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Secular trend analysis of growing degree-days in Croatia

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Abstract—The growing degree-days (GDD) for different temperature thresholds above 5 °C at Croatian stations with long-term time series of meteorological data have been analyzed. The range of the mean annual GDD for the 5 °C threshold is from approximately 2000 °C in the highlands to 4200 °C in the mid-Adriatic. The results of the linear trend and the Mann-Kendall test indicate significant positive trends in annual GDD values at the 0.05 significance level for all thresholds in the northern and mid-Adriatic. A progressive test in the mid-Adriatic shows that the GDD for the 25°C threshold has become significant since the early eighties and in the northern Adriatic since the early nineties. Such increase has a negative effect on plant growth and development on the Adriatic coast and islands.

Key-words: linear trend, climate change, growing degree-days, temperature thresholds, Croatia

1. Introduction

Degree-days, as a measure of accumulated air temperature deviation from the temperature thresholds, have many practical applications in various human-related activities such as home cooling and heating, power generation, and plant growth in agriculture (*Kadıoğlu et al.*, 1999).

Knowing how significantly air temperature affects plants, it is of the utmost importance to adequately define their reciprocal relationship. The simplest way of presenting the influence of air temperature on plants is by accumulating the required active air temperatures (degree-days). The beginning of vegetation depends on winter length and intensity, which is particularly important in the highlands, where the vegetation period is considerably shorter than in the rest of Croatia. Therefore, knowing the mean degree-days, it is possible to establish the temperature conditions in an area during a certain season, which helps the planning of plant cultivation.

The temperature thresholds typical for particular plant species in their different development stages are: absolute minimum, vegetation zero-point, optimal air temperature, and absolute maximum (*Penzar* and *Penzar*, 2000). With a drop in temperature below the vegetation zero-point, plant growth stops. However, if air temperature drops below the absolute minimum, the cold kills the plants. Plant activity is at its best at optimal air temperature. A growth in temperature above the absolute maximum results in the plants being killed by heat. Thus, one of the goals of this paper is to determine the degree-days above the different temperature thresholds, which is important for plant development. Since most recent climate research indicates an increase in growing-season temperatures, the second goal is to establish the existence of significant trends in degree-days for different temperature thresholds in Croatia using long-term time series of daily meteorological data.

2. Material and methods

Degree-days, also referred to as *heat units* or *temperature sums,* have been divided into cooling degree-days, when the temperature threshold is below 0 °C, and heating degree days, when the temperature threshold is equal to or above 0 °C. With most plant species, vegetation starts when enough temperature has been accumulated, i.e., above the 5 °C temperature threshold. Such specific degree-days are called growing degree-days. Therefore, the growing degree-days (GDD) have been analyzed for the 5 °C, 10 °C, 15 °C, 20 °C, and 25 °C temperature thresholds at five meteorological stations: Zagreb-Grič, Osijek, Gospić, Crikvenica, and Hvar, covering the different climatic regions of Croatia (*Fig. 1*).

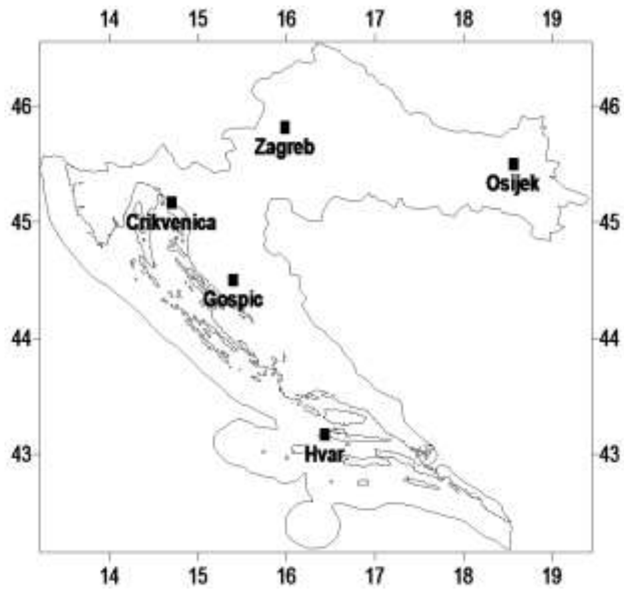

Fig. 1. Geographical position of Croatian stations with long-term time series of meteorological data.

