Royal Astronomical Society

Comparative equatorial Thermosphere-Ionosphere-Magnetosphere coupling

Conveners *(alphabetical order, first name):*

Dr Beatriz Sanchez-Cano (Leicester)**, Dr Greg Hunt** (Imperial) **& Dr Tom Stallard** (Leicester)

Agenda: Talks

10:00-10:30		Online Coffee with friends
10:30-10:35		Welcome and Introduction
10:35-11:05	**Aurélie Marchaudon**	Overview of the equatorial electrodynamics at Earth (*invited*)
11:05-11:35	**James O'Donoghue**	Observational evidence for upper-atmospheric heat transfer to Jovian equatorial latitudes from the auroral regions (*invited*)
11:35-11:50	**Greg Hunt** on behalf of **Sean Hsu**	Study of ring-planet interactions beyond Cassini
11:50-13:50		**Extended poster session and lunch in Gather Town**
13:50-14:00		Pre-talk Online Coffee
14:00-14:30	**Michiko Morooka**	Saturn's Dusty Ionosphere and its relation to the Ring (*invited*)
14:30-14:45	**Omakshi Agiwal**	Saturn's Azimuthal magnetic field constraints to thermospheric variability
14:45-15:15	**Nick Schneider**	Diverse & Dynamic Auroral Processes on Mars (*invited*)
15:15-15:30	**Scott England**	Impacts of atmospheric tides on the composition of Earth's upper atmosphere and the formation of the equatorial ionospheric anomaly
15:30		End of session**

**After the meeting ends, the RAS will have an Ordinary Meeting that you are all welcome to attend. We will also be leaving our Gather Town meeting open, to allow those who want to continue discussions to meet. We welcome you to bring your own beverages.

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Agenda: Posters *(alphabetical order, first name):*

Ali Sulaiman	A persistent, large-scale, and ordered electrodynamic connection between Saturn and its main rings as revealed by Cassini/RPWS
Anna Mittelholz	Magnetic Variations of a sol observed over a year on Mars with InSight
Henrik Melin	Jupiter's low-latitude hydrogen bulge
Ingo Mueller-Wodarg	Dynamics and variability of Saturn's equatorial thermosphere
Jess Vriesema	Modelling Electrodynamics in Saturn's Upper Atmosphere
Lina Hadid	Saturn's ionosphere: Electron density altitude profiles and ring shadowing effects from the Cassini Grand Finale
Luke Moore	The Influence of Saturn's Rings on its Ionosphere
Matthew Fillingim	Comparison Between Equatorial Ionospheric and Surface Level Magnetic Fields at Mars
Oleg Shebanits	Saturn's equatorial ionosphere and its immediate magnetospheric neighbourhood
Philip Valek	In situ ion observations above the Jovian ionosphere
Gabrielle Provan	Planetary Period Oscillations of Saturn's Dayside Equatorial Ionospheric Electron Density Observed on Cassini's Proximal Passes
Tommaso Alberti	Disentangling ionospheric structures from magnetospheric ones at low and mid latitudes

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Abstracts *(in alphabetical order, first name)*

1. **Ali Sulaiman, University of Iowa, US**

A persistent, large-scale, and ordered electrodynamic connection between Saturn and its main rings as revealed by Cassini/RPWS

Auroral hiss emissions are ubiquitous in planetary magnetospheres, particularly in regions where electric current systems are present. They are generally diagnostic of electrodynamic coupling between conductive bodies, thus making auroral and moon-connected magnetic field lines prime locations for their detection. However, the role of Saturn's rings as a dynamic conductive body has been elusive. Cassini's Grand Finale orbits afforded a unique opportunity to directly sample magnetic field lines connected to the main rings. Using plasma wave data, we provide strong evidence for the persistent and organised presence of auroral hiss demonstrably associated with the main rings. Further, we find this phenomenon consistent with plasma wave data during Saturn Orbital Insertion, when Cassini made an equatorial pass over the main rings. This suggests the main rings facilitate the closure of field-aligned currents by the action of radial currents across the rings. Our results provide a view of Saturn's rings as a system in continuous electrodynamic coupling with the planet, similar to that of Enceladus.

