The Use of Lagrangian Trajectories for Minimization of the Risk of Coastal Pollution

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Outline

- The BalticWay Project
- Model
- Lagrangian Trajectory Code
- Trajectory simulations
- Areas of Reduced Risk
- Methods
- Results
- Conclusions

Balticway project 1.1.2009 – 31.12.2011

The potential of currents for environmental management of the Baltic Sea maritime industry

Smart use of **semi-persistent current patterns (~a week)** to find areas from where the probability of transport of undesired substances to vulnerable areas is relatively small.

A solution: shift of fairway

Source: BalticWay, Oleg Andrejev

List of Participants and Principal Scientists

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Danish Meteorological Institute, Denmark	**Jun She**
GKSS Research Center Geesthacht, Germany	**Emil Stanev**
Leibniz Institute of Marine Sciences at the University of Kiel, Germany	**Andreas Lehmann**
Laser Diagnostic Instruments Ltd, Estonia	**Sergey Babichenko**

BalticWay Project (2)

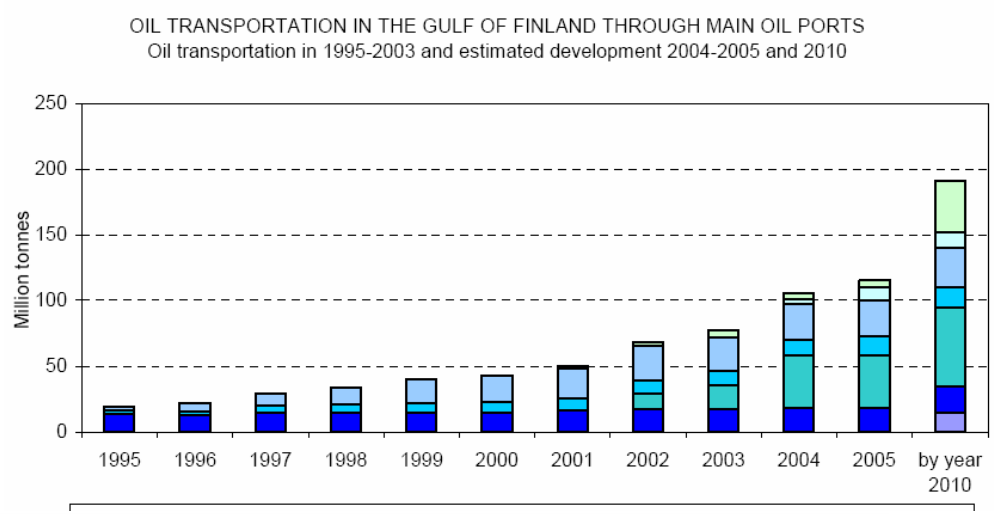
A selection of major threats to the Baltic Sea and its coasts:

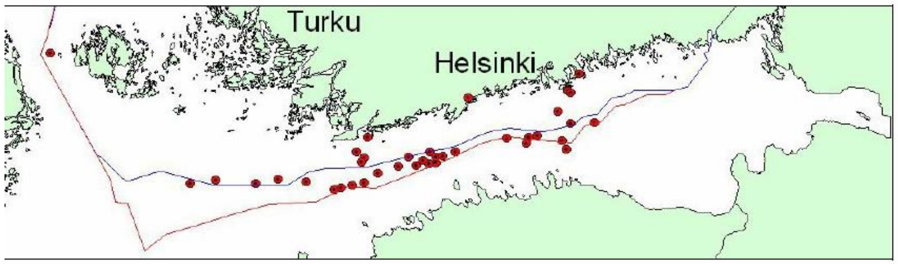
- Illegal deliberate and accidental discharges of oil from ship traffic
- Oil platforms (south of Baltics)
- Hazardous substances on the sea bottom and in sediments
  - War toxins dumped in the 1940s
  - Dioxins released in the 1960-1970s – Gulf of Finland, Bothnian Sea
  - Transport by currents after construction, dredging or dumping
- Adverse impacts from river discharge, etc.

Aims:

- To identify areas of reduced risk and their basic properties
  - (first approximation: source of pollution=ship traffic)
- To provide a prototype of the environmental management technology using the concept of areas of reduced risk
- To develop a method for assessing whether such a technology is applicable and economically feasible for a given sea area

Shipping Activities in the Gulf of Finland (GoF)





Source: SYKE, Heli Haapasaari and Finnish Frontier Guard

Classical direct problem:

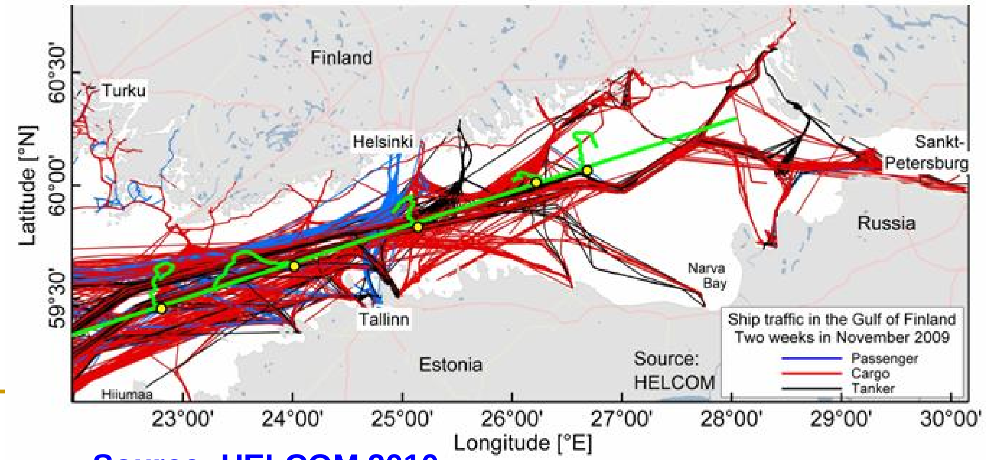
In the event of an accident, to identify affected areas and the impact time (circulation models).

Our approach - inverse problem:

(i) Example: to propose a fairway path that poses less risk to the coastal areas in the event of accident

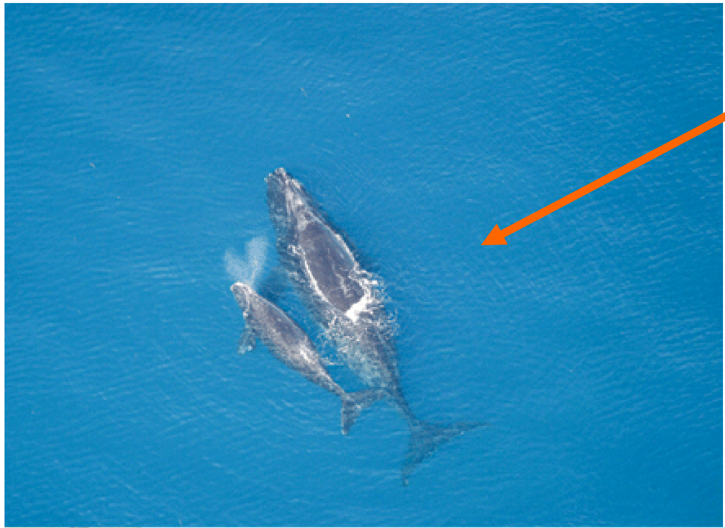
(ii) with the use of existing features of circulation

