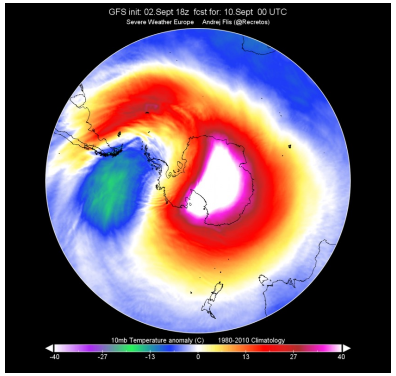
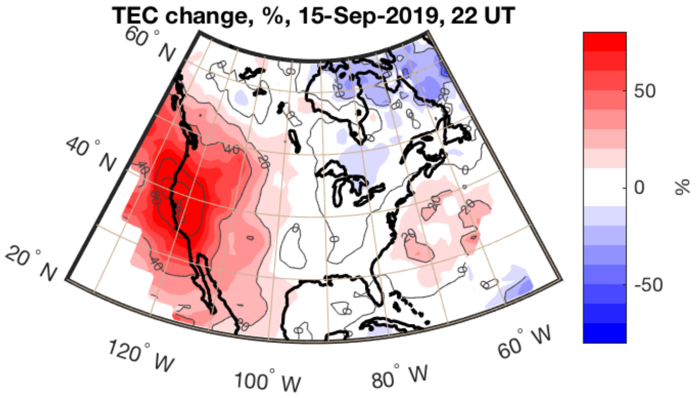
Sudden stratospheric warmings and the ionosphere/thermosphere system

L. Goncharenko,

MIT Haystack Observatory





ISR School, Boston University, Boston, MA
July 22-26, 2024

Sudden stratospheric warmings and the ionosphere/thermosphere system: how do you change research paradigm using ISRs

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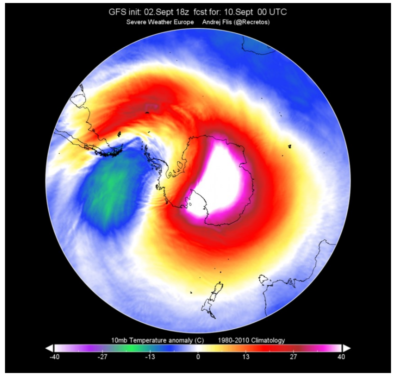

