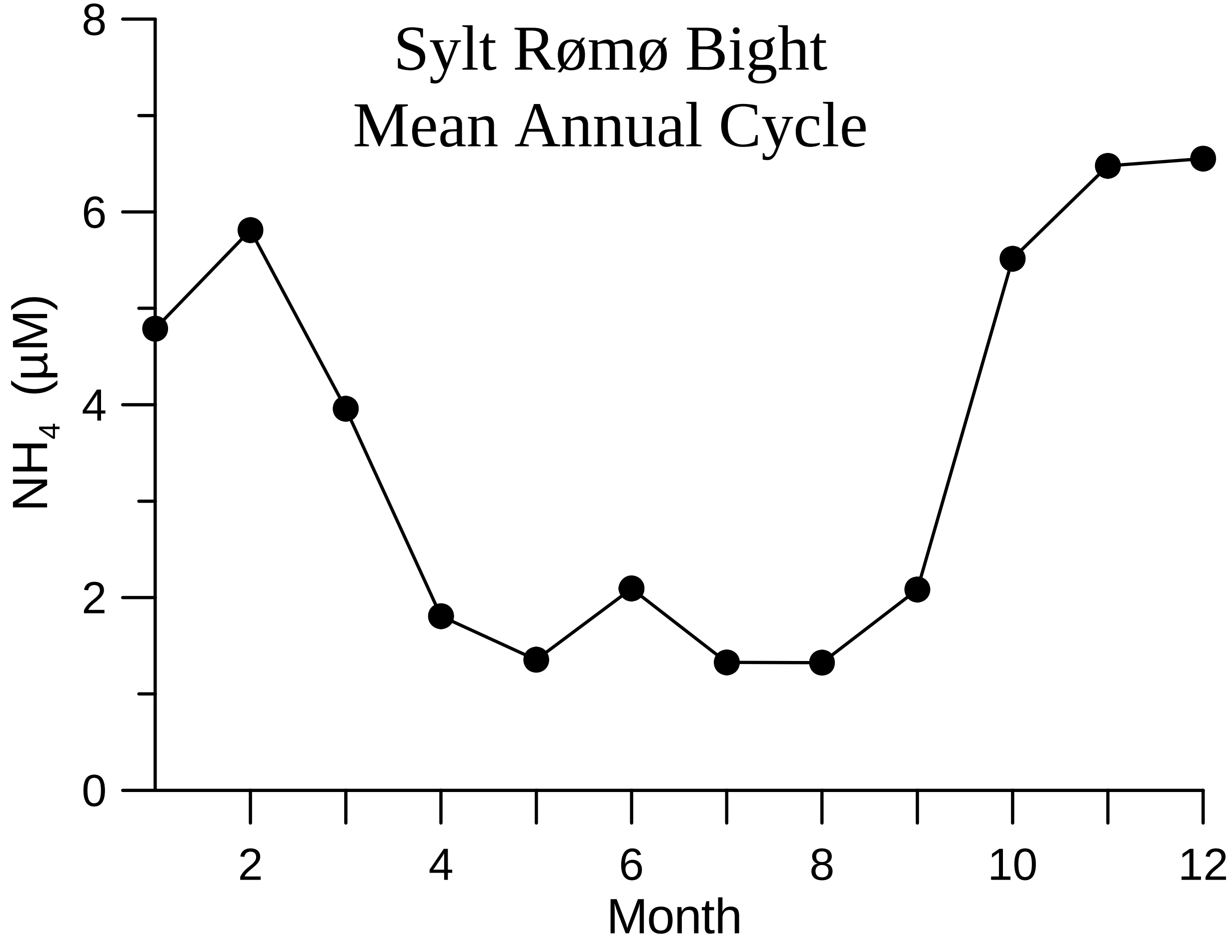
Long-Term SPM Dynamics in the Wadden Sea: Interannual Organic Import Variations?

Carbon budgets are tedious

- How to document changes in Import?
- How to detect any regional differences?

Seasonal Cycle of Nutrients
as Indicator of Changes
in the Intensity of the Annual Carbon Cycle

Changes in the Seasonal Cycle of Nitrogen (NH_4 + NO_2 levels in autumn)



