Trees and shrubs of Saint-Petersburg in the age of climate change

A remarkable meteorological record dating back to the eighteenth century and uninterrupted phenological record dating back to the nineteenth century have been accumulated in Saint-Petersburg, Russia. GENNADY A. FIRSOV and INNA V. FADEYEVA have studied the effect of climate on the survival of the woody plants that have been grown in St-Petersburg's parks and gardens for the last three centuries.

In Saint-Petersburg the earliest cultivation of trees and shrubs is connected with Peter the Great and goes back to the first years of existence of the new capital of Russia. It is also connected with his personal physician Robert Erskine, a nobleman from Scotland, who signed the edict on establishing the Apothecary Garden on 14 February 1714 (now the Botanic Garden of the Komarov Botanical Institute of the Russian Academy of Sciences, BIN). Using the main literature sources beginning with the first Catalogue of J. Siegesbeck (1736), it seems to be that more than 5,000 woody taxa have been tested here during three centuries. Another important dendrological collection in the city is the Arboretum of the State Forest-Technical University, FTU (established in 1833). More than 2,000 taxa are present in St-Petersburg's parks and gardens today.

The cumulative experience of exotic trees and shrubs in St-Petersburg has shown that the main limiting factor for cultivating them outdoors are low temperatures in the cold period of the year. A high degree of winter hardiness will determine the success of any introduction (Firsov, Fadeyeva, 2009b). The most important elements are the absolute minimum temperature (-36°C was registered on 17 January 1940) and the duration of hard frosts. The sum of positive temperatures during the growing season is also important. The regime of autumnal temperatures is of significance for the preparation of plants for winter. Long winter thaws are unfavourable, especially in the second half of winter when the majority of woody species are in forced rest: new growth may be damaged even by light frosts. So-called critical or abnormally cold winters are of special influence on trees and shrubs and after these, as a rule many species perish or suffer serious frost damage (Firsov, 2012).

Instrumental observations on weather in St-Petersburg were organized from 1 December 1725, almost immediately after the establishment of the Academy of Sciences. Systematic data on air temperature are available from the last months of 1751 (except between 1801 and 1804) – in fact this is the longest sequence of records in Russia, belonging to the Meteorological Station of St-Petersburg.

The eighteenth century was a period of harsh climatic conditions, with

18 very cold winters being recorded (Borisenkov, 1982) with the winters of 1708-09 and 1739-40 being exceptionally cold. New introductions of plants (*Acer tataricum* L., *Caragana arborescens* Lam., *Lonicera tatarica* L.) were therefore severely tested, but at that time there were very few exotic trees and shrubs in the city parks and gardens. The majority of species of Russian woody plants (such as *Actinidia kolomikta* (Maxim.) Maxim., *Acer mandshuricum* Maxim. and *Acer trauvetteri* Medw.) were still not described and unknown in cultivation.

If we analyse the general sequences of mean annual air temperatures in St-Petersburg, it happens to be that the maximum cooling of the climate occurred at the end of the eighteenth century with record low temperatures at nearly all levels. The ten-year periods 1780-1789 and 1781-1790 (mean annual air temperature 2.8°C) were the coldest ones, especially the years 1782 (1.5°C), 1785 (1.8°C) and 1758 (2.0°C), with a very cold winter in 1782-83 (mean January temperature -18.8°C). There was a second powerful peak of cooling at the beginning of the nineteenth century, with two coldest ten-year periods: 1807-1816 and 1808-1817 (2.8°C). The coldest year during the period of instrumental observations was 1809 (1.2°C), with 1810 being nearly as cold (1.3°C).

The first 20 years of the nineteenth century was the coldest period on record, judged by the intensity of cooling. The year 1809 was characterized by an especially cold winter (January: -18.6°C, February -13.9C°, March -10.8°C), and 1810 by an especially cold summer (June: 11.6°C; July: 14.9°C; August: 15.0°C). Throughout this period, the Medicinal Garden (as the Apothecary Garden was known by that time) was falling into decay, being in a very poor situation and state. At the same time, with the development of medicine, the use of medicinal herbs was continually losing its significance and its success was not encouraged by the breath of the 'Little Ice Age'. In 1812 the Botanic Garden of the Academy of Sciences was closed. It had been established in 1735 by Academician J. Amman and existed during 77 years, although always struggling for funds (Firsov, Volchanskaya, 2009). The role of the climate in its demise was significant too: plants were killed by frosts, and suffered from lack of summer heat.