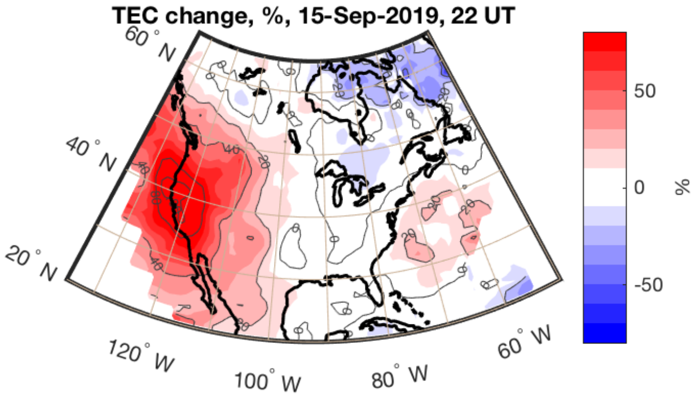

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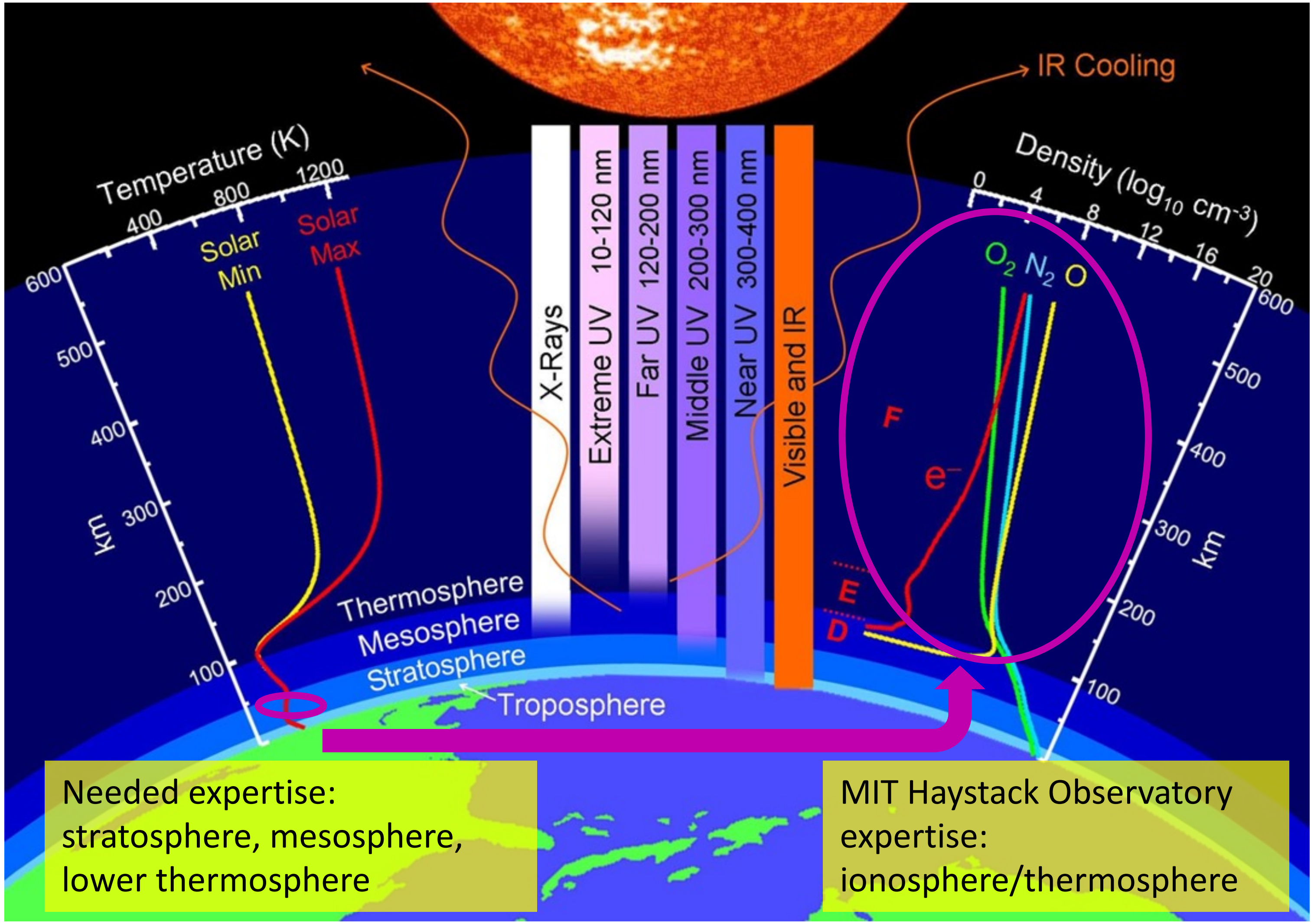
Atmospheric layers



Ionospheric electron density affects radio wave propagation, communication, navigation and precise point positioning capability

Overarching topics:

- **What drives ionospheric weather (large day-to-day variability, up to 50-100%)?**
- **How is the variability of the ionosphere/thermosphere system linked to the variability of lower atmospheric regions?**

Coupling from above:

Solar, magnetospheric and geomagnetic processes

Traditional school of thought:
Solar + magnetospheric drivers are dominant
Primary example:
Geomagnetic storm

Ionosphere-thermosphere

New school of thought:
Lower atmosphere drivers can be dominant
Primary example:
Sudden stratospheric warming

Coupling from below:

Gravity waves (GW), tides, planetary waves (PW)

- **Geomagnetic storms and sudden stratospheric warmings are two extremes**

Progress timeline

2006 → 2011 → 2019

2006

"The search for links between F-region phenomena and the lower atmosphere has a long history and few real outcomes" – *Rishbeth*, 2006

2011

"These new results (Chau et al., 2009, Goncharenko et al, 2010) have triggered an ***explosion*** of studies of mechanisms and types of possible connections between terrestrial and space weather during SSW and other large-scale perturbations in the lower atmosphere" – *Wang et al*., 2011

2019

"We have reached a paradigm shift, where any self-respecting space weather model of the upper atmosphere now needs to have some representation of the lower atmosphere" – *Jackson et al*., Space Weather, 2019