In Croatia there are three types of climate: moderate continental climate in the north-western and eastern part of the country, mountain climate in the highest part of the land, and Mediterranean climate on the Adriatic coast and islands. The northern and eastern parts of the country are the lowest parts of Croatia. It is the Pannonian Plain, which is the main cereal-production region and the most important part of Croatia as regards agriculture. The highest region in Croatia is the Dinaric Alps. This region is characterized by leaf forests and common spruce forests, which are very important for the economy. The Adriatic coast and islands are mostly characterized by viticulture, Mediterranean fruit and olive growing, with little farming and a lot of rocky ground. Pine tree woods and Mediterranean macchia are predominant. In this region, tourism plays the most important role in Croatia.

The Zagreb-Grič and Osijek stations are situated in the region of moderate continental climate: Gospić with mountain, and Crikvenica and Hvar with Mediterranean climate. The data obtained from these stations are the secular series of daily maximum and minimum air temperatures for the period 1901–2000 (except Gospić, which covers 1902–2000). However, only Zagreb-Grič has an uninterrupted series of meteorological data, while Gospić misses 20 years, Hvar 19 years, Osijek six years, and Crikvenica four years.

As the GDD models span from the simple averaging method to complex methods (e.g., *Zalon et al*., 1983; *McMaster and Wilhelm*, 1997; *Cesaraccio et al*., 2001; *Schlenker et al*., 2007), it is necessary to define the most suitable GDD method according to the different daily air temperature cycles of a specific climate region. Croatian research shows that the best methods are the simple averaging method, when daily minimum temperature is greater than the lower temperature threshold and the simple triangulation method, when the daily air temperature cycle is intercepted by the lower threshold (*Salopek*, 2007). In this study, the growing degree-days (GDD) have been defined by the simple averaging method as follows:

$$GDD = \sum_{i=1}^{n} (M_i - T), \qquad M = \frac{t_{\max} + t_{\min}}{2}, \qquad M_i > T, \tag{1}$$

where T is the temperature threshold, $t_{\max}$ is the maximum daily air temperature, $t_{\min}$ is the minimum daily air temperature, n is the number of days in the certain period, and M is the mean temperature.

The growing degree-days have been studied for the whole year as well as for the sub-periods: warm season from April to September and cold season from October to March, from multiannual data series and for the climatic period 1961–1990.

To determine the secular changes in GDD in Croatia, the linear trends of GDD for different temperature thresholds were analyzed. One of the methods for estimating the existence of a trend is the non-parametric Mann-Kendall rank test, based on the values of individual elements of the series and the position of these elements in the series (*Mitchell et al*., 1966). Namely, if a linear trend exists, the values should increase or decrease chronologically. For significant linear trends at the 0.05 significant level a progressive analysis by *Sneyers* (1990) was used to determine the beginning of a linear trend and its significance.

3. *Results and discussion*

It would be normal to expect the GDD values to decrease as the temperature threshold increases (*Table 1*). For the lowest and highest temperature thresholds the GDD values have also been depicted graphically in *Fig. 2*. For the seleted Croatian stations there were three warmer periods: in the late twenties and fifties, and the last one starting in the early nineties of last century. A comparison of the secular series with the 30-year normal shows a positive deviation (higher mean annual values of GDD for the period 1901–2000), except at Hvar, which has a negative deviation up to the 10 °C temperature threshold and a positive deviation above it.

The highest mean values of the GDD for all thresholds are found in Hvar and the lowest in Gospić. A temperature mean above 25 °C is very rare in Gospić. As the Zagreb-Grič and Osijek stations are in the same climatic region, their mean annual and sub-period GDD values are similar. There is a bigger difference between the coastal stations in Crikvenica and Hvar than between the inland stations of Zagreb-Grič and Osijek. The annual and sub-period GDD values vary from year to year, as shown by the relatively high standard deviation values.

So far, research on degree-days in the Croatian highlands and lowlands over a 30-year period (1961–1990) has not indicated a significant trend for any temperature thresholds (*Vučetić* and *Vučetić*, 1994, 1996). However, the most recent results from the highlands (1951–2004) showed a significant increase in the number of degree-days for the 15 °C and 20 °C thresholds, which is a consequence of a significant increase in the maximum air temperature in spring and summer (*Vučetić* and *Vučetić*, 2006).

