Gas Exploration Beyond the Shelf Break; an Oceanographic Challenge

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Abstract

Norway's second largest gas field, Ormen Lange, is located 140 km west off Kristiansund at an unprecedented depth when it comes to exploration. It will be the first Norwegian project beyond the shelf break. Exploration and development of the field is thus a challenge. An important issue during the planning stage is to understand the current conditions and hydrography of the site. This is especially important regarding pipeline design, deployment and operations. A complicating factor for estimating design currents is the extreme roughness of the local topography. Submarine slides have produced escarpments and sea mounts with height variations of up to 100 m. The hydrography seems to be equally complex; In situ moorings have revealed strong variations in current speed and temperature close to the seabed.

A variety of numerical experiments have been and are being set up in order to recapture and if possible forecast the observed variability. The results show that the flow is influenced by the inflow of Atlantic Water, tides, atmospheric forcing and by flow of water masses inside the Norwegian Sea basin. The variability near the seabed at Ormen Lange is strongly influenced by the local topography and the stratification. Realistic model studies therefore require high resolution models for the Ormen Lange topography connected to basin scale models. The models must be non-hydrostatic and the stratification realistic to enable realistic estimates of extreme events.

KEY WORDS: shelf break; shelf slope; offshore oil industry; currents; waves;

Introduction

Processes related to the shelf edges and shelf slopes have so far been of great scientific importance because of their role in the exchange of matter and energy between the shelves and the deep oceans. From the Norwegian offshore industries point of view, this research has been of limited interest since the oil and gas fields have been located on the continental margins at depth less than 300 m. But when Norsk Hydro in 1987 found a significant gas field, Ormen Lange (OL), in the core of the Storegga slide, the need for knowledge about continental slope and continental shelf break processes arose. The combination of large depths, between 800 and 1100 m, low temperatures, below 0 degrees, and extremely rough topography represent great challenges for the development of the field.

The general opinion has been that currents in the deep oceans are fairly weak. However, so far the focus has been more on the general flow and mean transports rather than on peak events in oceanography (Seidler et al., 2001). Observed time series from OL at 800 to 1100 m depth showed large oscillations in the density interfaces and that velocity peaks may exceed 50 cm/s (Eliassen et al., 2000), see Figure 1 for an example. Since rapid changes in the flow are seen, and the recorded velocities are time filtered, the true maximum velocities may be underestimated at present (Berntsen et al., 2001).

Regarding pipeline design, deployment and operations, the understanding of the current condition and hydrology at OL is crucial for a successful operation of the gas field. Accurate observations and numerical models are therefore important tools. Recordings of time series from OL (OCEANOR) and the Svinøy section (Orvik et al., 2001, Skagseth and Orvik, 2002) form the basis of the observations. When it comes to numerical models, several experiments with different grid resolutions are performed and reported in different technical reports (Avlesen and Berntsen, 2001, Alendal, 2002, Berntsen et al., 2001, Berntsen and Furnes, 2002, Eliassen et al., 2000, Eliassen and Berntsen, 2000, Heggelund and Berntsen, 2000, Heggelund and Berntsen, 2001, Sørflaten et al., 2001, Thiem et al., 2001, Thiem et al., 2002a, Thiem and Berntsen, 2002, Thiem at al., 2002b, Thiem et al., 2002c, Vikebø et al., 2001a, Vikebø et al., 2001b, and Vikebø et al., 2001c). The numerical experiments are based on the Bergen Ocean Model (BOM) (Berntsen, 2000) and the general circulation model developed and maintained at MIT (MITgcm) (Marshall et al., 1997a,b). Both models allow non-hydrostatic simulations.

The time mean current at OL is strongly dominated by the Norwegian Atlantic Current (NAC). The mean current is approximately 30 cm/s close to the shelf edge. At 800 m depth the mean is approximately 5 cm/s, see Orvik et al. (2001). Tidal effects are weak, i.e., less than 5 cm/s at these depths, but increasing towards the shelf edge. In the upper 100 m the flow is strongly affected by the atmospheric pressure and wind forcing. At intermediate depths the flow is mainly aligned with the general topography, while the flow in the bottom layer is strongly affected by the roughness of the topography and is much more directional unstable (Eliassen et al., 2000).