Progress timeline

2008: start of ISR World Days campaigns focused on SSW

2006 → 2011 → 2019

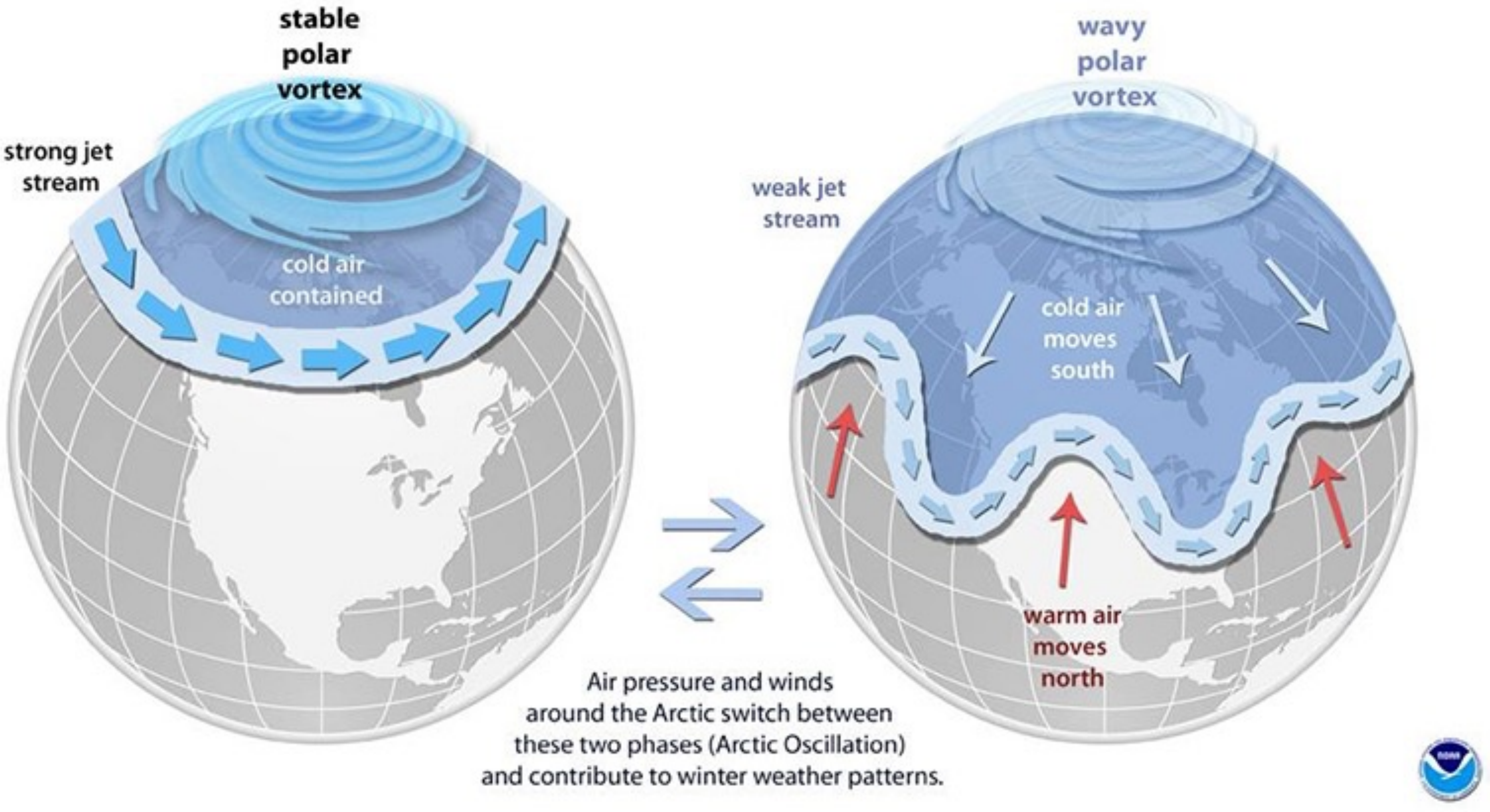
“The search for links between F-region phenomena and the lower atmosphere has a long history and few real outcomes” – *Rishbeth*, 2006

“These new results (Goncharenko & Zhang, 2008, Chau et al., 2009, Goncharenko et al, 2010) have triggered an ***explosion*** of studies of mechanisms and types of possible connections between terrestrial and space weather during SSW and other large-scale perturbations in the lower atmosphere” – *Wang et al.*, 2011

