STRONG TOPOGRAPHIC ENHANCEMENT OF TIDAL CURRENTS: TALES OF THE MAELSTROM*

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The Lofoten Maelstrom on the northwestern coast of Norway has been widely known for centuries for its strength and dangerous whirlpools. Fantasy descriptions appeared, and were reprinted, in mainstream European geographic literature in the 17th and 18th century, while several contemporary Norwegian authors gave more factual descriptions based on observations. Edgar Allan Poe and Jules Verne drew information from these sources for their celebrated worldwide known stories[1,2] where the tales of the Charybdis of the north play a central role. Recently there has been a renewed interest in understanding the dynamics of this strong tidal current. Here we complete the review[3] of an unique piece of historic literature and present results of model simulations which display, for the first time, the large scale dynamics of this remarkable phenomena which has fascinated and frightened people for ages.

The Lofoten Maelstrom, or Moskstraumen as local Norwegians call it, is located at 67°48′N, 12°50′E between The Lofoten Point (Lofotodden) and the island Værøy south west of the main chain of The Lofoten Islands (Fig.1-2). It has its name from the small island Mosken in the middle of the sound

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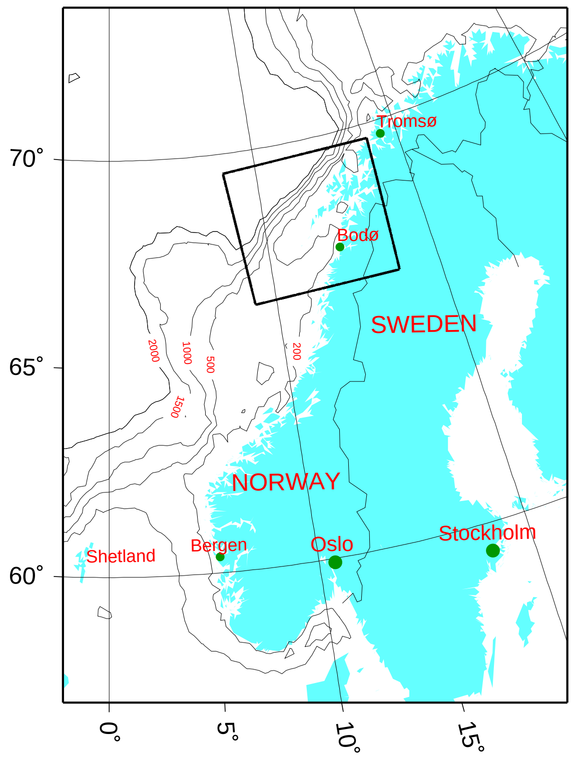

Figure 1: Map of Norwegian continental shelf with model domain (square box). Depth i meters.

between Værøy and Lofotodden (Fig.3). The current is basically of tidal origin but the prevailing northernly current in the area west of Lofotodden, together with storm forcing, may in some cases contribute significantly to its strength. It is said to run with speed up to 5-6 m/s, but there are no current records available which can be used for estimates of current extremes. Strong wave current interaction frequently occurs in the shear zones particularly on the flanks of the main jet, and small scale eddies with sea surface deflection of the order of 1 m are reported. No instrumental records are yet made of these eddies. Larger eddies and current shear-zone with wave current interaction can be seen on ERS-1 imageries[4].

The earliest accounts of the Maelstrom have survived through old Nordic tales.[5] A pair of ponderous and magic millstones, Grotte, sank into the ocean near Pentland Firth, north of Scotland, or on the northwestern coast of Norway. Here they continued to grind salt whereby the ocean became salt while water drawn into the holes of the stones formed large eddies. The term Maelstrom appearing on Dutch charts around 1590 is believed to come from the Dutch verb *malen* (Nordic *male*) meaning to grind. The first written account is probably due to Olaus Magnus (1490-1558), a Swedish bishop in Rome, who wrote a famous description of the Nordic countries.[6] On his Charta Marina from 1539 he drew a large eddy west of Lofoten and attributed its existence to a divine force and said it was much stronger than the Sicilian Charybdis.

