The Nansen Environmental and Remote Sensing Center

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NERSC

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Present understanding of currents and events at Ormen Lange

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1 Executive summary

The exploration of the Ormen Lange gas field represent new challenges to design, deployment, installation and maintenance. The field is, so far, the deepest reservoir of hydrocarbons that are under development in the Norwegian sector. The dynamics are different than atop of the continental shelf, and the operating temperature is different. In addition, the gas field is located at the scene of one of natures most extreme events, the Storegga landslide. The topography at Ormen Lange is extremely rough, which not only limits the corridor of the pipeline, such extreme terrain may also produce extreme current events.

In the past years a group, with members from the Department of Applied Mathematics, University of Bergen, Norsk Hydro, and Nansen Environmental and Remote Sensing Center, has studied extreme events at Ormen Lange, with focus on the current conditions. It seems evident that extreme currents occurs in connection with passing atmospheric low pressure systems, or when incoming interior pressure fronts interact with the continental slope.

A system for forecasting extreme events must rely on two main components; First an array of real time measurements must be operative. It is crucial that data is on-line and supplies three dimensional data. Secondly, the real time data must be incorporated into a modeling system, covering the Ormen Lange area, through inverse methods. It is crucial that the model system uses realistic environmental profiles and topography.

Design of, and selection of corridor for the pipeline relies on estimates on current conditions. It is important to determine, as accurate as possible, the probability density function for current to be able to predict the “hundred years” event. In this context, the most important part of the distribution function is the tail. To do this as accurately as possible, it is not sufficient to rely solely on measured data. There is always an uncertainty whether the collected data have sufficient material to include enough extreme events. Hence statistics is a tool, but it is important to understand the underlying processes that generated the extreme events.

At Ormen Lange it is necessary to develop directional statistics along a pipeline. It it also important to keep in mind the different water masses present at the location, and distinguish statistics on which water mass the data is taken from.

The suggested work plan to determine the tail of current distribution involves theoretical studies, laboratory experiments, in-situ measurements, and numerical simulations. The theoretical studies must include a literature survey and collection of available data from similar areas world wide.

Pressure fronts and low pressure systems are important. Later a regression method for determining maximum velocity as function of depth, and atmospheric low pressure depression is presented. Better statistics can be made if; First establish distribution functions for atmospheric low pressures, both the depression and the track taken by the storm, and stratification. Secondly, perform a number ($>$100) of numerical simulations where pressure depression, storm track and environmental profiles are taken randomly from the distributions, and collect current profiles from selected sites. And finally, do a regression on the available data. Such statistics will be valuable additions to in-situ measurements.

The interface between the Atlantic and the much colder Norwegian Sea Arctic Intermediate waters often passes through the Ormen Lange area. The high density gradient present through such an interface leads to complex dynamics. Knowledge on how disturbances on the interface propagate toward Ormen Lange, and how these disturbances interact with the continental slop and the rough topography is crucial for understanding underlying processes for extreme events.

Use of realistic temperature and salinity profiles are important for proper initialization of the models used in the studies. So far, climatological profiles, hence time averages, has been used. The profiles lacks the strong pycnocline often present in the area.

The rough topography generate dynamics that are important on all scales. Rough topography generate form drag that is important for regional modeling. Parameterization of this effect is still novice in ocean modeling. Atmospheric models show that it is an important effect for accurate weather forecasts. To build a reliable forecast system it is therefor crucial to study this effect and incorporate it into the regional model system. One necessary exercise, in order to establish such a parameterization, is to establish statistical characteristics of the topography at Ormen Lange, such as mean, standard deviation, and moments from the anisotropy tensor. Another analysis suggested is to repeat *Wåhlin* (2000, 2003) studies

2 Real time forecast network

To be able to forecast extreme events at the Ormen Lange gas field, it is necessary to combine measurements, models and physical understanding of the involved processes.

There are two things that are characteristics at the Ormen Lange area, a focused pycnocline and an abrupt topography. By measuring, if possible, vertical displacements of the pycnocline far from shore, a forecast on approaching events may then be possible. It is then important to know how such a disturbance interact with the continental slope, and what processes it will generate locally.

2.1 Real time measuring program

Such a network should consist of an array of stations that do real time, 3 dimensional, data collection. A CTD with telemetric capabilities are under development, that may be useful is such a context. Especially real time measurements on vertical movement of the pycnocline and incoming pressure fronts are important.

