Numerical studies of small scale eddies behind headlands in tidal inlets

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

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Maelstroms background

- From Dutch, «malen» = crush, «stroom» = current
- Edgar Allen Poe and Jules Verne uses the term to describe violent vortices that reach down to the sea floor
- Examples of maelstroms:
  - Moskestraumen, Norway
  - Saltstraumen, Norway
  - Corryvreckan, Scotland



Saltstraumen





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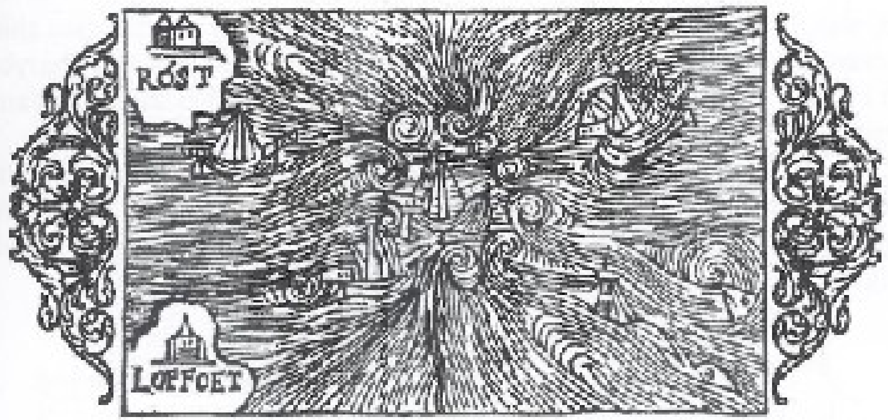
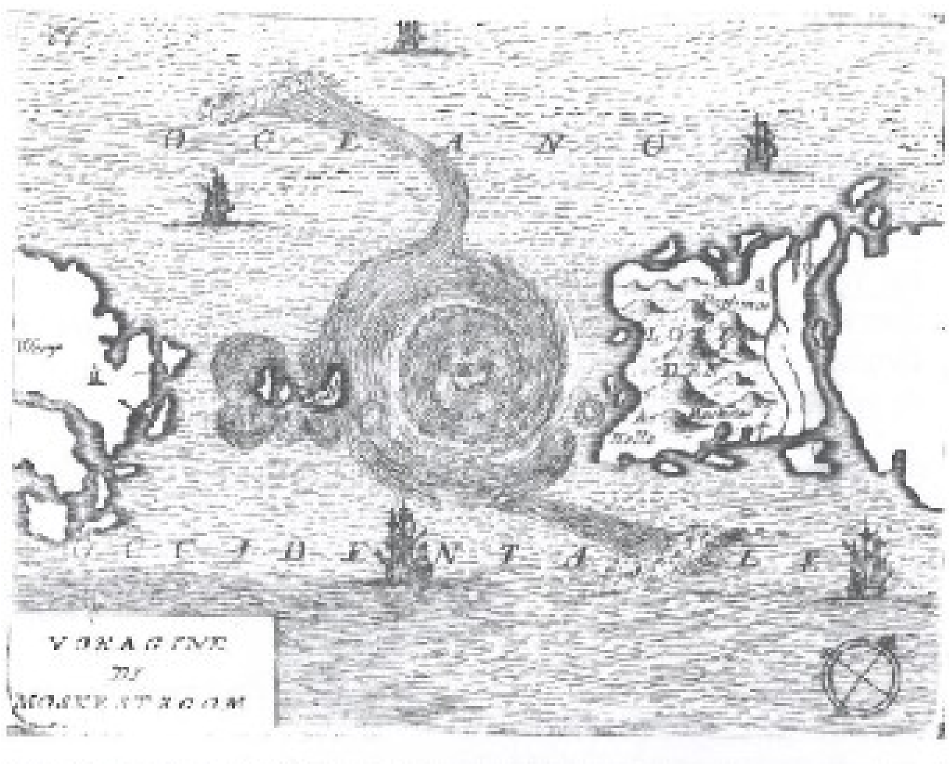
The Moskstraum eddy by Olaus Magnus -1555



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

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

The Moskstraum eddy by Cornelli (1650-1718)



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

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Flow from Lofoten to the Baltic Sea through a Tunnel

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).

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

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Why should we model such eddies?