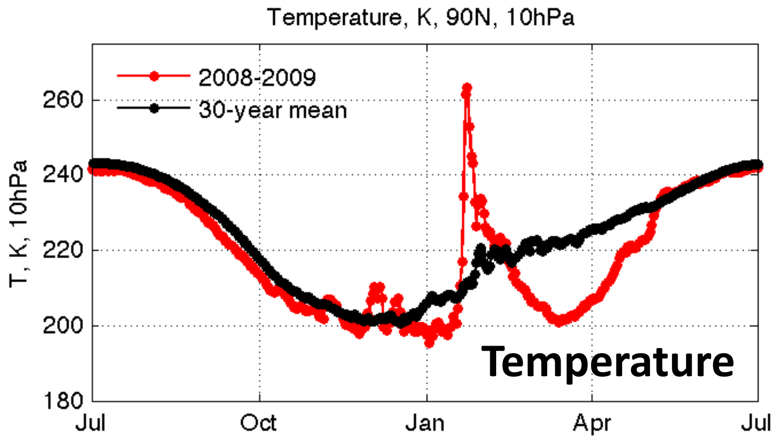
“**We have reached a paradigm shift**, where any self-respecting space weather model of the upper atmosphere now needs to have some representation of the lower atmosphere” – *Jackson et al.*, Space Weather, 2019

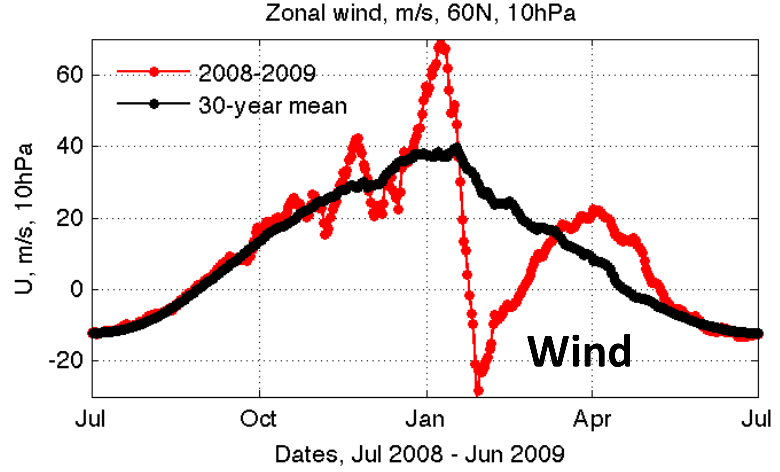
- First ideas: 2006
- **First ISR SSW campaigns: 2007-2008**
- First papers on ionospheric effects of SSW: 2008-2010
- In Heliophysics textbooks by 2016