Van Beusekom, unpublished

Catchment area

Source: Wadden Sea Quality Status Report 1999

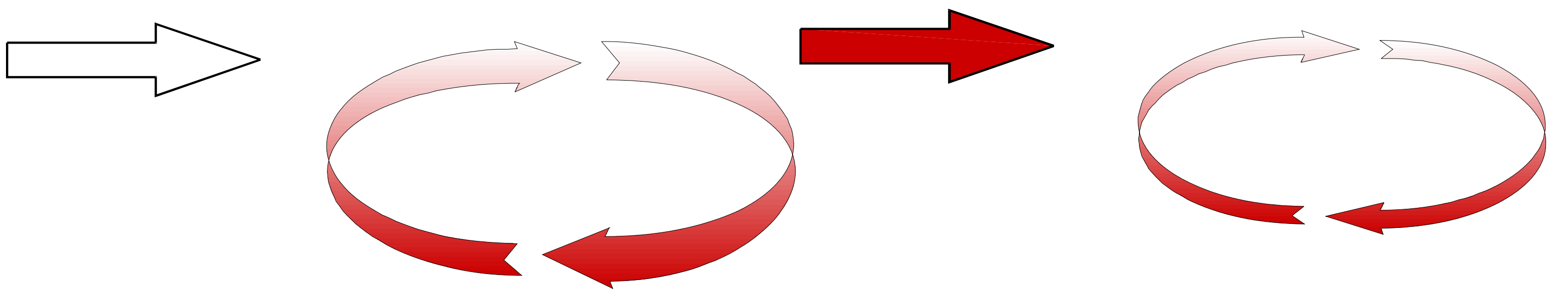
Conceptual Model

River **North Sea** *Wadden Sea*

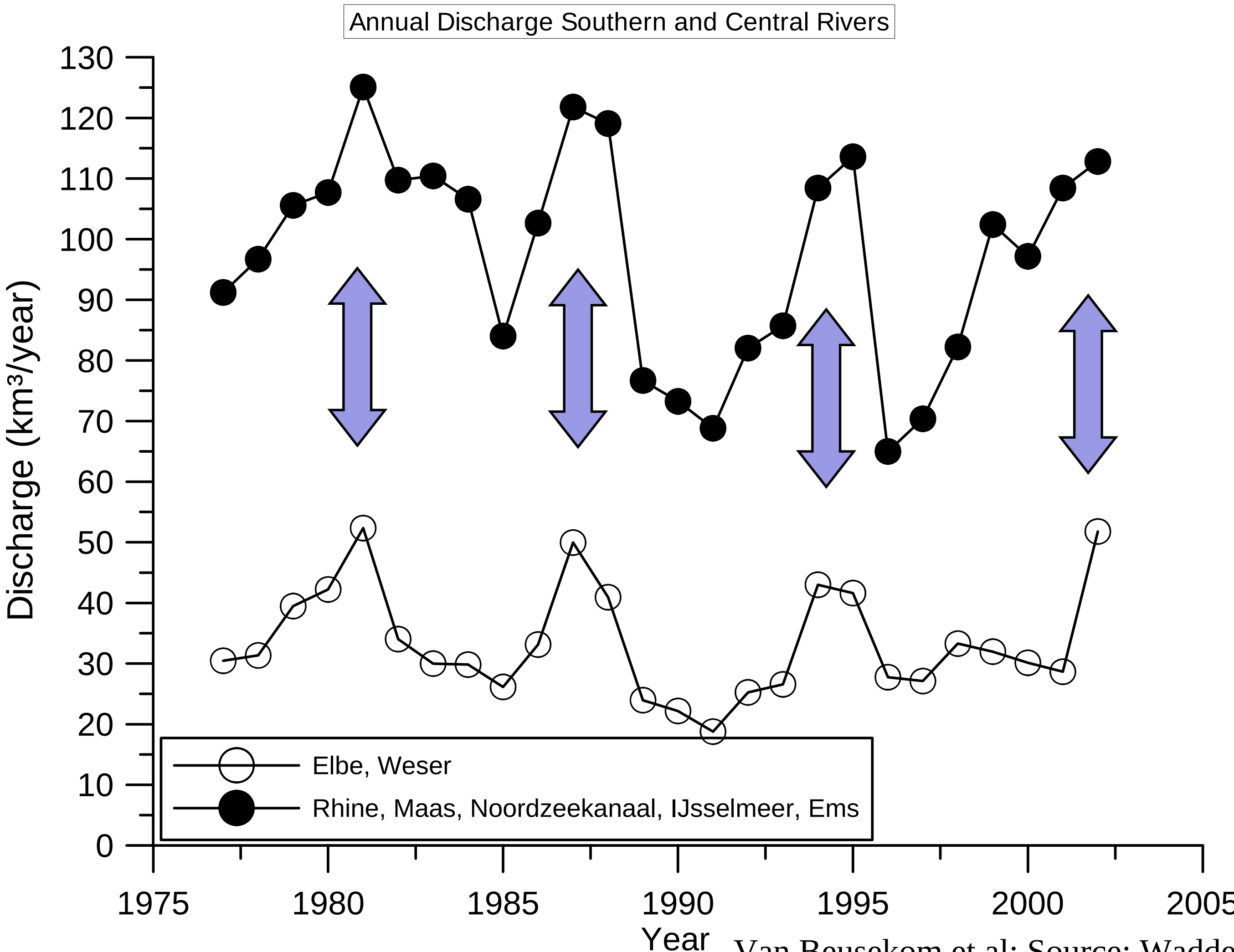
Nutrient Input **OM Import**

Production/
Remineralisation

Remineralisation/
Production

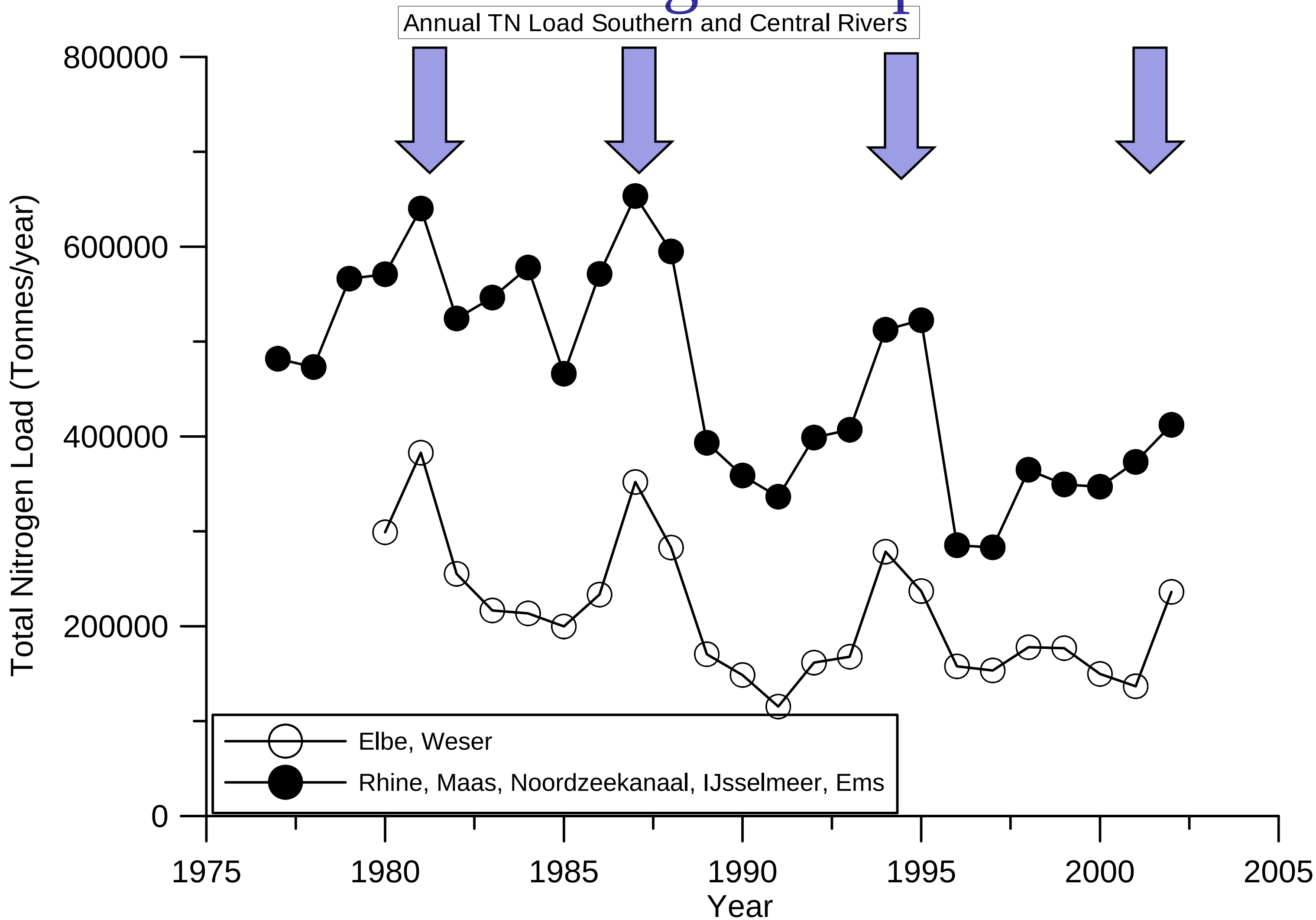


Trends in River input: Discharge



Van Beusekom et al: Source: Wadden Sea Q S R 2004

Trends in River Input
Total Nitrogen - Input



Van Beusekom et al: Source: Wadden Sea Q S R 2004

Changes in the seasonal cycle of nitrogen ($NH_4 + NO_2$ levels in autumn)

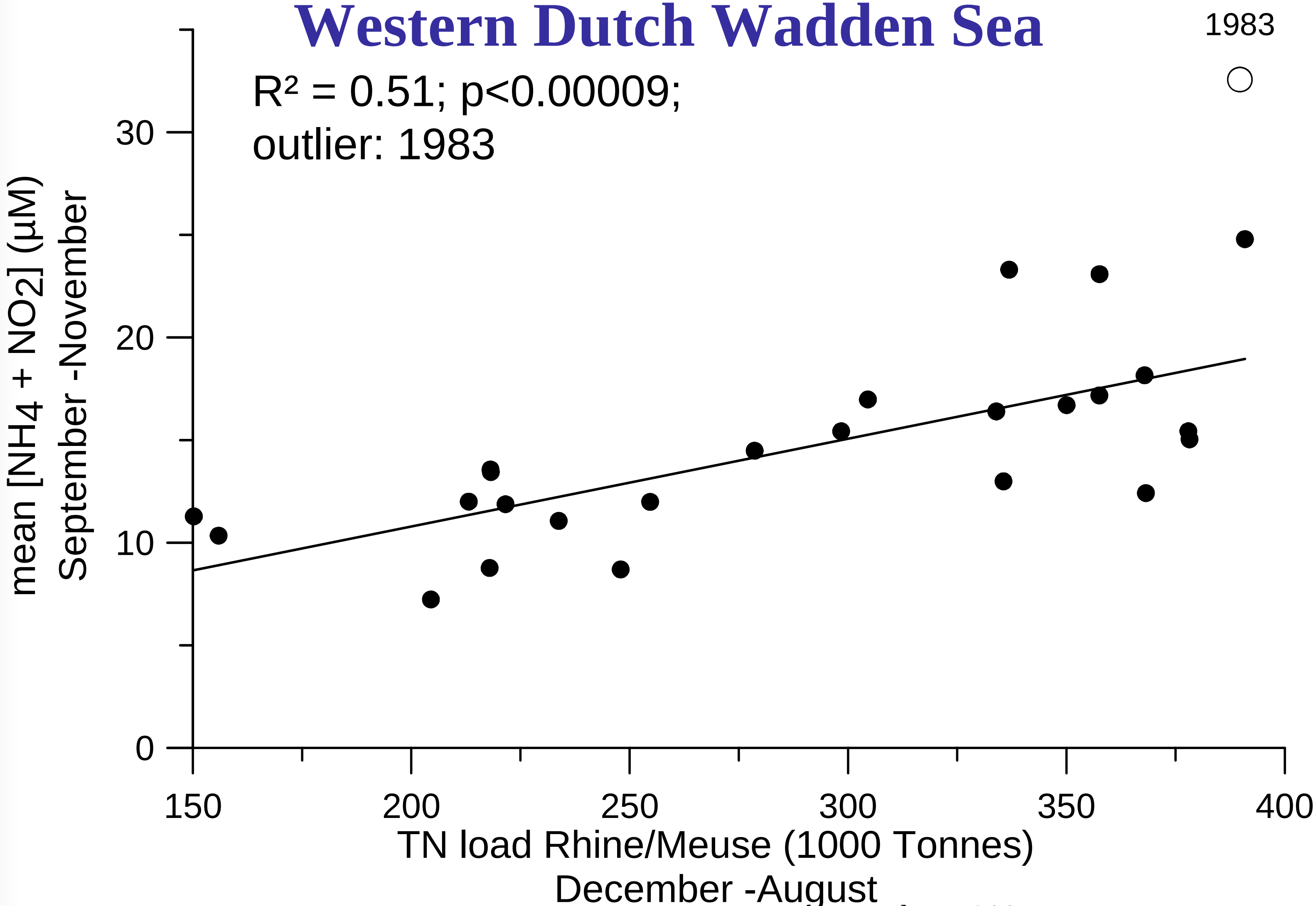
Multiple regression analysis

- dependent:
  - Autumn $NH_4 + NO_2$
- independent:
  - Riverine input (Rhine Meuse; Dec-Aug)
  - Chlorophyll (Sep - Nov)
  - Temperature (Sep - Nov)

Changes in the seasonal cycle of nitrogen (NH_4 + NO_2 levels in autumn)

- Significant effect of Rhine/Meuse in the Southern Wadden Sea
  - Western Dutch Wadden Sea
  - Eastern Dutch Wadden Sea
  - Norderney
- No significant relations in the Northern Wadden Sea

Changes in the seasonal cycle of nitrogen
(NH_4 + NO_2 levels in autumn)
Western Dutch Wadden Sea

