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Preliminary Results of Statistical Study on the Solar Cycle 24: Active Regions vs. Coronal Mass Ejections

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Abstract

To better understand the relation between different solar activity phenomena we summarized the active regions (ARs) data of NOAA Space Weather Prediction Center and coronal mass ejections (CMEs) SOHO/LASCO observations for the period of solar cycle 24 (December 2008 – December 2019). The initial sample consists of 1736 ARs and 16108 CMEs.

We present our first results of statistical analyses on the occurrence of different active processes during the last solar cycle.

Introduction

According to the SILSO Database of Royal Observatory of Belgium[1] in December 2019 began the solar cycle (SC) 25 that is expected to reach its maximum in July 2025, with peak of 115 sunspots [*Yan et al.*, 2021]. This makes the present moment appropriate for summarizing and analyzing the data about the previous solar cycle 24. It started with solar minimum in December 2008 and peaked in April 2014 with sunspot number of 116.4 (based on the 13-month smoothed monthly sunspot number time series[1]). That makes cycle 24 the fourth weakest solar cycle in history after cycles 5, 6 and 14 with maximum sunspot number of 82, 81.2 and 107.1, respectively. It lasted exactly 11 years, which puts it in the middle of the ranking of solar cycles' duration – 12 cycles lasted longer and 11 others ended before the eleventh year after their beginning. The longest one ever recorded (SC4, 1784-1798) continued 13 years and 7 months, while the shortest one – only 9 years (SC2, 1766-1775).

Coronal mass ejections (CMEs) are large structures of plasma and magnetic fields that are expelled from the Sun into the heliosphere [*Webb and Howard*, 2012]. Each CME can carry a mass of up to 10^{13} kg and release up to 10^{25} J of energy from the Sun into the heliosphere [*Guo et al.*, 2007]. As progenitor of the most powerful and extreme space weather events, they are of interest for technological reasons. They are considered as active solar events and therefore the frequency of their occurrence depends on the solar cycle progression. The peak of CMEs is usually 6-12 months after the maximum of the solar cycle [*Raychaudhuri*, 2005; *Robbrecht et al.*, 2009]. Near solar minimum appear about 0.5 CMEs per day, while near maximum the number increases up to 6 per day [*Yashiro et al.*, 2004]. Near the minimum of solar activity, they are observed at lower latitudes and tend to migrate to higher latitudes with cycle progression. Their latitude distribution is more similar to the distribution of helmet streamers than to the Maunder's butterfly diagram.

It is believed that CMEs often originate from active regions (ARs) [*Wang and Zhang*, 2008] – complex structures that unite various solar activity events that take place in different layers of solar atmosphere. As areas of magnetic flux concentration they appear as bright regions at latitudes between -30° and +30° [*Priest*, 2014].

According to a study of 32 CMEs, 84% are associated with ARs [*Subramanian and Dere*, 2001]. Other researchers link almost all CME events associated with flares (stronger than class C3.0) with ARs [*Yashiro et al.*, 2005]. More detailed analysis of 224 CMEs, observed between

[1] http://sidc.oma.be/silso/cyclesminmax

1997 and 1998, found that about 63% of the CMEs are AR-related, about 53% of the ARs produced at least one CME, and about 14% of ARs generated 3 or more CMEs during one transit across the visible disk [*Chen et al.*, 2011].

We present a new statistical study on the active regions and coronal mass ejections detected during the solar cycle 24. Our sample consists of 1736 ARs and 16108 CMEs observed between December 2008 and December 2019. These are preliminary results of larger research on different types of solar activity events of SC24.

Data selection

a) Active regions

We adopt the list of detected ARs during the SC24 given by the NOAA Space Weather Prediction Center[2]. The AR 11018 that appeared on 2009 May 23 is the first one observed at latitude higher than 30° since December 2008. Therefore, we assume it as the first AR from the SC24 and use it as a starting point in our analyses.

