# Baroclinic Rossby radius of deformation in the southern Baltic Sea*

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**Abstract**

The first baroclinic Rossby radius of deformation ($R_1$) is a fundamental horizontal scale of mesoscale processes. This scale is important for planning both numerical modelling and study areas.

$R_1$ was computed on the basis of an 11-year series of high resolution CTD measurements collected during r/v 'Oceania' cruises. The data set covered the three main basins of the Baltic Proper: the Bornholm Basin (BB), the Słupsk Furrow (SF) and the Gdańsk Basin (GB). The smallest mean value of $R_1$ was found in the Gdańsk Basin (5.2 km), the largest one in the Bornholm Deep (7.3 km).

The seasonal variability of $R_1$ is lower in the western basin than in the eastern one. The seasonal cycle of $R_1$ may be broken by extreme events, e.g. main Baltic inflows (MBI) of saline water. The inflowing water rebuilds the vertical stratification in the southern Baltic Sea and dramatically changes the $R_1$ values. The difference of $R_1$ between a stagnation period and an inflow situation is shown

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on the basis of observations made during 2002–2003. The main inflow occurred in winter, after ten years of stagnation, and the very low values of $R_1$ (about 4 km) changed to very high ones (more than 9 km).

Analysis of stagnation and saltwater inflow events may throw light on the value of $R_1$ in future climatic scenarios. The potential influence of climate change on Baltic Sea salinity, especially a decrease in MBI activity, may change the baroclinic Rossby radius of deformation and the mesoscale dynamics. Values of $R_1$ are expected to be lower in the future climate than those measured nowadays.

## 1. Introduction

The Baltic Sea is a marginal, shallow, semi-enclosed water body in Europe. It has a complicated shoreline and bottom topography, and its water column is highly stratified. Compared to the open ocean and the North Sea, the salinity in the Baltic is low, mainly due to the large river runoff (e.g. Helcom 2003, Omstedt et al. 2004). Water exchange with the open ocean occurs only through the shallow and narrow Danish Straits. Saline inflows from the North Sea produce a lateral salinity gradient along the entire Baltic Sea, with high surface salinities of about 25 PSU in the transition area of the Kattegat and low salinities of about 3 PSU in the Gulf of Bothnia. The vertical salinity gradient is also steep, with a permanent halocline in the Baltic Proper, located about 60 m below the surface (e.g. Elken & Matthäus 2008).

The Baltic Sea contains a number of deep basins isolated by shallows and narrow sills. The southern Baltic, especially the area of the Słupsk Furrow, is an extremely important area as regards the hydrology and biology of the entire sea. This is the only pathway along which inflowing highly saline and oxygen-rich water can enter the central and northern Baltic. These inflows are especially important in deep areas, where anoxic zones occur during prolonged periods of stagnation. The transport processes involved, especially the role of mesoscale eddies, are still not fully understood, however (Reissmann et al. 2009).

Numerical modelling is one of the ways of investigating marine dynamics. The crucial question in numerical investigations is: how should the horizontal resolution of the planned model be prepared? The Rossby radius of deformation is a length scale of fundamental importance in ocean dynamics (Gill 1982). It is a horizontal scale describing the effects of the Earth's rotation on fluid motion. The scale of the mesoscale eddies is of the order of the first baroclinic Rossby radius of deformation ($R_1$). This has been studied in many regions of the world ocean (Emery et al. 1984, Houry et al. 1987, Chelton et al. 1998), in the main basins of the Baltic Sea (Fennel et al. 1991) and in the Gulf of Finland (Alenius et al. 2003).

The aim of this article is to describe the computed first baroclinic Rossby radius of deformation ($R_1$) and its variability for the main regions of the southern Baltic Sea, on the basis of an eleven-year series of measurements carried out by the Institute of Oceanology, Polish Academy of Sciences (IO PAN), Sopot. To the best of the authors' knowledge no estimates of $R_1$ have yet been published for all four seasons for the Słupsk Furrow (SF) and Gdańsk Basin (GB). For the Bornholm Basin (BB) the estimates of Fennel et al. (1991) were based on different means of measurements and covered the decade before our calculations.