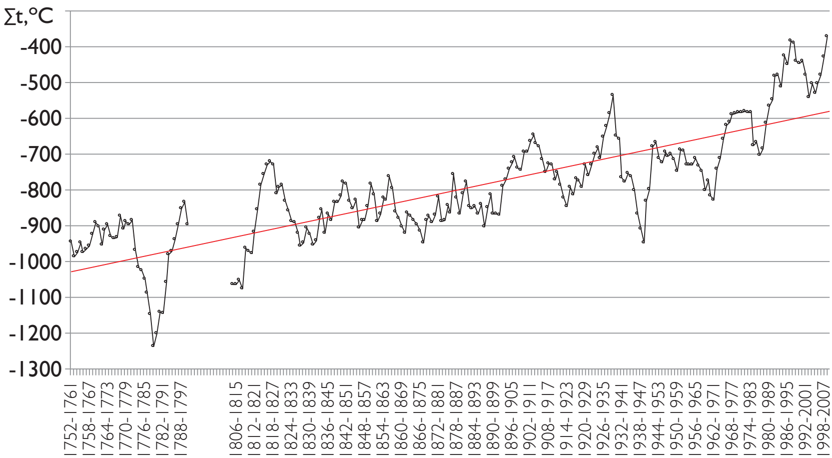
In general, in the eighteenth and first decades of the nineteenth centuries the mean annual temperature oscillated up and down with high amplitude. Then the amplitude diminished, and during the next several decades the annual mean temperature was more or less steady. In the middle and end of the nineteenth century, moderately cold winters with not so hard but steady frosts dominated, rising gradually and a steady increase in temperature began in the last quarter of the nineteenth century: from 3.7°C between 1876 and 1885 to 4.3°C from 1897 to 1906.

In the 1920s the character of winters changed again, becoming warmer, with frequent and prolonged thaws, late freezing over of the rivers and unstable ice cover. Starting with the decade 1923-1932 there was clear increase of temperature from 4.4°C to a maximum figure of 5.4°C in 1930 - 1939. This coincided with the global warming of the climate in the Northern Hemisphere (Shver et al., 1982), the famous warming of the Arctic, which began at the end of the nineteenth century and reached its maximum in the late 1930s, including with other areas the territory of St-Petersburg as well. From 1940, however, the climate of North-Western Russia and other high latitude areas of the Northern Hemisphere started to cool, with this phase of cooling being as strongly marked as the previous period of warming had been (Ugryumov, Kharkova, 2008). In the ten-year period 1931 to 1940 the mean annual temperature in St-Petersburg lowered to 5.1°C (0.3°C compared with the maximum), and in the next ten years 1932-1941 to 4.9°C. The lowest point 4.0°C was reached in the period 1939 - 1948. Until the abnormally cold winter 1986 - 87 the average year temperature on sliding decades oscillated between the limits 4.4°C (1962 - 1971) – 5.0°C (1966 - 1975). Since the end of 1980s the temperature curve began to climb up again, beating its own record: from 5.4°C (1981 - 1990) to 5.6°C (1985 - 1994) surpassing the record of the 1930s. In 1986 - 1995 it reached the level 5.9°C. And finally, in three recent ten year periods the mean annual temperature reached and exceeded the level of 6°C; from 1997 to 2006: 6.0°C; and from 1998 to 2007: 6.1C°; and in the ten-year period from 1999 to 2008 the record mean annual temperature for the whole period of observations was reached: 6.3°C.

In 2009 - 2011 the warming of the climate in St-Petersburg has continued. While previously it was principally dependant on the cold part of a year, there is now a tendency for the summer seasons to be warmer as well, which has been especially clear bearing in mind the abnormally hot summer of 2010. The hot weather that year lasted a very long time, from 6 July (30.1°C) until 14 August (31.5°C). And the absolute maximum for the whole period of observations was registered on 7 August 2010: 37.1°C; this high temperature exceeds by 3.5°C the former record in 1972. The average temperature of July 2010 (24.4°C) was the record since 1752. In the near future we have to pay special attention to the heat tolerance and drought resistance of woody plants. As for year temperatures, these were 6.2°C in 2009, 5.9°C in 2010 and 6.8°C in 2011.

