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Solar activities and climate change during the last millennium recorded in Korean chronicles

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ABSTRACT

Korean chronicles have a large amount of observational records of natural phenomena, including astronomical and meteorological events over two thousand years. Here we examine the correlation of solar activity and climate change from historical sunspot and frost records in the Korean chronicles. There are 42 sunspot records in Goryeo Dynasty (918–1392 CE) and 13 records in Joseon Dynasty (1392–1910 CE). The sunspot records in Goryeo Dynasty show a periodicity in good agreement with the well-known solar activity of 11 years. Korean sunspot records suggest that the solar activity in Joseon Dynasty decreased compared with that in the previous ~500 years. In order to examine the long-period variation of solar activity, we include Chinese historical sunspot records in our analysis to supplement the lack of Korean records, and find a new ~240-yr long-period solar activity from the power spectral analysis. Korean chronicles also have about 700 frost records during the last millennium. We investigate these frost records and find a sign of cooling down that can be interpreted as climate change during the last millennium. We also find ~240-yr cooling period from the historical frost records, which is well in accord with that of solar activity. Therefore, we conclude that the solar activity has decreased during the last one thousand years and also has a long-term variation of ~240 years.

1. Introduction

Korea has a long history of astronomical and meteorological observations over two thousand years. These observations were recorded in chronicles such as Samguksagi (三國史記), Goryeosa (高麗史) and Joseonwangjosillok (朝鮮王朝實錄, hereafter, Sillok), and so forth. Each of these chronicles has systematic and consistent records of dynasties that were maintained for ~500 to 1000 years. The Korean chronicles contain about 25,000 various astronomical observations, such as solar and lunar eclipses, sunspots, meteors and meteor showers, meteorites, comets, movement of planets, aurorae, and so forth (Park, 2008). Most Korean historical records are concluded to be actual observations through the astrophysical analysis. Typical verified phenomena include solar eclipse, sunspot, aurora, meteor and meteor shower, nova, and comet (Park and Na, 1994; Yang et al., 1998; Lee et al., 2004; Yang et al., 2005a; Yang et al., 2005b; Lee et al., 2009).

Since the instrument-based astronomical observation began only several centuries ago, the historical observations of astronomical phenomena are important materials for modern astronomical research. For example, the analysis of sunspot records reveals the long-term variations in solar activity. Though the sunspot is not easily visible, there are 42 clear sunspot records in Goryeosa, starting with 1151 CE (Kim et al., 1451). The sunspots were mainly recorded in Goryeosa and Sillok, spanning around one thousand years. Yang et al. (1998) and Lee at al. (2004) found that historical sunspot and aurora records in chronicles are real phenomena and show the well-known 11 year periodicity of solar activity.

It has been well known that the solar activity is a major factor of global climate change, since the solar radiation has a great influence on the earth temperature. Gray et al. (2010) summarized the current understanding in solar variance, solar-terrestrial interactions, and the mechanisms determining the response of the Earth's climate system. Recently Thiéblemont et al. (2015) compared two multi-decadal ocean-atmosphere chemistry-climate simulations with and without solar forcing variability and showed that the 11-year solar cycle synchronizes quasi-decadal NAO (North Atlantic Oscillation) variability intrinsic to the simulation. Korean chronicles fortunately have valuable sunspot records for the past millennium while the observation of sunspots in the

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West did not begin in earnest until the 17C. However, the Korean sunspot records are not enough in number to investigate the long term variation of solar activity. Korean chronicles also contain various and considerable amount of meteorological observations over two thousand years. These records, along with the sunspot records, are valuable data for understanding the climate change in the historical period.

Over the past few decades, many people have been interested in climate change (van Loon et al., 2004; Shibata and Kodera, 2005; Harrison and Usoskin, 2010). The causes of the climate change include solar radiation, volcanic activity, topography, earth's orbital variation, CO_2 and so forth. In particular, the variation of solar activity and the volcanic eruptions are known to be the major causes of the climate change over the historical time scale of the last few thousand years (Crowley, 2000).

There have been studies on the climate change over historical time scales. Dansgaard et al. (1969) studied the climate change during the past few thousand years using the Greenland Ice-core data. Zhu (1973) investigated the climate change during the past two thousand years based on the meteorological records in Chinese history and found that the estimated climate change is in good agreement with the Greenland ice-core result from Dansgaard et al. (1969), which means that the historical meteorological records can reflect the global climate change.

So far, there have been very few studies on climate change conducted with medieval literature records. The reason is that not only the systematic and continuous observation records are rare, but also it is hard to confirm whether these records are reliable or not. Korea and China have a lot of historical records with high reliability. The phenological and historical data from these countries are valuable sources for reconstructing the climate change during the period before the instrument-based observational records became available (Liu et al., 2011).

In this paper, we study the long-term variation of solar activity and the global climate change during the past one thousand years by using the Korean astronomical and meteorological records. For this purpose, we use the sunspot records in Korean chronicles as a proxy of solar activity and analyze the relationship between the historical sunspot and frost records. Since the Chinese sunspot records are more sensitive to the long-term variation of solar activity, we combine Korean and Chinese sunspot records in our analysis. The temporal variation of frost-free period can also provide the information on climate change. Thus, by comparing the temporal variations of sunspot and frost records, we examine the relationship between the climate change and the solar activity during the last millennium.

This paper is organized as follows. In Sec. II, we summarize Korean and Chinese sunspot records and Korean frost records, and describe how the sunspot records are analyzed using the Fourier spectral analysis method. We present our results in Sec. III, together with discussion. The summary and conclusions follow in Sec. IV.

