



# Operational forecasting – what's required in the heliosphere

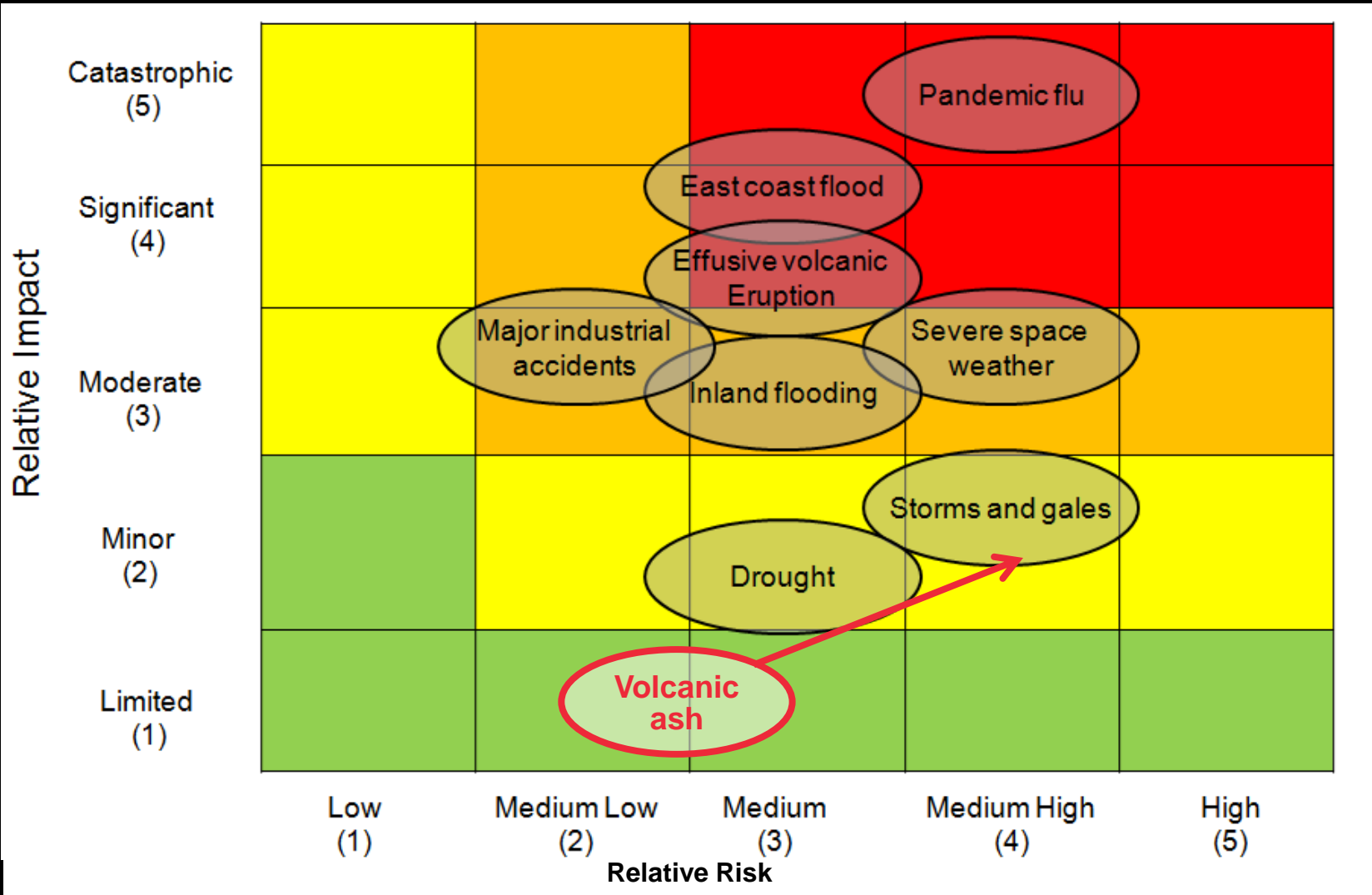
Mark Gibbs, Head of Space Weather

Met Office



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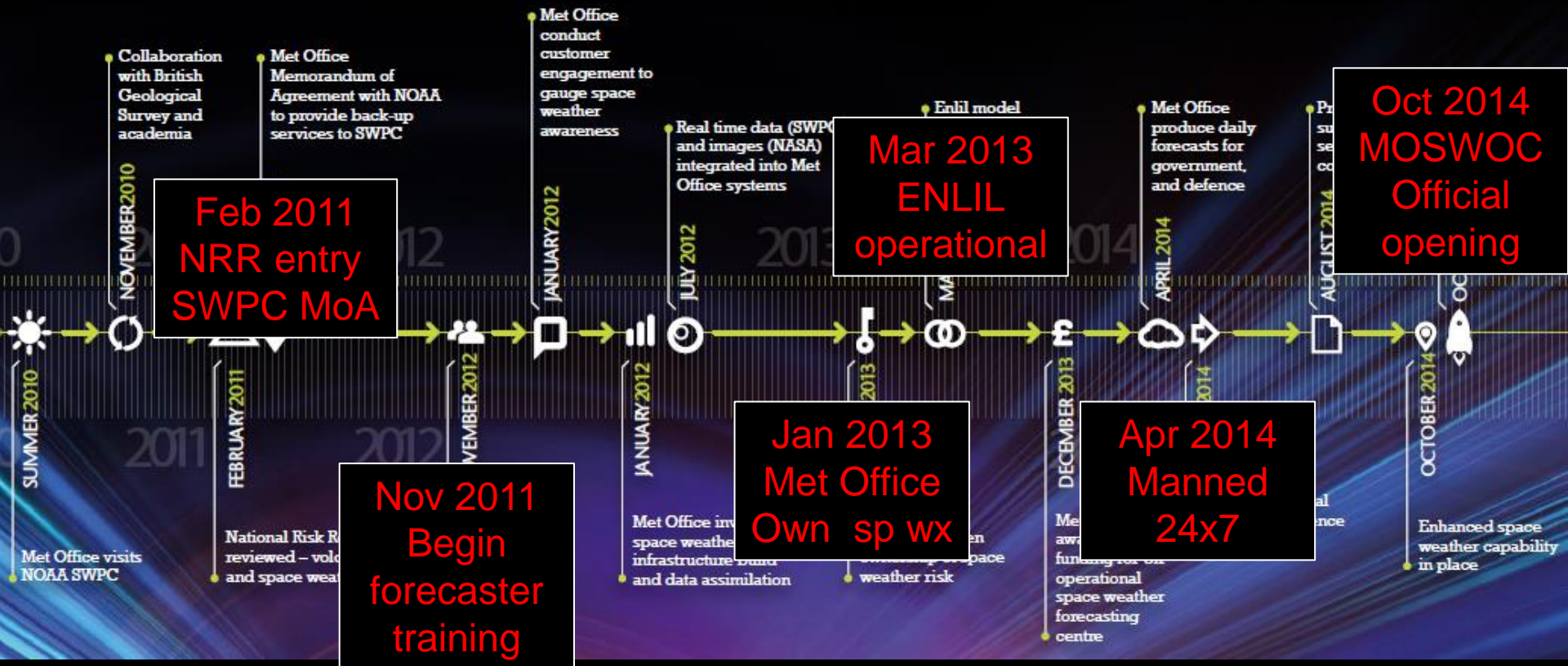
# Background





Met Office

# A space weather journey through time





# Met Office Space Weather Operations Centre (MOSWOC)



# 'Expert' forecast

## Met Office

Met Office Space Weather Technical Forecast

Space Weather Technical Forecast (Ref: M043)

Issued on Sunday, 01 February 2016 at 17:44 local

This scientific guidance document provides a four-day assessment of space weather events. The probabilities stated below are for reaching or exceeding the given levels. For more information about space weather impacts please see the Met Office Space Weather Store [http://www.metoffice.gov.uk/more/spot/14\\_091214spwstore.aspx](http://www.metoffice.gov.uk/more/spot/14_091214spwstore.aspx)

**1200 UPDATE:** No changes to the forecast. The anticipated high speed solar stream from C940 is now underway, with a rapid increase to 540km/s at the time of writing. Bz for Bz has been mainly positive (then strongly) with an erratic Phi angle indicative of crossing the edge of a coronal hole. The Phi appears to be mainly positive (away from the Earth) at 130 degrees during periods of enhanced solar wind. Geomagnetic activity is currently at the unsettled end of quiet (Kp) with an increasing chance of unsettled to active periods looking likely today. There activity remains low with two C2 flares since midnight, one from AR2288 at 01:04(23)UTC and the other from AR2277 at 01:06(24)UTC. A filament eruption along