Small Publications in Historical Geophysics

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A Secular Change in Storm Activity over the Baltic Sea Detected through Analysis of Sea Level Data

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1. Introduction

Storms and gales over the Baltic Sea normally result in strongly deviating sea levels at the "ends" of the Baltic, particularly in the Belt Sea at the German coast and in the inner parts of the Gulf of Finland and the Gulf of Bothnia. In the middle of the Baltic, close to Stockholm, sea level is normally not affected at all by such events. Thus the extremely long sea level series of Stockholm, commencing in 1774, does not contain very much information about storms.

There is another very long sea level series in the Baltic, that of Swinemünde, commencing in 1811. Swinemünde, nowadays Świnoujście, is situated on the south coast of the Baltic (Figure 1), originally a German station but since the end of the second world war a Polish one, close to the German border. This sea level station is considerably influenced by storms and gales, especially from north-east and south-west. Therefore, this sea level series should contain nearly 200 years of information on storm activity over the Baltic Sea.

However, the sea level variations at Swinemünde form a combination of long-term variations, due to more persistent winds, and short-term variations, due to temporary winds (storms), as explained further in the next section. Hence, in order to extract storm information hidden in the sea level data the long-term variations have to be in some way eliminated. Moreover, we concentrate on the winter season, because the elimination of the long-term variations will work better in winters and also because storms are more frequent during winters (and late autumns).

We will here, first, develop and apply a simple method for eliminating the long-term sea level variations, second, analyse the remaining short-term sea level variations and, third, interpret the results in terms of changing winter storm activity during the last 200 years.

2. Method for extracting the short-term sea level effect

Sea level variations in the Baltic Sea are mainly due to winds. These affect the sea level in two different ways; see Hela (1944) and Samuelsson & Stigebrandt (1996). We illustrate this schematically in Figures 2 and 3.

Figure 2 shows what happens when a persistent wind from south-west or north-east is blowing over the North Sea and the Baltic entrance, say during a month. Sea water is transported into or out of the Baltic, depending on the direction of the wind, thereby raising or lowering the Baltic Sea level as a