2. Data and methods

2.1. Historical Korean and Chinese sunspots

Korean and Chinese chronicles have sunspot records over a long period of time. The earliest one was recorded in 28BCE during the Han Dynasty of China. Korea also has a few early observations that seem to indicate sunspots in Samguksagi, which covers the Three Kingdoms period (57BCE ~ 935 CE). On the other hand, the observation of sunspots in the West started in earnest from 1611, except for only two observations of sunspots in Russia during the 14C (Park, 2008).

In Goryeo Dynasty (918–1392 CE) there are 42 clear records of sunspot, starting from 1151. The first record says “There is a black spot on the Sun and it is the size of an egg” (Kim et al., 1451). In Korean chronicles, the size of sunspots was described as that of a plum, egg, peach or pear in an effort to make a system of consistent measurements. For the same period, China changed dynasties several times and there are 66 sunspot records in total (Beijing observatory, 1988).

Joseon Dynasty (1392–1910 CE) was in succession to the former Goryeo Dynasty. Both Dynasties lasted about 500 years. Although Goryeo was replaced by Joseon Dynasty, the astronomical government office and astronomers succeeded in the work of the previous dynasty and continued to observe astronomical phenomena. Therefore, Korean historical observations were recorded in chronicles in systematic and successive ways. Hence, it can be argued that Korean historical

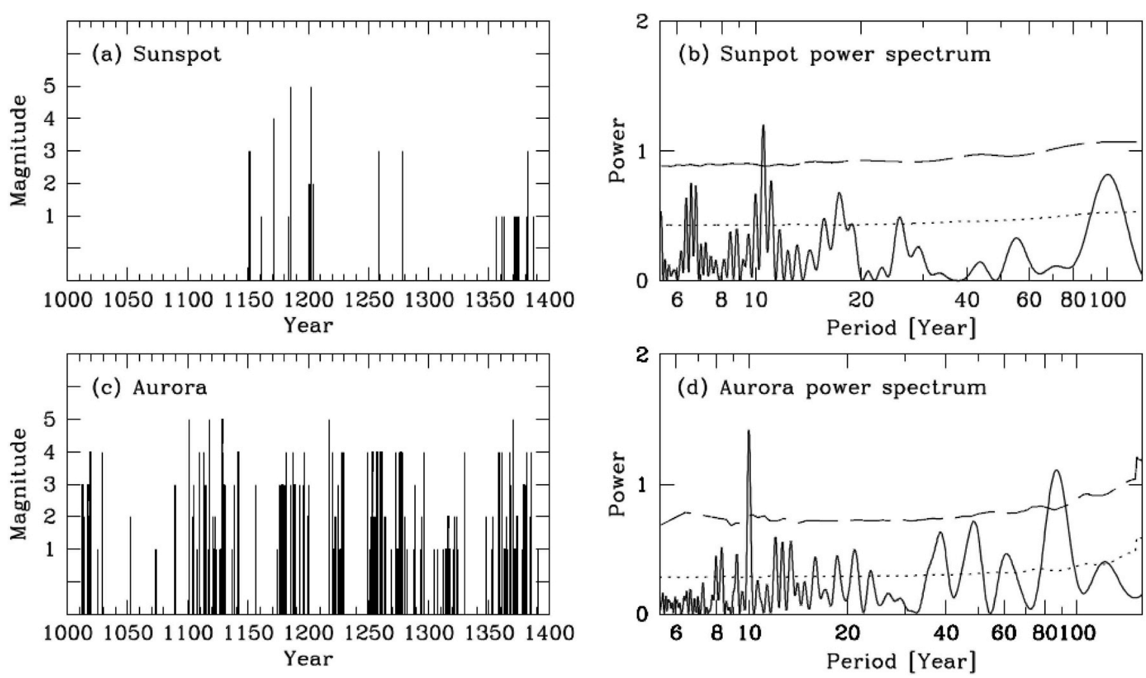

Fig. 1. Temporal distributions (a, c) and power spectra (b, d) of the sunspots and aurorae in Goryeo Dynasty (918–1392). The magnitude of sunspot and aurora is classified into five classes according to its size and intensity. The dotted and dashed lines in panels (b) and (d) indicate the confidence levels of upper 0.14 and 0.30% estimated from the Monte-Carlo analysis. In the power spectra, the normalization is arbitrary.

Table 1
Sunspot records in Goryeo and Joseon Dynasties (1151–1743).

Date of observation[a]	mag.[b]	Date of observation	mag.	Date of observation	mag.	Date of observation	mag.
1151 03 21	3	1201 04 06	2	1362 10 05	1	1402 11 15	1
1151 03 31	3	1202 08 23	5	1371 01 02	1	1520 03 09	2
1151 04 01	3	1204 02 03	2	1371 11 21	1	1556 04 17	3
1160 09 29	1	1204 02 04	2	1372 05 08	1	1603 04 16	2
1171 10 20	4	1204 02 05	2	1373 04 26	1	1604 10 24	3
1171 11 16	4	1258 09 15	3	1373 04 27	1	1604 10 25	3
1183 12 04	1	1258 09 16	5	1373 10 23	1	1608 05 10	5
1183 12 05	1	1278 08 31	3	1375 03 20	1	1608 05 17	5
1185 02 11	5	1356 04 04	1	1375 03 21	1	1648 01 16	1
1185 03 27	5	1356 04 05	1	1381 03 23	1	1720 06 01	1
1185 04 18	1	1361 03 16	1	1382 03 09	3	1743 10 19	1
1185 04 19	1	1361 03 17	1	1382 03 10	3	1743 10 20	1
1185 11 14	1	1361 03 18	1	1382 03 11	3	1743 10 21	1
1200 09 19	2	1361 03 19	1	1387 04 15	1		

[a] Based on Julian calendar for dates prior to Oct. 4, 1582, and on Gregorian calendar after Oct. 15, 1582. The same rule applies to all the tables below.
[b] The magnitude is classified into 5 classes according to the size of the sunspot. The size of sunspot described as black spot, plum, egg, peach, or pear is given a magnitude 1, 2, 3, 4, or 5, respectively.

observations are generally more reliable than those of other countries.

