Solar flare forecasting at the UK Met Office

Suzy Bingham, David Jackson, Michael Sharpe, Sophie Murray*

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* Trinity College Dublin

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Photography encouraged

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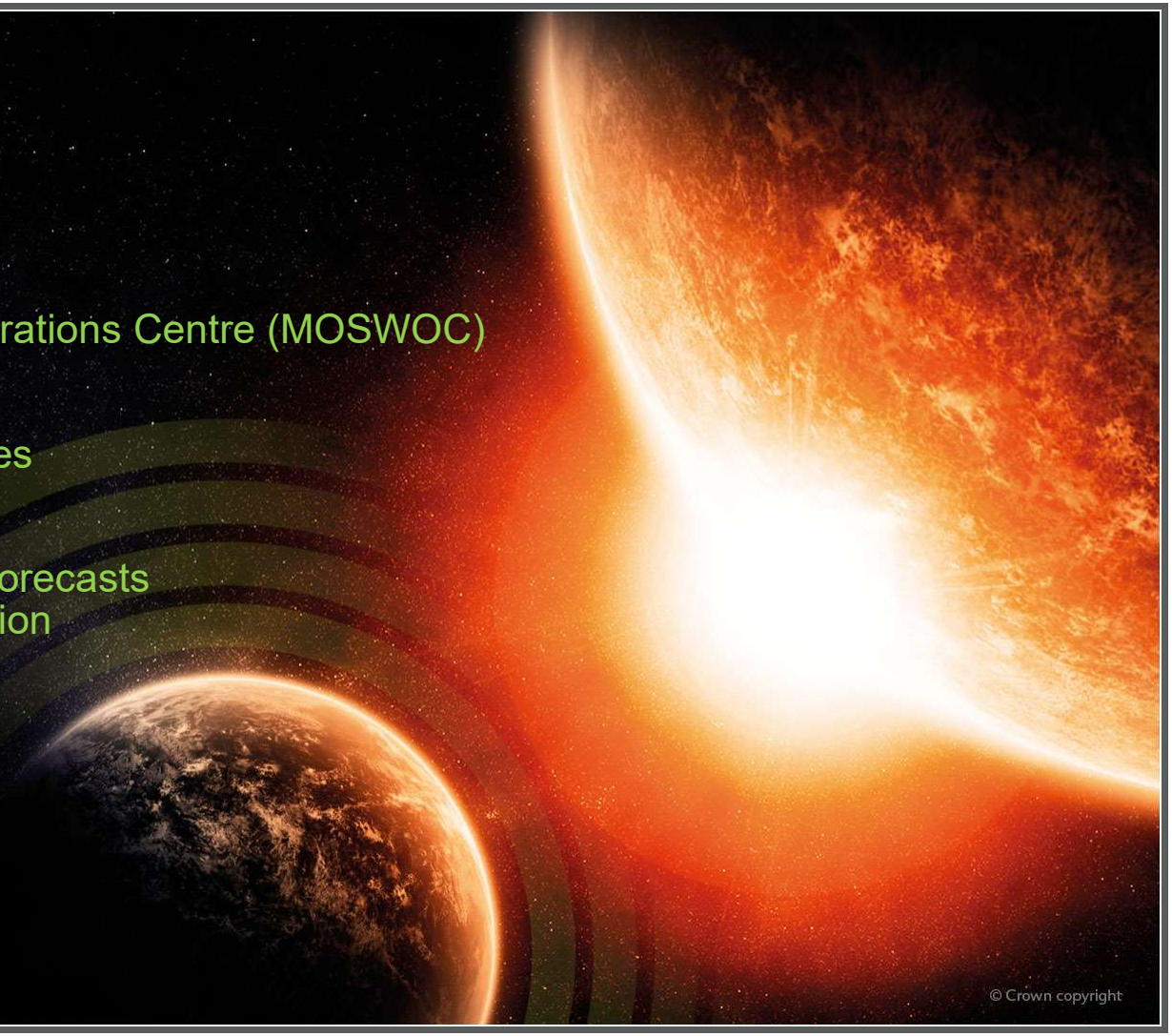
Outline