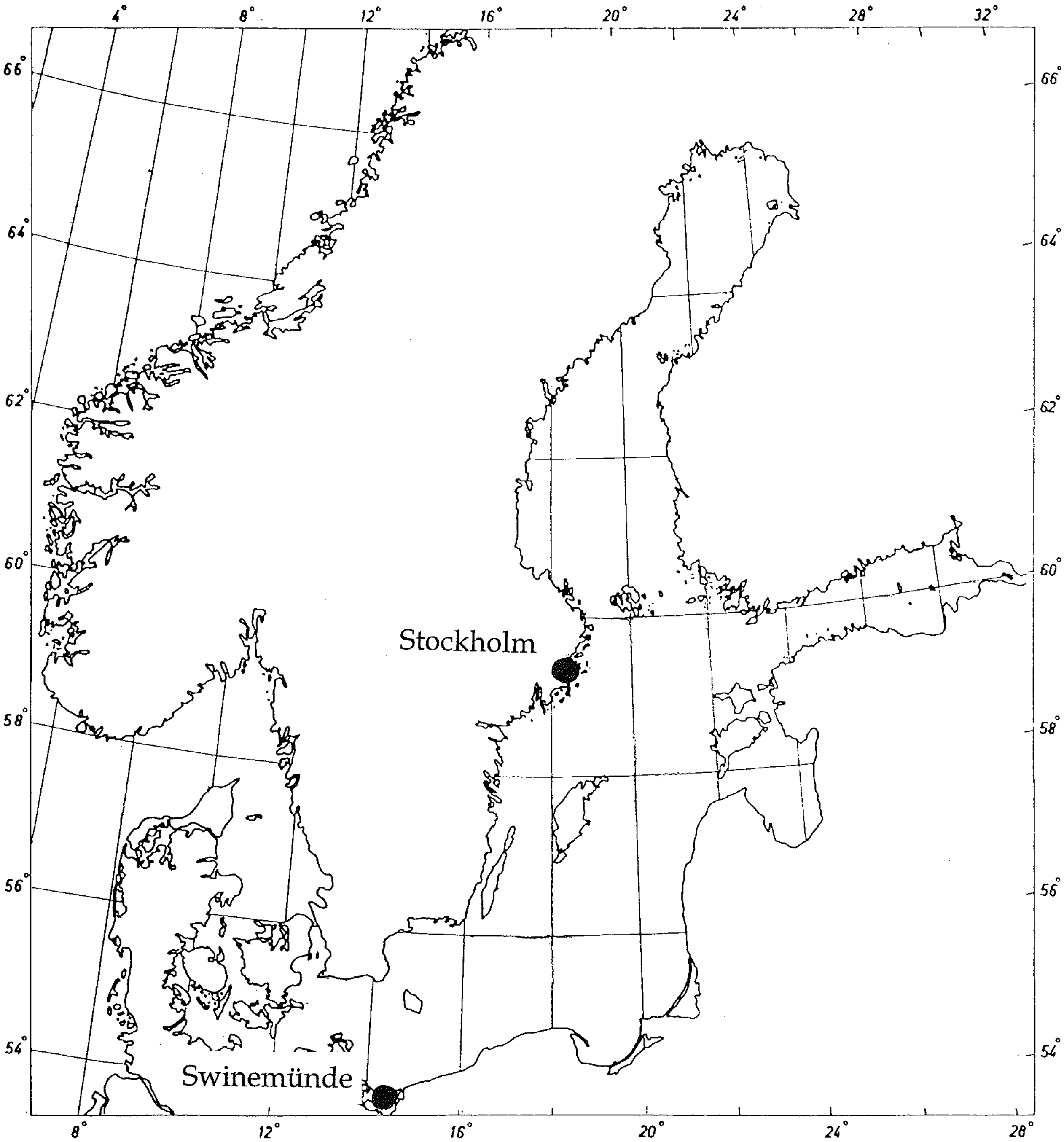

Figure 1. The locations of Swinemünde and Stockholm in the Baltic Sea.

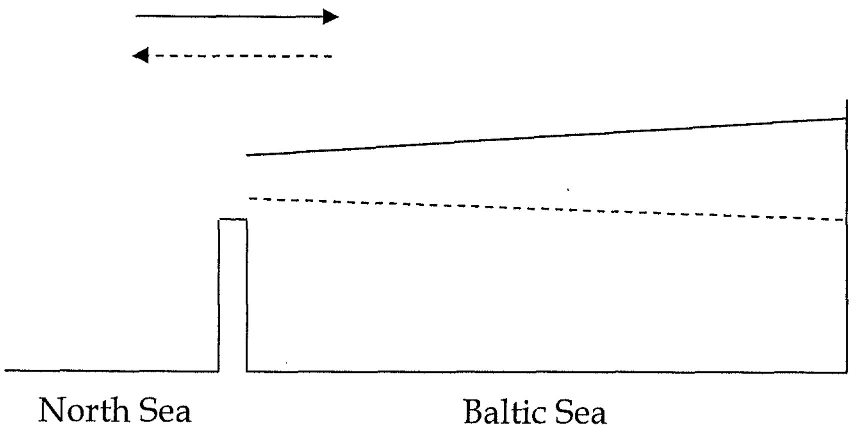

Figure 2. Effect on Baltic Sea level of a persistent wind from south-west (continuous line) or north-east (dashed line).