Yang et al. (1998) and Lee et al. (2004) analyzed the sunspot and aurora records of Goryeo Dynasty (918–1392 CE) using the Fourier spectral analysis and found the 11-yr period of solar cycle. Fig. 1 shows the temporal distributions of sunspot and aurora records (a, c) in Goryeosa, the representative history book of Goryeo Dynasty, and power spectra measured from these records (b, d). Note that Fig. 1 has been reproduced from Yang et al. (1998). It is notable that the power spectra of both sunspot and aurora records clearly show the well-known 11-yr period of solar cycle. The dotted and dashed lines in Fig. 1(b)and (d) indicate the confidence levels of upper 0.14 and 0.30% estimated from the similar analysis of random catalogs generated by Monte-Carlo method. As shown in the temporal distributions, all the sunspots and aurorae in Goryeosa were classified into five classes according to size and intensity (Yang et al., 1998). The sunspot records used in the analysis are summarized in Table 1. However, the aurora records that were classified with size and intensity are not presented in Yang et al. (1998). Instead, the aurora records categorized into seven levels of color are given in Table 2 of Lee et al. (2004).

Readers may find that there is discrepancy between the duration of dynasties and the period covered by the sunspot records. Goryeosa and Sillok are representative chronicles that describe the history of the Goryeo Dynasty (918–1392 CE) and Joseon Dynasty (1392–1910 CE). The astronomical records contained in these chronicles are distributed over the entire period of Goryeo and Joseon, although they are distributed heterogeneously. Based on this fact, we may consider that observations of sunspots were carried out throughout the dynasties. The absence of sunspot records in early Goryeo and late Joseon may be due to real observation or missing historical data. However, we emphasize that the actual sunspot records in Goryeo and Joseon Dynasties are distributed from 1151 to 1743 CE.

Although the Korean sunspot records clearly show the well-known 11-yr periodic signal in the power spectrum, they are not enough in number to investigate the long-term variation of solar activity. In this study, we supplement the lack of Korean records by adding Chinese historical sunspot records to the Korean records.

We collected the records of sunspots in Chinese chronicles between 918 and 1910 CE, which correspond to the Korean Goryeo and Joseon Dynasties. These records are from the 'General compilation of Chinese Ancient Astronomical records' (Beijing observatory, 1988), and there are 134 sunspot records in total during this period, actually spanning over 927–1905 CE. These Chinese sunspot records are listed in Table 2. There are some records with no month or day information, which are noted as '- -' in Table 2. The size of Chinese sunspots is also expressed in various ways. Thus, we classify the sizes of sunspots into five classes as in Korean sunspots, considering their relative size.

The Chinese sunspot records are generally more than Korean records. Although the distribution of Chinese sunspots shows a behavior similar to that of Korea from early 10C to early 16C, the number of sunspot records became too large after 16C and does not match with the solar activity minimum. This is probably due to the fact that the sunspot records were duplicated in many different Chinese chronicles. The Chinese historical sunspots are advantageous in finding long-period signals because of a lot of records over a long period of time, but they do not contain the reliable short-period information, not showing the 11-year periodicity of solar activity. Therefore, in this study, we use the Chinese sunspot records for the purpose of finding the long periodicity of the solar activity. On the other hand, Korean records are used to identify the relative changes in the number of sunspot records since it was confirmed in Fig. 1 that Korean records are very useful as the indicator of solar activity.

2.2. Historical Korean frosts

Combined with the astronomical observation records, the historical meteorological records can provide useful information for understanding the climate change. Korean chronicles contain diverse and numerous meteorological observations such as drought, earthquake, frost, flood, rain, hail, snow, etc. over two thousand years. In order to examine historical temperature variations, we use the frost records that are closely related to temperature changes.

The Korean chronicles, Samguksagi, Goryeosa, and Sillok contain 38, 48, and 667 frost records, respectively. Most historical frost records have their observation date, so we can determine length of frost-free period by year. The length of frost-free period can be used to estimate the mean temperature for that year. Therefore, we examined the first (in autumn) and last frost (in spring) records of each year from Korean chronicles. Because there may be missing records in the frost records, we should look at the overall trends in the long-term data.

In the analysis of frost records, the observation site is an important factor because temperature varies with latitude. The capital of Goryeo is located at higher latitude (N37.9° E126.6°) than that (N37.6° E126.9°) of Joseon. Thus, the frost records of the two Dynasties should be examined separately. The first and last dates of frost records in Goryeosa and Sillok are listed in Table 3. The frost records of the Joseon Dynasty collected at various regions are also listed in Table 4. In this study, however, frost records during the Three Kingdoms period are excluded because they are small in number and thus are not suitable for investigation on the climate change.

Table 2
Chinses historical sunspot records from 927 to 1905.