In the mid twentieth century the period after the warming of the 1930s was named by climatologists "the period of modern climate", with an average annual temperature in St-Petersburg of 4.3°C (Pokrovskaya, Bychkova, 1967; Borisenkov, 1982; Shver et al., 1982). Since that time the climatic norm has changed, the average year temperature having risen to 5.8°C in the period 1980 - 2009. Such warming may be regarded as very considerable. Research by the authors shows that the raising of the annual mean temperature by 1°C in St-Petersburg causes an increase of the growing season by 11.7 ± 0.97 days (Fadeyeva, Firsov, 2010). Within the last 30-year period (1980 - 2009) the warmer winters began in 1988 - 89, from when we have observed the intensive warming of the climate in St-Petersburg. The year 1989 was the warmest

Graph 1
Sum of winter temperatures in St-Petersburg, sliding ten-year average data (1752-2008).

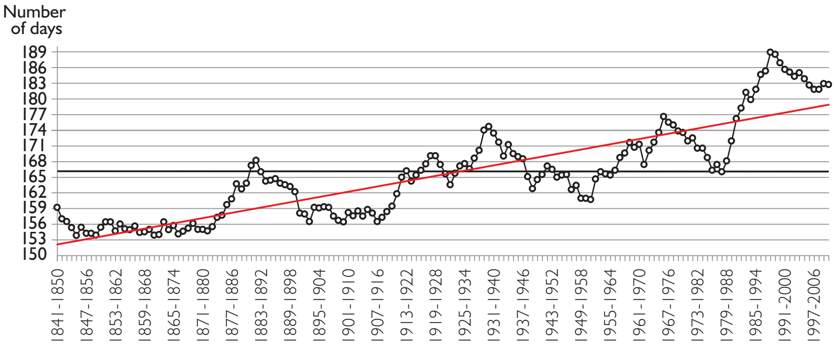


in history (7.6°C). The conclusion of an investigation by V. N. Komarova and G. A. Firsov (1995), who studied the meteorological and phenological anomalies of 1989 and 1990, was confirmed: events, which in the twentieth century were anomalies, had become the norm in the climate current in the twenty-first century. The year 2008 was nearly as warm as 1989: 7.3°C. The three last winters of the analysis period (2006-2009) were also warm, the winter of 2007-08 (the sum of temperatures -72°C) being the record for the whole period of observations. According to some prognoses, in the second half of the twenty-first century the mean annual temperature in St-Petersburg may surpass 7-8°C and in some years 10°C (Golitsin et al., 2004).

If we consider the temperature curve at St-Petersburg separately for warm and cold parts of the year, we can see that in the warm part of the year this curve also oscillates up and down with a general tendency to warming. Periods of summer cooling, the majority of which took place in the 1830s, are not so clearly developed as periods of warming. The winter temperature curve in general repeats that for the annual average (see Graph 1 above). Oscillations and the amplitude of the average annual temperature are mainly influenced by winter temperature. It is proved that the principal cause of the considerable increase in annual mean temperature over the long period is from the rise in winter temperature (Golitsin et al., 2004; Fadeyeva, Firsov, 2010).

Cyclicity is a very important feature of long meteorological and phenological series of observations – all of which are of oscillating character (see Graph 1 and 2, above and opposite). The tendency to the warming of the climate does not exclude the phenomenon of cyclicity, the alternation of so-called early-

Graph 2
Number of days between the beginning of flowering of grey alder (*Alnus incana* (L.) Moench) and complete change of colour of leaves of *Betula pendula* Roth at Arboretum FTA (Saint-Petersburg), sliding ten-year average data (1841-2009).



warm and late-cold cycles. It does not exclude the probability of recurrence of unfavourable bioclimatic situations (Fadeyeva, Firsov, Buligin, 2009). Certain warm-loving species of trees and shrubs were previously able to exist outdoors only in the interval between two late-cold cycles. (*Acer palmatum* Thunb., *Actinidia chinensis* Planch., *Persica vulgaris* Mill.) But with the warming of the climate the meteorological and phenological characteristics of the cycles have been changing. Both early-warm and late cold cycles become warmer, with earlier dates of seasonal phenomena.

In Graph 2, the changing of vegetative season at St-Petersburg is demonstrated (observations at Arboretum FTU), being calculated by sliding ten-year periods over the series 1841 - 2009. This is in fact the phenointerval between the beginning of flowering of male catkins of *Alnus incana* (L.) Moench until the full change of colour of the leaves of *Betula pendula* Roth. One can see maximum peaks and several minima, the last of them being in 1978 - 1987 (166 days), and the two coldest winters of the end of the twentieth century (1978 - 79 and 1986 - 87) took place at this minimum. One can see the tendency to the extension of the growing season: from 154-159 days at the beginning to 181-189 days in recent decades. If at the beginning there were several periods with minimum duration of vegetative season – 154 days (1845 - 1854, 1847 - 1857, 1848 - 1857, 1849-1858, 1858 - 1867, and 1861 - 1870), at the end of this series this figure was not dipping below 180 days (1984 - 1993), and in the decades 1988-1997 and 1989-1998 it reached the maximum of 189 days. The peak of temperature increase in the 1930s is clearly developed, with its 175 days of growing season in the decade of 1930 - 1939.