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

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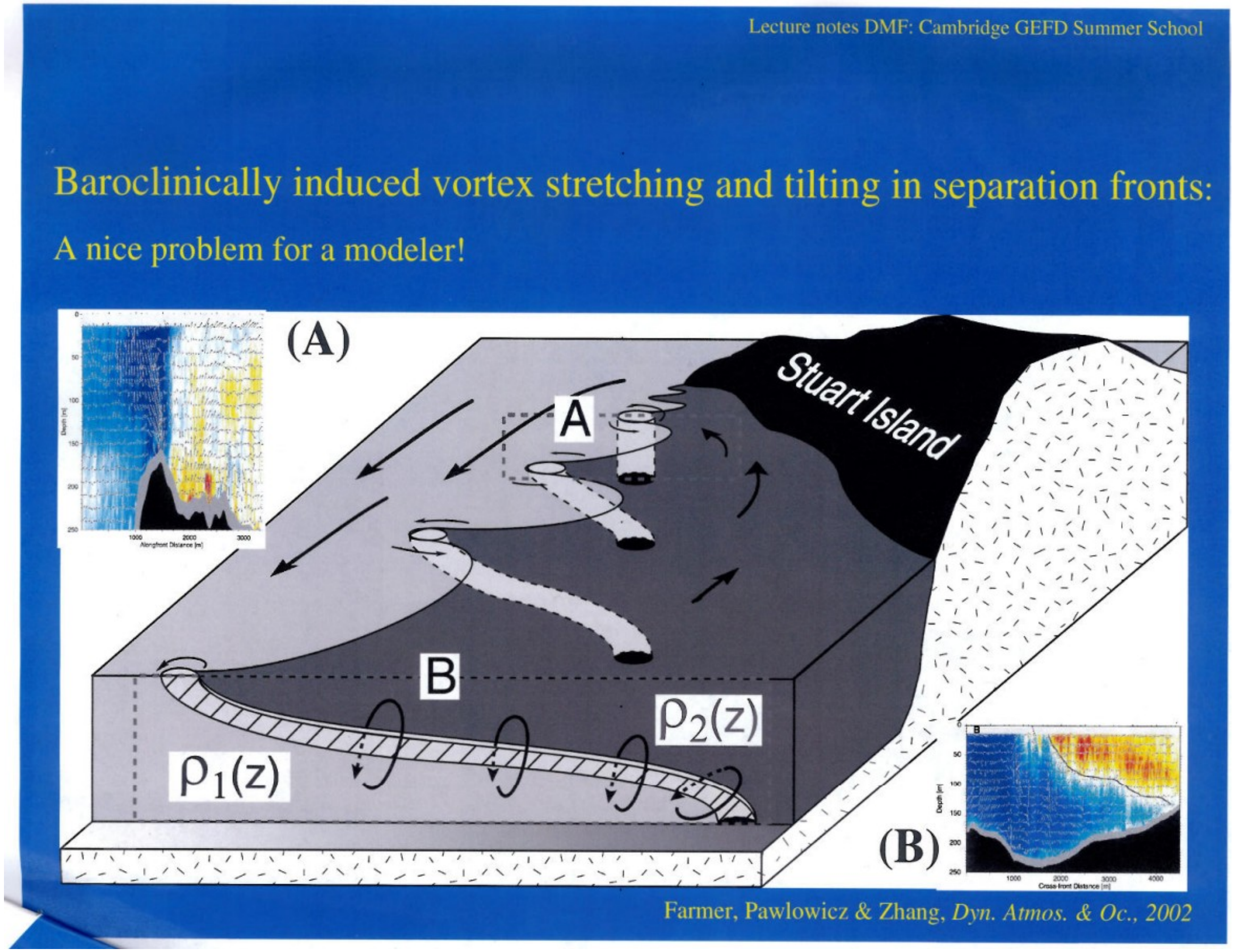
Mixing at tidal inlets - Flow over sills

- Mixing due to Internal Waves
- Mixing due to Overturning Vortices
- Mixing due to Horizontal Eddies
- Knight Inlet - British Columbia – Canada (50%=horiz.mix?)
- Loch Etive - Scotland - UK
- Two-dimensional model studies ignore the role of the horizonal eddies
- We need three-dimensional (3D) model studies

Eddies at Stuart Island

(a challenge for modellers from Farmer at the GFDL summer school)



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The backward facing step problem from CFD

