Forecast improvements from solar wind data assimilation

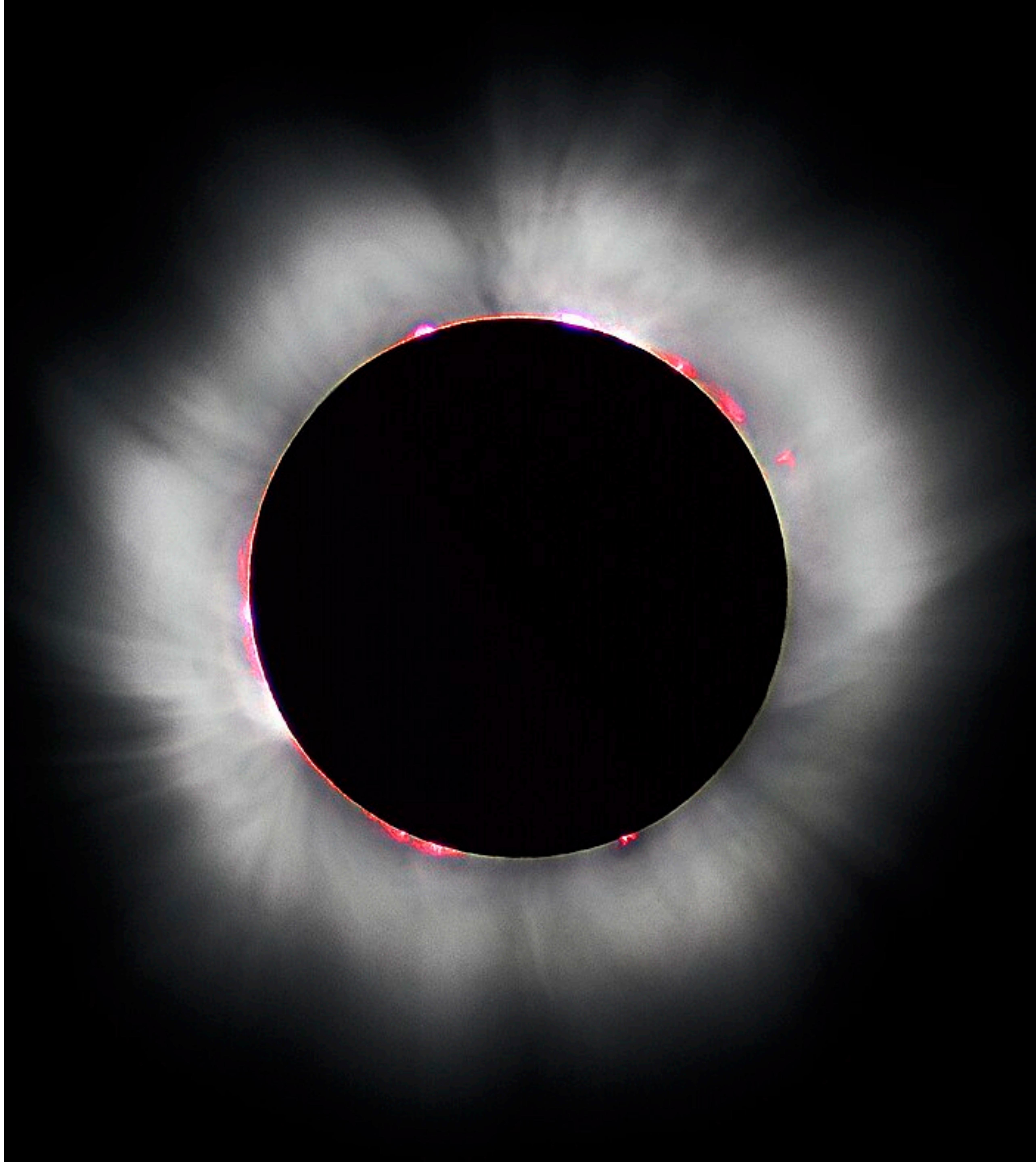
Harriet Turner, Mathew Owens, Matthew Lang, Mike Marsh & Siegfried Gonzi

Lunchtime seminar | 18/02/2025

Thesis overview

Motivation and aims

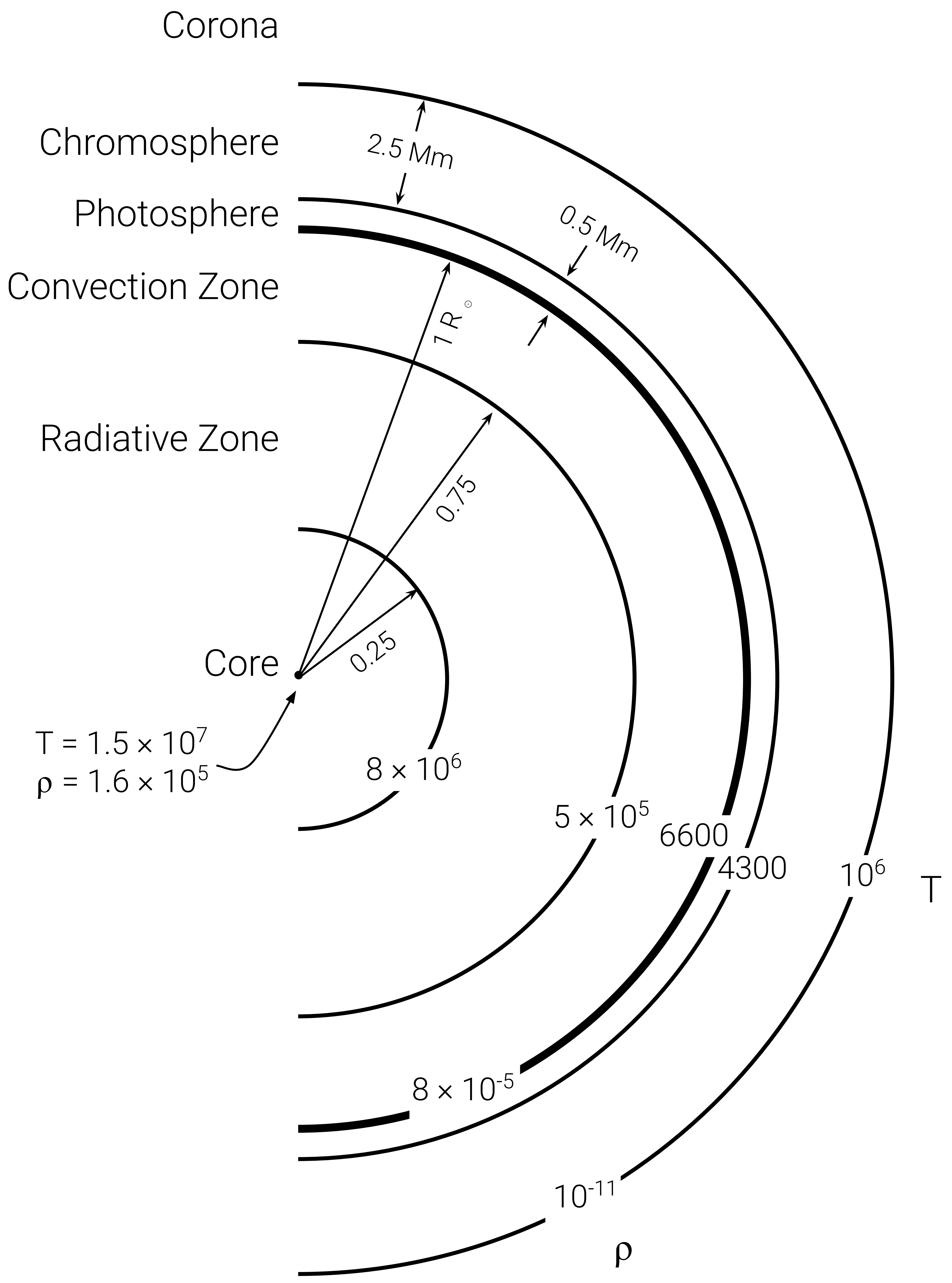
- Aim I. To understand some of the errors present in solar wind forecasts.
- Aim II. To verify solar wind DA forecasts under a range of conditions.
- Aim III. To transition to operational solar wind DA.



Introduction and background

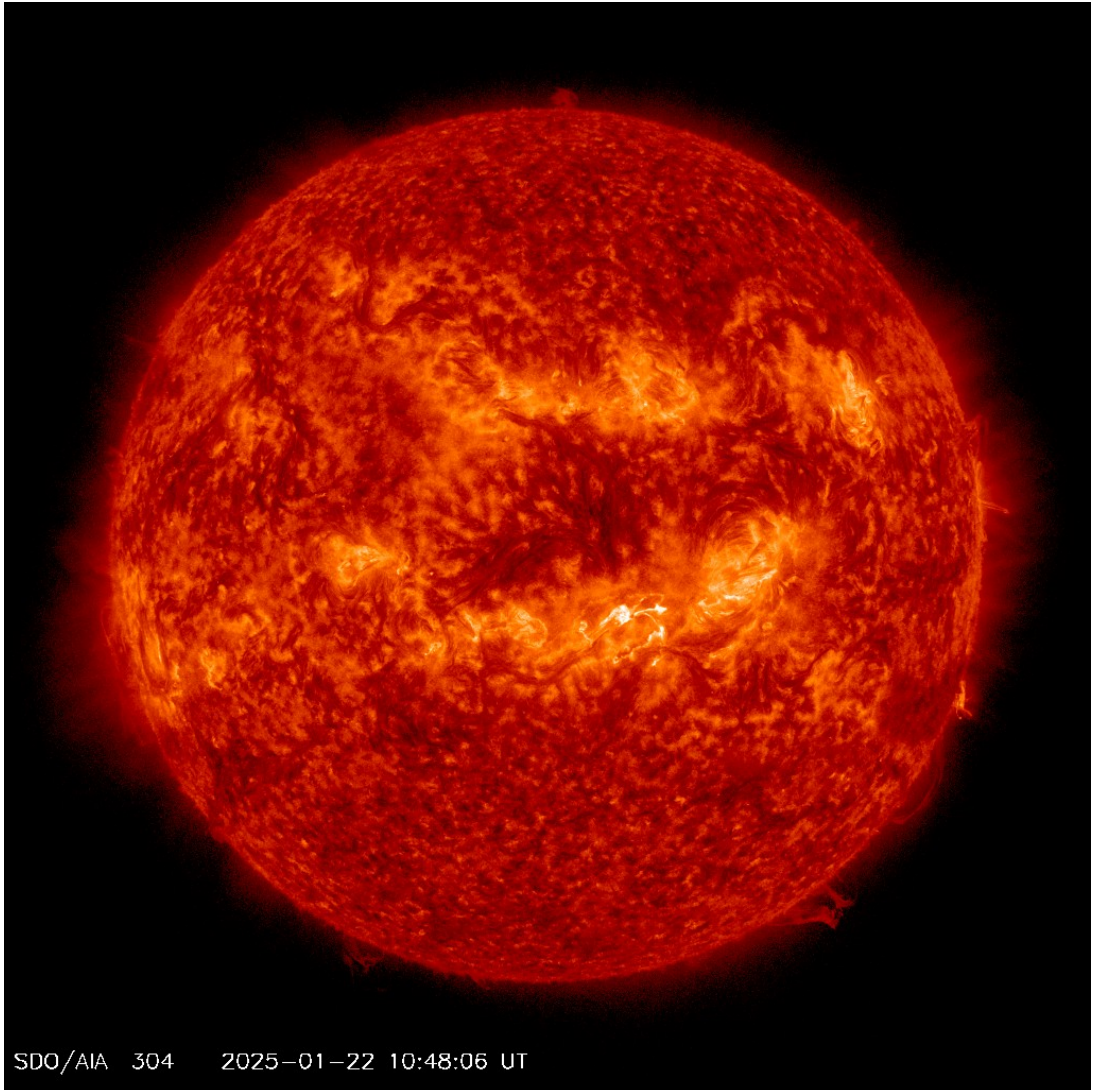
Structure of the Sun

- The Sun is an ordinary star of mass 2.0 x 10^{30} kg and radius 7.0 x 10^{8} m.
- Constructed of plasma.
- Constructed into several layers
  - Solar interior — core, radiative zone, convection zone, photosphere.
  - Solar atmosphere — chromosphere, corona.



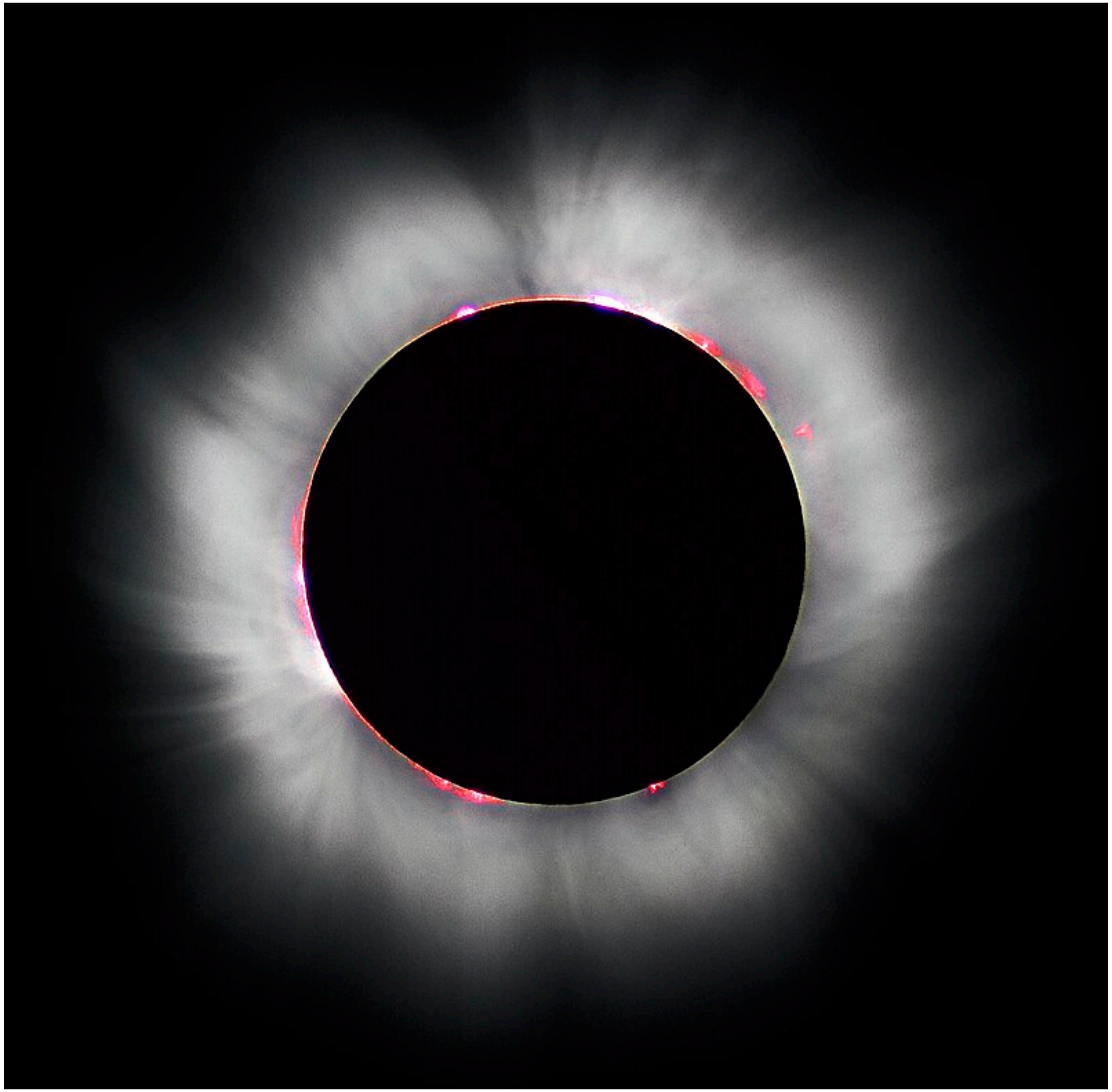
Solar interior

- The solar magnetic field is generated by the motion of plasma in the convection zone.
- The photosphere represents the visible surface of the Sun.
- Almost all the light we receive comes from the photosphere.
- Granular pattern from underlying convection.