The extreme events are driven by strong pressure gradients. That is, strong atmospheric low pressures and/or internal pressure gradients at fronts between warmer Atlantic water (AW) and colder Norwegian Sea Arctic Intermediate Water (NSAIW). Along the shelf slope at OL, steepening of the isopycnal separating AW and NSAIW may occur due to strong Ekman veering during storms and/or approaching internal density fronts (Vikebø et al., 2001a). Figure 2 is a rough sketch of the water masses along the shelf off mid-Norway. During such events the density surfaces tend to under/overshoot their equilibrium level, and as the forcing weakens, the suppressed water may run up/down along the shelf slope. During these events, peak values in the velocities are often found. If the event is a strong run up event colder and heavier water masses are lifted up on the shelf. As the wave retreats off shelf, some of the heavier water may be left atop of the shelf separated from the water mass it originated from. This high density on shelf water mass follow the general flow along the shelf, and may later on, flow down cross shelf canyons creating gravity currents. In the OL area, findings indicate that gravity currents are sometime present. Flow down the shelf can also be set up by sediment laden currents (Simpson, 1987). After front passages the oscillations of the thermocline may continue for days. Prediction of waves and currents is thus an important goal for the OL research. Since the water masses are accelerated by pressure gradients, a forecast is therefore dependent on the ability to measure and predict pressure differences in the atmosphere and in the ocean. For the atmospheric, low pressure forecasts are routinely produced and these are trustworthy up to one week ahead. For internal oceanic pressure gradients, an array of current meter and hydro graphical moorings surrounding OL is necessary to capture incoming fronts.

Models and model results.

To investigate the ocean dynamics, numerical models have shown themselves useful. The local dynamics, see Figure 1, are driven by both regional and global scale atmosphere forces and internal pressure fronts in the ocean. Hence, to be able to model effects at small scale it is not only necessary to resolve small scale variations, such as bottom topography, it is also important to understand the regional/global circulation and forcing.

BOM, which is a numerical timesplit σ-coordinate model, is the model that has been run most often during this research. BOM can be downloaded free from http://www.mi.uib.no/BOM/. The equations are the continuity equation for an incompressible fluid, the Reynold averaged momentum equations, conservation equations for temperature and salinity and the UNESCO equation of state. The reader is referred to Berntsen (2000) for further details concerning the governing equations and numerical methods.

Simulations with grid resolution 20 km, Figure 3, have been run to increase the understanding of how the atmospheric and the thermohaline forcing will affect the near seabed currents at OL. In these simulations travelling idealized atmospheric low pressures has been used, where the path, strength and radius has been changed. The simulations show that a strengthening of the thermohaline field will lead to an increase in the near seabed velocities and that the presence of atmospheric low pressures results in peak values in the near seabed velocities, but the currents are very sensitive to the path, strength and radius of the low pressure (Vikebø et al., 2001, Thiem et al., 2001). Passage of a strong atmospheric low pressure system north (south) of the site causes the density surfaces to sink (rise), see Figure 4 (Thiem et al. 2002c). When the atmospheric forcing decay or leave the area, the perturbed density surfaces will start to oscillate, see Fig. 5. Water with temperatures below 0 degrees, can then be displaced several hundred meters up and down the shelf slope, which can cause temperature peaks as in Fig. 3. Deep-water installations may then be exposed to freezing conditions. The oscillation of water up and down the shelf slope may also generate strong currents close to sea floor. Measurements and simulations indicate that these currents may exceed 1 m/s.

To get an impression of how the bottom topography will affect the near seabed currents, BOM was set up with a 4 km grid resolution in a sub domain of the 20 km model, Figure 3. The initial and boundary conditions were interpolated from the 20 km model, and a corresponding travelling low pressure was set up. New bottom topography was also created from a 5 minutes longitude/latitude database. The result was generally that the maximum velocities were reduced when the grid resolution was increased. Higher grid resolution, also showed that the oscillations after the low pressure had passed were damped more rapidly. The simulations also indicated that if the velocities are split into a mean and an oscillating part, it is the mean part that is reduced, and the oscillating part actually is increased with higher resolution. In Figure 5 we can see the effect of the bottom topography. Usually there will also be a shift in the phase, with a rough bottom giving shorter oscillation periods than smooth bottom. Since the bottom matrices in numerical studies often are smoothed to avoid noise at length scales near the grid resolution, the damping is probably often too weak (Thiem et al., 2002a and Thiem and Berntsen 2002).