2.2 Model-system

The model system require real time atmospheric and oceanographic data, incorporated by inverse methods, and it is important to assure use of real stratification and real topography. There are several regional ocean models available that can be extended to support forecast of events. Like for instance the model system at NERSC , which has the inverse methods already in place (*Evensen*, 2001), and the Bergen Ocean Model (BOM) (*Berntsen*, 2000). However, each of these models presently lack proper treatment of rough topography and sub-grid-scale effects. Hence, proper parameterization of these events are necessary.

3 Pressure fronts and storm surges

It it clear that extreme events occur during incoming pressure fronts or passing of atmospheric low pressure systems. The path taken by a storm passage is also important.

3.1 Storm track

A storm passing in the Norwegian sea creates strong Ekman veering and vertical movement of water masses on the continental slope (*Berntsen et al.*, 2001). Such altering of the water masses may generate extreme current events.

The generation differs on whether the storm passage is north or south of the Ormen Lange area. A storm passing north will predominantly generate southernly winds and pressure against the coast, resulting in downwelling. On the other hand, a storm moving south of the area gives northerly winds and move water masses aways from the continental slope, generating upwelling of heavy water in a relatively thin layer (*Thiem et al.*, 2002c).

As the wind forcing weakens the water masses goes through damped oscillations, until reaching new equilibrium. *Thiem et al.* (2002c) compared the difference in maximum speed of two storms passing north and south of the Ormen Lange area. There is no dramatic difference in the maximum velocity modeled.

3.2 The role of the numerical grid resolution

A regional model covering the Ormen Lange area should use as fine grid as is computational accessible. Higher resolution resolve more physics and gives more realistic topography, see 5.1. *Thiem and Berntsen* (2002) performed two simulations with 20km and 4km resolution of a storm passing the Ormen Lange area. Finer resolution damped the generated waves more rapidly and the maximum velocity at selected locations was lower compared with higher resolution. This is due to the unresolved physical processes that are lacking in the coarsest integration. High resolution also simulates flow along the shelf edge in a more consistent manner. However, even at 4km resolution there are processes, such as topographic effects, that need proper parameterization. Especially the form drag, presented in 5.2, is lacking.

3.3 Regression on maximum velocity as function of pressure and depth.

In *Vikebø et al.* (2001) an approximation of a second order polynomial function between the dimensionless number $G_{norm} = \frac{P/R}{P_s/R_s}$, where P is pressure in the center of the storm and R is storm radius (subscript s denotes reference values), and maximum velocity was performed. In order to study dependencies between the different parameters further, data was collected from *Vikebø et al.* (2001) and cross-correlation between some of them are shown in Tab. 1. The data samples in *Vikebø et al.*

	U$_{max}$	**Time**	**Depth**	**P**	**Dist**
U$_{max}$	1.00	-0.25	***-0.58***	***0.69***	0.13
Time	-0.25	1.00	*0.03*	-0.29	0.10
Depth	***-0.58***	*0.03*	1.00	0.00	-0.07
P	***0.69***	-0.29	0.00	1.00	0.00
Dist	0.13	0.10	-0.07	0.00	1.00

Table 1: *Cross correlations between Max velocity,* **U**$_{max}$*, time delay after storm passage,* **Time,** *depth,* ***Depth,*** *pressure depression enforced by the storm,* ***P****, and distance from bottom,* ***Dist****.*

(2001) are collected 10 and 50 meters above bottom at 5 stations. In the following depth represent the depth of the station with the distance from bottom subtracted, hence 10 locations are used. A correlation between maximum velocity and the two parameters depth and pressure depression is seen. The delay of max velocity show only weak correlation with depth and low correlation for the rest of the parameters.

Maximum velocity and time delay is shown as function of depth and pressure in Tabs. 2 and 3. Under the assumption that $U_{max} = U_{max}(d,p)$, where $U_{max}\,(m/s)$ is the max velocity, $d\,(m)$ is depth, and $p\,(hPa)$ is the low pressure depression, an second order regression model gives, using Matlab,

	Pressure depression (hPa)										
Depth (m)	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
207	220	220	70	78	77	71	71	71	71	71	71
247	38	38	77	75	75	74	74	74	71	71	71
449	77	103	77	102	77	77	77	77	79	79	77
489	40	75	79	75	77	77	77	77	79	79	75
714	240	167	107	104	104	91	89	90	87	78	81
754	239	239	239	108	107	89	88	86	83	83	82
785	132	158	105	90	90	88	77	87	80	85	83
825	158	158	106	88	88	87	87	86	83	83	84
1070	37	38	38	38	189	189	87	85	82	85	85
1110	37	37	37	37	63	64	74	85	75	86	85

Table 2: *Delay for max velocity (h) as function of atmospheric pressure depression and depth.*