Peterson et al.[3] recently published a comprehensive review of the historic evolution of concepts of ocean currents. They particularly reviewed Central European literature on geographical matters from 1600–1800 represented by authors as Varen (Varenius), Kircher and Happel, and their successors, who paid considerable attention to the Lofoten Maelstrom. These authors believed that large whirlpools played an important role for the ocean circulation, but their accounts of the Maelstrom are mostly characterized by exaggerations and speculations without basis in observations. Kircher even argued that the Maelstrom is generated at the entrance of a subterranean channel connecting the Norwegian Sea with the Gulf of Bohnia and the Barents Sea.

Less known are the contemporary writings of Petter Dass (1647–1707), a Norwegian priest of Scottish descent. He gave a surprisingly detailed and empirically based description of Moskstraumen, as well as other strong tidal currents in the area in his monumental poem, The Trumpet of Nordland,[7] written around 1685. He clearly attributed the current strength to the phases of the Moon, with strong current at full and new Moon and weaker currents at half Moon. Dass argued that since a large fjord basin inside the Lofoten Islands has to be filled and emptied in only 6 hours, this will cause strong currents over the shallow ridge west of Lofotodden where he anticipated that most of the water had to flow. The realism of Dass is in strong contrast to the prevailing speculative theories at that time and his descriptive poem clearly reflects the practical views of mariners and fishermen, who were forced to sail in these waters. Unfortunately, Dass' work has never been translated to English or any other widely used European language.

While Varen, Kircher and Happel's descriptions of the Maelstrom continued to be cited in geographical literature, without reservations, up into the nineteenth century more observational based descriptions were published in Denmark and Norway. In several of these the ideas of a subterranean channel was criticized and rejected.[8] In an article[9], probably first written before 1751 and printed in 1824, the rotation of the current during the tidal cycle was noted and it was also anticipated that the driving force must be the sea level difference across the Lofoten island chain.

When Edgar Allan Poe reveals a detailed knowledge of the landscape and local tales it can definitely be traced back to a Nordic source i.e. the rather fictitious description by Jonas Ramus from ca. 1715, quoted in Pontoppidan's[8] Natural History of Norway (1752). An English edition of Pontoppidan was published in London in 1755 and Jonas Ramus' description was also reprinted in Encyclopaedia Britannica (6th edition Edinburgh, 1823). It is interesting to note that Poe also had acquired detailed information on local fishing practice probably through the Anglo-American sources mentioned by Mabbott.[10]

In view of the early interest in the phenomena it is surprising that there have been no substantial modern studies of this strong tidal current. The Norwegian pilot book[11] provides some information on the tidal current in the area, but since documentation is missing most of this information is of limited scientific value. We have therefore implemented a high resolution depth integrated tidal model for the area with a similar technique as already described elsewhere.[12,13] The model spans more than 3 degree latitude and covers $1.2 \cdot 10^5$ km^2 sea area from the outer shelf edge to the inner coastline with 0.5 km grid resolution (Figs.1-2). It resolves both important fine scale feature of the bottom topography on the shelf and the complex coastline with fjords and islands. This enables a study of the transition of the tide from basically a northward progressive wave on the outer shelf to standing oscillations in the fjord basins, and the enhancement of the tidal current around Lofotodden and other major currents in the area. Boundary conditions on the oceanic boundaries of the model were obtained by interpolation from coarser grid models[12,14] using a FRS-technique[15] for model relaxation to the boundary conditions both for surface elevation and volume flux. Boundary data extracted from the coarser model are not necessarily fully consistent with the refined bathymetry. Theoretically an optimizing technique could have been used whereby the boundary conditions are adjusted to obtain the best fit to the observed tidal data from the interior of the model domain. With the large number of nodes of this model this would be a very time consuming process even for present supercomputers. We have therefore applied a more heuristic approach. First running the model with the interpolated boundary data, then estimating the differences between the modelled and observed harmonic constants which for all stations with available measurement were found to be less than 8 %. Finally we made small adjustments in

