NOOS Working Group on transports

NOOS

North West European Shelf
Operational Oceanographic System

Model to model comparison of transports through North Sea transects.

(José Ozer, MUMM, 2011/10/19)

1. Introduction

Model forecast of daily transports of water heat and salt through a series of North Sea transects is in place within the framework of NOOS (http://www.noos.cc) since 2004. Today, three NOOS partners are contributing: DMI (Danish Meteorological Institute), BSH (Bundesamtes für Seeschifffahrt und Hydrographie) and MUMM (Management Unit of North Sea Mathematical Models).

As NOOS member, the Met. Office is willing to participate with the new European Shelf operational tool being developed within the framework of the MyOcean Project. This new tool will be referred to as the UKMO model in this NOOS report.

In this context, it appeared interesting to proceed to a first assessment of such model products following a model to model comparison approach as well as, wherever possible, with a comparison with similar data found in the literature.

The main objectives are to assess the degree of coherence between the results of these operational tools, to check order of magnitudes and to verify how far these tools reproduce known features of the North Sea circulation. Trying to explain differences, if any, is, at this stage, outside the scope of the study.

The report is structured as follows. A first section deals with a short presentation of the three models for which daily transports for the year 2008 are available. These are: UKMO model (internally referred to as AMM7), BSH model (also known as BSHcmod) and MUMM model (also known as Optos_Nos). DMI was not yet participating to the exchange in 2008. Some details on the selected method are given in the third section. The core of the report deals with the presentation and discussion of the results. It is divided into two parts: i) the assessment of the daily transports; ii) the analysis of monthly and annual mean values. A summary and some conclusions are given in the last section.

2. Description of the models

UKMO model

For details on the UKMO model, we refer to O'Dea *et al.* (2010).

For the purpose of this report, it suffices to say:

- it covers the North east Atlantic, roughly speaking from 40°N to 65°N and from 20°W to 13°E;
- the model is nested in a series of one-way nests to the Met. Office global ocean models;
- tidal forcing (15 tidal constituents) is included as well along the open boundary as in the interior of the domain (equilibrium tide);
- hourly atmospheric forcing fields are provided by the UKMO mesoscale NWP model.
- the horizontal resolution is of the order of 7 km;
- the hydrodynamics are supplied by the UKMO Shelf Seas model and the ecosystem is supplied by the European Regional Seas Ecosystem Model (ERSEM; Baretta *et al.*, 1995);
- a Assimilation Correction Method (Martin *et al.*, 2007) is used to assimilate SST data.

BSH model

A new version (v4) of the three-dimensional baroclinic circulation model 'BSHcmod' (Dick *et al.*, 2001) has been introduced in operation in 2008 (Dick *et al.*, 2008):

- it covers the North Sea (from 4° W to 60° N) and the Baltic sea;
- the horizontal resolution is of the order of 5 km;
- a novel home made adaptive vertical co-ordinate system has been implemented;
- the tidal forcing is calculated from harmonic constants of 14 tidal constituents;

- external surges are provided by a2D NE Atlantic model;
- meteorological forecasts are supplied by the German Weather Service (DWD).

MUMM model

The MUMM' system of operational tools and services, referred to as OPTOS, is based on the COHERENS model (Luyten *et al.*, 1999; Pison and Ozer, 2003). Three different implementations are used:

- a 2D implementation covers the North West European continental shelf (Optos_csm). Only the barotropic mode is turn on. The model open boundary closely follows the 200m isobath. The horizontal resolution is or the order of 6 km. The model is driven by the tide (4 diurnal and 4 semi-diurnal tidal constituents) and by the numerical weather predictions provided by the Met. Office (at up to 6 hourly frequency and with a resolution equal to 0.556° in latitude and 0.833° in longitude).
- a full 3D baroclinic version is used for the North Sea. The horizontal resolution is as for the North West Shelf. 20 sigma layers are used along the vertical. Monthly mean fresh water discharges are introduced at the mouth of the main rivers. Time and spatial resolution of the meteorological forcing is as for Optos_csm.
- A last 3D baroclinic implementation is used for the Belgian coastal waters. The horizontal resolution is of the order of 750 m and 10 sigma layers are introduced in the vertical.

The transports delivered to NOOS are coming from the North Sea model implementation also referred to as Optos_Nos. The southeast limit of the model area is at 4°W and the northern one at 57°N.

3. Description of the method

The three models covering different areas, it was decided in a first stage to work only with that they have in common, *i.e.*, the North Sea from 4°W to 58°N. Nine NOOS transects are present in this area. Their position is given on Figure 1. Note that transects 7 and 8 are very close to the northern limit of MUMM model.

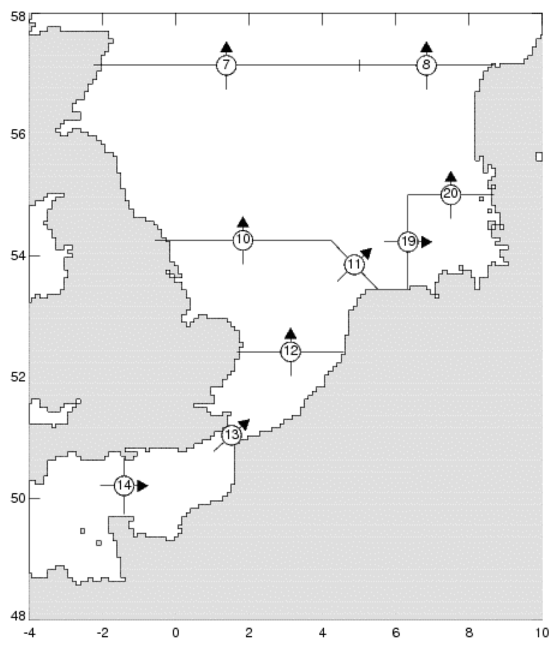


Figure 1: North Sea transects in the area common to BSK, MUMM and UKMO models. Arrows indicate the direction of a positive transport.

To stick with the most recent version of BSH model only 2008 model results will be analyzed.

Daily transports of water, salt and heat are first analyzed by means of a series of metrics aiming at providing useful information on the level of coherence existing between them.

Afterwards, averaged values over different time periods will be considered to verify how well the three models reproduce known features of the North Sea circulation at those time scales and how far, their results are in the range of estimates found in the literature.

4. Daily transports

Time series of daily transports of water through transects delimiting the area of interest (*i.e.*, transect 14 in the Channel and transects 7 and 8 at 57°N) are presented on Figure 2. There is a strong day to day variability in these transports. Part of it is presumably coming from the fact that not all tidal frequencies are filtered out by the two M_2 cycles averaging procedure. The largest part however is attributed to the variability in the wind forcing.