This article aims to bridge this gap and provide basic information for numerical modellers, projecting the size of the grid that is necessary to fully resolve mesoscale motions (e.g. eddies). On the other hand $R_1$ is a measuring strategy guide. Experimenters should consider the length of $R_1$ when planning larger scale experiments. The spatial coverage of measuring station grids should resolve at least the mesoscale structures within the basin examined.

Moreover, the results described in this article may shed light on the potential influence of climate change on $R_1$. According to the latest results, the salinity, stratification and volume of inflows into the Baltic Sea will change in this century (Meier 2006). Therefore, it seems reasonable to expect that the baroclinic Rossby radius of deformation may also change with changing climatic conditions.

## 2. Data

The dataset was obtained during regular scientific cruises of the IO PAN research vessel 'Oceania' between March 1998 and October 2008. It consists of 49 surveys and 24 914 CTD profiles. There is one main CTD transect, referred to as RS1RS2, which begins in the Bornholm Gate, continues over the Słupsk Sill, along the Słupsk Furrow before reaching the Gdańsk Deep. The location of the transect is shown in Figure 1. The properties of the water were measured with calibrated Sea Bird SB49, Seabird 9/11 or Guildline 8710 probes.

CTD measurements were not collected as classical vertical profiles, but along the transect, by means of a towed probe (i.e. with vertical movement from the surface to the bottom and from the bottom to the surface). This gives a high horizontal resolution of measurements; in a typical case, with a depth of 60–110 m, the spatial resolution of measurements is in the 200–500 m range. During the measurements, the probe was towed in a specially designed housing set horizontally in the direction of the vessel's movement. The housing also protected the probe from mechanical damage. Probe operation at 10 Hz frequencies gives about 30 measurements per one metre

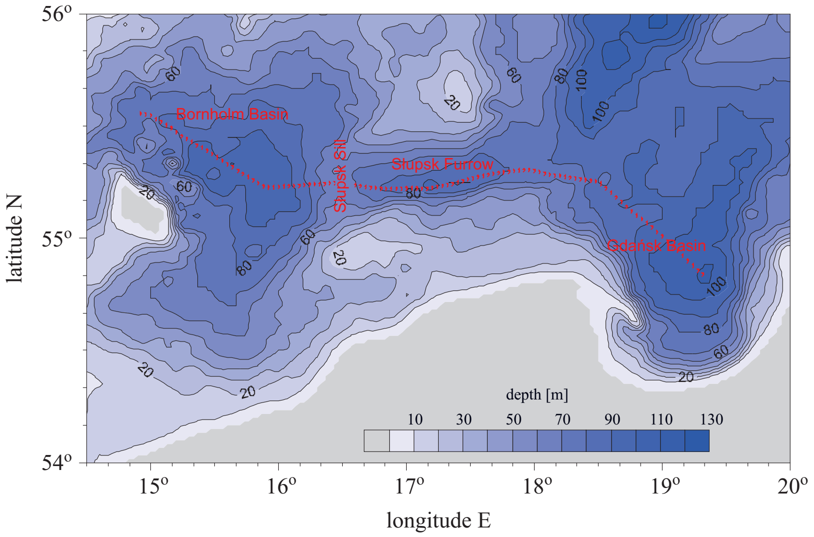


**Figure 1.** The bottom topography of the basins investigated and transect 1RS2RS (every second point of the station grid is marked by a red dot)

of depth. For analysis, the data were averaged over 0.5 dbar intervals corresponding to approximately 0.5 m. Horizontally, the data were averaged with an interval of 0.02°, which corresponds to about 1.3 km.

The profiles were collected in all seasons: winter (20 surveys), spring (10), summer (6) and autumn (13).

## 3. Methods

The Rossby radius of deformation is the distance that long gravity waves of phase speed $c$ can travel in time $1/f$, where $f = 2\Omega \sin\varphi$. $f$ is the Coriolis parameter for the Earth's rotation $\Omega$, and latitude $\varphi$.

