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RMIT University's practical space weather prediction laboratory

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Abstract – Space weather is a key component in the daily operation of many technological systems and applications, including large-scale power grids, high-frequency radio systems, and satellite systems. As the international space sector continues to boom, accessible space weather products, tools and education are increasingly important to ensure that space actors (both old and new) are equipped with the knowledge of how space weather influences their activities and applications. At RMIT University, the initiative was taken to develop a Space Weather Prediction Laboratory exercise for students as part of its new offering of a Bachelor's Degree in Space Science in 2020. This new Space Weather Prediction Lab exercise is offered as part of an undergraduate course on "Space Exploration", which has a diverse student in-take, including students with no background in physics; a key detail in the design of the Lab. The aims of the Space Weather Prediction Lab were to: (1) provide a short and intense introduction to the near-Earth space environment and its impact on various human technologies; (2) give students "hands-on" training in data analysis, interpretation and communication; and (3) create an immersive space science experience for students that encourages learning, scientific transparency and teamwork. The format of the lab that was developed can be easily scaled in difficulty to suit the students' technical level, either by including more/less space weather datasets in the analysis or by analyzing more/less complicated space weather events. The details of the Space Weather Prediction Lab developed and taught at RMIT in 2020, in both face-to-face and online formats, are presented.

Keywords: Tertiary education / space science / heliophysics / space weather prediction

1 Introduction

Since the first reported space weather impact on modern technology in 1841, in which geomagnetically induced currents interfered with a telegraphic rail signalling system, leading to a minor train delay (Cade III, 2013), our global society has become increasingly vulnerable to adverse space weather due to our heavy reliance on technological systems (e.g., National Research Council, 2008; Hapgood, 2011; Eastwood et al., 2017). Among the various threats posed by space weather, the most serious are intense emissions of electromagnetic radiation, known as solar flares, the emissions of Solar Energetic Particles (SEPs) that travel close to the speed of light, and large masses of solar material erupting out into the solar system called Coronal Mass Ejections (CMEs). In terms of economic impact, CMEs are projected to be the most significant (e.g., National Research Council, 2008). Historical accounts of "great" space weather events over the last 500 years suggest an occurrence rate of about 1 every 40–60 years (Knipp et al., 2021). At the same time, "everyday space weather" (i.e., not just the great events) is becoming increasingly understood to have measurable impacts on modern society (Guhathakurta, 2021, and references therein). For instance, since 2019, major space weather prediction centres around the world have issued various space weather advisories for the aviation industry as part of an International Civil Aviation Organization (ICAO) mandate (Knipp & Hapgood, 2019; Kauristie et al., 2021). These advisories relate to rather commonplace space weather effects, including

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radiation risk to air passengers, interruptions in high-frequency radio and satellite communications and Global Navigation Satellite System disruptions.

In 2018, the Australian Federal Government formed the country's first national space agency as part of its strategy to grow Australia's stake in the fast-growing global space industry.[1] The primary objective of the Australian Government is to grow the country's space sector from 10,000 jobs and a market share of 3.9 billion AUD in 2018 to 30,000 jobs and a market share of 12 billion AUD by 2030. In response to this rapid growth in interest and subsequent funding for space activities within Australia, various new initiatives have been launched, and numerous start-up companies have been formed that are aligned with several National Civil Space Priority Areas. These areas include (among others): Position, Navigation and Timing; Earth Observation; Communications Technologies and Services; Space Situational Awareness and Debris Monitoring, and; Robotics and Automation on Earth and in Space. Each of these priority areas has elements that are directly and indirectly impacted by everyday space weather. While the priority of space science education has not yet been formalized on the national level, it is clear that a prosperous national space sector will require a solid foundation of tertiary-level space science education – particularly in the areas of solar-terrestrial physics and space weather – to guarantee its long-term viability and success.

While not yet mainstream in universities around the world, "space weather" in some form is being taught at a number of institutions. A good example is running the Center for Integrated Space Weather Modeling (CISM) two-week summer school at Boston University (Simpson, 2004; Gross et al., 2009). This summer school was initially aimed at first-year graduate students but then took on a wider audience that included high school teachers. The CISM summer school has now evolved into the Boulder Space Weather Summer School and is now hosted by the High Altitude Observatory at the National Center for Atmospheric Research.[2] The University of Colorado Boulder offers a graduate-level "Space Weather Certificate",[3] in addition to a series of "Space Minor" courses that include "Space: Environment and Effects", which covers elements of space weather. The University of Colorado Boulder has also compiled an extensive list of space-weather education resources (Knipp & Cade, 2020). A Professional Certificate is currently under development.[4] The University of Michigan offers a course titled "An introduction to space weather"[5] and a Bachelor of Space Science and Engineering,[6] which includes a number of courses on the Solar-Terrestrial environment. This program aims to prepare students to undertake graduate degrees in space weather or join Government agencies/federal labs conducting space science research. Michigan also offers a Master's in Engineering[7] that requires a course in space environment and a PhD program[8] in which students pursue space weather topics, including using and developing the Space Weather Modeling Framework (Tóth et al., 2005), analyzing space data to better understand the Sun, solar wind, and Earth's magnetosphere and ionosphere, or building ground- or space-based instruments. Millersville University offers a graduate certificate program in "Space Weather and Environment: Science, Policy and Communication",[9] which is aimed at broadcast meteorologists, emergency responders, military personnel, federal and state policy advisors, among others. At the Queensborough Community College in the US, an integrated research and education program in space weather was developed for undergraduate students (Damas et al., 2020). The program includes a summer research internship and research projects that give students hands-on experience with space weather data, sometimes leading to student-led scientific conference presentations. Notably, a motivating factor in the development of this program was the need to increase diversity and inclusion in space weather and STEM more broadly. In the United Kingdom, the University of Leicester's offering of a Physics with Space Science BSc[10] includes a final year course option called "The Space Environment",[11] which has a focus on the solar wind – magnetosphere – ionosphere plasma interactions. Similarly, Lancaster University's offering of Physics Bsc Hons (and its variants)[12] includes a final year course option called "Space and auroral physics", which includes important elements of space weather. In Belgium, KU Leuven offers a Master of Space Studies,[13] which includes a course called "Space Weather". Whilst exhaustive, this list is only a subset of space weather education offerings that exist worldwide.

From these examples, it is clear that topics related to space weather are typically taught at the senior undergraduate/postgraduate level once the students have a solid foundation in physics and mathematics. In cases where space weather is taught to undergraduates, it is generally anticipated that the students will continue to specialize in this topic in their postgraduate studies and careers. The primary reason for this is possibly due to the fact that the jobs market has not needed university graduates with a strong (or even a basic-level) background in space weather, and those obtaining such a background normally go on active research and operations roles (e.g., Government/academia). For instance, the Australian Bureau of Meteorology Space Weather Services operates the Australian Space Forecast Centre (Wilkinson et al., 2018) and requires its forecasters to be experienced scientists, preferably with a PhD in space physics, or a related STEM discipline. However, access to space is now very affordable, which has had the flow-on effect of an increase in the diversity of new participants in various roles throughout the space sector.

[1] https://publications.industry.gov.au/publications/advancing-space-australian-civil-space-strategy-2019-2028.pdf
[2] https://www2.hao.ucar.edu/SWSS
[3] https://www.colorado.edu/aerospace/academics/graduates/curriculum/certificate-programs/space-weather-and-applications
[4] https://www.colorado.edu/spaceweather/space-weather-education
[5] http://www.lsa.umich.edu/cg/cgdetail.aspx?content=2320SPACE103001&termArray=w 21 2320
[6] https://clasp.engin.umich.edu/academics/undergraduate-studies/bse-space-science-engineering/
[7] https://clasp.engin.umich.edu/academics/graduate-studies/masters-program/masters-space-engineering/
[8] https://clasp.engin.umich.edu/academics/graduate-studies/phd-program/
[9] https://www.millersville.edu/programs/space-weather-environment-science-policy-communication.php
[10] https://le.ac.uk/courses/physics-with-space-science-bsc/
[11] https://le.ac.uk/modules/2022/pa3603
[12] https://www.lancaster.ac.uk/physics/study/undergraduate/
[13] https://fys.kuleuven.be/ster/education/master- space-studies/master-of-space-studies

At RMIT University, a new Bachelor of Space Science Program[14] was offered to students starting from the beginning of 2020. This program was specifically tailored to suit Australia's diverse interests in space. The degree incorporates the usual topics of physics and mathematics, but it also incorporates elements of geospatial science (e.g., remote sensing) and engineering, providing graduates with a broad range of skills to suit multiple career pathways in the Australian space sector. Four new courses dedicated to key space areas have been developed as part of this new degree. The new courses relate to daily space operations, space situational awareness, rocket science and microgravity science and are all core to the BSc Space Science. The flagship core space course within this program is "Space Exploration", a first-year course that takes students through the solar system and provides them with an introduction to human spaceflight operations. An important element of this course is the topic of space weather, for which a space weather prediction exercise was developed and delivered as a practical student assessment. A key benefit of this practical exercise is that it familiarizes students with the concepts and challenges involved in space weather forecasting and gives them an understanding of the various technologies and industries impacted by space weather. Participation by students is in the form of group work in order to encourage beneficial behaviour. The design of computer-supported collaborative learning environments that favour collaborative learning interactions have been shown to be effective systems for "critical inquiry" and "scientific argumentation" (Andriessen et al., 2013). Simply placing students into groups does not guarantee effective collaboration (e.g., Gadgil & Nokes-Malach, 2012), and therefore collaborative tasks must be predesigned with clear learning outcomes identified (Lam & Muldner, 2017).

This paper details the Space Weather Prediction Lab exercise that is used to teach RMIT's Space Science students. First, the datasets used and the space weather scales are introduced. Then, descriptions of the laboratory facility, students' prior knowledge, the learning goals and objectives and the practical exercise design are given. This is followed by a detailed overview of the space weather period used for the prediction exercise; 4–9 September 2017. Then, a brief discussion of the transition from face-to-face to online learning due to COVID-19 for this exercise is given. This is followed by an analysis of the students' performance and feedback for the Lab. Finally, a discussion of the laboratory evaluation and future plans is given.

2 Datasets and space weather scales

Space weather is intrinsically a global phenomenon. Therefore, the act of space weather monitoring and prediction requires a high level of international cooperation and transparent data sharing. As a result, many space weather datasets, both archived and in near-real time, are openly available online for anyone to use. The datasets used in this Space Weather Prediction Laboratory were all sourced from such online databases and are thus accessible to everybody. Operationally, space weather forecasters use any and all space environment data that are available to produce their forecasts. These data tend to include some crucial observations of the Sun and the solar wind and some observations that are made of the environment around Earth. While all three of these environments are covered well by this exercise, there exist other space weather datasets that were not chosen for the exercise in order to limit its scope. Below are descriptions and details of the datasets and space weather scales that were specifically used in the development and delivery of this Space Weather Prediction Lab exercise.

2.1 Solar Dynamics Observatory (SDO)

The Solar Dynamics Observatory (SDO) mission was the first space weather mission from NASA's Living with a Star Program (Pesnell et al., 2012). The SDO spacecraft was fitted with three solar remote-sensing payloads; the Atmospheric Imaging Assembly (AIA), the Extreme Ultraviolet Variability Experiment (EVE), and the Helioseismic and Magnetic Imager (HMI).

SDO's inclined geosynchronous orbit facilitates a high data rate transfer between the SDO and the ground, and the prompt posting of the data online[15] allows space weather prediction agencies and the general public to access near-real-time imagery of the Sun. Given that the SDO mission is primarily science-focused, such a prompt translation into operational space weather forecasting is a significant additional achievement.