The 4 km model was also set up with synoptic data for wind and atmospheric pressure. In two time periods, June and November 2000, high near seabed velocities were measured in connection with sudden changes in temperature and salinity at OL and the Svinøy section. These periods were therefore chosen for the validation of the models performance. The June period had an abrupt decrease in temperature, see Figure 6. The simulations strongly indicate that the two chosen events are connected to travelling density fronts, and not to local atmospheric activity. Since the initial conditions of the front is unknown, the simulations could not recapture these events (Thiem et al., 2002c).

In the OL area, findings indicate that gravity currents are sometimes present. There are two topics relevant to gravity currents at OL; where will the gravity current flow down the continental slope, and how large may the current speed be as the heavy water mass plunge into the deep ocean? The former requires a study of the local topography along the continental shelf. For the latter, a 500 m grid resolution model was set up with an idealized shelf slope for both the hydrostatic and non-hydrostatic case. In these simulations water with higher density than the surrounding water was placed on an idealized shelf. The water was then released and allowed to flow down toward its equilibrium level. Results from a non-hydrostatic simulation of gravity currents along the shelf slope are shown in Figure 7. Such simulations indicate that these gravity currents can reach a maximum speed of at least 0.7 m/s (Heggelund and Berntsen, 2001 and Vikebø et al., 2001b).

Some of the near seabed velocity measurements that have been done at OL differs strongly in amplitude and direction even if the measurements are done close to each other in time and space. This implies that the small scale effects will play an important role on the near seabed velocities. To study the topographic small scale effects, BOM has been set up with a 4 m grid resolution, hydrostatic and non-hydrostatic. These studies showed that the stratification is very important, since the stratification can be the decisive factor if the water is pressed over or around a sub sea ridge. The experiment also showed that for the topography in the experiment a magnification factor of the background flow up to 20 percent was predicted. The simulation also showed that even if the flow may be intensified near small scale hills, the small scale obstacles will extract energy from the general flow (Berntsen and Furnes, 2002).

The MITgcm is a numerical model for studying the ocean and atmosphere developed by Marshall et al. (1997b,a) which has non-hydrostatic capability. It is capable of simulating the ocean at a wide range of scales and can resolve many different processes. MITgcm is a z-coordinate model, but with a finite volume method to accurately represent the bottom topography (Adcroft et al., 1997). The model support curvilinear coordinates in the horizontal direction and varying resolution in the vertical. Hence, it is capable of grid focusing that assures necessary distance between the boundaries and the area of interest. The MITgcm was set up with 4 m and 1 m grid resolution for a small part of the OL area. Alendal (2002) has showed the importance of including the non-hydrostatic effect in simulations at this scale. Flow that approaches an obstacle will tend to move up and over the obstacle by the hydrostatic assumption. The signal of this vertical movement may propagate all the way to the surface. On the other hand, when non-hydrostatic effects are included the vertical movement will experience higher resistance. This will transfer some of the vertical energy to the horizontal directions, with more fluid passing along the sides of the obstacle.

The rough topography at OL is shown to induce topographic steering and blocking. Models focusing on general circulation do not resolve such small scale influence on currents and waves (Xing and Davis, 1999). As Figure 8 shows, the blocking is distributed into the water column, above the sea floor. This formdrag should be parametrised when the grid resolution is too coarse to resolve the topography. (Lott and Miller, 1997)

The stratification in this area is dominated by the water masses in Figure 2. The interface between the water masses has a radical change in density over a small depth. Such a strong stratification will trap internal waves and can focus these waves close to the seabed. This can result in mixing and strong currents near the sea floor (Legg and Adcroft, 2003).

Summary

Gas exploration beyond the shelf break of Norway has met major challenges. At OL installations and pipelines will be exposed to freezing conditions and strong rapid varying currents. The understanding of the driving mechanisms behind the dynamics is vital for the development of oil and gas fields in this area.

Model simulations indicate that atmospheric low pressures create strong current events and associate extreme temperature values. However, there are events in the recordings at OL that apparently are not connected to travelling atmospheric lows. These events may be caused by internal density fronts.

If a low pressure is passing north of an area, the response will be a down welling first followed by oscillations. If the path is south of an area there will be an up welling first. The amplitude depends on the magnitude and the path of the storm.

Strong atmospheric lows can probably generate gravity currents at OL, but there are still no recordings of such an event. Gravity currents at OL will probably be very local and follow the canyons in this area.