Benefits: Saves money and environment



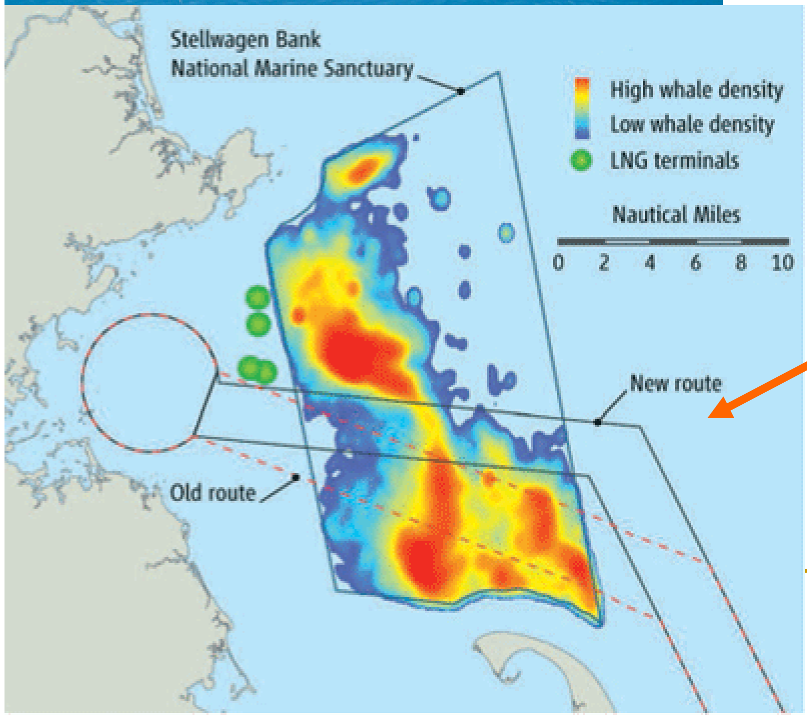
Source: HELCOM 2010

Example of shifting a fairway



Highly endangered
North Atlantic right whale

- Cargo ships traveling to Boston
- Highly endangered whales



Shift of fairway reduced the risk of collision by **56%** and it's made the trip only **15** minutes longer

SOURCE: Stokstad, E. 2009. U.S. Poised to adopt national ocean policy. Science, 326, 1618.

Model

- The **RCO** (Rossby Centre Ocean):
  Bryan-Cox-Semtner primitive equation circulation model coupled with an ice model following with a free surface and open boundary conditions in the northern Kattegat
- Model domain: the entire Baltic Sea
- Horizontal resolution **2 × 2** nautical miles
- **41** vertical levels in *z*-coordinates (Meier *et al*. 2003, Meier 2007).
- Forcing: 10 m wind data, 2 m air temperature and specific humidity, precipitation, cloudiness, and sea level pressure fields, river inflow, water exchange through the Danish Straits
  - calculated from the **ERA-40** re-analysis using a regional atmosphere model with a horizontal resolution of 25 km (Höglund et al., 2009)
  - Wind is adjusted using simulated gustiness to improve the wind statistics.

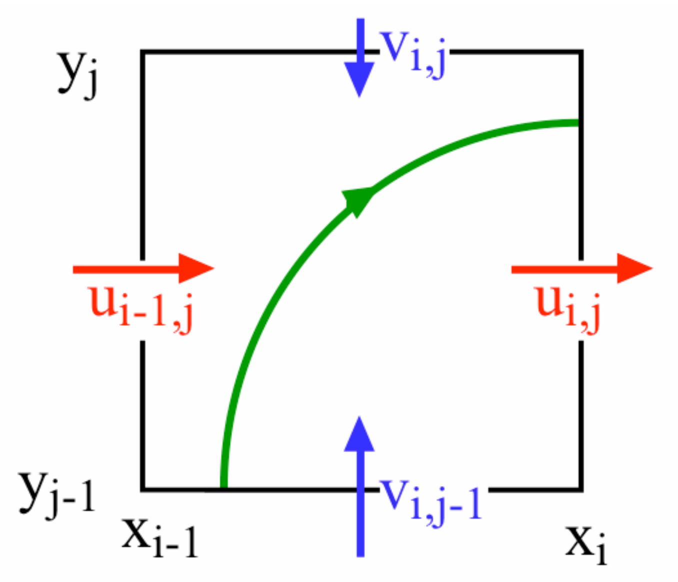
Model (2)

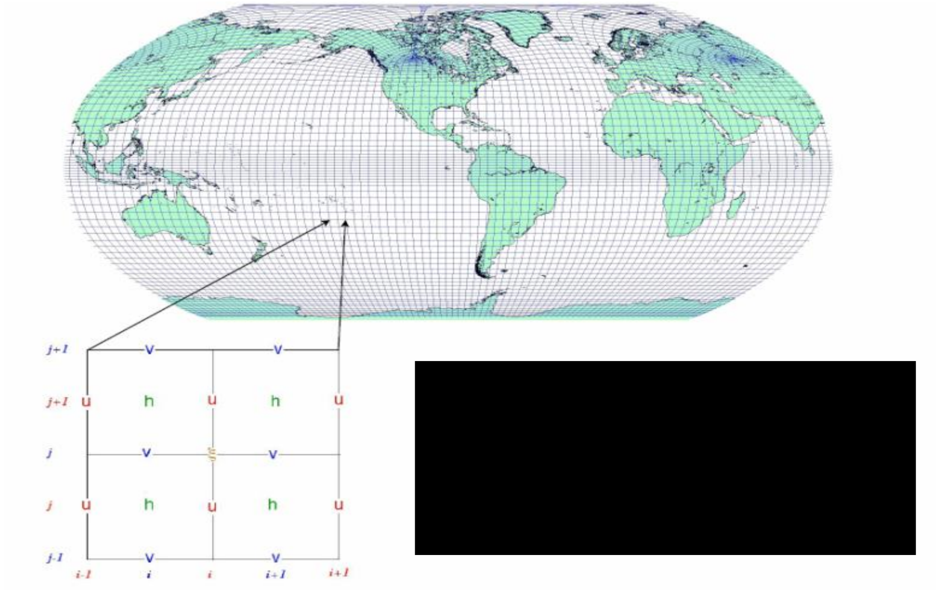
• Flux-corrected, monotonicity-preserving transport (FCT) scheme following Gerdes *et al.* (1991) is embedded
• No explicit horizontal diffusion is applied.
• Variable thickness of the vertical layers: 3 m close to the surface; 12 m in 250 m depth
•Time step splitting scheme: 150 s for the baroclinic
15 s for the barotropic timestep.

•We concentrate on the uppermost layer: depths 0-3 m
•Output is stored once in six hours.