Given that space weather forecasting agencies around the world are utilizing the SDO's near-real-time solar imagery, it was deemed appropriate to include SDO data in this space weather practical laboratory; in particular, data from the AIA and the HMI payloads. For the purpose of the space weather practical laboratory, the SDO imagery is used for characterizing the complexity and evolution of active regions on the Sun's surface and used to spot the occurrence and location of solar flares. In lieu of solar X-ray flux data, the intensity of solar flares is gauged from their brightness/saturation level in the SDO imagery for the purposes of this exercise.

2.2 The Solar and Heliospheric Observatory (SOHO)

The Solar and Heliospheric Observatory (SOHO) is a joint European Space Agency (ESA) and NASA mission that was the first "cornerstone" in ESA's long-term space science program (Domingo et al., 1995). In 1995, SOHO was launched and sent to orbit the Lagrangian point L1 between the Sun and the Earth to routinely monitor the Sun and the solar wind.

On board is a suite of 12 scientific instruments, including remote-sensing and *in situ* instruments measuring the Sun and the solar wind. One instrument on board SOHO that is unique at the L1 point is the Large Angle and Spectrometric COronagraph (LASCO) instrument, which images the outer solar corona by blocking the bright Sun with an occulting disk. LASCO is an important instrument for determining the direction of CMEs that are launched from the Sun.

For the purposes of the space weather prediction laboratory, the SOHO LASCO imagery[16] is used for imaging the solar wind emanating from the solar surface and detecting CMEs.

[14] https://www.rmit.edu.au/study-with-us/levels-of-study/undergraduate-study/bachelor-degrees/bachelor-of-space-science-bp330

[15] https://sdo.gsfc.nasa.gov/data/aiahmi/

[16] https://soho.nascom.nasa.gov/data/Theater/

2.3 NASA Goddard's space physics data facility – OMNIweb plus database

NASA's OMNIweb Plus Database[17] is a comprehensive collection of space weather datasets for research purposes. There are many data sources[18] included in the OMNIweb Database. They can all be accessed by selecting the "Low Resolution" (hourly, Papitashvili & King, 2020b) or the "High Resolution" (minutely, Papitashvili & King, 2020a) OMNIweb options. Users can then opt to see plots or download the data for a given time period. The specific datasets used in the space weather laboratory are detailed below.

2.3.1 The Kp and SYM-H indices

There are various indices available that measure/monitor the geomagnetic activity level on Earth, but the most commonly used are the Kp and Dst indices. Both indices rely on magnetic field observations from various locations around the world (Rostoker, 1972). The Kp index is constructed using magnetometer stations located at sub-auroral latitudes that effectively measure magnetic variations due to the convection electric field in the Earth's magnetosphere that forms as a result of the moving solar wind around it (e.g., Rostoker, 1972; Thomsen, 2004, and references therein). It is a 3-h index with values ranging from 0 to 9, with two steps between each integer, denoted with "−" or "+"; i.e., 0, 0+, 1−, 1, 1+, 2−, 2, 2+, etc. On Kp index plots, the "+" and "−" steps are characterized using steps of 1/3; e.g., 3− is 2.6667 and 4+ is 4.333. There are several aspects of the near-Earth space environment that are well correlated with the Kp index, making it a useful parameter for space weather prediction (e.g., Wing et al., 2005).

Alternatively, the Dst index employs low-latitude magnetometer stations around the world and effectively measures the strength of the magnetic field produced by the magnetospheric ring current in the equatorial plane (Wanliss & Showalter, 2006). It is an hourly index, and its value is essentially the magnetic field strength of the ring current in nT, as measured from the Earth's surface at the equator; more negative values indicate a weakening of the magnetic field at Earth's surface due to a westward magnetospheric ring current. The SYM-H index is a high-time-resolution version of the Dst index. It also uses low-latitude stations in its derivation, but it has a 1-min time resolution (Wanliss & Showalter, 2006), making it more useful for determining precise storm commencement/CME arrival times.

The Kp and SYM-H indices are used to quantify the level of geomagnetic activity observed on the Earth in this space weather prediction laboratory. The Kp index is included in the "Low Resolution" OMNIweb dataset, and the SYM-H is included in the "High Resolution" OMNIweb dataset.

2.3.2 F10.7 solar flux

Since the discovery of the relationship between active regions on the Sun's surface and the emissions of radiation at the wavelength of 10.7 cm in the late 1940s, the F10.7 index has been a staple dataset for space weather monitoring (Tapping, 2013, and references therein). The F10.7 flux, which is measured in "solar flux units (sfu)", equivalent to 10^{-22} Wm^{-2}, is used as a proxy for solar activity level, which is also related to the number of sunspots/active regions on the Sun's surface. Similar to the sunspot number, the F10.7 index shows the well-known 11-year solar cycle, which ultimately modulates the regularity of space weather events, such as solar flares and CMEs. Thus, the F10.7 solar flux obtained from NASA's "Low Resolution" OMNIweb database was used in this space weather laboratory to enable students to identify both long-term (i.e., years) and short-term (i.e., weeks) trends in solar activity.

2.3.3 In situ solar wind data

Spacecraft orbiting around the Lagrangian L1 point are important platforms for monitoring solar wind. The solar wind plasma that is detected at L1 is "upstream" from the Earth. Depending on the solar wind speed, the plasma detected at the L1 point is ~30 min to 1 h away from impacting Earth's magnetosphere and thus constitutes an important space weather prediction capability, particularly for Earth-directed CME arrivals.

Since the launch of NASA's Wind spacecraft in 1994 (Ogilvie et al., 1995), followed by the launch of NASA's Advanced Composition Explorer (ACE) spacecraft in 1997 (Stone et al., 1998), the solar wind has been routinely monitored from the L1 point. Given that both the Wind and ACE spacecraft were well beyond their expected mission lifetimes, NASA, NOAA, and the US Air Force launched the Deep Space Climate Observatory (DSCOVR) spacecraft to L1 in 2015 (Burt & Smith, 2012) to ensure a smooth continuation of vital upstream solar wind data for space weather forecasting and research.

The "High Resolution" OMNIweb database includes data from all three L1 spacecraft. Also provided are solar wind parameters that have been propagated to the magnetosphere's bow shock nose,[19] but for the purposes of simulating a space weather prediction environment, the original time stamps of the *in situ* data are used. The solar wind magnetic field strength, the Bz component, the plasma density and the plasma speed are used in this space weather laboratory as these are the most important solar wind parameters for space weather prediction.

2.3.4 GOES proton flux

The Geostationary Operational Environmental Satellites (GOES) mission consists of several multi-generation geostationary satellites launched by NASA and NOAA from 1975 onwards (Menzel, 2020). The GOES mission is largely concerned with tropospheric weather monitoring, but the satellites are also equipped with several instruments as part of their Space Environment Monitor (SEM) subsystems that are useful for space weather observations (Menzel & Purdom, 1994). The earliest GOES satellites were equipped with a solar X-ray sensor, a magnetometer and an energetic particle sensor (Donnelly et al., 1977). The most recent GOES-R series, the first of which was launched in 2016, has several more advanced instruments for solar and space environment monitoring (Sullivan, 2020), including a space environment *in situ* suite that monitors fluxes

[17] https://omniweb.gsfc.nasa.gov/

[18] https://omniweb.gsfc.nasa.gov/html/aboutdata.html

[19] https://omniweb.gsfc.nasa.gov/html/HROdocum.html

of energetic electrons, protons and heavy ions (Kress et al., 2020). For the purposes of this space weather laboratory, the GOES proton Flux for protons with energies >10 MeV, >30 MeV and >60 MeV were obtained from the "High Resolution" OMNIweb Plus database and used; although, the GOES Proton Flux data is limited to 5-min resolution.

2.4 NOAA space weather scales

The NOAA Space Weather Prediction Center (SWPC) has published a very useful set of space weather scales that connect space weather phenomena with direct technological impacts on its website.[20] These scales have also been adopted by Australia's Bureau of Meteorology in the Australian Space Weather Alert System.[21] In particular, there are three different space weather scales; (1) geomagnetic storm scale from G1 to G5 classifications, (2) solar radiation storm scale from S1 to S5 classifications, and (3) radio blackout scale from R1 to R5. Included in each of these scales is an occurrence frequency per solar cycle. The G scale classification depends on the geomagnetic Kp index, the S scale depends on the proton flux level observed by GOES satellites, and the R scale is determined using the X-ray flux observed by the GOES satellites. The NOAA SWPC scales provide an easy-to-read guide for non-space-weather-experts to connect space weather phenomena to real-world impacts. Thus, the NOAA SWPC G and S scales were used in this space weather laboratory to teach students about these relationships; in the interests of time and complexity of the lab for the students, it was decided to not use the R scale and reserve it for potential future lab versions for more senior students who already have familiarity with the G and S scales and the space weather datasets described above.

3 Space weather prediction laboratory design

3.1 RMIT's VXLab

The Virtual Experiences Laboratory (VXLab) at RMIT University (Peake et al., 2015) was established in 2013 to enable software engineering research focused on physical automation and the user experience, with robotics/manufacturing, visualization and computation facilities connected on a distributed sandbox network. A cluster of 40 Intel Xeon blades in an RMIT data centre provides computation services and simulation capacity. Themes such as simulation (Peake et al., 2021), software architecture and quality, and extended reality (Peake et al., 2016, 2017) have been emphasized, typically combined with training, particularly project-based training for final-year students in Computing Technology-related disciplines (Simic et al., 2016). The Global Operations Visualization (GOV) lab in the VXLab provides a prototyping platform for dashboards for local and global collaboration and acts as a portal for the wider VXLab.

GOV Lab augments a traditional teleconference meeting room with a 40-megapixel tiled display wall and a customized version of the open-source Scalable Amplified Graphics Environment Version 2 (SAGE2) (Marrinan et al., 2014). SAGE2 provides service-based deployment and orchestration of web-based parallel-rendered applications. For the space weather prediction lab, applications include SAGE2 PDF, video and web browsers, enabling multiple users using separate clients to interact with arbitrary applications on the wall using mouse pointer-style interaction. The detailed architecture of the GOV Lab portion used for the space weather practical lab can be found in Peake et al. (2015). A cluster of Ubuntu workstations on a dedicated 10Gbps network drives the displays in two tiers. Redundant SAGE2 servers enable exploration of scalability and failover. The display consists of seven columns of three HD LCD displays driven by workstations with consumer-class Virtual Reality graphics adapters running X Windows and Electron. Customization includes a configurable AMX touch panel with buttons to activate saved SAGE2 sessions, such as for different configurations of the space weather dashboard and switch the display between different instances or versions of the SAGE2 servers.

The VXLab facility was used in this space weather practical lab to visualize the time series data as static images (i.e., png files) and the solar and solar wind imagery in a looping video format (i.e., mp4). Displaying all of these data at once gives the students the feeling of working in a real-space weather forecasting centre, making it a key element of this exercise.

3.2 Prior knowledge

This space weather practical lab is part of a 1-semester core course for the Bachelor of Space Science students at RMIT University – "Space Exploration" – but it is also a University-wide elective, with only high-school level English and Mathematics as prerequisites. As such, the student intake is very diverse, and the presumed knowledge of the students about space weather is very limited. The students are required to undertake this once-off 2-h space weather lab at some stage during the first half of the semester, as dictated by timetabling and scheduling. Before undertaking the laboratory exercise, the students are given an introductory lecture in their first week on the Sun, including a detailed overview of space weather and operational space weather forecasting. To support the students in undertaking the lab exercise, this prior knowledge is augmented by the space weather laboratory instruction manual (attached as auxiliary material to this manuscript) that the students are required to read prior to conducting the lab; this manual is their primary source of background information. To further support the students, the questions they are asked are very specific and relate to the data they are analyzing; i.e., they are not questions with subjective/debatable answers. Further, as described below, the students are additionally supported by frequent class-wide discussions that are used to clarify/correct any misunderstandings.