For latitudes higher than 5° Rossby radii can be defined as (Gill 1982):

$$\mathrm{R}_n = \frac{c_n}{|f|}, \qquad n = 0,\ 1,\ 2, \ldots, \tag{1}$$

The $n = 0$ mode is called the barotropic Rossby radius of deformation and is compared to basin scales, where $c_0 = \sqrt{gH}$ for a water depth $H$ and the acceleration due to gravity $g$. The next modes are baroclinic ones. The first baroclinic mode, $n = 1$, is the most important one as regards mesoscale motions and is the subject of this article.

Baroclinic Rossby radii can be obtained by solving the Sturm-Liouville eigenvalue problem for the vertical structure $\phi(z)$ of the vertical velocity as an inverse eigenvalue of $c_n$. The eigenvalue problem can be written in the form

$$\frac{d^2\phi}{dz^2} = \frac{N^2(z)}{c^2}\phi = 0, \tag{2}$$

with surface and bottom conditions

$$\phi(0) = \phi(H) = 0. \tag{3}$$

The analytical approximate solution can be obtained by the so-called Wentzel-Kramers-Brillouin (WKB) method. Using this method the first gravity baroclinic wave speed is

$$c_1 = \frac{1}{\pi}\int\limits_{-H}^{0} N(z)dz, \tag{4}$$

where $N$ is the Brunt-Väisälä frequency (BVF). A very simple method, the WKB gives proper results if the variability of BVF in the vertical is weak (e.g. for the open ocean; Chelton et al. 1998). If not, the discrepancy is large and the WKB method is then unacceptable. This is the case for the Baltic Sea, where both the halocline and the seasonal thermocline are strong and produce highly variable BVF profiles. In such a case, the numerical solution for equation (2) is more appropriate. In this article the eigenvalues are computed by discretizing equation (2) for every vertical profile with an 0.5 m step in the vertical direction. The resulting values of $R_1$ are then horizontally averaged and analysed.

## 4. Results

The Rossby radius of deformation was computed using both WKB and numerical methods, but the analysis describes only the numerical results, as the WKB method is obviously less precise than the numerical one (Fennel et al. 1991, Alenius et al. 2003). The WKB gives smaller values of $R_1$. The differences between $R_1$ values calculated using the WKB and numerical methods depend strongly on stratification. In the investigated area the differences may be in excess of 2.5 km. The largest differences, up to 50%, occur in BB (Table 1).

### 4.1. Seasonal variability and spatial distribution of the Brunt-Väisälä frequency (BVF) in the southern Baltic Sea

Because of the depth of the halocline, the investigated basins are defined as regions with a depth of 70 m or more. These basins are quite large areas separated by sills. They have various hydrological conditions and

**Table 1.** Seasonal and annual mean of the first baroclinic Rossby radius of deformation

| Region | Season | $R_1$ (WKB method) [km] | $R_1$ (numerical method) [km] |
|---|---|---|---|
| Bornholm Basin | spring | $5.29 \pm 0.05$ | $7.72 \pm 0.09$ |
| | summer | $6.36 \pm 0.05$ | $8.31 \pm 0.09$ |
| | autumn | $5.16 \pm 0.04$ | $7.79 \pm 0.09$ |
| | winter | $5.25 \pm 0.07$ | $7.88 \pm 0.10$ |
| | **annual** | $\mathbf{5.51 \pm 0.05}$ | $\mathbf{7.92 \pm 0.09}$ |
| Słupsk Furrow | spring | $4.01 \pm 0.05$ | $5.46 \pm 0.11$ |
| | summer | $5.00 \pm 0.04$ | $6.01 \pm 0.08$ |
| | autumn | $4.06 \pm 0.05$ | $5.82 \pm 0.10$ |
| | winter | $3.63 \pm 0.04$ | $5.46 \pm 0.11$ |
| | **annual** | $\mathbf{4.18 \pm 0.05}$ | $\mathbf{5.69 \pm 0.10}$ |
| Gdańsk Basin | spring | $3.70 \pm 0.06$ | $4.80 \pm 0.14$ |
| | summer | $4.81 \pm 0.08$ | $5.57 \pm 0.10$ |
| | autumn | $3.91 \pm 0.06$ | $5.41 \pm 0.11$ |
| | winter | $3.28 \pm 0.06$ | $4.67 \pm 0.11$ |
| | **annual** | $\mathbf{3.92 \pm 0.06}$ | $\mathbf{5.11 \pm 0.11}$ |

different variabilities of BVF. Seasonal mean BVF profiles for each basin are plotted in Figure 2, in which the general features of the southern Baltic's stratification are discernible. There are two main layers: an upper one, from the surface to the halocline (the depth at which the BVF reaches a maximum), and a lower layer, beneath the halocline. In the upper layer the thermal stratification is the most important during the warm season.

