“O That Awful Deepdown Torrent”

by
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Abstract
The overflow of deep-water from the Nordic Seas through the Faroe-Bank Channel and the Denmark Strait into the North Atlantic proper is presented and discussed. These fluxes are of considerable importance for the global thermohaline circulation, and it is shown here how they can be modeled on the basis of rotating hydraulic theory. The study is concluded by noting how this formalism successfully has been applied to describe deep-water flows in the Baltic Sea, and it is suggested the same might be done for the underflow of highly saline deep-water debouching from the Persian Gulf through the Straits of Hormuz.

1. Introduction
The immortal words of Molly Bloom [1] reflected in the title of the present review refer to the Atlantic-bound transport of high-saline Mediterranean deep-water through the straits of Gibraltar. Similar fluxes of comparatively fresh (~34.9 o/oo) but very cold (~ -0.5^{o}C) dense deep water take place through the Faroe-Bank Channel as well as through the Denmark Strait between Iceland and Greenland. These are the two deepest passages through the Greenland-Scotland Ridge, which delimits the deeper regions of the Nordic Seas from the North Atlantic proper (cf. the map in Fig. 1), and hence play an important role as choke-points affecting the global thermohaline circulation.

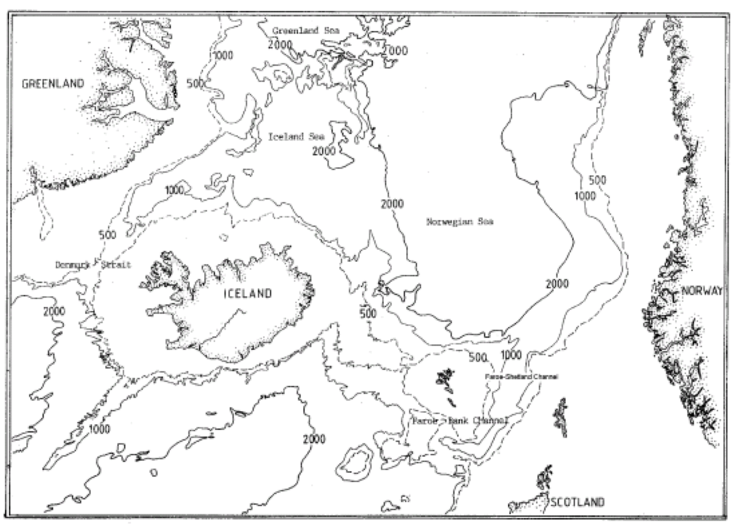

Fig. 1: Map of the Greenland-Scotland-Ridge Area

The characteristics of the Denmark Strait have been known since the 1890s when it was surveyed by Danish scientists, but due to its narrowness the Faroe-Bank Channel was not discovered until the 1940s, when echo-sounding equipment had come into general use. The first hydrographic surveys here were undertaken somewhat later, and in 1960 the International Council for Exploration of the Seas (ICES) organized the first international, multi-ship investigation of the deep-water overflow into the Atlantic [2], an undertaking which was repeated [3] in 1973.

2. Ongoing Field Investigations

Modern research on these overflows has to a considerable extent been undertaken within the Nordic-WOCE programme and its successors, *i.e.* as collaborative efforts between the Nordic countries as well as Germany and Scotland. In addition to periodic hydrographic surveys, the focus of these efforts has been on the maintenance of a number of Acoustic Current Doppler Profiler (ADCP) arrays as well as conventional recording current meters to monitor the fluxes across the Greenland-Scotland Ridge. Two ADCPs have been dedicated to investigating the deep-water transports through the Faroe-Bank Channel and the Denmark Strait, both upward-looking meters deployed on the thresholds of these passages.

The Denmark-Strait deep-water flux varies considerably over shorter time-scales. The hydrographic structure above the threshold is rather complex since the water column may comprise a number of different water masses. The mechanism behind this variability is presently not fully understood, but when estimating the transport over longer time-scales the overflow can be dealt with using rotating hydraulic theory, cf. [4].