The latest AR included in our report is the NOAA 12754 that appeared on 2019 December 25. One year after the beginning of the SC25 ARs with latitudes lower than 30° are occasionally observed after that, but they are not part of the current study because of the uncertainty about their affiliation to the SC24.

The explored sample consists of 1736 ARs. We tracked the changes in their position and configuration for each day they were detected, which makes overall 12108 different records in our sample.

b) Coronal mass ejections

We use LASCO coronagraphs data and the SOHO LASCO CME CATALOG [*Yashiro et al.*, 2004] to determine whether there was a CME associated with an AR. Since the CME location information is defined by central position angle (CPA), we convert the AR heliographic coordinates to two-dimensional CPA and require that the difference between the CPAs of the AR and the CME to be not more than 20° taking into account the irregular forms and sizes of both events and the projection effects [*Munro et al.*, 1979].

For the observed period between December 2008 and December 2019 a total of 16108 CMEs were detected by LASCO coronagraphs.

Association rates

The yearly mean total number of events, presented on Figure 1, confirms the well-known fact that both ARs and CME events follow the SC variation. The frequency of their occurrence increases around the solar maximum. The peak at their activity was observed in 2014 (coinciding with the solar maximum of SC24 in April 2014) when 6.79 CMEs and 0.85 ARs per day are detected on average. Their weakest activity was registered in 2018 with mean of 1.3 CMEs and 0.1 ARs per day. The values for CMEs are higher than reported by other researchers, but still close to the ones considered as typical [*Yashiro et al.*, 2004].

[2] https://www.swpc.noaa.gov/products/solar-region-summary

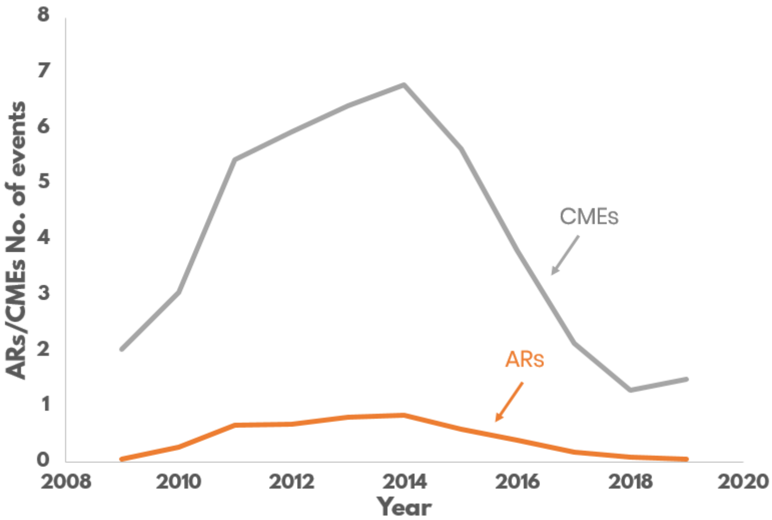
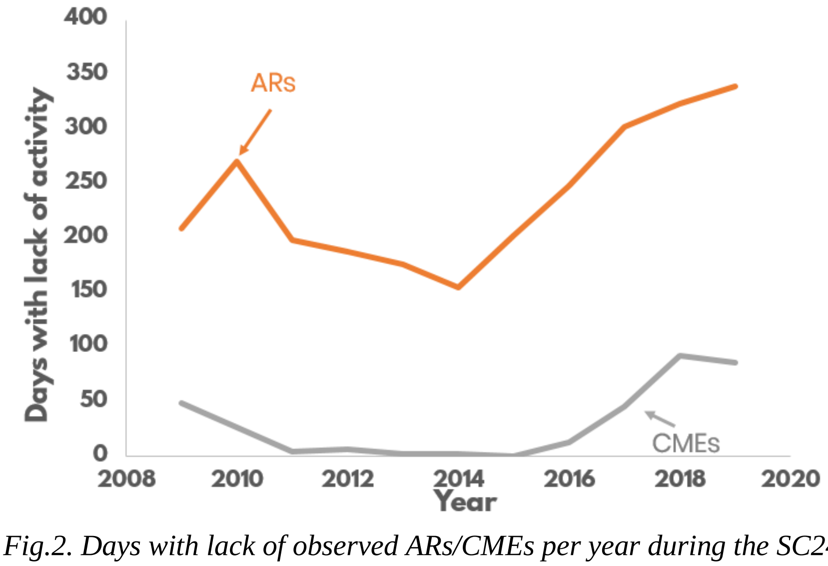