Example from Gartling 1990 – a much used benchmark

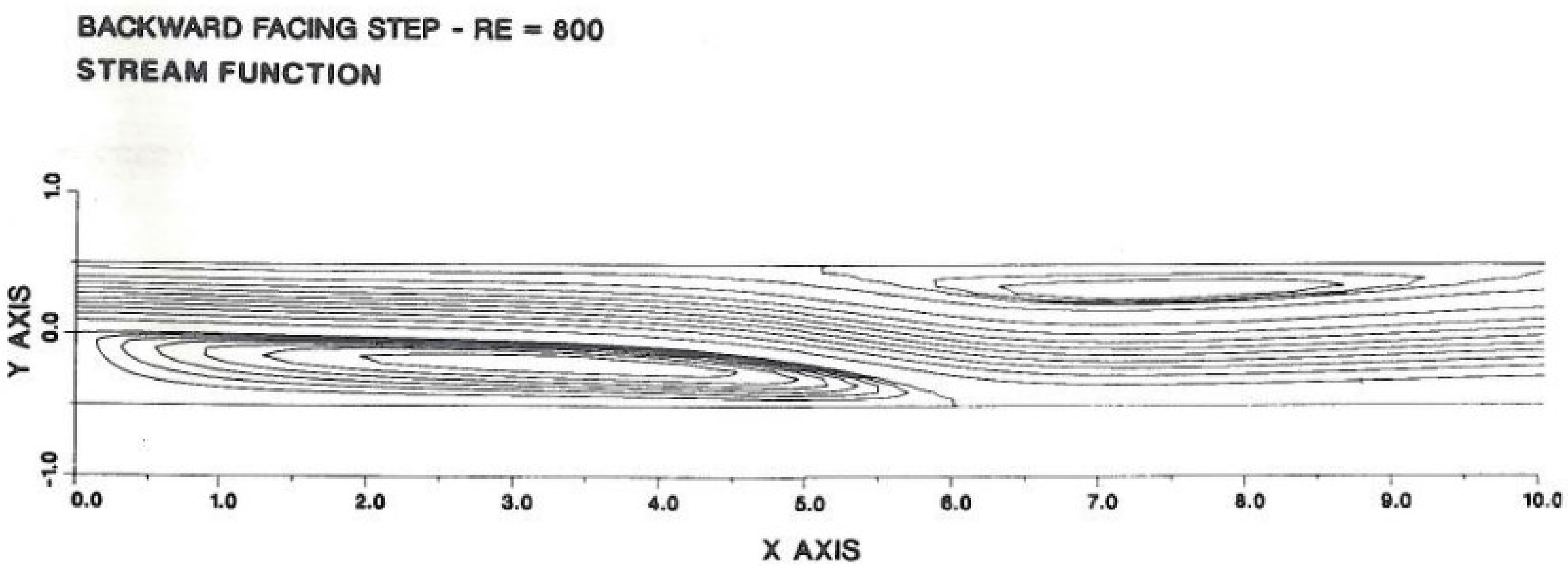

Figure 3. Streamfunction contours. Level values are −0·030, −0·025, −0·020, −0·015, −0·010, −0·005, 0·0, 0·050, 0·100, 0·150, 0·200, 0·250, 0·300, 0·350, 0·400, 0·450, 0·490, 0·500, 0·502, 0·504

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Our model

- The Bergen Ocean Model (BOM), developed at the Department of Mathematics, University of Bergen, Uni research, Bergen, with contributions from the Institute of Marine Research (IMR) Bergen.
- Development started around 1995, initally borrowing heavily from POM
- Non hydrostatic, sigma co-ordinate, regular grid
- Timestepping similar to ROMS, predictor corrector allowing for long 3d steps.
- Fortran 95, MPI parallelization, run time vizualisation, nearly all configuration via config files.
- Used in studies from lab scale(mm) up to models of the Norwegian seas with 20km resolution

Can we model such eddies with mode split ocean models?