Rough topography seems to damp oscillations faster and to shorten their period relatively to the case of smooth topography. Rough bottom also creates small scale effects as topographic steering and blocking. These effects generate a drag layer that should be parametrised when the model grid is too coarse to resolve the physics.

The stratification also governs the propagation and breaking of internal waves and such waves may be focused near seabed. The role of stratification on the near seabed currents, therefore needs more attention on future research activities.

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Figure Captions

Figure 1. Recordings of speed and temperature at 795 m depth, November 10 to 21, 1996 at Ormen Lange (OCEANOR).

Figure 2. The water masses in the region divided into four different layers; Norwegian Coastal Water (NCW), Atlantic Water (AW), Norwegian Sea Arctic Intermediate Water (NSAIW), and Norwegian Sea Deep Water (NSDW).

Figure 3. Bottom topography of the 20 km (left) and 4 km (right) grid resolution model with axis in km. Ormen Lange is located approximately at the **x** in the 4 km model, with Storegga to the right.

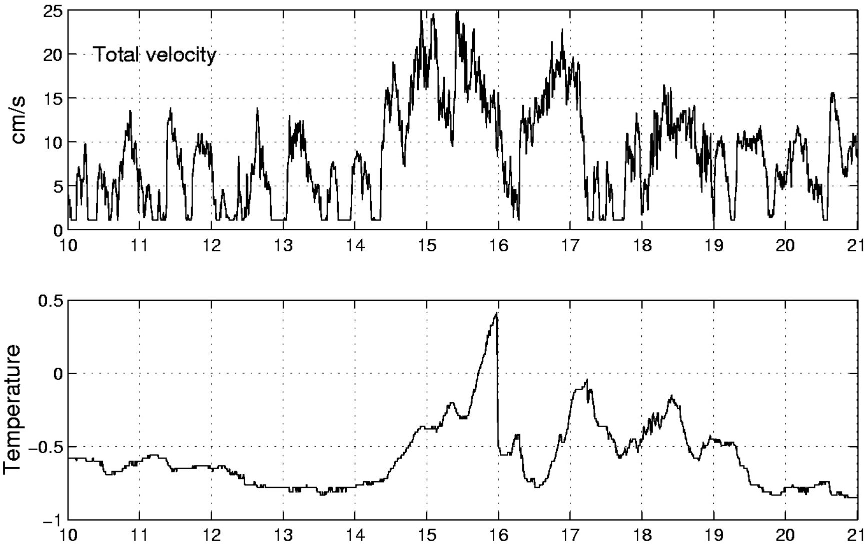
Figure 4. Rising and sinking of isothermals from the 20 km grid resolution model. Simulations where low is passing south (left) and north (right) of the section. The horizontal axes are in km, the vertical in m and the isothermals in degrees.

Figure 5. Model result from 4 km grid resolution model. Dashed line smooth topography interpolated from the 20 km grid resolution. Solid line bathymetry interpolated from the ETOPO-5 data base (Data announcement 88-MGG-02, Digital relief of the Surface of the Earth, NOAA, National Geophysical Data Center, Boulder, Colorado, 1988) with inserted finer resolution around OL.

Figure 6. Measurement from Ormen Lange and Svinøy 16/6-5/7 2000 shows that rapid drops in temperature are present at both locations with a lag in time. The measurement depth are approximately 460 m, and shows that NSAIW are moved up slope.

Figure 7. Idealised non-hydrostatic simulation of gravity currents from the 500 m grid resolution model(Vikebø et al. 2001b).

Figure 8. Model result from the MITgcm 4 m grid resolution model. The thickness of drag layer depends on the bottom irregularities with low velocities close to the seabed. The figure shows velocity in m/s, and axis in meters.



