Operational space weather forecasting at the UK Met Office

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(* Trinity College Dublin, ** Mullard Space Science Lab)

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Outline

- MOSWOC forecasting methods (models/ challenges/ assessment):
  - Flares
  - CME & geomagnetic activity
  - Electron flux
  - Proton flux
  - Aurora

- NRT forecast verification:
  - Flares
  - Geomagnetic storm activity

- Challenges in the way forward

- Summary
MOSWOC forecasting methods
Met Office Space Weather Operations Centre (MOSWOC)

- 24/7 space weather monitoring since 2014
- Set up in response to NRR
- Fully integrated in Met Office Operations Centre
- 2 space weather forecasters on duty (1 dedicated to space weather)
- Provides twice daily forecasts, & timely alerts & warnings
- 14 Forecasters, 6+ Scientists, 4 Programme managers, IT Developers
- National capability supporting: government, military & critical sectors (power, satellite operators, etc)
- Met Office owns risk on behalf of UK Government (Dept. for Business, Energy & Industrial Strategy (BEIS))
- Operations & associated research funded via rolling programme

Public webpages: https://www.metoffice.gov.uk/public/weather/space-weather/
Summary for next 4 days

Solar analysis

CME arrival time at Earth predictions

4 day probability forecasts:
- geomagnetic storms,
- X-ray flares,
- high energy protons &
- high energy electron events
Solar analysis

First the forecaster produces a synoptic map (based on SDO data)

- AR classification
- CH identification

- This identifies if there are complex ARs likely to produce CMEs, flares, SEPs
- ARs: drive the flare forecast
- CHs: drive geomagnetic storm forecast

Manual CH analysis is being replaced by automated methods (CHIMERA: Tadhg Garton, TCD)
Flare forecast

- Statistical model is used - links complexity of ARs with probability of occurrence of different classes of flares

- Forecaster uses experience to modify this before issuing forecast

- Flare forecast verification: MOSWOC issued forecasts better than raw model output – forecaster add value

- How to improve? operational implementation of SMART (Solar Monitor AR Tracker) & ensemble flare forecasts to improve flare forecasting (TCD)

<table>
<thead>
<tr>
<th>X Ray Flares Level</th>
<th>Probability (Exceedance)</th>
<th>Past 24 Hours (Yes/No)</th>
<th>Day 1 (00-24 UTC) (%)</th>
<th>Day 2 (00-24 UTC) (%)</th>
<th>Day 3 (00-24 UTC) (%)</th>
<th>Day 4 (00-24 UTC) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>Active</td>
<td>N</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Very Active</td>
<td>Very Active</td>
<td>N</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

Reliability plots: MOSWOC issued forecasts are more reliable than statistical model, Murray et al., 2017
Solar wind/CME forecasts

- Models solar wind speed & density (IMF modelled but no Bz input)
- To predict CME arrival times at Earth, Venus, Mercury & Mars
- Inputs:
  - WSA output: WSA uses (GONG) solar magnetograms to predict background solar wind speed & IMF - to provide inner BCs for Enlil (currently use NOAA files)
  - SWPC CAT output: CAT input: STEREO & LASCO images. Subjective fitting of cone over time. CAT uses triangulation between different spacecraft viewpoints. CME parameters (origin, direction, speed, half-width).
- Run every 2 hrs. Average CME arrival time error: +/- 7 hrs.
- Enlil ensemble: perturb CME parameters to get range of possible arrival times
- Add resilience: IPS-Enlil - viable alt. operational solar wind prediction system but need to extend study further
CHs influence solar wind and thus geomagnetic storms

How do we assess impact?

- CH perturbations should be picked up in magnetograms and thus WSA-Enlil initial conditions

- Use recurrence model:
  - CH size can grow / shrink from one solar rotation to the next
  - Driven by ACE/STEREO-A data & assumes spwx (today) = spwx (today - 27.25 days)

Geomagnetic storm & CME forecasting - Products

- Forecasters analyse images to identify CMEs and CHs and use WSA-Enlil & recurrence model to predict HSSs & CMEs

- Kp forecasts from BGS are statistical – no knowledge of current situation (e.g. CMEs)

- Geomagnetic storm forecasts are limited as Bz is unknown other than L1 (DSCOVR / ACE observations)

- So forecasters rely on their experience to interpret the information they have available

<table>
<thead>
<tr>
<th>Geo-Magnetic Storm</th>
<th>Level</th>
<th>Past 24 Hours (Yes/No)</th>
<th>Day 1 (00-24 UTC) (%)</th>
<th>Day 2 (00-24 UTC) (%)</th>
<th>Day 3 (00-24 UTC) (%)</th>
<th>Day 4 (00-24 UTC) (%)</th>
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</thead>
<tbody>
<tr>
<td>Minor Moderate</td>
<td>G1 to G2</td>
<td>N</td>
<td>5</td>
<td>40</td>
<td>60</td>
<td>60</td>
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<td>Strong</td>
<td>G3</td>
<td>N</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>10</td>
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<tr>
<td>Severe</td>
<td>G4</td>
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<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Extreme</td>
<td>G5</td>
<td>N</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Geomagnetic Activity - Earthbound Coronal Mass Ejections