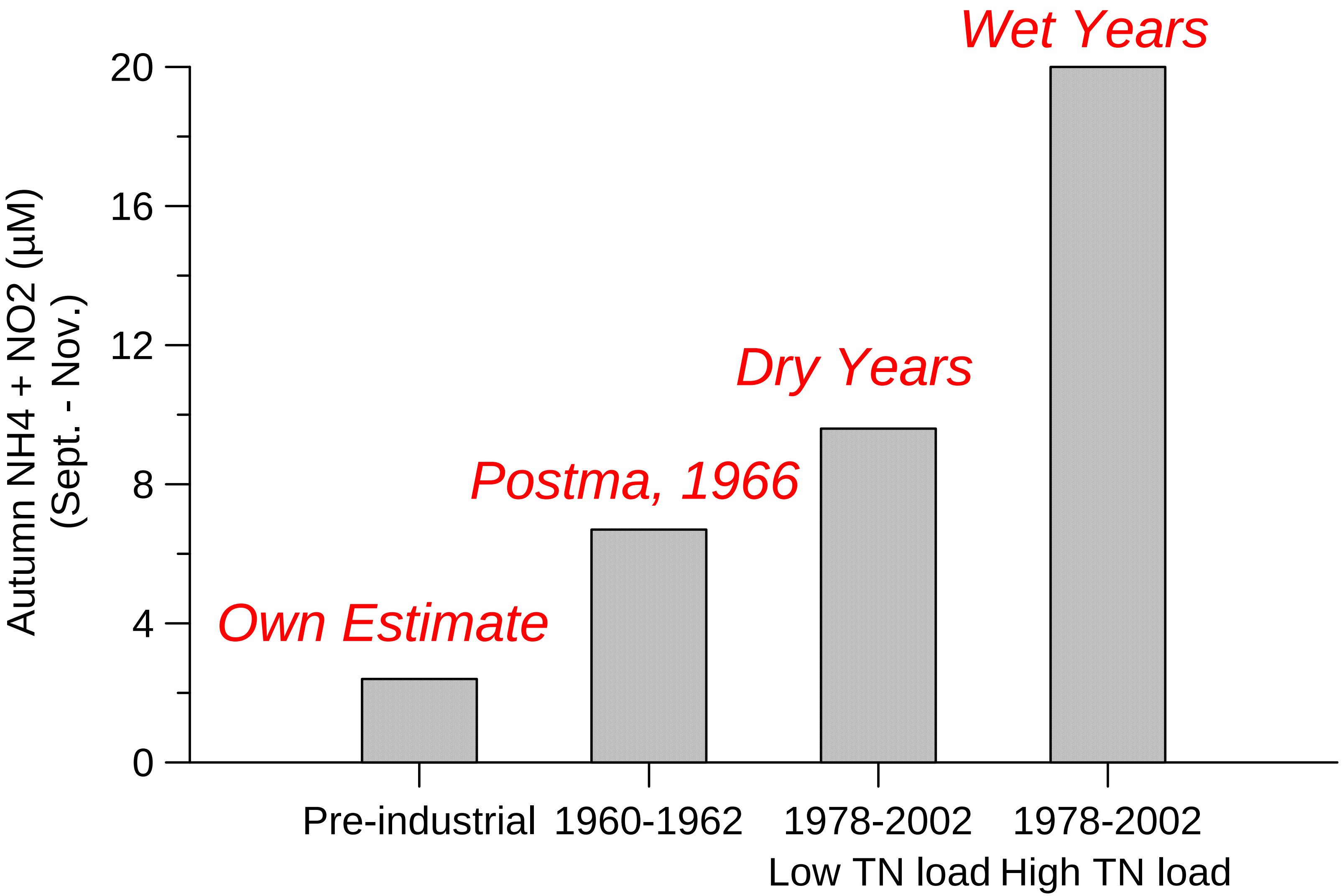


Van Beusekom, 2005

Changes in the seasonal cycle of nitrogen

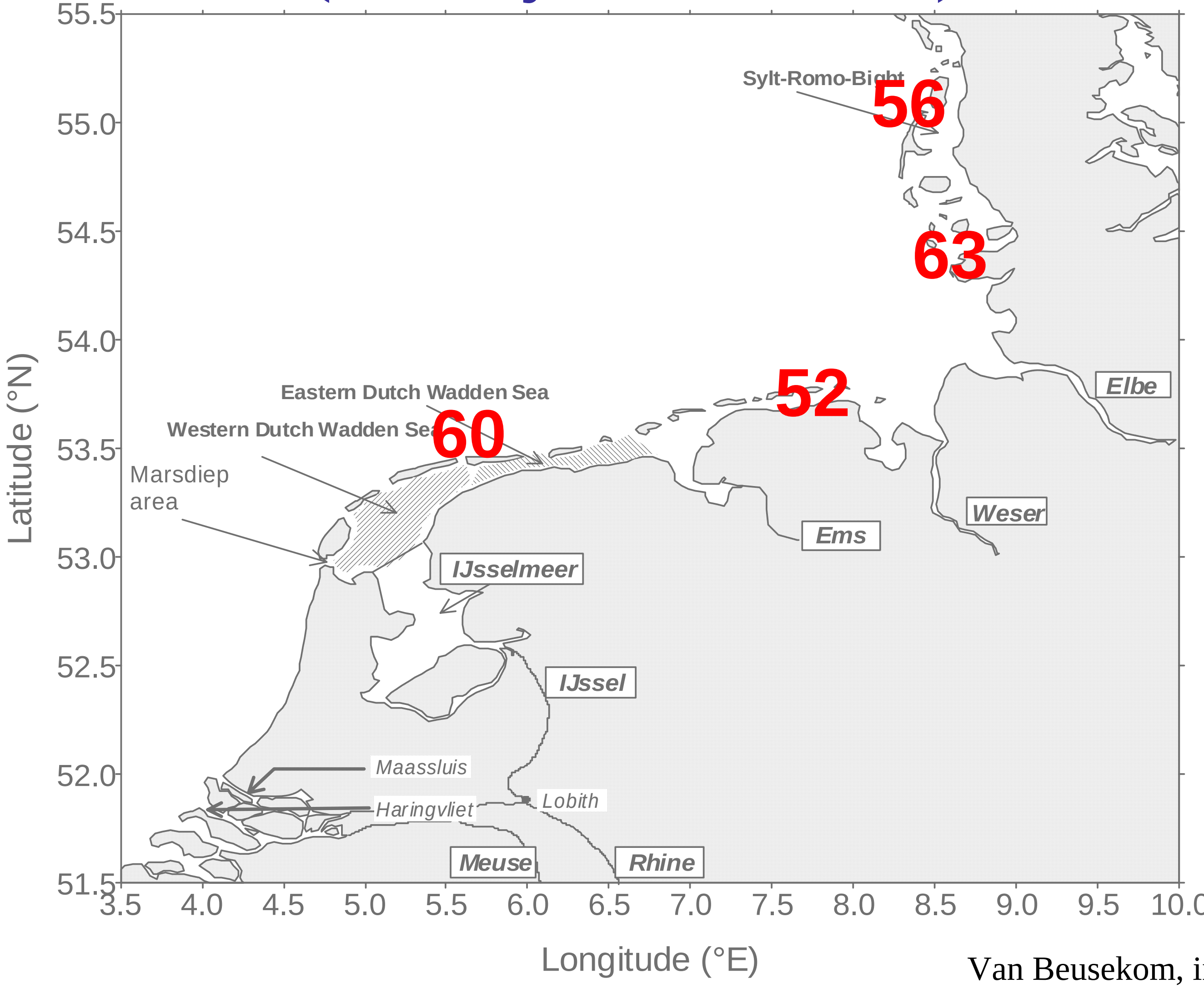
(NH_4 + NO_2 levels in autumn)

Western Dutch Wadden Sea



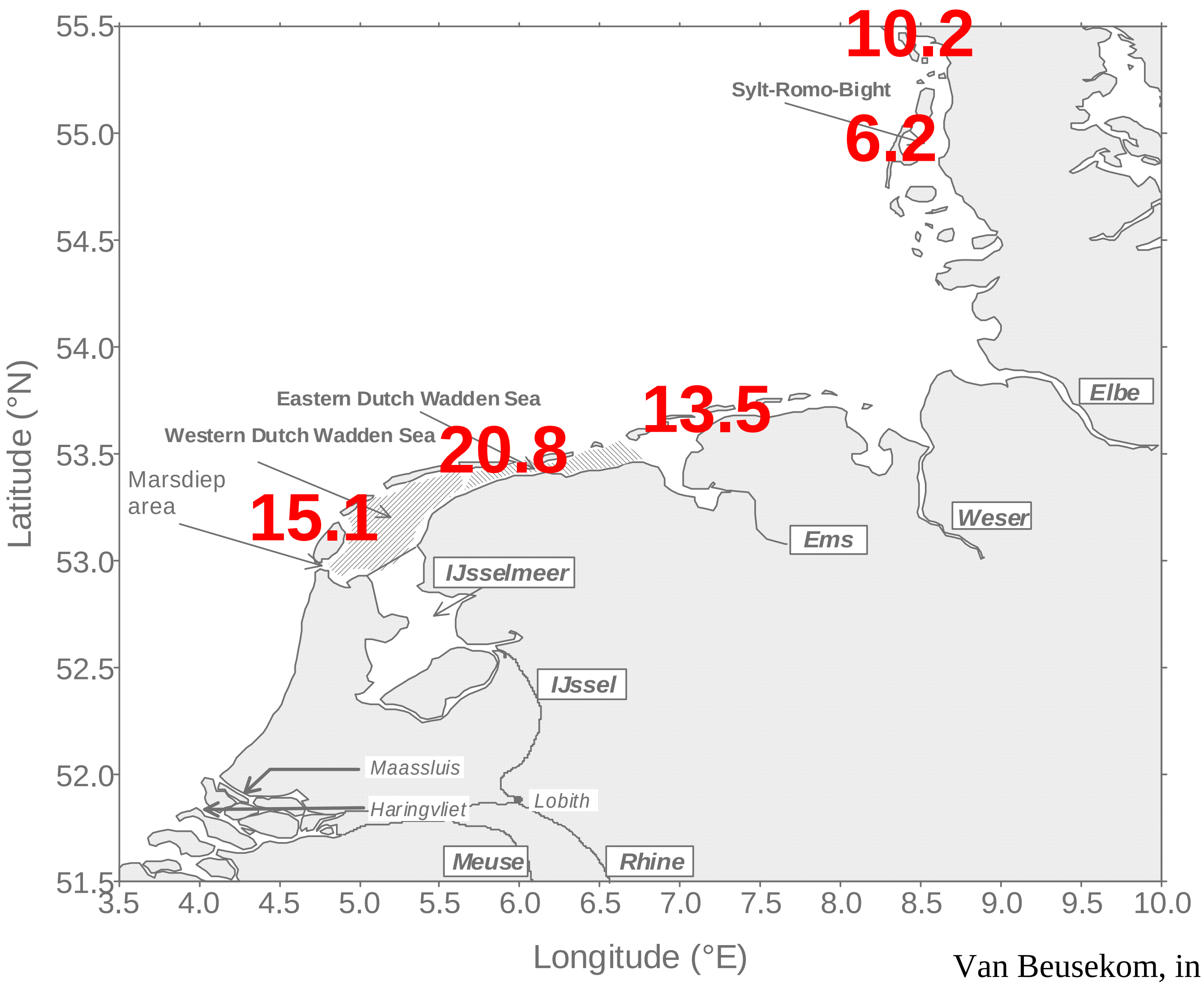
After van Beusekom, 2005

No Spatial Trends in Winter NOx (µM) (salinity-normalized)



Van Beusekom, in prep

Spatial Trends in Autumn $NH_4 + NO_2$ (µM)