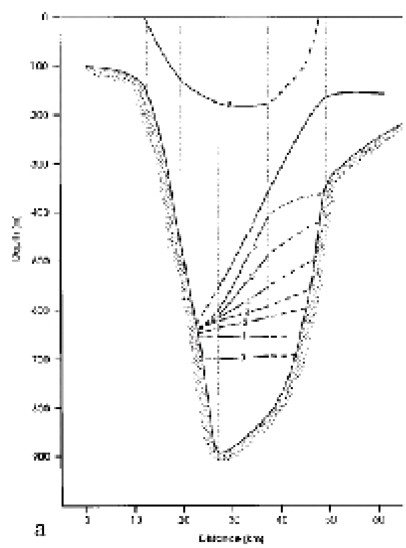

Fig. 2: Isotherm distribution across the Faroe Bank Channel

The Faroe-Bank Channel overflow is known to be almost steady over shorter time-scales, and is at all times in reasonable geostrophic balance, cf. Fig. 2 showing the isotherm distribution across the passage. The TS-diagram in Fig. 3 shows that in the Faroe region only two watermasses are involved, viz. cold Norwegian Sea Deep Water and warm North Atlantic Surface Water, and furthermore that in this region the temperature is a useful proxy for density, cf. Fig. 5.

It should, however, be pointed out that this deep-water flux shows a significant seasonality, with transports varying between around 2.5 Sv (1 Sverdrup=10^6 m^3s^{-1}) in summer and 1.5 Sv during winter, cf. Fig. 4. Based on satellite altimetry it has been demonstrated [5] that this variability is not (as erroneously stated in [6]) due to changing upstream conditions in the Norwegian Sea, but rather to the fact that the stronger wintertime atmospheric forcing of the flow of Atlantic surface water through the Faroe-Shetland Channel associated with an increased barotropic pressure gradient across the passage which inhibits the deep-water transport feeding the overflow, cf. the map in Fig. 1 as well as Fig. 4.

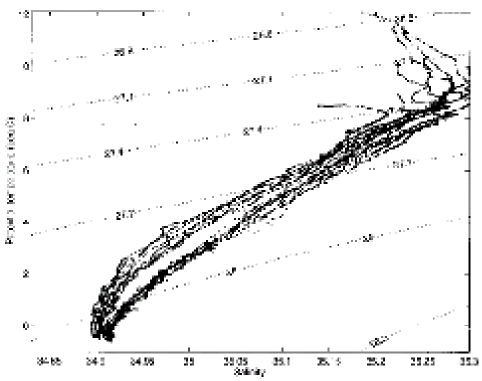

Fig.3: TS-diagram from the Faroe Islands region. Mainly cold Norwegian Sea deep- water and warm N. Atlantic water.

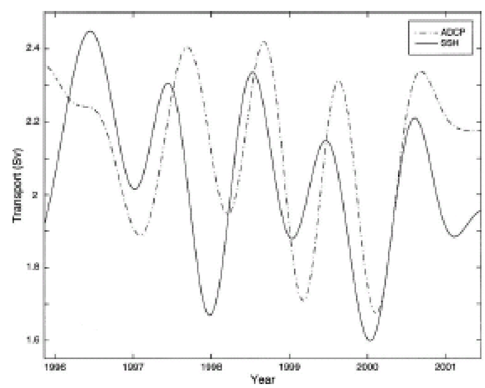

Fig. 4: Dashed line showing measured deep- water transports, solid line altimetrically determined sea- level difference across Faroe-Shetland passage

3. Rotating hydraulic theory

In [7] the formalism describing rotating hydraulic flow with a finite potential vorticity (PV) through a box-like channel was generalized to cover the case of a parabolic topography, cf. Fig. Q, which in many cases may serve as a reasonable approximation of bathymetries encountered in nature. The problem is governed by a set of nondimensional algebraic equations for the intersection points $-a, b$ of the interface with the sloping walls of the passage:

$$a^2 = r(1-\frac{\Delta}{\hat{D}_\infty}) - \frac{r}{\hat{D}_\infty^2}(\hat{\Psi}_i + \frac{1}{2}) - \frac{1}{2r}\left((2+r)\tanh\left(\frac{a+b}{2}\right) - 2a\right)^2 ,$$

$$b^2 = r(1-\frac{\Delta}{\hat{D}_\infty}) - \frac{r}{\hat{D}_\infty^2}(\hat{\Psi}_i - \frac{1}{2}) - \frac{1}{2r}\left((2+r)\tanh\left(\frac{a+b}{2}\right) - 2b\right)^2 .$$