2. **Anna Mittelholz, ETH Zurich, Switzerland**

Magnetic Variations of a sol observed over a year on Mars with InSight

The InSight Fluxgate Magnetometer (IFG) is the first magnetometer to operate on the martian surface. It has provided the first surface observations of static and time-varying magnetic fields and has recently reached its one-martian-year milestone. We expand on a previously-published study that investigated diurnal field variations for the first 389 sols of InSight operations. Specifically, we focus on variations of the magnetic field within and among sols over one martian year and compare these observations with predictions for magnetic fields due to ionospheric currents. IFG data show diurnal variations with typical peak amplitudes of 20–40nT in the early morning to mid-morning; the amplitude of the magnetic field varies over the first year of the mission and peaks around sol 100 and again around sol 550. We use satellite magnetic field data and a Mars global circulation model to predict temporal evolution of wind-driven fields in the ionosphere and compare predictions with IFG observations. Fields vary due to seasonal changes in the ionization profile and the winds, and in the altitude range of the dynamo region, that is, the region in which electric currents can be produced. We find that the amplitude and seasonal variability of the surface magnetic fields are generally consistent with those predicted from wind-driven currents. Moreover, regional dust storms in the vicinity of the InSight landing site might be responsible for the higher magnetic field amplitudes observed in the IFG data during dust season.

3. **Aurélie Marchaudon, IRAP, France**

Overview of the equatorial electrodynamics at Earth

At the Earth's equator, the combination of the magnetic field lines bathed entirely in the ionosphere and the strong neutral winds generated by solar illumination creates complex electrodynamics. In this presentation, a general review of equatorial electrodynamics will be given, by describing more specifically the equatorial electrojet formation and the equatorial fountain mechanism (called Appleton Anomaly). Then, a presentation of the peculiarities of the Earth's equatorial magnetic field will be made and how they can modify the electrodynamics and the underlying ionospheric and magnetospheric properties (e.g. South Atlantic Anomaly). These processes will be illustrated thanks to satellites and ground-based observations.The recurrent variations of the equatorial electrodynamics observed at sunset (called pre-reversal enhancement of the zonal equatorial electric field) will also be described, as well as the region-specific instabilities simultaneously generated (plasma bubbles responsible for GNSS scintillations) I will finally explain how to take the equatorial electrodynamics into account in physical models of ionosphere and thermosphere to accurately describe the environment.

4. **Greg Hunt on behalf of Sean Hsu and ISSI Team, Imperial College London, UK**

Study of ring-planet interactions beyond Cassini

Ring-planet interaction studies are multifaceted in nature and require cross-disciplinary effort. In 2019, we were selected to form an International Team at the International Space Science Institute to focus on the study of ring-planet interactions at Saturn, aiming to provide a generalized understanding about ring-planet interactions at Saturn and other giant planet systems. A white paper entitled "Ice Giants – The Return of the Rings" was submitted to the US National Academies Planetary Science and Astrobiology Decadal Survey in 2020 to emphasize the importance of ring-moon-planet interaction study for future ice giant missions. In this talk we will present a brief summary of the collective effort and to highlight open questions as we learned from the Cassini mission at Saturn.

5. **Henrik Melin, University of Leicester, UK**

Jupiter's low-latitude hydrogen bulge

Here, we provide an overview of the phenomenon called the H Ly-α bulge at Jupiter, which manifests itself as a brightening in hydrogen emissions at low latitudes at around 100° longitude. We present observations of H Ly-α and molecular hydrogen emissions on the body of Jupiter obtained during the Cassini flyby in late 2000 and early 2001. The H Ly-α emission is highly organised by System III longitude and latitude, peaking at a brightness of 22 kR between 90 and 120° longitude, confirming the presence of the bulge. These observations add to a number of previous studies, showing that the feature is very long- lived, present over several decades. We show that there is a strong correlation between the prevailing solar H Ly-α flux (measured at Earth) and the peak brightness of the H Ly-α bulge at Jupiter, which supports the idea that it is primarily driven by solar resonance scatter. However, the primary source of this emission feature remains unknown, and we discuss a number of potential solutions.