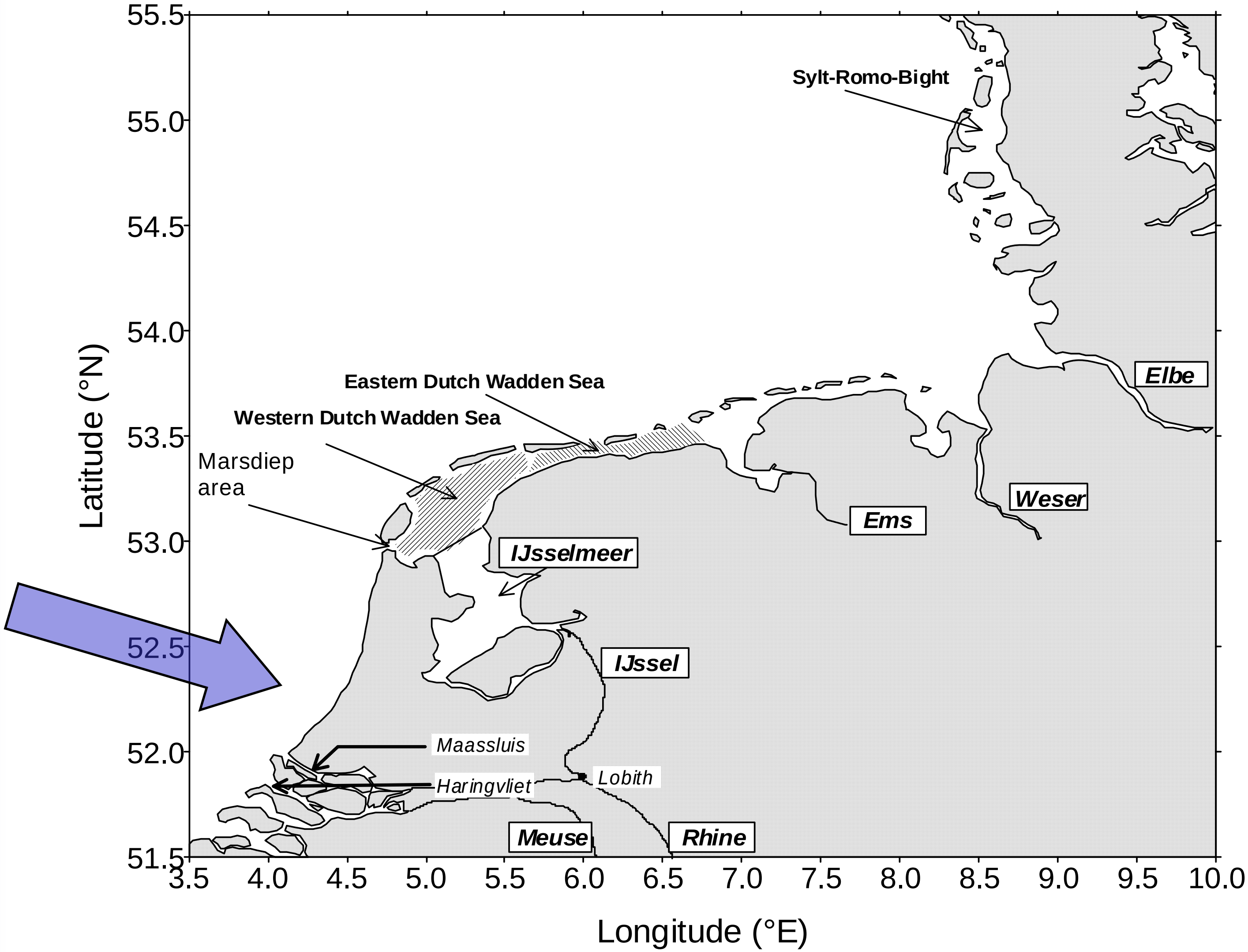


Van Beusekom, in prep

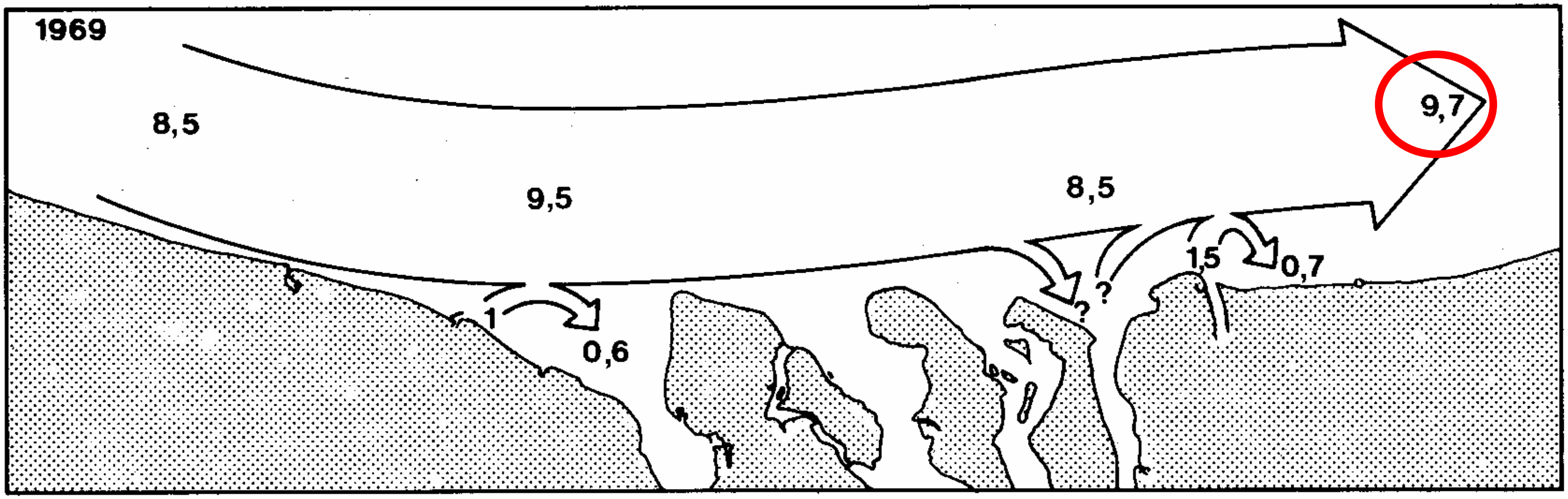
Long-Term SPM Dynamics in the Wadden Sea: Interannual Organic Matter Import Variations?

- Riverine TN input
  - Interannual TN Variability related to discharge
  - Long-term decrease (de-eutrophication)
- Response of the Seasonal Nitrogen Dynamics
- NH_4 + NO_2 in autumn are good indicators of OM turnover
- Northern Wadden Sea less eutrophic than the Southern part
- Compared to historic estimates:
  five-fold increase in OM Dynamics

Long-Term SPM Dynamics: The Dutch North Sea Coast



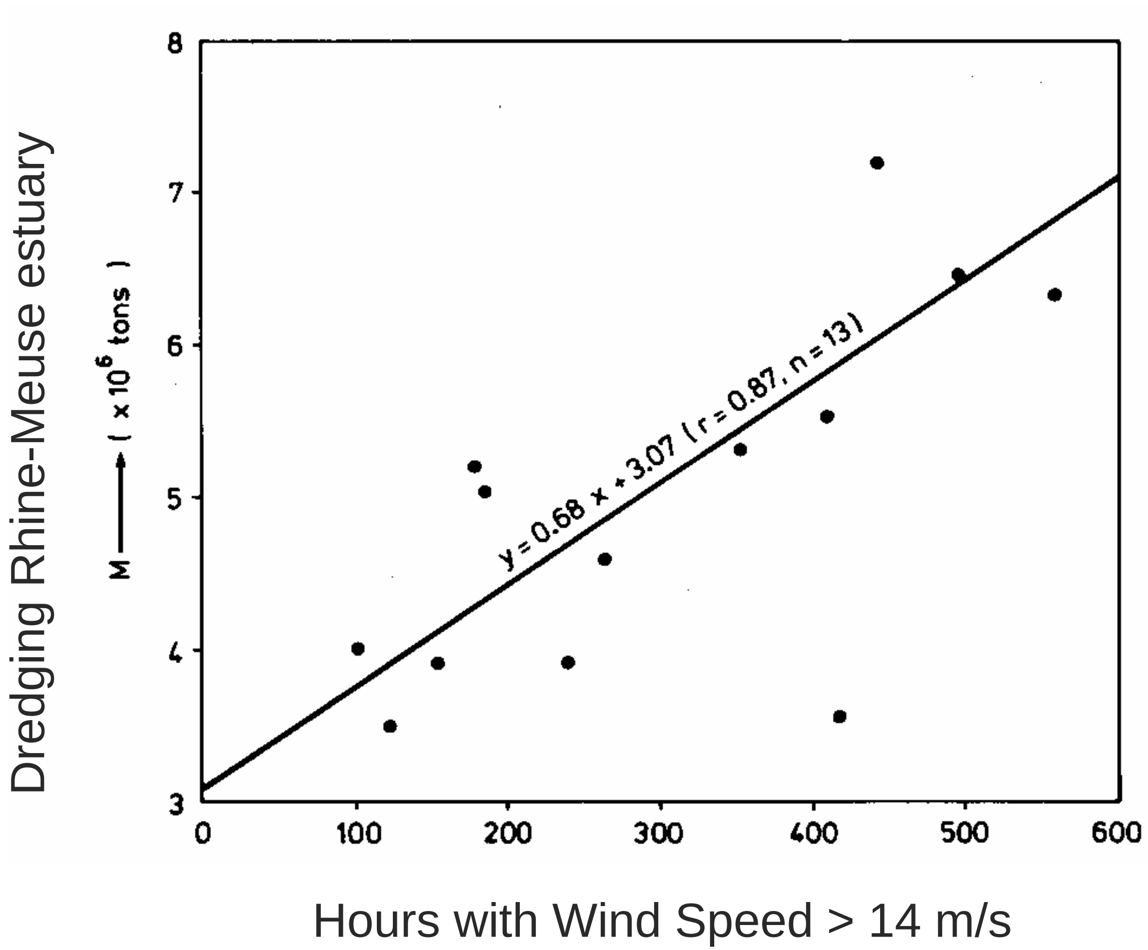
Long-Term SPM Dynamics: The Dutch North Sea Coast



1969	9.7 10^6 Tonnes y^{-1}
1970-1980	8.8 10^6 Tonnes y^{-1}
1980-1986	10.1 10^6 Tonnes y^{-1}
1986	6.8 10^6 Tonnes y^{-1}

Van Alphen, 1990

Long-Term SPM Dynamics: Wind?
Dutch North Sea Coast

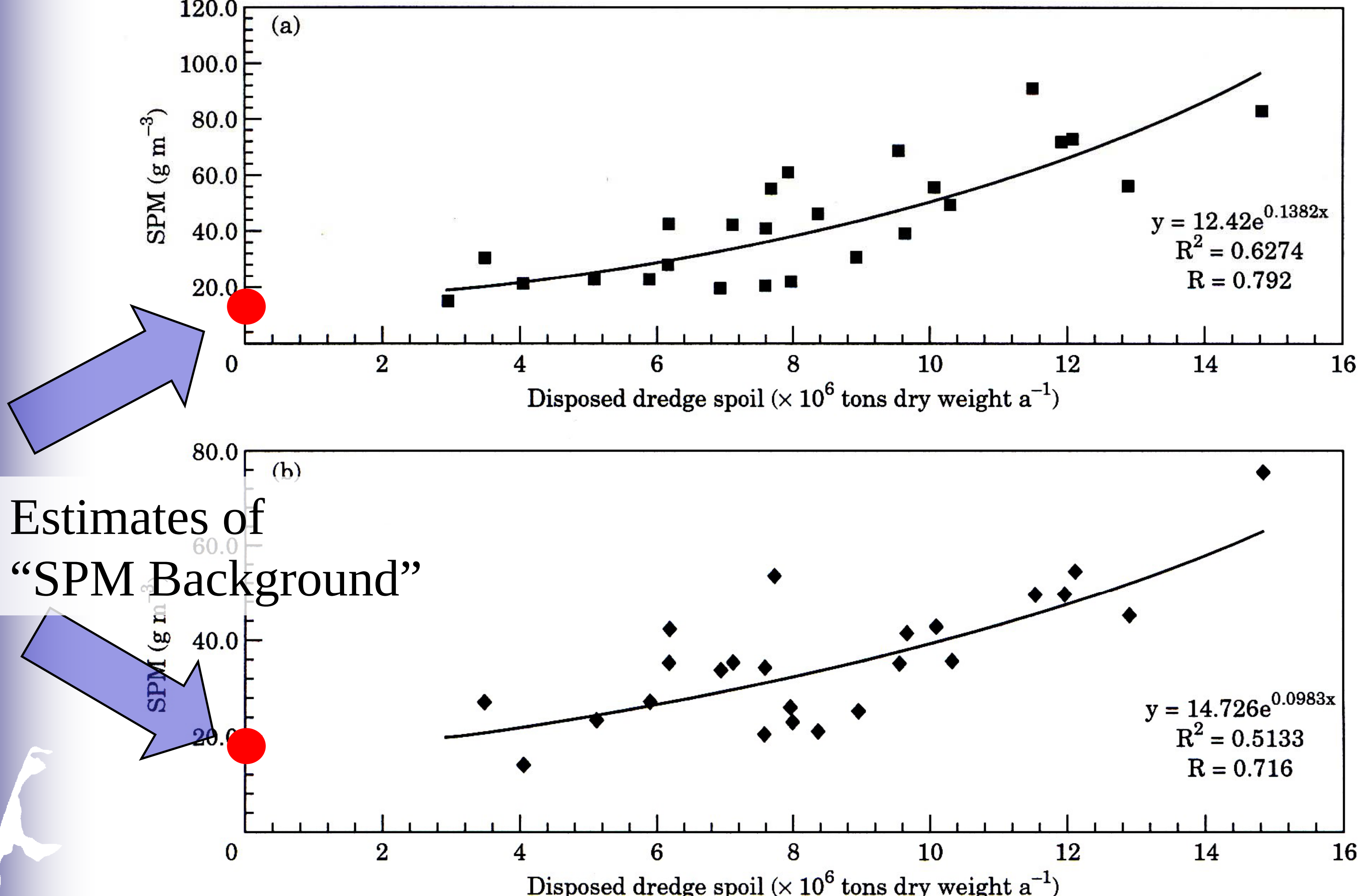


Wind Speed (resuspension) in Winter (quarter 4 and 1):