3.3 Learning goals and objectives

The primary goal of this exercise is to provide a hands-on learning experience for students in analyzing and interpreting data and effectively communicating their findings, all as part of a team effort.

[20] https://www.swpc.noaa.gov/noaa-scales-explanation
[21] https://www.sws.bom.gov.au/Category/About%20SWS/Australian%20Space%20Weather%20Alert%20System/BoM%20Australian%20Space%20Weather%20Alert%20System.pdf

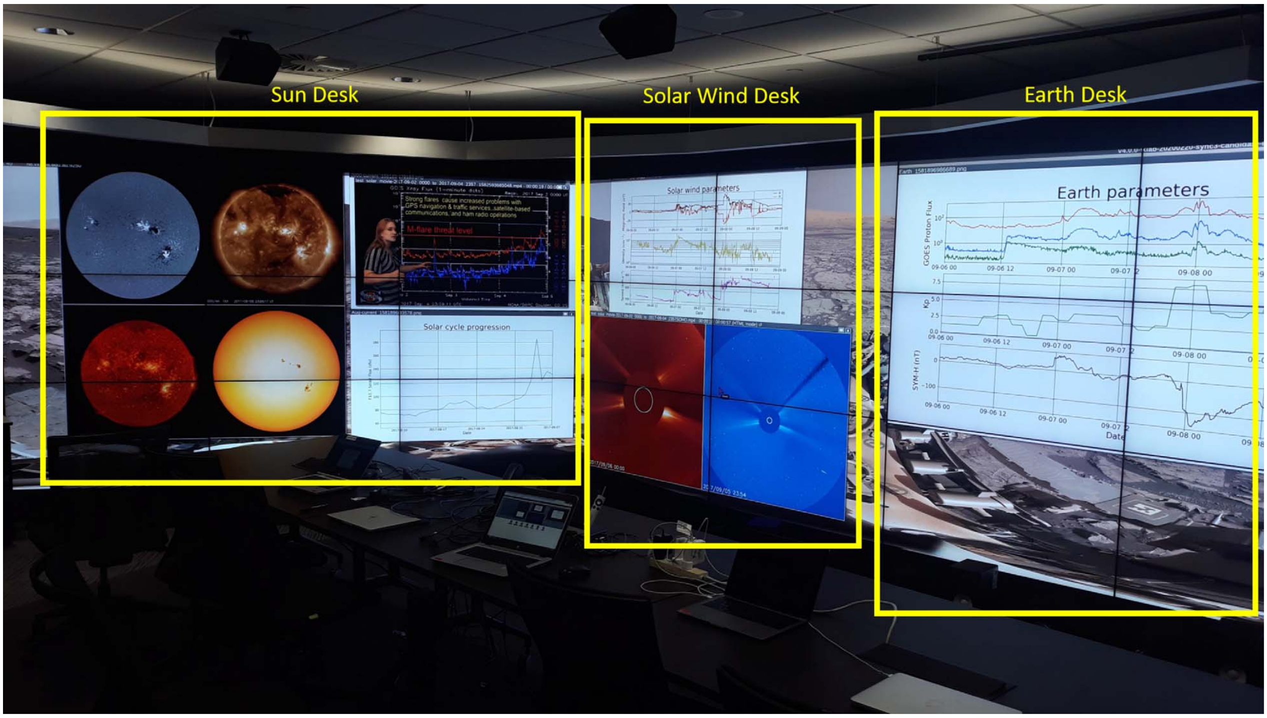

Fig. 1. Photo of RMIT's VXLab with the space weather laboratory data displayed. The yellow rectangles and labels highlight sections of the VXLab display that relate to each of the Desks in the exercise. One can also, notice on the Sun Desk display a still from an online space weather forecast video shown to the students at the end of the lab (see Sect. 4.3).

The specific learning objectives for reaching this goal are:

1. The students will be able to interpret all of the space weather datasets used in the exercise.
2. The students will know the metrics that are currently used to quantify the strength/severity of geomagnetic storms.
3. The students will be familiar with the NOAA SWPC scales and be able to connect the S and G scales with various technologies that are impacted by space weather.
4. Students will be productive members of a team and exhibit attributes that facilitate active group discussion and deliberation.

3.4 Format of practical exercise

A practical space weather prediction exercise can be done in several formats. For instance, more junior students can be separated into several groups and tasked with analyzing and interpreting limited space weather data from relatively simple events and then communicating their findings to the rest of the class. Alternatively, more experienced/higher-level students can be tasked with analyzing more datasets individually before communicating findings to the rest of the class, in conjunction with being given more complicated space weather events to analyze. Students participating in the undergraduate course "space exploration" were mostly junior level (in their first year), and so the lab was run by separating the students into three small (3–4 students) groups, called "The Sun Desk", "The Solar Wind Desk" and "The Earth Desk". Each Desk has a tailored data feed that uses historical space weather data. The students analyze and interpret the data presented at their Desk throughout the lab.

Figure 1 shows the presentation of data for each Desk in the RMIT VXLab. The SDO and SOHO data videos are set to play automatically, and the static data plots are presented in a large format for easy viewing by all students. Importantly, while each Desk has a dedicated data stream to analyze, the students can also view what data the other Desks are analyzing, which can help them gain a better sense of the space weather event. With this setup, the students need not directly interact with the data on the screens in order to conduct their analysis and to answer their question sheets; lab demonstrators are capable of interacting with the screens if students require, but this generally is not necessary and can actually serve as a distraction. The positioning of the Sun Desk data on the left, the Solar Wind Desk data in the middle and the Earth Desk data on the right also provides the students with the subliminal lesson of cause and effect (much like most space weather schematic diagrams); space weather starts at the Sun, travels through the region of space occupied by the solar wind and arrives at the Earth.

The lab exercise is run over a 2-h period with ~12 students in attendance. The students are randomly assigned to one of the three Desks by the instructors for the duration of the lab; instructors randomly assigning students to Desks prevents students from choosing to work with their friends and mixes together the stronger and weaker students (Gibbs, 1995). Each Desk is assigned a different set of questions to answer throughout the exercise tailored to help them identify important/noteworthy features in their data streams. The questions are provided to students as a paper handout, but as described in Section 5, shared online documents can also be utilized for online learning. Prior to the commencement of the lab session, students are required to be familiar with an accompanying space weather lab manual that explains each of the datasets and the types of features that they might come across throughout the exercise; the students are also recommended to bring these to the lab for reference.

The space weather lab is structured as follows:

- Welcome and introduction.
- Forecast Period 1.
- Desk presentations and class-wide discussion.
- Forecast Period 2.
- Desk presentations and class-wide discussion.
- Verification Period.
- Class-wide discussion and wrap-up.

The lab starts with a brief welcome and introduction, followed by the first of two "Forecast Periods". A hypothetical "current time" is issued at the beginning of the Forecast Period, and data spanning the 3 days prior to that time are presented to the students for analysis; the only exception to this is the solar cycle progression data, which spans back the previous month and the previous few years. The duration of the first Forecast Period is set to 30 min to allow the students to become familiar with their tasks. By the end of the Forecast Period, the students will have answered the provided question sheet based on the consensus formed by the students at that Desk. Each Desk will have also agreed upon a spokesperson to explain their findings to the class. An alarm is sounded to indicate the end of the first Forecast Period and the beginning of the class-wide discussion of the findings at each Desk; a total of 15 min is allocated for this. During this discussion, the appointed spokesperson for the Sun, Solar Wind and Earth Desks present their findings for the Forecast Period, which are aided by their answers to the question sheets that they completed. The student presentations are limited to ~2 min and are helped along by the head lab demonstrator to ensure that all of the important features/events are identified and discussed and to keep the class to the 15 min allocated. The head lab demonstrator ends the discussion by briefly summarizing the features/events identified across the Desks over the Forecast Period, and the question sheets are collected for marking.

Next, the second Forecast Period commences. By now, the students are familiar with the format of the exercise, so a completion time of 20 min is allocated for this Forecast Period. The "current time" has jumped forward to 1–3 days from the first Forecast Period so that there is some data/imagery overlap. The next question sets given to each Desk are once again tailored to that Desk's specific data streams, but they have similarities with the questions for the previous Forecast Period. A significant difference in the question sheets issued in the second Forecast Period is that all Desks are given the same hypothetical question at the end, a hypothetical situation in which their Desk must make a recommendation in an operational decision-making context. Once the alarm sounds, the Forecast Period is over, and the Desk presentations commence with different spokespeople assigned by each Desk. Once again, the head lab demonstrator facilitates the class-wide discussions, highlighting the features and noteworthy events in each Desk's dataset, and documents each Desk's recommendations to the hypothetical question. The student question sheets are collected for marking.

Finally, the class enters the "Verification Period", which again jumps into the future by 1–3 days, ideally after the most severe stages of the space weather event, in order to verify the forecasts produced by each Desk. Importantly, this is an opportunity for each Desk to assess whether or not, following their recommendations in the previous Forecast Period, adverse outcomes would have occurred. The only question offered to all students is a reflective "Were your recommendations correct given what occurred?" A total of 10 min are allocated to answering this question set. Then the final class-wide discussion about the event is carried out in the last 5 min. In that discussion, the head lab demonstrator highlights the known impacts of the event studied and, where possible, shows students the real forecasts for this event issued by space weather experts and agencies.

The session wraps up with the students being shown the websites of various space weather agencies that display real-time space weather data and forecasts, and space weather forecasting as a future employment option is highlighted.

4 The 4–9 September 2017 period

The strong solar flare events in early September 2017, the subsequent CMEs, the solar radiation storms and the geomagnetic storms (e.g., Redmon et al., 2018; Bingham et al., 2019; Dimmock et al., 2019; Piersanti et al., 2019; Soni et al., 2020) provided a good case study of a complex space weather event for students to study in this practical exercise. Further, many real-world impacts of space weather during this period have been documented (e.g., Berdermann et al., 2018; Clilverd et al., 2018; Gonzalez-Esparza et al., 2018; Linty et al., 2018; Redmon et al., 2018; Yasyukevich et al., 2018; Dimmock et al., 2019; Frissell et al., 2019; Sato et al., 2019; Simpson & Bahr, 2020, 2021). Using the NOAA SWPC scales, students are able to map these real space weather data to their various technological impacts (Sect. 2.4). The complexities of the event also allowed for the identification of significant features in each Desk's datastream in each Forecast Period, despite the Sun-to-Earth cause-and-effect aspect of space weather, as discussed below.