6. **Ingo Mueller-Wodarg, Imperial College London, UK**

Dynamics and variability of Saturn’s equatorial thermosphere

Grand Finale in-situ and remote observations by several instruments onboard the Cassini spacecraft have revealed a highly variable low latitude thermosphere which hosts atmospheric waves and strong equatorial jets. In the absence of significant external in-situ drivers these characteristics are most likely largely driven by dynamical coupling to the regions below (troposphere and stratosphere). This talk explores the low latitude atmosheric structure between the troposphere and thermosphere from observations and model simulations and discusses the likely dynamical drivers of the equatorial thermosphere region and its variability.

7. **James O'Donoghue, JAXA Institute of Space and Astronautical Science, Japan**

Observational evidence for upper-atmospheric heat transfer to Jovian equatorial latitudes from the auroral regions

Giant planet upper atmospheres, the transition regions between dense atmosphere and rarefied space, have for decades measured hundreds of Kelvin hotter than can be explained by solar heating alone. Enormous energy deposition leads to powerful auroral displays and heating in the polar atmosphere but, according to the majority of global circulation models, Coriolis forces arising from rapid rotation present a barrier to its equatorward redistribution. To determine the dominant heating source at Jupiter's non-auroral latitudes we present the first high-resolution maps capable of tracing global temperature gradients. We find that temperatures monotonically decrease from pole-to-equator, consistent with a global redistribution of auroral energy. If Coriolis forces are observably overcome at Jupiter, a key new physical constraint is provided to global circulation models.

8. **Jess Vriesema, University of Wisconsin–Eau Claire, US**

Modelling Electrodynamics in Saturn's Upper Atmosphere

Saturn possesses a strong magnetic field, a robust ionosphere, and strong winds in its upper atmosphere. Electrodynamics therefore plays a large role in Saturn's thermosphere. Recent observations from the Cassini magnetometer instrument near the equator during its Grand Finale tour revealed azimuthal magnetic field perturbations associated with ionospheric electrodynamics at low latitudes. These perturbations likely require an equatorial jet in Saturn's thermosphere, and are expected to be driven by vertical and horizontal gradients in the thermospheric wind and modulated by gradients in the Pedersen and Hall conductivities. We use the Saturn Thermosphere Ionosphere Model (STIM), a general circulation model of Saturn's ionosphere and thermosphere, to investigate the role of electrodynamics in Saturn's upper atmosphere, employing recent updates to the calculation of conductivities and currents. We impose an equatorial jet at the base of the thermosphere to drive low-latitude electrodynamics, and a field-aligned current profile, based on models of the magnetosphere, to drive high-latitude electrodynamics. We present results from several models using the updated STIM to explore the role of electrodynamics in Saturn's thermosphere.

Our models suggest that electrodynamics is sensitive to the meridional and vertical structure of the wind and conductivity profiles. Wind shears can drive strong electrodynamics, but require a forcing mechanism that is able to offset ion drag, which acts quickly to reduce wind shears along magnetic field lines. At low latitudes, this allows our imposed equatorial jet to be roughly constant with altitude in the thermosphere. Finally, we discuss the implications of our models for future work.

9. **Lina Hadid, Laboratory of Plasma Physics/ CNRS - École Polytechnique, France**

Saturn's ionosphere: Electron density altitude profiles and ring shadowing effects from the Cassini Grand Finale

We present the electron density altitude profiles of Saturn's ionosphere at equatorial latitudes (−15º ≤ ϕ ≤ 15º) and the ring shadowing effects from all the 23 proximal passes of Cassini's Grand Finale. The data are collected by the Langmuir probe (LP) and from the plasma wave frequency characteristics of the Radio and Plasma Wave Science (RPWS) investigation. A high degree of variability in the electron density profiles is observed. However, organizing them by consecutive altitude ranges revealed clear differences between the southern (winter) and northern (summer) hemispheres. We show a layered electron density altitude profile with evidence in the southern hemisphere of an electrodynamic type of interaction with the planets innermost D ring. Similar layers were observed during the Final Plunge of Cassini, where the main ionospheric peak is crossed at ∼ 1550 km altitude.

Moreover, from the ring shadow signatures on the total ion current collected by the LP, we reproduce the A and B ring boundaries and confirm that they are optically thicker than the inner C and D rings and the Cassini Division to the solar extreme ultraviolet radiation. Furthermore, observed variations with respect to the inner edge of the B ring shadow imply a delayed response of the ionospheric H+ because of its long lifetime and/or suggest the presence of ring-derived plasma from the C and D rings reducing the shadowing signatures.