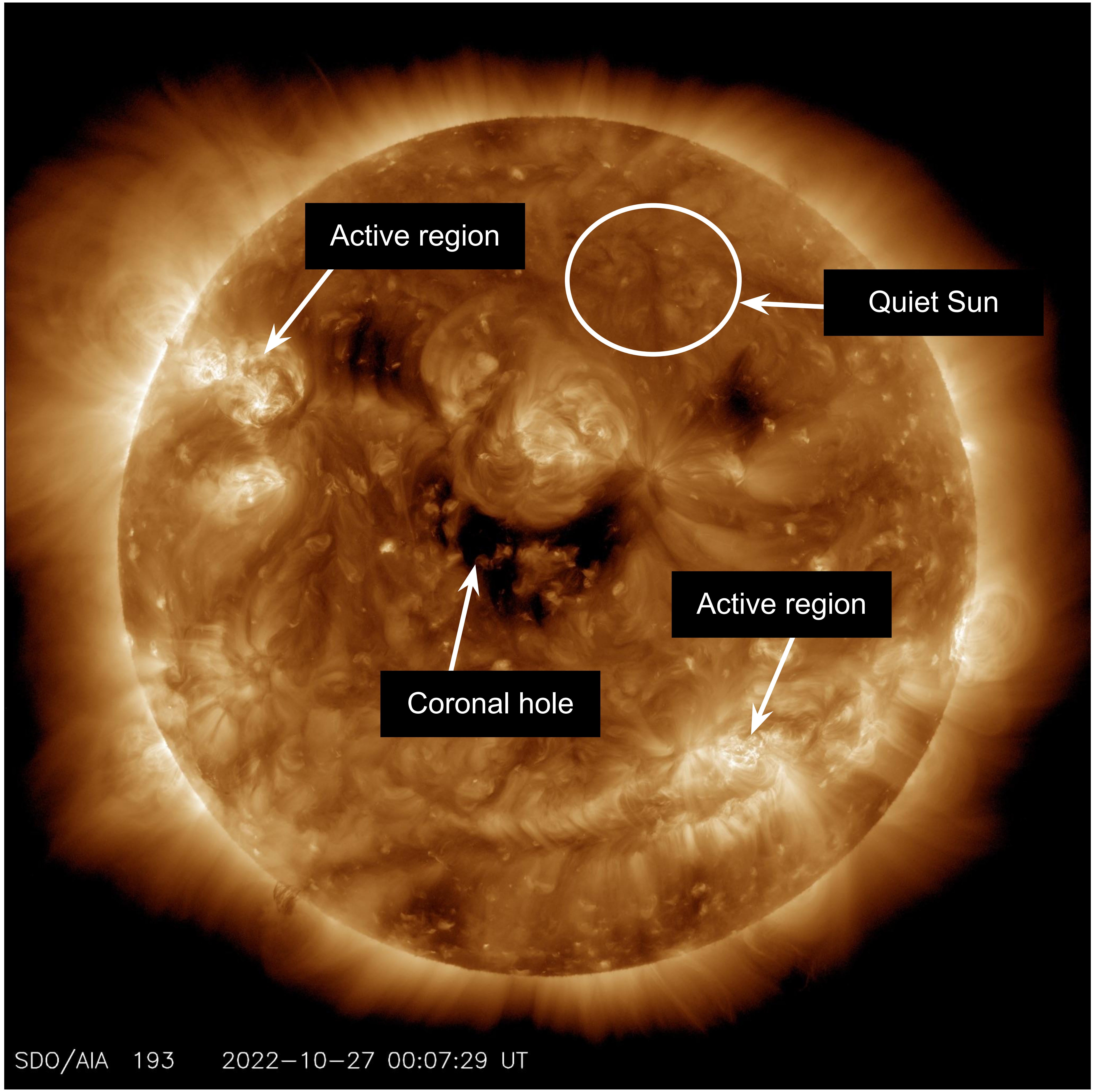
Solar atmosphere

- Temperature *increases* with radius.
- Physical processes behind temperature increase in debated.
- Corona only visible when the light from the photosphere is blocked out, e.g. eclipse or coronagraph.
- Source of the solar wind.



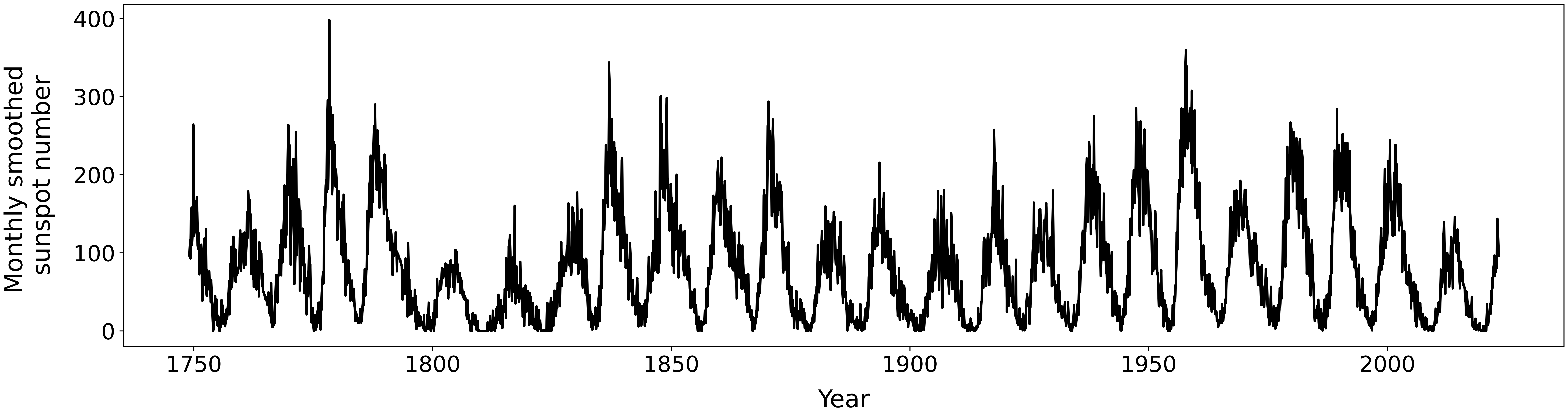
Corona

- Processes dominated by the coronal magnetic field.
- Comprised of open and closed magnetic field.
- Features include active regions and coronal holes.
  - Sunspots underly active regions.
- Structure varies throughout the solar cycle.



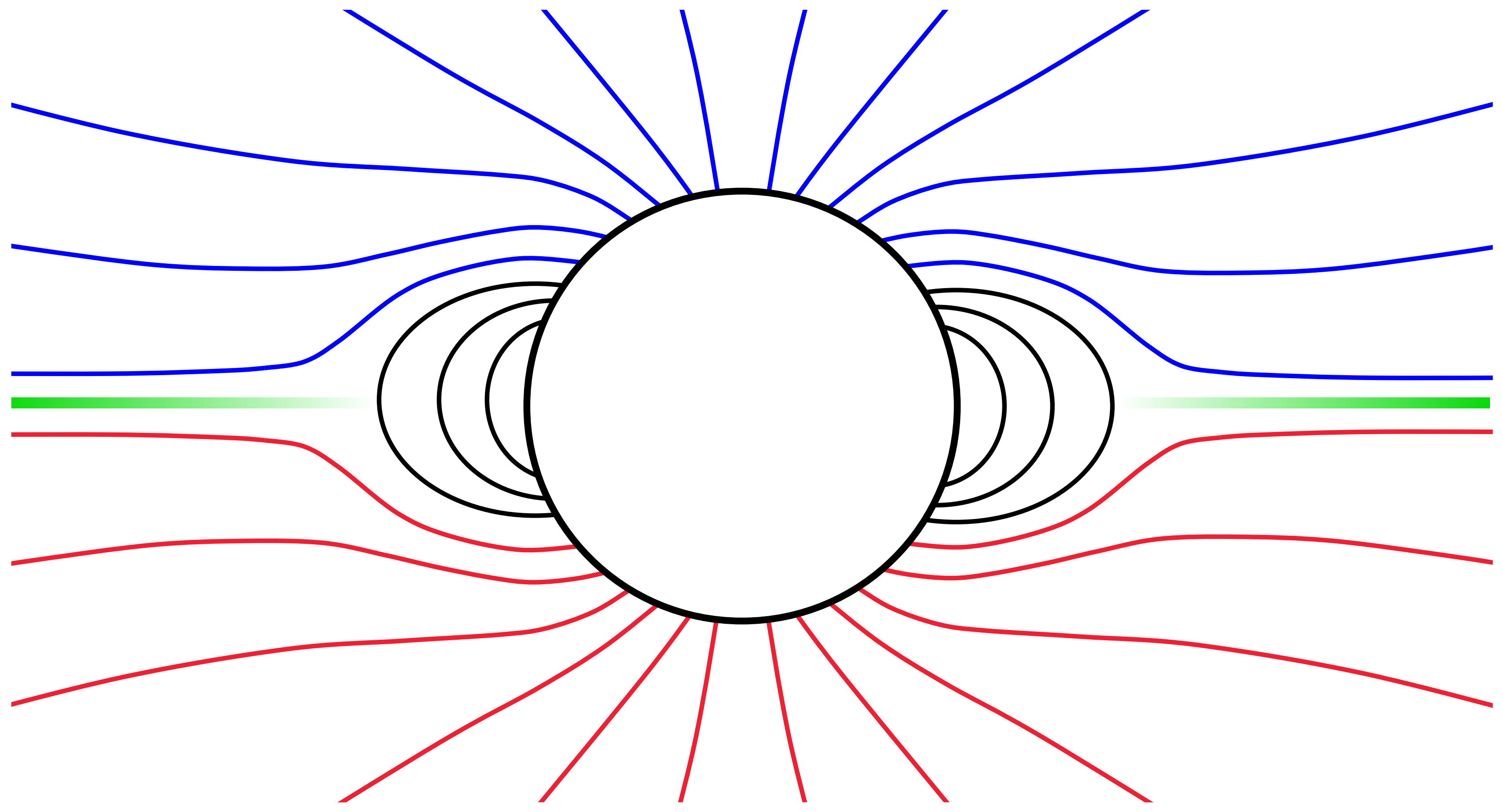
The solar cycle

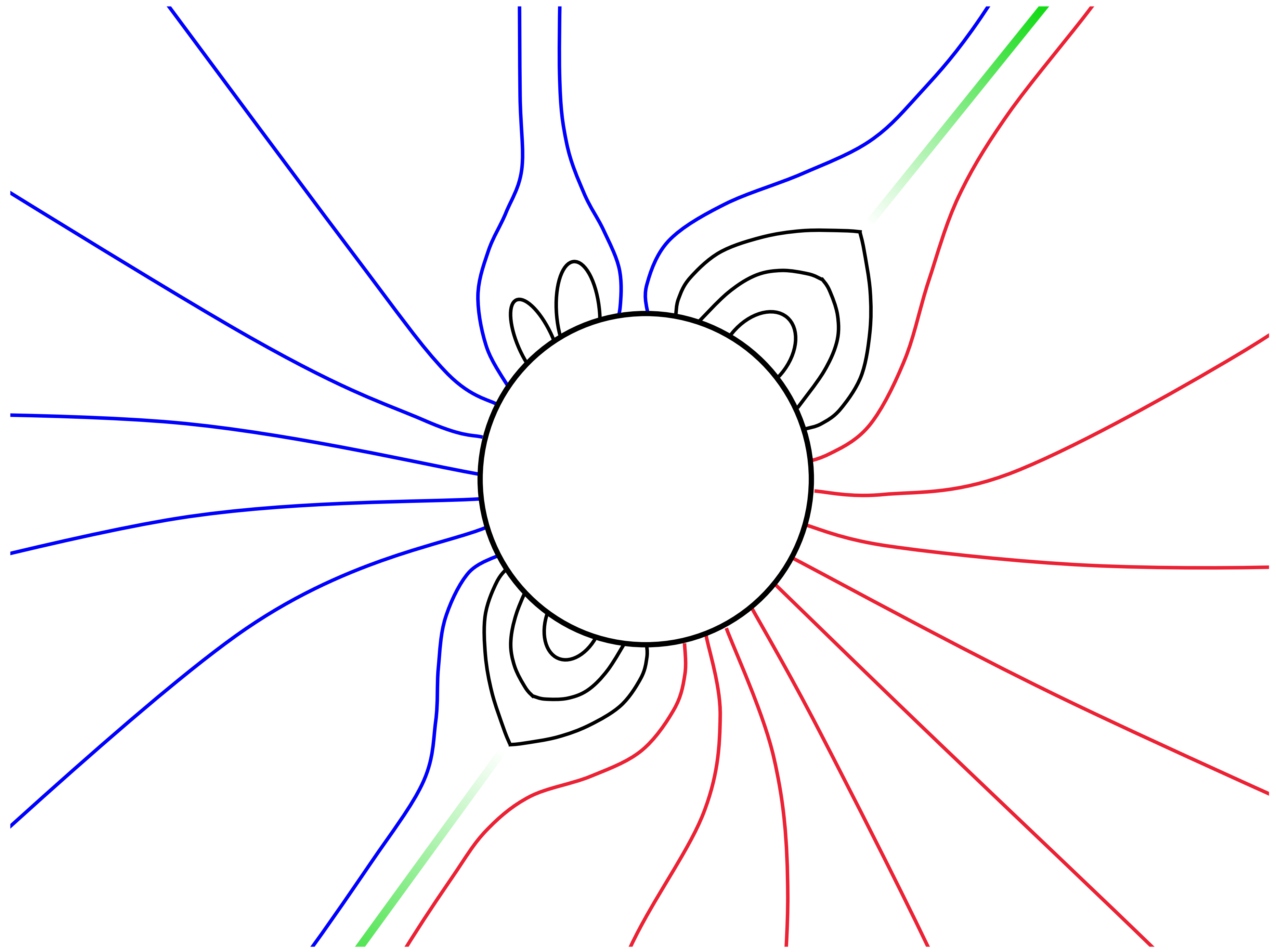
- Approximately 11-year activity cycle.
- Cycle can be monitored through the number of sunspots.
- The magnetic field changes structure throughout the cycle.



