Space Weather Modeling and Prediction for Intermediate Time-scales

Principal author: M. Dikpati (NCAR/HAO), 3080 Center Green Dr., Boulder, CO 80301, ORCID ID: 0000-0002-2227-0488

Coauthors: J. L. Anderson (NCAR/CISL, ORCID ID: 0000-0001-6227-6983), B. Belucz (Sheffield Univ., ORCID ID:), D. Biesecker (NOAA/NESDIS, ORCID ID: 0000-0001-9804-4199), G. Bothun (Oregon Univ., ORCID ID:), S. Chatterjee (SWRI, ORCID ID: 0000-0002-5014-7022), Y. Fan (NCAR/HAO, ORCID ID: 0000-0003-1027-0795), S. E. Gibson (NCAR/HAO, ORCID ID: 0000-0001-9831-2640), H. Gilbert (NCAR/HAO, ORCID ID: 0000-0002-9985-7260), P. A. Gilman (NCAR/HAO, ORCID ID: 0000-0002-1639-6252), G. A. Guerrero (Univ. Fed. de Minas Gerais & NJIT, ORCID ID: 0000-0002-2671-8796), J. T. Hoeksema (Stanford Univ., ORCID ID: 0000-0001-9130-7312), K. Jain (NSO, ORCID ID: 0000-0002-1905-1639), I. N. Kitiashvili (NASA/AMES, ORCID ID: 0000-0003-4144-2270), M. Korsos (Sheffield Univ., ORCID ID: 0000-0002-0049-4798), A. G. Kosovichev (NJIT, ORCID ID: 0000-0003-0364-4883), R. J. Leamon (UMBC, NASA/GSFC, ORCID ID: 0000-0002-6811-5862), M. Linkmann (Edinburgh Univ., ORCID ID: 0000-0002-3394-1443), S. W. McIntosh (NCAR, ORCID ID: 0000-0002-7369-1776), A. A. Norton (Stanford Univ., ORCID ID: 0000-0003-2622-7310), N. E. Raouafi (JHU/APL, ORCID ID: 0000-0003-2409-3742), B. Raphaldini (NCAR/HAO, ORCID ID: 0000-0002-0744-9746), M. Rempel (NCAR/HAO, ORCID ID: 0000-0001-5850-3119), S. C. Tripathy (NSO, ORCID ID: 0000-0002-4995-6180), L. Upton (SWRI, ORCID ID: 0000-0003-0621-4803), H. Wang (NJIT, ORCID ID: 0000-0002-5253-565X), S. Wing (JHU/APL, ORCID ID: 0000-0001-9342-1813)

Synopsis: Much of solar activity within a sunspot cycle occurs as bursts, or 'seasons' of strong activity over several months, separated by periods of much less activity. The most important space weather effects occur during these bursts. Previous modeling and forecasting efforts have focused on time-scales of hours-to-days and decades-to-centuries. The recent discovery of Rossby waves in the Sun, together with recently developed global models of solar MHD Rossby waves and their interactions with differential rotation and spot-producing magnetic fields, reveal the opportunity to simulate and predict the occurrence, strength and location of enhanced activity bursts a few weeks up to several months in advance. We now have a golden opportunity to fill in this gap in time-scales of forecasting space weather. This requires a) continuous observations of solar Rossby waves by various techniques; b) development of coupled nonlinear MHD models that simulate both global Rossby waves and the much smaller spatial scale emergence of new active regions; c) application of advanced data assimilation techniques to couple surface observations to update the model-system to integrate forward in time for creating forecasts months ahead. Then it will be possible to build operational prediction models to meet the needs of customers and stakeholders, including support of future NASA missions, regarding what kind and level of space weather to expect a few weeks to several months ahead.

1. Overview: "Space Weather" describes the conditions in the terrestrial system, particularly on its outer envelope, that can affect various ground- and space-borne technologies due to the impact of energetic particles and magnetic fields streaming from the Sun. This could be due either to the continuous flow of solar wind or to the onset of CMEs or flares in a short interval of time. The chain of processes involved in transmitting the adverse, hazardous effects of these energetic particles into the Earth's atmosphere is extremely complex. However, over the past several years considerable effort has been undertaken to understand and predict space weather on time-scales from a few minutes-to-hours up to a few days. A comprehensive roadmap can be found in Schrijver et al. (2015). Also, studies to understand the effects of adverse solar events occurring on longer time-scales from decades to centuries, on society's space-weather-sensitive instruments, industries, national security systems, etc., have continued for many years. In particular, progress has been made in recognizing that the most likely "seed" of the next sunspot cycle is the polar field of the previous cycle's minimum. (talk about the asymmetry in polar field and hence in sunspot cycle due to mc).