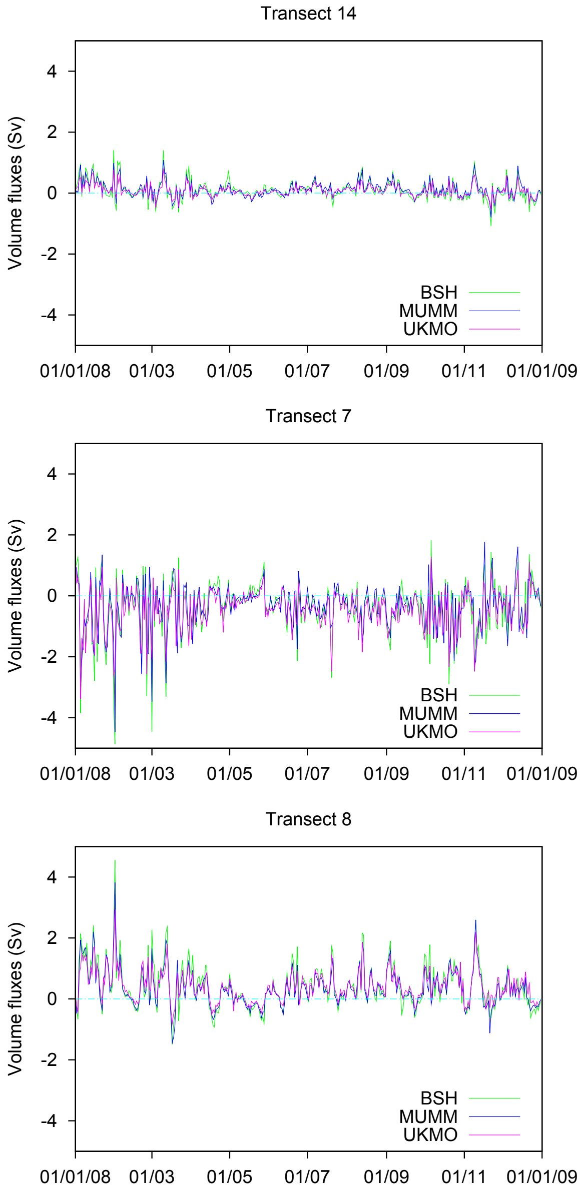


Figure 2: time series of daily volume fluxes (1 Sv = 10^6 m^3s^{-1}) through transect 14 (top panel), 7 (middle panel) and 8 (bottom panel). The green line shows the BSH model results, the blue one for MUMM model results and the magenta line presents the UKMO model results.

There seems to be a very good agreement between the results of the three models. Events do occur simultaneously with some differences in their amplitude. Most often, positive and negative peak values are larger in BSH model and smaller in UKMO model.

Despite that variability, it is noticeable that the circulation in the area has been most of the time in 2008 as expected: *i.e.*, inflow of Atlantic waters through the Channel and along the east coast of UK and outflow along the Danish coast. This is further confirmed by the % of positive and negative values of the volume fluxes through the different transects as presented on Figure 3. On average, the anticlockwise circulation is observed nearly 70% of the time. It seems to be slightly more stable in UKMO model than in BSH model. For instance, through the Dover Strait, 77% of the values are positive in UKMO model while this percentage is reduced to 62% in BSH model. Along the UK coast (transect 7), the percentage of negative values is equal to 76% in UKMO model and to 70% in BSH model.

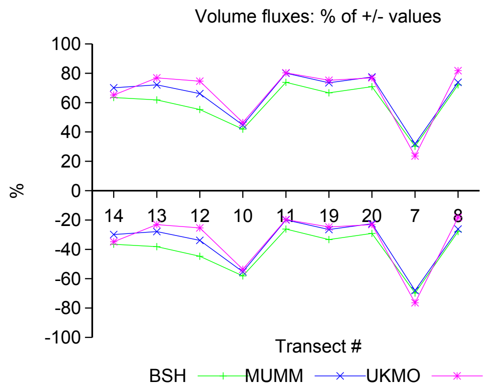


Figure 3: percentage (%) of positive and negative values of the volume fluxes through the different transects in the area of interest. Results are presented for year 2008. Color code is as on Figure 2. For the clarity of the graph, percentage of negative values is presented with a minus sign. Transects number is given along the x axis and these are organized from south to north.

To quantify the agreement between these model results, a series of metrics has been computed. Model results have been compared two by two (*i.e.*, MUMM compared two BSH, UKMO compared to BSH and UKMO compared to MUMM). For each comparison, the following metrics are computed: mean and standard deviation of each data set, root mean square difference, correlation coefficient, normalized standard deviation and normalized root mean square difference. This has been done for water, heat and salt transports. All values are given in tabular form in appendix.

Taylor diagrams are used to present the results in a concise way. Recall these diagrams are based on the correlation coefficient between two fields, the ratio between the standard deviation in the two fields and the normalized root mean square error. A detailed discussion on these diagrams can be found in Jolliff *et al.* (2009) for instance.

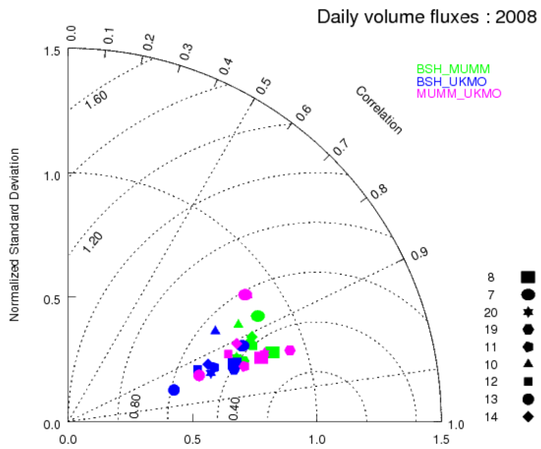


Figure 4: Taylor diagram for the daily volume fluxes through North Sea transects in 2008. A symbol is used to identify each transect (see legend). Color indicates the comparison: green is used when MUMM results are compared to BSH results; blue is used when UKMO results are compared to BSH results; magenta when UKMO results are compared to MUMM results.