- Related to the mean SPM amounts off the Dutch Coast
- Related to the amount of dredging in the Rhine/Meuse Estuary

Van Alphen, 1990

Long-Term SPM Dynamics: Dredging? Western Dutch Wadden Sea



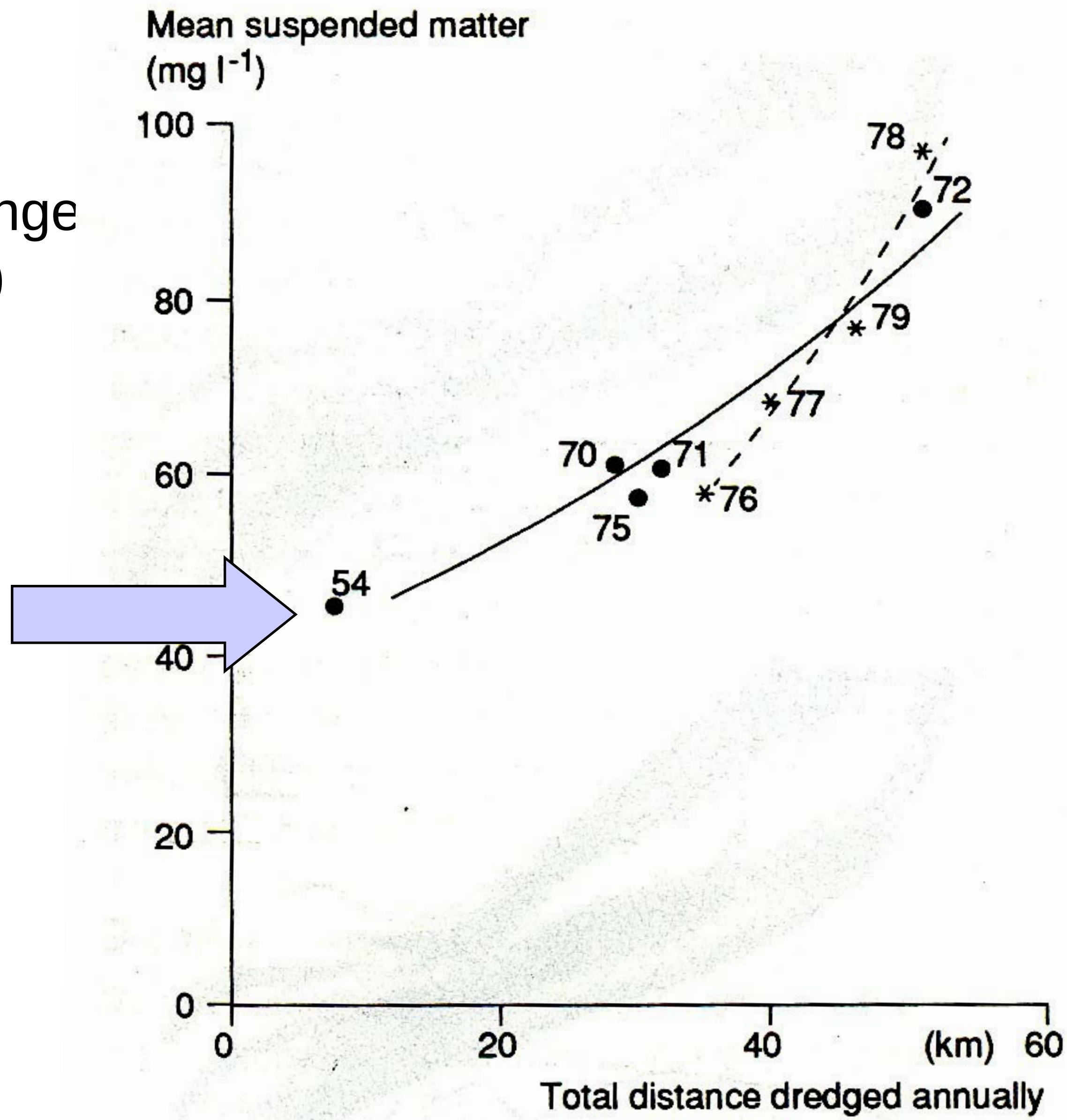
Estimates of "SPM Background"

De Jonge & de Jong, 2002

Long-Term SPM Dynamics in the Wadden Sea: Dredging?

Ems Estuary

- Increased tidal range (from 3.0 – 3.3 m)
- SPM Increase since 1954



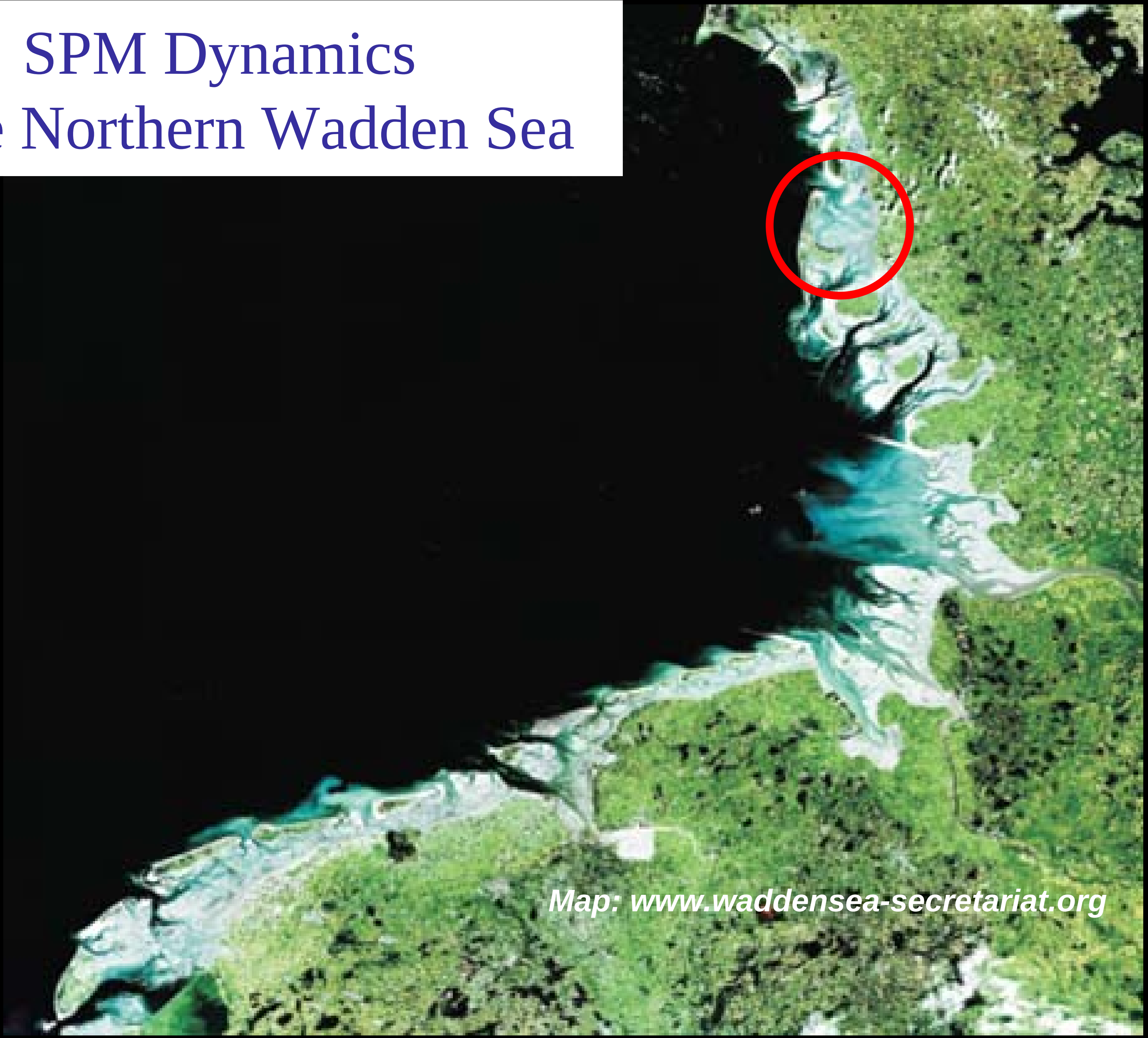
De Jonge, 1983

Long-Term SPM Dynamics
Dutch Wadden Sea and North Sea Coast
- Conclusions -

Present Wadden Sea Values:

- ~2 - 3 Times higher than ~50 years ago
- Large Interannual Variability
  - Wind?
  - Dredging?
  - Other Factors?