Date of observation[a]	mag.[b]	Date of observation	mag.	Date of observation	mag.	Date of observation	mag.	Date of observation	mag.
927 03 09	4	1185 02 15	1	1372 08 25	1	1624 03 17	3	1851 – –	1
947 11 26	4	1185 02 27	1	1373 11 15	1	1624 04 15	1	1852 01 19	1
974 03 03	1	1186 05 23	2	1374 03 14	1	1624 – –	1	1852 03 22	3
1077 03 07	4	1186 05 26	1	1374 03 27	1	1631 02 25	1	1852 04 02	1
1078 03 11	4	1193 12 03	1	1374 03 31	1	1635 02 17	1	1853 05 11	1
1079 01 11	4	1200 09 21	2	1375 03 23	1	1637 – –	1	1853 05 17	1
1079 03 20	4	1200 12 –	2	1375 10 21	1	1638 09 08	1	1853 06 07	1
1104 – –	2	1201 01 09	1	1376 01 19	1	1638 12 09	1	1855 01 20	1
1105 12 06	1	1202 12 19	2	1381 03 22	1	1638 – –	1	1855 – –	1
1112 05 02	2	1204 02 21	2	1381 03 25	1	1640 04 13	1	1856 02 08	1
1118 12 17	4	1205 05 04	2	1382 03 21	1	1643 02 19	1	1856 08 30	1
1120 06 07	2	1238 12 05	1	1383 01 10	1	1655 04 30	1	1860 12 04	2
1122 01 10	4	1276 02 17	5	1562 – –	1	1656 – –	1	1861 03 30	2
1129 03 22	1	1368 01 20	1	1564 08 07	1	1659 06 12	1	1861 11 24	1
1131 03 12	4	1370 01 01	1	1566 01 30	5	1661 07 05	1	1863 03 19	1
1136 11 23	4	1369 12 30	1	1567 – –	1	1665 02 15	1	1865 07 18	1
1137 03 01	4	1370 04 25	1	1597 06 15	1	1665 02 20	2	1873 02 23	1
1137 05 08	1	1370 10 02	1	1604 03 01	1	1703 08 13	1	1874 12 09	1
1138 03 16	1	1370 10 21	1	1613 03 30	1	1709 – –	1	1874 – –	1
1138 03 17	2	1370 12 07	1	1616 10 10	1	1732 05 11	2	1883 12 26	1
1138 11 26	1	1371 01 14	1	1617 01 11	1	1742 07 05	1	1885 07 05	1
1139 03 03	1	1371 03 31	1	1617 – –	1	1757 06 16	1	1900 02 15	1
1139 11 20	1	1371 06 13	1	1618 05 22	5	1795 – –	1	1904 02 16	1
1145 – –	1	1371 11 06	1	1618 04 25	1	1799 04 05	1	1905 02 04	5
1145 – –	1	1372 02 06	1	1618 06 20	1	1829 04 24	1	1905 10 31	1
1160 09 26	5	1372 04 03	1	1621 05 23	1	1848 05 03	1	1905 – –	1
1185 02 10	2	1372 06 19	1	1622 05 03	5	1851 12 25	1		

[a] Records with no month or day information are noted by "–".
[b] The magnitude of Chinese sunspots are also classified into five classes according to their relative size as in Korean records.

2.3. Data analysis

All historical Korean observations were recorded in luni-solar calendar. We have converted these dates into solar calendar dates by using Korean Chronological Tables (Ahn et al., 1999, 2000a; 2000b; Han, 2001). For the luni-solar conversions, we use Julian calendar for dates prior to Oct. 4, 1582, and use Gregorian calendar after Oct. 15, 1582. In this study, we use the records from Goryeo and Joseon Dynasties. Since these records have the specific year, month, date information, the date conversion is straightforward. However, many records during the Three Kingdoms period have only the year-month information and are small in number, so we exclude them in our analysis. The same conversion is made for the Chinese historical sunspot records. For the Chinese sunspot records that have only the year information, we simply set the date as January 1. Setting the date in this way does not affect our result for the long-term variation of solar activity.

The number density of historical records is not uniform due to political or environmental influences. Besides, some astronomical phenomena might be missed due to the weather condition. Therefore, it is

Table 3
The first and last frost records in Goryeo and Joseon Dynasties.

Date of observation[a]						
Goryeo Dynasty (918–1392)		Joseon Dynasty (1392–1910)				
1012 05 01	1280 05 12	1394 05 01	1423 09 15	1545 09 25	1645 05 16	1707 06 24
1013 05 27	1285 05 07	1396 09 08	1424 02 07	1547 05 08	1645 09 19	1716 05 07
1027 06 20	1286 05 02	1397 04 24	1428 09 18	1550 04 28	1648 05 09	1719 10 12
1031 05 04	1287 06 04	1397 09 14	1430 04 21	1552 09 30	1648 10 07	1723 09 24
1036 05 11	1289 04 23	1398 06 01	1433 09 27	1559 08 29	1650 05 03	1727 05 07
1042 05 05	1294 05 14	1400 04 30	1436 05 16	1562 05 07	1653 10 04	1736 05 10
1045 04 09	1295 04 26	1401 04 21	1441 04 30	1564 10 02	1660 05 14	1743 10 02
1048 06 10	1296 04 23	1401 09 28	1495 03 26	1595 05 24	1661 05 16	1747 05 08
1089 05 13	1297 05 10	1402 03 13	1503 09 17	1596 10 16	1663 05 20	1747 10 10
1096 04 28	1321 05 07	1405 05 16	1504 04 18	1599 10 05	1665 05 07	1754 05 13
1134 05 14	1366 09 22	1406 04 22	1516 10 03	1600 05 26	1667 05 11	1754 10 10
1139 05 17	1368 09 06	1407 06 27	1517 05 12	1601 05 11	1669 07 10	1756 10 14
1143 04 27	1373 05 30	1408 06 16	1519 04 10	1604 05 21	1671 10 01	1757 10 07
1162 05 05	1379 09 17	1409 09 06	1520 05 07	1609 10 07	1673 10 03	1758 05 11
1167 05 10	1380 08 26	1411 12 06	1520 10 03	1614 10 06	1675 05 14	1761 05 12
1179 05 12	1385 08 20	1414 04 26	1521 04 26	1617 09 22	1677 05 08	1765 10 16
1234 10 17	1386 05 09	1415 07 21	1523 04 29	1628 09 17	1686 05 12	1767 10 10
1251 04 20	1387 05 03	1415 09 28	1524 09 25	1631 06 13	1687 05 22	1781 10 16
1258 08 15	1389 05 02	1417 05 24	1527 05 28	1632 04 30	1695 05 25	1850 10 21
1272 05 09	1390 05 12	1417 10 01	1534 09 30	1636 05 24	1700 05 13	1876 09 29
1273 04 24	1392 07 31	1418 05 07	1539 05 06	1641 06 27	1700 10 03	
1276 04 21		1419 05 09	1542 05 06	1641 09 21	1701 05 17	

[a] It is the last frost before July 30 of each year and the first frost after August 1.