the East limb just north of the equator occurred between 00:00-09:00 UTC this morning, most likely resulting in a small non-earth directed CME (CME evidence already starting to show on STEREO A chromograph imagery at 01:10(24)UTC). A plasma jet also came out of AR2275 at 01:09(23)UTC on the west limb, which may also have produced a small non-earth directed CME.

**Space Weather Forecast Headline: No significant activity, chance of Minor Storm Sunday 01 and Monday 02 February.**

**Analysis of Space Weather Activity over past 24 hours:**

Solar activity has been Low over the last 24 hours, with the largest flare of the period a C1.8 from sunspot region 2268 at 21:35 UTC. There are now six numbered sunspot regions on the earth-facing solar disc. With 2268 and 2277 still large and complex, while 2276 and 2278 have both decayed to plage.

Analysis of available Lasco imagery did not show any Coronal Mass Ejections (CMEs) released through Saturday, meaning that there are not thought to be any CMEs en route at present. Geomagnetic activity has ranged from Quiet to Active in the past day, with a peak of 4 for Kp and 40 for Kp. Bz peaked at -12V, with Bz ranging between 0 to +6V. The solar wind has been relatively stable, peaking near 450km/s, while phi changed from largely negative during the morning towards the sun to mainly positive thereafter, finally becoming more erratic into the evening.

There were no solar radiation storms on Saturday, with recent elevated >10MeV proton levels gradually declining in the wake of the hiatus in recent in-class flare activity. Finally, >2MeV electrons at geosynchronous orbit have remained at Background flux throughout.