Lagrangian Trajectory Code

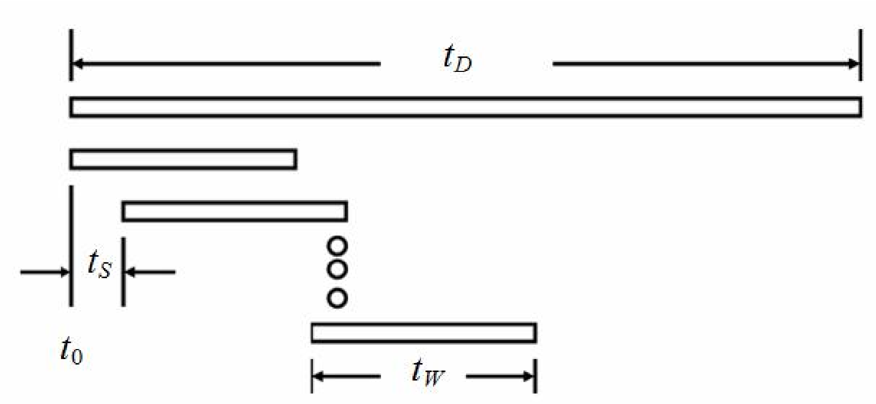
- A Lagrangian trajectory code (TRACMASS) for general circulation models. Developed by Döös (1995), Blanke and Raynaud (1997) and Vries and Döös (2001)

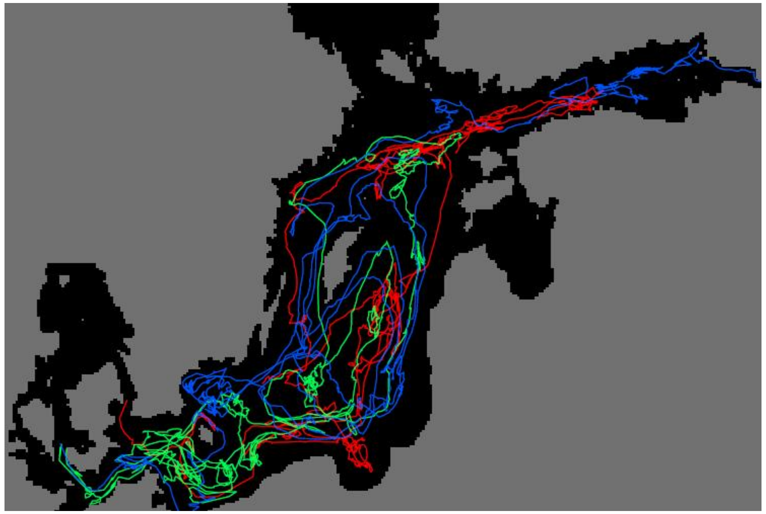




- Circulation data obtained from Rossby Centre Ocean (RCO) model
- Uses a 2*2 nautical mile grid
- 44 years of data to be analysed onwards from 1961

Lagrangian Trajectory Code (2)

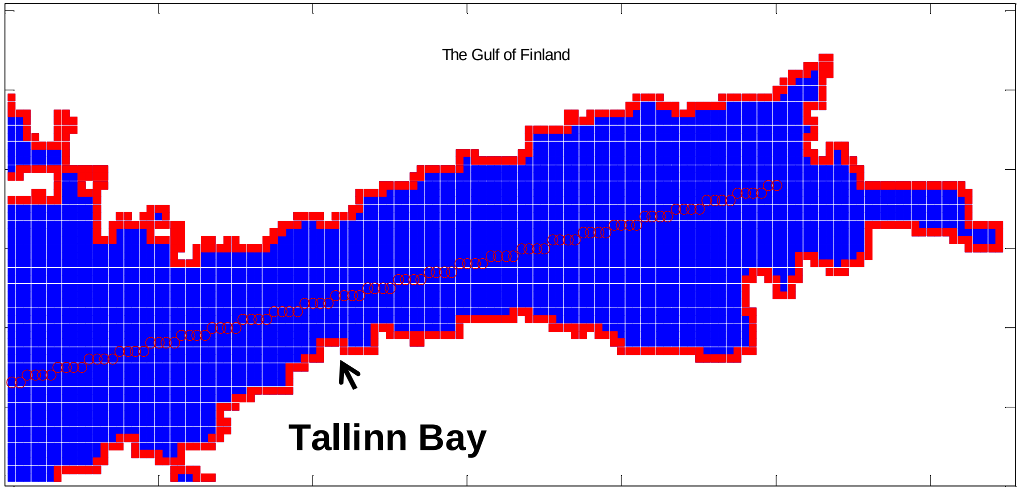




The complexity of trajectories.
Source: K. Döös

- Velocity fields are analyzed over different time intervals.
- The trajectories
  - TRACMASS model based on RCO precomputed velocity fields off-line
  - linear interpolation of the velocity field in each point of a particular grid cell
- Our interest: 5-20 days → trajectory points saved once in six hours.
  - No large effect on calculated statistics
  - side-effects such as trajectories crossing some peninsula or islands.
- To obtain reliable statistics:
  - simulations cover a longer time t_D
  - divided into many equal windows t_W
  - separated by the time lag t_s

Example of Trajectory Simulation



3 Alert zone cases

Case 1: 2 nautical miles (~3.7km)

Case 2: 4 nautical miles (~7.4km)

Case 3: 6 nautical miles (~11.1km)

Parameters used:

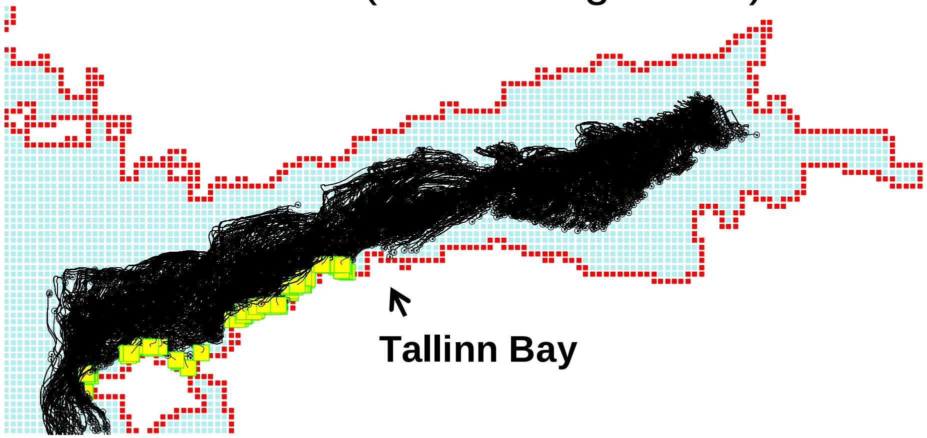
- The origin of the particles: red circles
- The red line: the nearshore (alert zone) with width of 2 nm (~3.7km)
- High risk when pollution < 6 nm from the coast.