For volume fluxes, the agreement between the three sets of model results is largely confirmed. Correlation is varying between 0.81 (MUMM-UKMO at transect 7) and 0.96 (BSH-UKMO at transect 14). On average, the correlation is better in the comparison BSH-UKMO (only one value below 0.9 and 4 values close to 0.95) than in the other comparisons. The normalized root mean square difference is always less than 0.6. Concerning the variability in the daily transport, the best agreement is between MUMM and BSH. The range of variation (estimated from the normalized standard deviation) in the MUMM results is between 72% and 84% of the range of variation in BSH results. For UKMO shelf model, the limits of this range are equal to 44% and 76%. As perceived on Figure 2, the volume transports computed by BSH are generally larger than those provided by the two other models. UKMO volume transports are on the average the smaller.

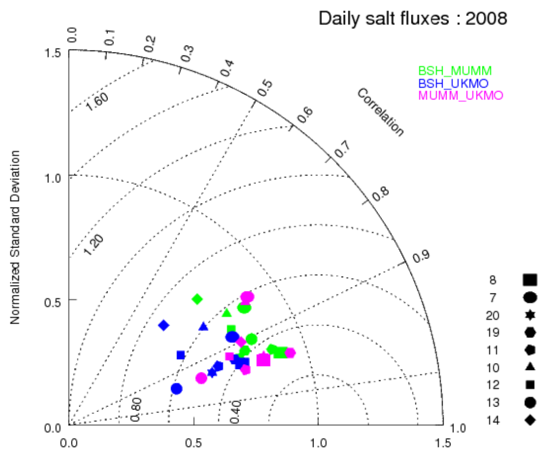


Figure 5: Taylor diagram for the daily salt fluxes through North Sea transect in 2008. Symbols and colors are as on Figure 4.

The agreement between daily salt fluxes seems to be less satisfactory than that obtained for the volume fluxes. Correlation coefficient is now varying between 0.69 (BSH-UKMO at transect 14) and 0.95 (a value which appears 4 times). On average, the highest correlation is found between MUMM and UKMO ($\bar{r} = 0.91$) and the smallest between MUMM and BSH ($\bar{r} = 0.87$). As for the volume fluxes, the range of variation in MUMM results is quite close to that in BSH results (normalized standard deviation varies between 0.72 and 0.90). The normalized root mean square error is greater than or equal to 0.6 four times.

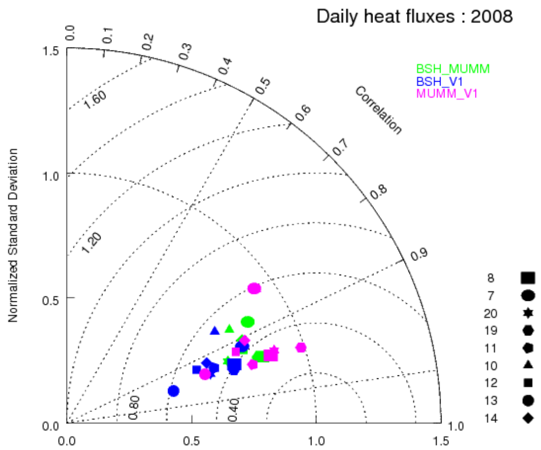


Figure 6: Taylor diagram for the daily heat fluxes through North Sea transect in 2008. Symbols and colors are as on Figure 4.

The Taylor diagram for the daily heat fluxes (Figure 6) is very similar to that for the volume fluxes (Figure 4). Here too, the best agreement seems to be between BSH and MUMM. In fact, as can be seen in the appendix, the statistics for heat fluxes are very close to those for volume fluxes. This could be due to the fact that that in heat fluxes temperature is expressed in degree Kelvin.

5. Time averaged values

The long term (*i.e.*, variations at tidal frequencies being removed) circulation on the North-West European shelf has been (and still is) the subject of a lot of studies (*e.g.*, Otto et *al.*, 1990; Prandle 1984a and 1984b; Smith *et al.*, 1996; Delhez *et al.*, 2004; Holt and Proctor, 2008).

The three driving forces of this circulation are the tide, the wind and atmospheric pressure and the water density gradients. Main characteristics are as follows. Atlantic waters enter the North Sea through the Dover Strait in the south, along the coast of Scotland and between Orkney and Shetland in the North. There is also in inflow of these waters at depth at the west of the Norwegian trench which in turns is the mean outflow area. A anti-clockwise circulation is generally observed in the Southern North Sea. Currents in central North Sea are more variable.

Estimates of monthly, seasonal and annual means of transport through some of the NOOS transects found in those publications are used to verify that those derived from the three model data sets used in this study are in the right order of magnitude. Explaining differences, if any, is outside the scope of this study. Differences in such model estimates may come from model physics and/or details of their implementation and there is no single model parameter that can explain them. The use of different meteorological forcing is suspected to play a significant role.

It must be stressed that monthly and annual mean values reported here are arithmetical means of the daily values using only those days common to the 3 models. They are some gaps in the 2008 time series, most of them coming from MUMM time series. Recall also that daily transports are obtained by averaging model results over two M_2 tidal cycles. There is *de facto* an overlap between two successive values that is almost impossible to remove. For these two reasons, monthly and annual mean values discussed here must be considered with some caution.

The 2008 residual circulation estimated from the three model results is depicted on Figure 7. All mean values of the transport through the different transects are also given in Table 1. In 2008, the three models produce a North Sea residual circulation in accordance with its long term mean. The largest inflow (~ 0.4 Sv) is observed along the UK coast at 57°N (transect 7) and all water (~ 0.4 Sv) is leaving the area along the Danish coast. The inflow *via* the Channel (~ 0.1 Sv) is approximately four times smaller.

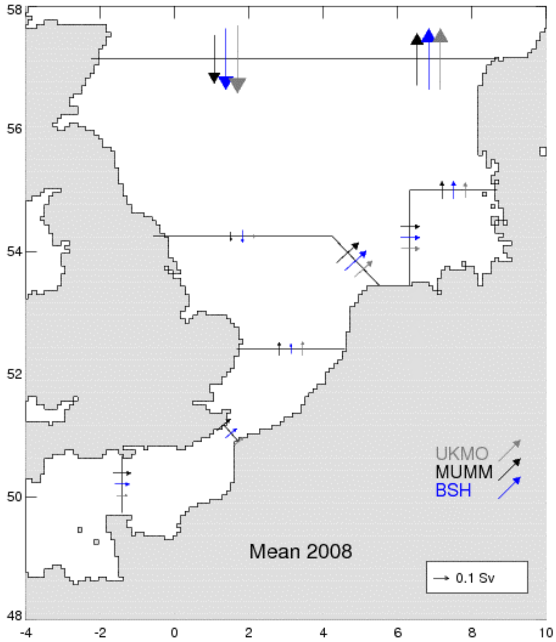


Figure 7: residual circulation in the North Sea derived from the daily transports of three models. Blue arrows present BSH model results, black arrows present those of MUMM model and results of UKMO model are presented by means of grey arrows.