**Four-Day Space Weather Forecast Summary:**

Moderate solar activity is likely in the next four days, with a flat 60% chance of in-class flares on all days, and a Bright Chance (10%) of in-class flares. While there are no CMEs thought to be en route at present, coronal hole 31 will give a Chance of Minor Storm on Sunday 01 and Monday 02 February. With Kp then falling towards midweek as the strength wanes. There is a slightly increasing chance of solar radiation storms in the four-day period: 20% chance on Sunday, rising to 25% by midweek. >2MeV electron flux is expected to rise in response to the anticipated coronal

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hole high speed stream, with the chance of the Active fluence threshold being surpassed rising from 1% on Sunday 01 February to 30% on Wednesday 04.



Figure 1: Coronal hole 30 - the main driver of space weather in the four-day period.

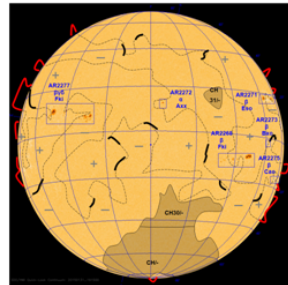


Figure 2: MOWBOO solar synoptic map, valid 18 UTC Saturday 31 January.

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Geomagnetic Storms:

Analysis of available Lasco imagery shows no CMEs emitted through Saturday, meaning that there remains none en route. The dominant element of space weather in the coming four-day period is the predicted onset of the northwestern lobe of the southern polar coronal hole, labeled 'C940' in the MOWBOO Solar Synoptic Map. As stated in the middle update, this feature's latitude gives it a 2-day repeat period, which means the Chance of Minor Storm periods peaks on Sunday 01 February and Monday 02 (both one and two). As well as C940, there is a second much smaller coronal hole, C942, which may become geomagnetic in the period. With the same polarity and similar longitude, the only distinguishing feature is likely to be a slower stream. C942 is thought to be near 500km/s, while C940 is a newly-emerged, less-defined and presumably weaker feature. The coronal holes' influence is expected to wane towards midweek, leading to lower probabilities of high Kp indices.

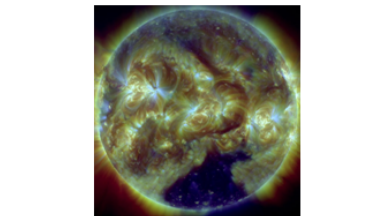


Figure 3: SOHO/ACE 171/190/211 Angstrom composite image, showing the dominant dark blue of the southern polar coronal hole. The northwestern lobe is noticeably shearing forward as it reaches lower latitudes with their faster rotation than the poles.

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Geomagnetic Activity - Earthbound Coronal Mass Ejections

Geo-Magnetic Storm Level	Past 24 Hour (Yes/No)	Day 1 (00-24 UTC) (%)	Day 2 (00-24 UTC) (%)	Day 3 (00-24 UTC) (%)	Day 4 (00-24 UTC) (%)
Minor or Moderate (E-exceedance) 01 to 02	N	30	20	10	5
Strong 03	N	10	10	1	1
Severe 04	N	1	1	1	1
Extreme 05	N	1	1	1	1

Date/Time (UTC)	Major Full or Partial	Source	Source Location	Estimated Speed	Estimated Arrival Time	Comments
Nil						

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Radio Blackouts - X-Ray Flares:

Solar activity has been Low through Saturday, with the largest flare of the day a C1.8 from sunspot region 2268 at 21:35 UTC. Activity has shown a marked downturn in the past 24 hours, with the sub-peak period in in-class flares of recent days replaced by a flat QOE=1.5 X-ray trace near the B/C boundary today. This is despite 2277 appearing to still retain a Delta spot in its intermediate portion, with the 2268 still Zurich Flare group. While both groups are somewhat laterally 2277 is now 23 degrees across, there is some consolidation of spots within each group, which may help to explain part of the lack of activity. MOWBOO new global observations for flares remain near 60% for in-class and 20% for X based on the F-groups. However these are not to be over-optimistic, and have been adjusted downwards to 60 and 10 respectively based on sunspot age and lack of even C-class activity.

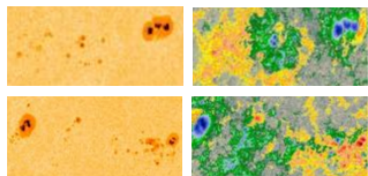


Figure 4: The four Zurich Flare groups on the disc: 2288 (top) and 2277 (bottom). HMI flattened intensitygram (left) and HMI colorized magnetogram (right). All images 22 UTC. The positive Wilson Delta spot is the north-west-most edge. Spot 2277.

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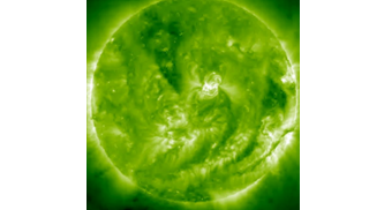


Figure 5: Stereo A EUVI 196 Angstrom image, with a notable bright region near the east limb revealing a large filament in relief. There is also a large equatorial coronal hole to the north of this, which may deliver further raised Kp indices in a week's time.

Using last-day status on the earth-facing disc, there are not thought to be any significant returning regions in the period: ex2259 and ex2261, which were both the Wilson Alpha groups, however in the southern portion of Stereo A's EUVI 196 is the brightest portion of the helioside disc (implying that there has been some development in this area in the last fortnight). The bright flux is also helping to pick out what appears to be a large filament bisecting this region and a possible coronal hole to its north - all nascent forecast elements that will need to be monitored in the next week or so.