In addition to very short (hours-to-days) and much longer (decadal to millennial) time scales where solar events could arise, there is an important intermediate time scale, the interval from weeks-to-months (see, e.g. Dikpati & McIntosh 2020 and references there in; see also Simoniello et al. 2012) over which solar activity varies strongly. These events are often called 'quasi-annual' or 'seasonal' variability, during which an enhanced burst of solar activity is followed by a relatively quiet interval. The strongest space weather events happen during the enhanced bursts of activity or "bursty seasons". Therefore, understanding the origins of and predicting major space weather events on time-scales from weeks to months ahead, has significant scientific and economic value. This 'intermediate' time-scale would also fill-in the gap between the short and longer time-scale forecasts of space weather.

For more than half a century, the Earth's weather has been forecasted by simulating the meanders of the mid-latitude "jet stream" and associated large scale weather systems, such as cyclones and anticyclones (low- and high-pressure patterns with counterclockwise and clockwise flows on weather maps). The jet stream is the product of interactions of global Rossby waves and mean East-West flows in the troposphere and lower stratosphere. Assimilating vast amounts of observational data into complex computational models has led to enormous improvements in forecasting the weather out to more than a week ahead, including cold outbreaks and winter storms as well as floods and dry periods. Over the past several years, solar Rossby waves have been observed starting with McIntosh et al. (2017; see also Löptien et al. 2018). The time-scale of the Rossby and other inertial modes might be related to the "seasonal" variability. While solar Rossby waves were modeled since late 1980's (Dziembowski & Kosovichev 1987), their nonlinear interactions with solar differential rotation and spot-producing magnetic fields have only recently been demonstrated to play roles in space weather, relating to the short-term (seasonal) variability patterns of solar magnetic activity (Dikpati et al. 2017, 2018). We are entering a golden era to forecast Rossby-like waves in the meandering pattern of the Sun's spot-producing toroidal magnetic fields, leading to an ability to forecast enhanced solar activity bursts weeks to months ahead. In turn, these will allow us to anticipate major space weather events well ahead of time, since they are closely tied to these bursty 'seasons' (McIntosh et al. 2015, see also Temmer et al. 2001).

2. Recent progress and current status: In recent years observational evidence for the existence of solar Rossby waves has been accumulating rapidly (McIntosh et al. 2017; Löptien et al. 2018; Hanasoge & Mandal, 2019; see Zaqarashvili et al. 2021 for a detailed review). In addition, surface velocity measurements give further hints of the presence of Rossby waves on the solar surface (Hathaway & Upton 2021). Rossby waves, which arise in thin fluid layers in stars and planetary atmospheres, occur due to variations in Coriolis force with latitude. But unlike planetary waves, solar Rossby waves are most likely magnetically modified. Very much like the Earth's jet stream, solar Rossby waves can create large-scale meandering patterns in the spot-producing magnetic fields (Cally et al. 2003; Dikpati et al. 2021).

Although signatures of solar Rossby waves have been detected in the photosphere and corona, it is likely that most of these waves are generated below the surface, in a much less turbulent zone, such as at or near the base of the convection zone (Triana et al. 2022, Bekki et al. 2022), or in the supergranular layer in a restricted way, since the supergranules have primarily large-scale horizontal motion (Dikpati et al. 2022). Theoretical model developments for solar Rossby waves in both hydrodynamic and magnetohydrodynamic regimes, including neutral and unstable waves, nonlinear waves and their interactions with differential rotation and spot-producing toroidal fields are rapidly advancing. It has been demonstrated that these interactions produce Tachocline Nonlinear Oscillations (TNOs; see, e.g. Dikpati et al. 2017, 2018a, 2018b). TNOs occur due to back-and-forth exchanges of energies among RW, DR and TF, in a way similar to nonlinear Orr mechanism in fluid dynamics (Orr 1907). TNOs may play a crucial role in determining the timings and latitude-longitude locations of magnetic flux emergence, and in turn, the 'seasons' of major space weather events. While originally applied to the tachocline itself, this shallow-water model of MHD Rossby waves can be applied to any layer below the solar surface that is subadiabatically stratified, such as the lower half of the convection zone found in numerical simulations (See, e.g., Kapyla et al. 2017).