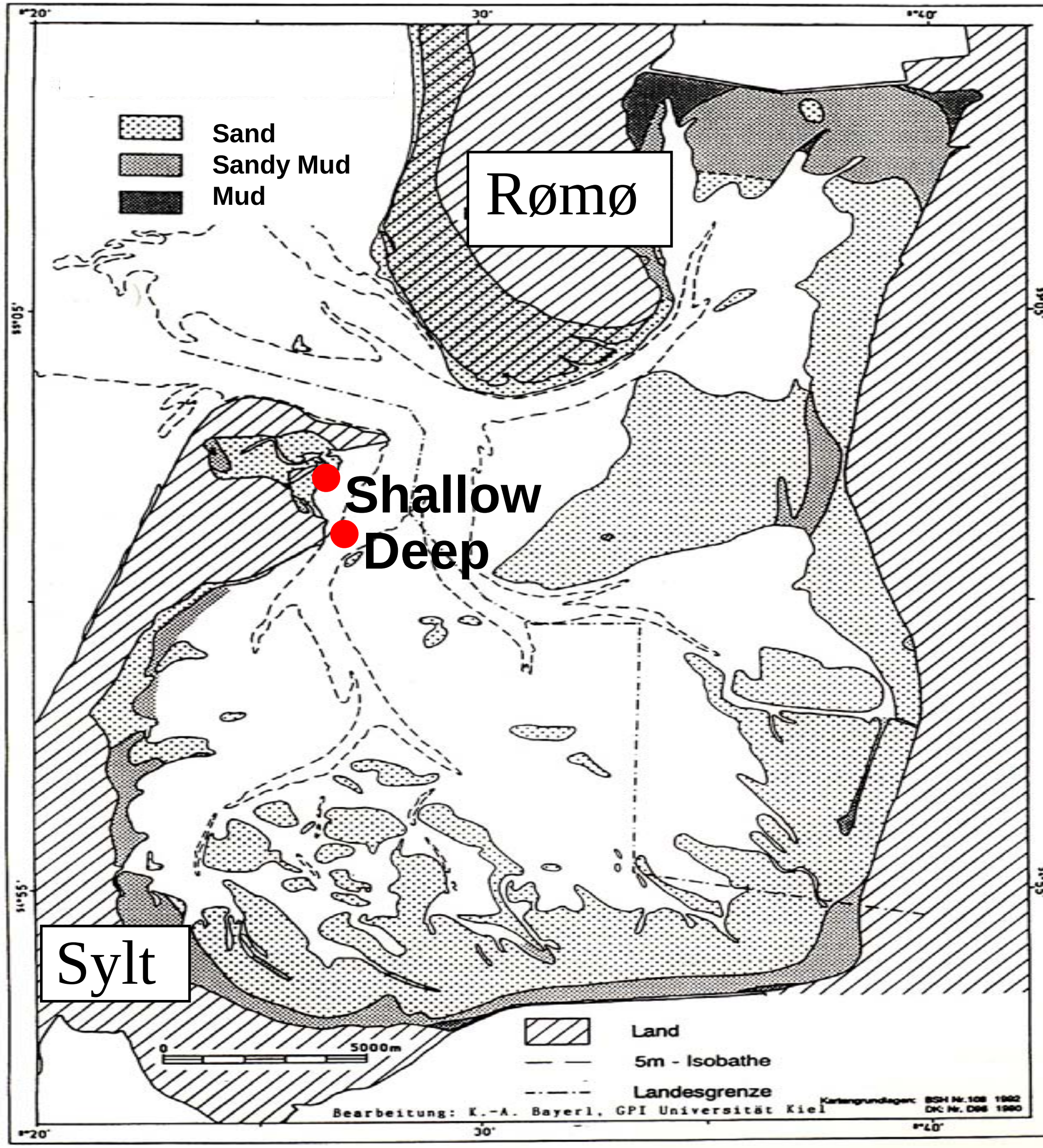
SPM Dynamics in the Northern Wadden Sea



Points to be addressed

- Seasonality
- Focus on winter
- Shallow Station:
  - Advection from Deep St
  - Wind
- Deep Station
  - Lag effect of Wind (Resuspension at the fringes)
- Interannual differences
  - Wind
  - Import of organic matter (and associated fines)