Table 4
The first and last frost records observed in four provinces of Joseon Dynasty.

Date of observation[a]						
in four provinces[b] of Joseon Dynasty (1392–1910)						
Pyeongan	1686 05 25	1526 09 07	1676 09 29	1524 09 25	1697 09 02	1628 10 07
1407 05 08	1692 07 02	1527 05 05	1683 07 06	1531 05 13	1701 05 29	1631 07 29
1413 09 10	1695 07 21	1531 06 05	1694 09 14	1547 06 01	1710 05 28	1633 10 09
1423 10 03	1695 09 06	1547 06 01	1695 06 13	1554 05 25	1713 06 06	1634 11 20
1424 09 12	1697 09 02	1548 05 19	1697 09 02	1559 04 06	1723 05 01	1641 06 19
1516 09 19	1700 05 15	1566 06 07	1700 05 29	1562 05 05	1733 09 14	1647 06 19
1517 04 20	1701 06 18	1580 06 17	1701 06 07	1600 06 15	1734 06 18	1652 06 04
1519 09 19	1702 07 13	1595 06 15	1702 09 24	1628 10 12		1656 06 07
1527 04 27	1702 10 15	1602 07 31	1706 05 23	1640 09 29	Gyeongsang	1660 05 19
1531 05 13	1703 09 21	1603 06 15	1708 04 12	1641 06 20	1402 10 20	1669 06 05
1535 09 04	1710 06 05	1604 06 07	1710 05 20	1642 07 13	1403 07 23	1682 06 13
1566 04 24	1712 05 17	1628 10 10	1713 06 24	1644 06 13	1403 08 21	1690 05 02
1606 10 24	1713 06 05	1631 06 22	1714 10 03	1645 05 31	1406 05 04	1692 05 14
1628 09 30	1716 05 27	1633 10 09	1716 06 24	1645 09 24	1414 06 16	1697 09 02
1629 05 26	1734 05 13	1635 10 08	1717 07 06	1647 07 02	1416 05 12	1704 04 08
1640 09 26	1764 05 07	1641 07 20	1718 06 05	1655 06 09	1417 09 05	1722 06 14
1641 06 18		1642 05 21	1725 07 09	1657 06 04	1433 05 07	1723 05 01
1641 09 23	Gangwon	1646 05 28	1727 05 21	1658 05 20	1447 05 06	1729 05 20
1646 06 21	1401 07 11	1646 10 26	1734 05 13	1662 06 06	1491 06 25	1732 06 20
1646 10 01	1409 05 27	1647 07 03	1737 07 01	1664 10 13	1495 04 15	1734 05 13
1651 06 17	1423 05 27	1648 05 16		1668 06 13	1524 04 21	1742 06 27
1664 05 16	1423 09 11	1653 07 08	Chungcheong	1672 05 21	1529 09 26	1749 05 21
1664 11 09	1424 09 13	1662 07 19	1402 01 23	1676 09 29	1547 06 01	1754 05 02
1667 05 18	1425 01 28	1664 05 09	1406 05 08	1677 06 24	1553 04 25	1791 10 13
1670 06 06	1515 06 21	1665 06 14	1406 09 24	1681 09 20	1555 04 14	
1671 04 25	1520 05 07	1667 06 12	1416 05 28	1694 09 14	1564 05 03	
1675 05 25	1524 09 18	1670 09 13	1430 05 16	1695 06 04	1589 06 10	
1676 09 29	1525 06 05	1672 05 30	1520 06 05	1695 09 06	1627 06 06	

[a] It is the last frost before July 30 of each year and the first frost after August 1.
[b] The location of the 4 provinces: Pyeongan (N38.5° E 125.5°), Gangwon (N37.8° E128.2°), Chungcheong (N37.3° E127.3°), and Gyeongsang (N35.9° E128.6°).

generally necessary to correct the effect of the non-uniformity of observations on the data analysis of astronomical records. However, in this work, we do not consider such bias in our Fourier spectral analysis of the sunspot records because the 11-year periodicity appears in the power spectrum of sunspot records of Goryeo Dynasty without the bias correction. Moreover, the purpose of this study is to identify the long-term changes in solar activity, so the effect of the non-uniform number density of historical records is not important.

We regard the temporal distribution of sunspot records as the point process, and express the number density field of the records $\delta(t)$ as the sum of one-dimensional delta functions. For N data points located at t_i's ($i = 1, \cdots, N$) during the time span of T, the density field can be decomposed into waves in the Fourier space as

$$\delta(t) = \frac{T}{\sum w_j} \sum_j w_j \delta^{(1)}(t - t_j) = \sum_{k'} \delta_{k'} e^{-ik't}, \tag{1}$$

where w_j is the weight for the jth data point and δ_k is the Fourier transform of the number density field and can be expressed as

$$\delta_k = \frac{1}{\sum w_j} \sum_{j \in T} w_j e^{ikt_j}. \tag{2}$$

The wavenumber k is related to the period by $\lambda = 2\pi/k$. The power spectrum of the temporal distribution of the discrete points is given by the variance of the Fourier mode,

$$P(k) = <|\delta_k|^2>. \tag{3}$$

For more detailed description, see Yang et al. (1998). In this study, we do not correct for the contribution due to the Poisson noise arising from the discrete data points because we are interested in finding the periodic signals, not in the actual normalization of the power spectrum.

