Vatlestraumen tidal current - Characterization of local transport properties

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Motivation for study

Background:
The rock fallpipe ship MV Rocknes capsized after grounding in Vatlestraumen south-west of Bergen on 19 January 2004.

- Rocknes carried a total of 470 m^3 heavy bunker fuel and 70 m^3 marine diesel, most of which was released during the first days after capsizing.
- A total of 45 km of shoreline was significantly contaminated by the oil spill.
- Strong tidal currents believed to be a significant factor in the grounding incident and oil spill dynamics.

Original motivation:

- provide information on strength and spatial variation of tidal current in connection with trail process following the accident.

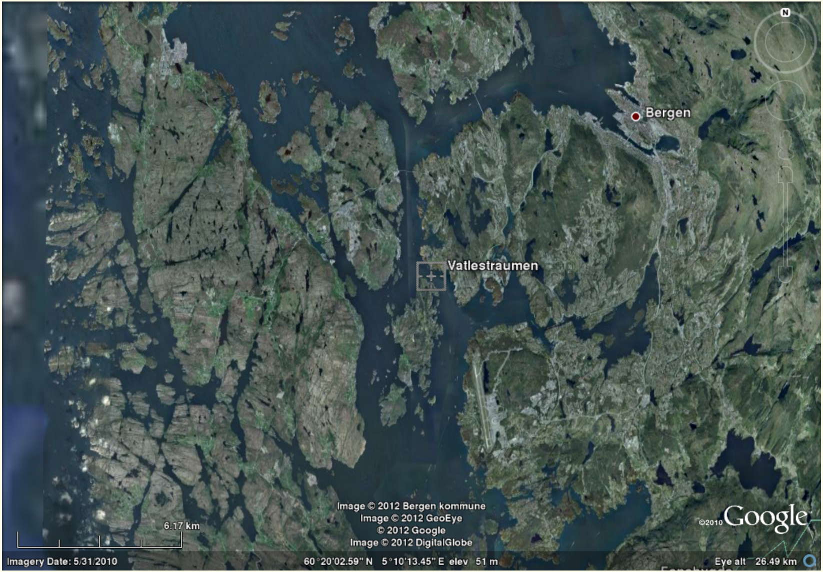
Extended study:

- oil spill test case for Lagrangian trajectory model
- identification of coherent flow structures

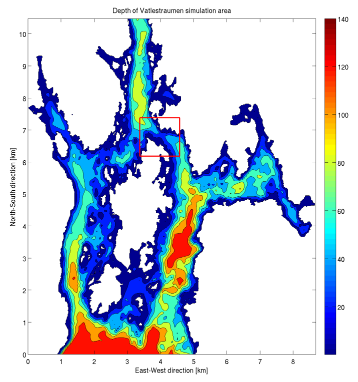
MV "Rocknes" before the accident.

Source: "ROCKNES"-ULYKKEN, The Norwegian Coastal Administration, 23. november 2004

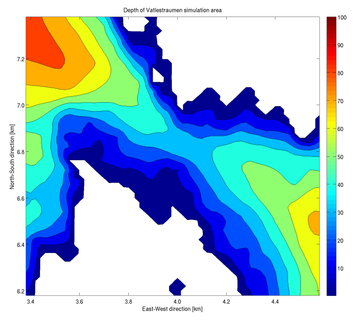
Model area - Vatlestraumen



Model area - Vatlestraumen



Topography of model area

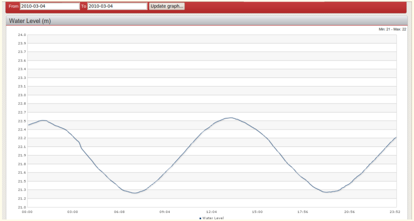


Detailed view of topography in Vatlestraumen

- Low resolution simulations: 80 m horizontal grid resolution, 10 sigma layers
- High resolution simulations: 20 m horizontal grid resolution, 31 sigma layers
- Bergen Ocean Model (BOM)
  - Numerical terrain-following 3D hydrodynamical model
  - Non-hydrostatic model equations; parallel code

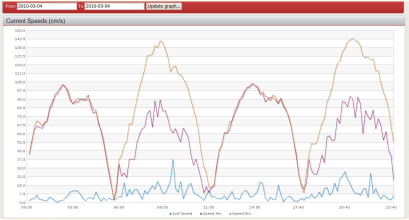
Tidal current measurements

Data from Aanderaa instruments measurement site in Vatlestraumen



Water level 2010-03-04

Measurements show tidal water level change of about 1.2 m. Tidal water level change at the time of the accident is believed to be slightly less than 1 m.