Fig.1. Yearly mean total number (total daily number of events/365) of ARs/CME events during the SC24.

A bit more complex is the comparison between the number of days with lack of activity per year (Figure 2). The least number of days without CMEs were registered in 2015 – 0 and for a period of 3 years around the maximum of SC24 (2013-2015) there were only 4 CME-less days. This coincides with the expectation that the peak of activity of CMEs might be registered 6-12 months after the solar maximum [*Raychaudhuri*, 2005; *Robbrecht et al.*, 2009]. At the same time, in 2018 the days without mass ejections were 92 (most for the explored period). ARs were observed least frequently in 2019 – in 339 days no ARs were detected, while in 2014 that happened in only 155 days. As the sunspots are largely accepted as the most representative active structure for the solar cycle progression, all days between 2012 and 2015 were completely spotless except for one day in 2014.



a) *Fig.2. Days with lack of observed ARs/CMEs per year during the SC24.*

Finally, the comparison between the number of observed CMEs and ARs (Table 1) shows that more than 31% of 16108 CMEs cannot be associated with an AR, but about 90% of ARs produce CMEs. The number of CMEs linked with AR source (about 68%) coincides well with previously reported results – 63% [*Chen et al.*, 2011] and is close to the value of 84% estimated by *Subramanian and Dere* [2001] despite the number of events included in the different studies is dramatically distinct (224 and 32, respectively vs. more than 16000). The reverse case shows closer values as we report about 10% ARs that do not generate any CME and that 73% of all 1736 ARs are CME-rich (produced more than 2 CMEs), which is exactly 81% of the ARs that are source of at least one ejection event. Other study estimated the CME-less ARs as 47% and 14% of CME-rich ARs [*Chen et al.*, 2011].

Table 1. Relationship between the ARs and CMEs observed during SC24.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="4">CMEs</td></tr>
<tr><td colspan="2">Number</td><td colspan="2">%</td></tr>
<tr><td colspan="2">AR-related</td><td colspan="2">10984</td><td colspan="2">68.2</td></tr>
<tr><td colspan="2">Non-AR-related</td><td colspan="2">5124</td><td colspan="2">31.8</td></tr>
<tr><td colspan="2">Total</td><td colspan="2">16108</td><td colspan="2"></td></tr>
<tr><td colspan="2"></td><td>-less</td><td>-productive</td><td>-rich (≥3)</td><td>Total</td></tr>
<tr><td rowspan="2">ARs</td><td>Number</td><td>169</td><td>1567</td><td>1269</td><td>1736</td></tr>
<tr><td>%</td><td>9.7</td><td>90.3</td><td>73.1</td><td rowspan="2"></td></tr>
<tr><td colspan="4"></td><td>81.0</td></tr>
</table>

Conclusions

We investigate the link between ARs and CMEs observed during the solar cycle 24 (December 2008 – December 2019) and found the following dependencies:

1. The frequency of occurrence of both events increases around the solar maximum (April 2014) – 6.79 CMEs and 0.85 ARs per day are detected on average.
2. Least days without any registered event were registered in 2015 (for CMEs – 0) and in 2014 (for ARs – 155).
3. More than 68% of explored CMEs are related with an AR.
4. Only less than 10% of all ARs are CME-less.
5. 1269/1736 (73.1%) ARs are CME-rich, which is 81% of the ARs that produced at least one CME.

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