In order to examine the long-term variations of solar activity in detail, we add the Chinese sunspot records (134 data points) to the Korean records (55 data points) and analyze the combined records. In the power spectrum estimation, each data point is weighted by the size of sunspot, and the ratio of number density of Chinese records relative to that of Korean records is multiplied to the weights of Korean data points in order to equalize the number density of both data sets.

To estimate the statistical significance of the periodic signals in the measured power spectrum, we generate 10,000 catalogs that include the random data points with the same number of data points (N = 189) as in the Korean-Chinese sunspot records within the same time span (918–1910 CE) and analyze them in the same way as the observation records are analyzed. The level of statistical significance at each wavenumber k is determined from 10,000 measured powers of the random catalogs. This Monte Carlo test enables us to assess the reliability of the historical records.

3. Results and discussions

3.1. Historical sunspot records and solar activity

Sillok, which covers the Joseon Dynasty, has ~20,000 astronomical observations. Although Sillok has much more records than Goryeosa with ~5000 records, it has only 13 clear records of sunspot (Chunchugwan, 1391–1863). As is well known, there were solar minimums of Spörer, Maunder, and Dalton, and they caused the Little Ice Age (LIA) from the 16C–19C (Michael, 2003). Those are the reason for the lack of sunspot records during the Joseon Dynasty. The temporal distribution of sunspot records shows that the solar activity in the 16th-17th centuries was lower than those in the previous two long cycles, which strongly suggests that the overall solar activity has declined for about 600 years (see the histogram of Korean sunspot records in Fig. 6).

Fig. 2 shows the power spectrum measured from the Korean-Chinese combined sunspot records. The dotted and dashed curves denote 3 and 4 sigma confidence limits, respectively, estimated from the Monte-Carlo test. A few significant periodicities are seen in the power spectrum of Korean and Chinese historical sunspots. In Fig. 2, the most notable signal corresponds to the peak around 240-yr periodicity of solar

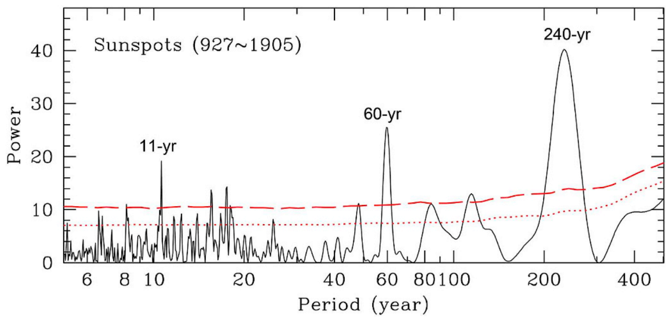

Fig. 2. Power spectrum of Korean and Chinese sunspot records in the last millennium. The three most powerful signals correspond to the periods of 240, 60, and 11 years. The 3 sigma and 4 sigma levels of statistical significance estimated from the Monte Carlo analysis are shown as dotted and dashed curves, respectively.

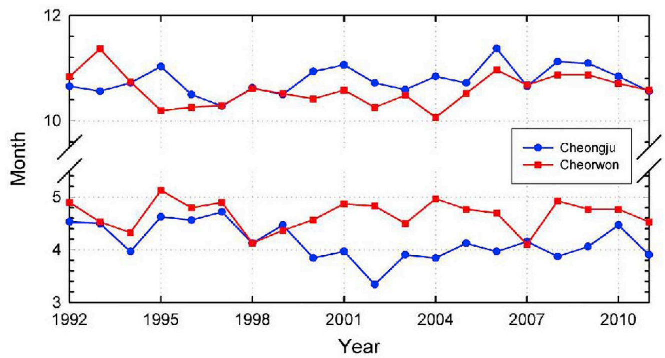

Fig. 3. Distribution of the first and last frost records of Cheorwon (N38.2° E127.3°) and Cheongju (N36.7° E127.5°) over the last 20 years. The interval between two frost records indicates temperature. Cheorwon (red squares), located at higher latitude than Cheongju, has shorter frost-free intervals.

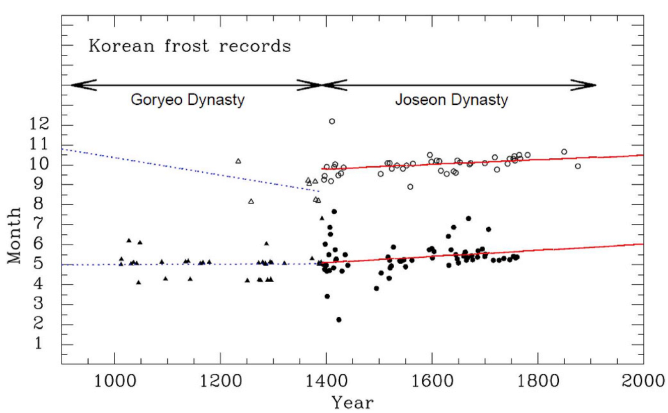

Fig. 4. Temporal distribution of the first and last frost records of Goryeosa and Sillok (918–1392 CE). Triangles and circles denote the records of Goryeo Dynasty (observed at Gaeseong) and Joseon Dynasty (at Seoul), respectively. Filled symbols represent the last frost records in spring season while open symbols the first records in autumn.

activity, while 60-yr and 11-yr periodicities of solar activity are the second and third distinct peaks.

Meanwhile, Vaquero et al. (2002) reported a notable 250-yr solar cycle using the spectral analysis of naked eye observations of 240 sunspots from 165BCE to 1918 CE, based on the catalogues of Yau and Stephenson (1988) and Wittmann and Xu (1987). They also reported the solar cycles of 115, 85, 60, and 11 years. Although some Korean historical sunspots are omitted in these catalogues, the result of Vaquero et al. (2002) is similar to our result.

Our results from the analysis of historical sunspot records indicate the following facts. First, the solar activity has decreased during the last one thousand years. Second, the long-term period of 240-yr solar activity has been verified with high significance from the power spectrum of sunspot records.