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

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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 (see e.g.7.32 Kundu&Cohen)
- Valid for small amplitude waves ($\eta << L$), but *how* close can η be to L?
- In mode split ocean models: η and P 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 $\tilde{U}^{n+1}$ at the new time step are obtained

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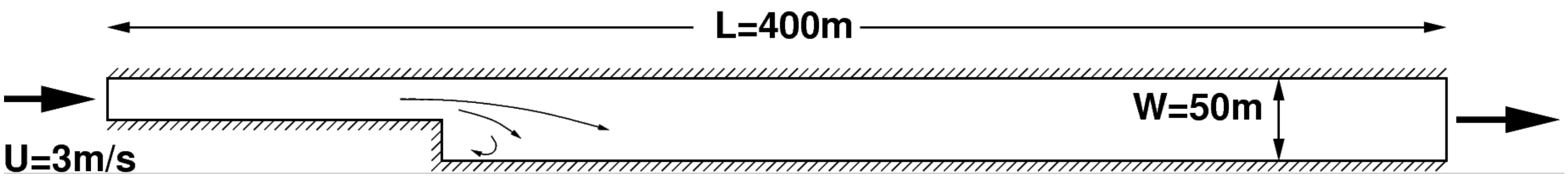
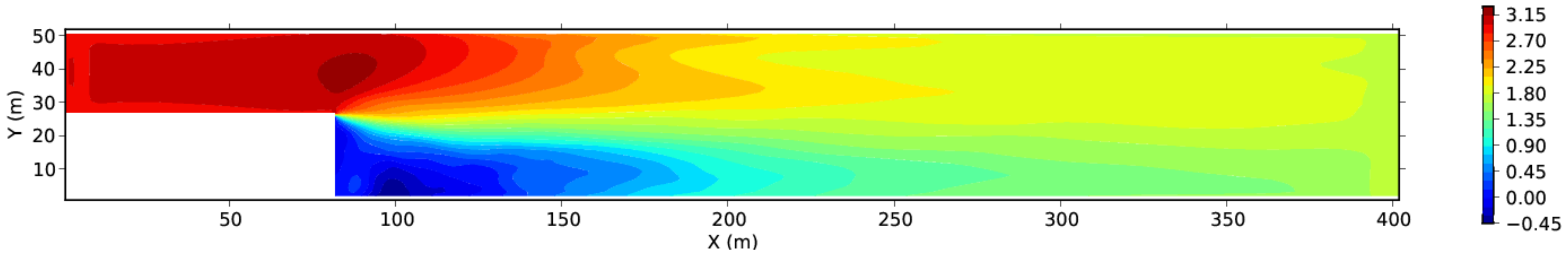
Non-hydrostatic Pressure in ocean models

- The non-hydrostatic pressure P_{NH} is computed from an elliptic equation forced by the divergence in $\overline{U}^{n+1}$
- 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 (*dP/dx* small)
- With the Neumann condition, $\frac{\partial P}{\partial n} = 0$ the velocity corrections are divergence free
- The surface elevation is determined in the short 2D time steps, consistent with the mode splitting idea

Flow past lateral step, *DX=1.25m*





x component of velocity, *U,* averaged over 5 minutes at z=-5m.

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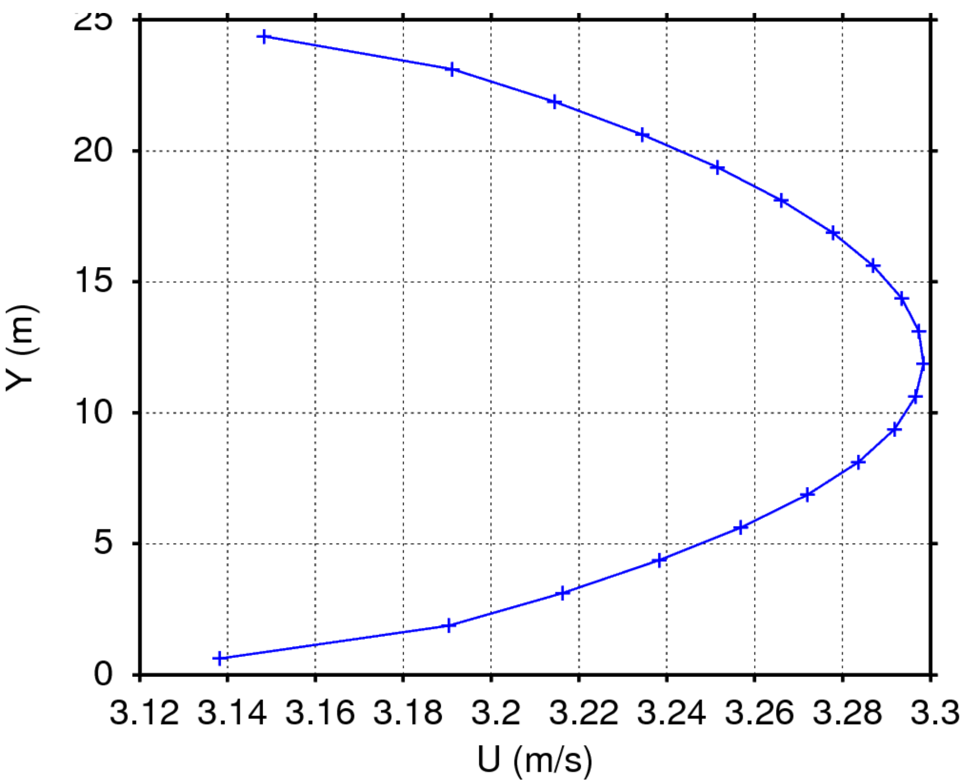
Across channel velocity profile