Simulations of Trajectories hitting coast

The alert zone 1 (**~3.7 km**) hitting count is **24 (24%),** day of first hit is **1** and major amount of particles has reached the shore by day **9**

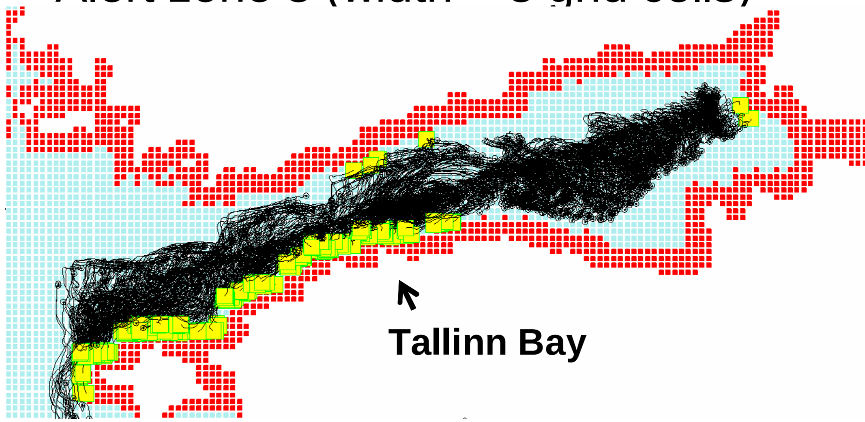
The alert zone 3 (**~11.1 km**) hitting count is **52 (52%)**, day of first hit is **1** and major amount of particles has reached the shore by day **8**

Alert zone 1 (width = 1 grid cell)



1 – 20 Dec 1987

Alert zone 3 (width = 3 grid cells)

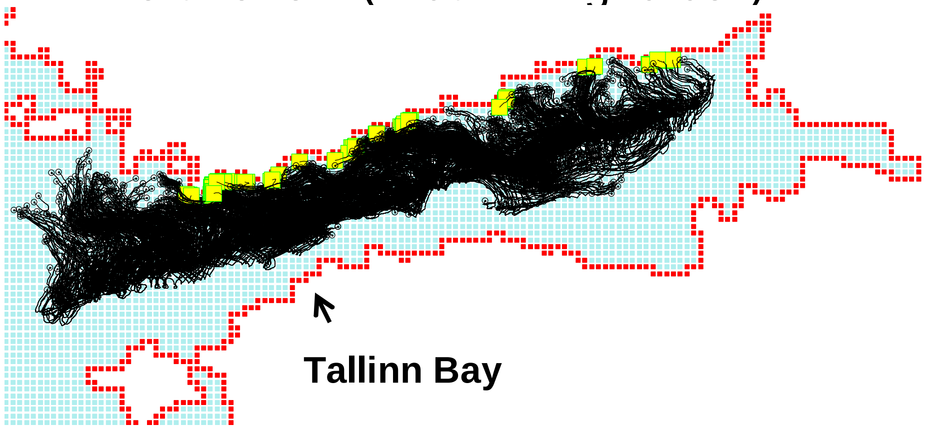


1 – 20 Dec 1987

Simulations of Trajectories hitting coast (2)

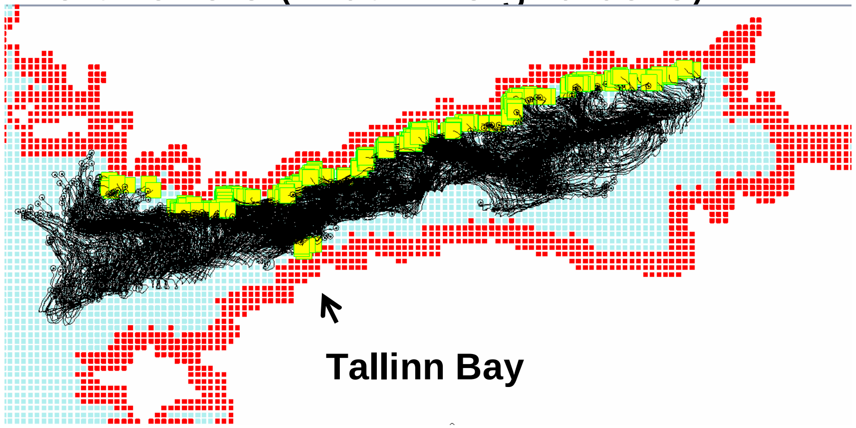
The alert zone 1 (**~3.7 km**) hitting count is **22 (22%),** day of first hit is **4** and major amount of particles has reached the shore by day **11**
The alert zone 3 (**~11.1 km**) hitting count is **59 (59%)**, day of first hit is **1** and major amount of particles has reached the shore by day **10**

Alert zone 1 (width = 1 grid cell)



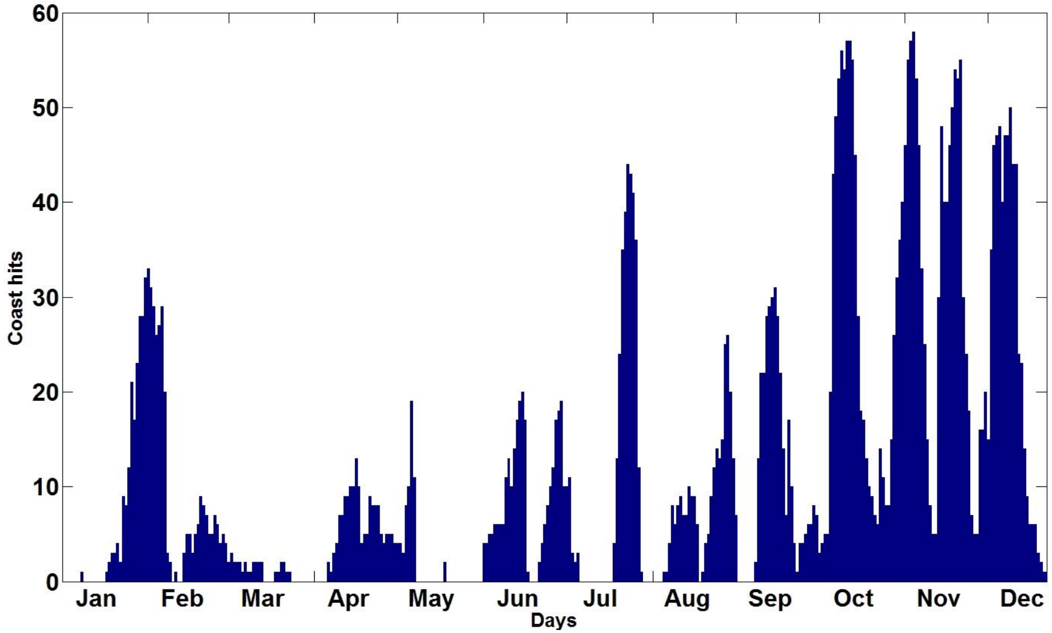
1 – 20 Oct 1987

Alert zone 3 (width = 3 grid cells)