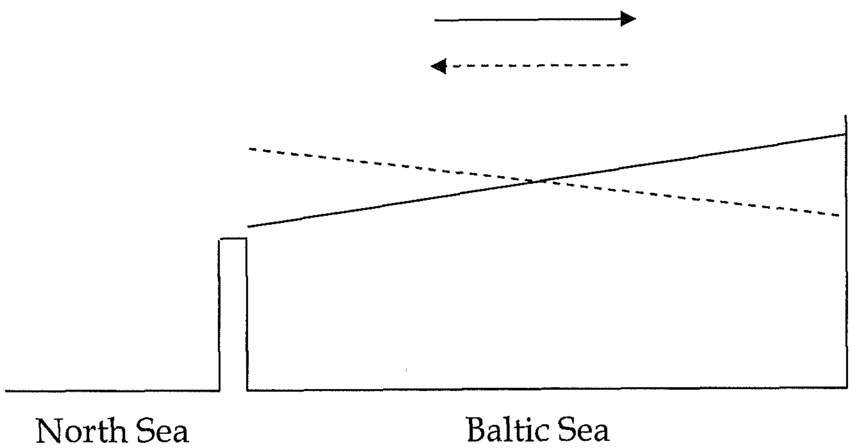

Figure 3. Effect on Baltic Sea level of a temporary wind from south-west (continuous line) or north-east (dashed line).

whole. This effect on the sea level is somewhat larger in the innermost parts of the Baltic and somewhat smaller at the entrance.

Figure 3 shows what happens when a temporary wind from south-west or north-east, say a storm, is blowing over the Baltic Sea. Water is then redistributed within the Baltic Sea, producing high or low sea levels at the ends of the Baltic depending on the direction of the wind. In the middle there is a nodal line with no variations at all.

Now, Swinemünde is located fairly close to the left end in the two figures, thereby being clearly affected by both long-term and short-term sea level variations. Stockholm, on the other hand, is located very close to the middle in the two figures, thereby being affected only by the long-term variations, which are more or less common to the whole Baltic Sea. This opens up a possibility to eliminate the long-term variations from Swinemünde by using those observed at Stockholm.

The quantity we want to study at Swinemünde is the short-term sea level effect in winters. We specify this as the winter mean of the short-term sea level variations. It can be calculated as the difference between winter mean sea level and normal sea level, from which is subtracted the winter mean of the long-term sea level variation:

$$\Delta H_s = H_W - H - \Delta H_l \qquad (1)$$

Here

$$H_W = (H_J + H_F + H_M)/3 - 0.7\cos(115° - 19.34°(T-2000)) \qquad (2)$$

$$H = 681.8 \qquad \text{before 1865} \qquad (3a)$$
$$H = 685.4 + 0.10(T-1900) \qquad \text{after 1865} \qquad (3b)$$

$$\Delta H_l = 0.71\ \Delta H_{St} \qquad (4)$$

(all sea levels being in cm).

We will explain these formulae a little closer. Formula (2), winter mean sea level, is the average of the three monthly mean sea levels for January, February and March, which is then corrected for the small lunar nodal tide of period 18.6 years. This is identical to the formula for winter mean sea level at Stockholm in Ekman (2003), where further explanations can be found.

Formulae (3a) and (3b), normal sea level, are two regression lines, the first one representing a constant sea level, the second one representing the global sea level rise occurring since the late 1800s. The regression lines have been determined from the annual mean sea levels together with information from the apparent land uplift in the Stockholm series; the inflexion point is fixed at the same year (1865) as at Stockholm in Ekman (2003). Formula (4), the winter mean of the long-term sea level variation, is the same quantity as at Stockholm but scaled down by a factor. This factor is determined from the table and map of Ekman (1996); they show that long-term sea level variations at Swinemünde are 0.140/0.196 = 0.71 times those at Stockholm. The factor itself has not changed with time.

3. Application of the method

The sea level data used when applying the formulae above are monthly mean sea levels from Swinemünde and winter mean sea levels from Stockholm. The Swinemünde data are those originally published by Seibt (1890) and Montag (1964), for the German period 1811 - 1944. For the Polish period, starting in 1951, the data are obtained from the Permanent Service for Mean Sea Level (PSMSL). The PSMSL data set for the earlier years is the same as that of Montag, except for an added constant of 689.1 cm. The Stockholm data are those published by Ekman (2003), with the initial year 1774 (also available from the PSMSL).