	Pressure depression (hPa)										
Depth (m)	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
207	17.3	16.6	16.4	20.9	28.0	37.1	48.0	58.7	71.3	85.1	100.4
247	15.2	15.3	16.8	19.5	24.0	30.6	38.0	46.8	56.4	66.9	78.9
449	16.7	16.8	19.0	21.6	26.3	32.0	38.9	46.8	56.1	66.0	77.7
489	10.9	11.9	13.8	16.4	19.8	24.6	30.5	36.4	43.7	51.4	60.3
714	6.3	6.5	8.1	10.5	13.3	16.6	20.2	24.4	30.0	36.3	43.1
754	5.0	5.1	5.6	8.0	10.1	12.5	15.7	19.5	23.9	28.9	34.1
785	5.6	5.7	6.3	8.5	10.9	13.8	17.3	22.2	27.8	33.9	42.0
825	4.2	4.2	4.5	6.0	8.5	12.2	14.1	18.3	22.3	27.2	33.4
1070	5.1	5.1	5.2	5.2	5.9	7.2	9.4	13.2	16.9	21.1	26.4
1110	5.3	5.3	5.3	5.4	6.2	7.5	9.5	11.9	14.8	18.2	23.3

Table 3: *Max velocity (cm/s) as function of atmospheric pressure depression and depth.*

$$U_{max} = 0.203 - 3.63\times10^{-4}d + 4.33\times10^{-3}p + 2.41\times10^{-7}d^2 - 6.79\times10^{-6}pd + 4.49\times10^{-5}p^2. \quad (1)$$

A contour plot of U_{max} as function of pressure and depth, Eq. (1), is shown in Fig. 1

Even if time delay only show weak correlation with depth, a second order polynomial fit gives

$$T = 121.7 - 1.1d + 0.007d^2. \quad (2)$$

Eq. (2) is shown in Fig. 2, notice the good relation at high pressures but bad accuracy for low pressure depression. The reason might be, for low pressure forcing the generated maximum velocity is small and may be hided in 'white noice'. By accident there is a local velocity that exceeds the pressure generated velocity.

Similar analysis by separating data collected 10 and 50 meters above bottom show minor differences and is not shown here. These results should be used with extreme care since they are based

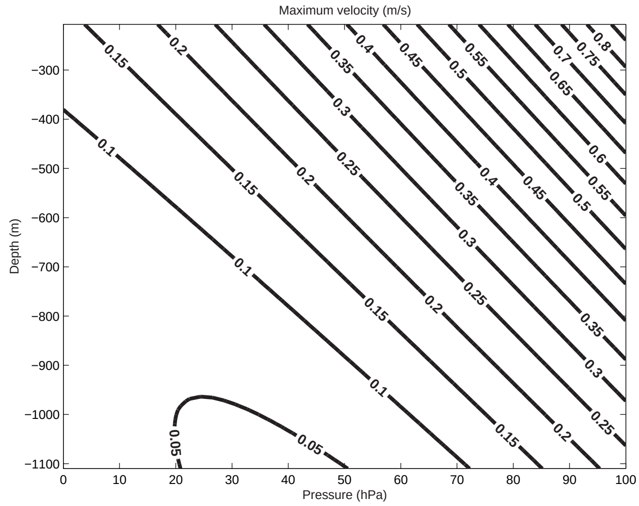

Figure 1: *Maximum velocity as function of depth and pressure depression*

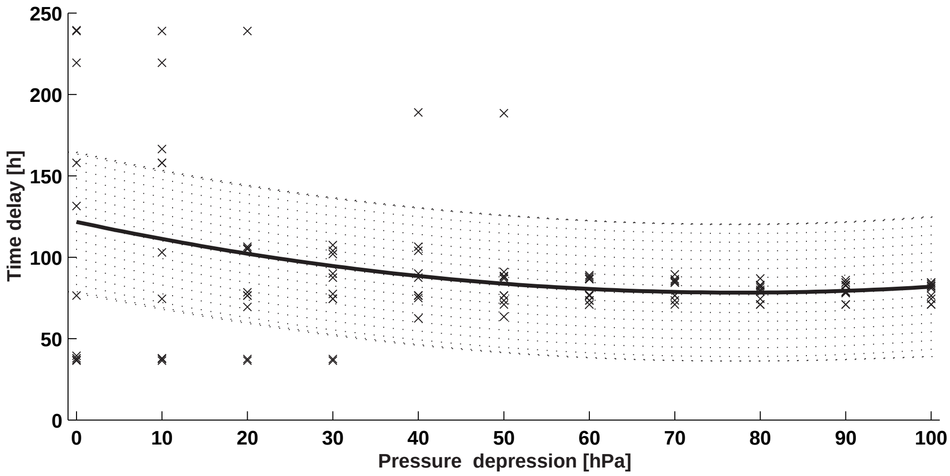

Figure 2: *Regression analysis of time delay of maximum velocity as function of pressure depression. Crosses show data points from Tab. 2 on the preceding page, the line with error-bars show the regression curve written in Eq.* (2)

on a limited number of numerical simulations, all having the same environmental profile and storm track.