The linear trend results and the application of this test to the data above the defined temperature thresholds are shown in *Table 2*. Linear trends of the mean annual GDD values at the 0.05 significance level exist for the Zagreb-Grič, Crikvenica, and Hvar stations.While for Hvar they are valid for all thresholds in both seasons, for Crikvenica they apply only to the 5 °C threshold. The growth of GDD values at the Zagreb-Grič station, resulting mainly from a significant increase in minimum air temperature (*Vučetić*, 2003), can not be blamed only on global warming but also on the rapid growth of the city of Zagreb in the last hundred years. Linear trend analysis has not confirmed the existence of a significant trend in the annual and sub-period GDD values for Osijek and Gospić, except in Gospić by T = 10 °C for the cold season. In Gospić, a growth in the maximum and minimum temperatures has been noticed in winter and spring, but significance has been obtained only for the maximum air temperature in spring (*Vučetić* and *Vučetić*, 2006). This leads to the conclusion that an extreme temperature increase is still not sufficient for a significant increase in the annual GDD values.

Table 1. Mean (MEAN), standard deviation (STD), maximum (MAX), and minimum values (MIN) of growing degree-days (GDD) for different temperature thresholds (T) for selected Croatian stations during the year (Y), warm season (W, April–September), and cold season (C, October–March) in the periods 1961–1990 and 1901–2000