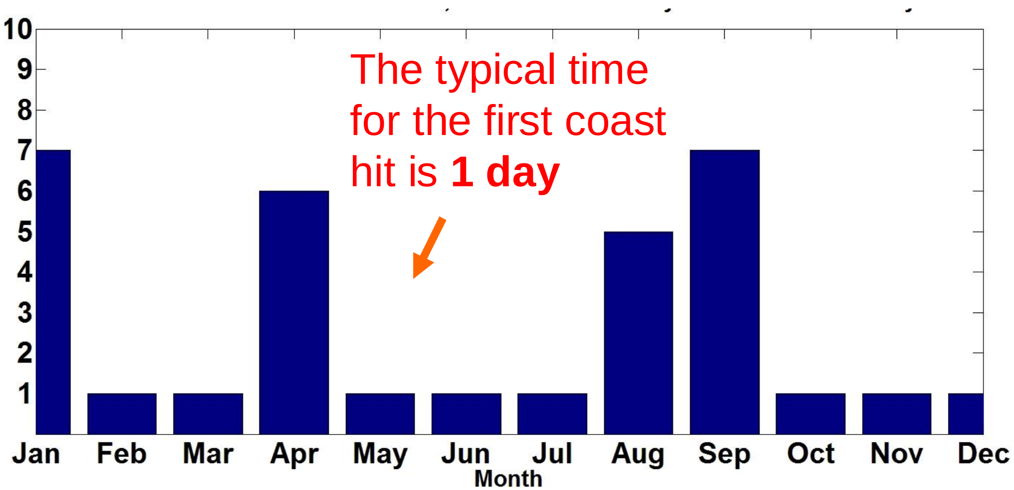


1 – 20 Oct 1987

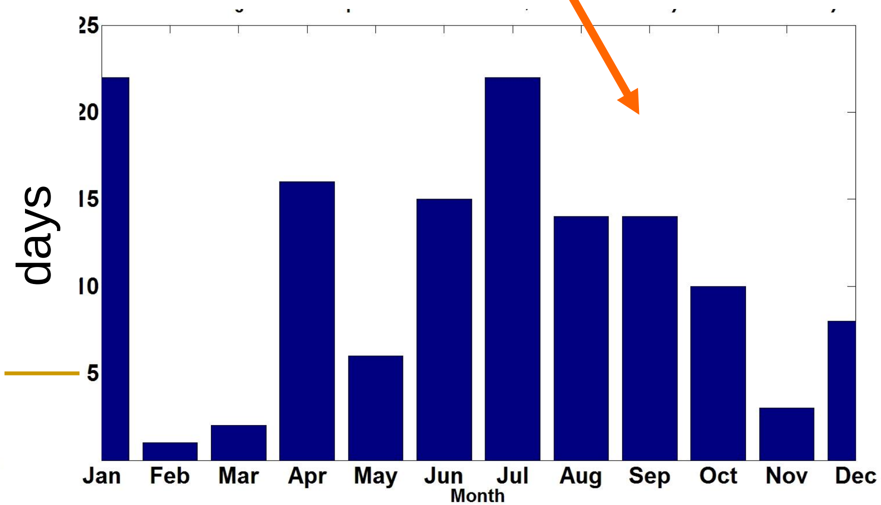
Simulations of Trajectories hitting coast for 1987: high seasonal variability



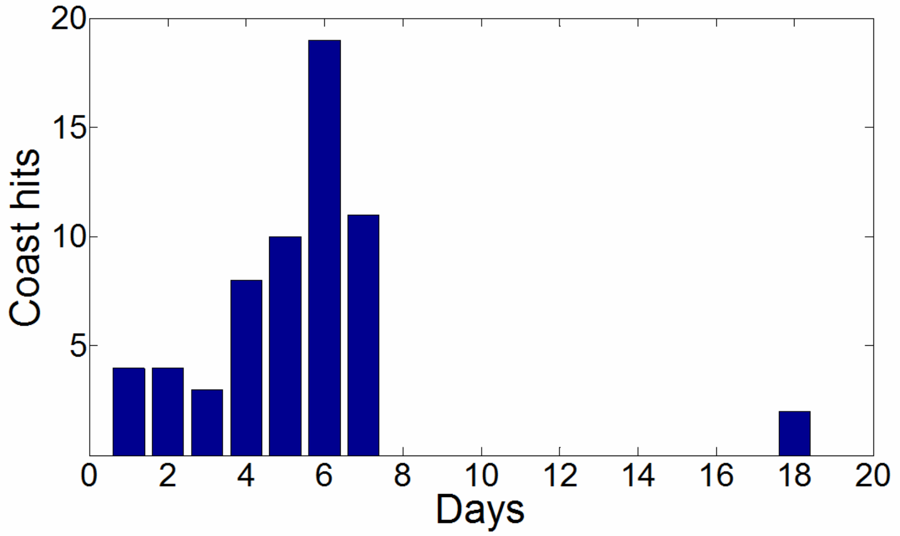
The typical time when a major part of trajectories have hit the coast is **12 days**



The typical time for the first coast hit is **1 day**

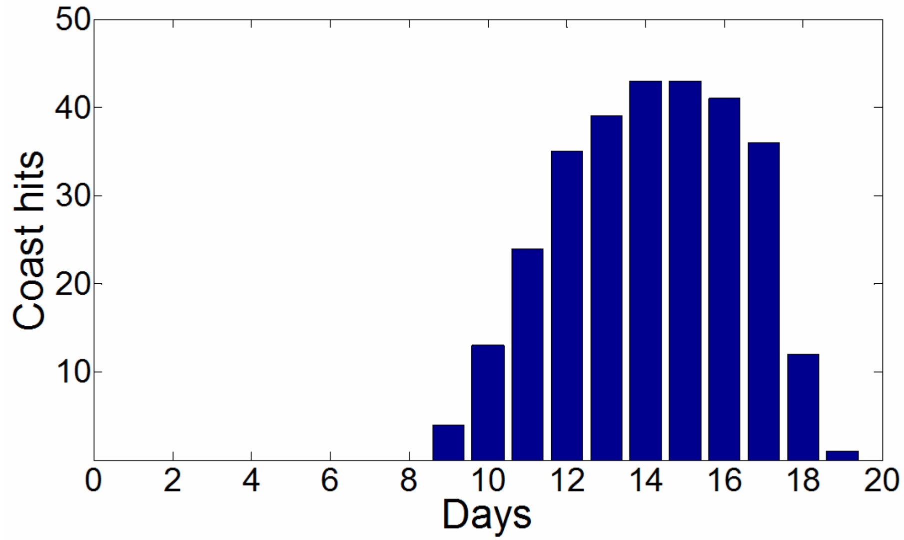


Simulations of Trajectories hitting coast for 1987



Strong seasonal variability!

Trajectories hitting the coast in May



Trajectories hitting the coast in July

Areas of Reduced Risk

The **equiprobability** line:
Probability of propagation of pollution to the northern and to the southern coasts is **equal**

- Only applicable for elongated sea areas
- Implicitly presumes the presence of probability gradient

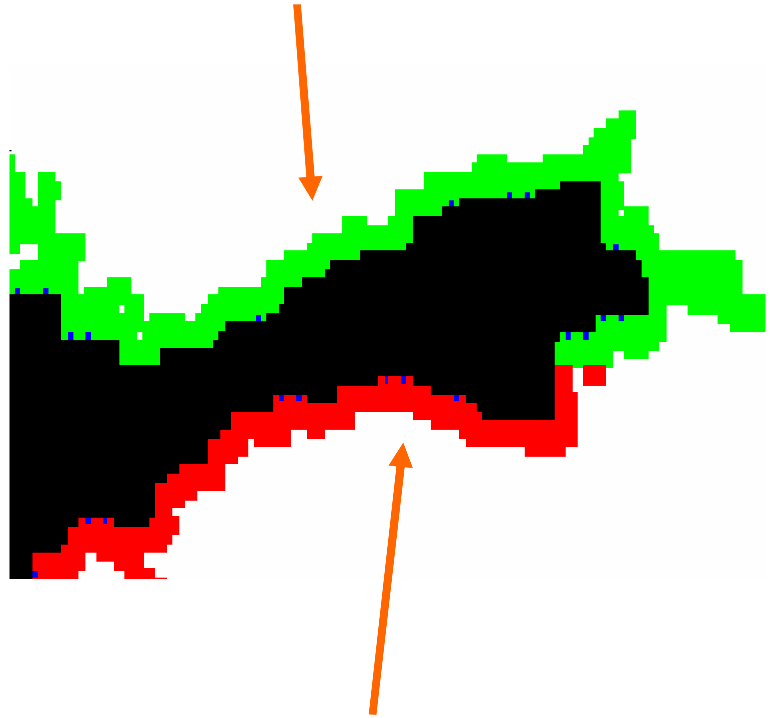
Area of reduced risk:
Probability of propagation of pollution to either of the coasts (north or south) is **small**