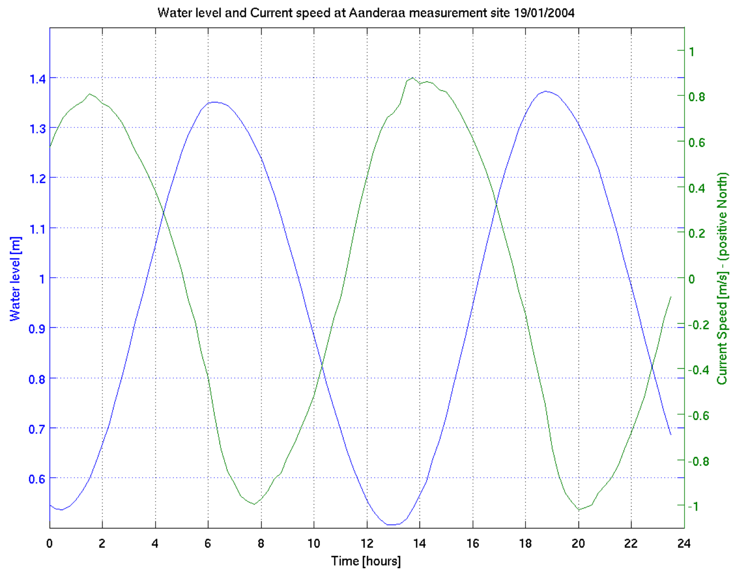


Current speed 2010-03-04

Current velocity measurements at surface (blue), 4 m depth (magenta) and 8 m depth (orange). Surface velocity data are probably wrong. Current speed measurements at 8 m depth regularly reach 0.8 m/s, with peaks exceeding 1 m/s.

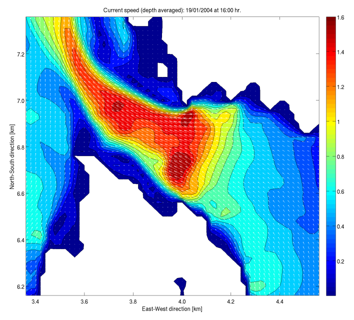
Maximum northward current occurs approximately 1.5 hours after lowest tide.

Simulated current and water level

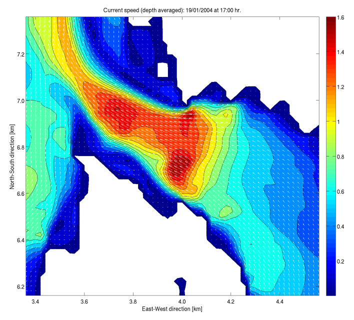


Simulated depth-mean current in Vatlestraumen

- Simulation forced with tide, water level and phase, through north and south boundaries
- no wind forcing
- Model spin up time: 24 hours



Depth-mean current 2004-01-19 at 16:00



Depth-mean current 2004-01-19 at 17:00

Figures show the depth-mean current in Vatlestraumen around the time of the accident.

- Maximum flow velocity: 1.6 m/s

Random walk particle tracking model

Particle tracking model

$$\begin{bmatrix} x(t_n) \\ y(t_n) \\ z(t_n) \end{bmatrix} = \begin{bmatrix} x(t_{n+1}) \\ y(t_{n+1}) \\ z(t_{n+1}) \end{bmatrix} + \begin{bmatrix} U(t_{n-1}) + \frac{\partial A_H}{\partial x} \\ V(t_{n-1}) + \frac{\partial A_H}{\partial y} \\ W(t_{n-1}) + \frac{\partial K_H}{\partial z} \end{bmatrix} \Delta t + \begin{bmatrix} \sqrt{2A_H}\gamma_1 \\ \sqrt{2A_H}\gamma_2 \\ \sqrt{2K_H}\gamma_3 \end{bmatrix} \sqrt{\Delta t}$$