Transect #	BSH model	MUMM model	UKMO model	(Max-Min)/Moy
	Sv	Sv	Sv	%
14	0.096	0.122	0.070	54
13	0.090	0.121	0.080	43
12	0.063	0.092	0.095	38
10	-0.085	-0.064	-0.027	99
11	0.202	0.207	0.163	23
19	0.128	0.130	0.127	2
20	0.122	0.121	0.105	14
7	-0.420	-0.337	-0.470	33
8	0.420	0.362	0.421	15

Table 1: annual mean values of volume flux through North Sea transects. Values are for 2008. The transect number is given in the 1st column. BSH, MUMM and UKMO results are given in the 2nd, 3rd and 4th column, respectively. The last column contains, for each transect, the ratio (expressed in %), between the difference (maximum value minus

minimum value) and the mean of model values. This ratio is considered as a measure of the model to model variablitiy.

For the Strait of Dover, an estimate of the net long term flow into the North Sea of 0.094 Sv is reported in Prandle *et al.* (1996). This estimate is obtained from year-long measurements of currents using shore based high frequency radar and a bottom mounted acoustic Doppler current profiler. Results from high resolution modeling studies available at that time (Salomon *et al.*, 1993) were in close agreement with this estimate. With a yearly mean volume flux of 0.096 Sv, BSH model is the closest to these estimates. MUMM model value (0.122 Sv) is approximately 30% lager while UKMO model estimate (0.070 Sv) is only 15% smaller.

As already explained, annual mean values listed in Table 1 can't unfortunately be used to really check whether or not there is (nearly) a balance between total inflow and outflow in 2008, neither for the whole domain nor for smaller parts of it. Note however that for the whole domain, the three models "accumulate" water (~0.1 Sv) and that in the Southern Bight, BSH and MUMM models are "storing" about 0.03 Sv while UKMO is releasing almost the same amount. Additionally to these "daily" transports, it could be of interest, within NOOS, to exchange better estimates of monthly, seasonally and annual means that would allow the verification of some of these balances.

Now model to model variability between these annual values is far from being negligible. In the last column of Table 1, the ratio (expressed in %) between the difference (maximum value minus minimum value) and the mean value for each transect is provided in an attempt to quantify it. At transect 14, this ratio is equal to 54%. The best agreement is observed in the German Bight. For the inflow through transect 19, the range is of the order of 2% of the mean value and for the outflow it is close to 14%. The largest spreading between the results is observed at transect 10 where the range is almost equal to the mean value. Volume fluxes through this section are quite small however.

Model to model variability has already been pointed out several times in the past (*e.g.*, Jamart and Ozer, 1989; Smith *et al.*, 1996; Proctor, 1997; Delhez *et al*., 2004).

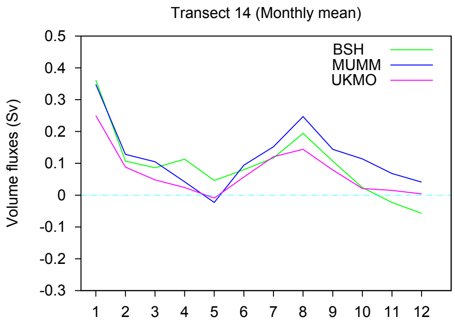
In Smith *et al.* (1996), yearly mean transports through North Sea transects computed by three different models are presented and discussed. The three participating models are: IfM 3D baroclinic hydrodynamic model (Backhaus and Hainbucher, 1987), IMR 3D baroclinic hydrodynamic model (Skogen, 1993) and POL 2D tide and storm surge model (Flather *et al.*, 1991). Even if the period of interest (1987-1993) differs and even if the transects are not exactly the same, looking at some of their results can help to see whether or not model to model variability has been reduced as time passes.

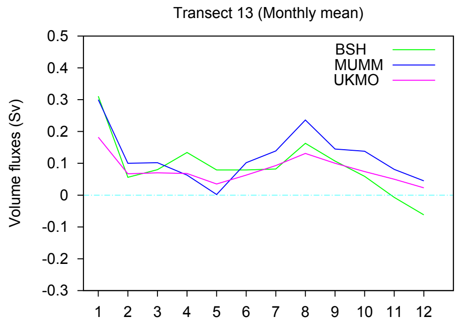
Transect #	IfM	IMR	POL	(Max-Min)/Moy
	Sv	Sv	Sv	%
10 (11)	-0.11+/-0.02	-0.04+/-0.03	-0.01+/-0.01	188
19 (12)	0.18+/-0.04	0.20+/-0.05	0.09+/-0.04	70
7 (7)	-0.46+/-0.08	-0.13+/-0.07	-0.14+/-0.08	137

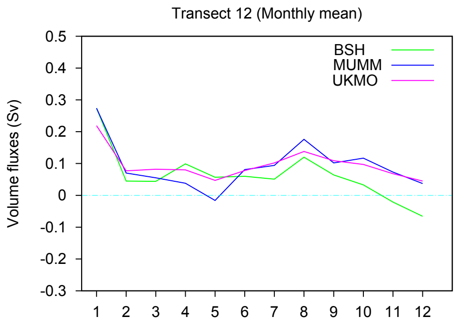
Table 2: yearly mean +/- one standard deviation volume fluxes through three North Sea transects provided by three different hydrodynamic models. In the first column, the first number is the transect number used in this study (see Figure 1) while the number in brackets is that used in Smith et al. (Fig.5).Yearly mean and standard deviation are coming from model runs over a seven year period (1987-1993).

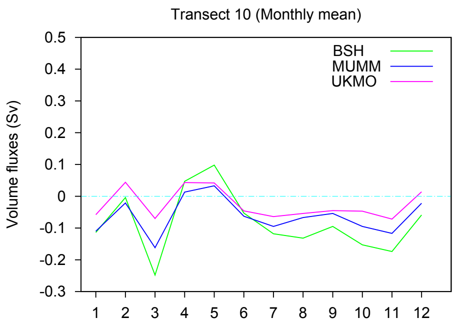
The number of transects is quite small and does not really allow to draw final conclusions. However, it seems well that model to model variability in NOOS is smaller than that sometimes observed in the past.

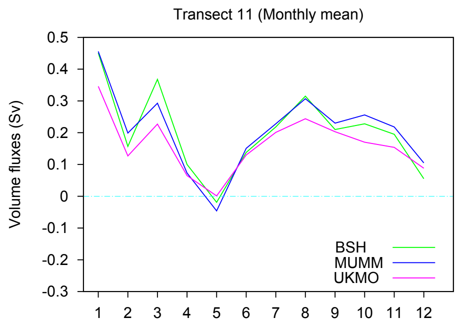
Time series of monthly mean values are presented on Figure 8. Month to month variability is coherent between the three models. It is in January that the North Sea circulation has been the strongest. For the inflow through the Channel, the second month in importance is August. In the North, large in- and outflow are also observed in October.