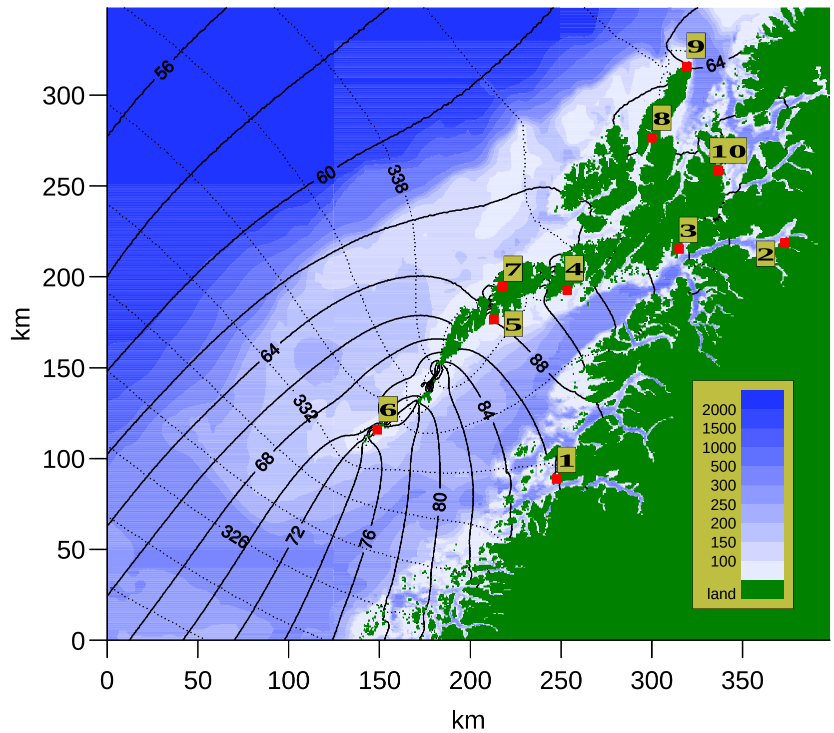

Figure 2: Computed tidal chart for model domain (square box, Fig. 1). The Lofoten islands stretches north-eastwards from Røst, marked by 6, to Lødingen (3). Vestfjorden between Lofoten and Bodø (1). Names and coordinates of tidal stations listed in Table 1. Colour depth scale in meters. Contour lines, solid, for M_2 amplitude (in cm) with 2 cm equidistance. Contour lines, dotted, for phase (deg, GMT) with 2 deg. equidistance.

the boundary data and rerun the model in order to obtain an even better fit to the measured data.

Results of simulations with quadratic bottom friction, without horizontal diffusion and the advective terms in the equation of motion are shown in Figs.2-4 and Table 1. The contour plot of the amplitude distribution of the dominant semidiurnal tidal component M_2 (Fig.2) shows a strong sea level gradient across the Lofoten island chain with up to 25 cm higher amplitudes in Vestfjorden inside the islands than on the northern side of the islands.

Table 1
Observed and modelled amplitude of the M_2 tide (in cm)

Station	No	Lat. (N) Long. (E)	Obs	Mod
Bodø	1	67°17′, 14°23′	86.9	86.3
Narvik	2	68°26′, 17°25′	99.3	100.0
Lødingen	3	68°25′, 16°00′	93.3	96.4
Kabelvåg	4	68°13′, 14°30′	92.6	91.6
Ballstad	5	68°04′, 13°32′	87.8	88.6
Røst	6	67°30′, 12°04′	77.5	75.9
Tangstad	7	68°13′, 13°38′	62.3	62.9
Risøyhamna	8	68°58′, 15°39′	67.7	66.3
Andenes	9	69°19′, 16°09′	64.8	63.1
Harstad	10	68°48′, 16°33′	69.3	66.4

In the middle of the sound between Lofotodden and Værøy (Fig.3) the sea surface gradient is about 12 cm over a distance of 10 km, with steeper gradients near land on both sides. This sea level gradient drives the current around Lofotodden and the other strong tidal currents in the narrow sounds between the islands further east. These characteristic features of variation of the M_2 amplitude are due to the transition in shelf width from a relatively wide shelf south of Lofoten to a narrow shelf to the north, and the scattering of the northbound tidal wave by the island chain and the shallow bank southwest of Lofotodden (Figs.1 and 2). This is particularly manifested by the convergence of the contour lines for M_2 amplitude on Lofotodden (Fig.2). Computed amplitudes of the M_2 tide agree well with observations (Table 1).

