Under Development: 02 Nov 2015 (Final Draft)

On the Contributions of Operational Space Weather Satellite Data for Earth Science Research

William Denig[1], Thomas Berger[1], Rodney Viereck[1], Naomi Maruyama[2,1], Peter Pilewskie[3], Cora Randall[3], Craig Rodgers[4], Janet Machol[2,1], and Arnaud Chulliat[2,1]

[1]National Oceanic and Atmospheric Administration

[2]Cooperative Institute for Research in Environmental Sciences, University of Colorado

[3]Laboratory for Atmospheric and Space Physics, University of Colorado

[4]University of Otago (New Zealand)

White Paper submitted in response to the Initial Request for Information for the 2017-2027 Decadal Survey for Earth Science and Applications.

This white paper discusses the status of operational satellite measurements that are primarily used for space weather applications but also contribute to earth science research. A key benefit of operational satellite data is the long-term consistency in the measurements over multiple decades thereby allowing one to better examine temporal changes in the earth-sun system. This white paper provides a broad view of how space weather data contribute to several active research areas in earth science. A background section provides an overview of the operational satellites with space weather sensors, mostly operated by the U.S. The remainder of this whitepaper describes relevant technology areas within which responses to the posed questions are provided within the context of available space weather data. Reference is made, as appropriate, to more detailed white papers that are submitted separately.

Background – Since the early 1970's, the U.S. Department of Commerce (DOC) and the Department of Defense (DoD) have continuously operated environmental satellite systems with sensors for monitoring the near-earth space environment and sun. The Polar-orbiting Operational Environmental Satellites (POES) and the Defense Meteorological Satellite Program (DMSP) spacecraft are located in polar sun-synchronous low-earth orbit (LEO) at altitudes of about 840 km. At this altitude these satellites are within the topside ionosphere and outer thermosphere. Farther out the Geostationary Operational Environmental Satellites (GOES) are located at about 6.7 earth radii and near the dayside separation between the earth's magnetosphere and interplanetary space. While the primary missions for these spacecraft are weather monitoring, each system includes a complement of space environment sensors that serve the real-time needs of operational space weather forecasters. Historical space weather data are made freely available to the research and applications communities through a number of data portals.

The POES Space Environment Monitor (SEM) measures the characteristics of the in-situ charged particle environment, electrons and protons, over a broad energy range from auroral energies (~160 eV) to several MeV. SEM packages (provided by the DOC) are similarly included on the European MetOp satellites, also in polar LEO orbits. Processed SEM data (1978-to-present) are available from the National Centers for Environmental Information (NCEI) (see Links to Data). Each DMSP satellite includes a complement of space weather sensors to measures the local thermal and energetic charged particle environment and magnetic field as well as ultraviolet imagery of the upper atmosphere and thermal ion densities and drifts. DMSP space weather data from 1982 to present are available from NCEI as well as from the Johns Hopkins University Applied Physics Laboratory (JHU/APL) and the Naval Research Laboratory (NRL). Unfortunately, there is considerable uncertain in the continuity of space weather data from LEO with DMSP and POES each reaching their respective end of life (EOL) in the near future. Only MetOp, with a projected EOL in 2023, will provide LEO space weather measurements into the mid-term. At the present time, there is no clear strategy for follow-on LEO satellites providing operational space weather data near the end of the decadal period.

The future of space weather data from the GOES at Geostationary earth orbit is considerably brighter. The GOES-R series of satellites should be operational throughout the decadal period. The space weather sensors on GOES provide a comprehensive set of measurements of the in-situ particle and magnetic field environments plus observations of the sun consisting of imagery and irradiance. Data from 1974 to present are available from NCEI and we expect continuity of these data throughout the life of GOES-R through 2036. "Space weather" data from GOES that are most applicable to earth science research include the extreme ultraviolet (EUV) solar-irradiance observations and measurements of energetic solar protons. It is likely that during the decadal period other nations will field space weather sensors on their respective geostationary satellites which would provide additional data useful to the earth sciences.

The following earth science technology areas benefit from the availability of space weather sensors on operational environmental satellites. The text below just general summarizes each area and more detailed white papers may be submitted separately.