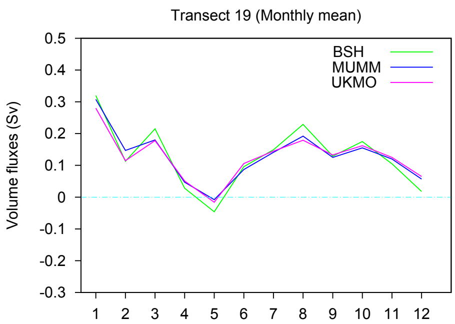

Transect 14 (Monthly mean)
Volume fluxes (Sv)
BSH
MUMM
UKMO

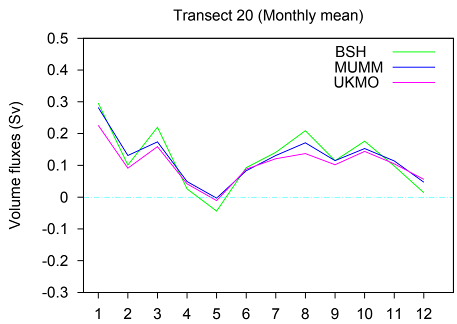

Transect 13 (Monthly mean)
Volume fluxes (Sv)
BSH
MUMM
UKMO

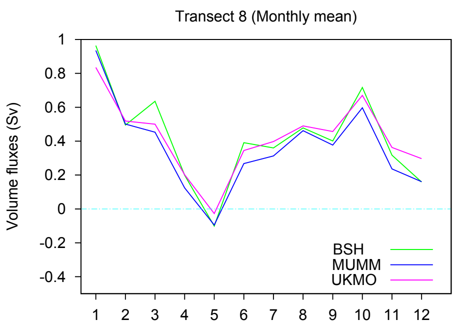

Transect 12 (Monthly mean)
Volume fluxes (Sv)
BSH
MUMM
UKMO


Transect 10 (Monthly mean)
Volume fluxes (Sv)
BSH
MUMM
UKMO


Transect 11 (Monthly mean)
Volume fluxes (Sv)
BSH
MUMM
UKMO


Transect 19 (Monthly mean)
Volume fluxes (Sv)
BSH
MUMM
UKMO


Transect 20 (Monthly mean)
Volume fluxes (Sv)
BSH
MUMM
UKMO


Transect 8 (Monthly mean)
Volume fluxes (Sv)
BSH
MUMM
UKMO

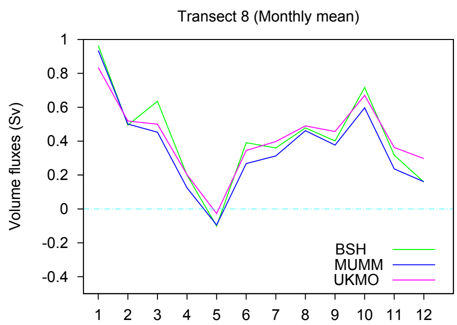

Transect 8 (Monthly mean)
Volume fluxes (Sv)
BSH
MUMM
UKMO

Figure 8: time series of monthly mean volume fluxes (Sv) through North Sea transects. Month number is given along the x axis. Note the change of y axis for transect 7 and transect 8. BSH model results are presented in green, those of MUMM model in blue and UKMO model results are presented in magenta.

6. Summary and conclusions

A comparison between transports through different North Sea transects as provided by three shelf seas numerical models has been carried out. It's well known that such transports are quite sensitive to model physics (*e.g.* turbulence closure schemes), model setups (*e.g.*, model domain, horizontal and vertical resolution), model forcing (*e.g.*, along the open boundaries and at the surface) and, last but not least, employed numerical schemes. Nevertheless, quantifying the degree of coherence between the results and whenever possible comparing them to estimates published elsewhere was found of particular interest in the context of the development of a new operational tool at the UKMO performed in the framework of the MyOcean project.

The other models results are coming from operational tools used by two NOOS partners, BSH and MUMM, respectively.

The area common to the model is the North Sea from 4°W to 57°N and they all have been run for the year 2008. Basic transport data are daily values (in fact two tidal cycles averaged values) of volume, heat and salt fluxes through nine transects which have been defined by NOOS.

Time series of daily transports though mean inflow and outflow sections already indicate a quite good correlation between the results. Major (wind) events occur simultaneously. Peak (positive and negative) values are slightly larger in BSH model results than in those of the two others models.

The degree of coherence between these daily values is quantified by means of a series of metrics: mean and standard deviation of each data set, and, for each pair of data, root mean squared differences and correlation coefficients. Results are presented by means of Taylor diagrams which provides a very synthetic overview. All values are also given in tables to be found in the appendix.

For volume fluxes, the domain of variation of BSH model results is clearly everywhere greater than that observed in MUMM and UKMO data. Correlation is quite high (between 0.81 and 0.95). It is between BSH and MUMM that the spreading between the results is the smallest. Normalized standard deviation is above 0.72 and normalized root mean square difference below 0.5. Between BSH model results and those of UKMO model, both limits are equal to 0.44 and 0.59, respectively.

The agreement is less satisfactory for salt fluxes. The correlation coefficient is several times smaller than 0.8. At some transects the variability in UKMO results is less than 60% of that observed in BSH results. The normalized root mean square difference is, at three transects, larger than or equal to 0.6. Agreement between heat fluxes is in between that for volume fluxes and that for salt fluxes.

While maybe slightly outside the scope of today operational oceanography, a comparison between monthly and annual mean values for the volume fluxes is proposed as well mainly because relatively similar values reported in the literature allow to check order of magnitudes and some general features.

In the three models, the North Sea 2008 residual circulation is as its long term mean, *i.e.* with inflow of Atlantic waters through the Channel and along the east coast of UK in the north, outflow along the Danish coast. From monthly mean values, it appears that it is in January that this anticlockwise circulation has been the strongest. For Dover Strait, a net long term inflow equal to 0.094 Sv has been derived from HF radar and ADCP current measurements (Prandle *et al.*, 1996). BSH estimate (0.09 Sv) fits nicely while MUMM estimate is 30% above and UKMO estimate is only 15% smaller. For the northern inflow, a long term mean value as that found here (~0.4 Sv) is reported in other model studies (Smith *et al.*, 1996) but for a smaller section.