GDD (°C)	**T = 5 °C**			**T = 10 °C**			**T= 15 °C**			**T = 20 °C**			**T = 25 °C**	
	Y	**W**	**C**	**Y**	**W**	**C**	**Y**	**W**	**C**	**Y**	**W**	**C**	**Y**	**W**
ZAGREB-GRIČ														
1901–2000														
MEAN	2855.9	2404.9	451.0	1636.5	1512.9	123.6	736.0	720.5	15.5	186.5	186.3	0.1	11.2	11.2
STD	183.7	148.6	89.2	152.2	141.1	43.3	119.3	117.4	12.6	65.8	65.7	0.6	13.8	13.8
MAX	3523.7	2824.4	743.2	2098.1	1915.6	257.4	1044.6	1040.2	66.5	391.9	391.9	4.6	60.1	60.1
MIN	2468.4	2078.9	246.0	1280.8	1217.7	27.1	459.9	459.6	0.0	67.2	67.2	0.0	0.0	0.0
1961–1990														
MEAN	2817.2	2362.0	455.2	1597.5	1468.6	128.9	691.1	675.4	15.7	160.0	159.8	0.1	7.2	7.2
STD	160.7	115.7	89.7	126.5	110.0	44.4	89.9	88.2	13.1	43.0	43.0	0.4	6.6	6.6
MAX	3069.3	2598.0	645.0	1803.5	1688.7	226.5	851.8	837.4	66.5	248.2	248.2	1.5	27.4	27.4
MIN	2468.4	2086.1	332.0	1290.5	1217.7	70.9	459.9	459.6	0.3	67.2	67.2	0.0	0.0	0.0
OSIJEK														
1901–2000														
MEAN	2763.6	2361.7	403.5	1589.7	1476.3	114.7	712.1	695.9	17.2	173.7	173.2	0.3	9.9	9.9
STD	149.9	130.3	80.3	127.2	122.8	42.0	102.0	100.9	15.5	55.0	54.6	1.2	10.0	10.1
MAX	3223.1	2735.0	629.4	1922.7	1829.6	240.8	967.9	967.9	84.2	323.6	323.6	9.0	55.1	55.1
MIN	2415.1	2072.6	224.7	1320.2	1225.7	38.3	488.7	481.7	0.0	74.3	73.8	0.0	0.0	0.0
1961–1990														
MEAN	2739.8	2337.2	402.6	1565.8	1449.3	116.5	684.3	667.4	17.0	154.7	154.5	0.2	6.2	6.2
STD	148.5	117.6	82.9	118.7	111.2	39.6	89.7	88.8	15.7	41.9	42.0	0.6	6.7	6.7
MAX	2974.2	2540.7	562.5	1774.7	1649.9	240.8	845.2	827.8	84.2	239.5	239.5	2.9	26.9	26.9
MIN	2415.1	2072.6	271.4	1320.2	1225.7	61.0	488.7	481.7	1.0	77.4	77.4	0.0	0.0	0.0
GOSPIĆ														
1902–2000														
MEAN	2039.3	1766.2	272.2	985.3	932.6	54.8	298.7	296.8	4.0	25.1	25.1	0.0	0.3	0.3
STD	158.3	137.6	67.0	130.8	124.1	29.8	86.0	85.0	5.2	23.6	23.3	0.2	0.9	0.9
MAX	2511.5	2168.0	469.9	1328.8	1285.0	153.6	522.3	519.8	27.9	112.8	112.8	1.5	6.1	6.1
MIN	1689.9	1479.1	108.8	706.1	685.0	4.2	139.5	139.5	0.0	0.0	0.0	0.0	0.0	0.0
1961–1990														
MEAN	1968.8	1704.8	264.0	925.1	872.5	52.6	255.4	252.5	2.9	16.2	16.2	0.0	0.0	0.0
STD	125.9	107.1	60.7	97.5	92.2	26.0	56.7	56.1	3.4	11.9	11.9	0.0	0.1	0.1
MAX	2160.9	1878.1	409.4	1123.6	1071.0	122.0	373.4	368.9	11.5	45.6	45.6	0.0	0.4	0.4
MIN	1689.9	1479.1	154.3	706.1	685.0	4.2	139.5	139.5	0.0	0.7	0.7	0.0	0.0	0.0
CRIKVENICA														
1901–2000														
MEAN	3446.1	2632.2	814.6	1972.5	1724.5	248.0	940.1	898.0	42.1	282.8	281.6	1.3	25.3	25.3
STD	230.0	174.7	100.0	203.0	172.0	59.1	164.9	154.3	24.2	106.3	105.4	2.5	27.4	27.4
MAX	4057.4	3134.3	1061.5	2558.3	2219.3	397.6	1418.0	1344.4	118.7	617.8	617.8	13.9	130.3	130.3
MIN	3006.3	2275.3	554.9	1516.5	1377.0	107.3	615.0	607.3	0.0	71.6	71.3	0.0	0.0	0.0
1961–1990														
MEAN	3416.9	2599.9	819.5	1941.7	1691.5	250.5	910.8	867.3	43.8	265.4	264.7	1.0	20.4	20.4
STD	134.8	108.4	71.6	126.5	108.3	48.1	104.5	99.0	19.2	63.3	63.4	1.8	12.7	12.7
MAX	3650.2	2786.6	975.0	2199.0	1884.0	318.6	1128.0	1076.4	88.9	401.6	401.6	6.9	53.4	53.4
MIN	3117.9	2405.5	678.5	1684.2	1500.1	121.5	737.2	708.6	0.0	167.3	167.3	0.0	1.2	1.2
HVAR														
1901–2000														
MEAN	4209.1	2942.3	1268.4	2531.4	2030.2	499.7	1277.4	1161.2	117.6	460.2	452.9	9.1	56.3	56.3
STD	170.0	123.1	93.8	151.1	121.4	67.6	127.9	112.4	38.2	96.2	94.6	8.5	32.4	32.4
MAX	4644.2	3264.3	1470.9	2948.2	2349.2	649.6	1602.6	1453.8	199.9	709.6	697.2	47.6	166.1	166.1
MIN	3779.7	2692.6	1055.5	2158.3	1782.8	314.8	999.3	928.0	29.9	152.4	151.8	0.0	4.0	4.0
1961–1990														
MEAN	4225.8	2943.4	1282.4	2536.6	2029.4	507.2	1277.1	1155.1	121.9	459.1	449.8	9.3	53.6	53.6
STD	122.3	103.7	63.7	118.2	103.5	48.2	106.7	94.7	37.5	76.8	74.4	7.2	24.2	24.2
MAX	4406.8	3102.6	1433.8	2719.5	2187.6	602.0	1444.6	1309.2	189.6	600.6	593.0	22.6	106.5	106.5
MIN	3939.8	2709.3	1165.8	2248.8	1794.6	440.9	1016.1	937.7	37.1	300.8	300.4	0.0	11.4	11.4

