Numerical studies of small scale eddies behind headlands in tidal inlets

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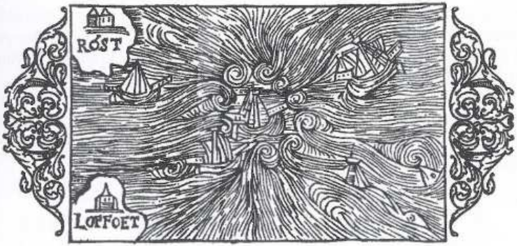
Outline of the Story

- Whirlpools in Tidal inlets The Moskstraumen Maelstrom
- The Backward Facing Step Problem in CFD
- Flow over sills
- Processes and their importance
- Two-dimensional versus Three-dimensional studies
- Pressure in fine scale ocean modelling
- Preliminary results
- Future plans

The Moskstraum eddy by Olaus Magnus -1555

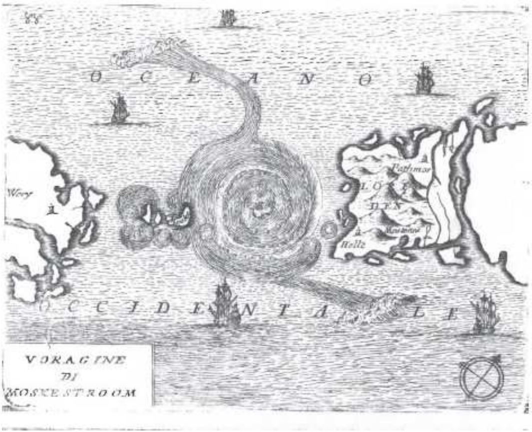
From Gjevik 2009 - Olaus Magnus was a Swedish Bishop - Connects the Moskstraum to Odyssev



Figur 12.2: Virvelen i Moskstraumen slik Olaus Magnus forestilte seg den i sin bok om historien til de nordiske folkene fra 1555.

The Moskstraum eddy by Cornelli (1650-1718)

From Gjevik 2009 - Vincenzo M. Cornelli was an Italian Map Drawer



From Gjevik 2009 - Mundus Subterraneus by A. Kircher (1602-1680) - Maelstrom at tunnel opening

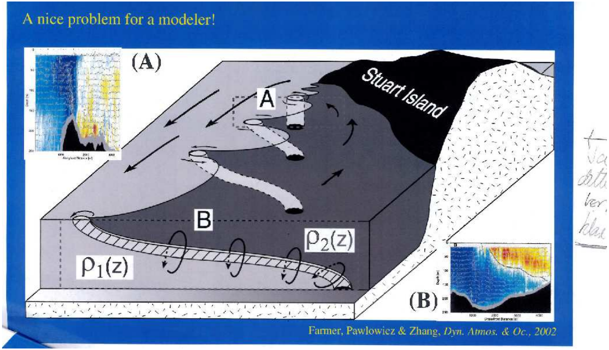
Figur 12.4: Kircher forestilte seg at det gikk en underjordisk tunnel mellom Lofoten og Østersjøen hvor sjøvannet strømmet. Ved tunnelåpningen ble det så dannet en stor malstrømsvirvel. (Tegning fra *Mundus Subterraneus* 1665).

Saltstraumen - Detailed view of an eddy

From Gjevik 2009 - This is a dangerous sport

Figur 13.9: Rafting i strømvirvelene i Saltstraumen. Disse folkene løper stor risiko for å bli trukket ned i dypet av kraftige vivler i kjelene. Foto: Scanpix ©.

From Farmer et al. 2002 - A Challenge for modellers



The Backward Facing Step Problem

From Gartling 1990 - A much used benchmark in CFD and DNS

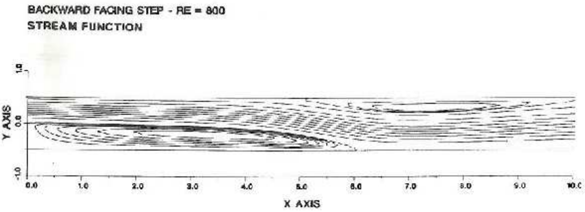


Figure 3. Streamfunction contours. Level values are −0·030, −0·025, −0·020, −0·015, −0·010, −0·005, 0·0, 0·050, 0·100, 0·150, 0·200, 0·250, 0·300, 0·350, 0·400, 0·450, 0·490, 0·500, 0·502, 0·504

Why should we try to model such eddies?