X-Ray Flares Probability (Exceedance)	Level	Past 24 Hour (Yes/No)	Day 1 (00-24 UTC) (%)	Day 2 (00-24 UTC) (%)	Day 3 (00-24 UTC) (%)	Day 4 (00-24 UTC) (%)
Active	R1.2 to M1	N	60	60	60	60

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Solar Radiation Storms - (High Energy Protons):

No solar radiation storms were seen on Saturday, with >10MeV protons showing a slow decline from a peak of 1.60u on Friday evening. The postulated cause of the enhancement was recent flare activity, most likely a restricted or eastern hemisphere event owing to the slow rise and fall. The presence of two Zurich Flares on the disc means that proton event probabilities are relatively high in the absence of significant flares. The westernmost group is around 40 degrees West, meaning that by day four it will be near 90 West and a prime position to affect earth should it produce a flare. Probabilities therefore rise from Bright Chance to Chance through the period.

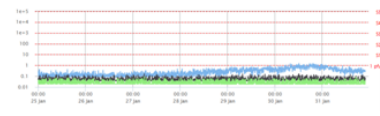


Figure 6: QOE=1.5 high-energy protons since 26 January. The blue line is >10MeV, showing recent enhancement.

Radiation Storms Probability (Exceedance)	Level (cm <sup>-2</sup> sr <sup>-1</sup> sr <sup>-1</sup> )	Past 24 Hour (Yes/No)	Day 1 (00-24 UTC) (%)	Day 2 (00-24 UTC) (%)	Day 3 (00-24 UTC) (%)	Day 4 (00-24 UTC) (%)
Active	≥ 0.1	N	20	20	25	25
Very Active	≥ 0.3	N	1	1	1	1

\* 0.3 = 10 MeV ≥ 1000 pfu and/or ≥ 80 MeV ≥ 10 pfu. (pfu = cm<sup>2</sup>sr<sup>-1</sup>sr<sup>-1</sup>)

Met Office Space Weather Technical Forecast

High Energy Electrons Event (≥ 2MeV)

>2MeV electrons at geosynchronous orbit have been at Background flux through Saturday, peaking at 30pfu. After having reached Moderate flux on Thursday 25 January, an Active period that existing magnetospheric electrons in the earth's van Allen belts, and they have since failed to recover. With the solar wind speed near 450km/s on Saturday, Active fluence is a Bright Chance until the high speed stream from coronal hole 31 is well established, giving a rising risk through the period.

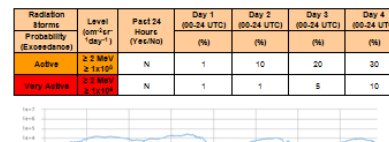


Figure 7: >2MeV high energy electrons since 28 January. Moderate flux has failed to be repeated since the raised geomagnetic activity late on 29 January.

Radiation Storms Probability (Exceedance)	Level	Past 24 Hour (Yes/No)	Day 1 (00-24 UTC) (%)	Day 2 (00-24 UTC) (%)	Day 3 (00-24 UTC) (%)	Day 4 (00-24 UTC) (%)
Active	≥ 2.5 MeV ≥ 1x10 <sup>10</sup>	N	1	10	20	30
Very Active	≥ 2.5 MeV ≥ 2x10 <sup>10</sup>	N	1	1	5	10



# Key Challenges

- CME arrival accuracy
  - Initial forecast
  - Forecast update
- Bz prediction or early measurement (sub-L1)
- Early identification of 'concerning' active region
- Radiation environment at aviation altitude
- SEP prediction
- Regional geomagnetic storm prediction
- Operationally reliable data & models



# What is operational

- Operational standards
  - 24/7/365 staffing of forecasting office.
  - 99+% reliability of observing, processing & dissemination systems
    - Key web products  $\geq 99.5\%$  others  $\geq 97.5\%$
  - Redundant power, cooling & networking at all facilities.
  - Contingency plans for outages of all forecast-critical system elements: e.g. alternate processing sites, backup instruments for observations and backup computers for model runs, etc...



# Operational MOSWOC

- All data & models mirrored across 2 computer halls (run models & systems in-house)
- 2 forecasters on duty (1 dedicated)
- BC laptop, relocate within building or outside
  - Use data products etc from SWPC
- Current issues
  - Dependent on SWPC IT infrastructure
    - Need multiple data centres
  - Dependent on non-operational observing systems



# UK SPACE WEATHER – THE BIG PICTURE

## Met Office

Met office

'Owns' NRA space weather risk. Monitors space weather and provides forecasts and alerts to departments, agencies and industry bodies that have signed up for them. Met Office would be in regular contact with CCS, SAGE, BIS and others. Leads on comms pre-event

Assess national risks and co-ordinate central response

Co-ordinate scientific advice to central Government

Co-ordinate Government severe space weather work (March 2015)

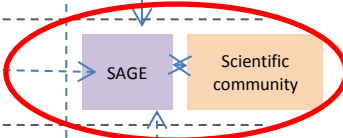
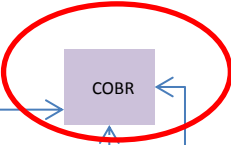
Departments responsible for own sectors