Even if model to model variability remains large, it seems smaller than that observed sometimes in the past.

The use of two tidal averaged values and the presence of some gaps in the available time series do not really allow checking long term balances between inflows and outflows in the area. The amount of water “accumulated” by the three models in 2008, ~0.1 Sv (equivalent to an increase of nearly 8 meters in mean sea level in a year), is however surprisingly high. It could be of interest, in the future, to exchange time averaged values allowing this kind of verifications.

7. Acknowledgments

NOOS partners (S. Dick for BSH and R. Furner for UKMO) are thanks for making their model results available. S. Legrand (MUMM) and A. Sellar (UKMO) are thanks for the numerous and very useful comments they made on a early version of this report. This work has been supported by the EC project MyOcean under contract *N*°: FP7-SPACE-1.

8. References

Bachaus, J., and D. Hainbucher, 1987. A finite difference general circulation model for the shelf seas and its application to low frequency variability on the North European shelf. In J.C.J. Nihoul and B. Jamart (eds) : Three dimensional models of marine and estuarine dynamics. Elsevier Oceanography Series 45, pp 221-244.

Baretta, J.W., W. Ebenhoeh and P. Ruardij, 1995. The European Regional Seas Ecosystem Model, a complex marine ecosystem model. Netherlands Jounral of Sea Research, 33 (3-4), 233-246.

Delhez, E.J.M., P. Damm, E. de Goede, J.M. de Kok, F. Dumas, H. Gerritsen, J.E. Jones, J. Ozer, T. Polhmann, P.S. Radach, M. Skogen and R. Proctor, 2004. Variability of shelf-seas hydrodynamic models: lessons from the NOMADS2 Project. Journal of Marine Systems, 45, 39-53.

Dick, S., E. Kleine, S.H. Müller-Navara, H. Keline and H. Komo, 2001. The Operational Circulation Model of BSH (BHCmod) – Model description and validation. Brichte des Bundesamtes für Seeschifffahrt und Hydrographie, Nr. 29, 44 pp.

Dick,S., E. Kleine and F. Janssen, 2008. A new operational circulation model for the North Sea and Baltic Sea using a novel vertical co-ordinate setup and first results. In: Dalhin, H., M.J. Bell, N.C. Flemming and S.E. Petersson (Editors),Coastal to Global Operational Oceanography: Achievements and Challenges. Proceedings of the Fifth International Conference on EuroGOOS, 20-22 May 2008, Exeter, UK, pp. 225-231.

Flather, R.A., R. Proctor and J. Wolf, 1991. Oceanograhic forecast models. In D.G. Farmer and M.J. Rycroft (eds): Computer modeling in the environmental sciences. Oxfort, Clarendon Press, pp 15-30.

Holt, J., and R. Proctor, 2008. The seasonal circulation and volume transport on the Northwest European continental shelf: A fine-resolution model study. Journal of Geophysical Research, 113, C06021, doi: 10.1029/2006JC004034.

Jamart, B.M., and J. Ozer, 1989. Some results on the Tidal Flow Forum Experiment. Advances in Water Ressources, 12 (4), 211-220.

Jolliff, J.K., J.C. Kindle, I. Shulman, B. Penta, M.A.M. Friedrichs, R. Helber and R.A. Armone, 2009. Summary diagrams for coupled hydrodynamic-ecosystem model. Journal of Marine Systems, 76 (2009): 64-82

Luyten, P.J., J.E. Jone, R. Proctor, A. Tabor, P. Tett and K. Wid-Allen, 1999. COHERENS – A Coupled Hydrodynamical-Ecological Model for Regional and Shelf Seas: User Documentation. MUMM Report, Management Unit of the Mathematical Models of the North Sea, 911 pp.

Martin, M.J., Hines, A. and Bell, M.J., 2007: Data assimilation in the FOAM operational short-range ocean forecasting system: a description of the scheme and its impact. Q. J. Roy Met Soc, 133, 981-995.

O'Dea, E., J. White, R. Furner, P. Hyder, A.Arnold, D. Storkey, J.R. Siddorn. M.Martin, H.Liu and J.T. Holt, 2010. UKMO-Shelf, towards operational oceanography with SS data assimilation on the North West European Shelf. Mercator Ocean Quaterly Newsletter, 39 (October 2010), 25-28.

Otto, L., J.T.F. Zimmerman, G.K. Furnes, M. Mork, R. Saetre and G. Becker, 1990. Review of the oceanography of the North Sea. Netherlands Journal of Sea Research, 26, 161-238.

Pison, V., and J. Ozer, 2003. Operational products and services for Belgian coastal waters. In: Dalhin, H., N.C. Flemming, K. Nittis and S.E. Petersson (Editors). Building the European capacity in Operational Oceanography. Proceedings of the Third International Conference on EuroGOOS 3-6 December 2002, Athens, Greece, pp. 503-509.

Prandle, D. and R.J. Player, 1993. Residuals currents through the Dover Strait measured by H.F. radar. Estuarine, Coastal and Shelf Science, 37, 635-653.

Prandle, D., 1984a. Monthly-mean residual flow through the Dover Strait, 1949-1980. Journal of the Marine Biological Association of th UK, 64, 722-744.

Prandle, D., G. Ballard, D. Flatt, A.J. Harrison, S.E. Jones, P.J. Knight, S. Loch, J. McManus, R. Player and A. Tappin, 1996. Combining modeling and monitoring to determine fluxes of water, dissolved and particular metals through the Dover Strait. Continental Shelf Reasearch, Vol. 16, No. 2, 237-257.

Prandle, D. 1984b. A modeling study of the mixing of 137Cs in the seas of European Continental Shelf. Philosophical Transactions of the Royal Society of London, A, 310, 407-436.
Prandle, D. and R.J. Player, 1993. Residuals currents through the Dover Strait measured by H.F. radar. Estuarine, Coastal and Shelf Science, 37, 635-653.

Prandle, D., G. Ballard, D. Flatt, A.J. Harrison, S.E. Jones, P.J. Knight, S. Loch, J. McManus, R. Player and A. Tappin, 1996. Combining modeling and monitoring to determine fluxes of water, dissolved and particular metals through the Dover Strait. Continental Shelf Reasearch, Vol. 16, No. 2, 237-257.
Proctor, R. (ed.), 1997. NOMADS – North Sea Model Advection Dispersion Study. Final report. Proudmann Oceanographic Laboratory, Internal Document No. 108, 55 pp. and Figs. (unpublished manuscript).

Salomon, J.C., M. Breton and P. Gueguenat, 1993. Computed residual flow through the Dover Strait. Oceanologica Acta, 16(5-6), 449-455.