Phase difference across the model domain agrees also well with available observations with about 10 degree phase delay from Bodø to Andenes, corresponding to a 20 minutes time delay of the tide. Similar amplitude and phase variation appear from simulations of the other two most important semi-diurnal components S_2 and N_2. The amplitudes are respectively about 35% and 20% of M_2. The main diurnal component K_1 is only 10% of M_2 and the simulated amplitude pattern shows evidence of shelf wave response particularly on the shelf edge northwest of Lofoten. The M_2 depth mean

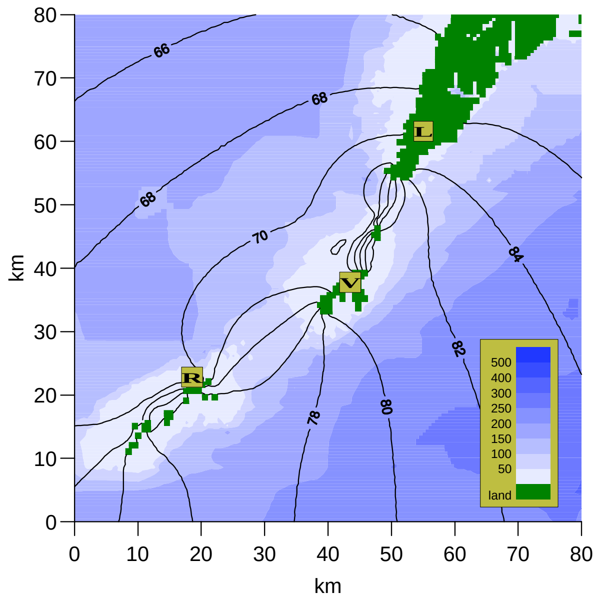

Figure 3: Detailed chart of the area southwest of Lofotodden or the Lofoten Point (L) with Værøy (V) and Røst (R). Mosken midway between L and V. Colour depth scale in meters. Contour lines for M_2 amplitude with 2 cm equidistance.

currents are of the order of 0.1 m/s in deep water with strong currents up to about 3.0 m/s on the shallow ridge with depth 50-100 m which stretches south-westwards from Lofotodden to Røst (Fig.4 and 3). The width of the zone with strong current is about 10 km (Fig.4). Lack of current data from this area hamper systematic validation of the model results. We have, however, validated the model by comparing with current measurements taken in three of the main channels between the islands about 50 km east of Lofotodden at Napp, Sundklakk and Gimsøy. The phase of the current in these channels, which shows features of a progressive tide, is an important parameter for validation of the model. Current shift is found to occur at about 2 hours before high water, with northward current at high water and southward current at low water, which agree well with observations.[10] Comparison has also been made with current measured at a few stations located in deep water on the shelf west of Lofotodden and in Vestfjorden which confirmed that the M_2 tidal currents in deep water are of order 0.1 m/s. The model also capture an interesting feature with dominating diurnal tidal currents in

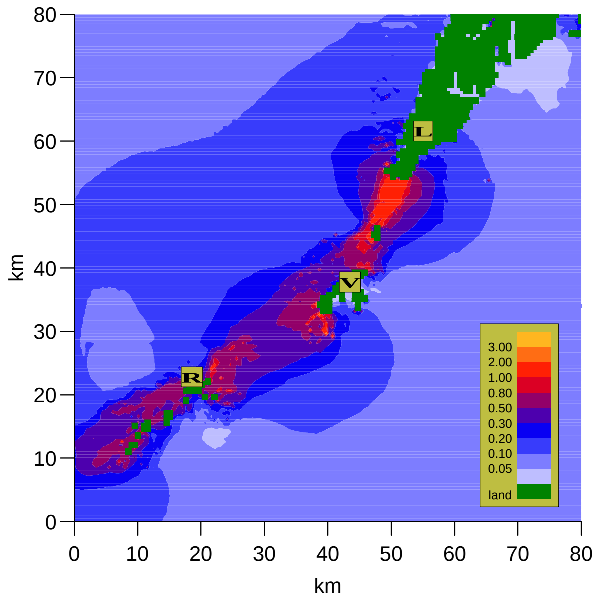

Figure 4: Maximum depth mean current for M_2 in the area southwest of Lofotodden (L) with Værøy (V) and Røst (R). Mosken midway between L and V. Scale in m/s.