Industry and operators and responders

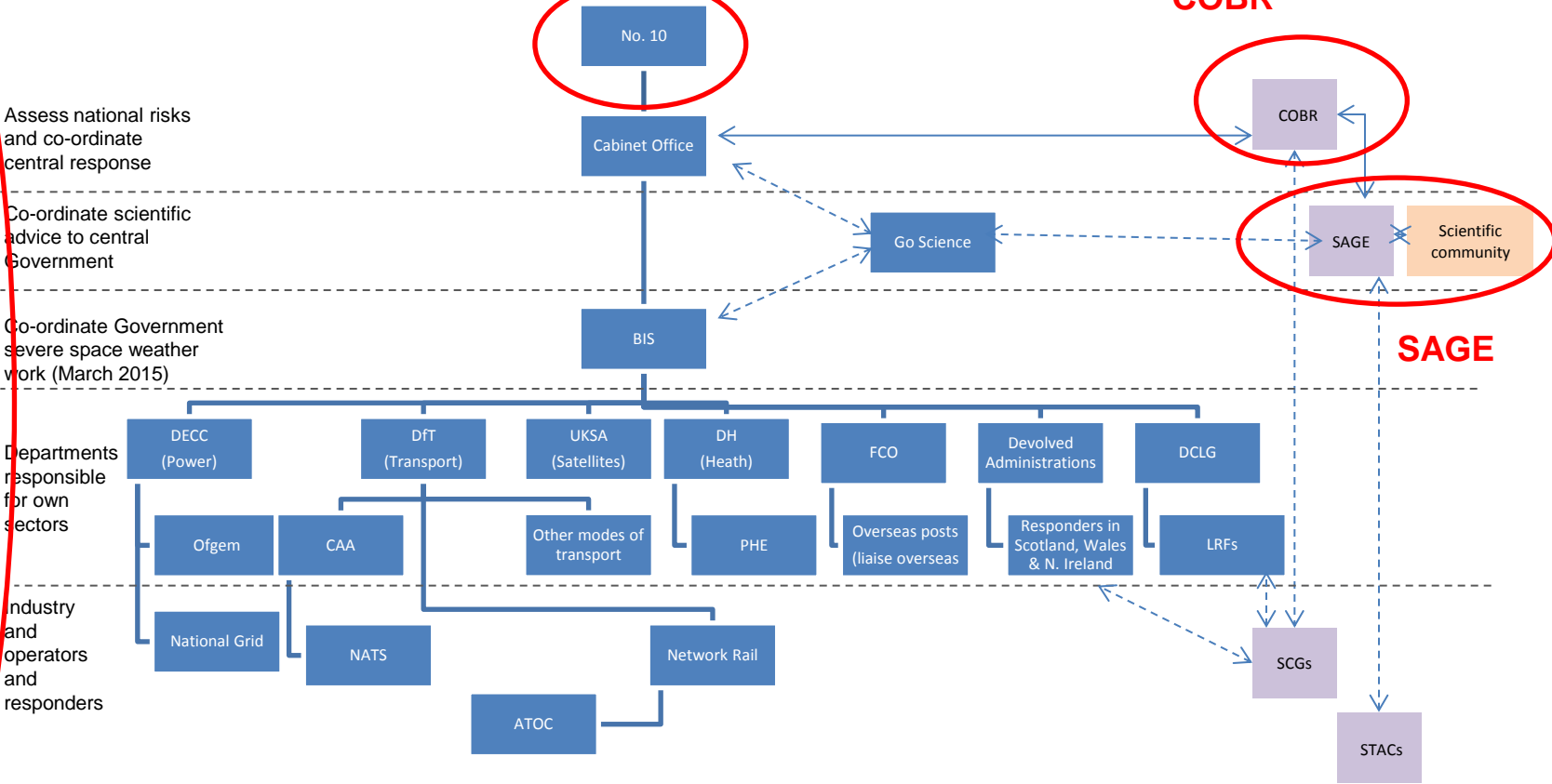
## Prime Minister



## COBR



## SAGE



- BIS- Depart. Business, Innovation & Skills
- DECC- Depart. Energy & Climate Change
- DfT- Depart. Transport
- UKSA- UK Space Agency
- DAS- Devolved Administrations
- DCLG- Depart. Communities and Local Government

- FCO- Foreign and Commonwealth Office
- OFGEM- Office of Gas & Electricity Markets
- CAA- Civil Aviation Authority
- ATOC- Association of Train Operating Companies
- NATS- National Air Traffic Services
- UKSA- UK Space Agency

- DH- Depart. Health
- PHE- Public Health England
- LRFs- Local Resilience Forums
- Posts- Overseas Diplomatic Posts
- COBR- Cabinet Office Briefing Room
- SAGE- Scientific Advisory Group for Emergencies

- SCGs- Strategic Coordination Groups
- STACs- Scientific & Technical Advice Cells
- Scientific Community- British Geological Society, Science & Technology Facilities Council etc.