- Lateral friction creates Poiseuille type profile before step



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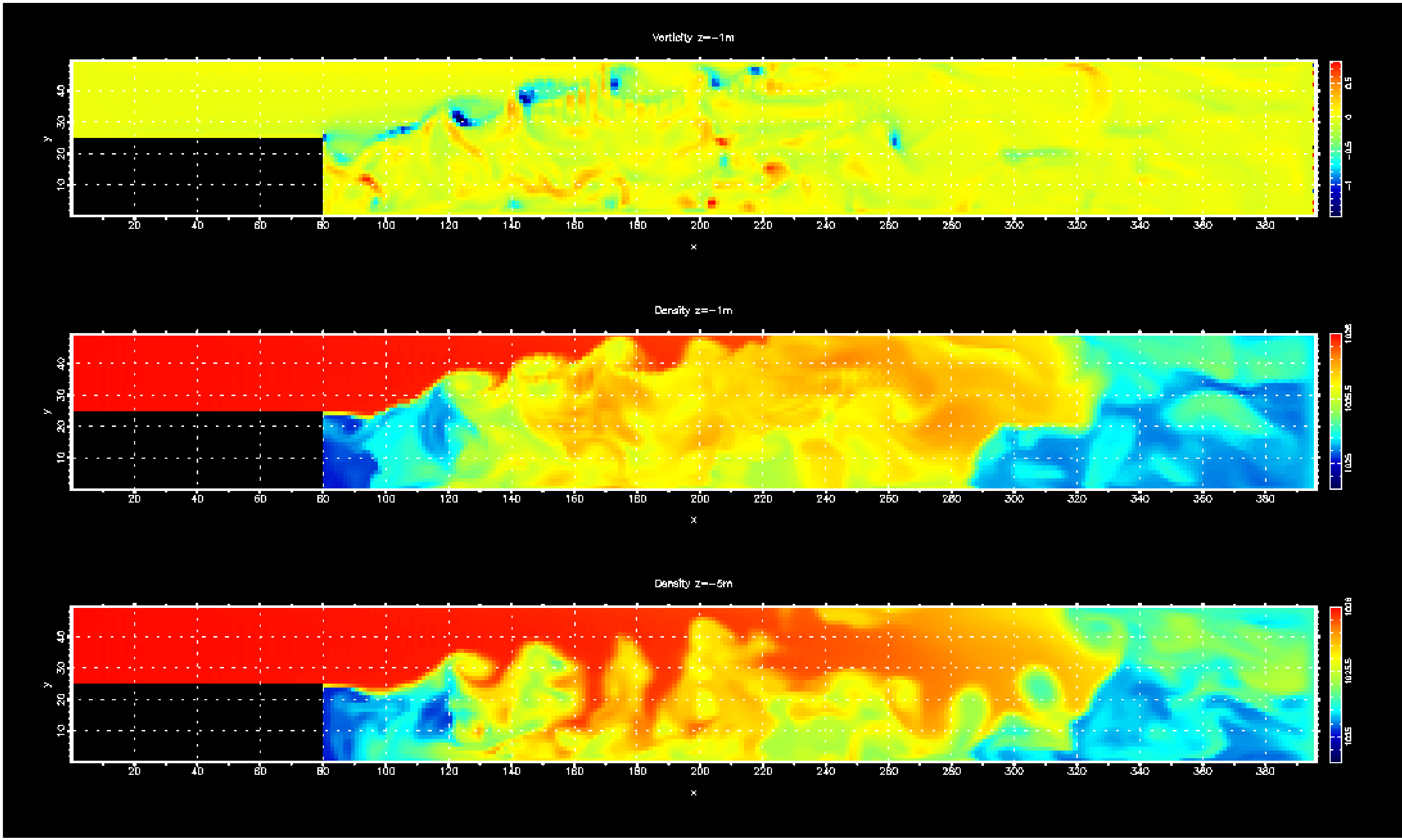
Instantaneous fields, *t=788s*