1. High Energy Particle Participation in the Atmosphere (HEPPA)

The HEPPA topical area is focused on the observational and modeling studies of atmospheric and ionospheric changes caused by energetic particle precipitation (EPP); e.g., solar proton events, medium and relativistic electron precipitation, and comparatively low-energy auroral electron precipitation. EPP affects atmospheric composition, mainly by formation of reactive nitrogen and hydrogen species, which interact with ozone. The science question addressed by this work is the EPP Indirect Effect (IE), whereby NO_x produced in the mesosphere or thermosphere via EPP (EPP-NO_x) descends to the stratosphere during the polar winter, where it can participate in catalytic ozone destruction [*Randall et al., 2007*]. There are also questions around the direct effect caused by the immediate ozone loss from HO_x [*Andersson et al.; 2014*] and the relative importance of the direct and indirect effects. The resultant application is in evaluating and constraining global models to investigate coupling of the upper and lower atmosphere by the EPP direct and IE, including any influences this might have on ozone trends and possibly on climate. POES/MetOp SEM measurements are fundamental to monitoring EPP and the likely loss of these data during the decadal period will be detrimental to the HEPPA technology area.

2. Integrated Dynamics in Earth's Atmosphere (IDEA)

NOAA has an operational need to implement IDEA as an extension to the current National Weather Service's operational Global Forecast System (GFS) model to improve our understanding of the connection between the terrestrial and space weather mainly driven by the solar-wind-magnetosphere interaction [*Akmaev et al., 2008; Fuller-Rowell et al., 2008*]. The strategy involves coupling the extended GFS called Whole Atmospheric Model (WAM) with the Global Ionosphere-Plasmasphere Electrodynamics (IPE) Model [*Sun et al., 2015*], due to the crucial mutual interaction between neutral and ionized species in the upper atmosphere. The overarching goal for the IDEA project is to advance our space weather forecasting capability which, in turn, would contribute to improved navigation and communications and to determinations of satellite drag. Both DMSO and POES measurements have provided significant contributions to developing and improving the IDEA model. Measurements of the atomic oxygen airglow by space-based ultraviolet imagery on DMSP can contribute to an improved gravity wave parameterization in IDEA. While the EOL for DMSP is nominally planned for 2022 recent Congressional action may prematurely terminate in program prior in the near future.

3. World Magnetic Model (WMM)

The SWARM research satellite is currently providing exquisite measurements of the earth's magnetic field, which are used to improve the accuracy and resolution of world magnetic models and to address DoD requirements for the WMM. While the operational DMSP spacecraft provides a supporting measurement of the geomagnetic field, the accuracy of the DMSP data is not sufficient to satisfy the needs of the magnetic modeling. Science questions to address from continued measurements ranging from quantifying the impact of ocean circulation on the measured secular field [*Manoj et al., 2006*] to verifying the physical source of recently observed geomagnetic jerks and pulses on the main field [*Chulliat et al., 2015*]. We expect that SWARM will reach its effective EOL in about 2021. Also, as noted above, the questionable longevity of DMSP, makes it all the more critical that a follow-on magnetic field mission be planned. A separate whitepaper has been submitted to the panel address that issues related to the World Magnetic Model.

4. Total Solar Irradiance (TSI)

Total solar irradiance (TSI) is a primary factor in the energy balance of the earth system. Precise measurements of TSI from satellites have been made since 1979 and are used to adjust the so-called "solar constant" from its nominal value of 1.361 kilowatts per square meter. TSI also varies on timescales ranging from decades to days due to fundamental changes in the solar features; for examples, sunspots and sunspot groups, traversing the solar disk. Variations in TSI are used as key inputs to climate models to discriminate solar drivers from other factors, including anthropogenic effects. TSI and the related Solar Spectral Irradiance are considered operational Climate Data Records [*Robinson et al; 2004*] and the continuity of these records is of key importance to the climate community. The unfortunate launch failure of the GLORY spacecraft, as a continuity follow-on to the NASA Solar Radiation and Climate Experiment (SORCE) satellite has been somewhat mitigated by the TSI Calibration Transfer Experiment (TCTE), launched in late 2013, and the planned deployment of the Total and Spectral Solar Irradiance Sensor (TSIS) on the International Space Station (ISS) in 2017 [*Woods et al, 2014*]. In 2015 the operational TSI monitoring mission within the U.S. was transferred from NOAA to NASA for TSIS-1. Details for the TSIS-1 follow-on after 2022, within the decadal period, have not yet been determined and should be a consideration for the panel. A specific whitepaper on TSI and a general whitepaper on operational CDRs, recently renamed Reference Environmental Data Records, are being submitted separately.