Smith, J.A., P.E. Damm, M.D. Skogen, R.A. Flather and J. Pätsch, 1996. An Investigation into the Variability of the Circulation and Transport on the North-West European Shelf Using Three Hydrodynamic Models. Deutszche <hydrographische Zeistchrift, 48 (3/4), 325-347.

Skogen, M.D., 1993. A User's guide to NORWECOM, the NORWegian ECOlogical Model system. Tech. Rep. 6. Institute of Marine Research, Division of Marine Environment, Pb. 1870, N-5024 Bergen.

Appendix

<u>Daily volume fluxes</u>: comparison MUMM/BSH, UKMO/BSH and UKMO/MUMM, respectively. Volume fluxes are expressed in **Sv (10^6 m^{3}s^{-1})**.

		BSH		MUMM		MUMM-BSH				
#	N	$\overline{O}$	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$\overline{M}$	σ_O	*RMSD*	r	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	E'	ϑ
		Sv	Sv	Sv	Sv	Sv	-	-	-	-
14	351	0.10	0.31	0.12	0.25	0.13	0.91	0.81	0.43	25
13	351	0.09	0.29	0.12	0.23	0.12	0.92	0.80	0.41	23
12	351	0.06	0.28	0.09	0.22	0.11	0.93	0.80	0.40	22
10	351	-0.08	0.36	-0.06	0.28	0.18	0.87	0.79	0.50	30
11	351	0.20	0.34	0.21	0.29	0.12	0.95	0.84	0.34	19
19	351	0.13	0.27	0.13	0.20	0.10	0.95	0.75	0.38	19
20	351	0.12	0.25	0.12	0.18	0.10	0.93	0.72	0.41	21
7	351	-0.42	0.86	-0.34	0.75	0.42	0.87	0.87	0.49	29
8	351	0.42	0.70	0.36	0.60	0.23	0.95	0.87	0.33	19
Mean							0.92	0.81	0.41	
Min							0.87	0.72	0.33	
Max							0.95	0.87	0.50	

*Table 3: results of the comparison between MUMM's OPTOS daily transports of water through North Sea transect in 2008 and those of BSHcmod. The latter are taken as the reference. Metrics provided are: mean and standard deviation for both fields, root mean square difference (*RMSD*) and correlation coefficient* (**r**) *between both fields, normalized standard deviation (γ), normalized root mean square difference (E') and ϑ (in degree) the angle which cosine is equal to* r.

		BSH		UKMO		UKMO-BSH				

#	N	$\overline{O}$	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$\overline{M}$	σ_O	$RMSD$	r	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	E'	ϑ
		Sv	Sv	Sv	Sv	Sv	-	-	-	-
14	351	0.10	0.31	0.07	0.19	0.15	0.93	0.61	0.49	22
13	351	0.09	0.29	0.08	0.13	0.17	0.96	0.44	0.59	17
12	351	0.06	0.28	0.10	0.16	0.15	0.93	0.56	0.52	22
10	351	-0.08	0.36	-0.03	0.25	0.20	0.85	0.69	0.55	32
11	351	0.20	0.34	0.16	0.22	0.16	0.94	0.63	0.47	20
19	351	0.13	0.27	0.13	0.19	0.11	0.95	0.70	0.39	17
20	351	0.12	0.25	0.11	0.15	0.12	0.95	0.61	0.47	19
7	351	-0.42	0.86	-0.47	0.66	0.37	0.92	0.76	0.43	23
8	351	0.42	0.70	0.42	0.49	0.28	0.94	0.71	0.41	19
Mean							0.93	0.63	0.48	
Min							0.85	0.44	0.39	
Max							0.96	0.76	0.59	

Table 4: as in Table 3 but now for the comparison between UKMO shelf model results (simulated field) and BSHcmod results (reference field).

		MUMM		UKMO		UKMO-MUMM				
#	N	$\overline{O}$	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$\overline{M}$	σ_O	$RMSD$	r	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$E^{'}$	ϑ
		Sv	Sv	Sv	Sv	Sv	-	-	-	-
14	351	0.12	0.25	0.07	0.19	0.11	0.91	0.75	0.45	25
13	351	0.12	0.23	0.08	0.13	0.12	0.94	0.56	0.51	19
12	351	0.09	0.22	0.10	0.16	0.10	0.92	0.70	0.45	23
10	351	-0.06	0.28	-0.03	0.25	0.16	0.82	0.88	0.58	35
11	351	0.21	0.29	0.16	0.22	0.11	0.95	0.74	0.37	17
19	351	0.13	0.20	0.13	0.19	0.06	0.95	0.94	0.31	18
20	351	0.12	0.18	0.11	0.15	0.06	0.94	0.84	0.35	19
7	351	-0.34	0.75	-0.47	0.66	0.44	0.81	0.88	0.59	36
8	351	0.36	0.60	0.42	0.49	0.21	0.95	0.82	0.34	18
Mean							0.91	0.79	0.44	
Min							0.81	0.56	0.31	
Max							0.95	0.94	0.59	

Table 5: as in Table 3 but for the comparison between UKMO Shelf model resulsts (simulated field) and MUMM OPTOS results (reference field).

<u>Daily fluxes of salt</u>: comparison MUMM/BSH, UKMO/BSH and UKMO/MUMM, respectively. These fluxes are expressed in **10^6 kgs^{-1}**.

		BSH		MUMM		MUMM-BSH				
#	*N*	$\overline{O}$	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$\overline{M}$	σ_O	*RMSD*	*r*	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	E'	ϑ
14	351	3.22	12.39	4.36	8.92	8.67	0.71	0.72	0.70	44
13	351	2.87	10.26	4.32	8.30	4.47	0.91	0.81	0.44	25
12	351	2.75	10.39	3.19	7.84	5.37	0.86	0.75	0.52	30
10	351	-4.13	12.97	-2.27	10.04	7.48	0.82	0.77	0.58	35
11	351	7.03	11.74	7.22	10.19	4.17	0.94	0.87	0.35	20
19	351	4.15	9.14	4.49	7.00	3.82	0.92	0.77	0.42	23
20	351	4.05	8.32	4.13	6.15	3.45	0.93	0.74	0.41	22
7	351	-12.1	31.81	-12.0	26.90	17.66	0.83	0.85	0.56	34
8	351	14.66	23.71	12.70	21.27	7.71	0.95	0.90	0.33	19
Mean							0.87	0.80	0.48	
Min							0.71	0.72	0.33	
Max							0.95	0.90	0.70	

*Table 6: results of the comparison between MUMM's OPTOS daily transports of salt through North Sea transect in 2008 and those of BSHcmod. The latter are taken as the reference. Metrics provided are: mean and standard deviation for both fields, root mean square difference (*RMSD*) and correlation coefficient* **(r)** *between both fields, normalized standard deviation (γ), normalized root mean square difference (E') and ϑ (in degree) the angle which cosine is equal to* r.

