Normalized density difference index - from the concept to main findings

OBSEE & CBK

MS2
ESRIN

October 21, 2019

Agenda

Swarm4Anom

I - dedicated to macro-scale features (Cont. of the previous studies) in the Earth's ionosphere and long-term analysis (CBK/ OBSEE)

II - dedicated to small scale perturbations originating from thunderstorm activity (AGH/ CBK/ OBSEE)

PART I - Swarm4Anom - Swarm I_{NDD} product for Ionospheric Anomalies

1. (Ewa Slominska, OBSEE) **Normalized density difference index - from the concept to main findings**
   - Status of the product,
   - main scientific results
   - applicability of the index to the equatorial ionosphere
2. (Marek Strumik, CBK) **TIEGCM modeling and 3D visualizations as tools for interpretation of Swarm (and other satellite) measurements**

Agenda - Part II

Part II - Swarm for TLEs (Transient Luminous Events)

1. **Capabilities of the Swarm magnetometers to detect events related to lightning activity**
   - Approach to the problem, main goals and review of selected results
   - Synergies with other satellite mission.
2. Swarm measurements and lightning activity: minimum variance and inter-satellite cross-correlation analysis (Marek Strumik, CBK)
3. Searching for correlations between magnetic field variation on Swarm and atmospheric discharges observed by ELF ground stations (Janusz Mlynarczyk, AGH)
4. Remarks on the "whistler" type waves registered in space (Jan Blecki, CBK)

I_{NDD} - Normalized density difference index - the idea behind and purpose of the study

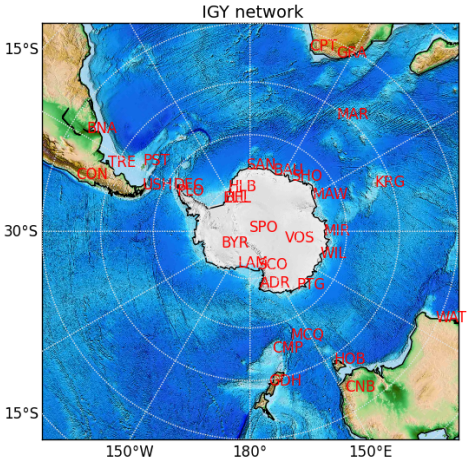
Swarm+Innovations: **Swarm4Anom**alies with main goals:

- to provide better representation of the Weddell Sea Anomaly (WSA) (multi-point observations, multi-instrumental observations, different altitudes),
- to expand analysis to more general phenomenon of a mid-latitude nighttime summer anomaly and nighttime density enhancements,
- to gain better understanding of the phenomena.
- to provide long-term representation of changes in the spatial morphology of the reversed ionospheric diurnal cycle

`http://swarm4anom.cbk.waw.pl/s4a/prodcdf/`

The Weddell Sea Anomaly (WSA) in brief

- The peculiar feature of the ionosphere in the vicinity of the Antarctic Peninsula, the Weddell Sea and the Bellingshausen Sea, was discovered in the late the 50's during the International Geophysical Polar Year (1957).
- Analysis from data of the $F2$ layer over Antarctica showed that, the regions of the Antarctic Peninsula and the Weddell Sea have an anomalous pattern in f_0F2.
- During the summer, the f_0F2 varies in such a way that the daily peak occurs at a local night and the daily minimum at local daytime. During the winter the f_0F2 shows a typical mid-latitude diurnal behaviour, when the maximum occurs at local noon and the minimum at a local night.



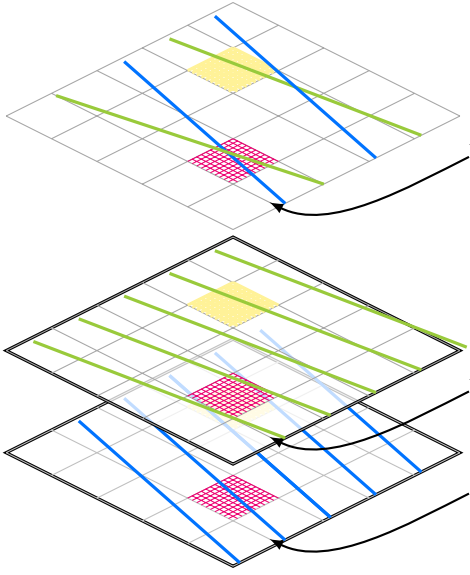
Identification of the WSA and NPDEs

Normalized density difference index - I_{NDD}

$$I_{NDD}(\lambda,\theta) = \frac{N_e^{night}(\lambda,\theta,@LT) - N_e^{day}(\lambda,\theta,@LT+12h)}{N_e^{night}(\lambda,\theta,@LT) + N_e^{day}(\lambda,\theta,@LT+12h)}.$$

- I_{NDD} index which estimates the values of normalized electron density difference
- relies on separation between measurements taken on ascending and descending passes (12-hour difference needed to capture diurnal variations)
- I_{NDD} varies in the range [-1:1];
- LT-frame representation, for WSA LT: (22:00-02:00)
- in the first approach $I_{NDD} > 0$ indicates regions with anomalous characteristics.

Identification of NPDEs with Swarm

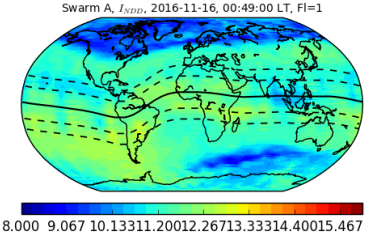


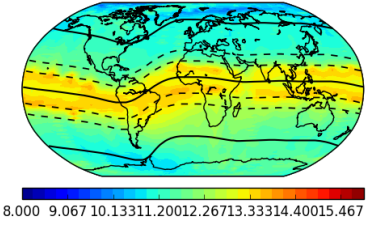
Using 6-day composite of Swarm EFI N_e data (separately for each satellite) we compute the index:

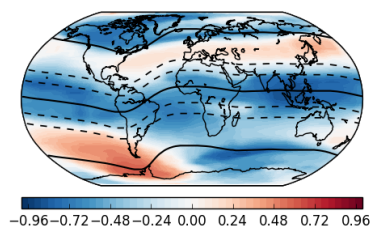
$$I_{NDD}(\lambda, \theta, T) = \frac{N_e^{des}(\lambda, \theta, T) - N_e^{asc}(\lambda, \theta, T + 12H)}{N_e^{des}(\lambda, \theta, T) + N_e^{asc}(\lambda, \theta, T + 12H)}.$$

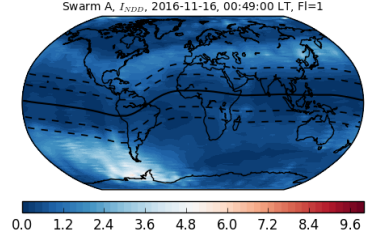
6 days of data provides sufficient spatial coverage, and still holds the conditions of equal local time

I_{NDD} in practice









Another approach for identification of NPDEs exploits:

- ratio of dayside and nightside registrations (4th fig.)
- or absolute difference in measurements

Interpretation of results is harder for multi-mission comparison.