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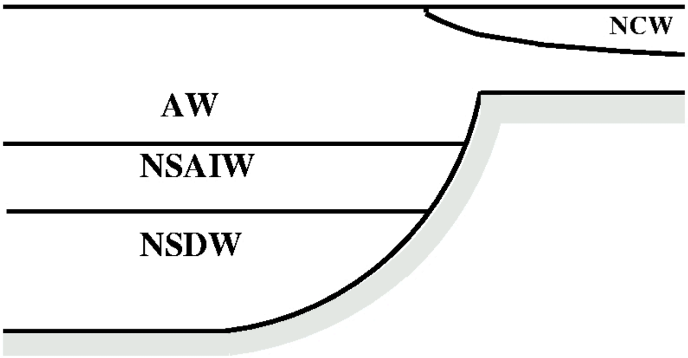

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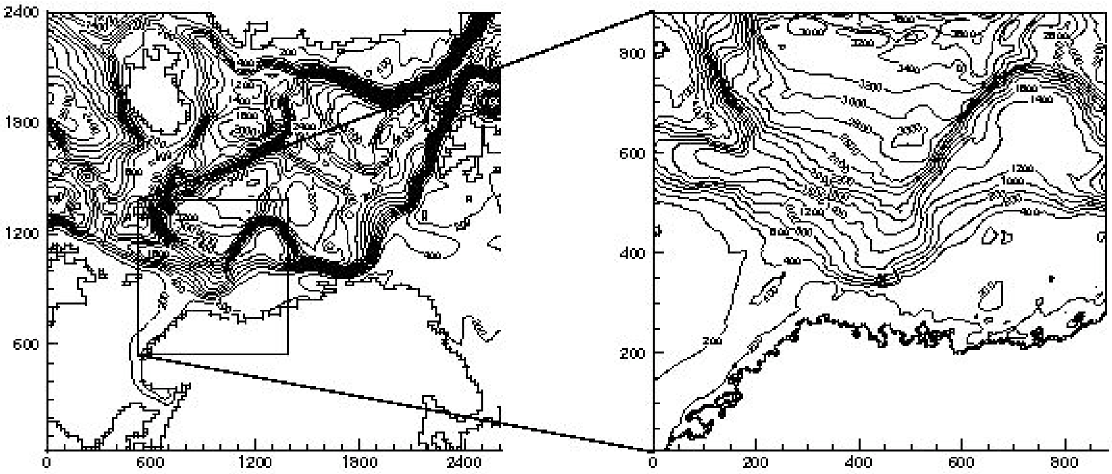

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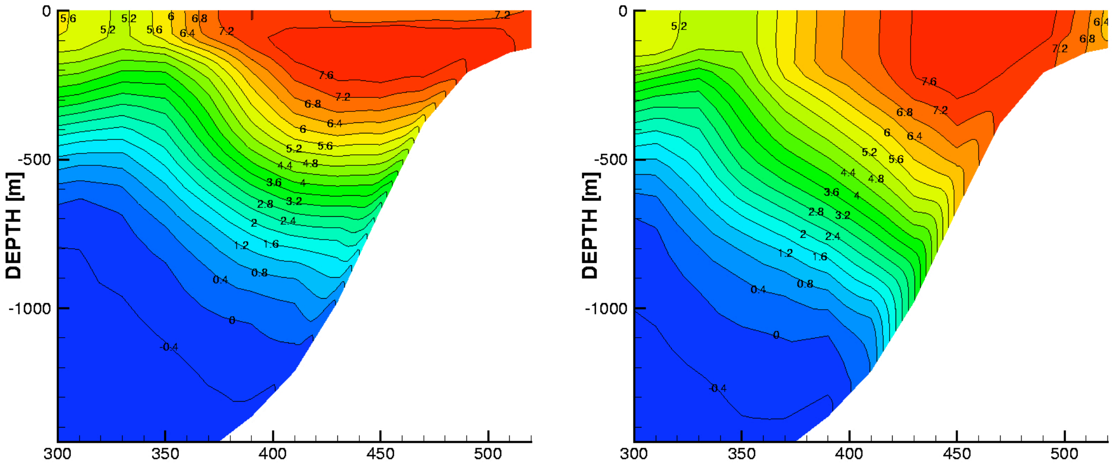

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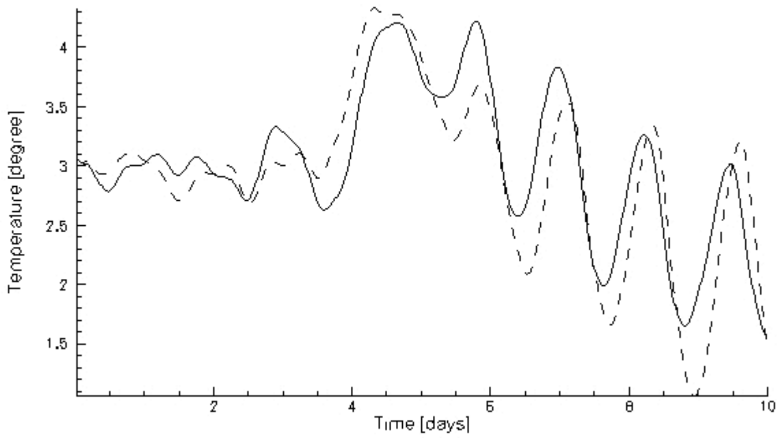