<table>
<thead>
<tr>
<th>Date-time 21.8R (UTC)</th>
<th>Halo: Full or Partial</th>
<th>Source</th>
<th>Source Location</th>
<th>Estimated Speed</th>
<th>Estimated Arrival Time</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>19/2100Z</td>
<td>Asymmetrical Halo</td>
<td>2371</td>
<td>NE Quadrant</td>
<td>900km/s</td>
<td>21/1200Z</td>
<td>+/- 12 hours</td>
</tr>
<tr>
<td>19/1700Z</td>
<td>Asymmetrical Halo</td>
<td>N/A</td>
<td>SW Quadrant</td>
<td>400km/s</td>
<td>23/0100Z</td>
<td>+/- 12 hours</td>
</tr>
</tbody>
</table>

Top: 4-day probabilistic geomagnetic activity forecast
Below: CME arrival time forecast
High energy electron flux forecasts at GEO

Forecasts based on:

- Assessment of CHs
- Assessment of NRT data from GOES
- Model (REFM) forecasts of >2 MeV fluence at GEO
  - Used to gauge: trend in fluence
  - Development in progress – to improve visualisation of 3hrly runs

**GOES electron flux**

**REFM**

**HEE forecast**

The high energy electron flux (greater than 2MeV) at geosynchronous orbit is expected to remain at normal levels throughout the period, with the 24-hour fluence also remaining below the warning threshold. Coronal hole 63 is due to become geoeffective on day four (Monday 06 June), however this should not have an effect on electron counts until after this forecast period.

<table>
<thead>
<tr>
<th>Radiation Storms (Probability)</th>
<th>Level (cm² cm⁻² s⁻¹ day⁻¹)</th>
<th>Past 24 Hours (Yes/No)</th>
<th>Day 1 (00-24 UTC) (%)</th>
<th>Day 2 (00-24 UTC) (%)</th>
<th>Day 3 (00-24 UTC) (%)</th>
<th>Day 4 (00-24 UTC) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>2 MeV x10⁻¹²</td>
<td>N</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Very Active</td>
<td>2 MeV x10⁻¹²</td>
<td>N</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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</table>
High energy proton flux forecasts at GEO

Forecasts based on:
- AR analysis
- Assessment of NRT data from GOES

Plan to implement SPARX operationally

SEP modelling challenges:
- Complexity of physics of their propagation in the 3D turbulent plasma
- Computational expense due to timescales required to produce actionable forecast
Aurora forecast: OP-2013

OVATION PRIME 2013:

- (Auroral) Oval Variation Assessment, Tracking, Intensity, and Online Nowcasting
- Developed by John Hopkins University
- Empirical model which predicts intensity of auroral energy at locations on Earth for next 30mins
- Based on current solar wind at L1
- Currently testing 3-days forecast version
- OP-2013 evaluation (D. Morosan) against AMPERE hemispheric power observations (Bob Robinson, CUA), & against Twitter aurora photos

AMPERE Hemispheric power v OP-2013. OP produces accurate baseline but misses intensifications.
Forecast verification
NRT forecast verification

- Adapted NRT terrestrial weather verification systems to verify 4-day probabilistic forecasts: flares & geomagnetic storms
- Currently adapting for HEE & HEP (challenge: not many events)

Example forecast to verify

<table>
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<th>X Ray Flares</th>
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<th>Day 3 (00-24 UTC) (%)</th>
<th>Day 4 (00-24 UTC) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>Rs-Rx M Class</td>
<td>N</td>
<td>20</td>
<td>0</td>
<td>20</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Very Active</td>
<td>Rs to Rx X Class</td>
<td>N</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

- Treat as multi-category
- Compare against benchmark: short-term climatology
- Calculate RPSS to understand forecast’s skill in predicting category which obs fell into

Space Weather

Verification of Space Weather Forecasts issued by the Met Office Space Weather Operations Centre

M. A. Sharpe & S. A. Murray

Accepted manuscript online: 9 October 2017

- Treat as separate categories
- Calculate ROC plot (forecast resolution)
- Calculate Reliability Diagram
Forecast verification results

- Rolling 12-month analysis using RPSS indicates:
  - Day 1 geomagnetic storm activity forecasts typically perform better than a climatology benchmark
  - No consistent evidence for flare forecasts (flares are more difficult to predict)
- ROC & Reliability plots suggest: forecasts are skilful at identifying M-class flares & geomag storms, although both were over-forecast
- It’s early days for operational space weather verification – not enough X-class flare occurrences since service began, to allow meaningful verification
- Common meteorological verification techniques can be easily adapted for space weather
- Near real-time verification is particularly useful in the operational environment
- Current work: a space weather forecasting metric – monitoring overall progress in space weather forecasting
Some of the bigger challenges