Polar vortex

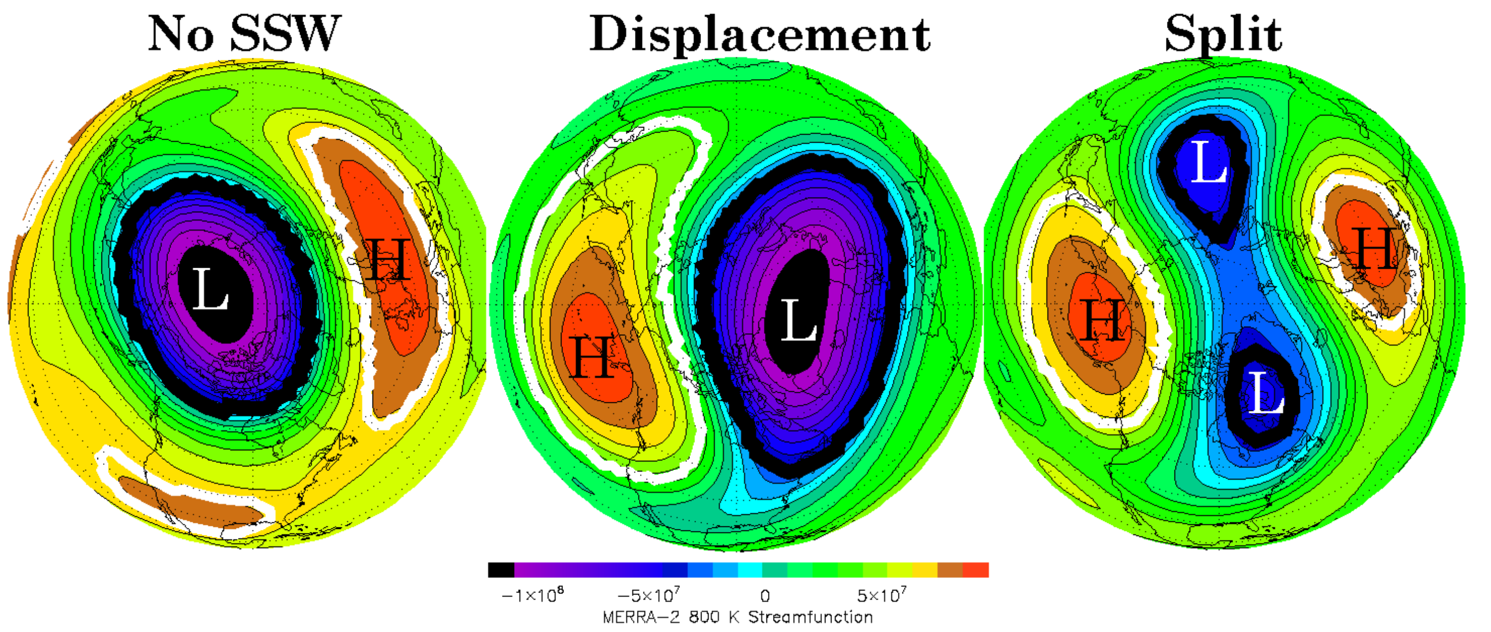


Special case: sudden stratospheric warming





- Large disruption of the polar vortex
- Largest known meteorological disturbance
- Rapid increase in temperature in the **high-latitude** stratosphere (25K+)
- Change in the zonal mean wind
- **Anomalies can last for a long time in the stratosphere (2 weeks +)**
- SSW events occur 1-3 times per winter



“Normal” polar vortex is small, round, centered on the North Pole

Disturbed vortex is broken into 2 cells

Disturbed vortex is broken into 4 cells

Downward impacts of SSW: persistent and strong *regional* anomalies in temperature and precipitation

Winter of 2020-2021:
SSW, record cold in Texas, USA

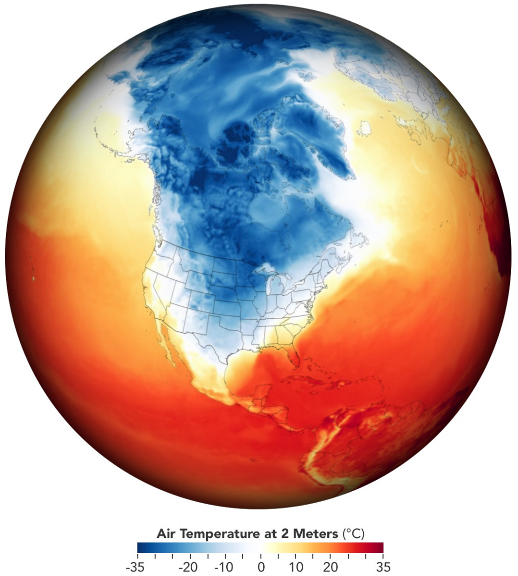


Image: Joshua Stevens

- *Temperature in Texas 50 degrees lower than usual*
- *4 million customers in Texas without power*
- *Energy emergency*

Destruction in Austin, Texas, from the deadly winter storms that knocked out power and water.
Feb 19, 2021 Credit: Tamir Kalifa, The New York Times

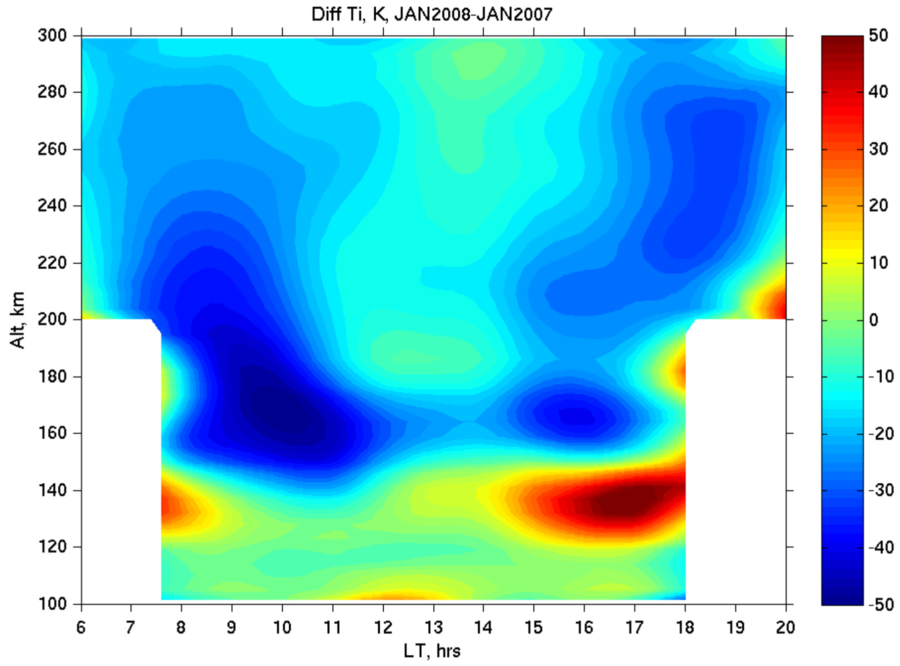
Winter of 2023-2024:
3 SSWs, record cold in China