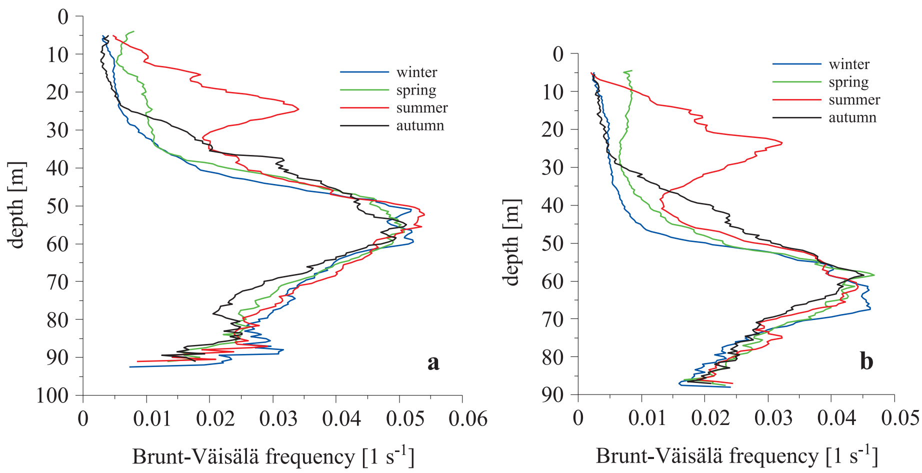


**Figure 2.** (*continued next page*)

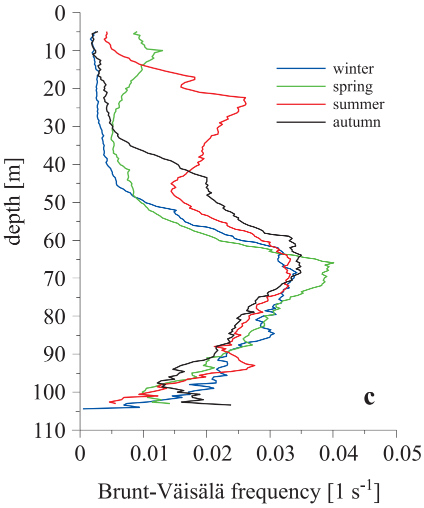


**Figure 2.** Profiles of seasonal mean Brunt-Väisälä frequency in (a) the Bornholm Basin, (b) the Słupsk Furrow and (c) the Gdańsk Basin

During this time, the local maximum of mean BVF occurs at 24 m depth in all three basins. The thermocline is strongest in BB, where the mean BVF reaches a value of 0.034 $s^{-1}$, and weakest in GB, where the mean BVF is 0.027 $s^{-1}$. The so-called winter water occupies the space between the seasonal thermocline and the permanent halocline. The thickness of this layer changes from 26 m in the western part to 36 m in the eastern part of the area investigated (Figure 2). During autumn the thermocline erodes, weakens and moves deeper. This process is visible as the line of the mean BVF autumn profile crosses the line of the summer mean BVF at a depth of about 40 m (Figure 2). Because in winter the upper layer is well mixed as a result of thermal convection and strong wind forcing, the mean BVF reaches a minimum value in the whole upper layer. During spring the thermal structure builds up, and the mean BVF values are highest in the top few metres. The lower boundary of the upper layer runs from 50 m in BB, through 55 m in SF to 60 m in GB. The thickness of the halocline is about 10 m in all three basins. The halocline is strongest in BB (BVF=0.05 $s^{-1}$) and weakest in GB (BVF = 0.035 $s^{-1}$). There is no pronounced seasonality either in the halocline or in the bottom layer. The only exception is spring in GB, where the mean value of BVF in the halocline is the highest of all the seasons.