5. Solar Extreme Ultraviolet (EUV) Irradiance

Solar emissions at extreme ultraviolet (EUV) wavelengths are absorbed in the earth's upper atmosphere, heating the thermosphere and creating the ionosphere. While the TSI variability is 0.1%, the EUV variability is >100%. These variations in the EUV flux drive the dynamics of the thermosphere and ionosphere, and so EUV spectra are essential inputs for thermospheric / ionospheric models which are used in satellite drag and communications models (e.g. WAM and IPE, as previously discussed). During the decadal period the GOES-R Extreme Ultraviolet and X-Ray Irradiance Sensor (EXIS) will be an operational monitor of the solar EUV irradiance. An international effort is continuing to ensure the accuracy of the EUV record and the GOES-R EXIS will contribute to the development of a calibration baseline for the community. Solar EUV irradiance measurements will also contribute to the HEPPA technology area previously discussed.

References

Akmaev, R. A., T. J. Fuller-Rowell, F. Wu, J. M. Forbes, X. Zhang, A. F. Anghel, M. D. Iredell, S. Moorthi, and H.-M. Juang (2008), Tidal variability in the lower thermosphere: Comparison of Whole Atmosphere Model (WAM) simulations with observations from TIMED, Geophys. Res. Lett., 35, L03810, doi:10.1029/2007GL032584.

Andersson, M., P.T. Verronen, C.J. Rodger, M.A. Clilverd, and A. Seppälä (2014), Missing driver in the Sun–Earth connection from energetic electron precipitation impacts mesospheric ozone, *Nature Comm.*, doi:10.1038/ncomms6197.

Chulliat, A., P. Alken, and S. Maus (2015), Fast equatorial waves propagating at the top of the Earth's core. *Geophys. Res. Lett.*, *42,* 3321–3329. *doi:* 10.1002/2015GL064067.

Fuller-Rowell, T. J., et al. (2008), Impact of terrestrial weather on the upper atmosphere, Geophys. Res. Lett., 35, L09808, doi:10.1029/2007GL032911.

Gruss, M (2015), Senate Spending Bill Echoes House Call To Shelve DMSP-F20, Space News, 12 June 2015, http://spacenews.com/senate-spending-bill-backs-house-recommendation-to-shelve-dmsp-f20/, Last referenced on 22 October 2015.

Manoj, C., A. Kuvshinov, S. Maus, and H. Luhr (2006), Ocean circulation generated signals, Earth Planets Space, 58, 429–437.

Randall, C. E., V. L. Harvey, C. S. Singleton, S. M. Bailey, P. F. Bernath, M. Codrescu, H. Nakajima, and J. M. Russell III (2007), Energetic particle precipitation effects on the Southern Hemisphere stratosphere in 1992–2005, J. Geophys. Res., 112, D08308, doi:10.1029/2006JD007696.

Robinson, D. et al (2004), Climate Data Records from Environmental Satellites: Interim Report Committee on Climate Data Records from NOAA Operational Satellites, National Research Council, ISBN: 0-309-09168-3, p. 150, http://www.nap.edu/catalog/10944.html, Last referenced on 30 October 2015.

Sun, Y.-Y., T. Matsuo, N. Maruyama, and J.-Y. Liu (2015), Field-aligned neutral wind bias correction scheme for global ionospheric modeling at midlatitudes by assimilating FORMOSAT-3/COSMIC h_mF_2 data under geomagnetically quiet conditions, *J. Geophys. Res. Space Phys., 120*, 3130–3149, doi:10.1002/2014JA020768.

Woods, T., R. Cahalan, W. Denig, G. Kopp, P. Pilewskie and T. Sparn (2014), Rapid Coordination Extends Space-Based Sun-Climate Record, *Eos Trans. AGU*, *95*(*47*), 429.

Links to Data:

POES/MetOp SEM: http://www.ngdc.noaa.gov/stp/satellite/poes/index.html

DMSP (Particles and Fields): http://www.ngdc.noaa.gov/stp/satellite/dmsp/

DMSP (UV Sensors): http://ssusi.jhuapl.edu/

GOES SEM: http://www.ngdc.noaa.gov/stp/satellite/goes/index.html