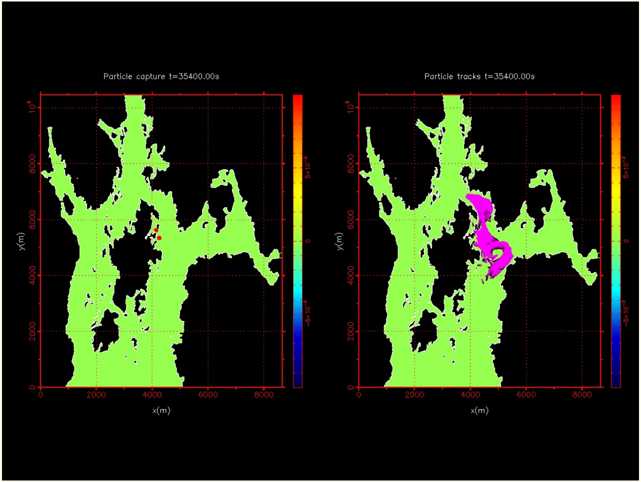
(x, y, z)	Position of particle at time t (stochastic variable)
(U, V, W)	Fluid velocity at (x, y, z)
Δt	Discrete time step
A_H, K_H	Eddy diffusion coefficient (horizontal,vertical)
$\gamma_1, \gamma_2, \gamma_3$	$\sim N(0, 1)$

Particle tracking model run on-line with BOM, as an internal module.

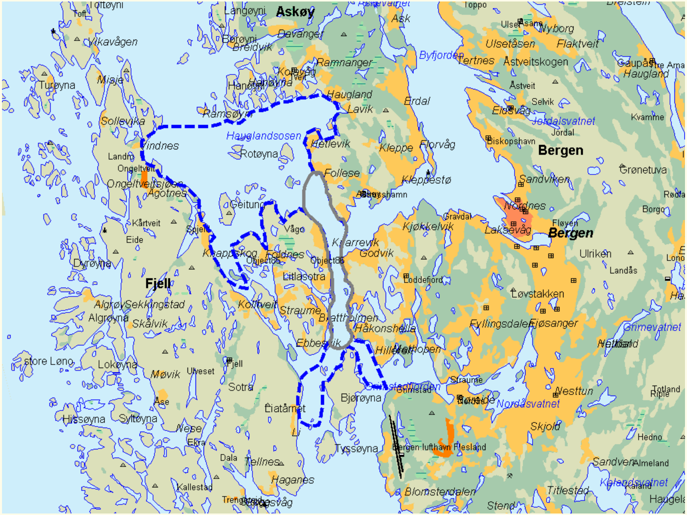
”Oil spill” transport by particle tracking

- Simulation with 5000 particles, seeded at 3 m depth
- Constant horizontal eddy diffusion coefficients

$$A_H = 0.1 m^2/s \qquad K_H = 0 m^2/s$$



Extent of oil spill, January 20, 9:45 am



Source: ”ROCKNES”-ULYKKEN, The Norwegian Coastal Administration, 23. november 2004

Okubo-Weiss parameter

Okubo-Weiss parameter

$$W = s_n^2 + s_s^2 - \omega^2$$

where

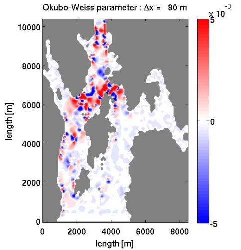
$$\begin{aligned} s_n &= \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \quad \text{normal strain} \\ s_s &= \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \quad \text{shear strain} \\ \omega &= \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \quad \text{relative vorticity} \end{aligned}$$

- Analysis of output velocity fields from BOM.
- Provides an instantaneous measure for the relative contribution of deformation and vorticity.

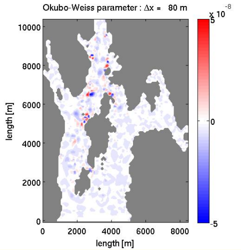
OW-parameter over 6 hours

Results for 80 m horizontal grid resolution.