The mean BVF values are not distributed uniformly, even in one basin (Figure 3). The highest mean BVF values are near sills and are weakest in central parts of basins. Above the Słupsk Sill the mean BVF may reach

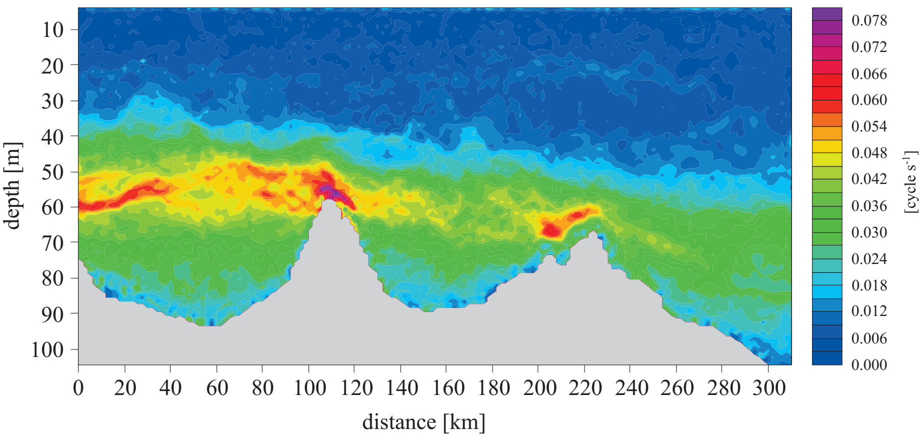


**Figure 3.** Vertical section of the annual mean Brunt-Väisälä frequency along transect 1RS2RS

0.08 $s^{-1}$. This is because the saline water does not always flow over the sills (Piechura et al. 1997, Piechura & Beszczyńska-Möller 2004); and during such events BVF reaches extremely high values.

### 4.2. Annual mean and seasonal variability of the baroclinic Rossby radius of deformation ($R_1$)

The internal Rossby radius of deformation depends on both bottom topography and stratification. Therefore, significant changes of bottom topography and stratification in different regions of the southern Baltic Sea cause a high spatial variability in mean $R_1$. It is not surprising that the lowest values of annual mean $R_1$ were found in shallow areas, above and near sills separating basins, and the highest values in the deepest parts of basins. On average, $R_1$ in deep basins is twice as high as in the areas separating the basins. But even in areas with the same depth, $R_1$ can be quite different among basins (e.g. in BB and GB). The smallest annual mean of $R_1$ occurs in GB (Figure 4), the highest in BB. In the central part of BB, $R_1$ is almost 9 km, whereas in GB, at the same or even greater depths, the maximum value of $R_1$ is about 6 km.

Because of the blocking role of the Słupsk Sill, $R_1$ in SF is similar to that in GB. The maximum value of $R_1$ in SF is not exactly in the deepest part, but is shifted westwards, probably because of the shape of the halocline, which is maintained by eastwards advecting saline bottom water. In other areas, regions of $R_1$ maxima correlate with maximum depth.

The seasonal variability of $R_1$ was also examined. For all three basins, summer is the period of the highest values of $R_1$. This is due to the influence