To briefly describe the physics, we display in Figure 1 a snapshot of a shallow-water model-output that shows upward bulges that extend into the convection zone above. If these bulges contain toroidal fields, they are likely sources of magnetic flux that could emerge in the photosphere as active regions. But to model how this flux gets to the photosphere requires a different class of models, which are more local in nature and focus on interactions between rising flux tubes and convection, influenced by Coriolis forces (see Fig 2 for a schematic of the combined physical system). Models for both local and global scale processes defined above currently exist, but they have yet to be coupled into a single model system that describes the whole sequence of processes that take dynamo generated toroidal fields deep inside the Sun and emerges them as active regions, whose number and strengths wax and wane through solar seasons of 6-18 months duration. Such coupled models should be a major priority in solar-terrestrial physics over the next decade. For predicting solar activity bursts several months ahead it is necessary to model the evolution of the spot-producing toroidal fields from the depth where they are generated. These models will create and evolve the “imprints” of spatio-temporal distribution of active regions that are observed in magnetograms.

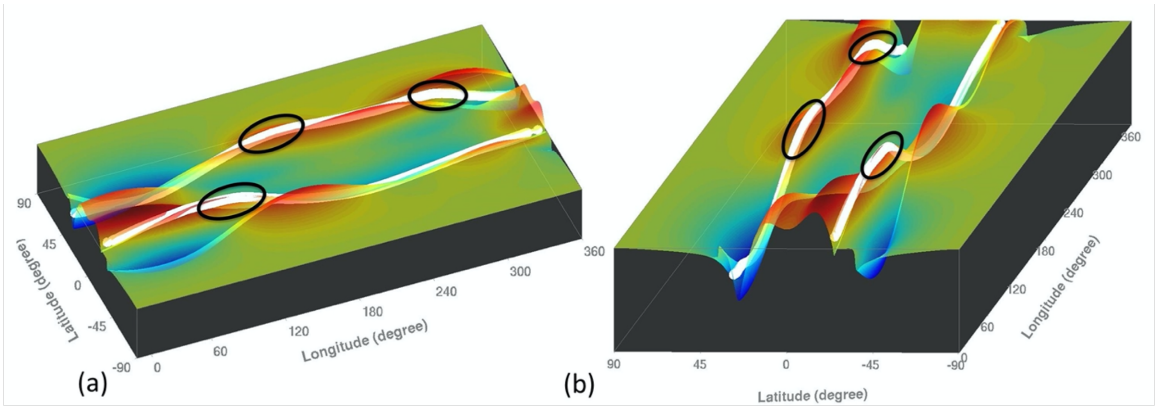

Figure 1. Two perspective snapshots of top-surface (color-shade) of a tachocline fluid shell, viewed respectively along longitude (left panel) and latitude (right panel), during its MHD evolution; red/orange represents swelling of the fluid and blue/sky-blue the depression. Yellowish-green represents neutral thickness. The shallow-water tachocline model has a rigid bottom and deformable top; vertical extent denotes the tachocline thickness (20 times enlarged). Portions of the toroidal magnetic bands (two white tubes one each in the North and South hemispheres) that coincide with swelled fluid are shown encircled by black ellipses – these portions start entering the convection zone, and hence are more likely to buoyantly erupt at the surface.

The coupling of global and more local scale physical processes is somewhat analogous to what is modeled for weather forecasting. In that case, global hydrodynamic Rossby waves and jet streams (analogous to the solar differential rotation) interact to produce geographic areas where the most significant weather occurs. This weather is closely tied to patterns of cloudiness, as seen in satellite images, and typically occurs on considerably smaller horizontal scales than are defined by Rossby waves and jet streams. Weather forecasting models are much more advanced than are the solar models described above. They include the full range of physics, and spatial scales needed to model both the global and smaller scale processes responsible for the weather. What weather occurs, particularly precipitation patterns, is of course closely linked to the geographic distribution of moisture and the locations where large scale motions have an upward component that causes the moisture to condense as clouds resulting in rain or snow (Eixmann et al. 2010). Generally speaking, where moisture levels are high, more weather involving precipitation occurs in places where there is upward flow; where moisture is low, there are still Rossby waves and jet streams, yet much less cloudiness and therefore less weather, even if there is still upward flow.