3.2. Historical frost records and temperature variation

To test whether or not the frost records reflect temperature at the observation site, we analyze the modern Korean frost records collected by Korea Meteorological Administration (KMA) from 1992 to 2011 (KMA, 2012). Fig. 3 shows the annual variation of the last (in spring) and the first (in autumn) dates of frost observation in two sites, Cheorwon and Cheongju of Korea, with red squares for Cheorwon and blue circles for Cheongju. Geographically, Cheorwon is located in the north latitude, 1.6° higher than Cheongju and has higher altitude above the sea level than Cheongju. Thus, the mean temperature of Cheorwon is definitely lower than that of Cheongju. We can see that the colder city, Cheorwon has a shorter length of frost-free period than Cheongju, which demonstrates that the frost records are a good temperature indicator.

In order to know the correlation between solar activity and climate change, we analyze 753 historical frost records that reflect climate change. Fig. 4 shows the last and first frost records from Goryeosa and Sillok, where the records of Goryeo Dynasty are denoted as triangles while those of Joseon Dynasty as circles. Linear regression lines are shown separately for each dynasty because the capitals of Goryeo and Joseon were in different locations. Note that the capital of Goryeo, Gaeseong is located at the higher latitude than that of Joseon, Seoul. Based on the linear fits to the frost observations, especially from the fit to the last frost observations in spring, we deduce that the temperature had been cooling down during the Joseon Dynasty. For Goryeo Dynasty, such a behavior is not clearly seen and it is difficult to clarify the climate change during this period due to the lack of observational records. The tendency of temperature variation is similar to the solar activity (the long-term decline of sunspot number) shown in the Korean historical sunspot records.

Korean frost records show that temperature (i.e., the length of frost-free period) gradually became lower from Goryeo to Joseon Dynasties. In Fig. 4, there are two notable cold epochs in the early 15C and the late 17C. We surveyed the frost records of Joseon Dynasty and draw distributions of the frost records observed at various regions. As shown in Fig. 5, the two cold epochs also appear in the plots of frost observations in four provinces of Korea. These frost records also roughly show that temperature decreased during the Joseon Dynasty. In particular, the last frost records in spring, which are large in number, show this tendency more clearly. On the other hand, the first frost records in autumn, which are less in number, show behaviors inconsistent with the spring records in some areas including Seoul. We think that a more careful follow-up study is needed for this issue. Besides, the cold period influenced by the solar cycle is also evident in other studies on the weather of the Joseon Dynasty. For example, based on the several kinds of meteorological records, Bae (2004) reported that the temperature of the Korean Peninsula was unusually low during the 18C century.

3.3. Correlation between solar activity and temperature variation

To investigate the correlation between the solar activity and the temperature change, we compare the temporal distributions of frost and sunspot records in Fig. 6, where the distribution of Korean frost records and the histogram of Korean and Chinese historical sunspots are shown together. We can see that the two cold epochs correspond to periods of the minimum solar activity. The sinusoidal curve along with the histogram shows the solar activity variation of 240-yr periodicity derived from the power spectral analysis.

The distribution of Chinese sunspot records shows that the number

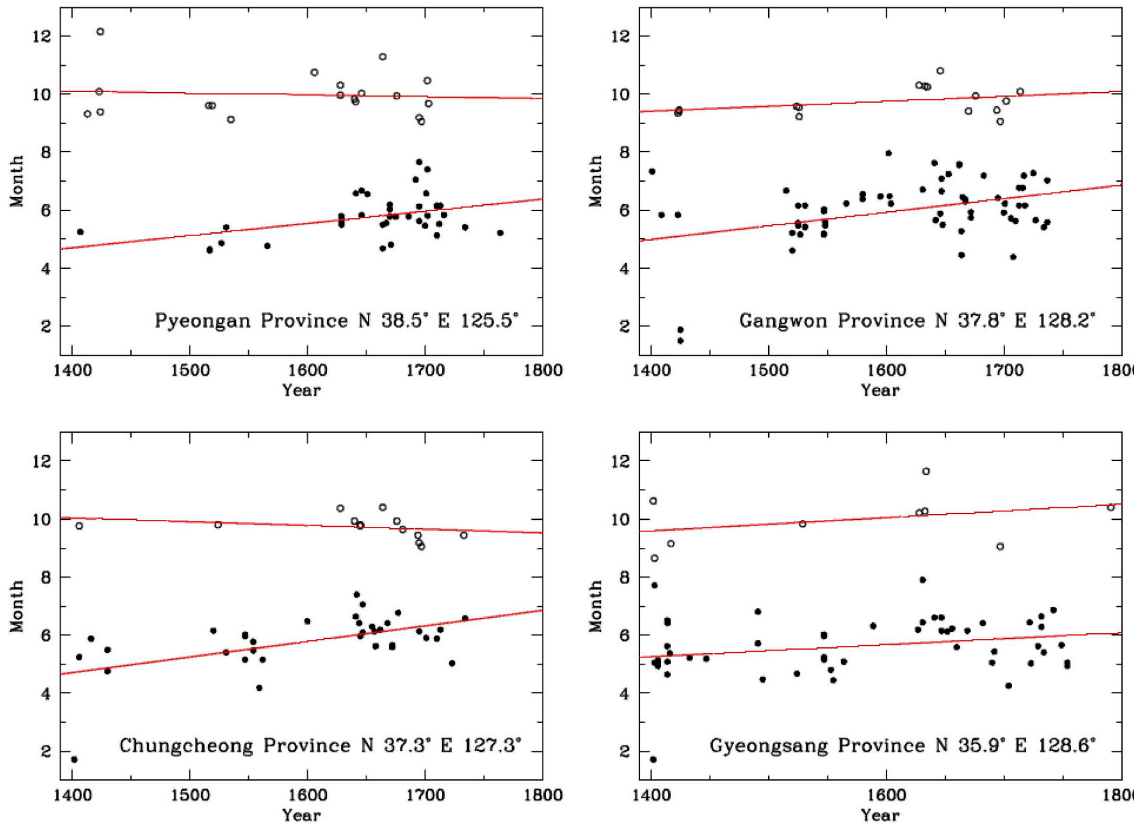

Fig. 5. Temporal distributions of frost records observed in four provinces of Joseon Dynasty (1392–1910). The four provinces are Pyeongan, Gangwon, Chungcheong, and Gyeongsang of Korea, and their representative geographical locations are N38.5° E125.5°, N37.8° E128.2°, N37.3° E127.3°, and N35.9° E128.6°, respectively.