- Met Office Space Weather Operations Centre (MOSWOC)
- Flare forecast process
  - Sunspot Region Summaries
  - 4-day forecasts
- Verification of MOSWOC flare forecasts
  - Impact of human intervention
  - Near real-time systems
- Summary



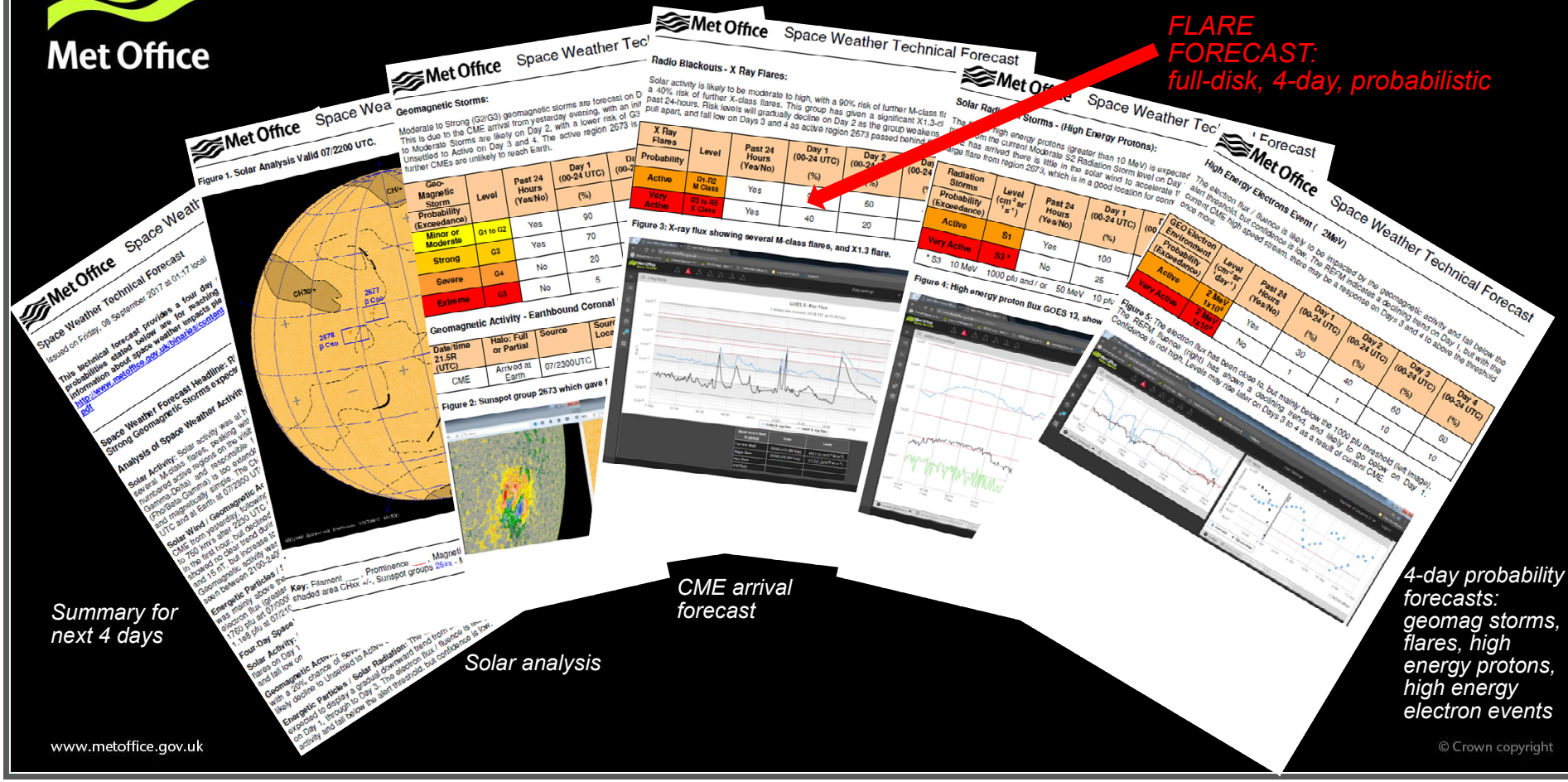
Met Office Space Weather Operations Centre (MOSWOC)