Solar magnetic field

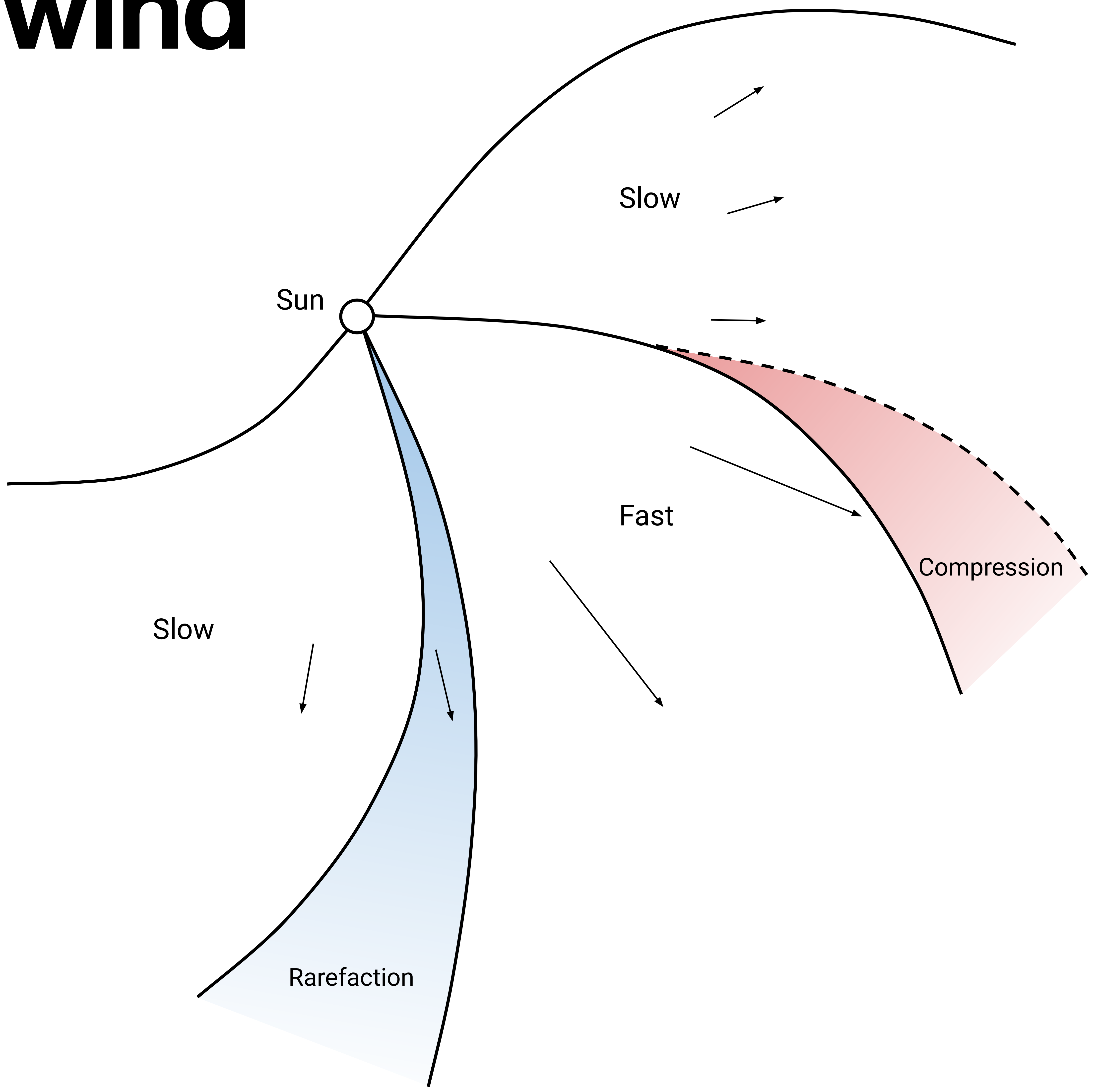
- Solar minimum is approximately dipolar, whereas solar maximum is more dynamic.
- The heliospheric current sheet forms between regions of opposite magnetic polarity.





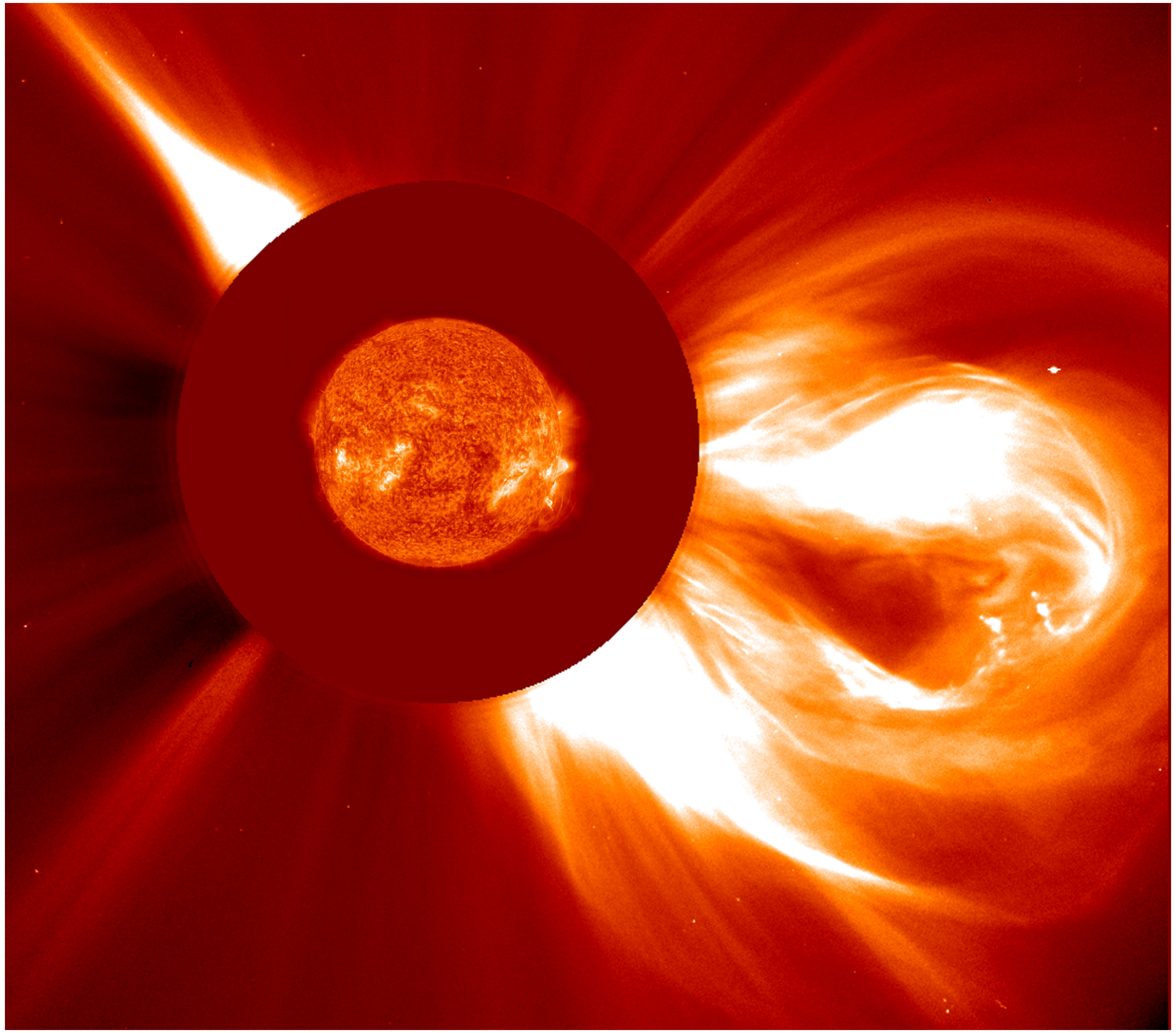
The solar wind

- Constant stream of charged particles that flows into the heliosphere, dragging with it the Sun's magnetic field.
- Fast solar wind emanates from regions of open magnetic field, whereas slow solar wind comes from closed regions.
- Due to the rotation of the Sun, the solar wind forms into a spiral shape, known as the Parker Spiral.



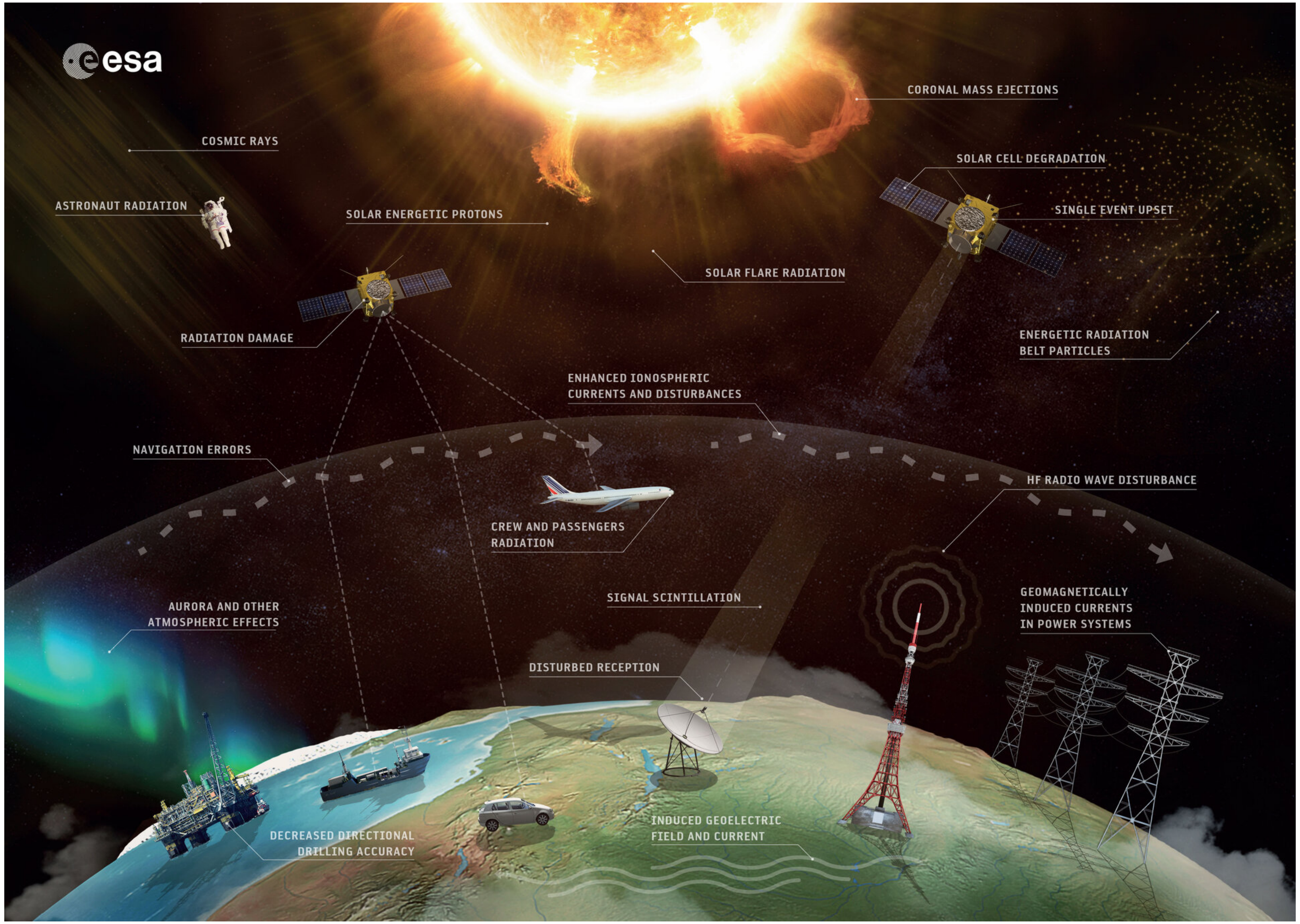
Coronal mass ejections

- Coronal mass ejections (CMEs) are transient eruptions of plasma and magnetic field.
- They propagate through the solar wind, with the background conditions affecting their travel through space.
- Occurrence rate varies with the solar cycle.



Space weather impacts

- Space weather refers to the changing plasma conditions in near-Earth space.
- CMEs are a cause of severe space weather.