The common time period for Swinemünde and Stockholm thus starts in 1811. However, most of the Stockholm data for the years 1812 - 1824 have been transformed from København data to fill a gap in the Stockholm series (Ekman, 2003). Because of this we will here restrict ourselves to using data from 1825 onwards.

Putting the above sea level data into formulae (2) - (4), and then inserting these into (1), yields the results presented in Table 1. Here we have listed, for every year, the resultant short-term sea level effect ΔH_s. This short-term sea level effect is also graphically illustrated in Figure 4. Large positive values of ΔH_s mean frequent high sea levels, mostly depending on strong temporary northerly to easterly winds over the Baltic. Large negative values of ΔH_s mean frequent low sea levels, mostly depending on strong temporary southerly to westerly winds over the same area. As can be seen, ΔH_s normally keeps within - 12 and + 12 cm (except for one year with - 16 cm; this is not a data error).

Table 1. Short-term sea level effect (ΔH_s) in winter at Swinemünde 1825 - 1999 (in cm).

1825	0.2	1854	-2.6	1883	-1.1
1826	-4.9	1855	9.8	1884	0.0
1827	2.9	1856	2.0	1885	-6.0
1828	0.7	1857	-5.4	1886	-3.9
1829	4.9	1858	-10.4	1887	-5.9
1830	-2.2	1859	-9.5	1888	6.8
1831	11.1	1860	-4.7	1889	2.0
1832	-9.0	1861	-3.1	1890	-6.6
1833	-1.3	1862	5.8	1891	-1.4
1834	2.4	1863	-12.0	1892	1.0
1835	-10.2	1864	-10.3	1893	-0.3
1836	-16.3	1865	-3.9	1894	-11.1
1837	-6.9	1866	-11.6	1895	5.9
1838	-4.1	1867	2.1	1896	-4.7
1839	-7.3	1868	-0.2	1897	-3.7
1840	-4.6	1869	-3.4	1898	-0.9
1841	4.5	1870	-4.4	1899	1.4
1842	-6.1	1871	-3.3	1900	4.0
1843	4.4	1872	-8.7	1901	-2.8
1844	8.8	1873	-8.3	1902	-2.2
1845	2.8	1874	-6.4	1903	-8.8
1846	11.0	1875	-0.8	1904	-4.3
1847	2.3	1876	3.1	1905	-5.4
1848	-8.7	1877	-1.1	1906	-6.4
1849	1.3	1878	4.8	1907	-5.3
1850	12.0	1879	7.6	1908	-1.8
1851	-2.8	1880	-1.7	1909	-6.5
1852	-1.0	1881	7.5	1910	-8.5
1853	3.0	1882	-2.5	1911	1.2

1912	-4.0	1940	3.1	1973	-3.7
1913	-7.8	1941	4.7	1974	-3.1
1914	-0.1	1942	0.9	1975	0.7
1915	-1.2	1943	-7.1	1976	-1.4
1916	2.2	1944	-8.1	1977	-3.5
1917	2.9			1978	-1.9
1918	-3.4	1951	-4.0	1979	4.4
1919	-3.0	1952	-3.8	1980	-1.1
1920	-6.8	1953	1.6	1981	1.5
1921	-6.8	1954	-5.6	1982	1.0
1922	-2.9	1955	1.1	1983	0.3
1923	1.6	1956	3.9	1984	-6.5
1924	-0.4	1957	-2.9	1985	4.8
1925	-5.1	1958	5.2	1986	-2.8
1926	0.0	1959	-2.5	1987	6.2
1927	-3.2	1960	-0.2	1988	0.3
1928	-10.2	1961	-5.2	1989	-8.0
1929	1.1	1962	2.0	1990	-12.1
1930	-6.2	1963	4.1	1991	-5.0
1931	0.0	1964	4.2	1992	-1.5
1932	0.6	1965	3.3	1993	-3.8
1933	-2.6	1966	2.7	1994	-5.4
1934	-8.4	1967	-2.1	1995	-4.5
1935	-5.3	1968	4.3	1996	0.9
1936	-0.2	1969	0.6	1997	-4.5
1937	-8.8	1970	-1.8	1998	-0.2
1938	-4.4	1971	4.5	1999	1.4
1939	-3.1	1972	-0.2		