Human forecaster 24/7

- 24/7 operations
- Fully integrated within Met Office Operations Centre
- National capability supporting government, military and critical sectors
- Produce twice daily forecasts
- Team includes:
  - Forecasters
  - Scientists
  - Programme managers
  - IT developers

- Officially opened in 2014; in response to UK National Risk Register
- Monitors risk on behalf of UK Government – Dept of Business, Energy & Industrial Strategy (BEIS)

MOSWOC twice daily forecasts



FLARE FORECAST: full-disk, 4-day, probabilistic

Summary for next 4 days

Solar analysis

CME arrival forecast

4-day probability forecasts: geomag storms, flares, high energy protons, high energy electron events

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Flare forecast process
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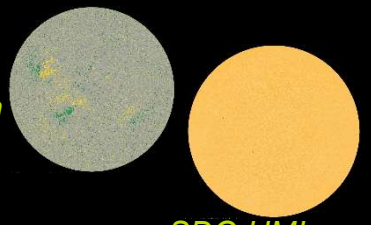
Flare forecast process: producing a Sunspot Region Summary (SRS)

1. Analyse each active region (AR)
   - Both SWPC numbered & any new ARs
   - Use SDO HI imagery
     - Overlay magnetograms & intensitygrams to compare magnetic structure of ARs to the sunspots



SDO HMI magnetogram

SDO HMI intensitygram

2. Assign Modified Mount Wilson & McIntosh classifications to each AR
   - Manually determine location, length & area (using internal software)

3. Calculate flare probabilities for each AR, based on historical flare rates for each McIntosh class
   - Database of GOES flares & McIntosh classifications is used, compiled from:
     - Kildhahl data, 1969-1976 [Bloomfield et al., 2012]
     - SWPC data, 1988-1996 [Bloomfield et al., 2012]
     - ASSA system data, 1996-2011
   - Database is used to calculate average daily flare rate for each McIntosh classification according to Bloomfield et al., 2012
   - Forecaster calculates flare probabilities for M- & X-class flares using Poisson stats technique [Gallagher et al., 2002]

Met Office — Sunspot Region Summary

Space Weather Product

For PWS users

Forecast Issued on: Monday, 18 April 2016 [illegible] Issue 03:15 Local

Observed Sunspot Regions:

Report issued four times a day (0300, 0900, 1500, 2100 UTC) from analysis of NASA SDO imagery and data from NOAA SWPC.

No.	Loc	Lo	Area	Z	LL	NN	Mag Type	Growth	M	X	P
2529	N11W52	342	900	Eki	13.0	10	Beta	Decrease	34	1	5
2532	N06E53	237	60	Cai	6.0	5	Beta	Increase	12	0	1
Total Raw %									42	1	5
Total Issued %									30	1	5

Comments: Region 2529 continues to show signs of decay, with almost all intermediate and trailer spots now very tenuous with only rudimentary penumbra at best. However this region recently (18/0029UTC) produced an M6.7 flare, the largest observed since 25th June 2015, so still has flare potential. Issued probabilities of M-class flares increased to 30% in light of this. Region 2532 has developed some intermediate spots since previous analysis, so is now classed Cai (from Cao).