I_{NDD} in practice

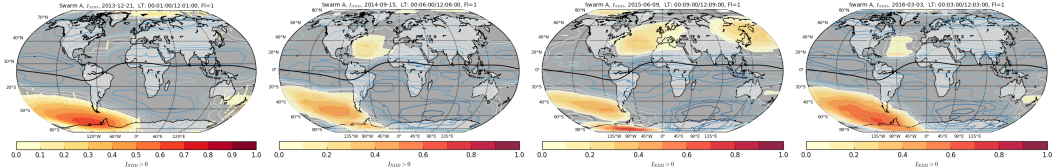
- I_{NDD} is a sort of metric that quantifies a contrast between two ionospheric states separated by 12 hours.
- I_{NDD} reproduces certain ionospheric structures that occur on selected LTs
- Index product:
  - the index I_{NDD} product: 6-day gridded data CDF product (6-days medians with 1-day sliding window overlapping), updated on a daily basis.
  - `http://swarm4anom.cbk.waw.pl/s4a/prodcdf/`
  - Since the beginning of the mission approx. 1558 files for each satellite + reprocessed CHAMP data

Scientific analysis based on the index product

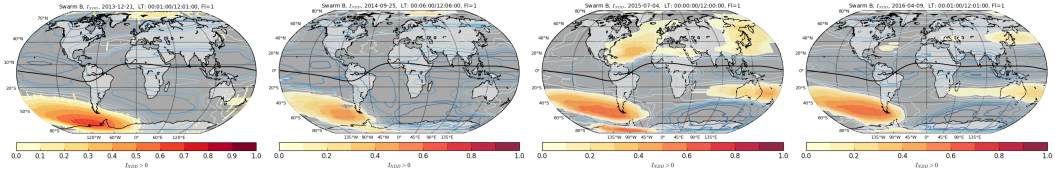
- Initially I_{NDD} was developed for the analysis utilizing dataset from the DEMETER mission (CNES mission) with the satellite operating in the fixed LT frame 10:30/22:30
- Limited LT coverage did not give full insight into daily evolution of the anomaly
- Using Swarm and CHAMP we were able better to gain fuller insight into typical diurnal behavior of the anomaly
- Using all three Swarm satellites we obtained global representation of nighttime plasma density enhancements and its seasonal variations.

Spatial patterns of I_{NDD} - seasonal changes for 00/12 LT

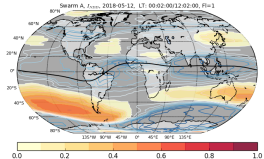
Alpha:



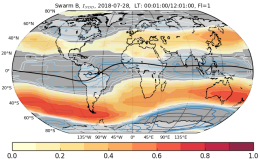
Bravo:



A: (2018-05-12) - - →



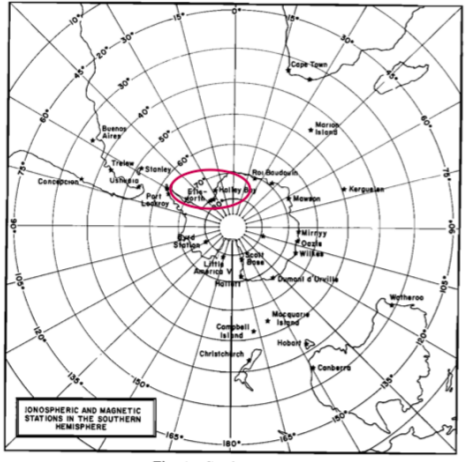
B: (2018-07-28) - - →



Long-term analysis of the index

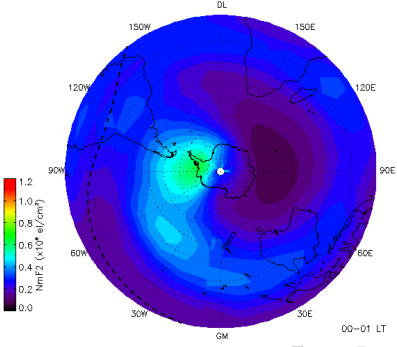
- **Can we detect the impact of long-term changes in the Earth's magnetic on the spatial structure of the WSA-like features?**
- How strongly decreasing solar activity impact the WSA? Or... what is the response of the index to changes in the solar activity?

Weddell Sea Anomaly or the Bellingshausen Sea Anomaly

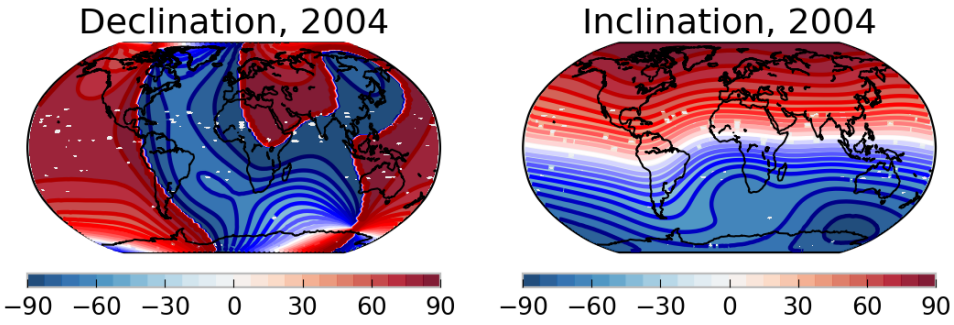


Images: 1. (Pendorf, 1978) 2. http://cism.hao.ucar.edu/

- **Why it is called the Weddell Sea Anomaly, when noticeable part of the anomaly is located in the Bellingshausen Sea region?**
- *Webb and Essex, 2003* - postulate to change name of the phenomenon