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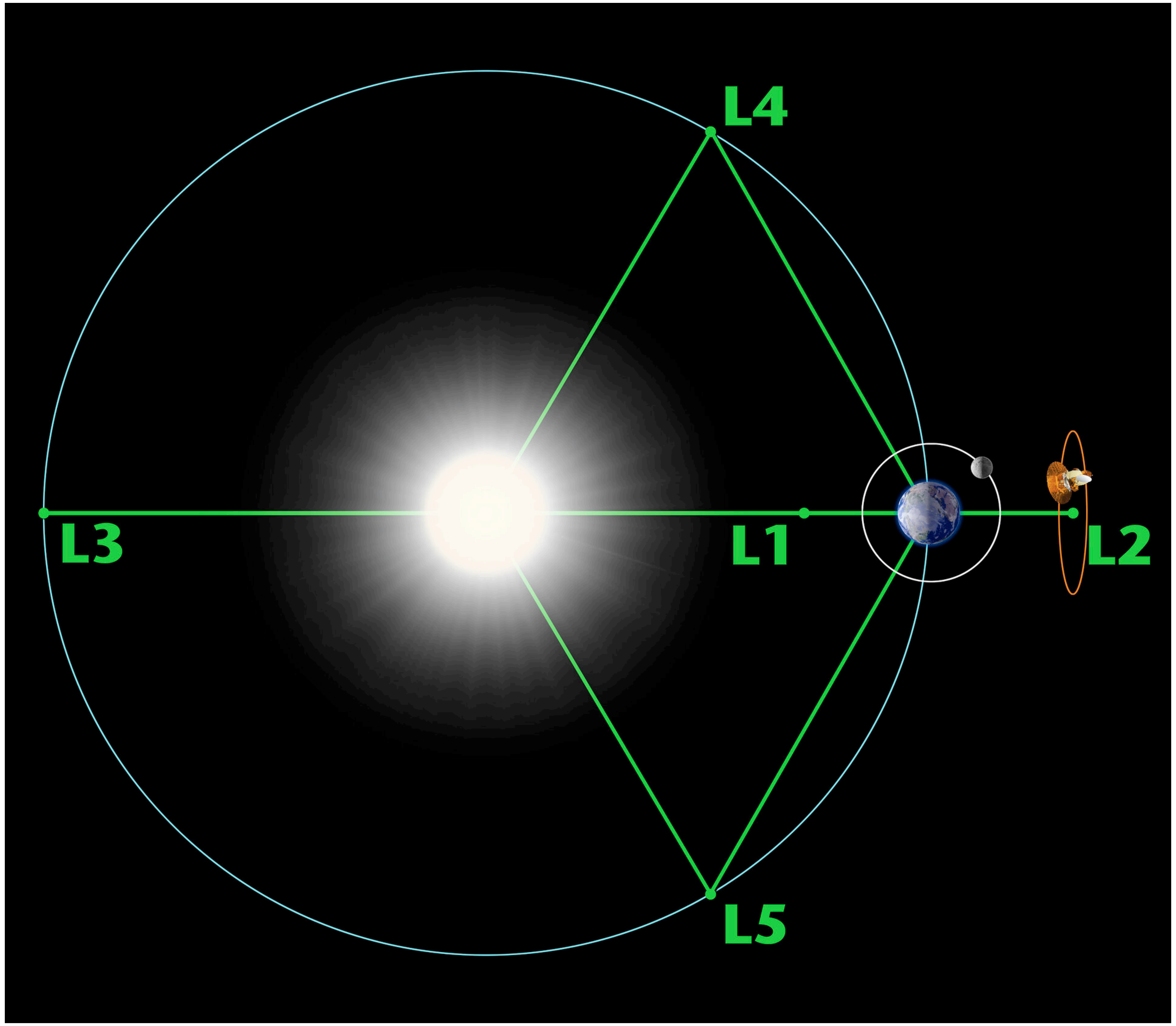
Methodology

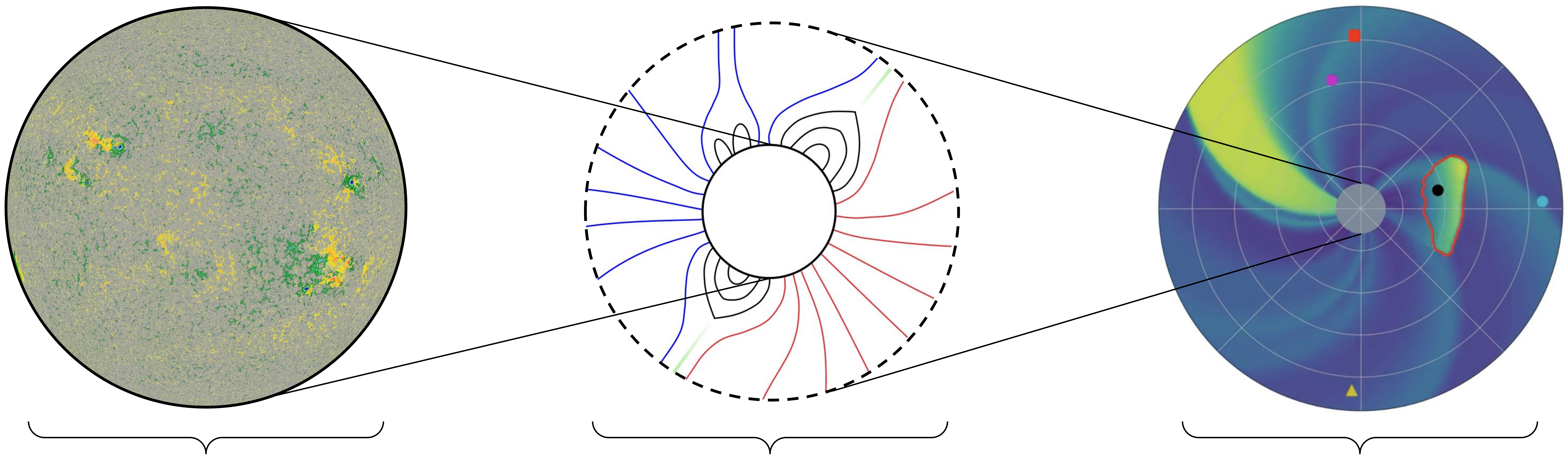
Spacecraft missions

- STEREO — twin spacecraft mission, orbiting at ~Earth's radial distance.
- ACE & DSCOVR — in the L1 position.



Current solar wind forecasting

- Coupled coronal model and solar wind model, initiated with observations of the photospheric magnetic field.
- The solar wind model can be a full physics-based model (e.g. Enlil) or a reduced-physics model such as HUX/ HUXt.



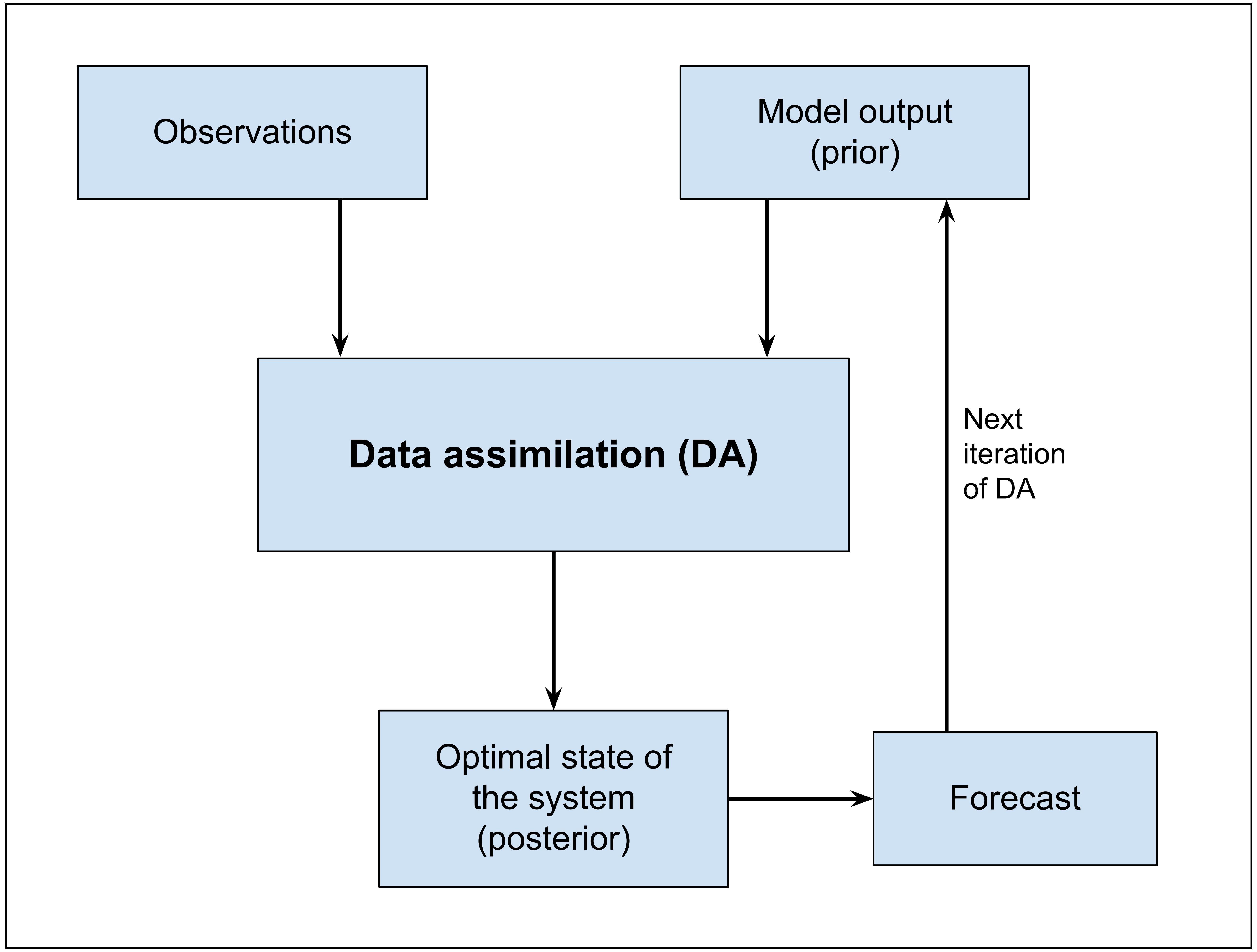
Observed magnetic field from the photosphere

Coronal model (e.g. MAS or WSA)

Solar wind model (e.g. HUXt or Enlil)

Data assimilation

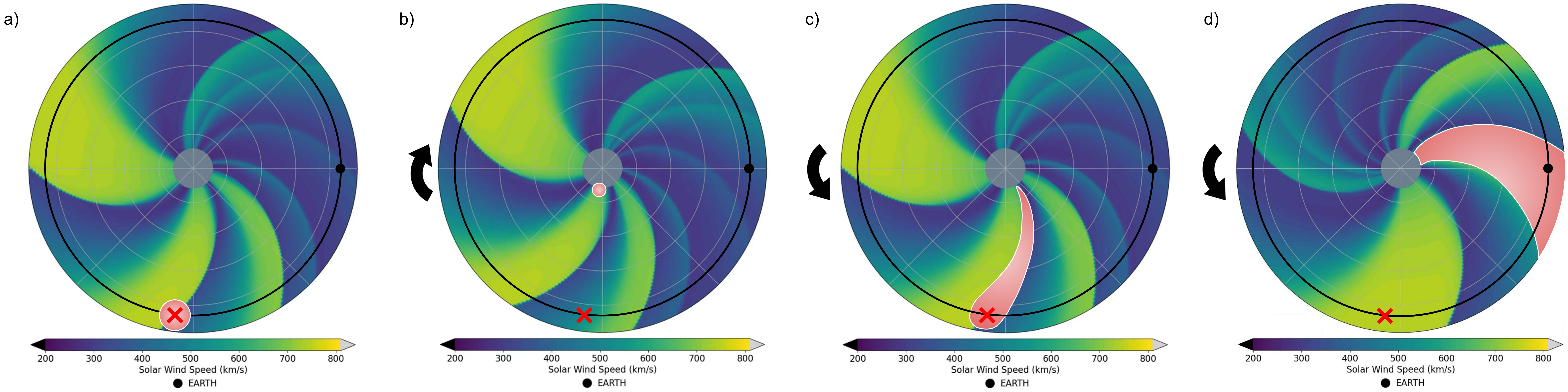
- DA is a technique that has led to large forecast improvements in terrestrial weather forecasting.
- It combines observations and model output to form an optimum estimation of reality.
- It has been underused in space weather forecasting.



BRaVDA scheme

Burger Radius Variational Data Assimilation

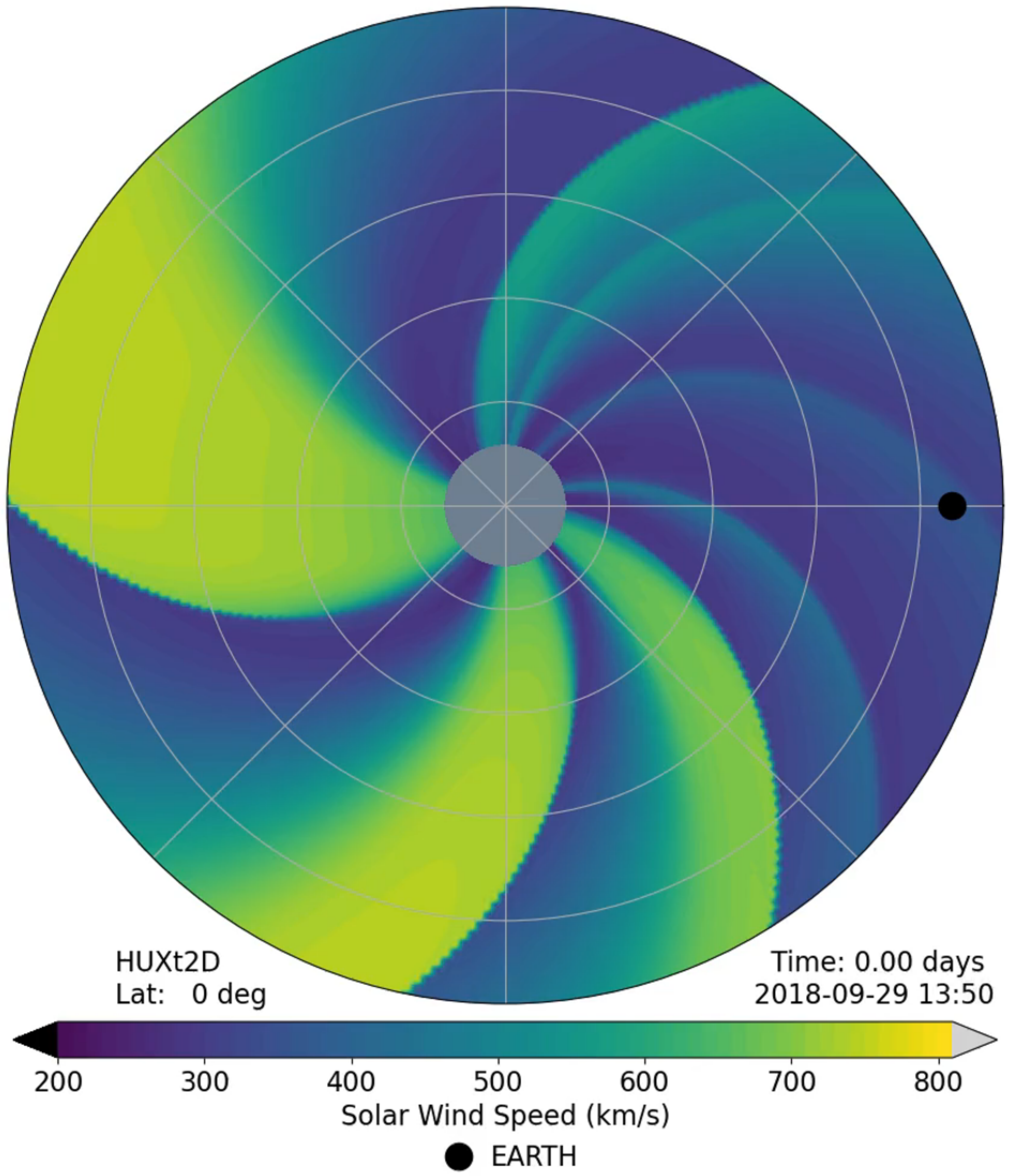
- 4D-Var data assimilation scheme, using the adjoint method to assimilate observations from close to Earth's latitude with the HUX model.
- Information from the observations is used to update the initial conditions of the solar wind model.