		BSH		UKMO		UKMO-BSH				

#	N	$\overline{O}$	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$\overline{M}$	σ_O	$RMSD$	r	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$E^{'}$	ϑ
14	351	3.22	12.39	2.46	6.82	9.13	0.69	0.55	0.74	46
13	351	2.87	10.26	2.92	4.67	6.02	0.95	0.46	0.59	19
12	351	2.75	10.39	3.30	5.49	6.43	0.85	0.53	0.62	32
10	351	-4.13	12.97	-0.56	8.64	7.83	0.81	0.67	0.60	36
11	351	7.03	11.74	5.74	7.56	5.45	0.93	0.64	0.46	21
19	351	4.15	9.14	4.49	6.53	3.89	0.93	0.71	0.43	22
20	351	4.05	8.32	3.57	5.09	3.95	0.94	0.61	0.47	20
7	351	-12.1	31.81	-16.8	23.67	15.66	0.88	0.74	0.49	28
8	351	14.66	23.71	14.88	17.47	9.30	0.94	0.74	0.39	20
Mean							0.88	0.63	0.53	
Min							0.69	0.46	0.39	
Max							0.95	0.74	0.74	

Table 7: as in Table 6 but now for the comparison between BSHcmod results and those of UKMO shelf.

		MUMM		UKMO		UKMO-MUMM				
#	N	$\overline{O}$	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$\overline{M}$	σ_O	$RMSD$	r	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$E^{'}$	ϑ
14	351	4.36	8.92	2.46	6.82	4.05	0.90	0.77	0.45	26
13	351	4.32	8.30	2.92	4.67	4.19	0.94	0.56	0.50	19
12	351	3.19	7.84	3.30	5.49	3.52	0.92	0.70	0.45	23
10	351	-2.27	10.04	-0.56	8.64	5.75	0.82	0.86	0.57	35
11	351	7.22	10.19	5.74	7.56	3.73	0.95	0.74	0.37	17
19	351	4.49	7.00	4.49	6.53	2.17	0.95	0.93	0.31	18
20	351	4.13	6.15	3.57	5.09	2.16	0.94	0.83	0.35	19
7	351	-12.1	26.90	-16.8	23.67	15.76	0.81	0.88	0.59	36
8	351	12.70	21.27	14.88	17.47	7.22	0.95	0.82	0.34	18
Mean							0.91	0.79	0.44	
Min							0.81	0.56	0.31	
Max							0.95	0.93	0.59	

Table 8: as in Table 6 but now for the comparison between OPTOS results and UKMO shelf model results.

<u>Daily heat fluxes:</u> comparison MUMM/BSH, UKMO/BSH and UKMO/MUMM, respectively. These fluxes are expressed in **10^{12} W**.

		BSH		MUMM		MUMM-BSH				
#	N	$\overline{O}$	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$\overline{M}$	σ_O	$RMSD$	r	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	E'	ϑ
14	351	117	374	142	290	167	0.90	0.78	0.45	25
13	351	110	356	142	271	152	0.92	0.76	0.43	23
12	351	79	338	108	259	140	0.92	0.77	0.41	22
10	351	-104	433	-74	325	221	0.87	0.75	0.51	30
11	351	247	417	241	337	147	0.95	0.81	0.35	19
19	351	156	328	151	233	131	0.95	0.71	0.40	19
20	351	148	300	141	207	129	0.93	0.69	0.43	21
7	351	-506	1041	-388	864	509	0.87	0.83	0.49	29
8	351	510	843	420	697	289	0.95	0.83	0.34	19
Mean							0.92	0.77	0.42	
Min							0.87	0.69	0.34	
Max							0.95	0.83	0.51	

*Table 9: results of the comparison between MUMM's OPTOS daily transports of heat through North Sea transect in 2008 and those of BSHcmod. The latter are taken as the reference. Metrics provided are: mean and standard deviation for both fields, root mean square difference (*RMSD*) and correlation coefficient* (**r**) *between both fields, normalized standard deviation (γ), normalized root mean square difference (E') and ϑ (in degree) the angle which cosine is equal to* r.

		BSH		UKMO		UKMO-BSH				

#	N	$\overline{O}$	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$\overline{M}$	σ_O	$RMSD$	r	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$E^{'}$	ϑ
14	351	117	374	86	228	187	0.92	0.61	0.50	
13	351	110	356	98	159	209	0.96	0.45	0.59	
12	351	79	338	117	190	177	0.93	0.56	0.52	
10	351	-104	433	-32	302	237	0.85	0.70	0.55	
11	351	247	417	200	263	194	0.94	0.63	0.46	
19	351	156	328	156	230	128	0.95	0.70	0.39	
20	351	148	300	129	183	140	0.95	0.61	0.47	
7	351	-506	1041	-572	798	444	0.92	0.77	0.43	
8	351	510	843	514	600	340	0.94	0.71	0.40	
Mean							0.93	0.64	0.48	
Min							0.85	0.45	0.39	
Max							0.96	0.77	0.59	

Table 10: as in Table 9 but now for the comparison between BSHcmod results and UKMO shelf model results.

		MUMM		UKMO		UKMO-MUMM				
#	N	$\overline{O}$	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$\overline{M}$	σ_O	$RMSD$	r	**Fehler! Es ist nicht möglich, durch die Bearbeitung von Feldfunktionen Objekte zu erstellen.**	$E^{'}$	ϑ
14	351	142	290	86	228	127	0.91	0.79	0.44	25
13	351	142	271	98	159	132	0.94	0.59	0.49	19
12	351	108	259	117	190	111	0.92	0.73	0.43	23
10	351	-74	325	-32	302	190	0.82	0.93	0.59	35
11	351	241	337	200	263	116	0.95	0.78	0.35	17
19	351	151	233	156	230	72	0.95	0.99	0.31	18
20	351	141	207	129	183	70	0.94	0.88	0.34	19
7	351	-388	864	-572	798	512	0.81	0.92	0.59	36
8	351	420	697	514	600	227	0.95	0.86	0.33	18
Mean							0.91	0.83	0.43	
Min							0.81	0.59	0.31	
Max							0.95	0.99	0.59	

Table 11: as in Table 9 but now for the comparison between OPTOS results and UKMO shelf model results.