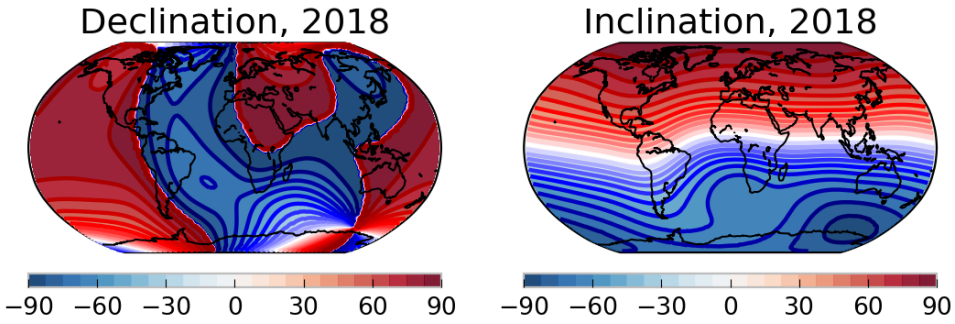


Expected effect



- Due to geomagnetic secular variation, particular features like the dip equator, the South Atlantic Anomaly, the Sq and equatorial electrojet current systems slowly evolve in time (times scales of decades)

Expected effect



- Due to geomagnetic secular variation, particular features like the dip equator, the South Atlantic Anomaly, the Sq and equatorial electrojet current systems slowly evolve in time (times scales of decades)

Expected effect - II

WSA is in close proximity to the SAA, similar consequences related to changes in the main field may be observed

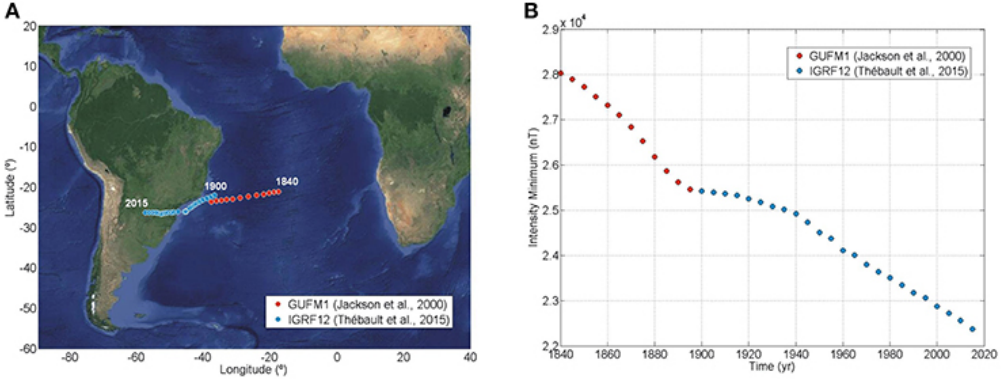


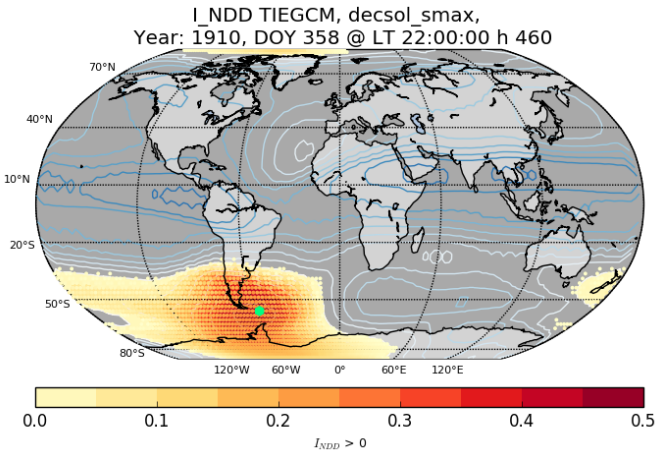
image source: *The South Atlantic Anomaly: The Key for a Possible Geomagnetic Reversal*, F. Javier Pavon-Carrasco, and Angelo De Santis

TIEGCM Synthetic index I_{NDD}

- TIEGCM - Thermosphere-Ionosphere-Electrodynamics General Circulation Model - developed by NCAR. TIEGCM is a time-dependent, three dimensional model that solves the fully coupled, nonlinear, hydrodynamic, thermodynamics, and continuity equations of the neutral gas self-consistently with the ion continuity, momentum, and energy equations
- Realistic magnetic field implemented (IGRF-12)
- **Goal: Use Stand-alone runs to reconstruct "historical index" with fixed configuration representing solar and geomagnetic conditions.** In such way the main effect of the role of magnetic field in formation of the WSA is captured
- For a fixed LT frame - certain ionospheric features (expressed by ionosphere fields such as N_e, hmF2, TEC...) remain at specific locations. Intensity of observed features may vary with season and solar activity - On a time scales of couple of years remain unchanged, but... we may expect changes on scales of decades.

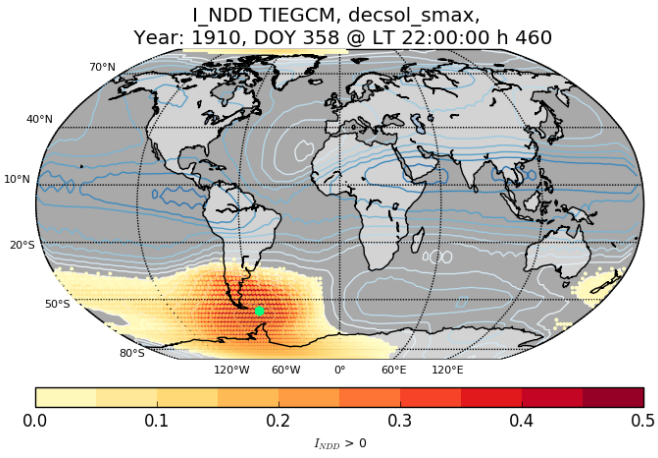
Synthetic index and the impact of the magnetic field - December solstice

- For a given LT we track max. of the anomaly ($I_{NDD} > 0$) in the 3^{rd} quadrant (WS hemisphere)



Synthetic index and the impact of the magnetic field - December solstice

- For a given LT we track max. of the anomaly ($I_{NDD} > 0$) in the 3^{rd} quadrant (WS hemisphere)
- 1910