Carrington 0-deg Longitude: at 18/0200 UTC = 290°

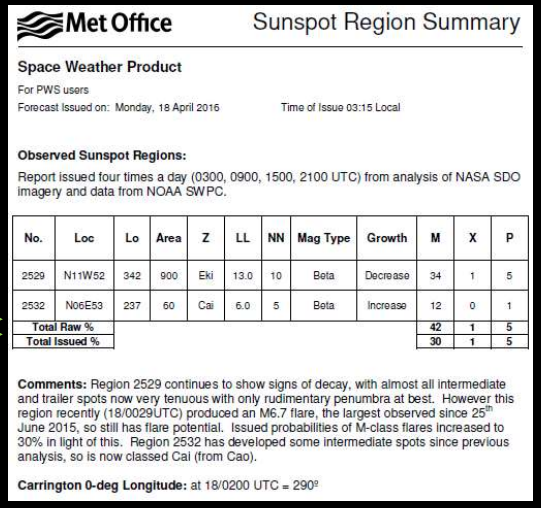
AR – location – characteristics – class – probability of flaring

Flare forecast process continued: producing a Sunspot Region Summary (SRS)

4. Combine resulting probabilities for each AR to give a full-disk probability, ‘total-raw’

5. Forecaster looks at solar data & uses experience to adjust raw, giving ‘total issued’

6. Issue SRS every 6 h, valid for following 24 h



Met Office — Sunspot Region Summary

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Flare forecast process continued: producing 4-day forecast

1. Use SRS's 'total issued' M- & X-class probabilities as basis for MOSWOC day-1 forecast
2. For days 2-4, add forecaster experience (e.g. how ARs evolving, leaving/emerging on disk)
3. Issue 4-day forecast at midnight. Update at midday.

X Ray Flares Probability	Level	Past 24 Hours (Yes/No)	Day 1 (00-24 UTC) (%)	Day 2 (00-24 UTC) (%)	Day 3 (00-24 UTC) (%)	Day 4 (00-24 UTC) (%)
Active	R1-R2 M Class	N	20	20	15	10
Very Active	R3 to R5 X Class	N	2	2	1	1

Example MOSWOC flare forecast

Flare category

Flare occurred in past 24h?

Probability that flare will occur for each of the next 4 days. Not exceedance, i.e. probability is of M-class occurring, not M-class or above