Aim I.
To understand some of the errors present in solar wind forecasts.

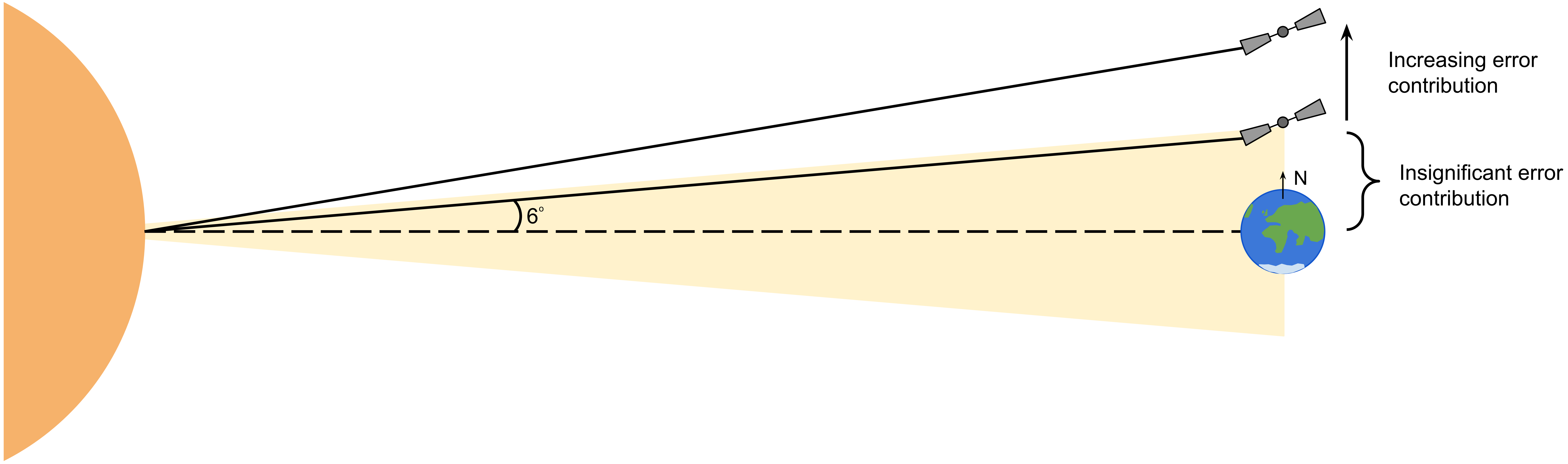
Corotation forecasts

- Corotation forecasts use the rotating structure of the solar wind to use observations as a forecast, assuming steady state conditions.
- Useful way to investigate the errors present due to, for example, spacecraft configuration.
- Can inform the DA scheme as to how best to use the observations.



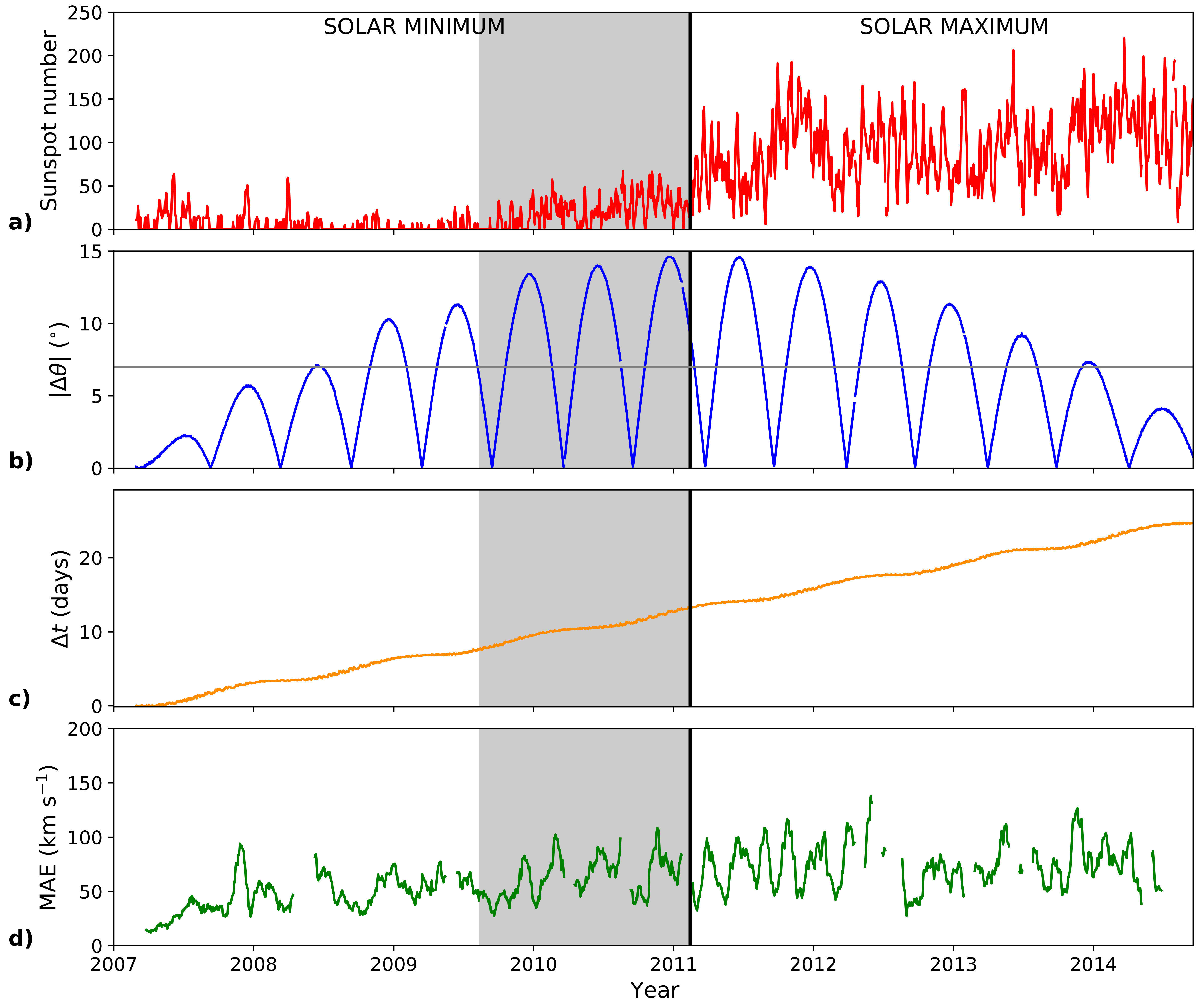
Spacecraft latitudinal offset

- Spacecraft orbiting at Earth's radius can be used for corotation forecasts.
- There is often a latitudinal difference between the spacecraft and Earth.
- Challenging to isolate the latitudinal effect due to aliasing factors.



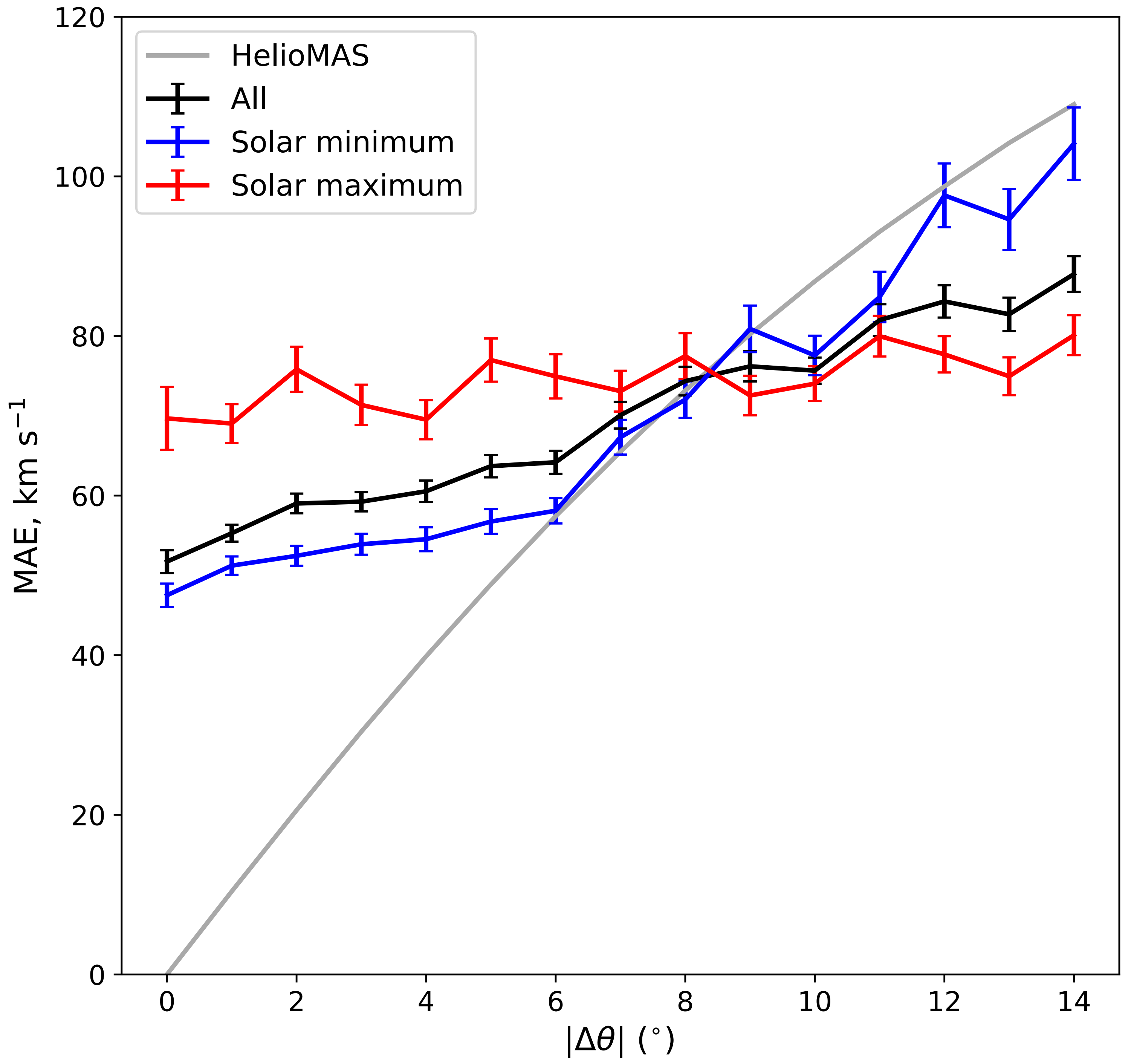
Aliasing

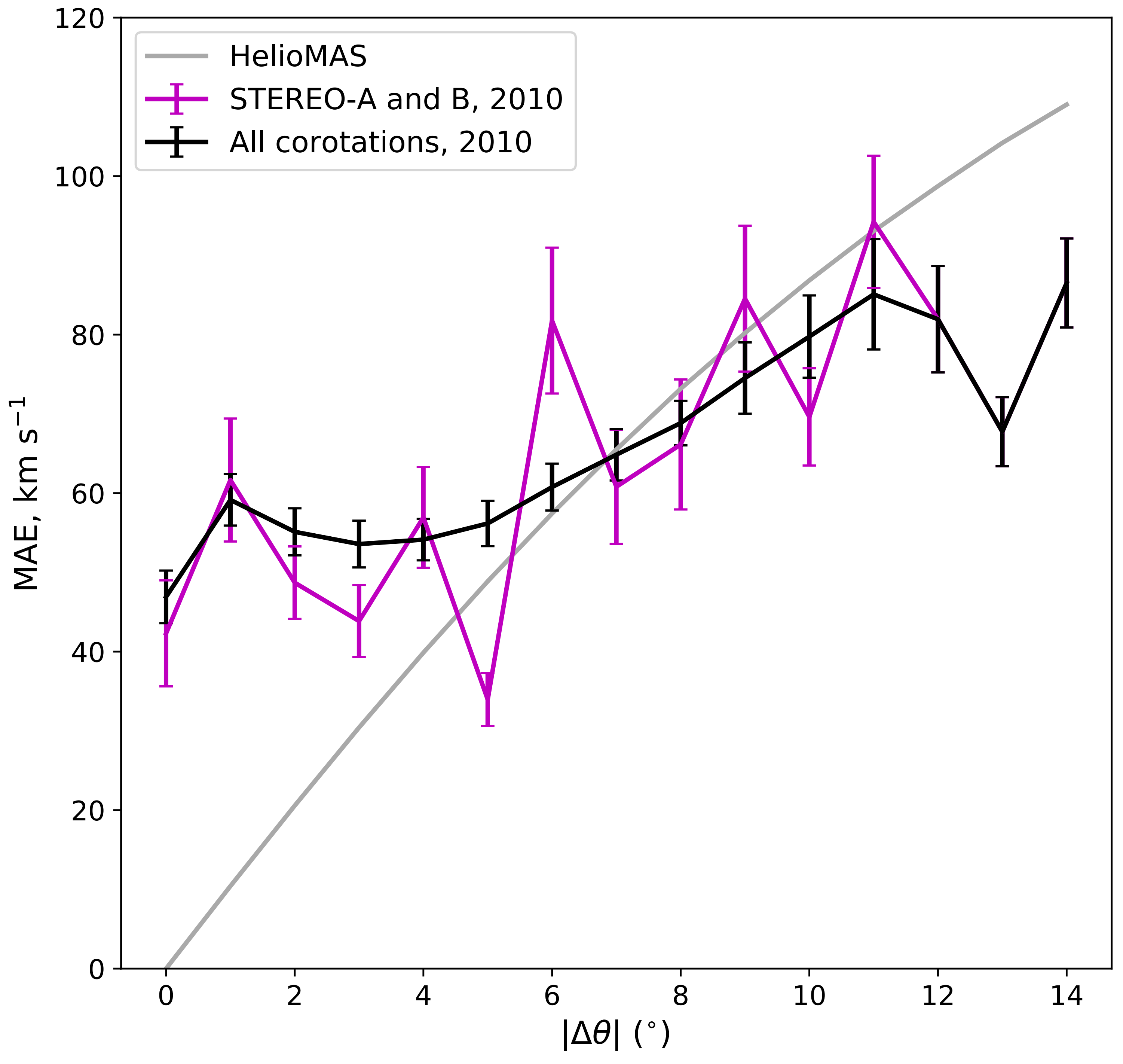
- Longitudinal separation — the larger the separation, the less the steady state assumption holds.
- Solar cycle — at solar maximum, the solar wind is more dynamic and evolves more quickly.
- These factors are interlinked.
- Used a time restricted time period to prevent aliasing.