February 20, 2024

- Extremely cold or warm temperatures for days and weeks; snowstorms or heavy rain
- Lots of data, strong impact on society
- **Exact mechanisms responsible for connections are not fully known yet**

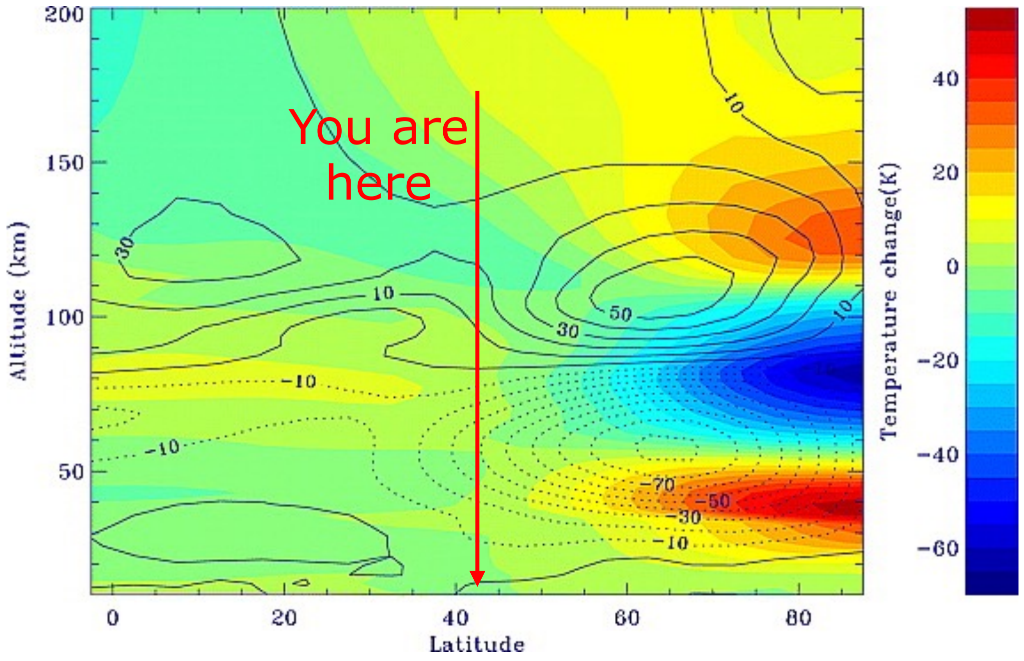
First evidence in the ionosphere: temperature variations during SSW