- Probability gradient small or missing

Two methods

- Direct method
- Smoothing method

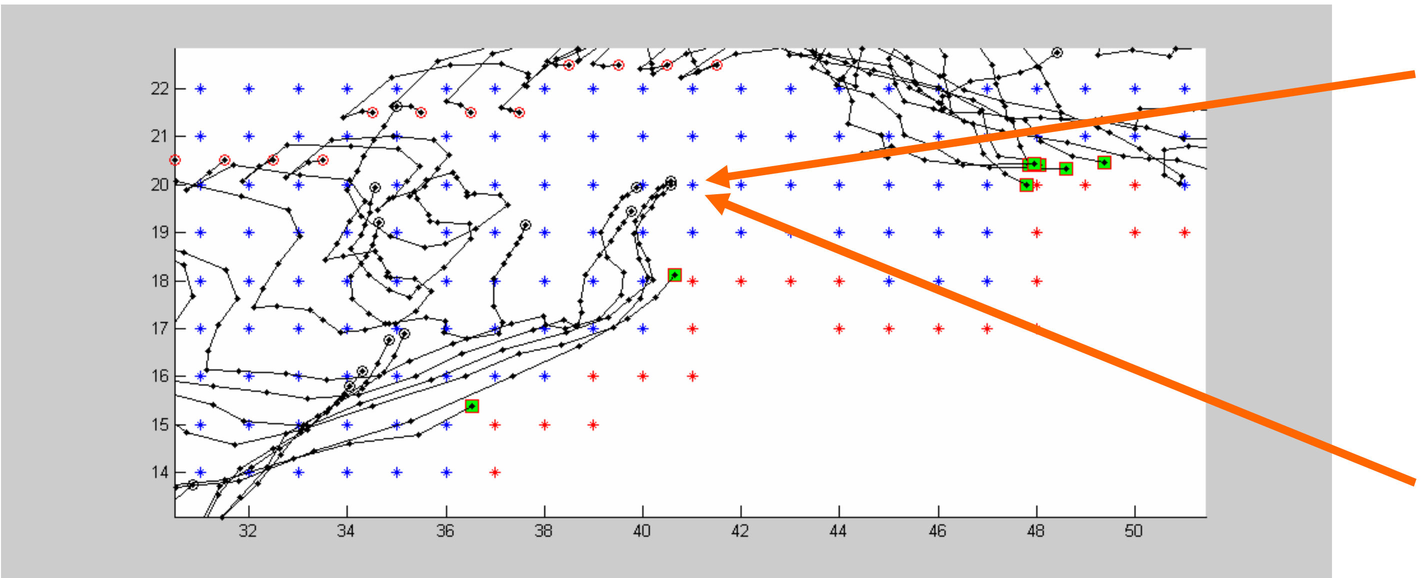
Northern coastal zone (green), probabilities denoted as "**-1**"

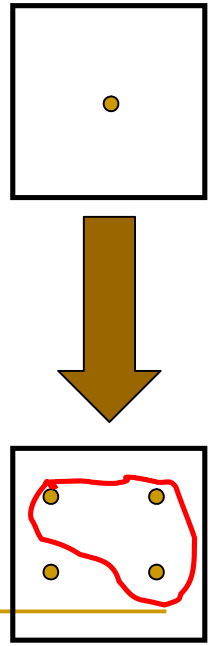


Southern coastal zone (red), probabilities denoted as "**1**"

Direct method

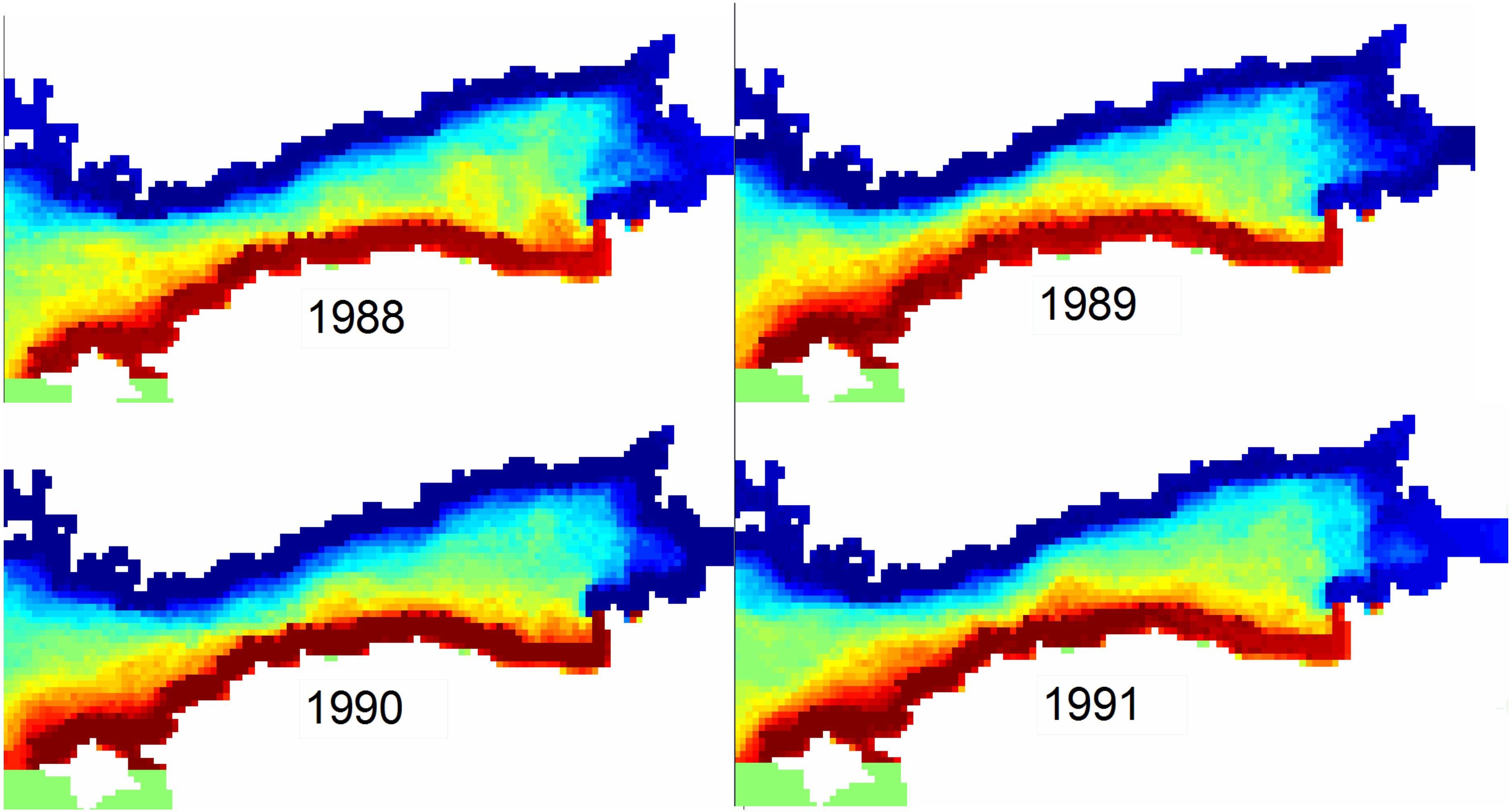
- Simulation with 3131 grid cells and 4 particles in each
- Map of probabilities of pollution hitting northern coast, southern coast and neither of the coasts