The analog to moisture in the Sun is, in some sense, the toroidal field. If there is a strong toroidal field in a bulge into the convection zone (see, e.g., the black ellipses in Fig. 1), which itself is caused by upward flow in shallow water systems, then that location is more likely to be the site of rising magnetic flux precursor of an active region on the surface. With a weaker toroidal field, the ARs produced should be smaller. With no toroidal field there, then no active regions will be formed (detailed scenarios of flux emergence are described in Dikpati et al. 2021). On Earth, high moisture areas with downward motion will not produce much weather. In the Sun, a stronger toroidal field located in a depression of the tachocline created by inward motion is less likely to generate outward propagating magnetic flux that results in a surface AR.

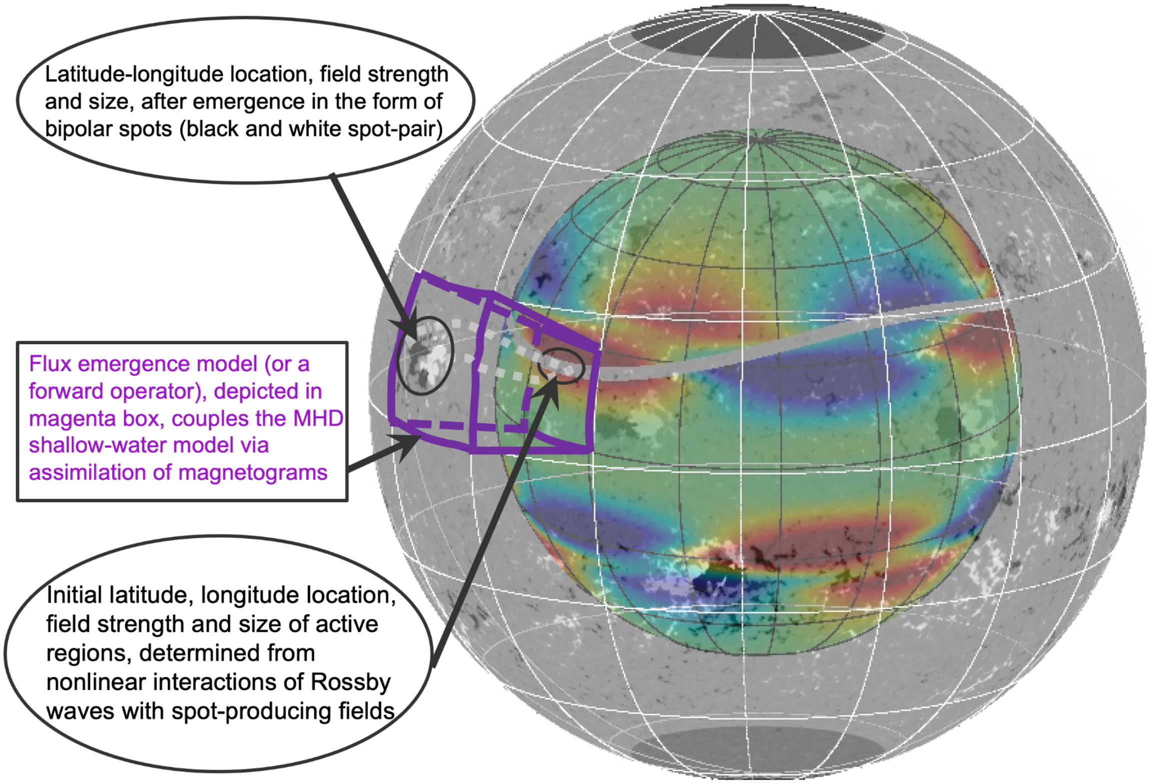

Figure 2. Inner sphere in the rainbow colormap shows tachocline top-surface, on which spot-producing magnetic band is wrapped-up, displayed in grayish-white. Meandering pattern seen in this band is created due to nonlinear interactions of Rossby waves with spot-producing magnetic fields, which could coincide with bulging (red), depression (blue) or neutral thickness (yellowish-green). If the spot-producing magnetic fields coincide with bulging (such as that in the black ellipse in the inner sphere), they get pushed up to enter convection zone, through which they make their buoyant rise to the surface to emerge as bipolar active regions (black ellipsed region in the semi-transparent outer sphere). Magenta box denotes a flux-emergence recipe (an MHD model or a forward operator), which determines the surface locations of the emerged flux, their strength, size, timing as well as tilts, which are compared with surface observations. Data assimilation procedure compares outputs of this model-system (global MHD tachocline model coupled with flux-emergence recipe) with surface observations, and corrects the initial conditions to simulate spatio-temporal patterns of active regions' emerence.