Sortlandsundet northeast of the Lofoten islands, between station 4 and 8 on Fig.2, as measured earlier by The Norwegian Hydrographic Services (NSKV), Stavanger.

A weak clockwise rotating eddy with diameter about 6 km appears in the M_2 simulations with center about 5 km southwest of Lofotodden, west of a line from Lofotodden to Mosken, at the time of current shift on rising sea. A similar sized anticlockwise rotating eddy appears with center nearer Lofotodden at the time of current shift on falling sea. The current speed in these eddies is of the order 0.1 m/s and they are therefore only a bleak reminiscence of the monster eddy described in the old literature. Sensitivity tests clearly reveal that the eddies found by the model owe their existence to bottom friction and topography. Eddies of similar size have been seen on ERS-1 SAR imageries in the same area.[4] The model also shows that the current in the area northwest and east of Mosken has a clockwise rotary character which may mistakenly have been interpreted as a manifestation of a large whirlpool by the early observers.

We have also calculated the M_2 volume flux through sections between Lofotodden and Værøy and between Værøy and Røst to be respectively $0.35 \cdot 10^6$ m^3/s and $0.55 \cdot 10^6$ m^3/s at peak, which correspond to a mean current speed of about 1.0 m/s and 0.5 m/s, for the two sections respectively. From model data for the other main tidal components we estimate the peak total volume flux at spring tide to be about a factor 1.8 larger. In view of the moderate tidal range (~ 3.0 m) and relatively weak tidal currents in the surrounding shelf area this represents an exceptional strong topographic enhancement of the tidal current.

The Rossby and Keulegan-Carpenter numbers for the flow near Lofotodden are clearly within the parameter range for flow separation and shear flow instability to occur.[16] The generation and advection of small scale eddies remain a subject for future studies. These local effects are not likely to change the large scale pattern of amplitude variation found here.

References

1. Poe, Edgar Allan, A Descent into the Maelström. (First published 1841).

2. Verne, Jules, Vingt mille lieues sous les meres. (First published 1869).

3. Peterson, R. G., Stramma, L., and Kortum, G. Progr. of Oceanogr., **37**, 1–115 (1996).

4. Wahl, T., Nordic Space Activities **2-3**, 22-23 (1995)

5. Guerber H. A., The Norsemen, 128-130, Senate, Studio Editions Ltd. London (1994)

6. Magnus, Olaus Historia om de nordiska folken, 89-90, (Swedish edition by Gidlunds förlag, Stochholm, 1982. First publish in Rome, MDLV)

7. Dass, Petter, Nordlands Trompet (ed. Didrik Arup Seip) 94-98 (Aschehoug & Co, Oslo, Norway, 1947)

8. Pontoppidan, E., Norges Naturlige Historie, 123-140, (Reprint by Rosenkilde og Bagger, København, 1977, First printed, Kiøbenhavn, 1752, English edition, London, 1755).

9. Schelderup, A. [Skjelderup, O.], Kongelige norske Videnskabersselskabs Skrifter, Trondhjem, Norway, **2**,1, 78–85 (1824).

10. Mabbott T. O., Collected works of Edgar Allan Poe, **II**, 574-597, The Belknap Press of Havard University Press, Cambridge Mass. (1978).

11. Den Norske Los, **5**, 6th edition, 241-242, The Norwegian Hydrographic Services, Stavanger (1987).

12. Gjevik, B., Nøst E, and Straume T., J. Geophys. Res. **99**, C2, 3337–3350 (1994).

13. Davies A. M., Jones J. E., and Xing J., J. Hydraulic Eng. ASCE (In press)

14. Gjevik, B. in Modeling Marine Systems (ed A. M. Davies) **I**, 187-219 (CRC Press Inc, Boca Raton, Florida, 1990)

15. Martinsen, E. A., and Engedahl, H., Coastal Engineering **11**, 603-627, (1987).

16. Signell, R. P., and Geyer W. R., J. Geophys. Res. **96**, C2, 2561-2575 (1991)

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