10. **Luke Moore, Boston University, US**

The Influence of Saturn's Rings on its Ionosphere

Recent ground-based and space-based results have revealed a more expansive interaction between Saturn's rings and atmosphere than anticipated. Here, we review the impact of these interactions on ionosphere chemistry, and present new model comparisons with in situ data from Cassini's final orbits. At mid-latitudes, charged ring particles stream into the atmosphere along magnetic field lines, impacting the atmosphere at conjugate latitudes. This process, termed "ring rain", reduces local electron densities leading to a modification of the IR emissions from H3+, a major ion. Saturn's equatorial atmosphere, meanwhile, is bombarded by a massive influx of ring material that is de-orbited by atmospheric drag. This process, which we will term "equatorial inflow", represents a mass transfer of up to 20,000 kg/s. Measured volatiles in Saturn's upper atmosphere are dominated methane and other hydrocarbons, so the introduction of these species into Saturn's hydrogen-dominated upper atmosphere leads to fundamental changes in plasma chemistry as they diffuse downward. In particular, as opposed to being primarily H+ and H3+, Saturn's equatorial ionosphere is dominated by heavy molecular ions and charged dust grains. We find that, based on these new equatorial constraints, the major ion at the ionospheric peak is likely to be HCO+. With no Saturn missions on the horizon, future monitoring of the ring-atmosphere interaction at Saturn – a proxy for ring mass loss – will likely therefore rely on remote observations of H3+ at mid-latitudes, and H3+/H3O+/HCO+ at low-latitudes.

11. **Matthew Fillingim, Space Sciences Laboratory, University of California, Berkeley, US**

Comparison Between Equatorial Ionospheric and Surface Level Magnetic Fields at Mars

With both the Mars Atmosphere and Volatile Evolution (MAVEN) mission and the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission concurrently operating at Mars, we are able to make two-point comparisons of the vector magnetic field at Mars for the first time. InSight, which landed in the near equatorial region (4.5 degrees north latitude), carries the first magnetometer on the surface of Mars, the InSight FluxGate magnetometer (IFG). During MAVEN overflights of the InSight landing site, we compared deviations in the ionospheric magnetic field to variations in the surface level magnetic field. We find significant orbit to orbit variability in the magnitude and direction of the ionospheric magnetic field residuals as well as significant day to day variability of the surface level magnetic field residuals. We attribute this variability to time varying ionospheric currents. The ionospheric magnetic field deviations are largest at low altitudes (in the ionospheric dynamo region) on the dayside near local noon where ionospheric currents would be expected to be strongest. However, when analyzing the ensemble of 36 individual MAVEN overflights of the InSight landing location, we see no clear correlation between the magnitudes or directions of the ionospheric magnetic field perturbations and the surface magnetic field perturbations as might be expected. Weak, small scale ionospheric currents, particularly on the nightside, and/or modification of the ionospheric magnetic field due to the interplanetary magnetic field may be responsible for the lack of clear correlation.

12. Michiko Morooka, Swedish Institute of Space Physics (IRFU), Sweden

Saturn's Dusty Ionosphere and its relation to the Ring

A series of the orbits during the end of Cassini mission, the Grand Finale, provided direct observations of Saturn's upper atmosphere and ring. Unexpected result by INMS is that the upper atmosphere consists of complex neutral chemistries such as CH4, NH3, H2O and heavier organics in addition to H2 and He. The plasma density comparison between RPWS and INMS showed that the upper atmosphere consists of H+ and H3+, while the density discrepancies found at the lower altitudes indicated that the dayside ionosphere must be dominated by the heavier ion species (> 4 amu). At the lowest altitudes, the positive ion density obtained by the LP was enhanced by 5-10 times compared to the electron density. Quasi neutralities requires that the ionospheric plasma is dusty, where the negative charged ion or particles dominates.

In the terrestrial atmosphere, the dusty plasma is often observed in the noctilucent cloud. The ice particles of the noctilucent cloud are compound of metal atoms exist as a result of meteoric ablation. Observations of CDA and MIMI reported the inflow of the water particles from the D ring into Saturn's atmosphere. The precipitating nanometer-sized ice dust of the "ring rain" chemically interact with the upper ionosphere create the layer of H+ and H3+, further undergo sublimation and fragmentation when they impact the deeper atmospheric layers. Grains on the order of 1–10 nm deposit their energy in the altitude range of 1,700–1,900 km, and the accumulation of such particles may form a grain-rich atmospheric layer.