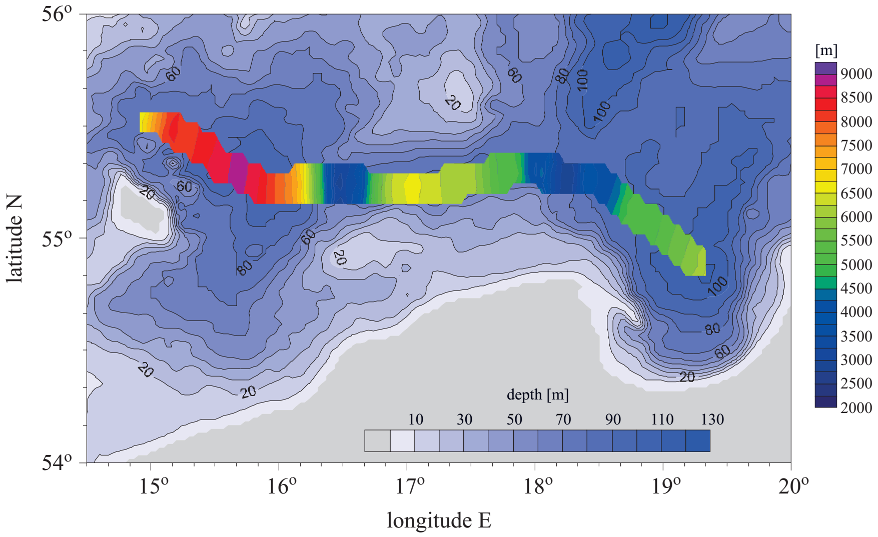


**Figure 4.** Spatial distribution of the annual mean baroclinic Rossby radius of deformation

of the thermal structure of the upper layer on the vertical profile of BVF. In the shallow regions, the difference between summer and annual mean $R_1$ (seasonal anomaly of $R_1$) can reach 1 km; in areas deeper than 70 m, the seasonal anomaly of $R_1$ is not much higher than 0.5 km (Figure 5).

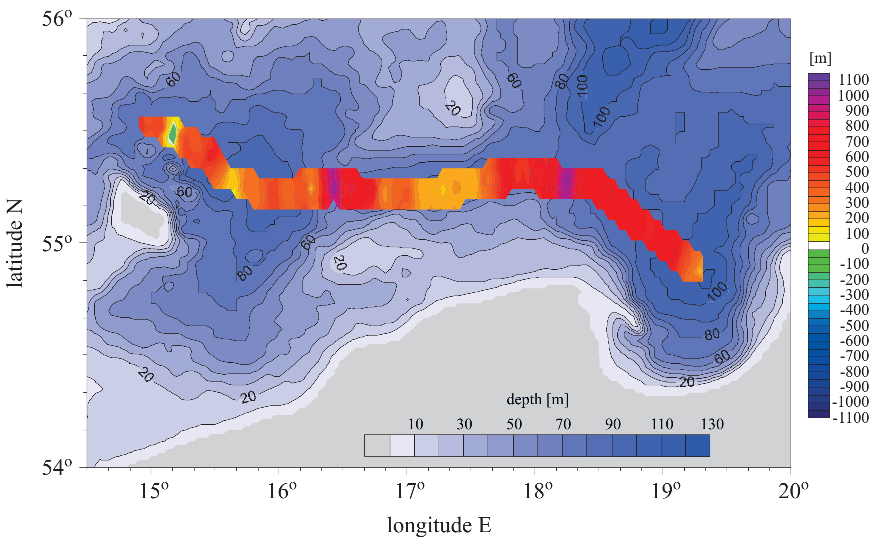


**Figure 5.** Spatial distribution of the anomaly (annual mean value minus summer value) of the baroclinic Rossby radius of deformation for the summer season

During autumn the thermocline gradually erodes, but $R_1$ is still higher than the annual mean. The lowest values of $R_1$ occur during winter, when a well-mixed upper layer is present. The only exception is the Bornholm Basin, where the seasonal autumn anomaly of $R_1$ is close to zero and the seasonal variability is the lowest (spring anomaly: −0.2 km, summer anomaly: +0.39 km). The highest seasonal variability in $R_1$ (winter anomaly: −0.45 km, summer anomaly: +0.45 km) occurs in GB, where the halocline is the weakest. The winter and summer seasonal anomalies of $R_1$ for the Słupsk Furrow are −0.23 km and +0.32 km respectively.

### 4.3. Case study: comparisons of $R_1$ in periods of stagnation and main Baltic inflow

Stagnation is a normal state in the Baltic Sea. Inflowing saline waters from the open ocean are intermittent and large main Baltic inflows (MBI) are episodic (Matthäus & Frank 1992). During the last two decades the frequency of main inflows decreased from 4–5 years to every 10 years (Meier et al. 2006).

After ten years of stagnation a main inflow took place in 2003 (Piechura & Beszczyńska-Möller 2004, Feistel et al. 2006). The previous one, the 1993 MBI, was described by Matthäus & Lass (1995). Because the hydrology of the Baltic Sea is very dependent on salt water inflows, it is reasonable to expect $R_1$ to vary with stagnation period and after the transport of high salinity water has taken place.