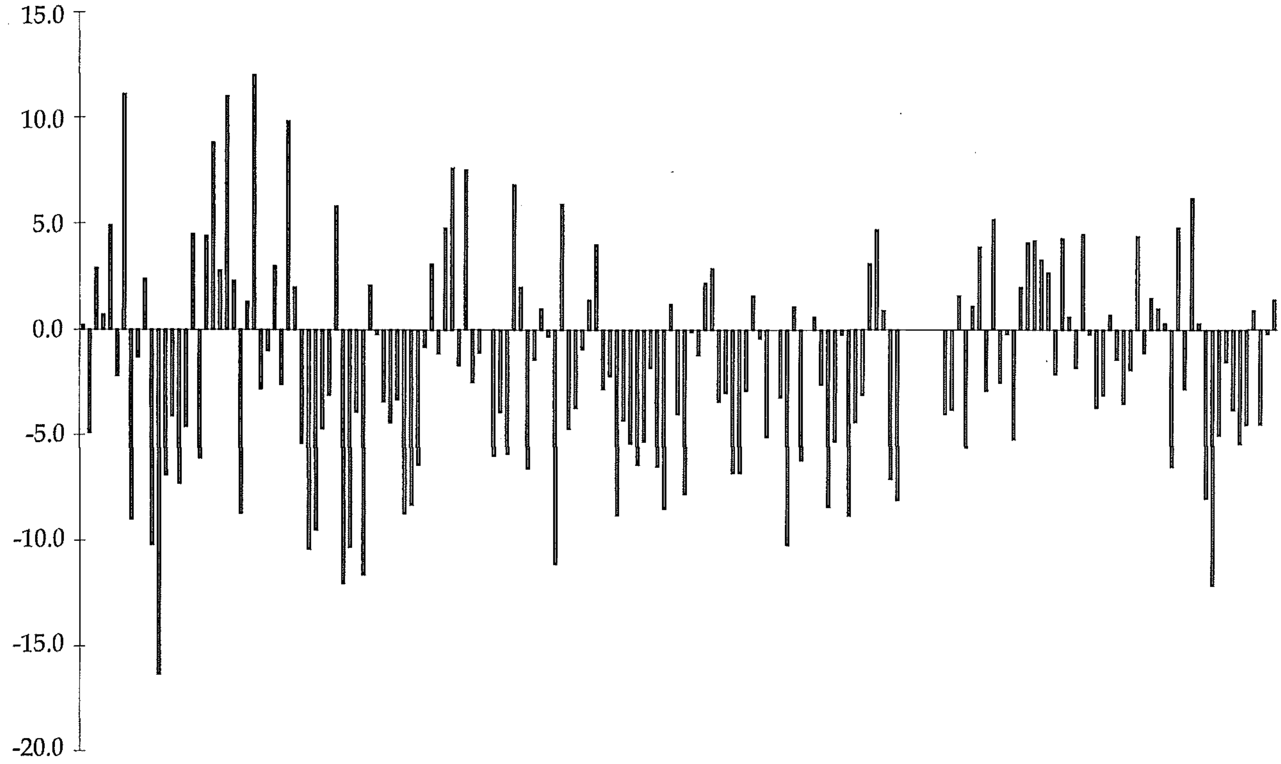

Figure 4. Short-term sea level effect in winter at Swinemünde 1825 - 1999; data according to Table 1.

4. Secular change of the short-term sea level effect

Table 1 as well as Figure 4 reveal a tendency of larger values - both positive and negative - of the short-term sea level effect during the 1800s and smaller values during the 1900s. This calls for a closer investigation to judge whether this tendency is a real (systematic) phenomenon or just an accumulation of random events.