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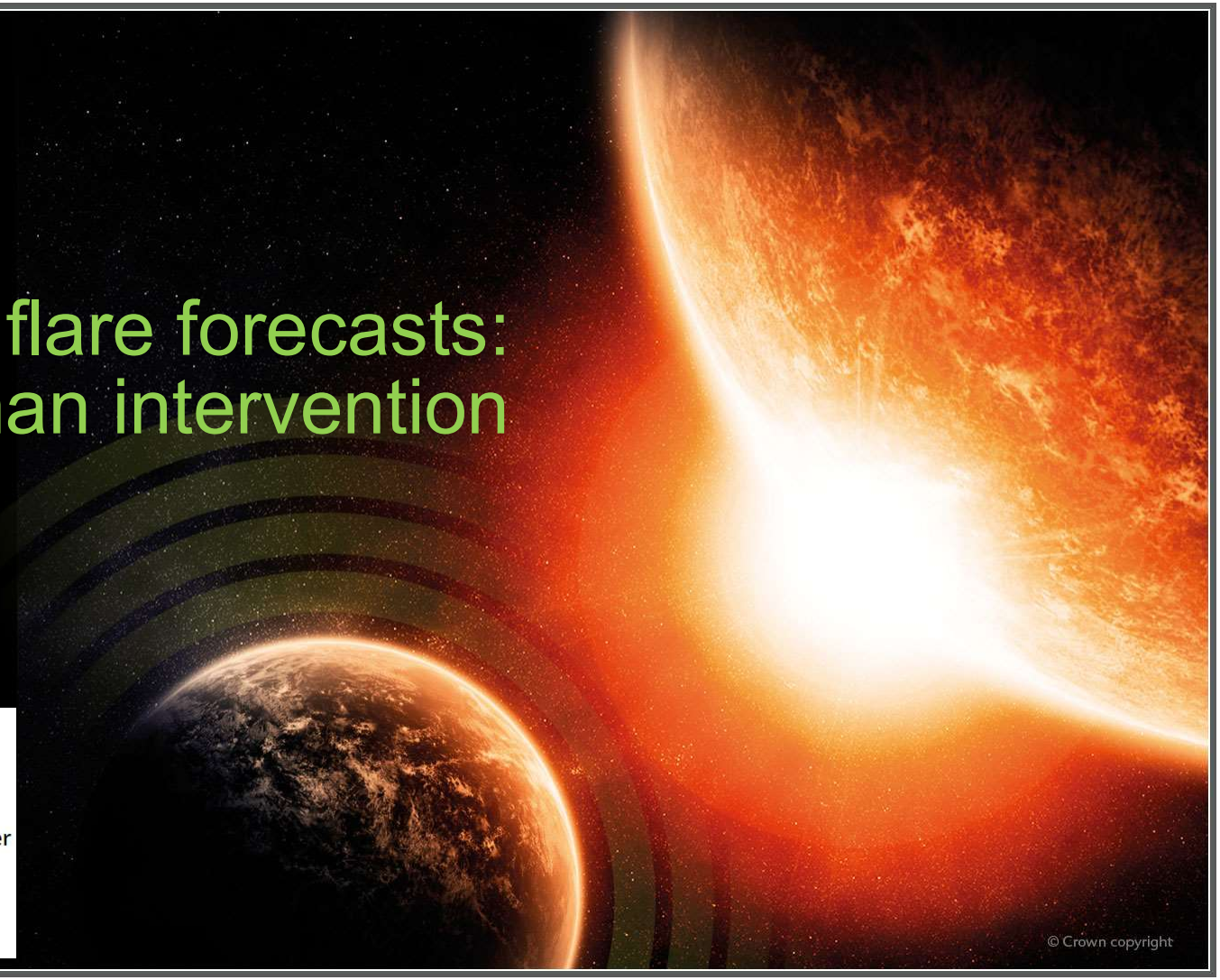
Verification of flare forecasts: impact of human intervention



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Research Article

Flare forecasting at the Met Office Space Weather Operations Centre

S. A. Murray ✉, S. Bingham, M. Sharpe, D. R. Jackson

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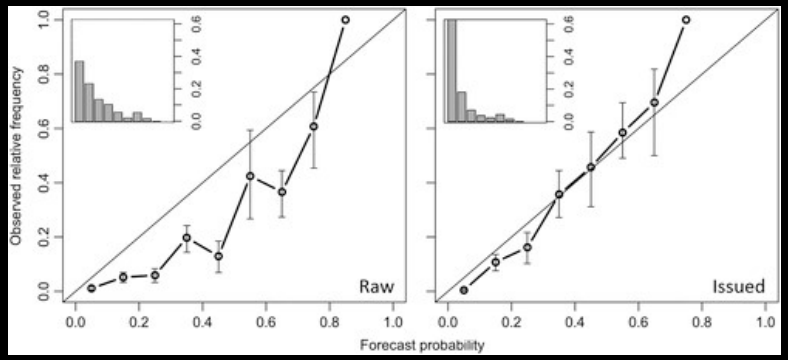
Verification of SRS forecasts: Reliability. Raw-model V human-edited



SRS full-disk for next 24 h - reliability diagrams, Jul '15 – '16.