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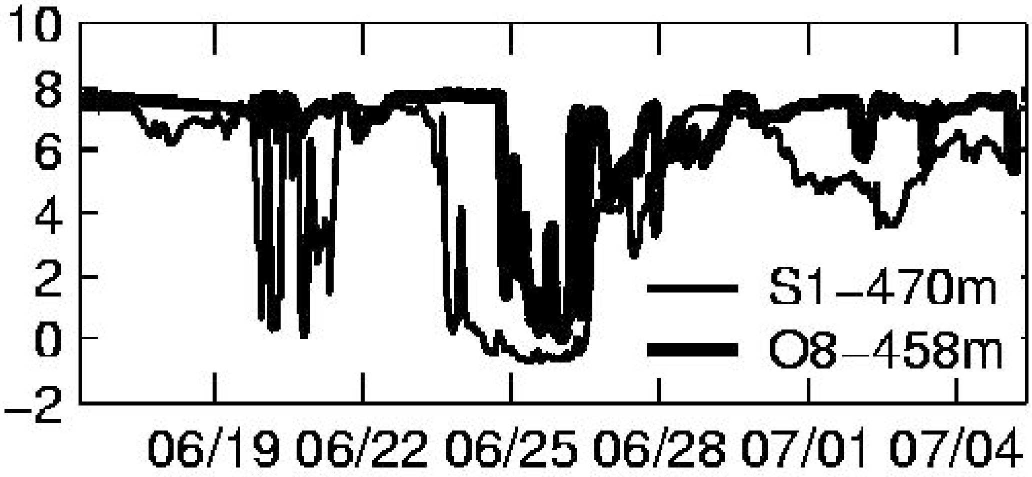

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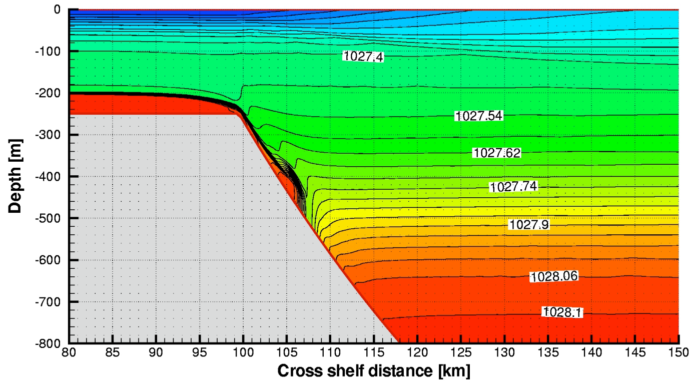

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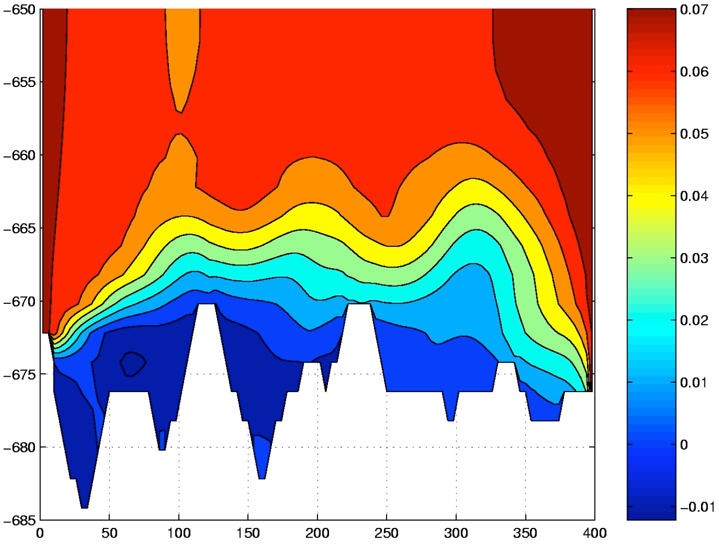

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