List Tidal Basin

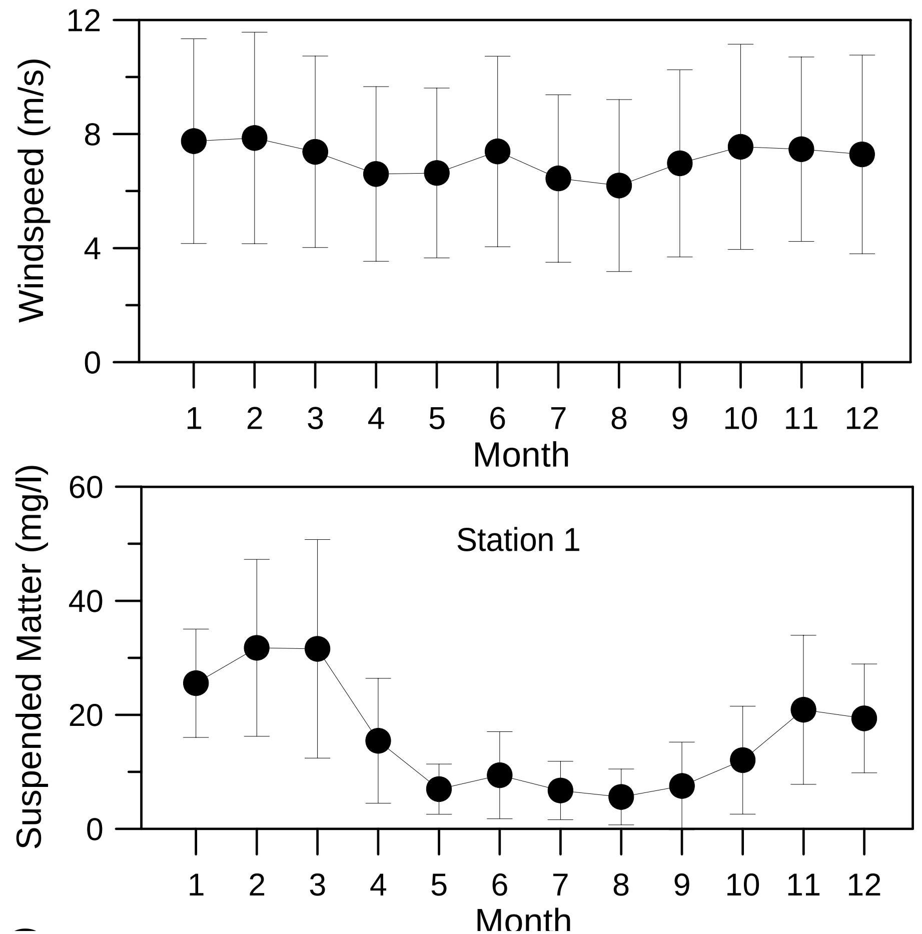


Bayerle et al. 1998

Seasonality
of Wind and Suspended Matter

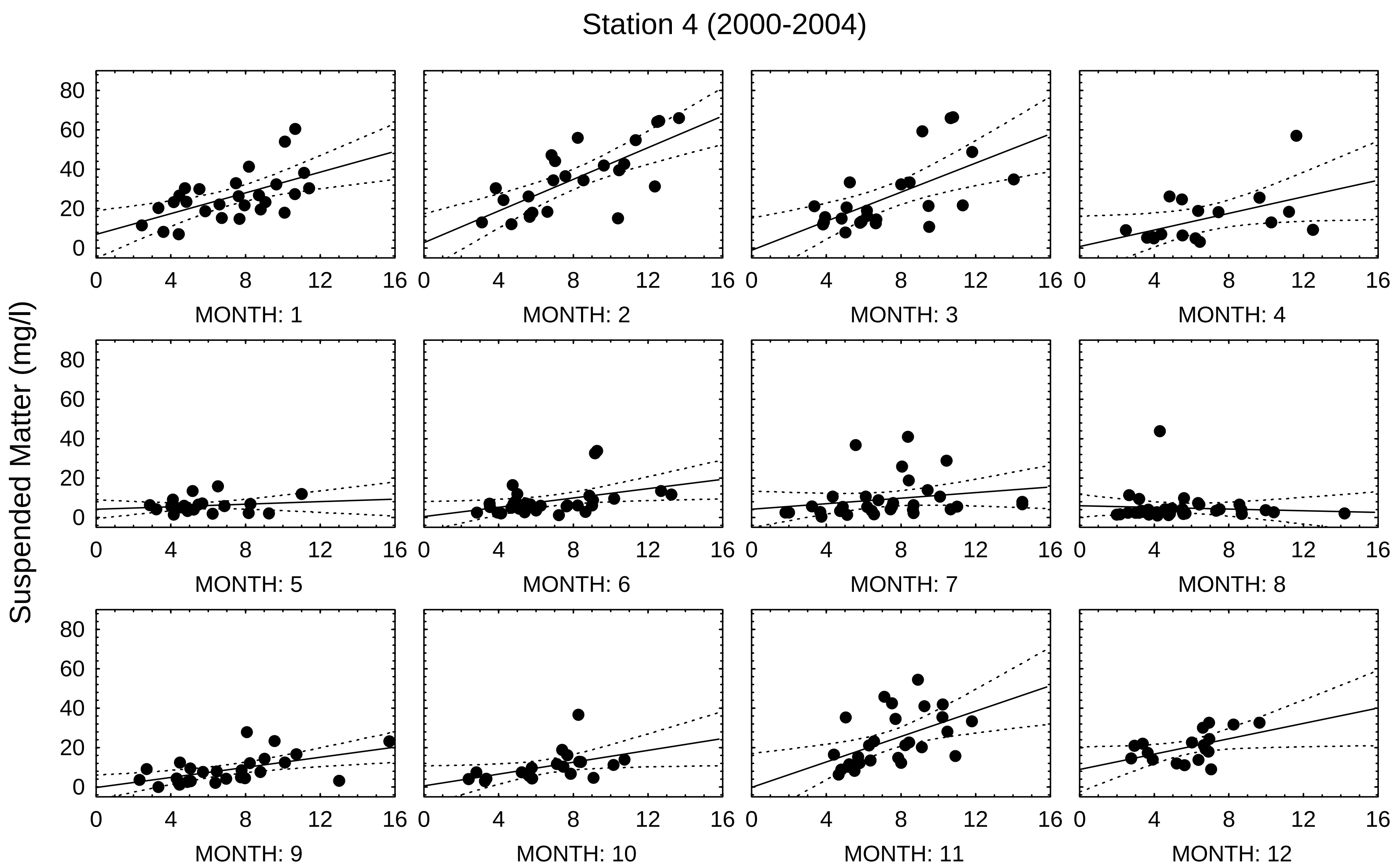
- Wind Speed:
  Summer ~ 20% lower

- Suspended Matter
  Summer ~ 80% lower



Van Beusekom et al., in prep

Seasonality of Wind and Suspended Matter



Van Beusekom et al., in prep

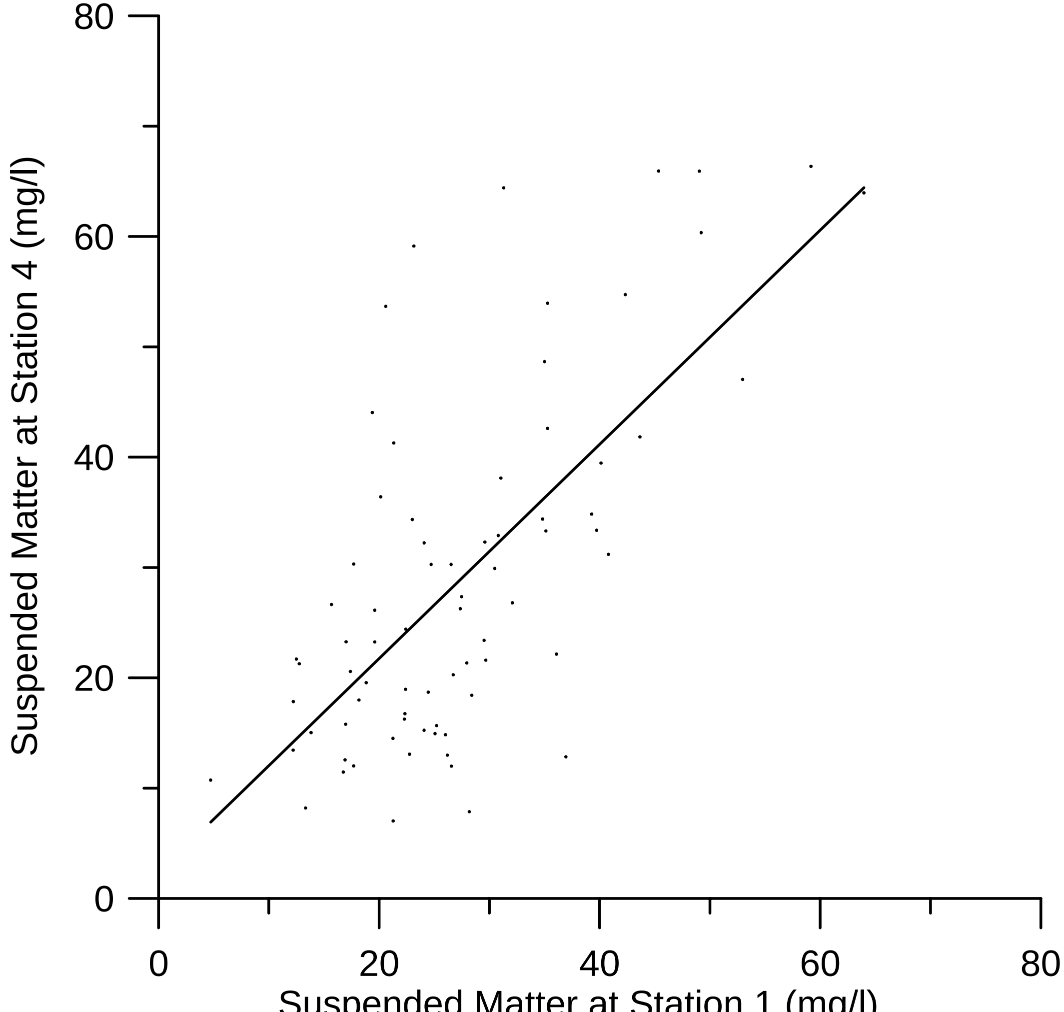
Advection from the Main Channel and Wind influence SPM at the Shallow Station

- Linear Regression:
  - SPM at Deep Station

  $R^2 = 0.50$; N=75; $p \ll 0.0001$

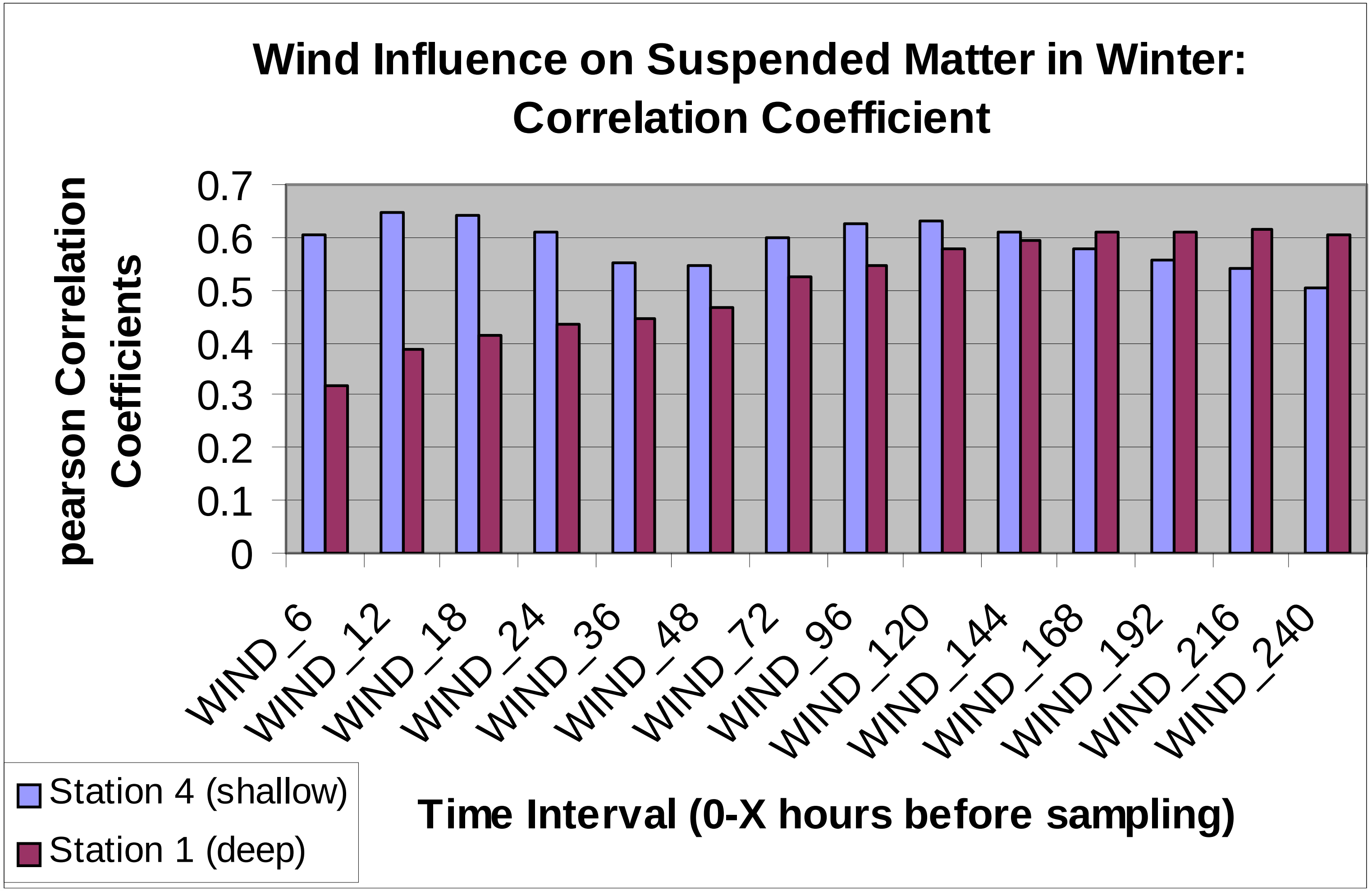
- Multiple regression:
  - SPM at Deep Station
  - Wind speed (12 hr before sampling

  $R^2=0.62$; N=75; $p \ll 0.0001$



Van Beusekom et al., in prep

The Deep Station Responds Slow to Resuspension "events"



Van Beusekom et al., in prep

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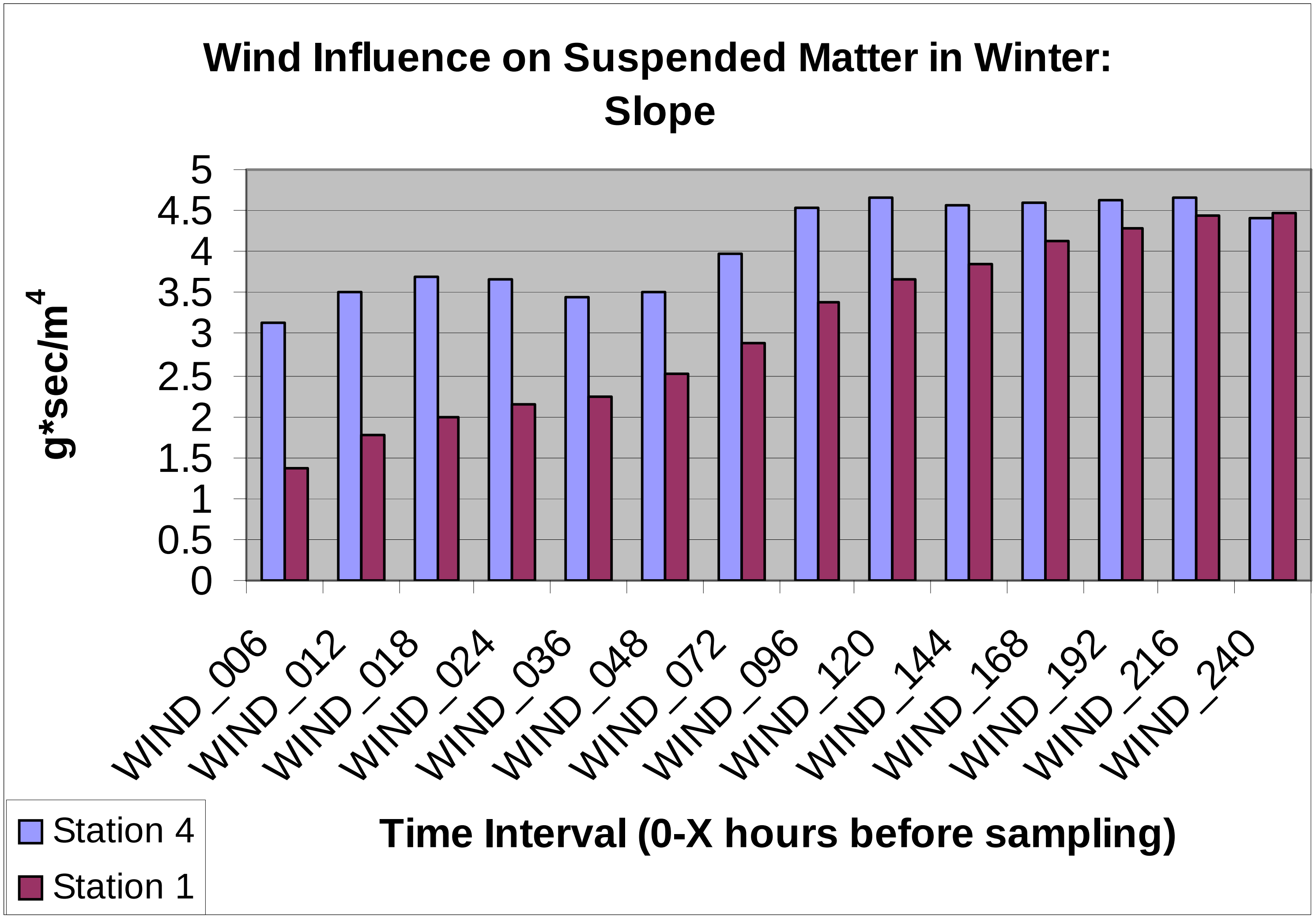
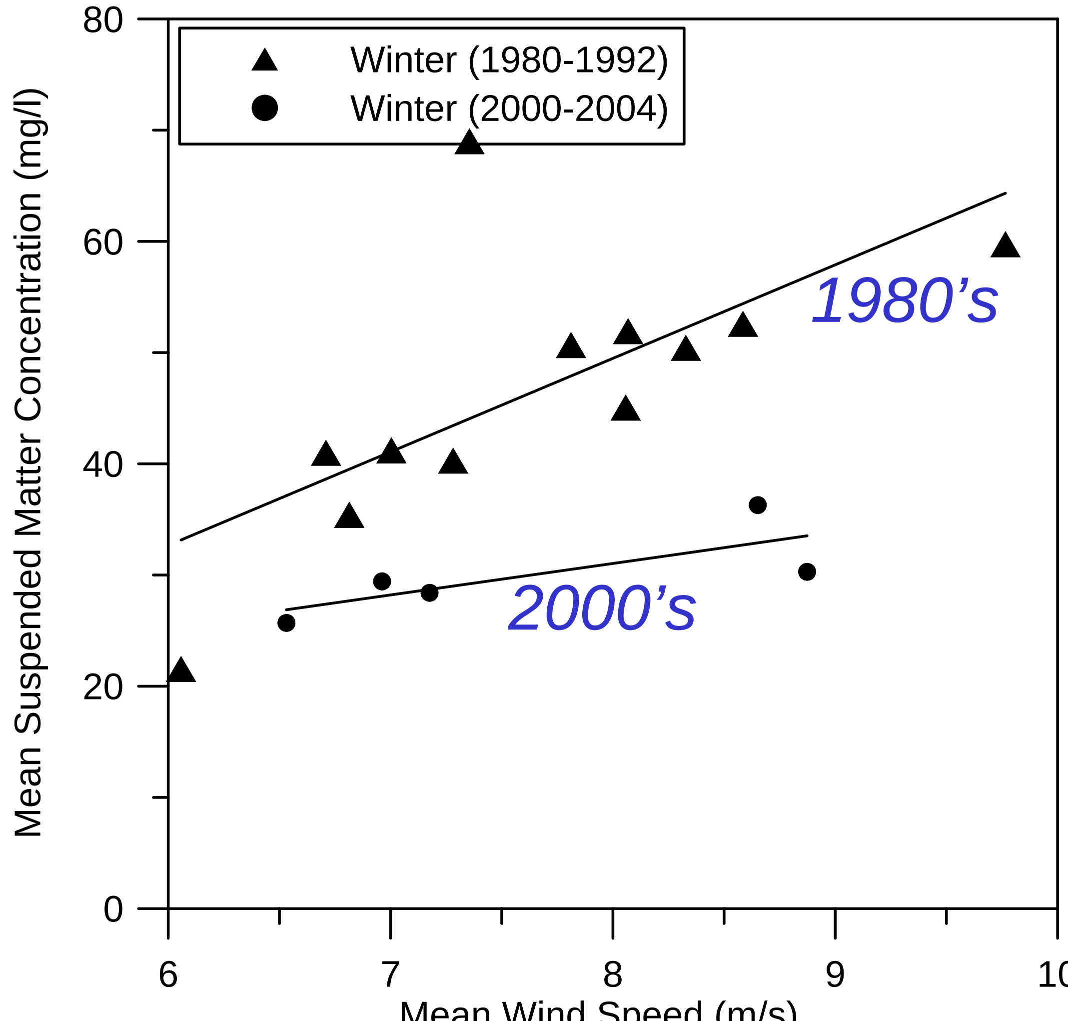