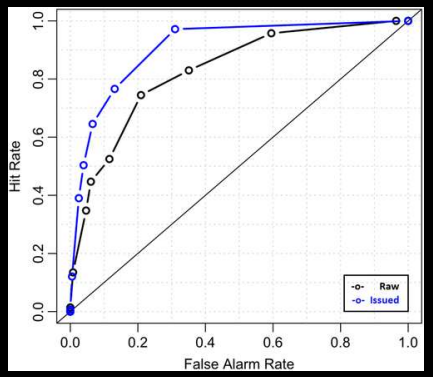
Left: raw-model forecast

Right: forecaster-issued forecast

Subplot: distribution of probabilities during study

- Reliability diagram: measures how closely forecast probabilities correspond to actual chance of observing M-class flare
- Perfect reliability: forecast probability = frequency of occurrence (diagonal)
- Raw model: below diagonal, i.e. over-forecasting
- Forecaster added-value to issued forecasts, closer to diagonal
- Subplot distributions show forecasters tend to decrease probability values, i.e. less over-forecasting

Verification of SRS forecasts: ROC. Raw-model V human-edited



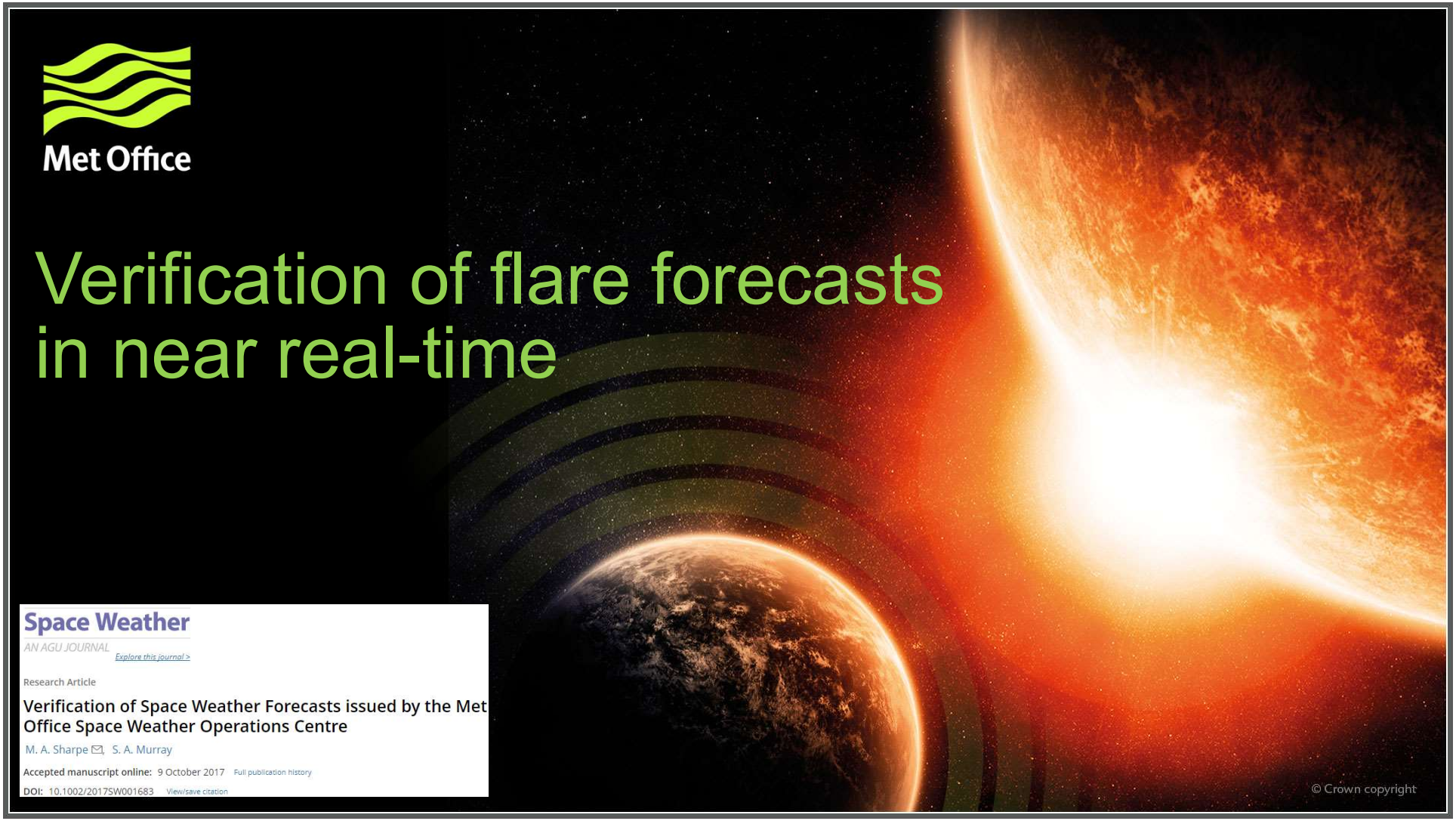
- ROC plot: measures forecast discrimination – provides info on false alarm rates & hit rates when using different probability thresholds to classify whether M-class+ events occur or not
- Skillful forecast system: hit rates exceed false alarm rates - ROC plot tends to top left corner
- Forecaster is adding value to raw-model forecast