The warming of the climate has been confirmed by the fact that while in the second half of the twentieth century abnormally cold winters occurred on average once per eight to 13 years, but since the last such winter (1986 - 87) they have been absent (Firsov, Fadeyeva, 2009b).

St-Petersburg before (1970 - 1994) fell within the parameters of the United States Department of Agriculture's hardiness zone 5 (winter temperatures of -28.8°C to -23.4°C (Firsov, 2003), in the climate of the early twentieth-first century it may be placed into the warmer zone 6, with mean minimum of -21.9°C for 2001 - 2009.

The spring and summer sub-seasons and phenostages of local Calendar of Nature are beginning to occur at earlier dates. While in the period 1951 to 1980 the winter was the longest season of a year (occupying 35% or 126 days), now the winter period has shortened on average to 28% of the calendar year. But the duration of other seasons has extended, especially of spring and summer (Firsov, Fadeyeva, Volchanskaya, 2010).

A set of species (*Acer triflorum* Kom., *Ampelopsis aconitifolia* Bunge, *Calycanthus floridus* L.) which were considered to be not promising by arboriculturists of the eighteenth and nineteenth centuries, are now of interest for re-introduction. Many of them are successfully cultivated, winter hardy, with quite a few producing self-sown seedlings (which were not observed earlier). The re-introduction of more than 300 of the most interesting species is possible, including those (*Robinia viscosa* Vent., *Sciadopitys verticillata* Seibold et Zucc., *Viburnum orientale* Pall.), which were considered not winter hardy in the past (Wolf, 1917). There is also considerable potential for primary introduction. No doubt, the warming of the climate will have really tremendous consequences for the cultivation of trees and shrubs in St-Petersburg as well as in other parts of the globe (Grimshaw, Bayton, 2009) as has already been seen, with the cultivation of many more species than was possible before (Firsov, Fadeyeva, Volchanskaya, 2010).

In the first half of the twentieth century it was considered that the hardiest woody plants in St-Petersburg came from four geographic regions: Europe, Siberia, the Far East and the forest zone of North America (Gursky, 1957). Of Chinese species, only a few happened to be hardy. And from America, the only survivors were those whose habitats in the wild extend to the northern and colder areas. For species from the west of North America, only a few proved to be hardy, and only those which in the native range extends to Alaska and British Columbia. There were no hardy species from Kashmir (India), Australia, New Zealand, Africa and South America. A small numbers of species from the southern hemisphere were tested by Egbert Wolf (1917). Usually in Wolf's experiments such species were dead after the first winter. But now the situation has changed. Evergreen barberry (*Berberis buxifolia* Poir.) from South America and certain conifers from New Zealand such as *Podocarpus nivalis* Hook. have appeared for the first time and have survived several winters – earlier they were considered as indoor plants only.

At the end of the twentieth and beginning of the twenty-first century in St-Petersburg the number of trees and shrubs reaching the reproductive stage has been considerably enlarged, such as *Pterocarya pterocarpa* (Michx.) Kunth. ex I. Iljinsk. and *Abies semenovii* B. Fedtsch. (both since 2000). This gives the possibility to grow more species from locally produced seeds.

An interesting feature are 'epiphytes' (as in the tropics and subtropics) – self-sown specimens of trees and shrubs established on older trees (like a fruiting specimen of *Deutzia parviflora* Bunge in the fork of an old tree of *Malus sylvestris* Mill. at Arboreum BIN), which now occur more often than earlier, sometimes several metres above the soil surface (in former colder times they usually were killed by frosts and were short lived).

The observation of winter hardiness and peculiarities of seasonal dynamics of development, of flowering and fruiting during the last 25 years (1985 - 2009) has shown that three main groups may be identified: 1) steady under any changes of bioclimatic situation, not only after normal but also after cold and warm winters (though there are very few species that never suffer from frost damage) – such as *Picea glehnii* (Fr. Schmidt) Mast.; 2) sensitive to cold winters, which are considerably damaged after periodically repeated cold and very cold winters, but are quite hardy in normal (average) winters (*Taxus baccata* L.); 3) having a strong reaction to the warming of the climate (*Prinsepia sinensis* (Oliv.) Bean. And in recent years there are more and more species which react to warm winters (*Salix schwerinii* E. Wolf).