Synthetic index and the impact of the magnetic field - December solstice

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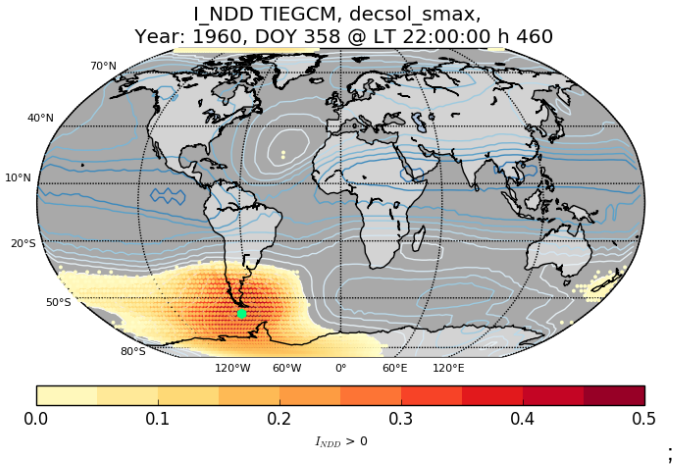
- 1960



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Synthetic index and the impact of the magnetic field - December solstice

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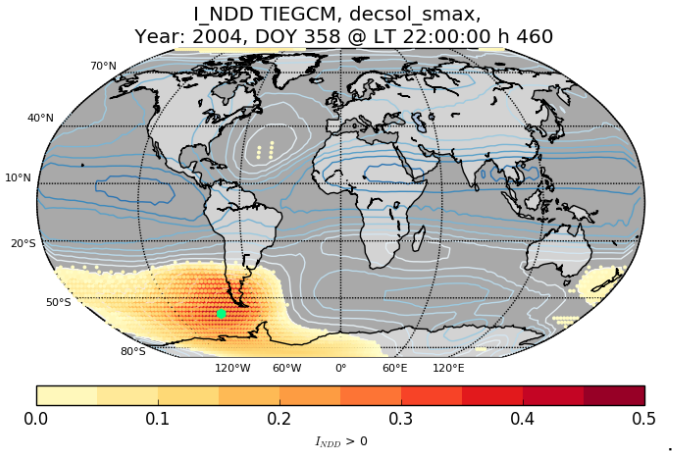
- 2004



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Synthetic index and the impact of the magnetic field - December solstice

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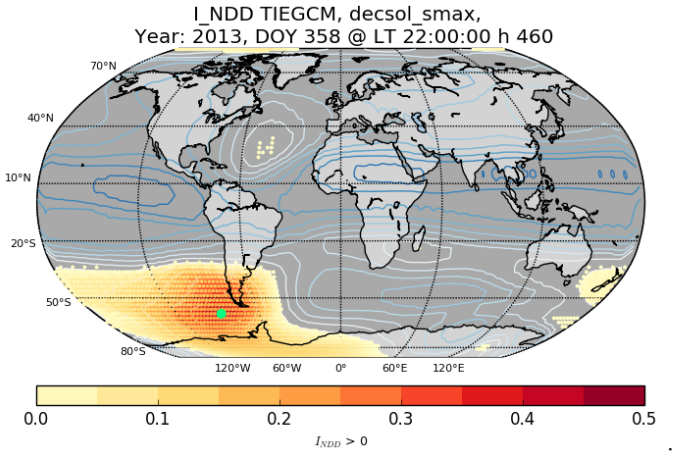
- 2013



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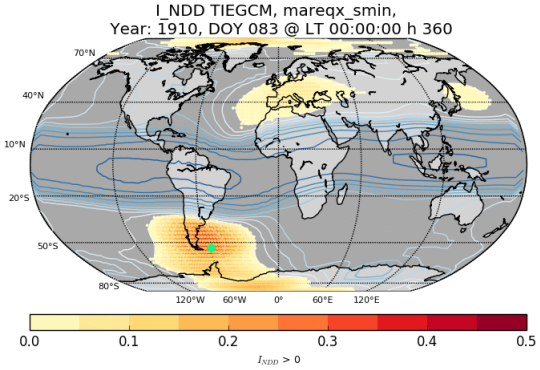
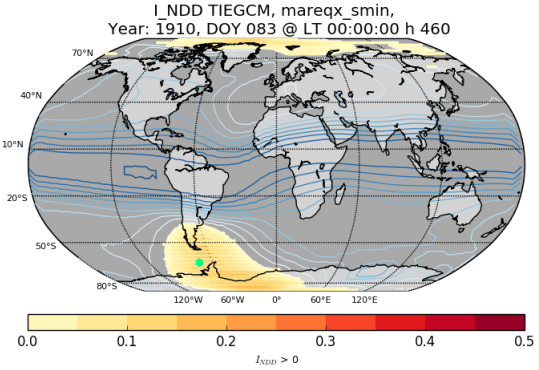
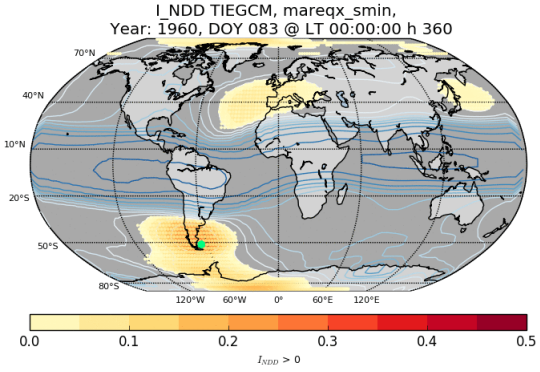
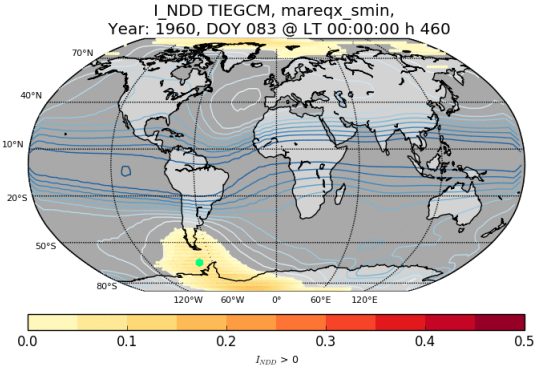
TIEGCM results - I_{NDD}@(360 km & 460 km) - March equinox (1910)