The physical analogies between Earth and Sun described above, and the sustained success that atmospheric modelers have had in predicting weather a week or more ahead, gives great support to the concept of achieving similar success over the next decade in model-based forecasting of solar activity bursts several months ahead. One day on Earth is one rotation on the Sun, so a year is about 13 solar 'days'. Rossby waves, differential rotation and toroidal fields evolve due to their mutual nonlinear interactions on a time scale of a few months (a few solar 'days') to a year or so. Simulating and predicting this mutual evolution accurately from observed initial conditions is essential for predicting the evolution of surface solar activity on solar 'seasonal' time scales. Hence this should be a realistic goal for research and development over the next decade.

Thus, a key to forecasting space weather on intermediate time-scales requires an accurate estimate of amplitudes and phases of solar Rossby waves and the link between the observations and model-outputs through data assimilation techniques. Such techniques are also being implemented in solar models. So, what are the necessary future steps to advance forecasting on these time-scales?

3. Exciting future efforts and projects

We list below an overlapping sequence of efforts to achieve the goal of forecasting future solar activity bursts and the space weather that they stimulate..

3.1: Continuous observations of Rossby waves are necessary for the next few sunspot cycles: Observational methods would include helioseismic, as well as surface global velocity and magnetic patterns. Along with space-borne observations (such as from STEREO, SoHO, SDO and proposed future solar polar observations, e.g. Hassler et al. 2022 white paper), ground-based measurements (such as ngGONG -- the Next Generation GONG network: A. A Pevtsov, et al. 2022, Future Ground-based Facilities for Research in Heliophysics and Space Weather Operational Forecast, White Paper submitted to the Decadal Survey for Solar and Space Physics (Heliophysics)) will also be needed. A unique enabling measurement would be made by the proposed COSMO telescope using coronal spectropolarimetric measurements of line-of-sight magnetic field, which at the solar limb is equivalent to toroidal magnetic field, and would be measured globally and synoptically (Tomczyk et al. 2022 white paper). Aligning with our goals of predicting space weather on intermediate time-scales, the observations would be optimal to be most sensitive to changes on time scales of weeks to months.

3.2 Theoretical models of global MHD Rossby waves and flux-emergence models need to be advanced and merged: So far, models for meandering pattern-development due to interactions of Rossby waves with mean flows and magnetic fields have been developed in 3D thin-shell shallow-water regimes to conform with the large horizontal scales and much less variation in vertical scale. Models including substantial variations in the vertical are necessary in order to model and predict the attenuation of these waves as they propagate to the solar atmosphere. The Rossby wave models also need to allow for interactions with other waves and instabilities in both the tachocline and the convection zone.

Theoretical models for how toroidal flux rises from the base of the convection zone to the photosphere, and its nature in the photosphere, need to be greatly advanced. The relative roles of convection and magnetic buoyancy in this process need to be determined. Furthermore, coupling of flux-emergence, being one of the complex issues, needs to be explored through physical models (see, e.g., Fan 2009) as well as flux-emergence recipes derived from the applications of data assimilation, machine learning, artificial intelligence and information theory (e.g., see Wing et al., 2018), and also by simulating the flux emergence in global-scale (see, e.g., Guerrero et al. 2019).

A particular challenge for the next decade is to accurately simulate and predict the latitude-longitude location, timing and complexity of emerging delta-spots, which are responsible for about 80 percent of X-class flares and CMEs, which are major components of space weather that impact the Earth.

3.3 Connecting model-outputs with observations using advanced data assimilation methods:

These prediction models would be initialized using data assimilation of the observations (surface and helioseismic) most closely associated with the physics of each model, to test their ability to predict velocities and magnetic field changes on time scales of weeks to months. Some form of each class of model, or a combination of models, can be tested to determine how model-outputs compare with observed emergence of solar magnetic fields for many magnetic cycles. Advanced data assimilation techniques that produce estimates of forecast uncertainty and error correlation are required. Recent advancements in the NCAR-DART tools provide constraints to be put on physically bounded quantities; a solar example will be the bounds in phase speed of Rossby waves inferred from observations (Anderson 2022).