Two cruises, one in February 2002 and the other in January 2003, took place just before the MBI. A negative anomaly (the difference between the

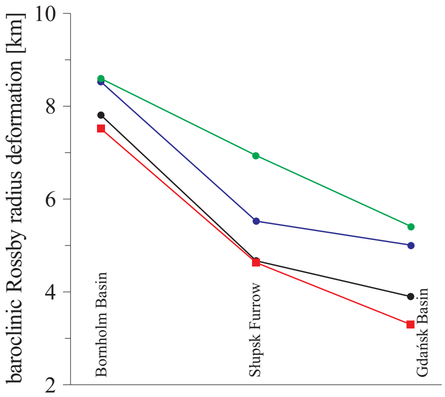


**Figure 6.** Baroclinic Rossby radii of deformation before and after the main saltwater inflow in the investigated areas. Results from cruises in February 2002 (black), January 2003 (red), March 2003 (blue) and April 2003 (green)

measured value of $R_1$ and the annual mean of $R_1$) was found in all the basins investigated. After the main Baltic inflow IOPAN made measurements in March and April 2003, by which time the saline water, originally from the North Sea, had reached all three basins. The SF is a transition zone, and the highest values of $R_1$ were recorded there during the March and April cruises. In spring 2003 $R_1$ reached a higher than normal value in all basins. Figure 6 shows that there is a highly conspicuous shift in $R_1$ values between measurements before and after the MBI.

## 5. Discussion and conclusions

We have used an 11-year CTD data set to show the spatial and temporal variability in the distribution of the Brunt-Väisälä frequency and the first baroclinic Rossby radius of deformation in the southern Baltic Sea. The results reveal a significant spatial variability in both BVF and $R_1$. The values of $R_1$ in each sub-basin are different in the southern Baltic, even though the basins are in close proximity to one another. Moreover, values of $R_1$ in the shallower and sill areas are very low.

The seasonal variability is well pronounced, mainly because of the occurrence of the summer thermohaline. The highest difference between summer and winter $R_1$ is 0.9 km, 0.55 km and 0.59 km in GB, SF and BB respectively.

The interannual and/or interdecadal variability could be much higher than the seasonal one owing to the advection of saline North Sea water. The MBIs dramatically change the vertical structure of BVF and in consequence the value of $R_1$. The scale of interannual variability is more than three times larger than the seasonal one.

The values of $R_1$ given here are higher than those in the previous study by Fennel et al. (1991) by about 1 km in BB. The difference could be due to the natural variability of the system. The data set used by Fennel et al. covered the period 1977–1988. During that time weak and moderate saltwater inflows occurred and there was no strong inflow, whereas the 2003 MBI can be classified as a strong one (Feistel et al. 2003). Moreover, we believe that our approximation is more accurate as a result of our method of data collection. If fewer points are taken into analysis in the vertical, the BVF profile is smoother and the resulting values of $R_1$ are smaller.

Assuming that the eddy-permitting numerical models need 2–3 horizontal nodes per mesoscale structure and eddy-resolving needs 4–5 nodes, we can conclude that eddy-permitting and eddy-resolving models should have respective horizontal resolutions of at least 5 km and 2.5 km for the main basins of the southern Baltic.

Recent climate modelling results suggest that the river runoff into the Baltic Sea may increase in the future and thus possibly drive the Baltic Sea into a new state (Meier 2006). If the mean wind speed and amount of freshwater entering the sea both increase, the inflow of saline water into the Baltic may be reduced (Rodhe & Winsor 2002). If climate change leads to a reduction in main saltwater inflows, bringing about in consequence a lower mean salinity and weaker stratification in the Baltic, we can expect that the value of $R_1$ will decrease. Mesoscale processes would thus be on a smaller scale and the distribution of $R_1$ may then be more similar to the stagnation period distribution discussed in this paper. This change may be more pronounced in GB than in BB. This is contrary to what one can expect in the world ocean, where warming increases the strength of the thermocline and thus increases $R_1$ values (Saenko 2006).

## References

Alenius P. A., Nekrasov A., Myrberg K., 2003, *Variability of the baroclinic Rossby radius in the Gulf of Finland*, Cont. Shelf Res., 23 (6), 563–573.