3.4 Suggested studies

3.4.1 Study historical data and data from similar locations.

There are other locations world wide where similar features has been measured and studied. A literature survey of existing and available reports and data sets is important. Also, the studies so far has been limited to a few extreme events. The data analysis should be extended to more events and building statistical data.

3.4.2 Obtain current statistics through Monte Carlo simulations

The regression analysis in 3.3 was based on a very small number of simulations, using the same storm track and stratification. Better statistics can be build by performing Monte Carlo simulations. Pressure depression, storm tracks, and stratifications should be picked randomly from distribution functions, and a number (>100) simulations should be carried out. Statistics at specific points, based on data from these simulations, should then be build. This provides a statistically better distribution of max velocity as function of depth, stratification, storm track and storm pressure reduction. These data is also easier to compare with in-situ data since a number of realizations has been made and the comparison is no longer taken at snapshot from a single integration.

4 The role of the pycnocline

The events with a sudden drop in temperature at Ormen Lange and at the Svinøy section are connected to vertical displacement of the interface between the Atlantic and the much colder Norwegian Sea Arctic Intermediate waters. Such a displacement may be forced by passing atmospheric low pressure systems. But, it is also evident that other processes, such as heat and momentum fluxes between the atmosphere and the ocean, that took place weeks or months earlier may cause such perturbations (*Thiem et al.*, 2002b).

In *Thiem et al.* (2002b) the model was forced with synoptic data from pressure and wind to study two of the major extreme events in the year 2000. The studied suggested that these two oceanic events were caused by other atmospheric events than the passing storm which was too weak to generate the extreme drop in temperature. Hence, these two events are believed to connected to an incoming pressure front. Measurements of such pressure fronts are sparse and it is therefore hard to determine the origin.

Studies of the pycnocline requires realistic environmental salinity and temperature profiles. *Thiem et al.* (2002b) used climatological data, ie. data that has been averaged over time, that are lacking the high density gradient present in the ocean.

4.1 Suggested studies

4.1.1 Studies of waves on the interface between the Atlantic and the Norwegian Sea Arctic Intermediate waters

Theoretical, numerical and laboratory experiments on waves propagating on the interface, and how they interact with the sloping continental slope will be important. It is expected that small disturbances in the mid-ocean can produce dramatic effects as the interface cut through the slope.

4.1.2 Measurements of the interface in mid-ocean

A measuring program on behavior of the interface in mid-ocean can be a preparation for a forecast system. It will also be valuable as input to the studies in the previous subsection.

5 Topographic effects

The Ormen Lange gas field is located off the continental shelf at depths ranging down to 700 meters. In addition, the location was scene for the dramatic Storegga landslide. Hence, the topography is extremely rough with hills and valleys with up to several tens of meters depth difference within a couple of ten meters. In addition to the dynamical features produced by the sloping continental slope, such rough topography produces dynamic processes of importance for design, installation, and maintenance of sub-sea constructions.

Weather forecast models have become much more reliable after inclusion of a form drag felt by the atmosphere when flowing over mountain ranges and small scale topography. Such form drag, as distinct from surface frictional drag, may constitute 50% of the total drag felt by the atmosphere (*Baines*, 1995). The drag is manifested in stratified effects such as internal waves. In Ocean General Circulation Models parameterization of this effect is still novice.

5.1 Effects of bottom topography on regional modeling

A study on effect from bottom topography has been performed in *Thiem et al.* (2002a) using two different bathymetric sets, both with 4km resolution. The first was a smooth interpolation from a 20 km grid resolution, while the second used the ETOPO5 data set, originally with 4 km resolution,. The former gave very smooth topography, while the latter gave rough topography.

The study show the importance of having realistic bottom topography. The location of the different stations, used to collect data and statistics, differs in depth for the two grids, and the oscillations are longer with rougher topography. The speed is also altered considerably, especially the fluctuating part of the velocity vector.

Hence; Bottom matrices should be produced with bathymetric data close to the grid resolution. Avoiding interpolating coarser grid matrices to finer grid. However, using very high resolution grids demands large CPU resources and small scale process studies should be used to supply large scale models with a proper parameterization of sub-grid scale topography and dynamics.