From t=400s to t=850s, ρ is increased from 1025 to 1026. (Total time simulated is 1800s)



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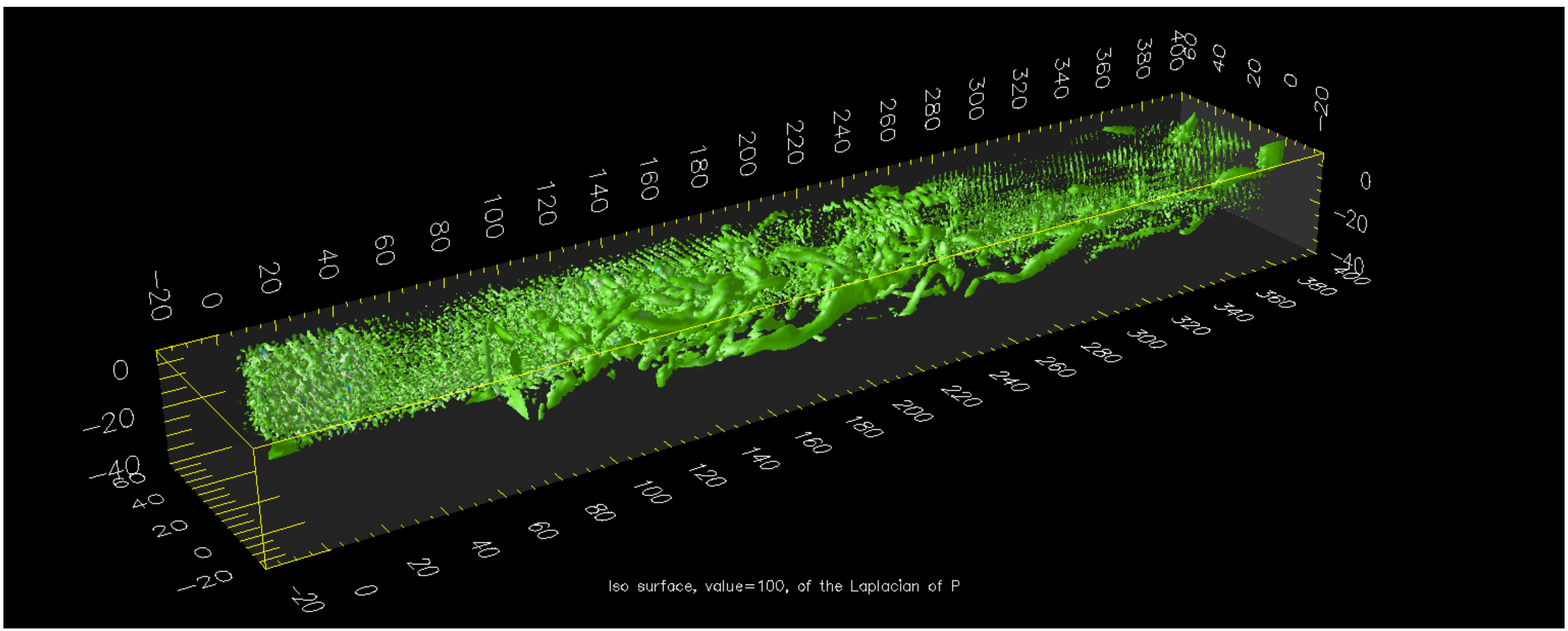
Visualization of vortices

- Following Tanaka and Kida, Nagaosa and Handler, we intend to look at methods using low pressure criterias such as

$\nabla^2 P = Q_S$

$Q_S^{+} = Q_s \nu / u_\tau^{2}$

$\overline{Q}_S = (Q_S^{+} - \langle Q_S^{+} \rangle)/Q_S^{rms} = 5/4$, a snapshot of $\nabla^2 P$ alone indicates structures:



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Discussion & future

- With grid sizes close to 1m: 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

Finally a couple of animations if time allows?