Here $\hat{D}_\infty$ is a nondimensional measure of the upstream-reservoir depth and $\hat{\Psi}_i$ specifies the distribution of the volume flux between the side-wall boundary layers of this basin, whereas r and Δ are morphological parameters describing the passage bathymetry, For a discussion of the finer points of these equations as well as their derivation, the reader is directed to [7]. The problem can be treated numerically, but additional insight is gained by dealing with the problem using analytical techniques. In [7] it was demonstrated how the problem could be resolved analytically by using a regular perturbative expansion with the solution for non-rotating hydraulic flow serving as the lowest-order result, whereas in [8] the analogous expansion was based on the zero-PV solution. In both cases problem requires a preliminary rescaling before the governing equations above can be dealt with on the basis of series expansions

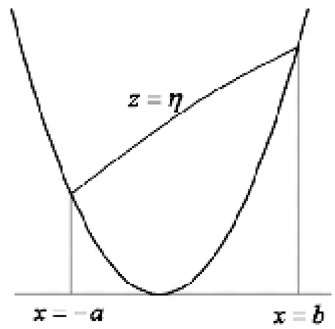

Fig. 5: Parabolic bathymetry.

4. Phenomenology of the Deep-Water Flow

From Fig. 2 it is recognized that the Faroe-Bank Channel cross-passage isotherms show a tendency towards pinching behaviour on the Southwestern side of the passage. One possible explanation [9] for this almost persistent feature is that the overflow also comprises a third water mass, which, if its potential vorticity is conserved, gives rise to precisely this feature. The TS-diagram shown in Fig. 3 comprises data from situations with pinching as well as without, and it may be recognized that for the "pinched" states the diagrams show indications of the presence of a third water mass constituted by North Icelandic Winter Water/Arctic Intermediate Water.

In [7] it was shown that the Froude number assumed the following form:

$$F^{-2} = \left(\frac{\hat{D}_\infty}{r}\right)^4 (2+r)^2 \left((a+b) - 2\tanh\left(\frac{a+b}{2}\right)\right)^2 \times$$
$$\left[\left(a+b-(2+r)\tanh\left(\frac{a+b}{2}\right)\right)^2 + 2r(a+b)\coth(a+b) - 2r - r(2+r)\tanh^2\left(\frac{a+b}{2}\right)\right].$$

In [10] it was shown (cf. Fig. 6) that the application of this formula to the results from the long-term ADCP records yields convincing evidence that the deep-water flow across sill of the Faroe-Bank Channel is controlled in the classical hydraulic sense, *viz*. that no signal emanating downstream can penetrate into the upstream reservoir

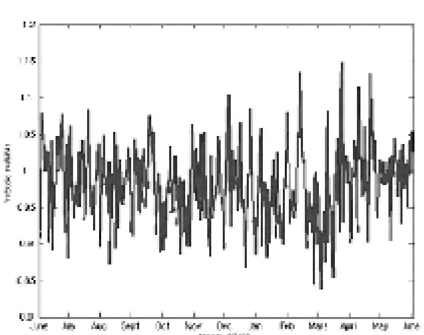

Fig.6: Deep-water flow Froude number during 1997/98.

Other interesting features that have been investigated on the basis of field measurements during a period when three ADCPs were deployed across the Faroe-Bank Channel threshold are the consequences of the fact that the deep-water flow is not characterized by a uniform potential vorticity, *viz*. one of the basic assumptions underlying the theoretical treatment of the rotating hydraulic-flow problem. As, however, demonstrated in [11], the cross-channel variations are so small that the maximal-flow predictions based on the assumption of critical flow at the sill of the passage are not seriously impaired

5. Outlook

In this review (which has focused on research topics the author has been directly engaged in) it has been demonstrated how useful rotating hydraulic theory has been for analyzing the large-scale overflows across the Greenland-Scotland Ridge. The same has proved to hold true for the Baltic Sea, where the saline deep-water originating from the Kattegatt and Skagerrak makes its way towards the interior basins via a series of constrictions and sub-surface conduits. A number of analyses [12-14] of these smaller-scale overflows have been undertaken, all with remarkably successful results.

In view of how versatile this formalism has been found, it would be highly interesting to launch a research programme aimed at subjecting the outflow of highly saline deepwater from the Persian Gulf into the Arabian Sea to an analysis based on rotating hydraulic theory.

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