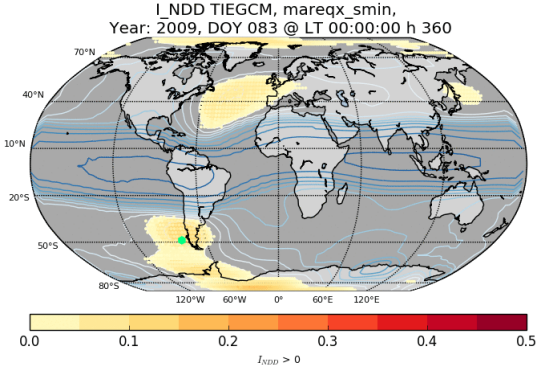


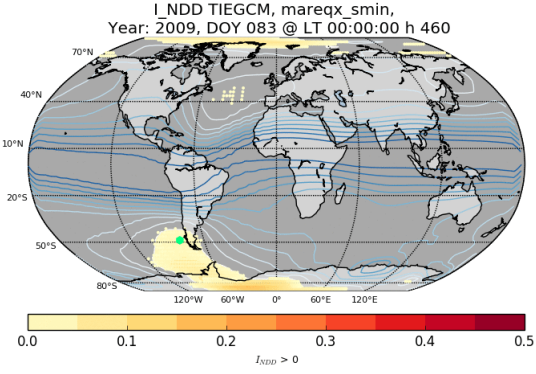
TIEGCM results - I_{NDD}@(360 km & 460 km) - March equinox (1960)





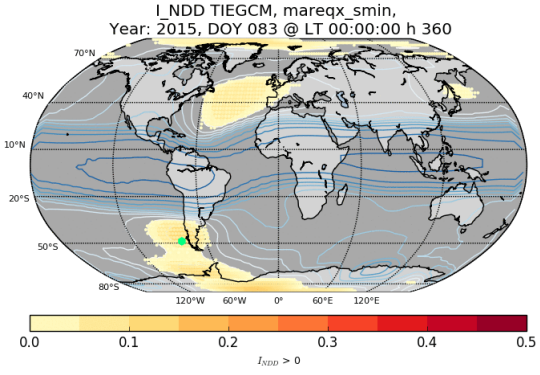
TIEGCM results - I_{NDD}@(360 km & 460 km) - March equinox (2009)

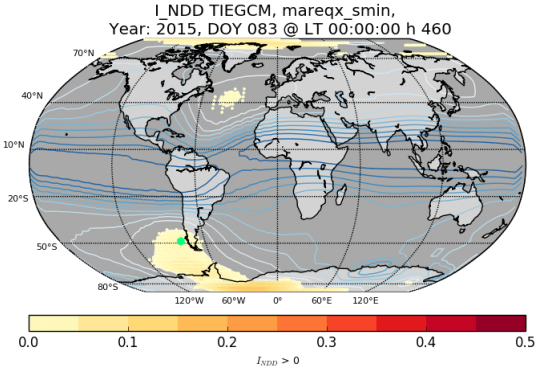




Evidences of NPDEs in the Atlantic sector at the altitude of 460 km starts to emerge

TIEGCM results - I_{NDD}@(360 km & 460 km) - March equinox (2015)

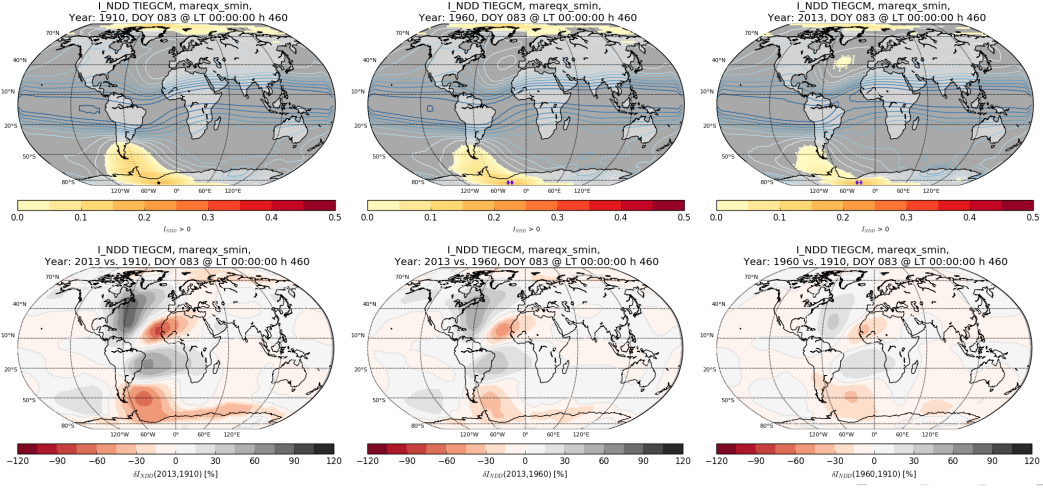




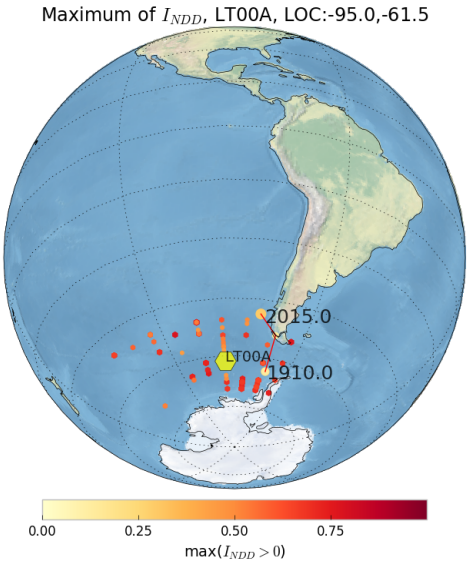
NPDEs in the Atlantic sector are getting stronger

Magnetic field secular variations and the WSA - theoretical analysis

- Based on model simulation there is constant decrease of I_{NDD} in the region of the Weddell Sea, and increase in the Bellingshausen Sea



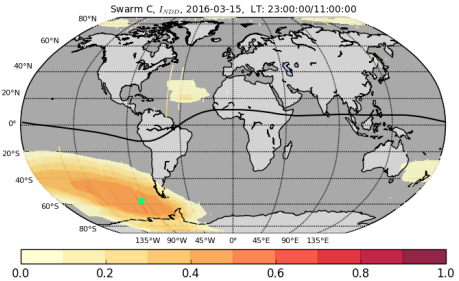
Finding Location of $Max(I_{NDD})$

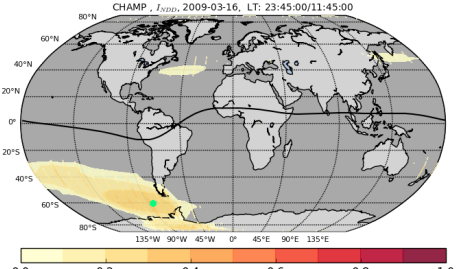


Key finding:

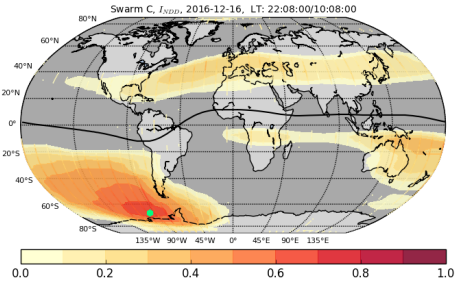
Satellite	LT bin	Long./Lat.
CHAMP	22/10	-90./-60
Swarm A	22/10	-105./-62.5
Swarm B	22/10	-105./63.5
Swarm C	22/10	-105./-62.5
CHAMP	00/12	-85./ -63.5
Swarm A	00/12	-95./-61.5
Swarm B	00/12	-95./-54.5
Swarm C	00/12	-95. /-61.5
CHAMP	02/14	-75./-57.5
Swarm A	02/14	-85./-56.
Swarm B	02/14	-85./ -53.5
Swarm C	02/14	-85/ -56.5

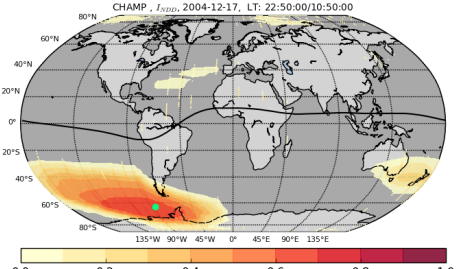
Results: Position of the WSA maximum - Champ vs. Swarm (I)



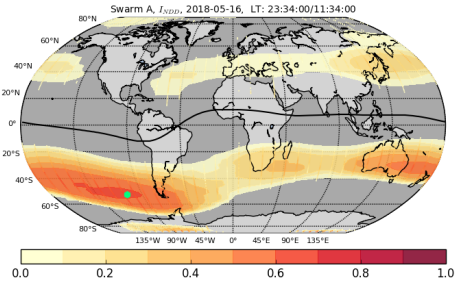


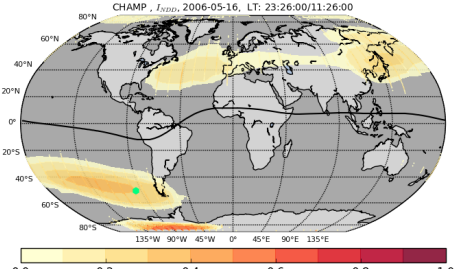
Results: Position of the WSA maximum - Champ vs. Swarm (II)





Results: Position of the WSA maximum - Champ vs. Swarm (III)





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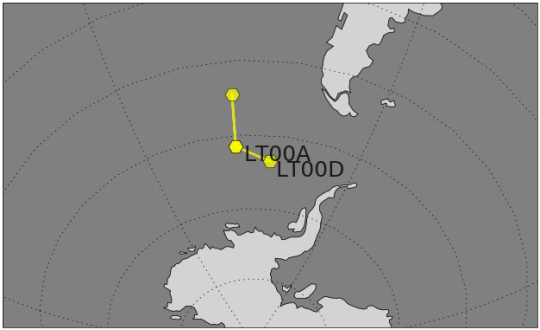
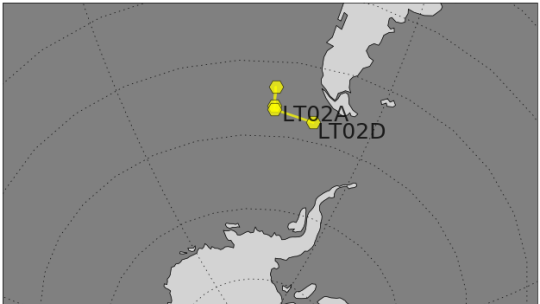
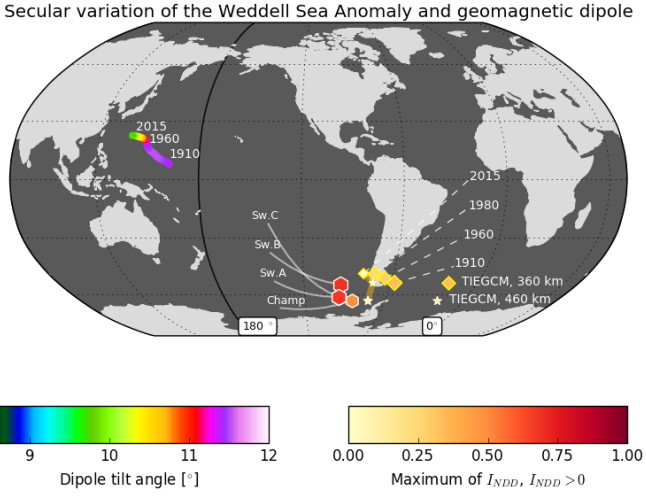




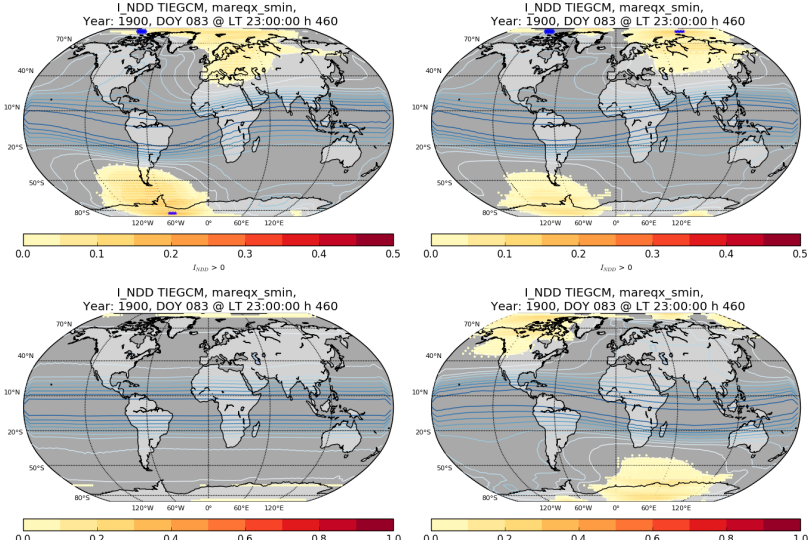
Linking migration of the WSA with the magnetic field changes



Results submitted to JGR

TIEGCM suggests that for fixed solar conditions, and varying configuration of the main magnetic field maximum of I_{NDD} in the WSA region gradually shifts in the direction of the Pacific Ocean.