SRS full-disk for next 24 h – ROC plots, Jul '15 – '16

Black: raw-model forecasts

Blue: forecaster issued

Verification of flare forecasts in near real-time



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Research Article

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

M. A. Sharpe ✉, S. A. Murray

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Adapting terrestrial near real-time verification systems

MOSWOC probabilistic forecast

System 1 — *Used for shipping forecast*

System 2 — *Used for gale warnings*

Treat as **multi**-category – e.g. assess all flare classes for day-1, & calculate 1 score

Assess human forecast skill by comparing against observations & calculating:
Ranked Probability Score (RPS)

As a performance benchmark, calculate RPS for a 'short-term climatology' (based on previous 120 days of flare obs)

Assess forecast performance by comparing RPS_{MOSWOC} to RPS_{ref}:
Ranked Probability Skill Score (RPSS)

Treat each category/level separately, e.g. assess just M-class on day-1

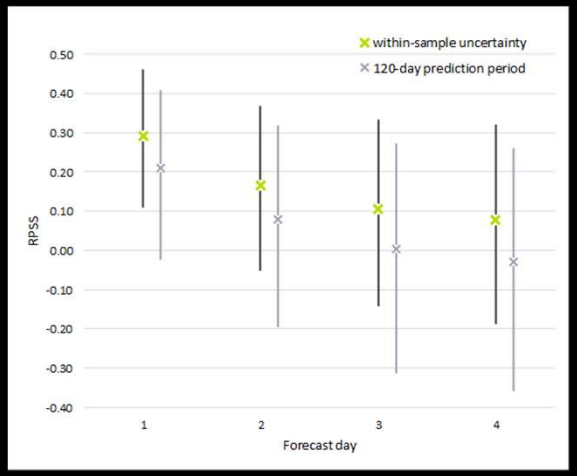
Assess forecast resolution:
Relative Operating Characteristic (ROC) plots

Assess forecast reliability:
Reliability diagrams

[RPS: sum of squared differences in cumulative probability space for a multi-category probabilistic forecast. Penalises forecast when probabilities are further from observation. For 2 forecast categories, RPS=Brier Score.

RPSS: relative improvement of probability forecast over reference forecast in predicting category which observation fell into]

Treating forecast as multi-category: 3 year period performance plot



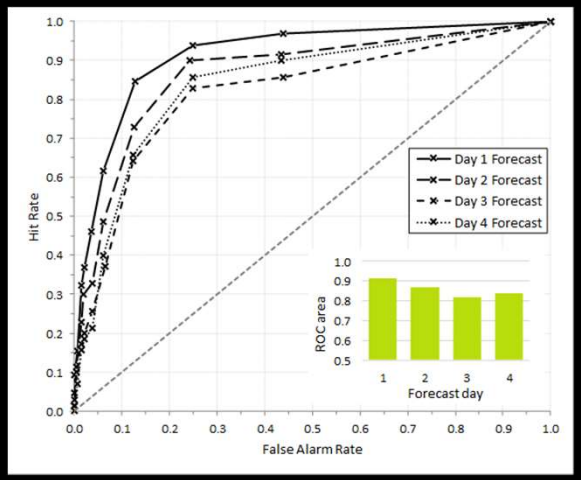
RPSS for day 1-4 forecasts. Jan '16 – Dec '18.