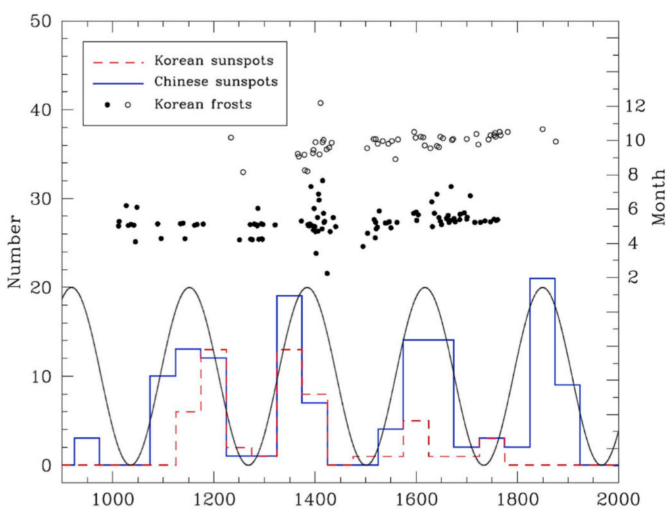

Fig. 6. Histogram of Korean (1151–1743 CE; red dashed) and Chinese sunspot records (927–1905 CE; blue solid curves). For comparison, a sinusoidal curve with a period of ~240 yr is drawn on the histograms together and frost records of Goryeo and Joseon Dynasties presented in Fig. 4 are shown above the histogram of sunspot records.

of sunspots is very small before 1151 CE while it becomes large after 1500 CE, even though the solar activity is very weak. The reason why the Chinese sunspot records still appear many times since 16th century is that they were recorded in duplicate in many chronicles so that the astronomical records from many sources were mixed together. On the other hand, the sunspot records of Goryeo and Joseon Dynasties are collected from the single chronicle for each dynasty.

Korean frost records indicate that temperature has cooled down for the past one thousand years and this matches well with the variation of solar activity. We also find that the transient cooling periods around 15C and 17C from the frost records are in good agreement with the solar minima with 240-yr cycle.

After the 14th century, the frost records in Korea were abundantly collected for several regions so that the temperature variation can be examined in detail during this time. We have identified two periods of abrupt cooling down in the frost records: early 15C and late 17C. Compared with the result of sunspot records, the two periods are closely related to the 240-yr solar activity cycle, which demonstrates that the long-term temperature variations over the last one thousand years have been directly affected by solar activity. Studies of medieval climate change also suggest the cooling down at the same time. Bard et al. (1997) reported cooling periods around 15C and early 18C based on the ^{10}Be measurements of South Pole ice and Δ^{14}C values of American-European tree rings. Liu et al. (2011) also showed that there was an extremely cool epoch around 17C from the analysis of Tibetan tree-rings. In Fig. 6, we also found that there is a slight time delay between the temperature change and the solar activity cycle, which needs further investigation in the future.

4. Summary and conclusions

In this study, we analyzed historical sunspot and frost records in order to inspect the long-term variation in solar activity and the climate change during the historical times. Two important features were identified in the sunspot and frost records in Korean chronicles. First, during the last millennium, both the solar activity and the temperature gradually decreased, indicating that the long-term solar activity has constantly caused the climate change for over a thousand years. Since around 14th century, which corresponds to the Little Ice Age and the solar minimums of Spörer, Maunder and Dalton, Korea's sunspot records are very small in number. Thus, in order to study the long-term variation of solar activity, we supplemented the lack of Korean records by adding the Chinese sunspot records in our analysis and found a long-term periodicity around 240-yr. Second, in the frost records, there are two periods during which the temperature decreased sharply, in good agreement with the solar activity cycle of 240-yr. The variation of frost-free period in the Korean frost records also implies that the temperature gradually decreased from 1200–1800 CE. This result coincides with the trend of solar activity shown in the sunspot number distribution over the same period, and is also similar to that of Chinese historical records and the climate change reconstructed from the Greenland Ice-core data analysis (Dansgaard et al., 1969; Zhu, 1973). This also confirms that the temperature variations over the past one thousand years were directly affected by the solar activity. In addition, the correlated long-term change of 240-yr in the sunspot and frost records suggests that the cooling around early 15C and late 17C was due to the variation of solar activity.

There are many historical records in Korean chronicles during the past two thousand years. They have been found to be factual records through various researches and are very useful materials for modern researches of astronomy and meteorology. Among them, the historical sunspot records provide the useful information to understand the long-term variation of the solar activity and climate change. In particular, the historical sunspot records in chronicles directly show the level of solar activity at the time of observation because the size of sunspots, which is proportional to the strength of solar activity, was classified into multiple grades. The distribution of Korean sunspot records clearly shows that the solar activity decreased over the past one thousand years (see Fig. 6). Historical frost records in Korean chronicles are also useful for studying the long-term variation in temperature since observation dates of the last frost in spring and the first frost in autumn reflect the temperature at the observation sites.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jastp.2018.10.021.

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