From one point of view, in warm winters with light frosts, especially often repeated in recent years, many species survive without damage at all. Nevertheless, *Acer japonicum* Thunb. in Arboretum BIN was damaged to ground level in the warm winter of 2006 to 2007 (though later recovered). Some other species (for example, *Cotoneaster alaunicus* Golits.) have also suffered serious damage, especially among Far Eastern species, although in their natural habitats they can successfully survive very low temperatures (below -30°C). Large branches died on *Betula schmidtii* Regel (though some slight damage to shoot tips is usually observed after normal and cold winters). Apparently, the duration of deep rest is important in this case. *Betula schmidtii* has a very short period of rest, and becomes sensitive when it comes into growth. The winter of 2006 - 07 was the shortest on record (from 20 January until 2 March), only 41 days. In contrast the autumn of 2006 lasted nearly five months. December 2006 was the warmest on record (+0.8°C). Abnormally warm weather in December and the first half of January resulted in the early development and flowering of many trees and shrubs (*Daphne mezereum* L., *Hypericum patulum* Thunb., *Lonicera praeflorens* Batal.), which was later interrupted by frosts to -22°C (Firsov, Fadeyeva, Volchanskaya, 2008).

Another new problem is perishing of some plants such as *Chamaecytisus* *ruthenicus* (Fisch. ex Woloszcz.) Klaskova, *Crataegus maximowiczii* C. K. Schneid., *Genista tinctoria* L., which is apparently connected with their being too wet in winter and rotting near the base. Certain specimens of *Parthenocissus tricuspidata* (Siebold et Zucc.) Planch., *Rhododendron schlippenbachii* Maxim. died after the winter of 2006 - 2007; *Quercus dentata* Thunb., after the winter of 2007 - 2008 and *Oplopanax elatus* (Nakai) Nakai, after the winter of 2008 - 2009. In 2010 several old specimens of rhododendrons rotted and died in Arboretum BIN and had to be replaced by other younger plants in the displays.

The considerable increase of precipitation in St-Petersburg in recent years and decades may provoke this situation. So, while in the period 1907 - 1931 (Egbert Wolf's period of activity) the average annual precipitation was 554mm, in the period from 1955 - 1984 it reached 615mm, and during the last quarter of a century (1985 - 2009) it climbed up to 652mm. The increase in precipitation continues, in the twenty-first century (2001 - 2009) it reached 682mm. The figure of 842mm for the year 2003 is the record for the whole period of observations since 1740. The year 2009 (801mm) is similar, surpassing all other years in the previous centuries. The enlarged amount of precipitation causes ground water to rise, which is not good for woody plants. This is especially true for Arboretum BIN, which is situated on an island at the mouth of the Neva River at only 2 to 3m above sea level. Additionally, in recent years several cases of snow break were observed due to the plentiful snowfalls and sticking of the wet and heavy snow to branches of trees and shrubs, which resulted in the breakage of many good specimens.

Summer heat, as demonstrated by the abnormally hot summer experienced in 2010, has increased throughout most of the European part of Russia, and in future heat hardiness may become a very important factor in St-Petersburg, and outside of the city area as well as the tolerance of fires.

There is a probability of mass and intensive reproduction of pests with the warming of the climate. Recently Dutch elm disease began to increase significantly throughout city parks and gardens; this may in fact be the real ecological catastrophe of the end of the twentieth century / beginning of the twenty-first century. The agent of distribution for Dutch elm disease, *Scolitus multistratus* Marsch, was first recorded in 1998 (Dorofeeva, 2008). In consequence several dozen elms of certain species (*Ulmus glabra* Huds., *U. laevis* Pall., *U. americana* L., *U. minor* Mill.) of different ages had to be felled in recent years at Arboretum BIN.

As a result of changing climate, the promising assortment for city planting should be considerably re-examined (Firsov, Fadeyeva, 2009a). On further warming the assortment may be enlarged due to new species which become less prone to frost damage (e.g., *Ptelea trifoliata* L.). On the other hand, many woody plants, which in the twentieth century survived even cold winters may possibly not be hardy under new climatic conditions (e.g., *Prinsepia sinensis* (Oliv.) Bean). From the point of view of ex-situ conservation constant and uninterrupted monitoring is urgently needed. Considering the continuous warming of the climate, new methods of agrotechnics and cultivation should be developed.

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