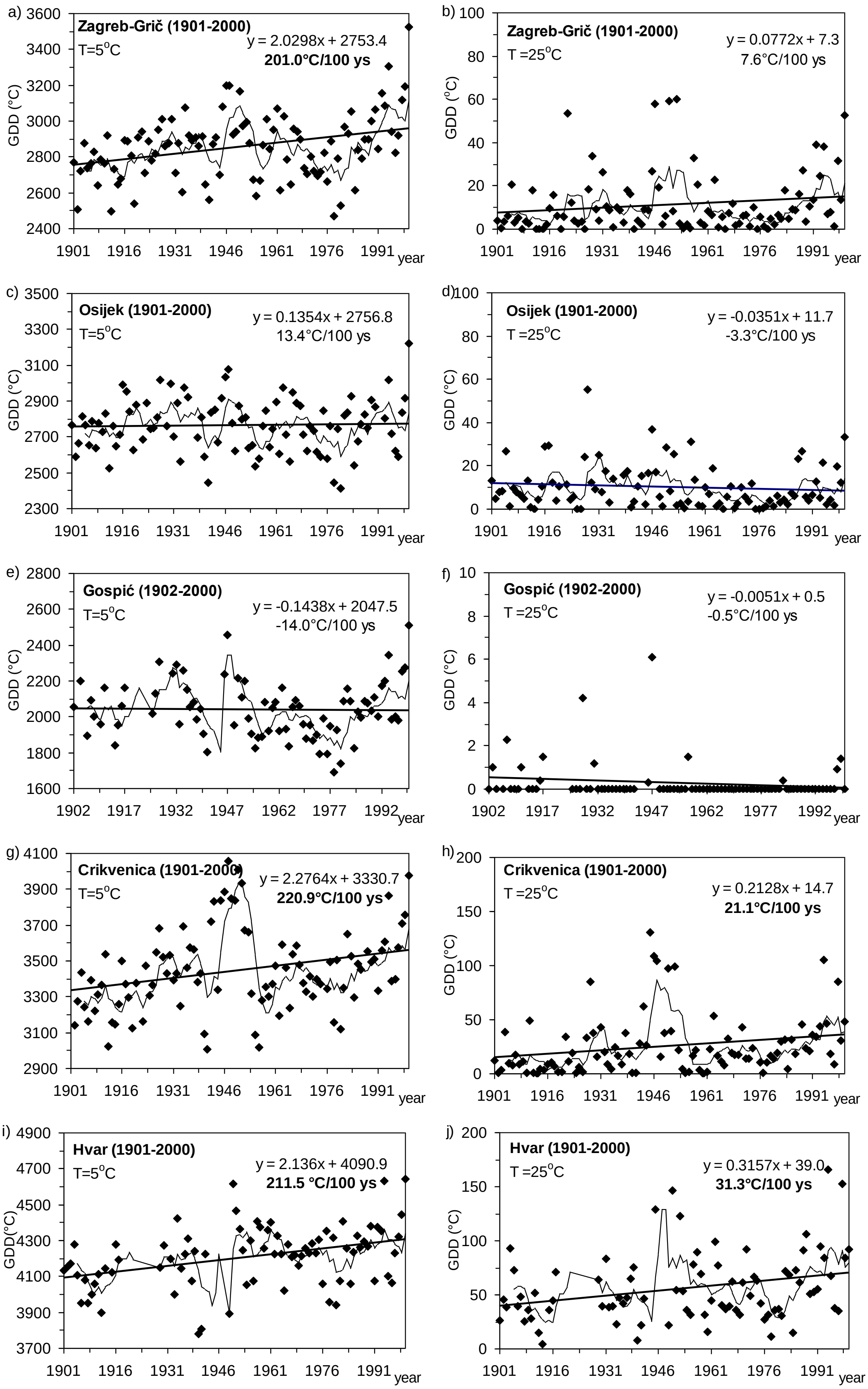

Fig. 2. Time series of the growing degree-days (GDD, diamonds) for the temperature thresholds of 5 °C and 25 °C, curves of the 5-year running average (thin line) and linear trends (thick line) for selected Croatian stations during the period 1901–2000. *x* is the number of years (1, 2, 3…) and the *α* significant level of 0.05 is bold according to the Mann-Kendal test.

Table 2. Linear trend of growing degree-days (°C/100 years) for different temperature threshold (T) for selected Croatian stations during the year (Y), warm season (W, April–September), and cold season (C, October–March) for the period 1901–2000. Linear trends at the 0.05 significant level are bolded according to the Mann-Kendal test

Trend	**T = 5 °C**			**T = 10 °C**			**T= 15 °C**			**T = 20 °C**			**T = 25 °C**	
	Y	**W**	**C**	**Y**	**W**	**C**	**Y**	**W**	**C**	**Y**	**W**	**C**	**Y**	**W**
Zagreb-Grič	**201.0**	**115.6**	**85.4**	**144.0**	105.4	**38.6**	76.7	71.3	**5.5**	35.0	35.0	–	7.6	7.6
Osijek	13.4	3.3	5.3	12.9	-2.4	12.0	-1.4	-9.6	-0.1	-12.7	-12.6	–	-3.3	-3.3
Gospić	-14.0	-25.1	33.4	-28.2	-35.5	**15.2**	-28.3	-33.5	0.7	-2.4	-2.4	–	-0.5	-0.5
Crikvenica	**220.9**	**143.9**	**73.6**	**177.7**	**140.1**	34.2	**142.2**	**127.9**	11.6	**94.0**	**93.8**	–	**21.1**	**21.1**
Hvar	**211.5**	**107.5**	**99.8**	**168.9**	**103.0**	**67.1**	**126.9**	**93.4**	**32.1**	**100.8**	**94.7**	–	**31.3**	**31.3**