The September space weather event occurred during solar minimum, with a sharp increase in solar activity in early September that was associated with the emergence of sunspot regions AR2673, AR2674 and AR2675. In particular, AR2673 underwent rapid changes in structure and magnetic complexity in early September that ultimately led to a series of solar flares, which included an X-class flare at ~12 UT on Sep 6. This was the largest solar flare in the previous 10 years (Redmon et al., 2018; Soni et al., 2020) and is the most intense solar flare since, at the time of writing. Two CMEs were launched associated with this spike in solar activity, both of them towards the Earth. The first of these was detected at the Lagrangian L1 point by the DSCOVR spacecraft at the end of Sep 6, which was associated with a flare on Sep 4. The second was detected at L1 almost 24 h later on Sep 7. The impact of these CMEs caused a geomagnetic storm that peaked with an

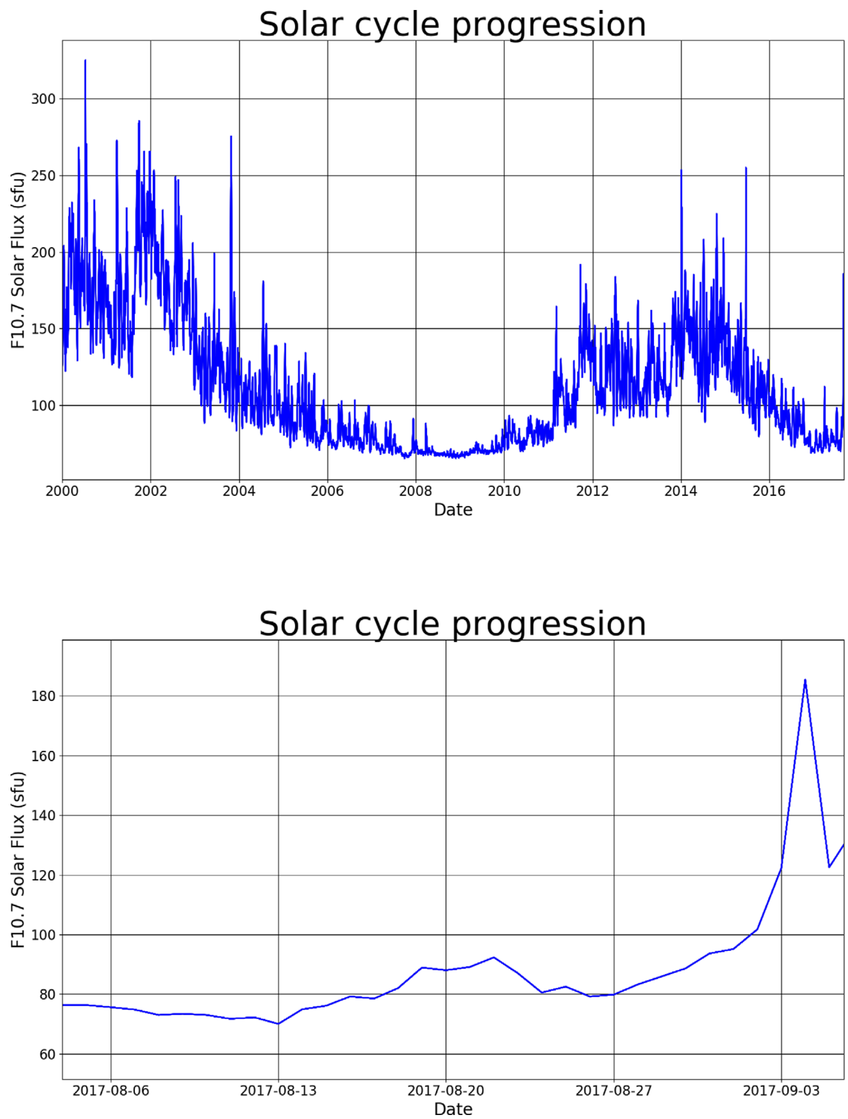

Fig. 2. The solar cycle progression displayed to the students, showing both the long-term (top panel) and the short-term (lower panel) trends in the F10.7 flux.

SYM-H of −146 nT at 01:08 UT on Sep 8, with a corresponding Kp = 8 that later peaked at 8+ at 12 UT that day. Both solar flares on Sep 4 and 6 caused near-instantaneous solar radiation storms (or “Solar Energetic Particle (SEP) storms”), as detected by the GOES spacecraft. All-in-all, many aspects of this event allow students to connect these real space weather data streams to the real-world impacts of space weather using the NOAA SWPC scales.

4.1 Forecast period 1: 02-Sep-2017 to 05-Sep-2017

The first Forecast Period was selected to show the rise of AR12673 (denoted below and in the lab materials, using the standard 4-digit AR designation, i.e. “AR2673”), both in terms of size and complexity. This imparts critical knowledge to the students related to the trend in Sun activity towards the end of this period.

4.1.1 The Sun Desk

The questions asked of the students at the Sun Desk relate to the solar cycle and what phase in the cycle the Sun was in. Figure 2 shows the solar cycle progression data displayed to the students; the top panel shows the long-term features in the F10.7 flux, while the bottom panel shows the F10.7 variations over the previous month. Here students should be identifying that they were in solar minimum but that the recent activity was abnormal to solar minimum conditions. The students should also be able to relate the recent F10.7 spike in the long-term plot to the large F10.7 spike in the short-term plot, corresponding to 185.5 sfu on Sep 4.

Next, the Sun Desk students’ attention is turned to the SDO video. The instruction manual tells them what each panel is showing them. The students are asked to rank the named active regions, AR2673, AR2674 and AR2675, by their complexity

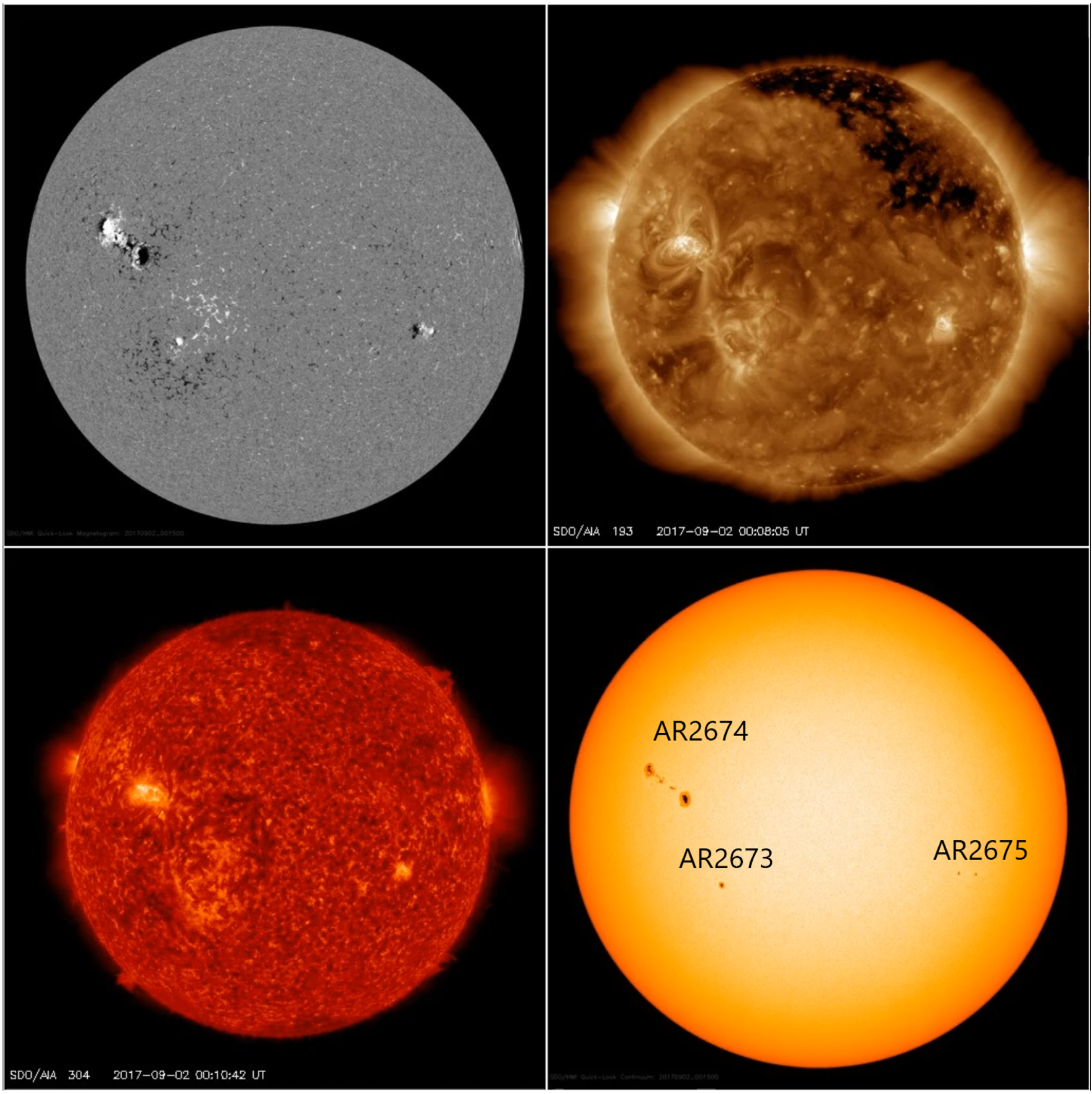

Fig. 3. An early snapshot of the Sun Desk SDO video in the first forecast interval. The SDO HMI magnetogram is shown in the top-left. The SDO AIA 193 image is in the top-right. The SDO AIA 304 is in the bottom left, and the SDO HMI Continuum (visible) image is shown in the bottom right. In each video frame, the timing of each image lies within 20 min of one another. The locations of the designated active regions AR2673, AR2674 and AR2675, are also shown in the SDO HMI Continuum (visible) panel.

and to note how these rankings change from the beginning to the end of the 3-day Forecast Period. Figures 3 and 4 are snapshots taken from this video displaying the relatively calm conditions at the beginning of the Forecast Period and the moment of the largest solar flare on Sep 4, respectively. The complexity of the sunspot region AR2673 (the only sunspot region in the southern hemisphere) markedly increased from Sep 2 to Sep 4. This is not only obvious in the visible image but also in the HMI magnetogram image, which shows multiple interlocking magnetic poles indicated by the black and white patches (Fig. 4).

The students are asked to watch the data stream carefully and note the time of the brightest solar flare in the Forecast Period. The students are also asked to indicate which AR poses the most significant space weather threat to Earth and why. The flare shown in the AIA 193 image in the top-right of Figure 4 is the event that the students should highlight, occurring close to 20:30 UT on Sep 4. The students should also cite the rapid development of AR2673 over the 3-day period compared to the other regions as the rationale for that region posing the most significant space weather threat to Earth.