Performance of MOSWOC M-class flare forecasts compared to 1) rolling 120-day prediction period, 2) within-sample uncertainty (3 year).

- X-axis: 1-4 day forecast
- Y-axis: RPSS
- Crosses: mean RPSS for MOSWOC forecast compared to reference forecast
- Vertical lines: 90% bootstrapped with replacement confidence intervals (CIs)
- If y>0, no-skill line, then MOSWOC forecast is more skilful than reference
- Most RPSSs lie above no-skill line suggesting MOSWOC forecasts show skill
- Results indicate MOSWOC struggle to add value to reference forecasts

- Most CIs cross no-skill line, so no statistically significant evidence that MOSWOC forecast outperforms reference in predicting max daily flare class
- MOSWOC day 1 forecast shows significantly statistical evidence that it's more skilful than 3 year frequency of occurrence

Treating forecast as separate categories: ROC plot from near real-time data



ROC plot (above) and ROC area (inset) for day 1-4, flare forecasts of M-class flares or above.
Apr '15 – 31st Dec '18.

- Points lie above diagonal no-skill line (chance) so forecast has skill at discriminating between whether M-class+ flares occur or not
- Suggests day 1 forecast is most skillful

ROC plot: measures forecast discrimination – provides info on false alarm rates & hit rates when using different probability thresholds to classify whether max daily flux is at least an M-class

ROC area: quantifies ability of forecast to distinguish between whether M-class+ occurred or not

Summary

- MOSWOC flare forecast process is based on database of flare classifications & rates
- SRS verification has shown forecaster does improve raw-model forecasts
- Near real-time verification systems have been implemented to understand performance & skill – updated daily
  - Rolling prediction period of 120-days provides a skillful frequency of occurrence reference forecast (calculated using 10 year period between 2006 and 2015)
  - MOSWOC showed some skill at identifying M-class flares but were over-forecasting (Reliability diagrams – see poster)
  - 3 year analysis using RPSS shows no consistent evidence that MOSWOC are more skillful than rolling 120 day reference (flares are difficult to predict!)
  - Day 1 forecasts show more skill than those with greater lead-times, & do outperform 3 year frequency of occurrence reference
- Next step: operational ensemble flare prediction system – using available forecasts; verifying using nrt system

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Thank you

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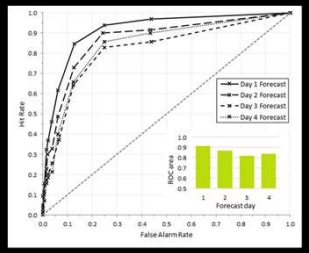
Poster overview

X4.175 – 1045-1230 Wed 10th

Near real-time verification of operational solar flare forecasts

Suzy Bingham[1], David Jackson[1], Michael Sharpe[1], Sophie Murray[2], Jesse Andries[3] and Catherine Burnett[1]

- Met Office near real-time forecast verification systems – adapted from terrestrial weather verification systems – updated daily: ROC, Reliability, RPSS
- MOSWOC flare forecast verification results
  - Statistically significant evidence that MOSWOC day 1 forecast is skillful compared to a 3 year reference forecast. Generally over-forecasting.
  - Increased lead-time leads to less skillful forecasts



- ISES - primary organisation engaged in international coordination of space weather services since 1962
- Recommendations for verifying ISES members' probabilistic flare forecasts, e.g.
  - Metrics to use
  - Consult with an expert group