Results

- Latitudinal separations of less than 6 degrees have a limited impact on forecast error.
- Increasing error contribution for separations of greater than 6 degrees.
- Implies that for use in solar wind DA, observations of less than 6 degrees separation would be preferable.
- Future L5 missions would reach a maximum of 5 degrees difference from Earth.





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Key Points:

- Solar wind speed corotation forecast error is affected by solar activity and spacecraft longitudinal and latitudinal separation
- Latitudinal separation has little effect when it is below 6°, but increasing importance above this
- A period in solar minimum gives a 46% increase in mean absolute error (MAE) from low to high latitudinal offset for Solar Terrestrial Relations Observatory (STEREO)-A and B corotations

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

H. Turner,
h.turner3@pgr.reading.ac.uk

Citation:

Turner, H., Owens, M. J., Lang, M.

The Influence of Spacecraft Latitudinal Offset on the Accuracy of Corotation Forecasts

Harriet Turner[1], Mathew J. Owens[1], Matthew S. Lang[1], and Siegfried Gonzi[2]

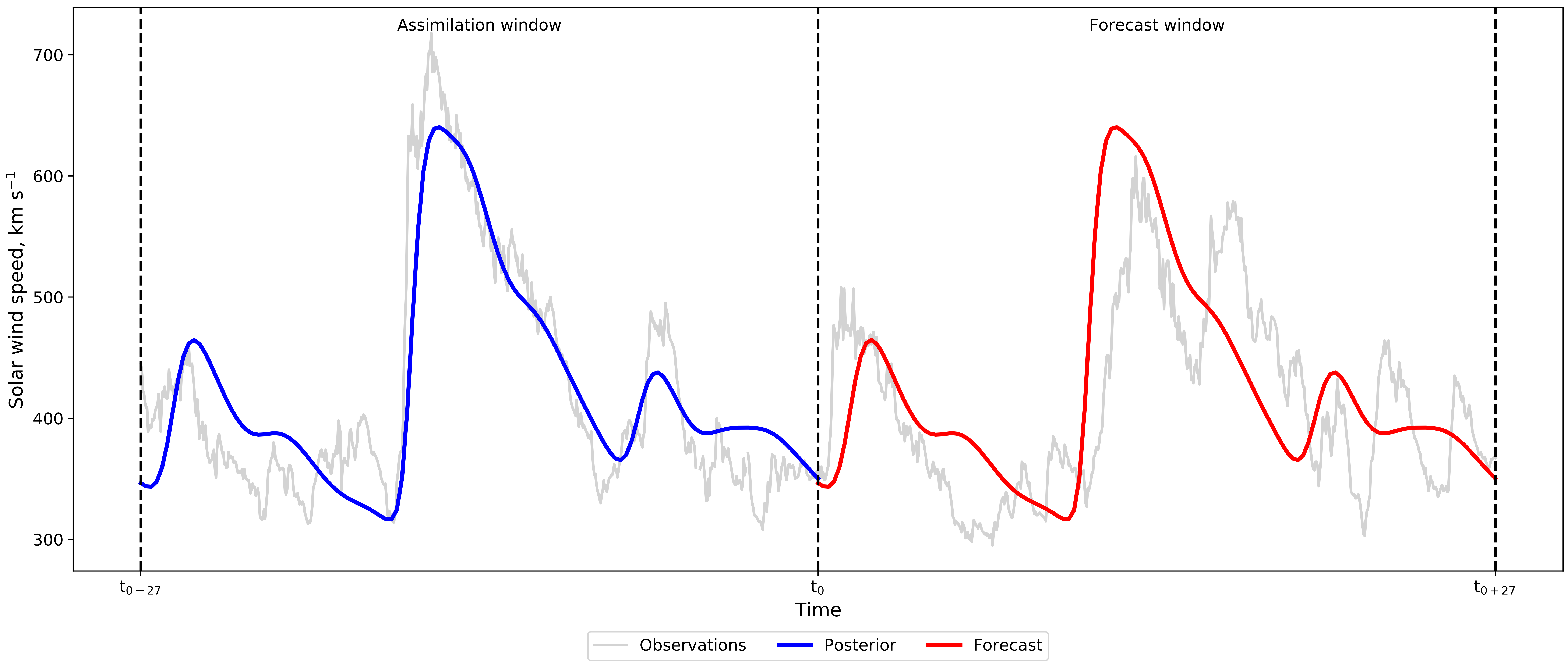
[1]Department of Meteorology, University of Reading, Reading, UK, [2]Met Office, Exeter, UK

Abstract Knowledge of the ambient solar wind is important for accurate space weather forecasting. A simple-but-effective method of forecasting near-Earth solar wind speed is "corotation," wherein solar wind structure is assumed to be fixed in the reference frame rotating with the Sun. Under this approximation, observations at a source spacecraft can be rotated to a target location, such as Earth. Forecast accuracy depends upon the rate of solar wind evolution, longitudinal and latitudinal separation between the source and target, and latitudinal structure in the solar wind itself. The time-evolution rate and latitudinal structure of the solar wind are both strongly influenced by the solar cycle, though in opposing ways. A latitudinal separation (offset) between source and target spacecraft is typically present, introducing an error to corotation forecasts. In this study, we use observations from the Solar Terrestrial Relations Observatory (STEREO) and near-Earth spacecraft to quantify the latitudinal error. Aliasing between the solar cycle and STEREO orbits means that individual contributions to the forecast error are difficult to isolate. However, by considering an 18-month interval near the end of solar minimum, we find that the latitudinal-offset contribution to corotation forecast error cannot be directly detected for offsets <6°, but is increasingly important as offsets increase. This result can be used to improve solar wind data assimilation, allowing representivity errors in solar wind observations to be correctly specified. Furthermore, as the maximum latitudinal offset between L5 and Earth is ≈5°, corotation forecasts from a future L5 spacecraft should not be greatly affected by latitudinal offset.

Aim II.
To verify solar wind DA forecasts under a range of conditions.

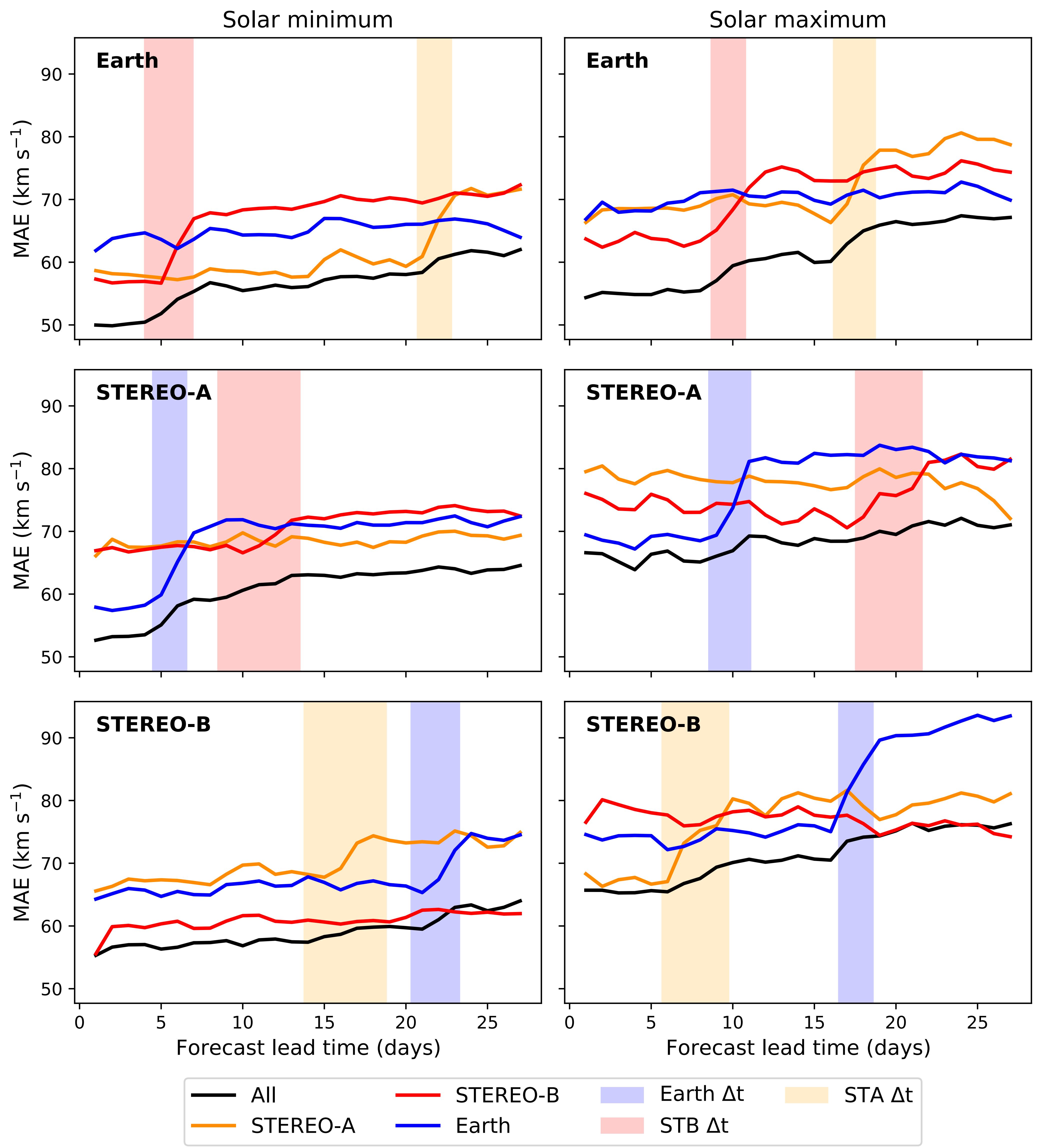
BRaVDA forecasts

- BRaVDA generates a reconstruction of the solar wind for the previous 27-days.
- This can be used as a forecast for the next 27-days.



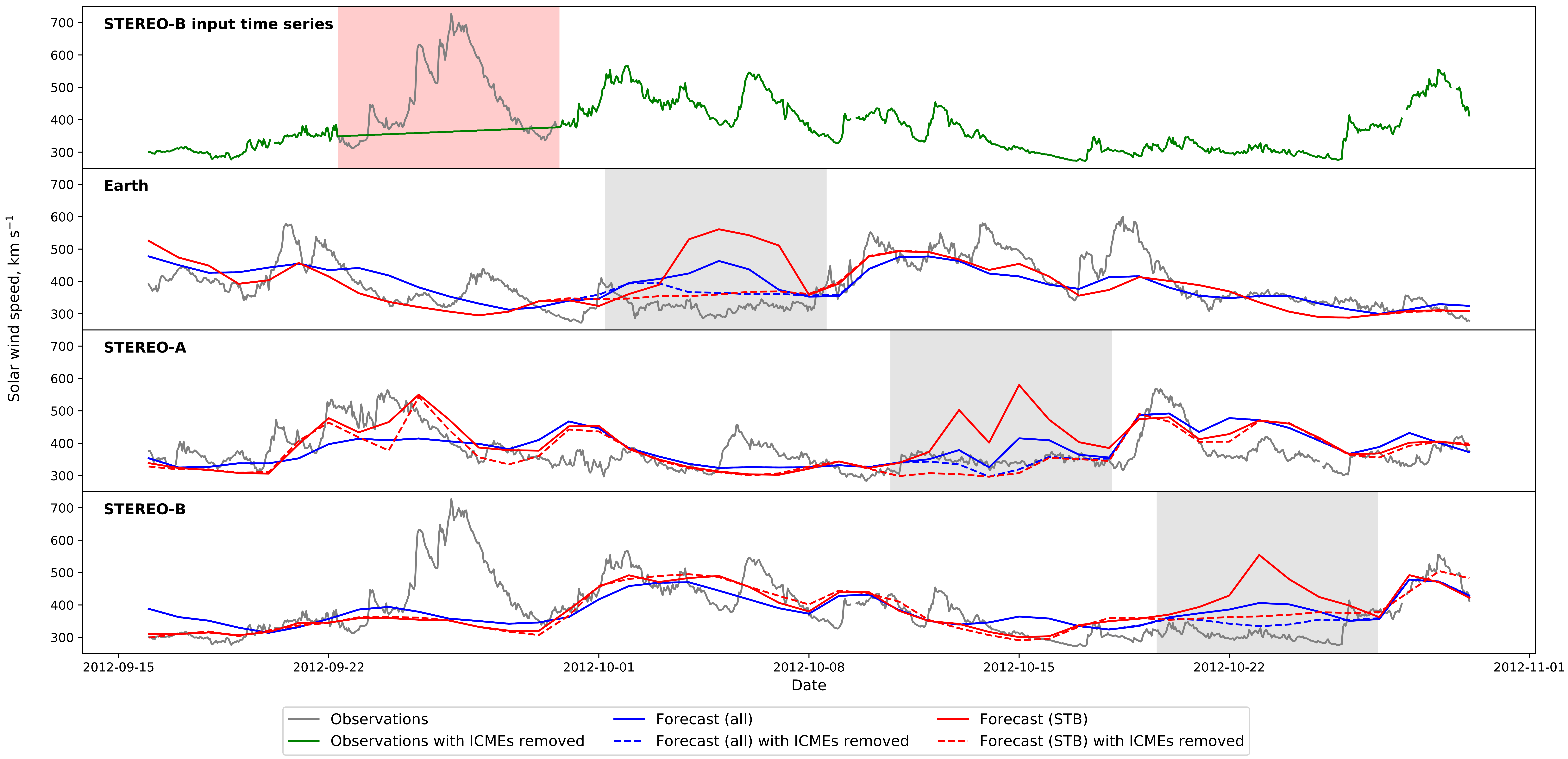
Age of observations

- Found a sharp increase in forecast error when forecast lead time exceeds corotation time when assimilating a single observation source.
- For lead times greater than the corotation time, the observations are effectively from the previous solar rotation.
- Assimilating multiple sources of observations reduces this effect.