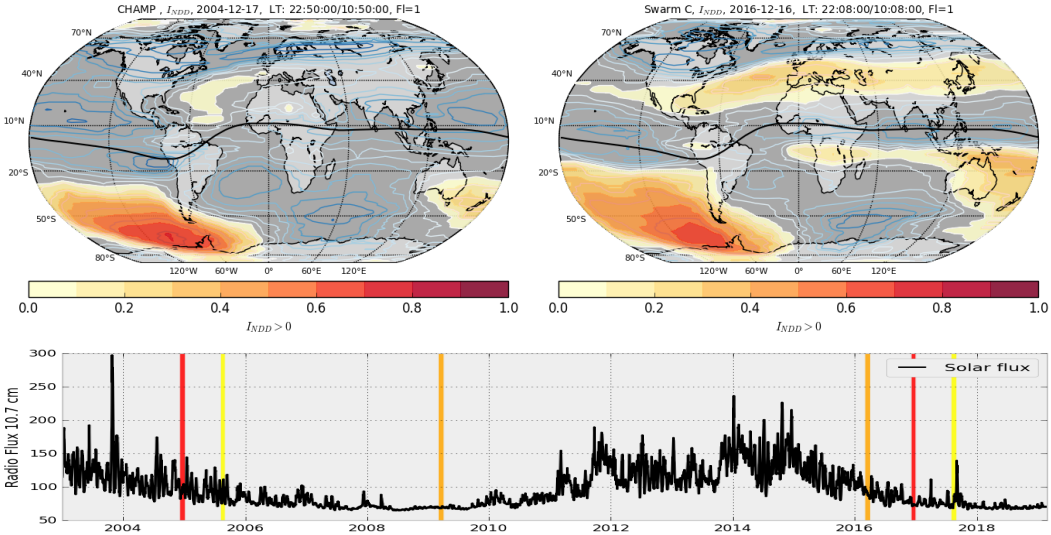
Dipolar components and settings - Interpretation - Dipole tilt angle dependence



Main conclussion (I)

- Swarm- and CHAMP-derived index I_{NDD} seems to confirm modeled prediction - westward drift of the maximum of the WSA.
- The influences of the secular changes of the orientation of the geomagnetic field: the variation of the eccentric dipole field center, the movement of the geomagnetic poles, and the variations of I and D, should be reflected in the substantial movement of certain ionospheric features (including WSA)
- Configuration in the eccentric dipole representation is as an important indicator of the increasing asymmetry of Earth's field with respect to the Earth's center and the Earth's spin axis.

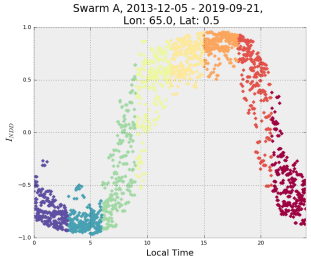
Decreasing solar activity and Swarm mission

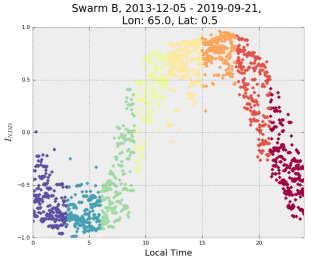


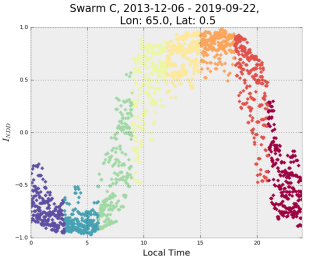
CHAMP ('2004) and Swarm ('2016) - December solstice (red indicators)

Decreasing solar activity and Swarm mission

I_{NDD} covers the whole range of LTs, outside time slots suitable for WSA and WSA-like phenomena, worth to expand the study to other regions.

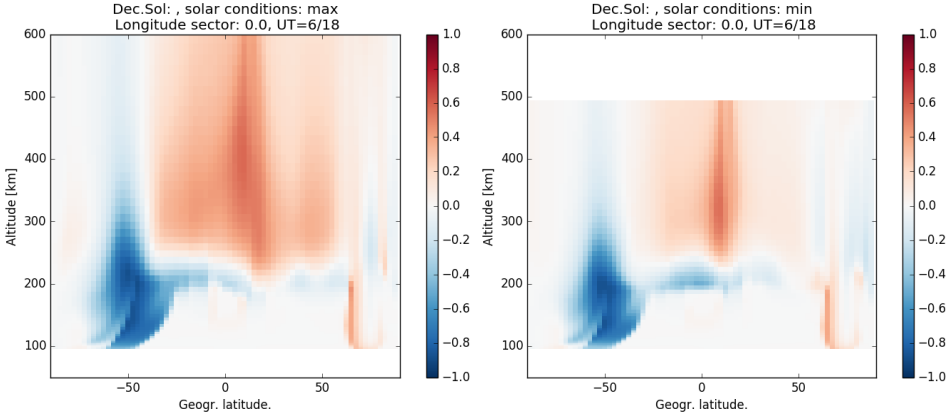






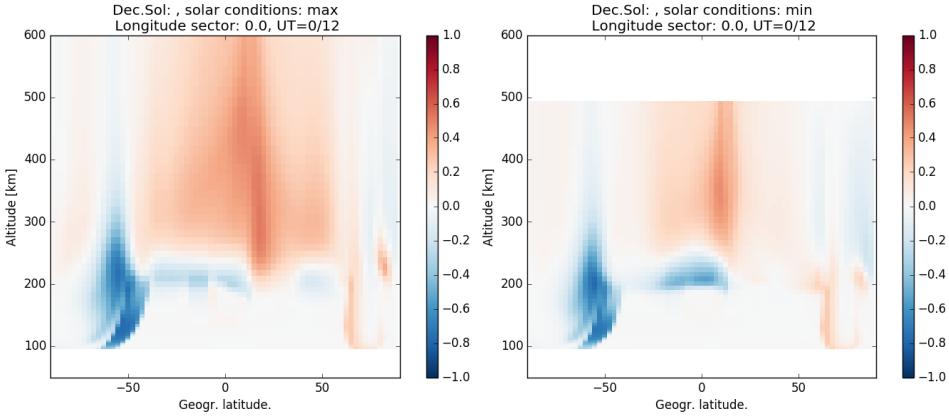
Decreasing solar activity and Swarm mission - Expected effect - TIEGCM simulation

Using the TIEGCM model, we make a prediction of expected effect.