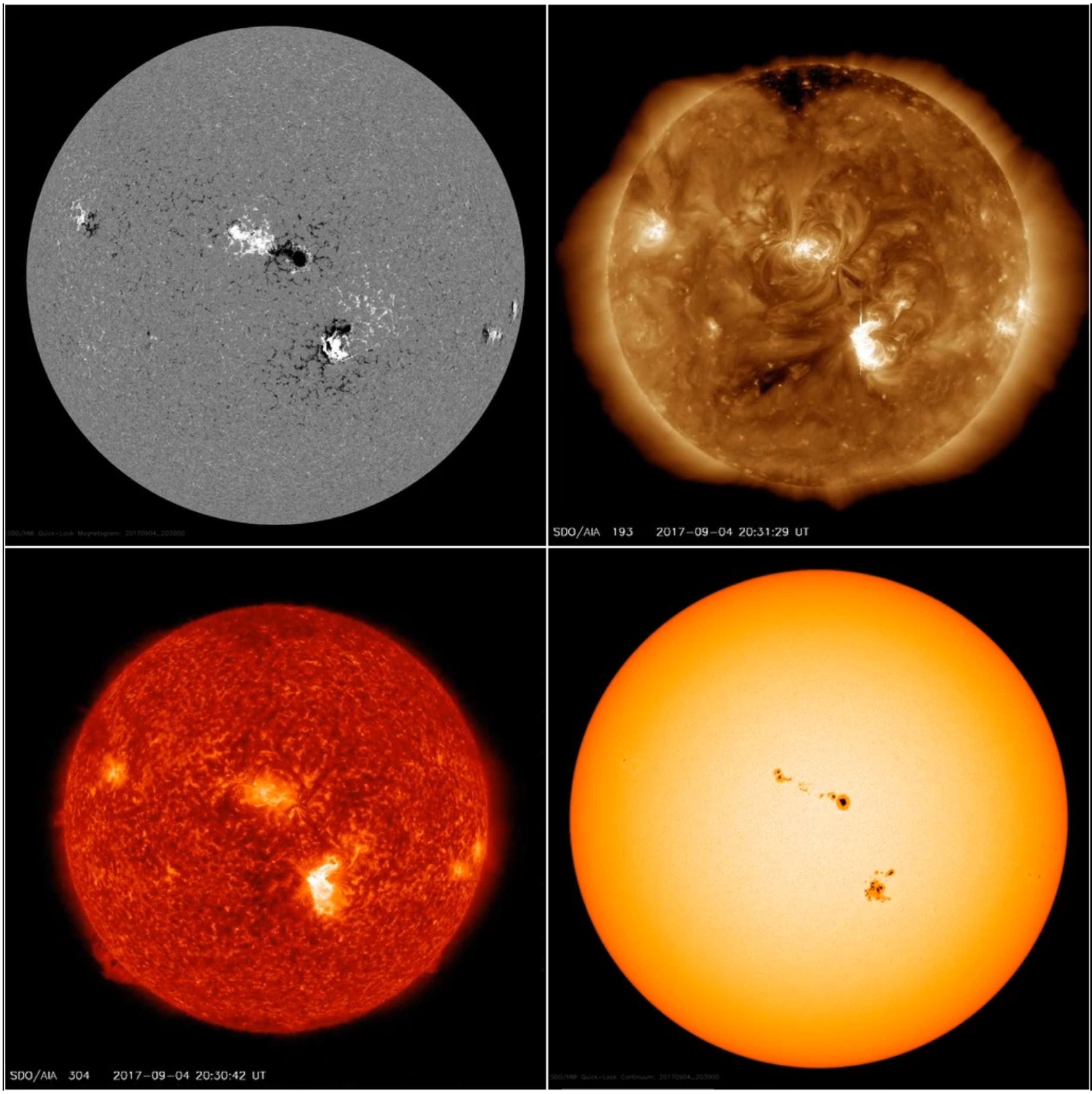

Fig. 4. Same as Figure 3, but a snapshot during a solar flare, as seen in the AIA 193 image in the top-right.

Based on the trends in these data, the students are then asked to explain whether they think the respective ARs pose a similar/increased/decreased threat to space weather for Earth over the next 2 days and why. They will be noting that AR2675 rotates away from Earth view, posing a decreased threat, AR2674 will be posing a similar threat due to its lack of change over the previous 3 days, and AR2673 will be posing an increased threat due to its rapid changes and flaring activity.

4.1.2 The Solar Wind Desk

At the Solar Wind Desk, the students are first directed to visually search the SOHO coronagraph images for any CMEs (Fig. 5). During this period, there were two notable CMEs in both c2 and c3 coronagraphs; one on the western limb at ~6 UT on Sep 2 and the other at ~21 UT on Sep 4 that is Earth-directed. The instruction manual indicates the differences between limb CMEs and Halo CMEs, so the students should be able to discern that the later CME, being a Halo CME, is of significance for future space weather conditions on Earth. The students are asked to give approximate arrival times for this CME, for which the students consult the instruction manual that states that 1–3 days of travel time is typical.

A noteworthy point for the instructor is that the Halo CME is visible in the coronagraphs only 30 min after the strongest solar flare that the Sun Desk should highlight in their discussion. These events are indeed related.

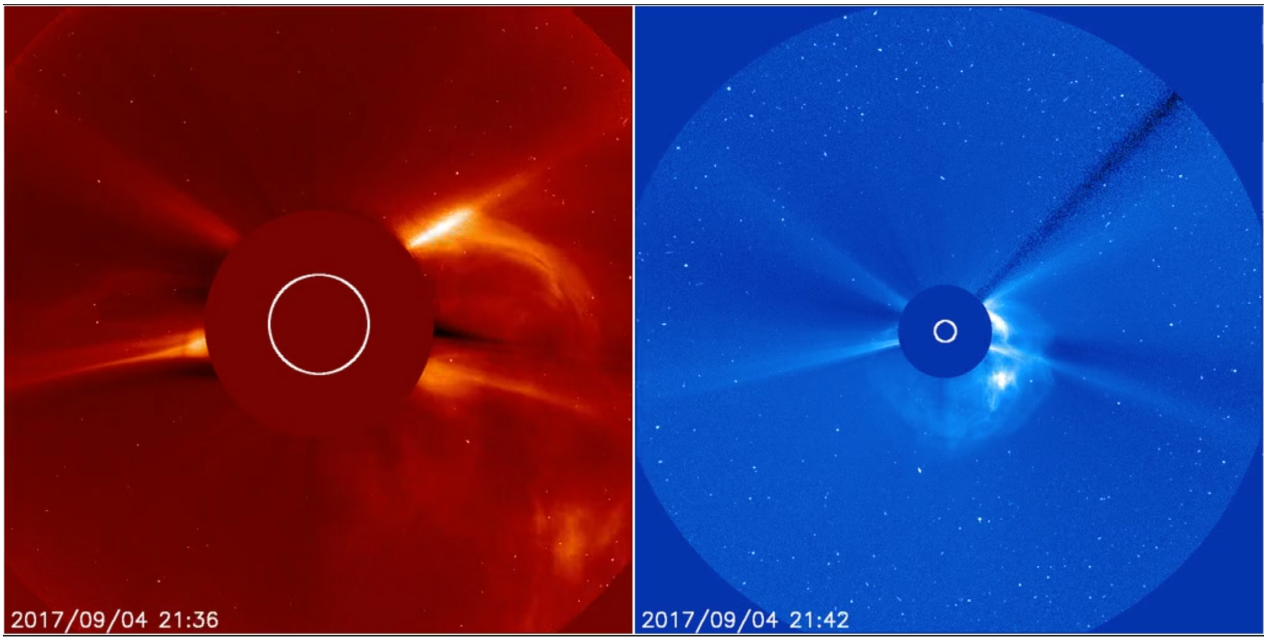

Fig. 5. A snapshot of the SOHO c2 (left) and c3 (right) coronagraph video showing the launch of an Earth-directed CME into interplanetary space during the first forecast interval. As with Figure 3, each frame contains images taken within 20 min of each other.

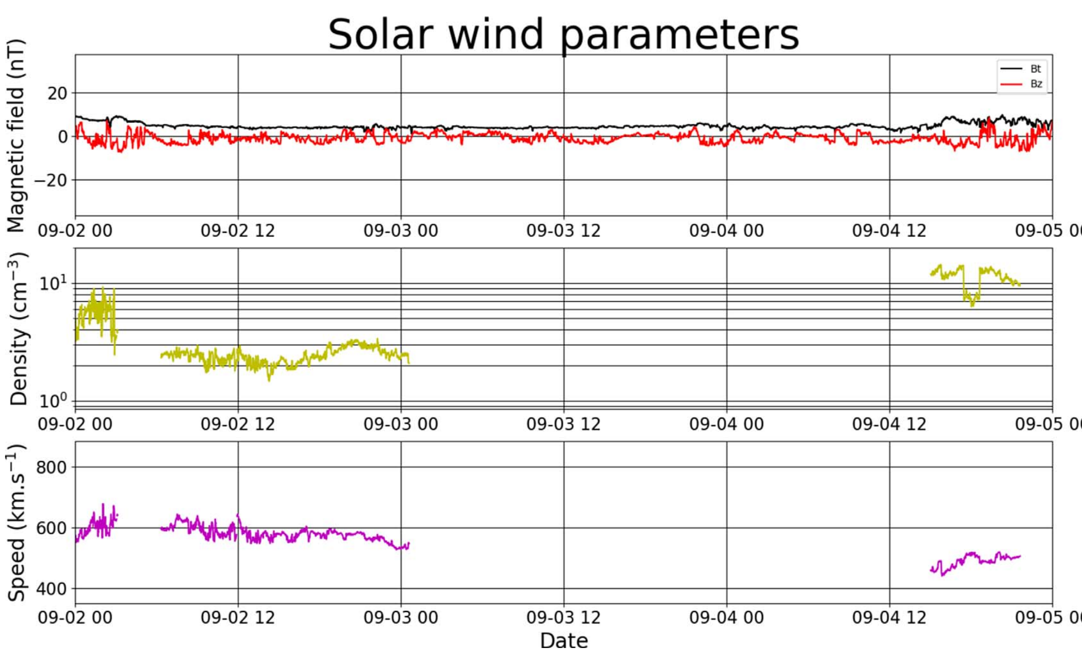

Fig. 6. Solar wind *in situ* data collected during the first forecast interval. The top panel shows the IMF strength (Bt, black) and the IMF Bz (red) component. The middle panel shows the solar wind proton density. The bottom panel shows the solar wind speed.

Next, the Solar Wind Desk students are directed to the *in situ* data (Fig. 6), for which they establish that the IMF variations are relatively stable, with the exception of some moderate activity in early Sep 2 and in late Sep 4 that could mean some moderate space weather activity for Earth during those times.

Also, the analysis of Figure 6 is an opportunity to teach students about data gaps. The students were asked what they could state about the solar wind speed and density between 12 UT on Sep 3 and 0 UT on Sep 4, for which there were obviously no data. Some students will attempt to interpolate across the data gap, but of course, the correct is an answer that they simply cannot state anything about these parameters over this period due to the lack of information. Importantly, this highlights to the students that data gaps, which can be rather common for some space weather datasets, can impact their situational awareness of the space environment.

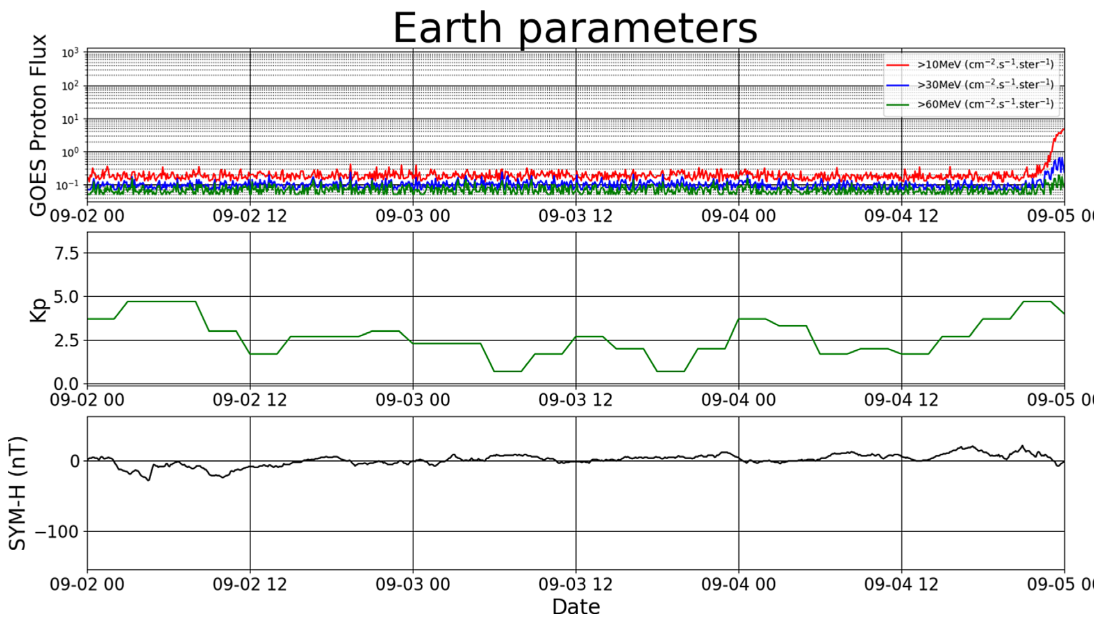

Fig. 7. The data displayed for the Earth Desk during the first forecast period. The top panel shows the GOES Proton Flux for energies >10 (red), >30 (blue) and >60 (green) MeV. The middle panel shows the 3-h Kp index. The bottom panel shows the minutely SYM-H index.