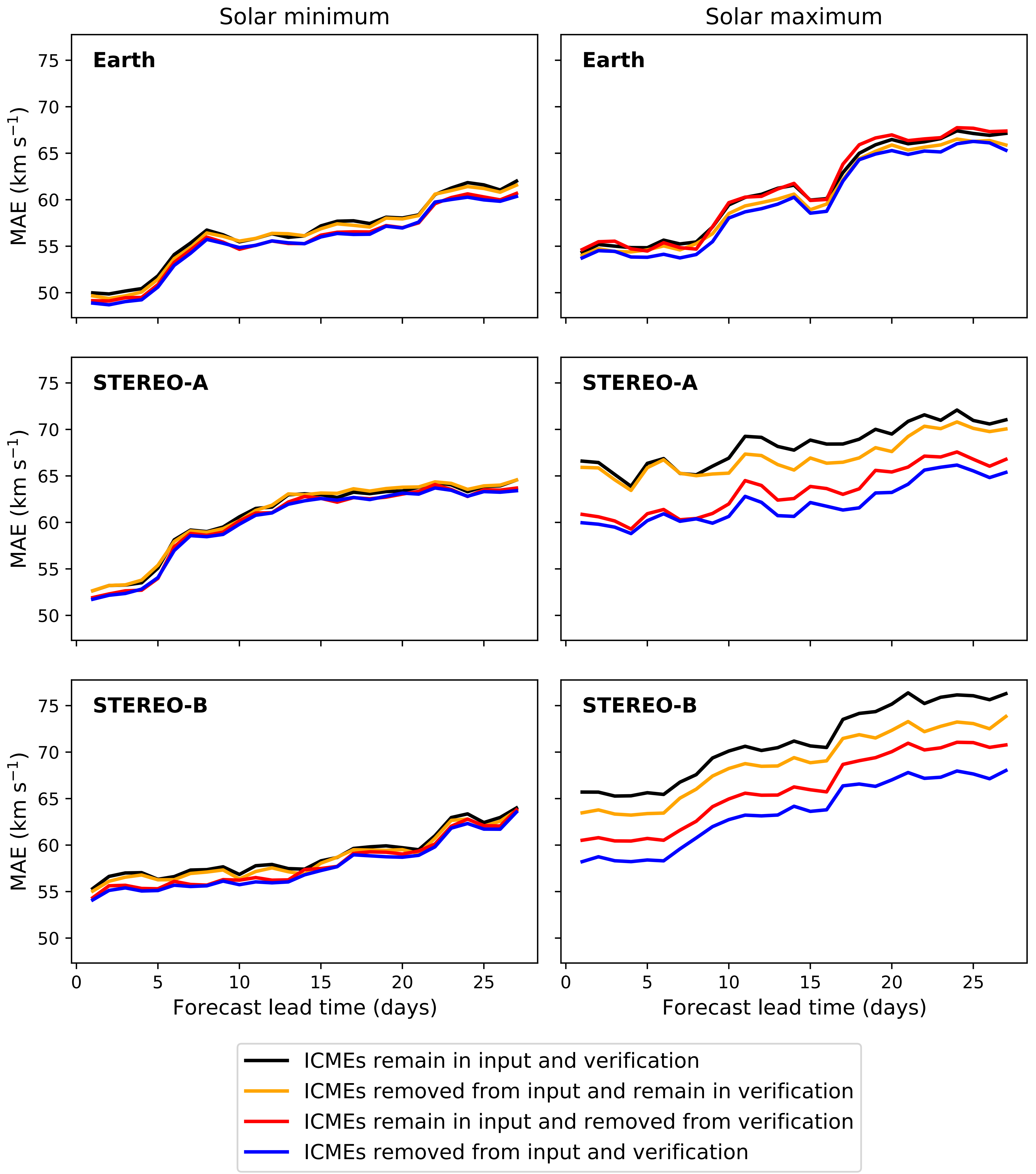
CME removal

- CMEs present in the input time series can introduce a false fast stream.



CME removal

- Removing CMEs from the input time series can reduce the appearance of false fast streams in the forecast.
- Assimilating multiple sources of observations reduces the impact of CMEs.
- Largest impact on isolated, fast CMEs.



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RESEARCH ARTICLE
10.1029/2022SW003109

Quantifying the Effect of ICME Removal and Observation Age for in Situ Solar Wind Data Assimilation

Harriet Turner[1], Mathew Owens[1], Matthew Lang[1], Siegfried Gonzi[2], and Pete Riley[3]

[1]Department of Meteorology, University of Reading, Reading, UK, [2]Met Office, Exeter, UK, [3]Predictive Science Inc, San Diego, CA, USA

Key Points:

- Assimilating in situ data from multiple spacecraft provides higher forecast skill than from any one spacecraft individually
- The age of observations, in terms of time when the required Carrington longitude was last observed, has a large effect on forecast skill
- Removing interplanetary manifestations of CMEs from the assimilated time series provides a small increase in forecast skill

Correspondence to:

H. Turner,
h.turner3@pgr.reading.ac.uk

Citation:

Turner, H., Owens, M., Lang, M., Gonzi, S., & Riley, P. (2022). Quantifying the effect of ICME removal and observation age for in situ solar wind data assimilation. *Space Weather*, *20*, e2022SW003109. https://doi.

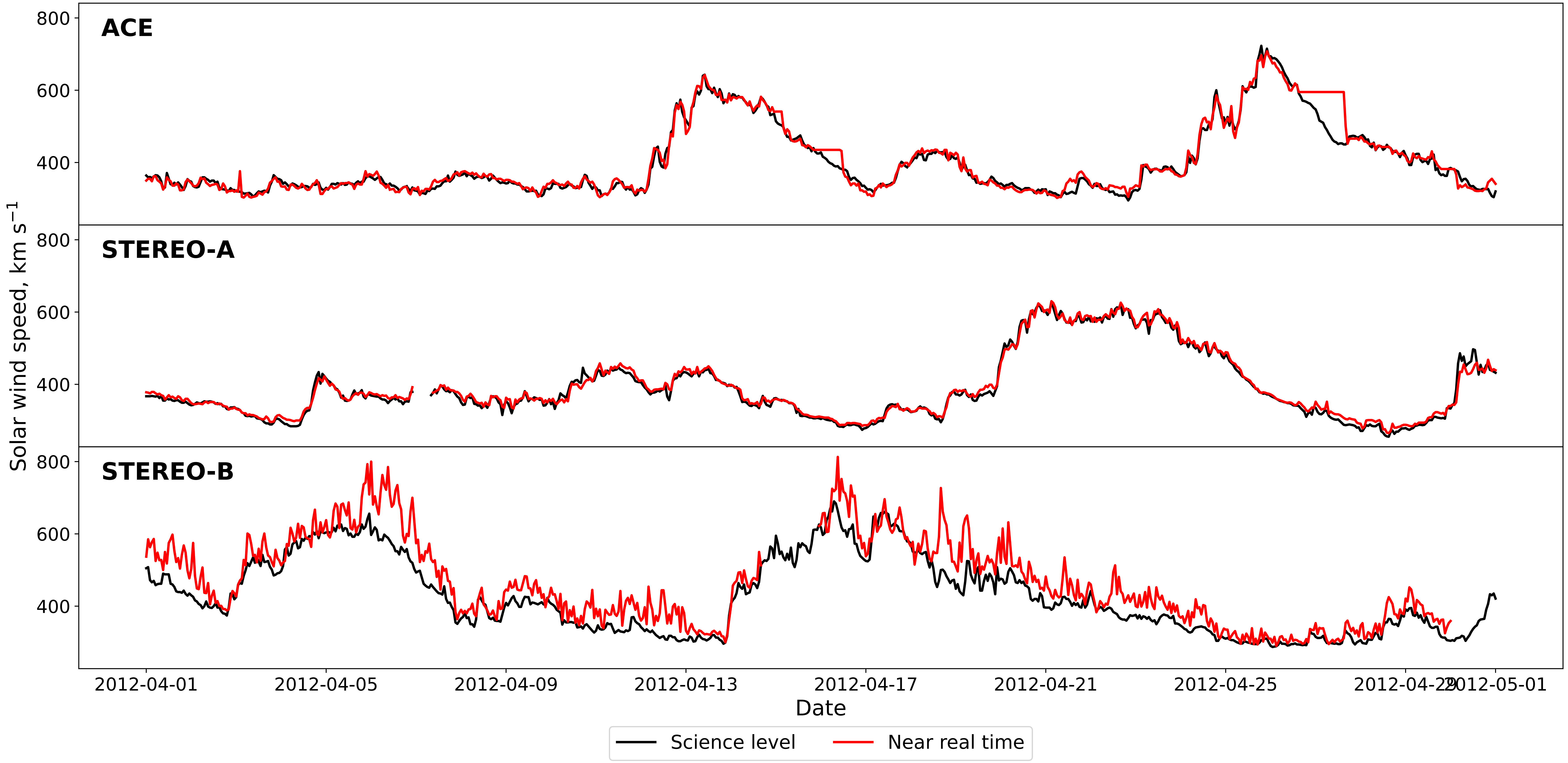
Abstract

Accurate space weather forecasting requires advanced knowledge of the solar wind conditions in near-Earth space. Data assimilation (DA) combines model output and observations to find an optimum estimation of reality and has led to large advances in terrestrial weather forecasting. It is now being applied to space weather forecasting. Here, we use solar wind DA with in-situ observations to reconstruct solar wind speed in the ecliptic plane between 30 solar radii and Earth's orbit. This is used to provide solar wind speed hindcasts. Here, we assimilate observations from the Solar Terrestrial Relations Observatory and the near-Earth data set, OMNI. Analysis of two periods of time, one in solar minimum and one in solar maximum, reveals that assimilating observations from multiple spacecraft provides a more accurate forecast than using any one spacecraft individually. The age of the observations also has a significant impact on forecast error, whereby the mean absolute error (MAE) sharply increases by up to 23% when the forecast lead time first exceeds the corotation time associated with the longitudinal separation between the observing spacecraft and the forecast location. It was also found that removing coronal mass ejections from the DA input and verification time series reduces the forecast MAE by up to 10% as it removes false streams from the forecast time series. This work highlights the importance of an L5 space weather monitoring mission for near-Earth solar wind forecasting and suggests that an additional mission to L4 would further improve future solar wind DA forecasting capabilities.

Aim III.
To transition to operational solar wind DA.

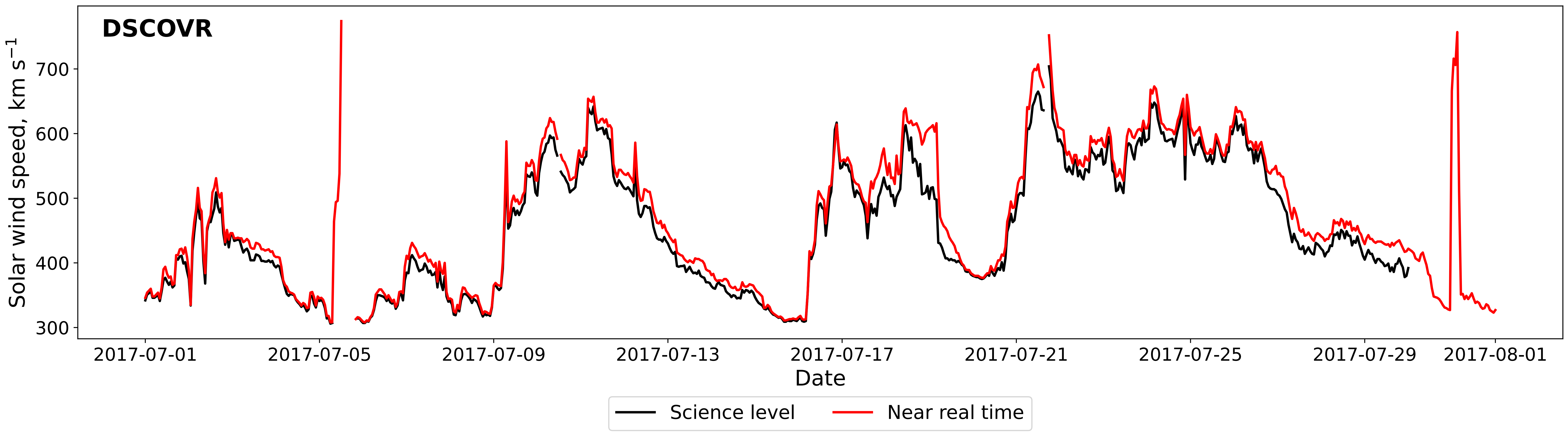
Real time observations

- Previous experiments with BRaVDA have used pre-processed data of higher quality than real-time data.
- It would need to work with real-time data to be operational.