Data: Millstone Hill ISR, 42°N



Goncharenko and Zhang, 2008

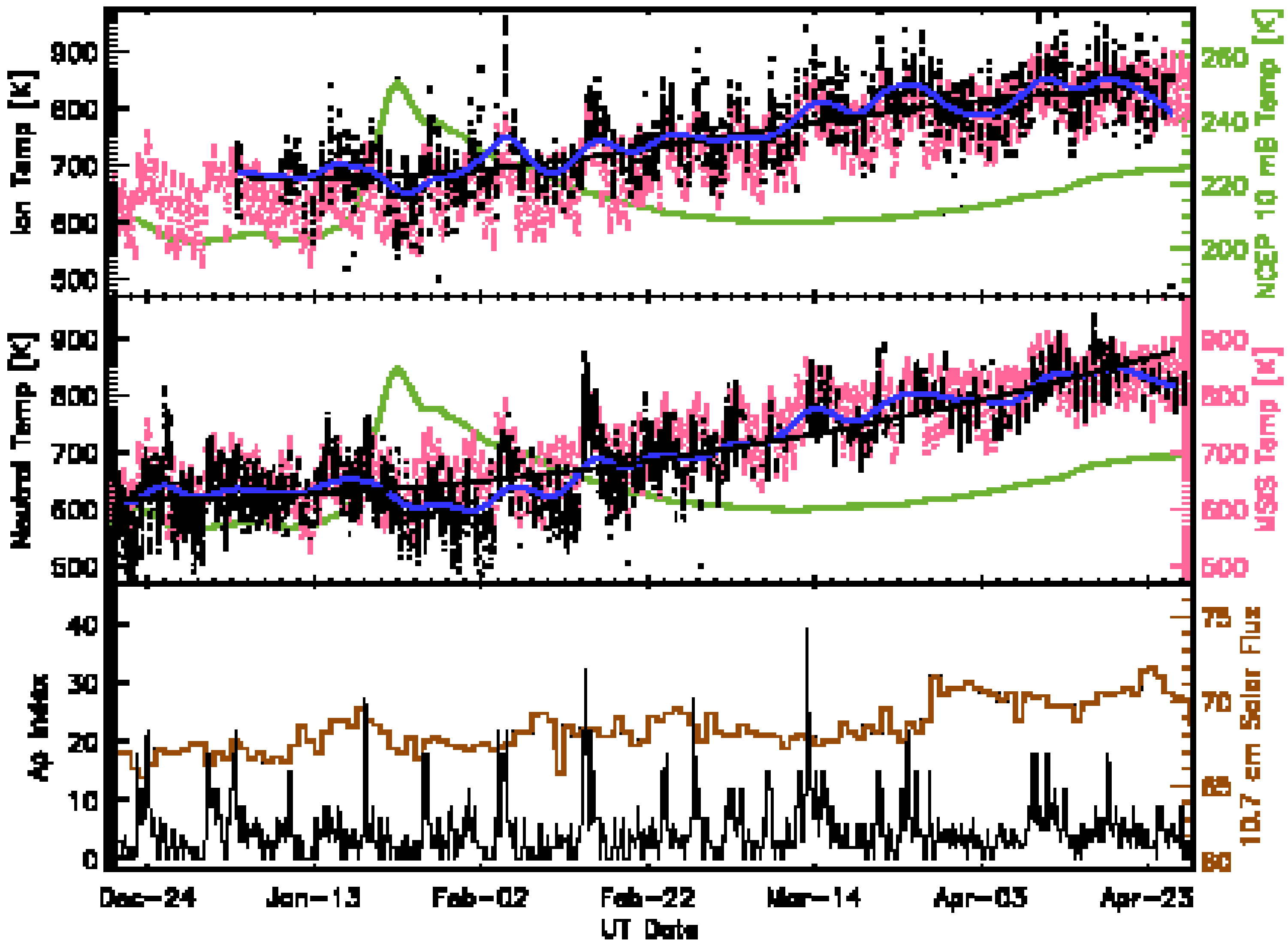
Model: TIMEGCM



Liu and Roble, 2002

- Data: warming at 120-140km; cooling above ~150 km; 12-hour wave;
- First experimental evidence of alternating warming and cooling of upper atmosphere
- Model: mesospheric cooling and secondary lower thermospheric warming