4.1.3 The Earth Desk

The data at the Earth Desk indicates the impact of the space environment on the Earth. Therefore, the students at the Earth Desk are in charge of assessing what warning/alert level has been reached or is likely to be reached, based on the data they analyze. Figure 7 shows the Earth Desk data i.e., the GOES proton flux for high-energy protons (with energies >10, >30 and >60 MeV), the Kp index and the SYM-H index over the Forecast Period.

Given the Earth Desk's analysis includes the solar radiation and the geomagnetic activity levels, the Earth Desk students directly draw on the NOAA Solar Radiation (S) and Geomagnetic Activity (G) Scales. Using the NOAA S and G scales, which are reproduced in the lab instruction manual for the students' reference, the students are asked to determine whether any thresholds have been breached that would initiate issuing an "Alert". A "Warning", on the other hand, is said to be issued in the event that there is a good possibility of a threshold being breached in the near future.

As can be seen in Figure 7, the flux of protons with energies >10 MeV (red line) exceeds 10^0 at the "current time" of the Forecast Period, but not the 10^1 threshold, which defines the beginning of an S1 level solar radiation storm. The students are asked whether any Alerts or Warnings need to be issued based on the Earth Desk data. In this case, the students should indicate that no Alerts be issued, but that an S1 Warning will be issued due to the trend of the >10 MeV proton flux in Figure 7.

Finally, the Earth Desk students are asked about whether any geomagnetic storms have occurred in the 3-day Forecast Period using the SYM-H index. In the instruction manual, the students are taught that $4 \leq \text{Kp} \leq 6$ or $-50\ \text{nT} \geq \text{SYM-H} \geq -150\ \text{nT}$ indicates moderate geomagnetic activity level, but Figure 7 only shows that the Kp index reaches this threshold on Sep 2 and Sep 4. This apparent disagreement is something the students discuss amongst themselves before answering the direct question that there were no geomagnetic storms over the 3-day period, using the SYM-H index.

4.1.4 Highlights of forecast period 1

1. Solar activity is abnormally high given that it is solar minimum – Sun Desk.
2. A strong solar flare takes place close to 20:30 UT on Sep 4 – Sun Desk.
3. An Earth-directed (i.e., "Halo") CME was observed at ~21 UT on Sep 4, and is expected to arrive at Earth within 1–3 days – Solar Wind Desk.
4. Some moderate activity was observed on Sep 2 and Sep 4 in *in situ* data – Solar Wind Desk.
5. Solar radiation storm appears to have commenced at ~23 UT, but still below S1 level on the NOAA Solar Radiation Storm scale – Earth Desk.
6. Some moderate geomagnetic activity was observed on Sep 2 and Sep 4 but not enough to register a G1 level on the NOAA Geomagnetic Storm scale – Earth Desk.

As the question sheets supplied to the students are worded very specifically to tease out these highlights (e.g., *At what time was the strongest solar flare?*), the students generally perform very well in observing each of these highlights. In instances where there are mistakes/misunderstandings, the class-wide discussions on these highlights serve as good opportunities to make clarifications. It is highlighted to students that items 2, 3 and 5 above all relate to the same space weather phenomenon. The relationship between items 4 and 6 is also mentioned as well.

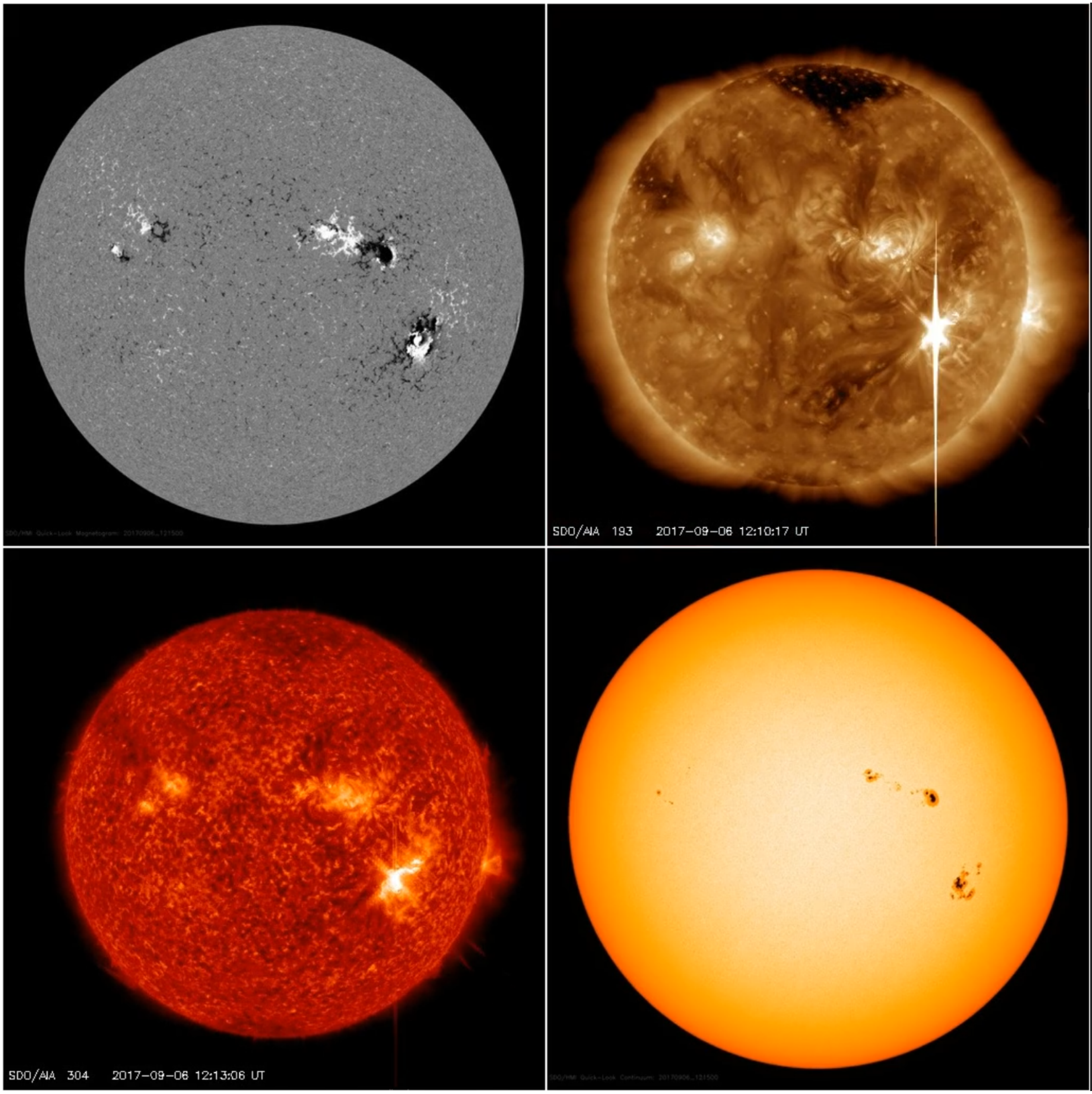

Fig. 8. Same as Figure 3, but during the strong solar flare on 06 Sep 2017.

4.2 Forecast period 2: 04-Sep-2017 to 07-Sep-2017

The next Forecast Period overlaps with the previous Forecast Period by 1 day, Sep 4; the students should recognize the overlapping data. The questions being asked of each Desk have some similarities to what was asked in the first Forecast Period.

4.2.1 The Sun Desk

The Sun Desk's SDO data stream shows the further development of AR2673, and the occurrence of significant flare activity on Sep 6. The strongest of these solar flares is the X-class flare at ~12 UT (see Fig. 8), which was the strongest in the previous decade.

The Sun Desk students are first asked if their forecasts for AR2673 were correct (i.e., increasing/decreasing/similar threat to space weather at Earth) and why. Then they are asked once again to mark down the time of the brightest solar flare. Finally, the students are asked to provide a short 2-day forecast for the activity expected from AR2673.

4.2.2 The Solar Wind Desk

The Solar Wind Desk students are first directed to examine the SOHO coronagraphs for more Halo CMEs. They should notice the CME on Sep 4 that they already spotted in the previous Forecast Period, but their attention quickly turns to another large Halo CME at ~13 UT on Sep 6 (Fig. 9). Once again, the

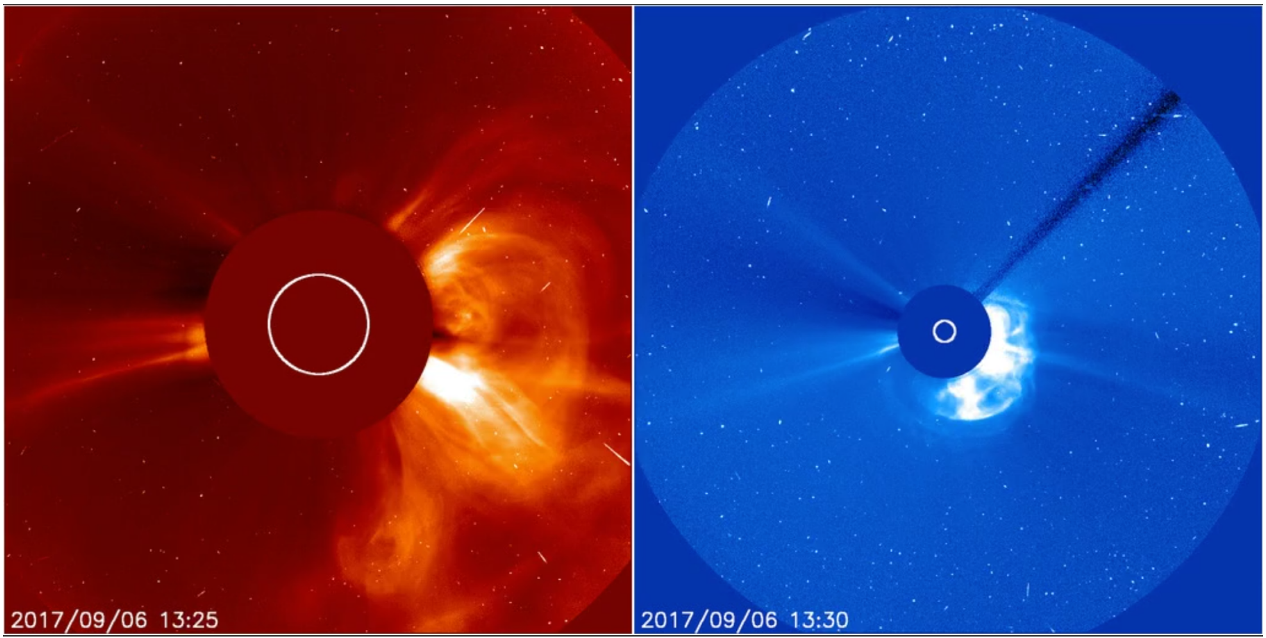

Fig. 9. Same as Figure 5, but showing the CME eruption associated with the strong solar flare shown in Figure 8.