13. Nick Schneider, LASP, U. Colorado, US

Diverse & Dynamic Auroral Processes on Mars

Mars' lack of a global magnetic field led to low expectations for aurora on the planet, but MAVEN observations have shown three types of aurora that are frequent, distinct in nature, and often global in scope. In addition to ultraviolet and optical emissions, aurora are responsible for heating and chemistry in the ionosphere and thermosphere. Ironically, Mars' lack of a global field is actually responsible for most of the activity, which leads to a new perspective for non-magnetized objects in our solar system and beyond. Each of the three types of aurora is a tracer of a different important process involving the interaction between solar influences and the near-Mars magnetic and charged particle environment. MAVEN's Imaging UltraViolet Spectrograph has made critical observation of each. First, discrete auroras were detected in regions of strong crustal magnetic fields by the SPICAM instrument on the European Space Agency's Mars Express orbiter. Subsequent IUVS observations have imaged discrete aurora and shown they are triggered in evening hours for unknown reasons. New work shows they can occur anywhere on the plan, even far from crustal fields. Second, IUVS discovered diffuse aurora that can engulf the entire visible nightside of Mars due to the lack of a global magnetic field. They are caused by solar energetic electrons which deposit energy down to the mesophere. Third, IUVS discovered proton auroras caused by energetic protons from the solar wind precipitating into a planetary atmosphere. The interaction causes atomic hydrogen emissions and may lead to patchy ionospheric structures.

14. **Oleg Shebanits, Swedish Institute of Space Physics, Sweden**

Saturn's equatorial ionosphere and its immediate magnetospheric neighbourhood

The Grand Finale of the Cassini mission has delivered the first in-situ measurements of Saturn's ionosphere and magnetosphere planetward of its rings, revealing the complicated ionosphere-magnetosphere-ring coupling. We present two in-situ studies of the regions involved in this coupling, the conductivities of the equatorial ionosphere where the interhemispherical currents are expected to close, and the detection of Alfvén waves in the region between Saturn and its rings. The equatorial ionosphere of Saturn is shown to be 10-100 times more conductive than estimated by remote measurements (an effect of dust grains) and the azimuthal magnetic field reveals standing Alfvén waves patterns of ~3-5 nT amplitudes, probably driven by global magnetospheric eigenmodes.

15. **Omakshi Agiwal, Imperial College London, UK**

Saturn's Azimuthal magnetic field constraints to thermospheric variability

The Cassini spacecraft completed 22 orbits around Saturn known as the `Grand Finale' over a 5 month interval, during which time the spacecraft traversed the previously unexplored region between Saturn and its equatorial rings near periapsis. The magnetic field observations reveal the presence of temporally variable low-latitude field-aligned currents which are thought to be driven by velocity shears in the neutral zonal winds at magnetically conjugate thermospheric latitudes. We consider atmospheric waves (amongst other sources) as a plausible driver of temporal variability in the low-latitude thermosphere, and empirically constrain the region in which they perturb the zonal flows to be between ± 25 degrees latitude. By investigating an extensive range of hypothetical wind profiles, we present and analyse a timeseries of the modelled velocity shears in thermospheric zonal flows, with direct comparisons to empirically inferred angular velocity shears from the azimuthal magnetic field observations. We determine the maximum temporal variability in the peak neutral zonal winds over the Grand Finale interval to be ~ 350 m/s assuming steady-state ionospheric Pedersen conductances. We further show that the ionospheric currents measured must be in steady-state on ~ 10 minute timescales, and axisymmetric over ~ 2 hours of local time in the near-equatorial ionosphere. Our study illustrates the potential to use of magnetospheric datasets to constrain atmospheric variability in the thermosphere region.