Note that currently the magnetic field distribution of the entire solar surface is captured through a Carrington map (also known as Synoptic map; see e.g., Figure 3) which is a cylindrical projection of the spherical Sun. It is constructed by weighted combination of shifted longitude bands (generally 60 degrees across the central meridian) in sine(latitude) vs. Carrington longitude grid over the whole Carrington rotation (CR) period (average~27.27 days when observed from the Earth).

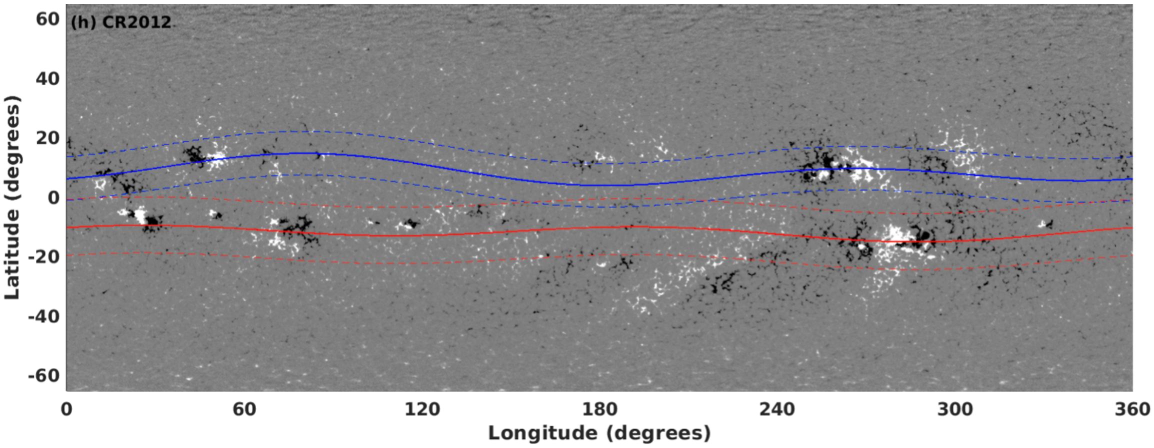

Figure 3. Synoptic map for Carrington Rotation 2012. Bipolar active regions are dark and bright regions on the gray map. Blue (red) band in North (South) hemisphere denotes active regions (AR) in a tight-fit global toroid pattern; solid blue (red) indicates latitude-longitude locations of AR centroids, whereas two dashed blue (red) lines indicates the width of the North (South) toroid.

Therefore, a Carrington map does not provide an instantaneous picture of the entire solar sphere. Also, temporal averaging of each latitude-longitude point may lead to some inaccuracies such as feature smearing.

In the future, a 4pi (Firefly) mission (see, e.g., white paper by Raouafi et al. 2022) could thus provide a more accurate instantaneous 360-degree view through near-simultaneous sampling of the entire solar surface through multiple constellation members. Also, the measurements at higher latitudes (>60 degree) are highly noisy due to projection effects and often ignored in currently available Carrington maps. Out of the ecliptic measurements, enabled through the 4pi (Firefly) mission will thus generate much superior measurements at higher latitudes.

3.4 Operation of predictive model for the needs of customers and stakeholders: The use of sequential data assimilation that updates the model every few days as new data become available will enable us to predict the enhanced activity bursts up to several weeks ahead. Similar to the way that weather forecast models operate, the accuracy of the prediction is expected to improve as the target time (~four weeks ahead) is approached.

Given recent advancement of Rossby waves observation and theory as described above, and the demonstrated predictive skill through success in 'hindcasts' of timings and locations of major space weather events, in the future, forecasting what to expect in the next few weeks to months will be possible. Close collaborations are necessary among the appropriate Federal agency research and operational programs, involving significant technology transfer to the agency making the forecasts, such as SWPC of NOAA, NASA, NSF, and the Air Force, to make decisions on whether (i) space equipment is taken off-line now or after waiting for a few days, (ii) a GNSS (Global Navigation Satellite System) related activities can be planned for next week or the week after.

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