# What is the 'job'?

## following CME launch

- Is it Earth directed – is it fast?
    - NOAA CAT & NASA CME tool
  - Modelled arrival time  $\Delta V_{sw}$ ,  $\Delta D_{sw}$ 
    - Assume substantial–ve Bz component
    - Issue Watch
  - ??
  - In-situ Ace data  $\Delta V_{sw}$ ,  $\Delta D_{sw}$ , Bz
  - Issue warnings
- ASAP
  - +2-4 hrs
  - +4-8 hrs
  - -18 to 40 min



Is this where HI fits?

What is the minimum no. of HI frames required?



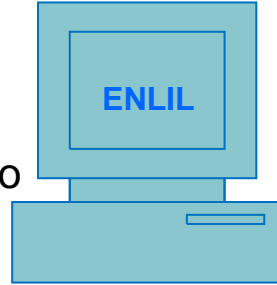
# Initial CME forecast

- During 'STEREO age' CME accuracy  $\pm 7$  hrs
- Without STEREO  $\pm 12$  hrs ?
- Improved CME parameterisation
  - Coronagraph head-on & side-on views
- Improved background heliospheric field
  - Improved inner boundary
  - Magnetic structures towards the east limb



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# Data assimilation primer



Put **analysis** into **forecast** model

Ability to provide a more accurate running forecast to end users

## DA cycle

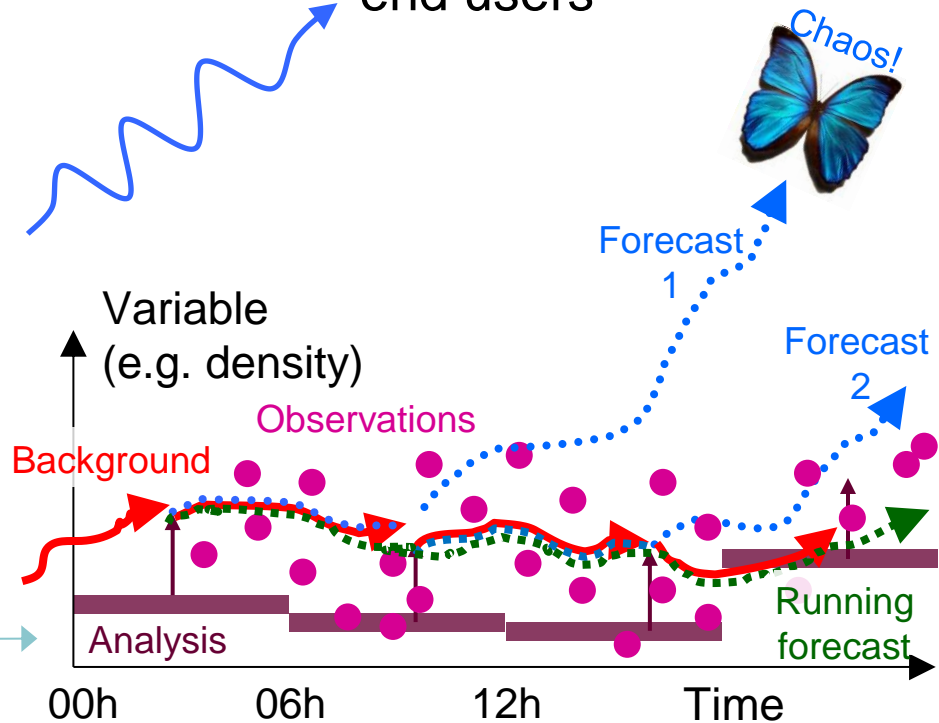
→ better **forecast**

→ **“analysis”**:  
Model solar wind state brought closer to **observations**

Do data assimilation on innovations (differences)

Compare **observations** with improved model **“background”** (previous **forecast**)

START!



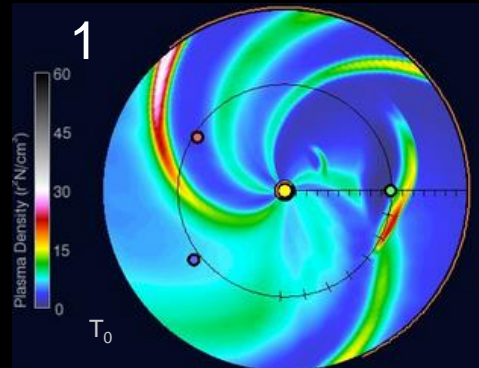
## DA timeline



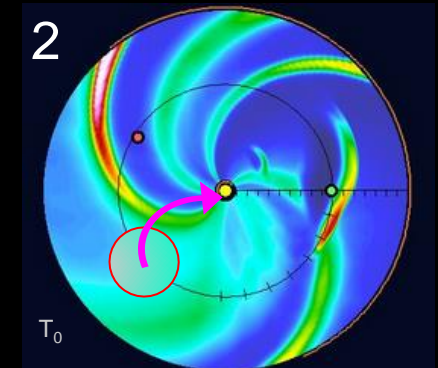
L5 mission Carrington?