5.2 The form drag

In all fluid mechanical modeling there are topographic features that are not resolved, so called sub-grid scale (SGS) topography. The usual way to incorporate effects from SGS topography is to include a surface frictional drag with a suitable roughness parameter, which is a localized drain of energy.

Such drag force is not capable of describing effects from larger orography, such as mountain ridges. In order to incorporate such effect a form drag is necessary. For proper description of the topography in such parameterization, four other parameters are introduced (*Baines*, 1995); The usual standard variation, and three variants of the topographic gradient tensor; the angle of the principle axis with the x-axis, the mean square slope, and the anisotropy of the orography.

Under the assumption that the sub-grid scale topography is statistically uniform, a representative obstacle with known shape, orientation, and height that characterize the topography can be calculated. The problem of specifying the effect from the complex terrain is thus replaced by finding effects of a single repetitional obstacle.

A form drag parameterization build on the topographic statistics is given in *Lott and Miller* (1997).

5.3 Local current distributions

In *Berntsen and Furnes* (2002) it was demonstrated that, even with smooth climatological stratification, the effects of stratification is very strong. Theory of topographic effects in stratified flows (*Baines*, 1995) suggest that topographic intensification may become stronger with stronger stratification or large buoyancy frequencies. At Ormen Lange the buoyancy frequency may become particularly large at the interface between Atlantic water and the much colder Norwegian Sea water masses. This interface is generally at 5-700 meter at Ormen Lange, but may alter between 3-900 meters.

Topography will also have local influence on flow field that might be crucial to pipelines and bottom mounted constructions. Flow intensifies at the top of an obstacle (*Alendal*, 2002), and corner effects can be produced as the current is forced to pass the obstacle on lateral sides. There is also a possibility that hydraulic jumps may be generated, leading to super critical flows (*Baines*, 1995).

5.4 Suggested studies

5.4.1 General theory overview

A review of the theory behind flow over obstacles should be performed. A good starting point is to review the book by *Baines* (1995).

It is important to gain better understanding on the dynamics of currents over rough topography. These are important processes that also have influence on larger scale dynamics. To obtain this understanding a mixture of theoretical considerations, numerical simulations, and laboratory experiments should be carried out. These activities should interact with each other.

5.4.2 Statistical characteristics of topography at Ormen Lange

By following the procedure in 5.2 statistical characteristics of the bottom topography at Ormen Lange should be produced. The exercise should be repeated for different statistical resolutions. In the process it should also be studied whether the topography is statistically stable, ie. reproduce the same characteristics for different averaging resolution. A new acquisition program by Norsk Hydro will deliver maps with 5 meter, and at selected locations down to 1 meter, resolution of the whole Ormen Lange area.

5.4.3 Map analysis

The high resolution map of topography at Ormen Lange show areas where sediments are piled up, at other areas there are no sediments at all. There are also locations where the current dig up sediments. By use of map analysis, and understanding of the ongoing processes, it should be possible to estimate local current conditions at Ormen Lange.

5.4.4 Topographic steering of dense currents

Wåhlin (2000, 2003) used an analytical model to describe how a geostrophic flow may lean on topographic irregularities and descend downhill toward the deep sea. The model was applied to the continental slope east of Greenland, and showed that the capacity of the topography is sufficient to redistribute the Denmark Strait overflow from 400 meters down to 2000 meters in consistency with observations.

By analyzing the topography at Ormen Lange in a similar manner, locations of areas of high risks of downflows may be identified.

5.4.5 Local flow field simulations

In the high resolution studies performed in *Berntsen and Furnes* (2002) and *Alendal* (2002), the horizontal boundaries have been moved away from the area of interest. To be able to gain better understanding of the underlying physics, some simulations with simplified topography would be valuable. Apart from looking at simplified Gaussian bumps, simulations on separate obstacles in the terrain, neglecting the rest of the topography, should be performed.

In the present study the stratification has no distinct thermocline. In the presence of a high vertical density gradient, the behavior of internal waves becomes more complex (*Baines*, 1995). Hence further simulations with a distinct thermocline should be performed, both for a single obstacle and for the full topography. Studies of a time dependent thermocline that flushes over the topography would give even more complex dynamics.

To be able to study as many locations along the pipeline as possible a study that clarifies the influence on the dynamics from the distance to the boundary should be performed. By repeating the present studies with different stretching of the grid, hence different locations of the boundaries, a minimum distance at which the boundary effects are negligible could be identified. Several studies along a pipeline may then be performed at lowest possible CPU cost.

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