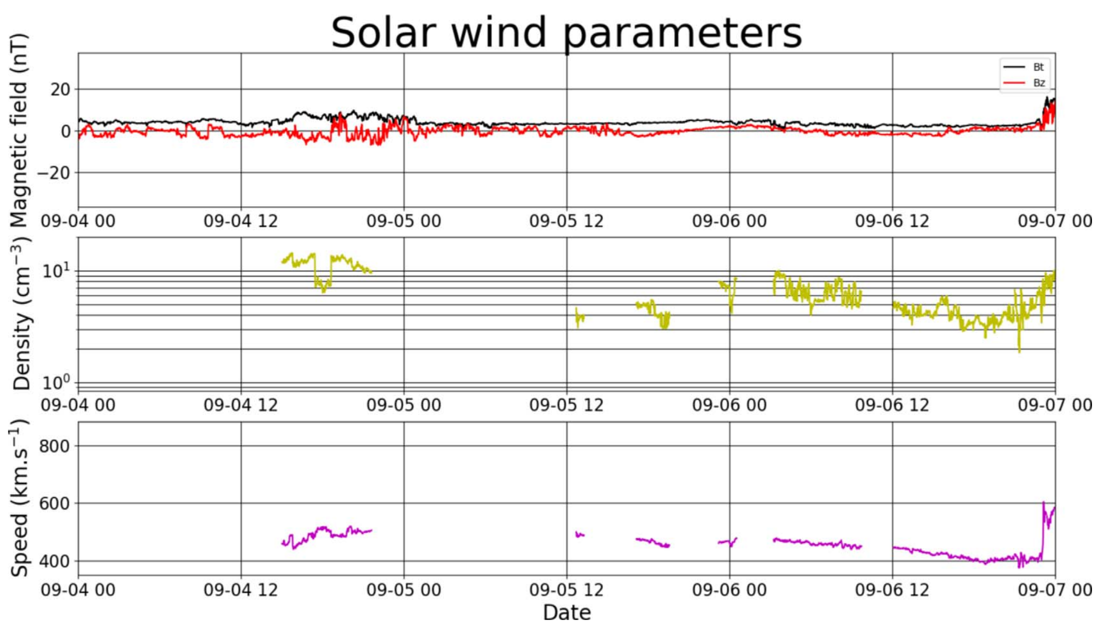

Fig. 10. Same as Figure 6, but for Forecast Period 2.

students are asked for the expected arrival time window for this CME within 1–3 days.

A note for the instructor is the fact that once again, the CME detected at the Solar Wind Desk is associated with the large solar flare detected at the Sun Desk in the same Forecast Period.

The students are directed to analyze the *in situ* solar wind data (Fig. 10) and are asked whether there are any notable features in that data that would be relevant for space weather on Earth. This time, the students should notice the sudden jumps in the IMF and solar wind speed data late on Sep 6. The instruction manual shows that sudden increases in solar wind speed indicate the arrival of a CME that is going to impact Earth. Thus, the students should be linking the Halo CME observed in the previous Forecast Period with this CME arrival at L1.

4.2.3 The Earth Desk

The Earth Desk students are shown the latest Earth parameters plot (Fig. 11) and are asked what Alerts and Warnings should be issued. In particular, it is clear from Figure 11 that the GOES proton flux has exceeded the 10^1 threshold for an

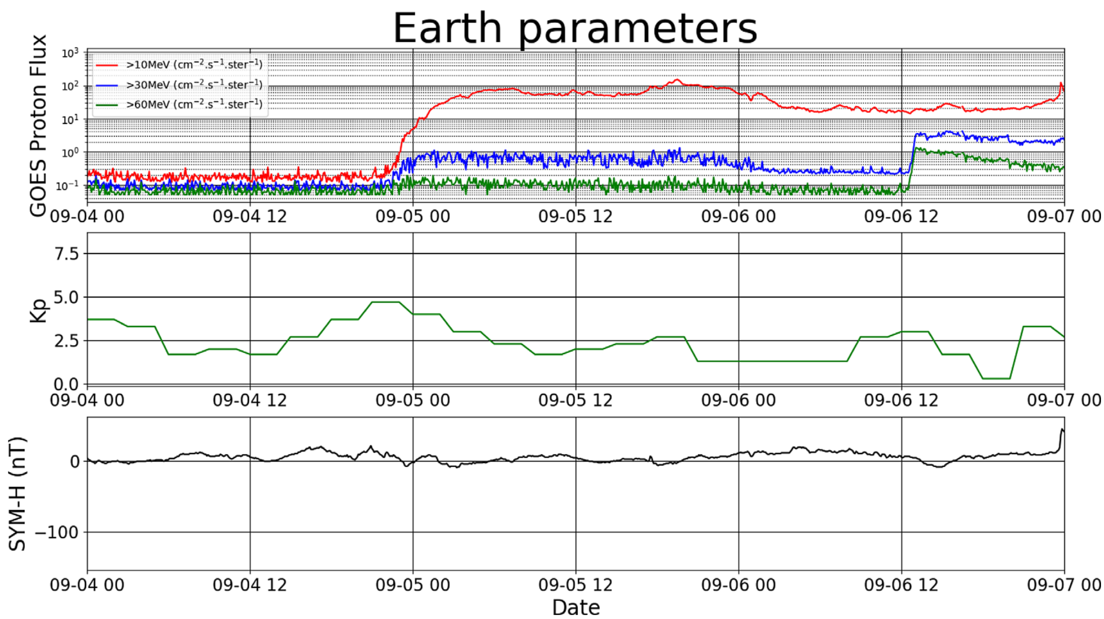

Fig. 11. Same as Figure 7, but for Forecast Period 2.

S1 storm, so an S1 Alert should be issued, but that geomagnetic activity is still low.

With respect to issuing Warnings, the students are asked which, if any, should be issued for the next 24–48 h, given the developing space weather conditions. At this point, they are aware that there is an ongoing solar radiation storm and that the CME that was launched on Sep 4 is en-route. Therefore, the students should be issuing Warnings for both solar radiation storms of S2 or higher and geomagnetic storms of G1 or higher based on their information. Some students might even notice that the CME has actually arrived very late on Sep 6, as indicated by the sudden spike in the SYM-H index (Fig. 11), indicating the commencement of a potential geomagnetic storm.

Another noteworthy connection for the instructor to consider is the timing of the strong solar flare identified by the Sun Desk, which was only moments before the sharp rise in the >30 MeV and >60 MeV protons in Figure 11. Thus, these phenomena are connected in the same manner as the flare, and solar radiation increase noted in the first Forecast Period. While direct communications between the Desks have not occurred for this Forecast Period, the SDO data is also visible from the Earth Desk, and the Earth Desk students are now familiar with the appearance of solar flares in the SDO imagery. Therefore, the more observant students might actually be able to independently connect these phenomena in their group discussions.

4.2.4 Hypothetical space weather scenario

All Desks share the same final question in Forecast Period 2. One can devise one of many options for this question, but the *highly unlikely* fictional scenario used in the running of this space weather prediction lab is as follows:

Your Desk has just received an urgent phone call from Roscosmos (the Russian Space Agency). One of their cosmonauts on board the International Space Station (ISS) has fallen ill and urgently needs to come back down to Earth to receive treatment. The Soyuz spacecraft that is currently docked with the ISS appears to have suffered engine loss, so the Russians want to launch an urgent crewed rescue mission with two cosmonauts within the next 24–48 h. For launch, radar is needed for telemetry and correct orbit insertion. Further, the Soyuz spacecraft is only lightly shielded against radiation compared to the ISS and its flight controls have electronics sensitive to radiation exposure.

Is your advice to:

1. *Delay the rescue mission for the next 48–72 h until space weather conditions ease.*
2. *Launch the rescue mission.*
3. *Launch the rescue mission, but make sure it is quick (~48 h).*

There are a few important points here for the students to consider. First is the mission time; within the next 1–2 days. Next is the reliance on the radar. Finally, the relatively light radiation shielding of the Soyuz spacecraft compared to the ISS. As part of their deliberations, the students are asked to refer to the NOAA scales, particularly the "Effect" section, to see which applications are affected at which levels.

At this stage in the exercise, there is a lot of space weather activity going on. The Earth Desk should notice that one CME has just hit Earth, but its severity is not yet known. An S1/S2 solar radiation storm is well underway. Further, another CME is en route and is expected to arrive within the next 1–2 days. Given all of this activity, and the mentions of radar, radiation to astronauts and spacecraft/satellite problems for the various S and G levels in the NOAA Scales, the students should be cautious and recommend delaying launch. However, it is often the case that students like taking risks and recommending to launch but making sure it is quick. At first glance, this scenario may invoke some ethics-themed discussions among the students, similar to the so-called "Trolley Problem", in which a choice must be made to sacrifice an individual or a group. Thus, students like to ask for details regarding the health of

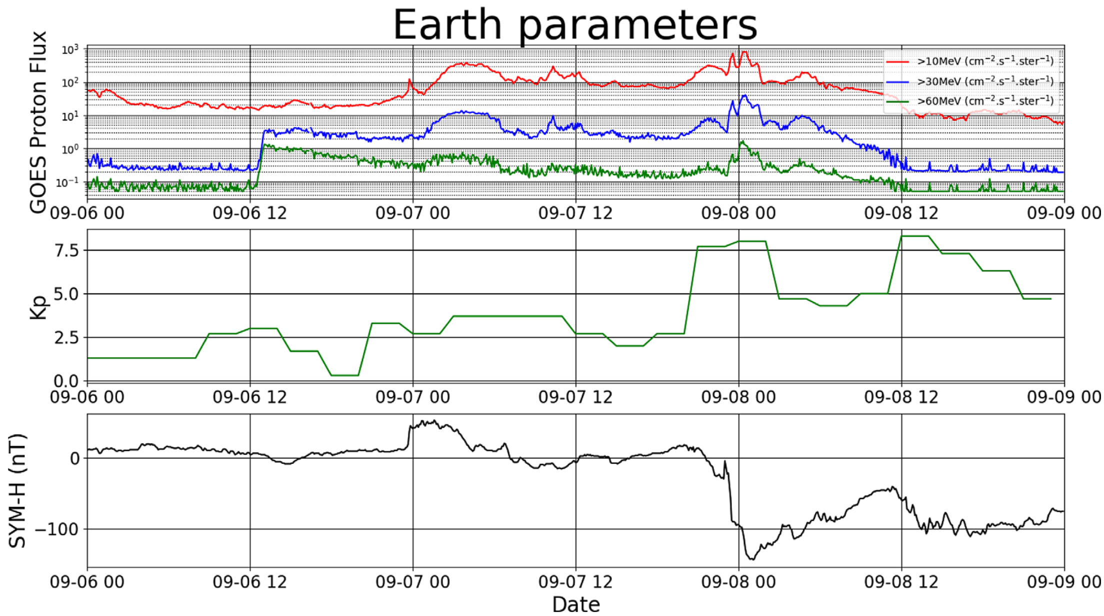

Fig. 12. Same as Figure 7, but for the Verification Period: 06-Sep-2017 to 09-Sep-2017.

the cosmonaut (e.g., "Are they likely to make it?"), but no further details are provided. Despite the interesting ethical side to this question, we take the correct answer to recommend delaying the mission and waiting for space weather conditions to ease. This answer is based upon the many relevant "Effects" of space weather in the NOAA scales, in combination with the ambiguous wording regarding the cosmonaut's status. Most student groups correctly opt to recommend delaying the launch. The second half of this question, which is worth equal marks, asks the students for their reasoning. This way, the students are evaluated based on the validity of their arguments as well.