Chelton D. B., deSzoeke R. A., Schlax M. G., El Naggar K., Siwertz N., 1998, *Geographical variability of the first baroclinic Rossby radius of deformation*, J. Phys. Oceanogr., 28 (3), 433–460.

Elken J., Matthäus W., 2008, *Baltic Sea oceanography*, [in:] *Assessment of climate change for the Baltic Sea basin. Annex A.1.1*, H. von Storch & A. Omstedt (eds.), BALTEX Publ., Springer, Berlin, 474 pp.

Emery W. J., Lee W. G., Magaard L., 1984, *Geographic and seasonal distributions of Brunt-Väisälä frequency and Rossby radii in the North Pacific and North Atlantic*, J. Phys. Oceanogr., 14 (2), 294–317.

Feistel R., Nausch G., Hagen E., 2006, *Unusual inflow activity in 2002–2003 and varying deep-water properties*, Oceanologia, 48 (S), 21–35.

Feistel R., Nausch G., Matthäus W., Hagen E., 2003, *Temporal and spatial evolution of the Baltic deep water renewal in spring 2003*, Oceanologia, 45 (4), 623–642.

Fennel W., Seifert T., Kayser B., 1991, *Rossby radii and phase speeds in the Baltic Sea*, Cont. Shelf Res., 11 (1), 23–36.

Gill A. E., 1982, *Atmosphere-ocean dynamics*, Int. Geophys. Ser. 30, Acad. Press, London, 662 pp.

HELCOM, 2003, *The Baltic marine environment 1999–2002*, Baltic Sea Environ. Proc. 87, 48 pp.

Houry S., Dombrowsky E., De Mey P., Minster J.-F., 1987, *Brunt-Väisälä frequency and Rossby radii in the South Atlantic*, J. Phys. Oceanogr., 17 (10), 1619–1626.

Matthäus W., Franck H., 1992, *Characteristics of major Baltic inflows – a statistical analysis*, Cont. Shelf Res., 12 (12), 1375–1400.

Matthäus W., Lass H. U., 1995, *The recent salt inflow into the Baltic Sea*, J. Phys. Oceanogr., 25 (2), 280–286.

Meier H. E. M., 2006, *Baltic Sea climate in the late twenty-first century: a dynamical downscaling approach using two global models and two emission scenarios*, Clim. Dynam., 27 (1), 39–68, doi: 10.1007/s00382-006-0124-x.

Meier H. E. M., Feistel R., Piechura J., Arneborg L., Burchard H., Fiekas V., Golenko N., Kuzmina N., Mohrholz V., Nohr C., Paka V. T., Sellschopp J., Stips A., Zhurbas V., 2006, *Ventilation of the Baltic Sea deep water: A brief review of present knowledge from observations and models*, Oceanologia, 48 (S), 133–164.

Omstedt A., Elken J., Lehmann A., Piechura J., 2004, *Knowledge of the Baltic Sea physics gained during the BALTEX and related programmes*, Prog. Oceanogr., 63 (1–2), 1–28.

Piechura J., Beszczyńska-Möller A., 2004, *Inflow waters in the deep regions of the southern Baltic Sea – transport and transformations*, Oceanologia, 46 (1), 113–141.

Piechura J., Walczowski W., Beszczyńska-Möller A., 1997, *On the structure and dynamics of the water in the Słupsk Furrow*, Oceanologia, 39 (1), 35–54.

Reissmann J. H., Burchard H., Feistel R., Hagen H., Lass H.U., Mohrholz V., Nausch G., Umlauf L., Wieczorek G., 2009, *Vertical mixing in the Baltic Sea and consequences for eutrophication – a review*, Prog. Oceanogr., 82 (1), 47–80, doi:10.1016/j.pocean.2007.10.004.

Rodhe J., Winsor P., 2002, *On the influence of the freshwater supply on the Baltic Sea mean salinity*, Tellus, 54 A, 175–186.

Saenko O. A., 2006, *Influence of global warming on baroclinic Rossby radius in the ocean: A model intercomparison*, J. Climate, 19 (7), 1354–1360.