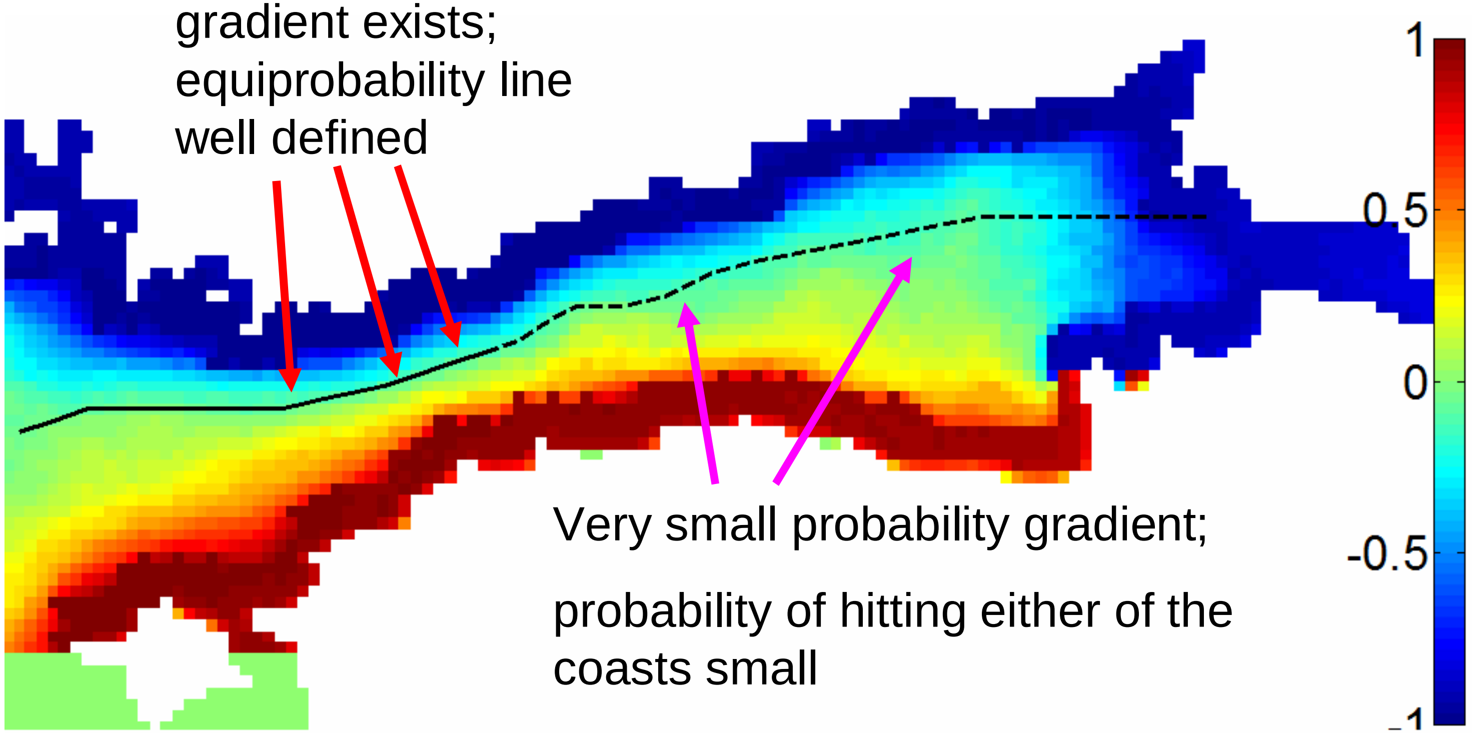
>50%, assigned **-1 / 1**
Otherwise **0** (undefined)

Direct method(2)



Direct method(3)

Clear probability
gradient exists;
equiprobability line
well defined



Very small probability gradient;

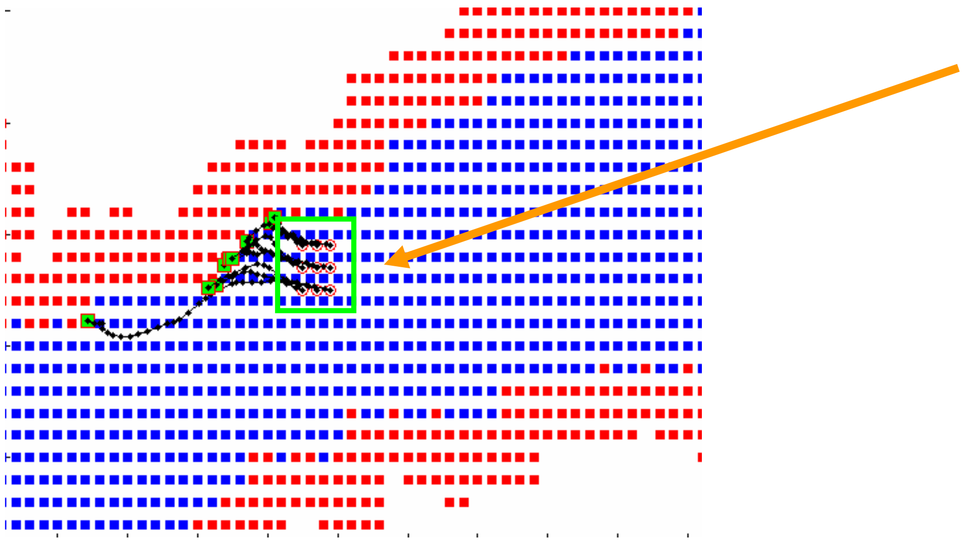
probability of hitting either of the coasts small