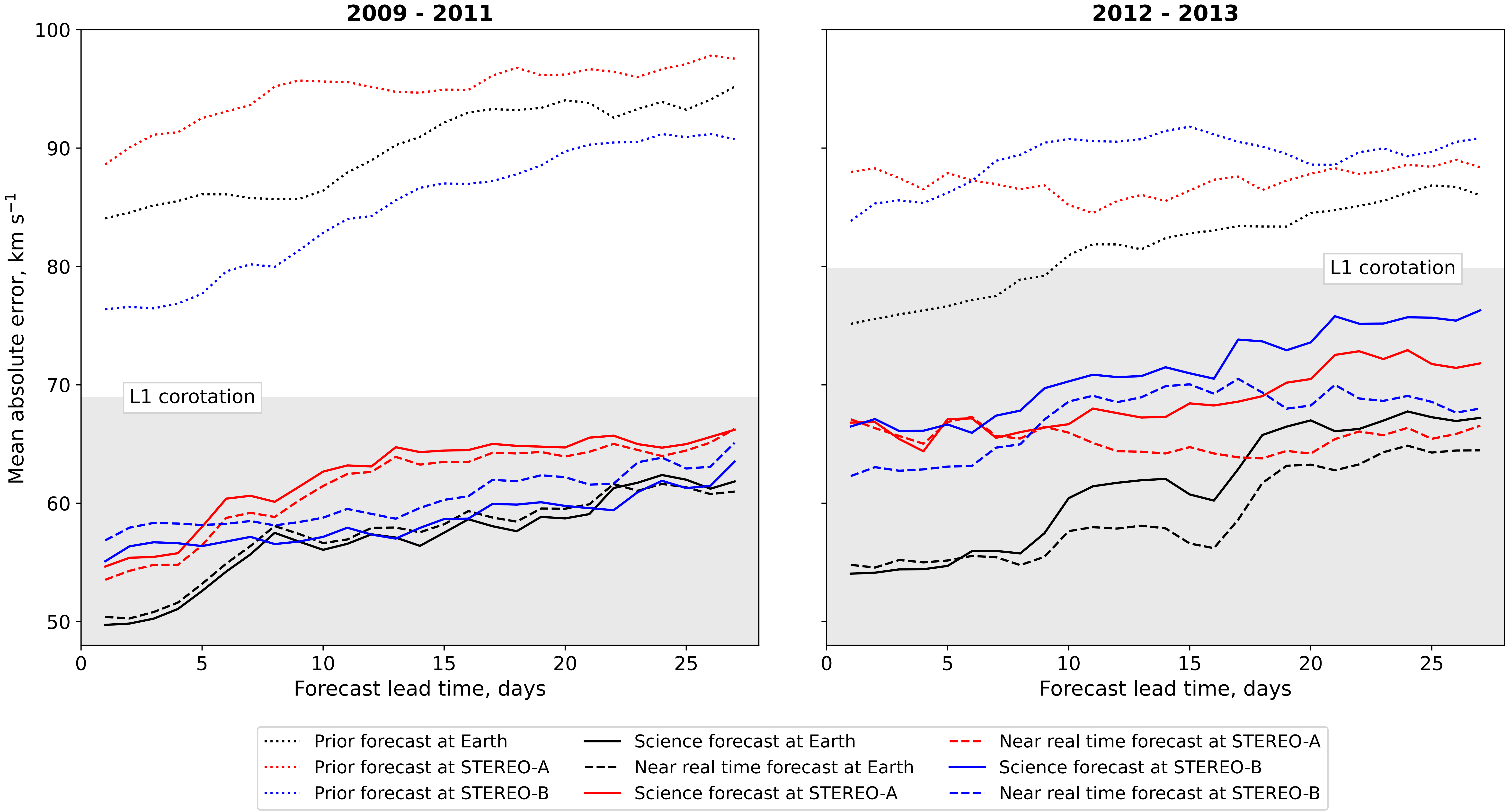
DSCOVR data

- Spacecraft positioned at L1 for space weather monitoring.
- Designed for its real-time capability.
- Quality issues compared to the science (pre-processed) data.



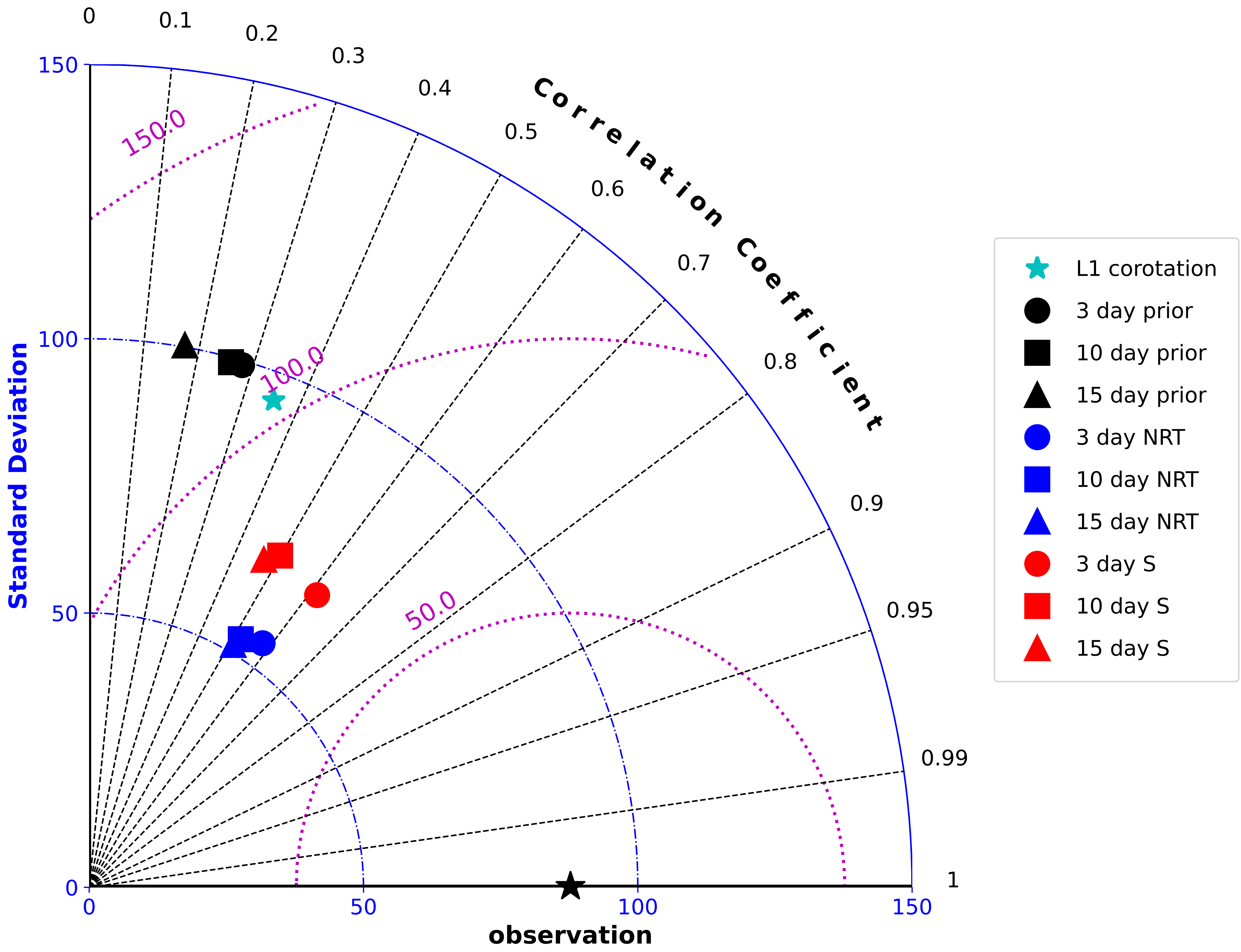
Forecasts

- Comparing assimilation of real-time data with science-data.
- Found that using real-time data has little impact on forecast quality when using DA, so it is suitable for operational use.



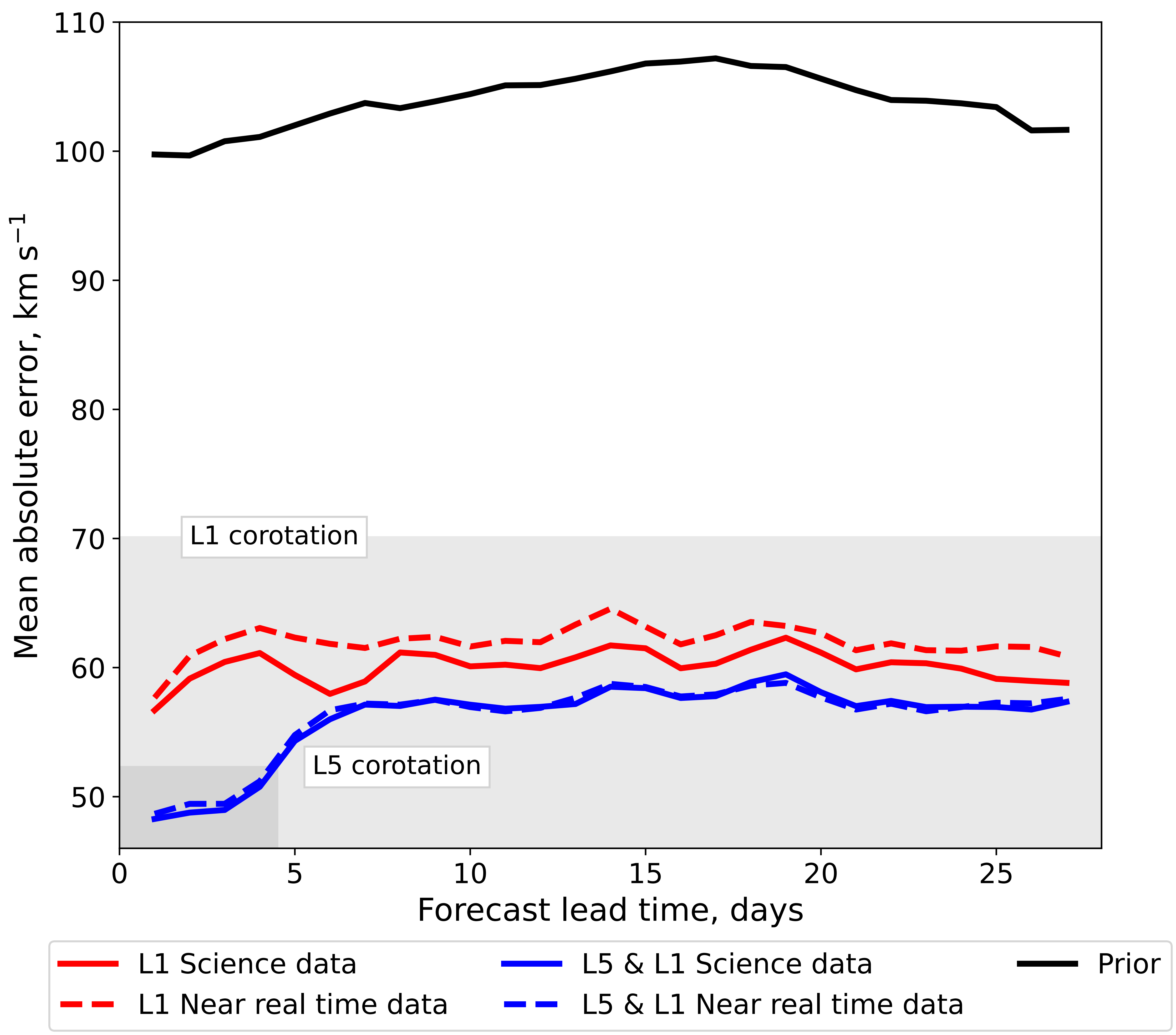
Is real time better?

- It appeared that assimilating real time performed better than the science data.
- However, this is due to the real time forecast not capturing the full variation of the observations so appears to be performing better with the chosen metric.



L5 experiments

- Future *Vigil* mission to L5 for space weather monitoring.
- Simulated an L1-L5 pairing for solar wind DA, mimicking a future Vigil-DSCOVR pairing.
- Inclusion of L5 data over only L1 improves the forecast performance, particularly for lead times of up to 5 days.



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Key Points:

- Solar wind data assimilation needs to perform well with near-real-time (NRT) data for it to be used operationally for space weather forecasting
- Despite lower data quality, solar wind speed forecasts based on NRT data are comparable to those based on science-level data
- Assimilation of L1 and L5 data gives forecast error improvement of 15% for lead times up to 5 days over assimilation of only L1 data

Correspondence to:

H. Turner,
h.turner3@pgr.reading.ac.uk

Citation:

Turner, H., Lang, M., Owens, M., Smith, A., Riley, P., Marsh, M., & Gonzi, S. (2023). Solar wind data assimilation in an operational context: Use of near-real-time data and the forecast value of an L5 monitor. *Space Weather*, *21*, e2023SW003457. https://doi.org/10.1029/2023SW003457

Solar Wind Data Assimilation in an Operational Context: Use of Near-Real-Time Data and the Forecast Value of an L5 Monitor

Harriet Turner[1], Matthew Lang[1], Mathew Owens[1], Andy Smith[2], Pete Riley[3], Mike Marsh[4], and Siegfried Gonzi[4]

[1]Department of Meteorology, University of Reading, Reading, UK, [2]Northumbria University, Newcastle-upon-Tyne, UK, [3]Predictive Science Inc., San Diego, CA, USA, [4]Met Office, Exeter, UK

Abstract For accurate and timely space weather forecasting, advanced knowledge of the ambient solar wind is required, both for its direct impact on the magnetosphere and for accurately forecasting the propagation of coronal mass ejections to Earth. Data assimilation (DA) combines model output and observations to form an optimum estimation of reality. Initial experiments with assimilation of in situ solar wind speed observations suggest the potential for significant improvement in the forecast skill of near-Earth solar wind conditions. However, these experiments have assimilated science-quality observations, rather than near-real-time (NRT) data that would be available to an operational forecast scheme. Here, we assimilate both NRT and science observations from the Solar Terrestrial Relations Observatory (STEREO) and near-Earth observations from the Advanced Composition Explorer and Deep Space Climate Observatory spacecraft. We show that solar wind speed forecasts using NRT data are comparable to those based on science-level data. This suggests that an operational solar wind DA scheme would provide significant forecast improvement, with reduction in the mean absolute error of solar wind speed around 46% over forecasts without DA. With a proposed space weather monitor planned for the L5 Lagrange point, we also quantify the solar wind forecast gain expected from L5 observations alongside existing observations from L1. This is achieved using configurations of the STEREO and L1 spacecraft. There is a 15% improvement for forecast lead times of less than 5 days when observations from L5 are assimilated alongside those from L1, compared to assimilation of L1 observations alone.

Conclusions

- Aim I. To understand some of the errors present in solar wind forecasts.
- Aim II. To verify solar wind DA forecasts under a range of conditions.
- Aim III. To transition to operational solar wind DA.

- Ultimately, solar wind DA works and could be a useful tool for solar wind forecasting and will hopefully lead to improved CME speed and arrival time estimates.

Since the PhD

- Submitted February 2024, Viva-ed (?) April 2024 and graduated July 2024.
- Currently working on NERC funded project "Why have space weather forecasts not improved in over a decade?"
- Essentially continuing the work from my PhD.
- Has felt quite slow to get going but I am close to start writing a paper looking at using a different coronal model with BRaVDA.

"All models are wrong, DA should be less wrong."

A ~~wise~~ jaded supervisor, 2024