Let us divide the whole time period into two subperiods, one for each century, i.e. one for 1825 - 1899 and one for 1900 - 1999. For each of these subperiods we compute the standard deviation σ of the quantity ΔH_s. The standard deviations, together with the corresponding degrees of freedom f, are given in Table 2. It indicates that the variability of the short-term sea level effect might have decreased. Partial comparisons with the neighbour station Kolberg confirm the findings from Swinemünde.

We now apply an F-test to the standard deviations squared, i.e. we determine the probability level α satisfying the confidence interval

$$F_{1-\alpha/2}(f_x, f_y) < \sigma_x^2 / \sigma_y^2 < F_{\alpha/2}(f_x, f_y) \qquad (5)$$

where x and y denote the two subperiods. The clear result is included to the right in Table 2: The decrease in variability of the short-term sea level effect from the 1800s to the 1900s is highly statistically significant, at the level of 99.9 %. (Omitting the exceptional year mentioned above will not alter this.) It may be remarked here that, although there is some negative correlation between the short-term sea level effect at Swinemünde and the long-term sea level at Stockholm, there is no correlation between the secular changes in these quantities. We conclude that a systematic change in the short-term sea level variations of the Baltic has occurred and, hence, a corresponding change in the short-term wind conditions.

Table 2. Standard deviations of ΔH_s, degrees of freedom, and significance level according to F-test.

1825 - 1899	6.0	74	99.9 %
1900 - 1999	4.0	93	

5. Conclusions on storm activity

The main conclusion from the above analysis in terms of winds is that the storm (and gale) activity during winters over the Baltic Sea has decreased from the 1800s to the 1900s. This decrease is more pronounced in storms from around north-east (positive bars in Figure 3), and less pronounced in storms from around south-west (negative bars in Figure 3).

The analysis performed in this publication is based on measurements of sea level since 1825. Measurements of wind velocities do not exist as far back in time as that. Estimating geostrophic winds from air pressure data at several stations since 1881, Alexandersson et al (1998, 2000) found a slightly decreasing trend in storminess for that period. Using only two stations (Lund and Stockholm) with air pressure data since 1823, which limits wind information to directions from around north-west and south-east, Bärring & von Storch (2004) did not find any trend at all. The present investigation is sensitive to storms from around north-east and south-west, i.e. directions perpendicular to theirs; moreover it is concentrated on the winter season.

References

Alexandersson, H, Schmith, T, Iden, K, Tuomenvirta, H (1998): Long-term variations of the storm climate over NW Europe. The Global Atmosphere and Ocean System, 6, 97-120.

Alexandersson, H, Tuomenvirta, H, Schmith, T, Iden K (2000): Trends of storms in NW Europe derived from an updated pressure data set. Climate Research, 14, 71-73.

Bärring, L, & von Storch, H (2004): Scandinavian storminess since about 1800. Geophysical Research Letters, 31.

Ekman, M (1996): A common pattern for interannual and periodical sea level variations in the Baltic Sea and adjacent waters. Geophysica, 32, 261-272.

Ekman, M (2003): The world's longest sea level series and a winter oscillation index for Northern Europe 1774 - 2000. Small Publications in Historical Geophysics, 12, 31 pp.

Hela, I (1944): Über die Schwankungen des Wasserstandes in der Ostsee mit besonderer Berücksichtigung des Wasseraustausches durch die dänischen Gewässer. Annales Academiæ Scientiarum Fennicæ A, mathematica - physica, 28, 108 pp.

Montag, H (1964): Die Wasserstände an den ehemaligen Pegelstationen des Geodätischen Instituts Potsdam bis 1944. Arbeiten aus dem Geodätischen Institut Potsdam, 5, 53 pp.

Samuelsson, M, & Stigebrandt, A (1996): Main characteristics of the long-term sea level variability in the Baltic Sea. Tellus, 48 A, 672-683.

Seibt, W (1890): Das Mittelwasser der Ostsee bei Swinemünde. Veröffentlichung des Königl. Preussischen Geodätischen Institutes, 38 pp.