16. **Philip Valek, Southwest Research Institute, US**

In situ ion observations above the Jovian ionosphere

The orbit of Juno enables repeated in situ observations above the Jovian ionosphere. The low altitude and high velocity of Juno at perijove permits direct sampling of ionospheric ion populations by the Jovian Auroral

Distributions Experiment Ion sensor (JADE-I). When looking into the spacecraft ram direction, JADE-I can measure ion energy distributions to below 1 eV/q along with ion composition. At equatorial latitudes, the low energy ions consist of protons and heavier ions, protons being the dominant species. Heavy ions—primarily oxygen and sulfur likely originating from the magnetosphere—are seen most passes, but their intensity varies. Other trace light ions - H3+ and He+ - are observed during some of the perijoves. Ionospheric ions are observed up to altitudes of ~7,000 km. We present here the in situ observations of ions above the Jovian equatorial ionosphere, and discuss possible sources for the heavy ions.

17. Scott England, Virginia Tech, US

Impacts of atmospheric tides on the composition of Earth's upper atmosphere and the formation of the equatorial ionospheric anomaly

One of the main processes that is believed to contribute to the formation of the equatorial ionization anomaly at Earth is the E-region dynamo. The E-region dynamo is driven by horizontal winds blowing in the lower and middle thermosphere. These wind patterns are known to be modulated by atmospheric tides, and thus a signature of these tides is present in observations of the ionospheric anomaly. However, both theory and modeling suggest that other mechanisms such as changes in the neutral atmosphere's density and composition should also play some role that may add to or compete against the E-region dynamo. Providing observational confirmation of this has proved difficult, owing to the observations of the composition being influenced by changes in the ionosphere, that may be misinterpreted. Analogous observations at Mars have also revealed similar atmospheric waves, and corresponding ionospheric features. However, at Mars it is believed that modification of the atmospheric density and composition is the primary cause of the ionospheric signatures, and electrodynamics plays no role. The new ICON spacecraft, with coordinated observations of Earth's upper atmosphere and ionosphere offers an opportunity to see if the same mechanism that is so dominant at Mars can also play a role at Earth.

18. Gabrielle Provan, University of Leicester, UK

Planetary Period Oscillations of Saturn's Dayside Equatorial Ionospheric Electron Density Observed on Cassini's Proximal Passes

We examine electron density data obtained in Saturn's dayside equatorial ionosphere during the Cassini proximal passes, specifically data derived from electric field wave spectra*, for evidence of modulations with the planetary period oscillations (PPOs) observed ubiquitously throughout Saturn's magnetosphere. In common with previous examination of proximal magnetic field data, we show that density modulations are in general simultaneously present due both to the northern and southern PPO systems. Clearest evidence is found in the ionospheric diffusive layer at altitudes ~3000-4000 km on the inbound passes, where northern system modulations by factors ~4-5 and southern system modulations by factors ~2 were observed. Simultaneous modulations by factors ~2-3 for both systems were also observed in the inbound ionospheric transport region at altitudes up to ~7500 km. Modulations were not detected in the photochemical equilibrium layer at altitudes ~1800-2000 km. Northern system modulations were also observed in the diffusive layer and transport regions on the outbound passes. Where clear modulations were observed, their phases in the diffusive layer were close to those of the principal PPO meridians for both systems, with modulations in the transport region typically moving to 'earlier' phases by a few tens of degrees. * Persoon, A. M. et al. (2019). Geophysical Research Letters, 46, 3061-3068. https://doi.org/10.1029/2018GL078020

19. Tommaso Alberti, INAF-IAPS, Italy

Disentangling ionospheric structures from magnetospheric ones at low and mid latitudes

There is a growing interest in the development of models and methods of analysis aimed to recognize the different contributions coming from the various sources both internal and external to planetary environments. Here by applying the Multivariate Empirical Mode Decomposition (MEMD) to the measurements of the vertical component of the geomagnetic field at low and mid latitudes during a geomagnetically quiet period we recognize the different contributions coming from the different regions, giving new insights into the analysis of the geomagnetic field of external origin and to separate the ionospheric signal from the magnetospheric one in a simple and rapid way. This study can be rapidly extended to measurements collected into different space environments, helping to improve our understanding of similarities and differences and to provide a deeper understanding of planetary magnetosphere-ionosphere-thermosphere system.

Reference

Alberti, T., Giannattasio, F., De Michelis, P., Consolini, G. (2020). Linear versus nonlinear methods for detecting magnetospheric and ionospheric current systems patterns. Earth and Space Science, 7, e2019EA000559. https://doi.org/10.1029/2019EA000559