Obviously, in reality, such situations are highly unlikely, and space weather is only one of many aspects that are considered in human space flight operations, but it does make for some entertaining education to have the students role-playing in this way. Other options for this question are not difficult to envisage, given the many applications impacted as listed in the NOAA scales, but the option of a potential scenario in which humans are directly involved is certainly one that attracts the students' motivation and attention.

4.2.5 Highlights of forecast period 2

1. A strong solar flare is observed close to 12 UT on Sep 6 – Sun Desk.
2. Another Earth-directed CME was observed at ~1330 UT on Sep 3, and is expected to arrive at Earth within 1–3 days – Solar Wind Desk.
3. L1 *in situ* data indicates the arrival of the first CME late on Sep 6 – Solar Wind Desk.
4. The first CME has just arrived at Earth, as indicated by the SYM-H data, but not enough time has elapsed for the storm intensity to register on the NOAA G scale – Earth Desk.
5. The solar radiation storm that commenced at the end of the previous Forecast Period is ongoing and has intensified to the S1 level on the NOAA S scale – Earth Desk.
6. The high-energy proton flux sharply increased at ~13 UT on Sep 6, potentially indicating another solar flare – Earth Desk.

Once again, the students typically perform very well in observing and noting each of these highlights. As part of the class discussions, the head lab demonstrator connects items 1, 2, and 6 together and notes that items 3 and 4 are linked.

4.3 Verification Period: 06-Sep-2017 to 09-Sep-2017

The Verification Period focuses on the Earth Desk data in Figure 12. The students are asked to review this data in the context of the answer to the hypothetical question they were all asked in the second Forecast Period. In particular, they must determine which solar radiation storm and geomagnetic storm levels were reached throughout the period, according to the NOAA scale definitions.

The students for all Desks are asked to determine whether their answer to the hypothetical question was correct or not, based on the Earth Desk data from Sep 6 to Sep 9. Ultimately, this part of the exercise allows the students to learn by assessing their own forecasts against what took place.

The laboratory exercise concludes with an online video of Dr Tamitha Skov's overview and forecast for the September 2017 events that were recorded at the time[22]; this video can also be seen on display in Figure 1. Showing this video to the students reveals to them how well they did during the exercise and how much they have learned, in addition to reinforcing many of their lessons over the 2-h period. Finally, the students are encouraged to keep their own eyes on the real-time space weather data feeds on the NOAA SWPC[23] and Bureau of Meteorology Space Weather Services[24] websites, which are

[22] https://www.youtube.com/watch?v=oMAl5b5cXm0
[23] https://www.swpc.noaa.gov/
[24] https://www.sws.bom.gov.au/SpaceWeather

shown to the students in the lab as well. This conclusion to the laboratory practical is intended to highlight to the students the real-world importance of space weather prediction.

5 Transition to online learning due to COVID-19

The space weather prediction laboratory was designed to be conducted in person in the VXLab at RMIT. However, a sudden transition was made to an online learning environment as part of the University's response to the threat of COVID-19 in 2020 and the associated Government-imposed travel restrictions and social distancing requirements.

In order to most closely match the format of the laboratory exercise described in Section 3.4, the capability to interact with the class together and in small separated groups was required. BigBlueButton was one of the few platforms available that had the option of "break-out" rooms in addition to a class-wide voice and text chat facility, and it was chosen to run the online version of the space weather prediction lab.

This platform allowed us to run the lab in very much the same format as described in Section 3.4. The introductions, post-forecast period class discussions and final conclusions were conducted within the "main" room, and the Forecast and Verification Periods in which each Desk analyzed data and discussed their forecasts were conducted within the Desk-specific "break-out" rooms. Importantly, each break-out room required a lab demonstrator to display the data for that Desk and facilitate the group discussions. In addition, access to an online version of the question sheet was given to each student so that they could collectively work on the answers together.

The students generally made the transition to an online environment very quickly. The specific BigBlueButton platform runs directly from almost any web browser, so no additional training was required for the students. Also, the shared online question and answer sheets were also hosted in the standard web browsers. Despite some technical difficulties preventing some students from providing input with voice, the text chat facility enabled students to actively participate. This was a good opportunity for students to utilize their teamwork skills.

6 Student performance and feedback

Prior to going into the details of the student performance and feedback, it is worth highlighting that at the time of taking the lab, the students have not yet engaged in any active teamwork activities as part of this "Space Exploration" course. Further, this laboratory exercise is a once-off 2-h activity, with 3 groups of 3–4 students. As such, a little care was needed in deciding how to fairly award marks for this exercise, given that the students' familiarity with each other and teamwork activities, in general, was limited. To facilitate some mixing of weaker and stronger students, these groups were chosen at random by the instructors (Gibbs, 1995). To ensure some degree of fairness in the student assessment, the students' performance throughout the laboratory exercise was measured using a combination of two components; (1) the answer sheets submitted by each Desk following both the Forecast Periods and the Verification Period (worth 80%), and (2) the individual student's ability to work effectively as a team member (worth 20%).

As the answer sheets submitted by each Desk are the culmination of the group's collective work, all students at each Desk were awarded the same marks for this component. On the teamwork component, each student was awarded individual marks, and the feedback supplied was based on the demonstrators' observations throughout the 2-h laboratory. It was chosen to assess students on their teamwork abilities in an attempt to engage all students in the exercise (and to discourage individuals "free-loading" off their teammates), and to promote healthy teamwork attitudes and practices. This rationale of awarding marks to students both on a team basis and an individual basis is supported by previous pedagogical studies (e.g., Gibbs, 1995; Adams, 2003). While this method of marking is more work for the demonstrators and relies on a healthy teacher: student ratio, providing all students with some individual feedback is of significant benefit (Adams, 2003), particularly to poorly performing students.

In terms of the expectations of students regarding the teamwork component, the students were all informed at the beginning of the exercise that they were being marked on their ability to work as a member of a team, and that talking over the top of one another, interrupting and excluding others from the group's discussions and decision-making were to be avoided. Particularly positive feedback and high marks were issued for students that actively encouraged their quieter teammates to participate in the group discussions.

One aspect of the laboratory that could, in principle, be used to mark the students and provide feedback is the oral presentations that are given to the wider class following each Forecast Period. For instance, the students could be marked on their ability to communicate to the class the most important aspects of their Desk's data analysis, using the correct scientific terminology, and on their oral presentation style/professionalism etc. However, given that this student cohort was quite junior, it was decided to not apply this additional pressure and to instead provide a more relaxed learning environment. Assessing student performance based on these presentations is certainly possible for more advanced/experienced students.

Figure 13 shows the distribution of student marks awarded in the 2020 cohort. A total of 50 students participated in the laboratory, achieving average and median marks of 85% and 86%, respectively. The most common bin was 15 students that achieved a mark between 90% and 95%; only 4 students achieved higher than this. The high marks exhibited collectively by all students are arguably the result of the heavily weighed group work component of the exercise, coupled with the high demonstrator-to-student ratio of 1:4. Although importantly, Figure 13 is evidence that this space weather laboratory exercise was not too difficult for these early undergraduate students, despite them only having limited prior knowledge beforehand.

In terms of student feedback, students are invited to provide course feedback at the end of each semester in order to measure and track the quality of the students' experience. Within the course feedback for "Space Exploration", there were several notable mentions of the laboratories in the comments. For instance, "*Lab was super fun and interesting*" and "*The mission control and space weather practicals for this course were very*

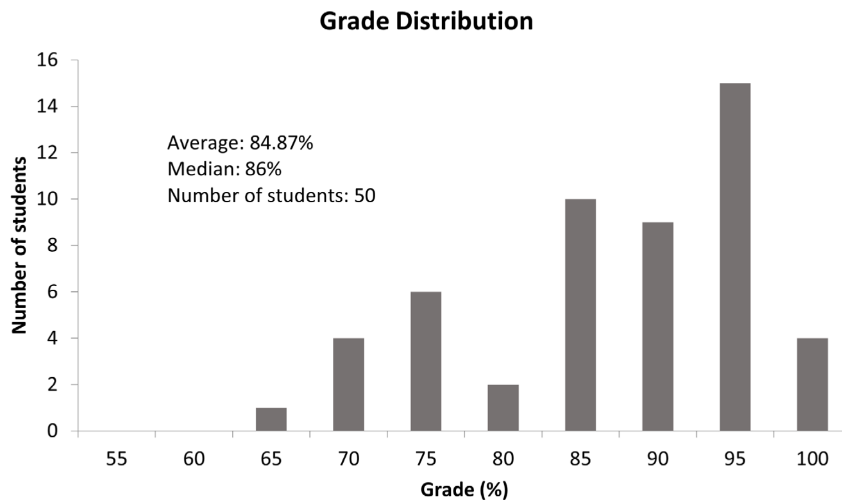

Fig. 13. Distribution of class marks for 50 undergraduate students received after participating in the space weather practical session.

engaging". Importantly, no negative feedback regarding the laboratories was received by the 2020 student cohort.

7 Laboratory evaluation and future plans

While the student grades and feedback provide some insight into the effectiveness of the Space Weather Prediction Laboratory, it falls short of determining its true impact on the students and their learning. To address this, plans are in place to prepare a formal survey for the students undertaking the space weather laboratory for us to quantify whether the goals of the space weather prediction lab are being met. In particular, it would be important to measure the students' knowledge of space weather prior to and after undertaking the lab, their comfort level in interpreting scientific data in a time-pressure environment, and whether the students find the laboratory environment to promote learning and healthy teamwork attitudes for them and their peers.

Plans are also in place to develop more complicated offerings of this laboratory exercise to challenge more senior/advanced students. For instance, additional datasets – such as the Solar TErrestrial RElations Observatory (STEREO) data (Kaiser et al., 2008) and the GOES X-ray flux – and the NOAA R scale could be used for more advanced students. Further complexity in the exercise could come from the choice of more challenging space weather events (e.g., so-called "stealth CME events") or even artificially generating data gaps to add more "known unknowns" to the exercise. A significant benefit to teaching space weather practical labs such as this is the ability to easily scale the difficulty to suit the level of the students.

Another aspect of the space weather lab that is being considered for the future is the teamwork component of the exercise. As Adams (2003) discusses, a "team" consists of individuals that take on different and interdependent roles that make reaching the team's goal(s) possible. Whereas in this exercise, the students work together towards a common goal, but without specific roles being defined and assigned to the students; as such, one would perhaps use Adams (2003)'s definition of a "group" to describe them. In future offerings of this lab exercise, we, therefore, have plans to create and assign specific roles to students to enhance their teamwork experience.

8 Summary

A new Space Weather Prediction Lab exercise was developed to give students: (1) a short and intense introduction to aspects of space weather and its impact on technologies; (2) hands-on experience in space data analysis, interpretation and communication; and (3) an immersive space science experience that fosters learning, teamwork and scientific transparency. Importantly, the Lab was designed to suit students with a range of backgrounds, not just physics and mathematics. While initially pitched at first-year undergraduate students, the exercise is scalable to suit more/less advanced students by selecting more/less complicated space weather events and more/less datasets to examine. The Lab was designed for face-to-face learning, leveraging RMIT's VXLab facility, but was versatile enough for prompt adaptation for online learning in the face of COVID-19 restrictions. Importantly, the marks of the first students to do the lab provide a strong indication that the students successfully grasped the core elements of space weather prediction and that the difficulty of the lab exercise was pitched appropriately. Collaborative tasks produced expected outcomes, with all groups completing the activity and demonstrating shallow and deep knowledge outcomes. Finally, student experience feedback received for the Space Weather Lab exercise was very positive.

Supplementary materials

Supplementary material is available at https://www.swsc-journal.org/10.1051/swsc/2022025/olm

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