→area of reduced risk,

→equiprobability line not easy to identify

Smoothing method

- Extended version of the direct method
- 3x3 cell clusters
- Reduction of noise

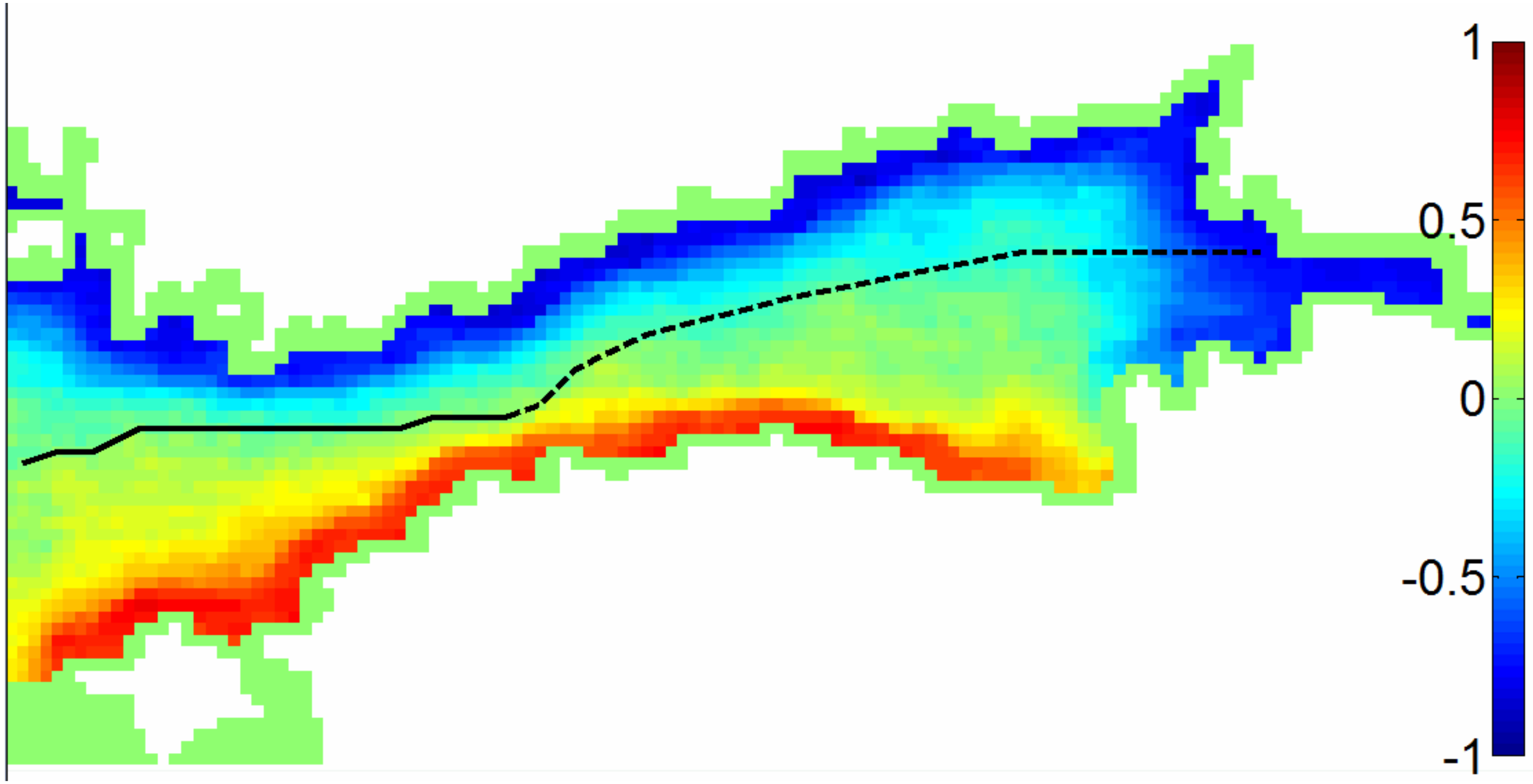


A cluster of **3x3** cells

2463 clusters

>50%, assigned **-1 / 1**
Otherwise **0** (undefined)

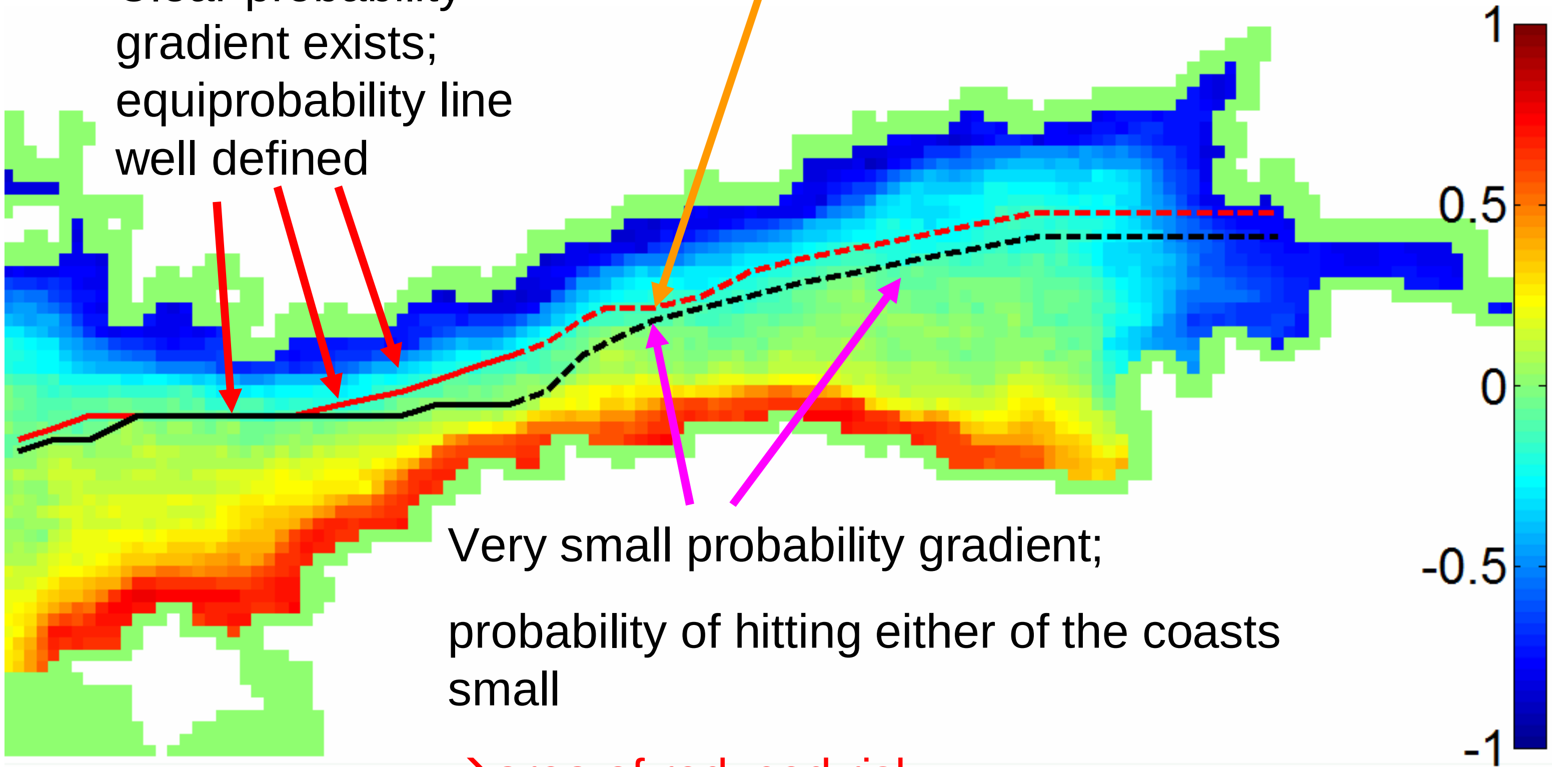
Smoothing method(2)



Smoothing method(3)

Difference between lines usually below 6-7km, at a few locations up to 10 km

Clear probability gradient exists; equiprobability line well defined



Very small probability gradient;

probability of hitting either of the coasts small

→area of reduced risk,

→equiprobability line not easy to identify

Conclusions

- Using a trajectory model we are able to estimate
  - areas of high and low risk
  - areas with clear gradient of probability of hitting the coast
    - equiprobability line in these areas

- The equiprobability line: does not coincide with the axis of the GoF
  - anisotropic transport predominantly to the southern coast

- Assistance to decision-makers on the perfect fairway design:
  - Following an equiprobability line (if exists)
  - Or over areas of reduced risk (if exist and wide enough)

- The difference between the two methods (direct and smoothing) → a measure of uncertainty related with this type of solution

Thank you !