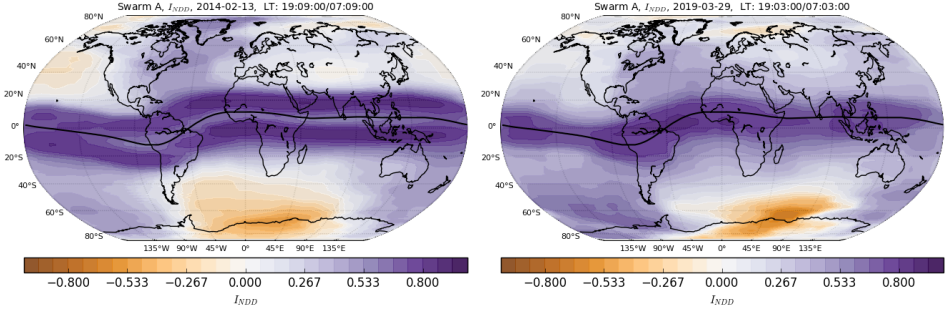
Height-Altitude profile for a selected longitude sector (Dawn/Dusk situation)

Decreasing solar activity and Swarm mission - Expected effect - TIEGCM simulation



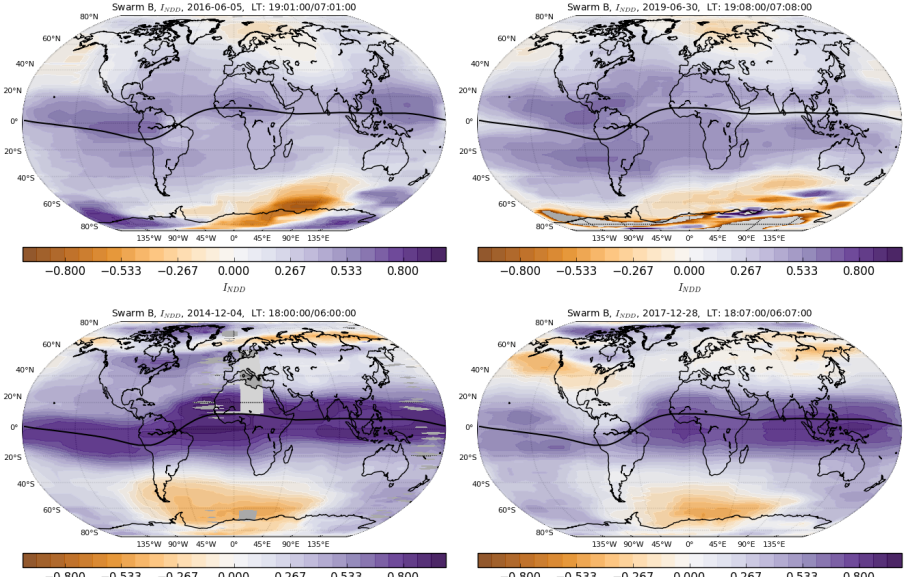
Height-Altitude profile for a selected longitude sector (Noon/Midnight situation)

Swarm enters the solar minimum

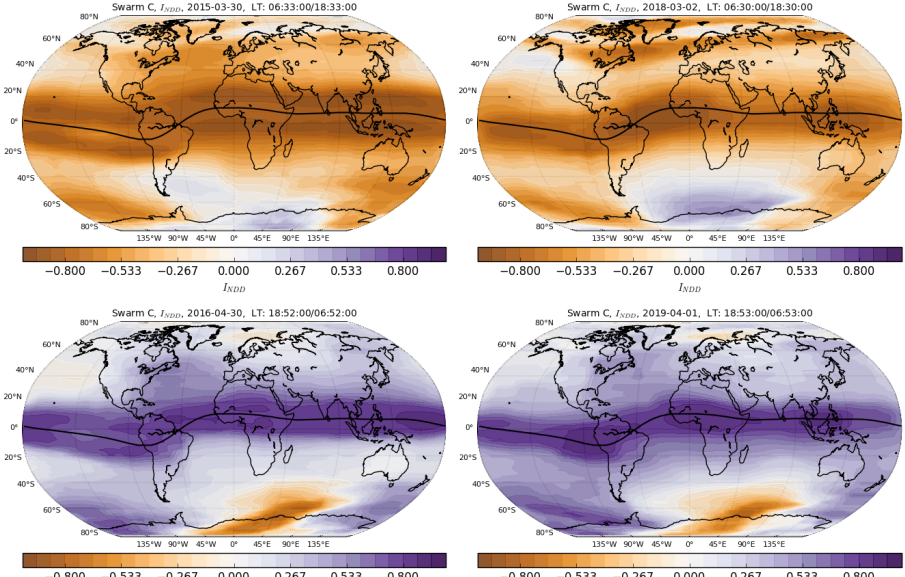


- There is an indication, that with decreasing solar activity, the difference in registrations separated by 12 hours weakens.
- The strongest effect seems to occur in the equatorial region: For example, signatures of the equatorial anomaly in the spatial pattern of I_{NDD} do not show two enhanced bands on both sides of the dip equator - and instead there is rather one wider "ribbon" along the dip equator (comparison between 2014 and 2019, Swarm A).

Swarm enters the solar minimum



Swarm enters the solar minimum



Summary

- During 6 years of Swarm mission, we have gained better knowledge about the WSA-lek phenomena
- Keeping Swarm in-orbit at possibly unchanged configuration (respecting the altitude), would be beneficial for verification of the assumption that the secular variations of the magnetic field is also reflected in the spatial morphology of in-situ electron density.
- The WSA seems to be drifting towards the Pacific Ocean, but modeling results indicate that more pronounced changes are expected in the longitude sector of the Atlantic Ocean.