- Interesting in their own right
- Important for ship routing and safety
- Dispersal of fish eggs and larvae ++
- Test beds for understanding the mixing in the ocean
- Test beds for understanding fish behaviour
- Parameterization of mixing in large scale ocean models is not well understood
- Subgrid scale parameterization techniques need validation and improvements

Mixing at tidal inlets - Flow over sills

- Mixing due to Internal Waves
- Mixing due to Overturning Vortices
- Mixing due to Horizontal Eddies
- Knight Inlet - British Columbia - Canada
- Loch Etive - Scotland - UK
- Two-dimensional model studies ignore the role of the horizonal eddies
- We need three-dimensional (3D) model studies

Can we model such eddies with mode split ocean models?

- Non-hydrostatic pressure effects are important
- Free surface effects are important
- Grid sizes less than 1 m may be required
- Feasible for small area, one vortex street, studies
- Surface tension is neglected
- Effects of bubbles of air neglected
- $P = P_{atm} + P_{\eta} + P_{int} + P_{nh}$

Pressure in ocean models

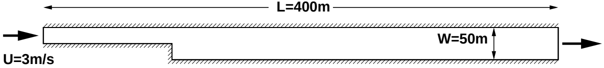
- From Fluid Mechanics: Dynamic Boundary Condition
- $P = P_{atm}$ at both sides of the surface
- In Ocean Modelling: $P = P_{atm}$ at the atmospheric side and $P = P_{atm} + P_{\eta}$ at the ocean side
- Valid for small amplitude waves ($\eta \ll L$)
- In mode split ocean models: η and P_{η} computed from the depth integrated equations
- P_{int} computed in longer 3D steps from the density gradients
- Including the effects of P_{atm}, P_{η}, and P_{int} provisional velocities $\tilde{\underline{U}}^{n+1}$ at the new time step are obtained

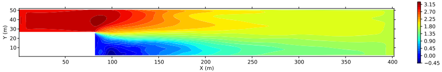
Non-hydrostatic Pressure in ocean models

- The non-hydrostatic pressure P_{nh} is computed from an elliptic equation forced by the divergence in $\tilde{U}^{n+1}$
- Neumann conditions at closed boundaries (no-flow)
- P_{nh} = 0 at the free surface is suggested
- The velocity corrections may not be divergence free
- Adjustments of η required
- Non-hydrostatic pressure effects near the surface are difficult to capture ($\frac{\partial P_{nh}}{\partial x} \sim 0$ near surface)
- With the Neumann condition $\frac{\partial P_{nh}}{\partial n} = 0$, the velocity corrections are divergence free ($\frac{\partial P_{nh}}{\partial x} \neq 0$ near surface fronts)
- The surface elevation is determined in the short 2D time steps, consistent with the mode splitting idea

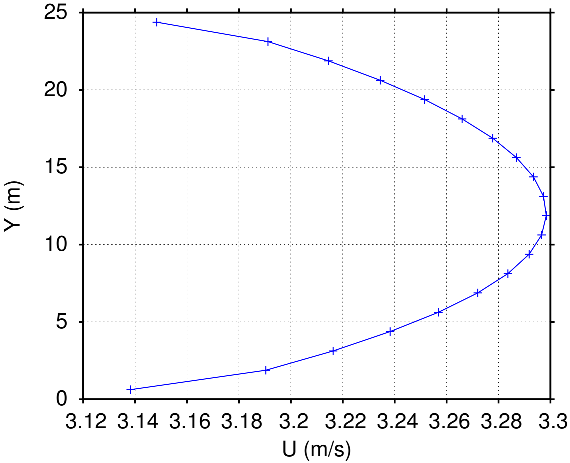
Tidal flow over a step

Results from experiments with $\Delta x = 1.25$ m
Model domain and Time mean U-field



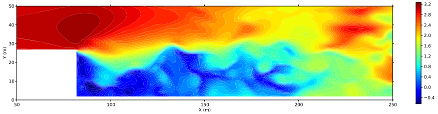


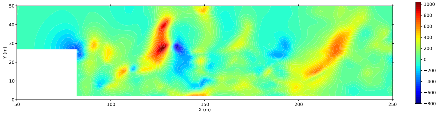
Lateral friction create a Poiseuille type velocity profile before the step



U and P - instantaneous fields after spin up

U-field on top and P_{nh} below





Discussion

- With grid sizes close to 1 m: small scale eddies similar to those observed
- Sensitivity to the grid size
- Sensitivity to the sub-grid scale closures
- Vertical structure of the eddies
- Balance between the centrifugal force and pressure gradients
- Energy budgets
- Effects of stratification
- Combinations of lateral steps and sills
- A new sequence of 3D inlet/sill papers