Solar / heliosphere:
- Don’t know Bz until L1
- Can’t predict CMEs, flares & SEPs prior to eruption

Magnetosphere:
- Substorms hard to quantify – these cause a lot of the large GICs

Ionosphere:
- Scintillation is key impact – observation-driven nowcasts (where obs available); forecasts difficult

Atmospheric radiation (aviation level)
- Very sparse observations so performance of models difficult to assess

Goal: Sun-to-Earth model for space weather forecasting – coupled modelling

Collaboration is key!
Observation network challenges

- Apart from DSCOVR and GOES, all observations “science” not “operational”

- Risk to CME monitoring as SOHO and STEREO are beyond planned lifetime. Solutions:
  - L1 and L5 missions (USA, ESA, respectively) planned for ~2022 – operational missions
  - Alternative observations – ground based radio telescopes (IPS)

- Magnetosphere – quite a lot of GEO obs but few elsewhere

- Ionosphere - well observed but thermosphere & radiation are not
Summary
Summary: some key challenges

• 24/7 operational requirements mean limitations (e.g. timescale on which model required to run to provide useful forecast)

• Bz forecasts need to be addressed - short warning time to prepare once we know speed and size of events

• Challenges in coupling models

• Unable to predict CMEs, flares & SEPs prior to eruption

• Sparse & non-operational observations

Collaboration between research and operational communities remains vital in order to implement suitable models & prediction techniques to forecast solar transient impacts
Thank you
Extra slides
CME forecasting: monitoring

CME may not yet be visible in coronagraph so forecaster monitors early warning signs:

- Monitor ARs for flares as can be associated with CMEs
- Any filaments disappeared? – often associated with CMEs
- Type II radio burst? – radio emission at CME shock front
- Any coronal dimming? – localised decrease in plasma density due to escaping plasma can indicate CME – difficult to automate as many intensity changes in corona
Adding resilience to Enlil forecasts

Siegfried Gonzi, Mario Bisi (RAL-Space) & Bernie Jackson (UCSD)
Funding: European Office of Aerospace R&D (EOARD)

- Project to assess impact of IPS on Enlil forecasts. WSA-Enlil (GONG) v IPS-Enlil. ‘14 & ‘16 data.
- Assessed quality of ambient solar wind (speed, density, magnetic field) forecasts against OMNI data, using a range of metrics.
- Forecasts are broadly similar in representing ambient solar wind. Both have similar skill in identifying Stream Interaction Regions (SIRs).
- Therefore IPS is a viable alternative operational solar wind prediction system. Reasonably robust conclusion but only based on two years of data. Next step: extend study to more years.
- Initial assessment of how well IPS-Enlil can represent a CME (CME only appeared in IPS shortly before arrival- more studies required)

Observed solar wind speed at L1 from OMNI v IPS-Enlil (left) & WSA-Enlil (right). May – Oct ‘16.
Analysed 2 events in ‘17 using Twitter aurora photos. Location & date compared with OP-2013:

- Locations of visible aurora matched very well with OP-2013 predictions in UK, Ireland, Iceland, Sweden, Norway

- OP-2013 didn’t predict the aurora spotted in some SH locations but these sightings were just above the horizon – more investigation required

Hemispheric power comparison with AMPERE data (Bob Robinson, CUA):

- Obtained by averaging aurora energy flux over NH & SH

- HP measurements show that OP-2013 produces an accurate baseline HP for NH but misses transient intensifications in HP derived from AMPERE

- Transient intensifications are still being investigated to rule out instrument effects
IMAGE satellite comparison

Michaela Mooney: work in progress

- IMAGE satellite: Apr 2000 – Dec 2002, 3 onboard cameras including Wideband Imaging Camera (broadband UV images)

- Longden et al., 2010: technique to identify inner & outer edges of auroral emission from IMAGE data

- Use Longden inner & outer boundaries to create ‘truth’ & compare to OP-2013 probability nowcast

- ROC/reliability & RPS analysis
D-Region forecasting

- D-Region Absorption Prediction
- Real-time global map showing impact of flares & SEPs on HF radio comms
- Understanding of radio signal degradation/blackouts
- Used as a *qualitative indicator* of highly perturbed conditions (SWPC validation report)
Towards Coupled Modelling

Thermosphere / ionosphere:
- Raising UM (to ~150 km) in development + coupling to TIEGCM
- Eventually whole atmosphere UM (to ~600 km) to couple with other spwx models

Magnetosphere:
- SpWx Modelling Framework (SWMF) (U. of Michigan – used at SWPC) being implemented and tested
- Will enable Magnetosphere / Ionosphere coupling
- Solar wind / magnetosphere coupling, but issues with Bz

Goal: Sun-to-Earth model for spwx forecasting
Collaboration is key!