Van Beusekom et al., in prep

Mean Wind Speed influences SPM,
but interdecadal differences remain unexplained

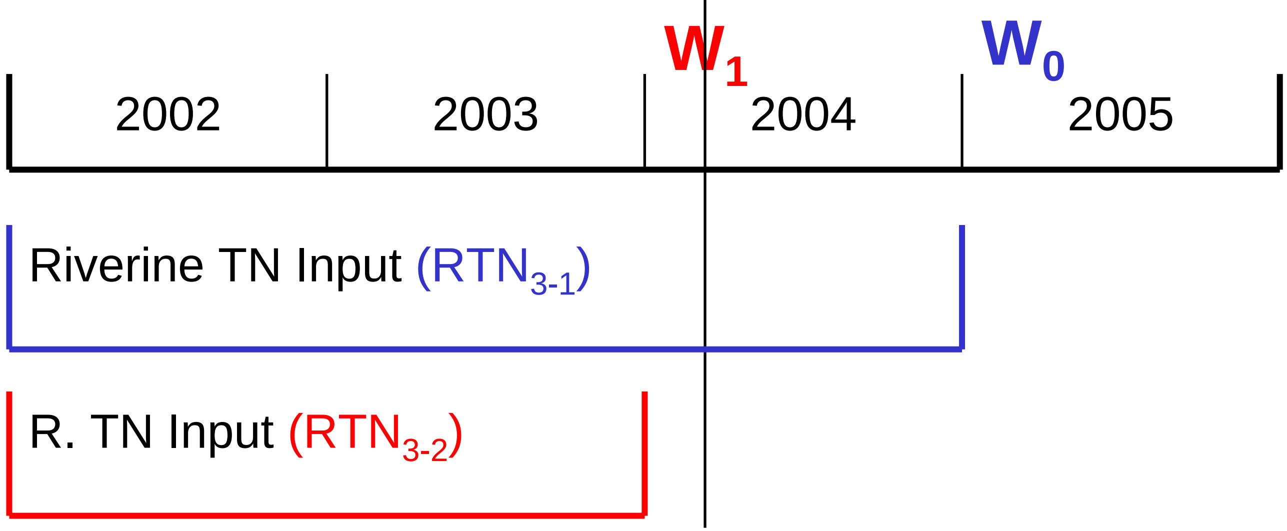
1980’s:

- Higher Nutrient Loads into the North Sea
- Higher Prim. Prod. in the North Sea
- Larger OM Import into the Wadden Sea
- Larger Import of Fines into the Wadden Sea



Van Beusekom et al., in prep

Relating Winter SPM with Riverine Nutrient (Total Nitrogen) Input (averaged over three previous years) and Wind Speed



$$SM_{2005} = \text{Cons.} + A{*}W_0{*}\ RTN_{3\text{-}1} - B{*}W_1{*}\ RTN_{2\text{-}1}$$

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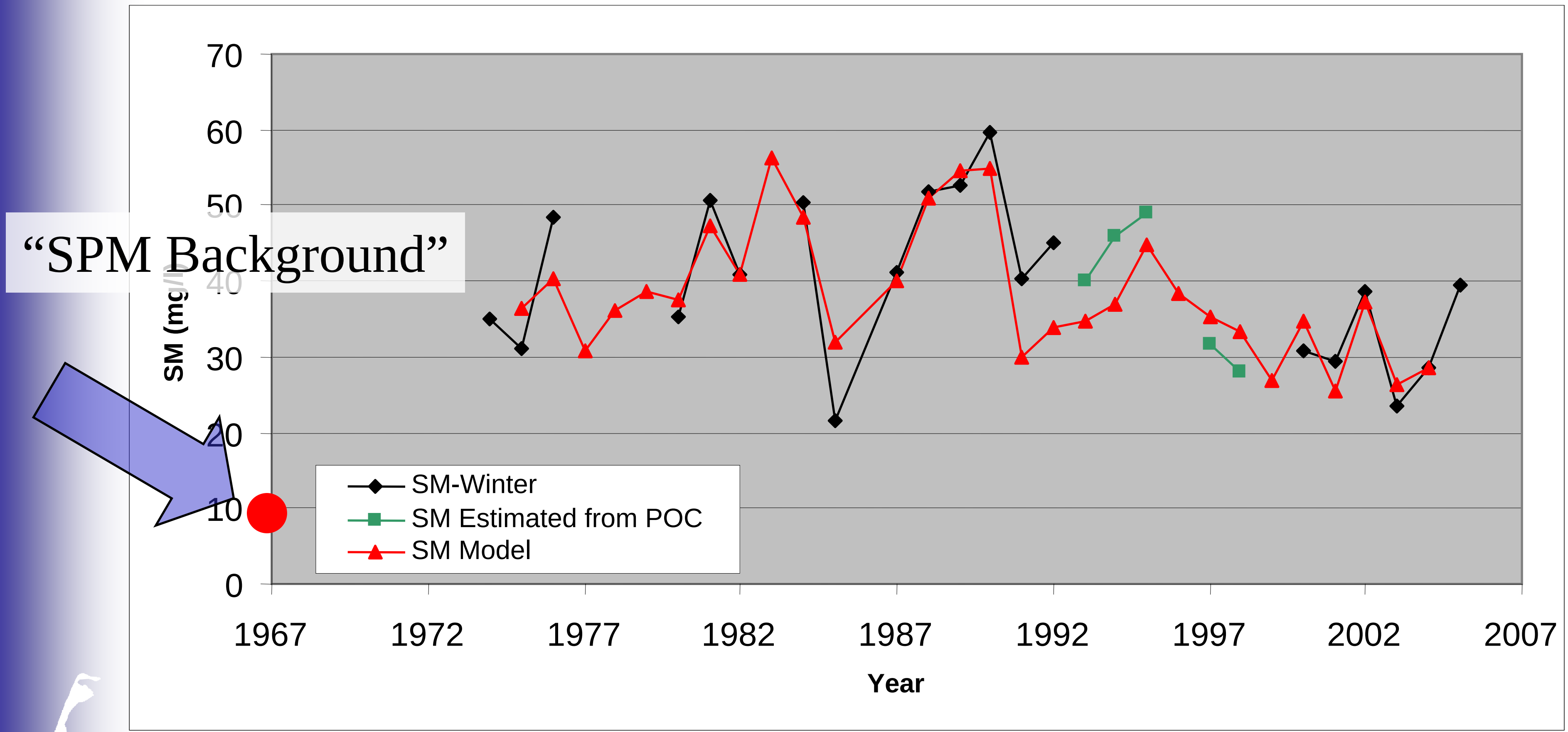
Time-Series of Modeled and Measured Winter SPM (significant correlated: R^2=0.75*)



* Excluding 1986

Van Beusekom et al., in prep

SPM Dynamics in the Northern Wadden Sea
- Summary and Outlook -

- SPM Seasonality, Biology Rules
- SPM Dynamics in Winter in Sandy Coastal Basins
  - Wind-induced immediate local resuspension
  - Advection of resuspended matter from the inner area (Lag Effects)
- Interannual differences
  - Wind (mean winter wind speeds)
  - Riverine Nutrient (Total Nitrogen) Input (Nutrients enhance off-shore productivity, leading to enhanced accumulation of fines in the Wadden Sea)
- Consequences of Eutrophication
  - Clogging of sediments -> Remineralisation Shift to Pelagic
  - Worse light conditions -> Primary Production Shift to Pelagic

General Conclusions

- **SPM-Dynamics**:
  Essential for Coastal Biogeochemistry but difficult to grasp
- **Sandy Sediments**:
  Global Role Underestimated?
- **Time Series**:
  Essential for Identifying Responses to Management

Acknowledgements

- Rijkswaterstaat, TMAP Data Units for making available the necessary data
- CoSa Partners
- EU for funding support under the FP 5 EESD programme
- LOICZ for the kind invitation