# ENLIL assimilation plans

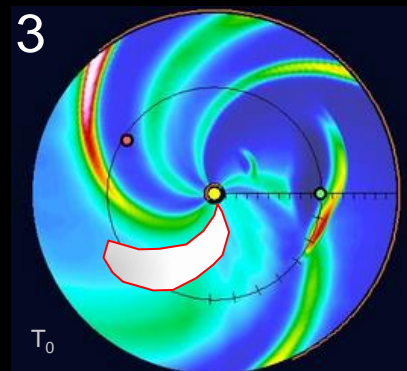
- Developing in conjunction with University of Reading
- Starting with in situ data (plasma, magnetic field)
- Other observations may be useful later
  - e.g. HI data – increments more complex – 3D from 2D – yet coverage better – less of a point measurement
- Will be doing this with STEREO data; proof of concept for L5



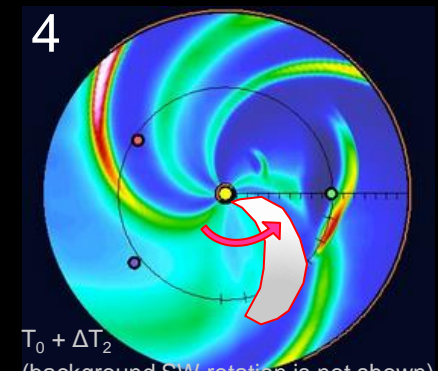
1  
Compare ENLIL background solar wind & in situ data at  $T_0$  (here data lower density)



2  
Get local increment, & via e.g. variational technique the source increment at  $25 R_s$  at  $T_0 - \Delta T_1$



3  
Apply source increment, run ENLIL forward to  $T_0 \rightarrow$  good analysis – model solar wind is balanced, yet closer to observations – more realistic

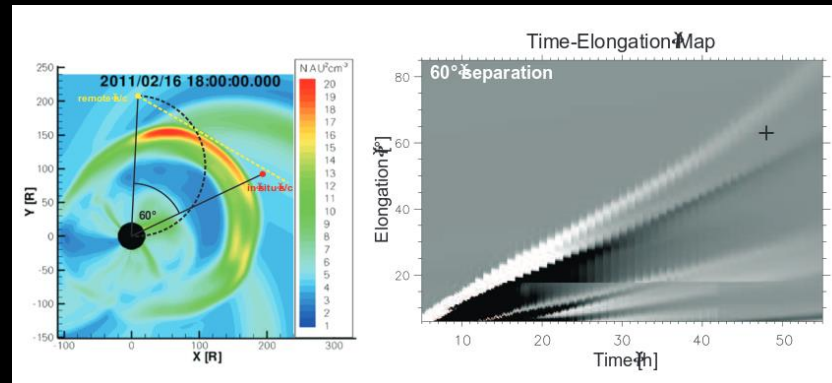
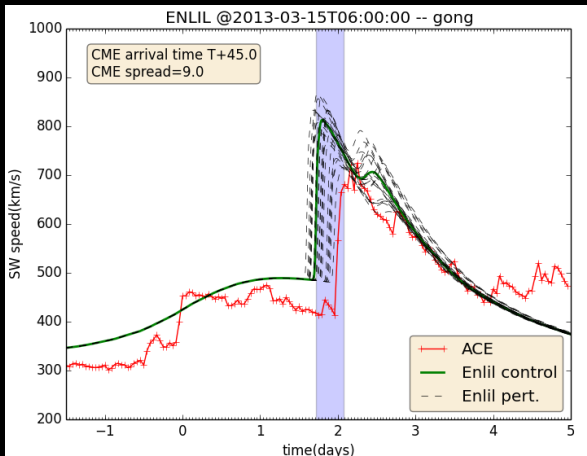


4  
 $T_0 + \Delta T_2$   
(background SW rotation is not shown)  
Persist source increment to  $T_0 + \Delta T_2 \rightarrow$  better solar wind forecasts at earth; better also between sun & earth  $\rightarrow$  more accurate CME arrival times

# Heliospheric imagers

## Pruning a CME ensemble forecast?

- Generate synthetic Jmaps for each member



Lugaz 2009,  
Rollett 2013

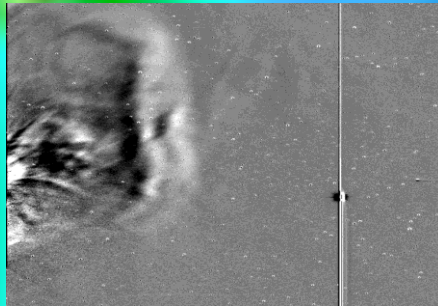
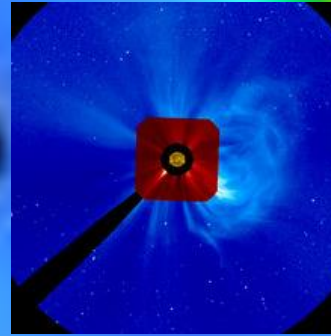
- Compare actual & model Jmaps (auto or manual)
  - Reject model members disagreeing with obs
- More realistic ensemble spread
- Intermediate step
  - Forecaster apply bias correction to ENLIL run subjectively

# The ideal World?

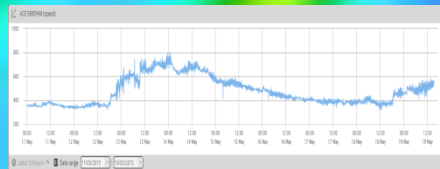
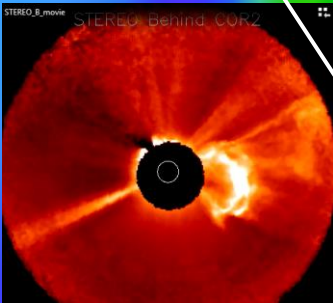