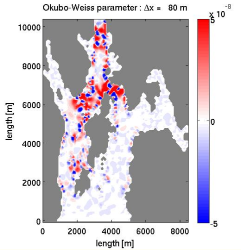
25 hours



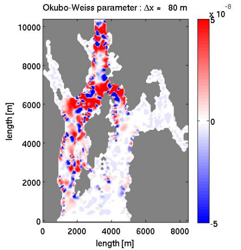
26 hours



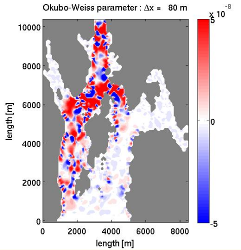
27 hours



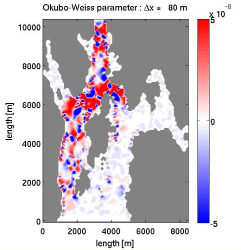
28 hours



29 hours



30 hours



Finite Time Lyapunov Exponents (FTLE)

Measure based on stretching between neighboring particles.

- Theory based on the (right) Cauchy-Green deformation tensor

$$\mathbf{C}_{t_0}^{t_0+\tau}(\mathbf{x_0}) = \left[\frac{\partial \mathbf{x}(\mathbf{x_0}, t_0, t_0+\tau)}{\partial \mathbf{x_0}}\right]^T \left[\frac{\partial \mathbf{x}(\mathbf{x_0}, t_0, t_0+\tau)}{\partial \mathbf{x_0}}\right]$$

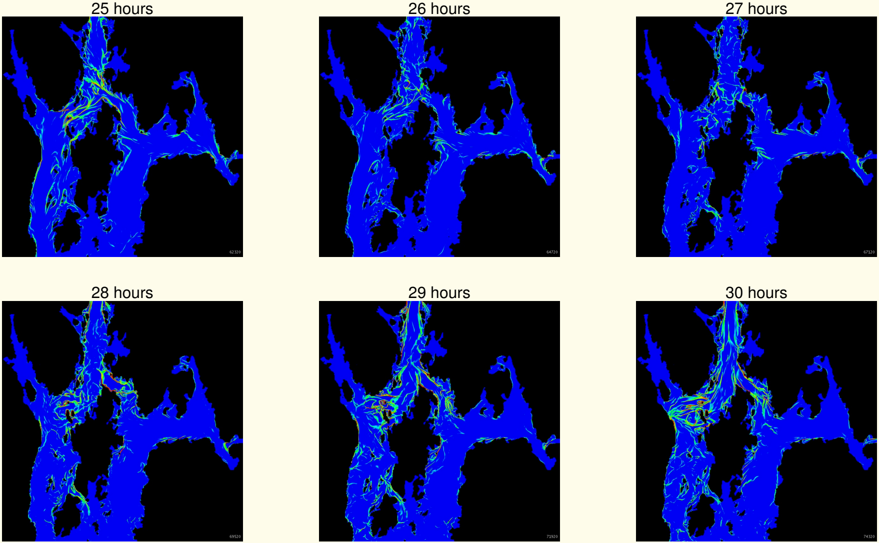
- maximum FTLE

$$\mathrm{FTLE}_\tau(\mathbf{x_0}) = \frac{1}{\tau} \ln \sqrt{\lambda_{\max}\left(\mathbf{C}_{t_0}^{t_0+\tau}\right)}$$

  where $\lambda_{\max}\left(\mathbf{C}_{t_0}^{t_0+\tau}\right)$ is the maximum eigenvalue of $\mathbf{C}_{t_0}^{t_0+\tau}$

- Practical calculation based on largest increase in separation distance between particles in a cloud during some time window τ.
- Ridges of FTLE indicate lines of flow separation, similar to separatrices of vector field topology.
- Results for FTLE obtained by off-line trajectory model, using time window $\tau = 30$ min.

FTLE over 6 hours



25 hours

26 hours

27 hours

28 hours

29 hours

30 hours

Comparison: Okubo-Weiss vs. FTLE

- Both methods identify regions of high dynamic variability.
- The dynamically active and passive regions identified by the Okubo-Weiss parameter and FTLE match well with behavior of Lagrangian particles.

Okubo-Weiss

- Easy to compute. Only the Eulerian hydrodynamic model is required.
- Regions of high strain and high relative vorticity are almost stationary throughout the tidal cycle.

FTLE

- Requires an additional model for computing of Lagrangian trajectories.
- Reveals Lagrangian coherent structures which display significant variability over a tidal cycle.

Thank you for your attention!