A progressive test (*Sneyers*, 1990) of the annual GDD trend in Hvar shows that GDD growth started at the end of the 1940s (*Fig. 3*). It became significant in the early 1960s for the thresholds below 10 °C and in the early 1980s for the higher thresholds, while the significant period in Crikvenica started in the early 1990s. As most plants suffer from heat stress, the positive trend in GDD above 25 °C reveals an increasing negative effect of high temperatures on plants, especially on the Adriatic coast and islands.

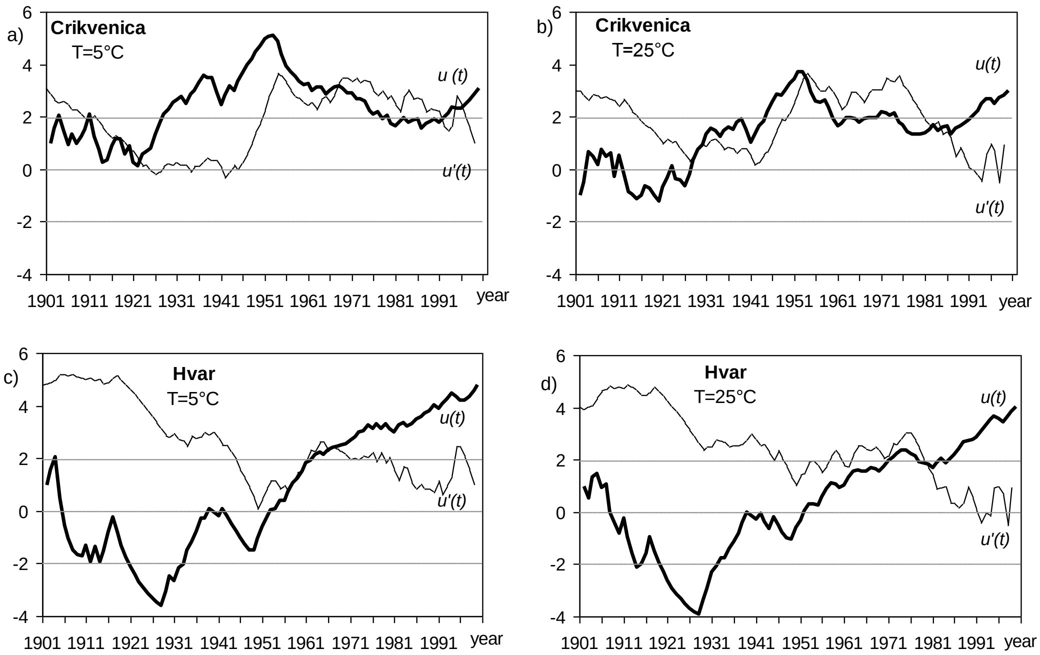

Fig. 3. The progressive trend test in growing degree-days for the temperature thresholds of 5 °C and 25 °C for the forward series *u*(*t*) (thick line) and backward series *u'*(*t*) (thin line) for Crikvenica and Hvar during the period 1901–2000. The positive *u*(*t*) points show an increasing trend, while the negative *u*(*t*) points are at a decreasing trend. In order to identify the beginning of the possible trend, *u*(*t*) has been calculated from the first to the last date, forming a progressive onward test series. The backward test series *u'*(*t*) has been formed in the same manner, calculated from the last to the first term. If there is no trend, the *u*(*t*) and *u'*(*t*) curves overlap several times, whereas in the case of a trend, the intersection point designates the beginning of the trend, becoming significant at the 0.05 level in the case when the absolute *u*(*t*) exceeds the 1.96 value.

4. *Conclusion*

The significant positive trend in the growing degree-days for the 25 °C temperature threshold indicates that the mid-Adriatic coast and islands are subject to the highest vulnerability to climate change in Croatia. In this region, the growth in high temperatures and the risk of summer droughts account for high current vulnerability in agriculture and forestry. This vulnerable region has spread from the middle Adriatic to the northern Adriatic in the warm season, but there is no higher risk towards the inland mountains. If all available potential adaptation measures (particularly irrigation systems) were implemented in this region, the vulnerabilities could be brought to a lower level.

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