60°

L1



L5





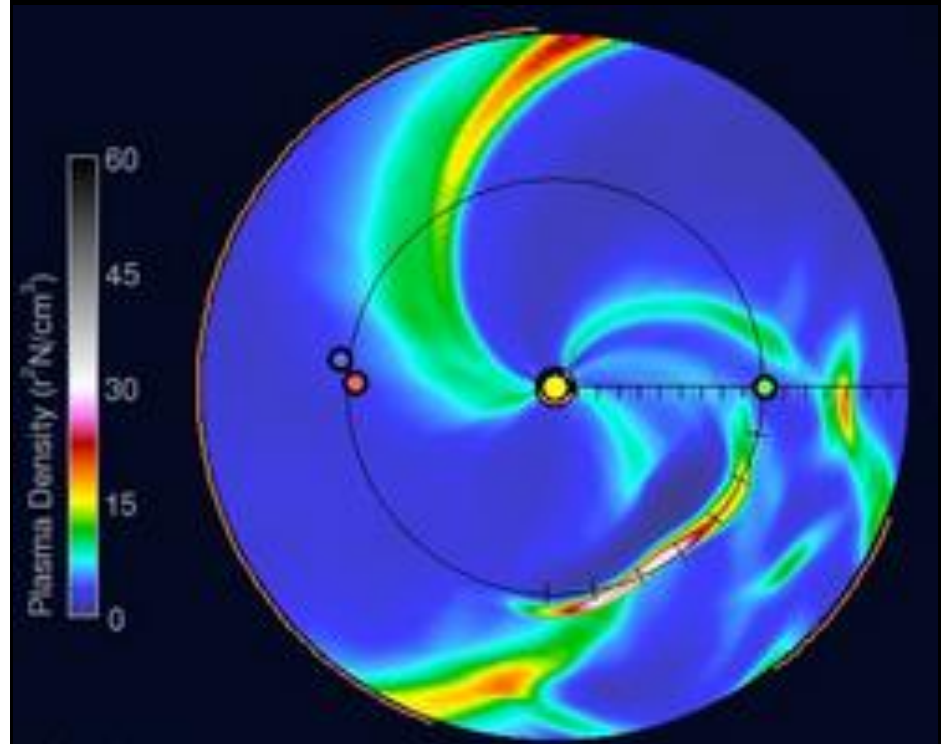
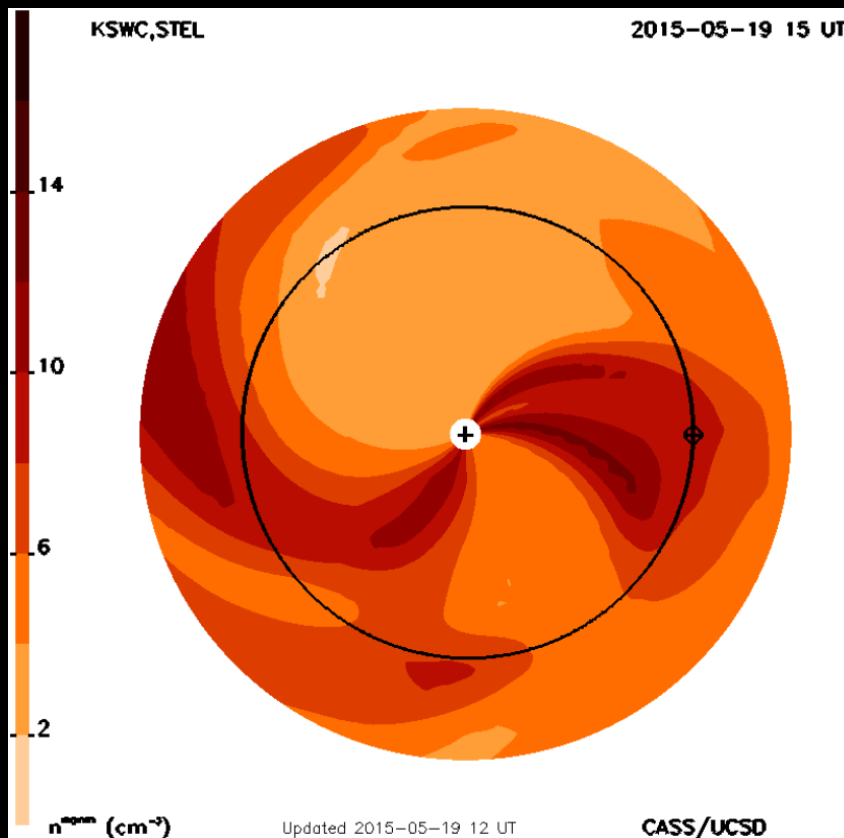
# Current reality

## 10 Sept 2014

- X1.6 17.45utc
- No LASCO imagery until 23.00utc
- SDO AIA imagery 'suggested' a CME
- Type II radio burst  $3,750\text{kms}^{-1}$ !!!
- **1st image 5 hours into a possible 18 hour arrival CME!**
- What can we do without LASCO?
  - Currently no STEREO
- Can Type II give a realistic speed?



# Comparing IPS & ENLIL





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Thank you