Other evidence of temperature change in the upper thermosphere/ionosphere



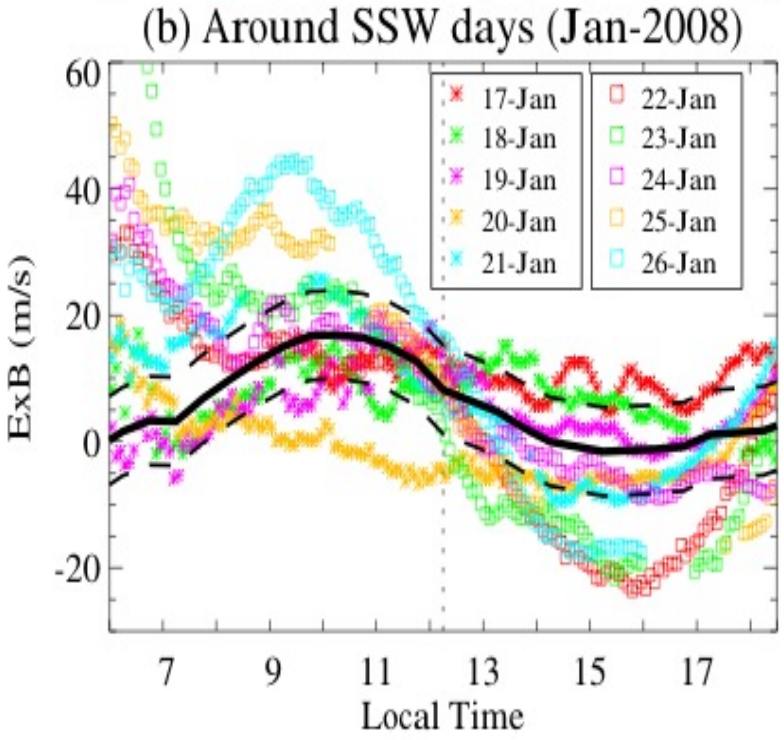
Conde and Nicolls, 2010

- Poker Flat FPI and ISR: **50 – 100 K cooling** in both Tn and Ti during January 2009 SSW event (*Conde and Nicolls, 2010*)
- Ti increase at 120-142 km in EISCAT data (*Kurihara et al, 2010*)
- GOLD data: ~50 K Tn decrease at low latitude (*Yigit et al., 2023*)

Several studies demonstrate warming at 120-150 km or cooling in the F –region related to SSW

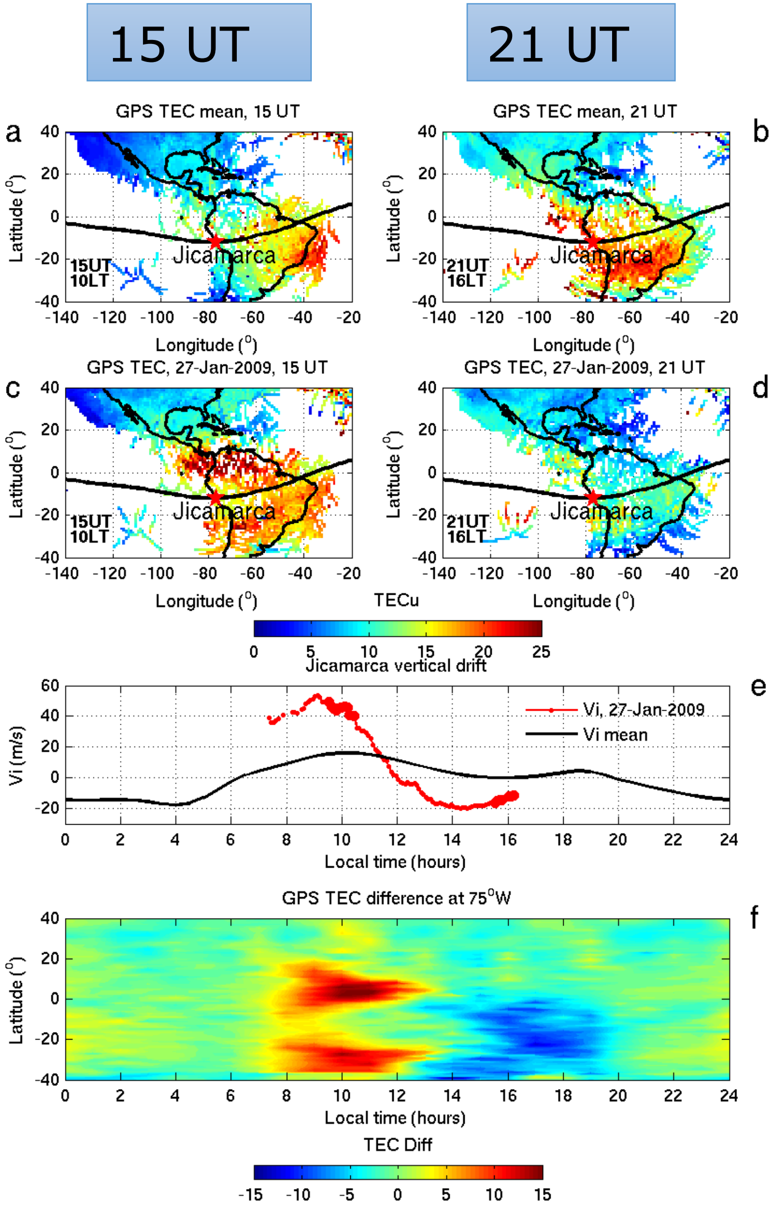
GOLD-based study: 15 years after ISR-based publications

Upward influence of SSW: large ionospheric anomalies at low latitudes



Vertical plasma drift
Chau et al., 2009

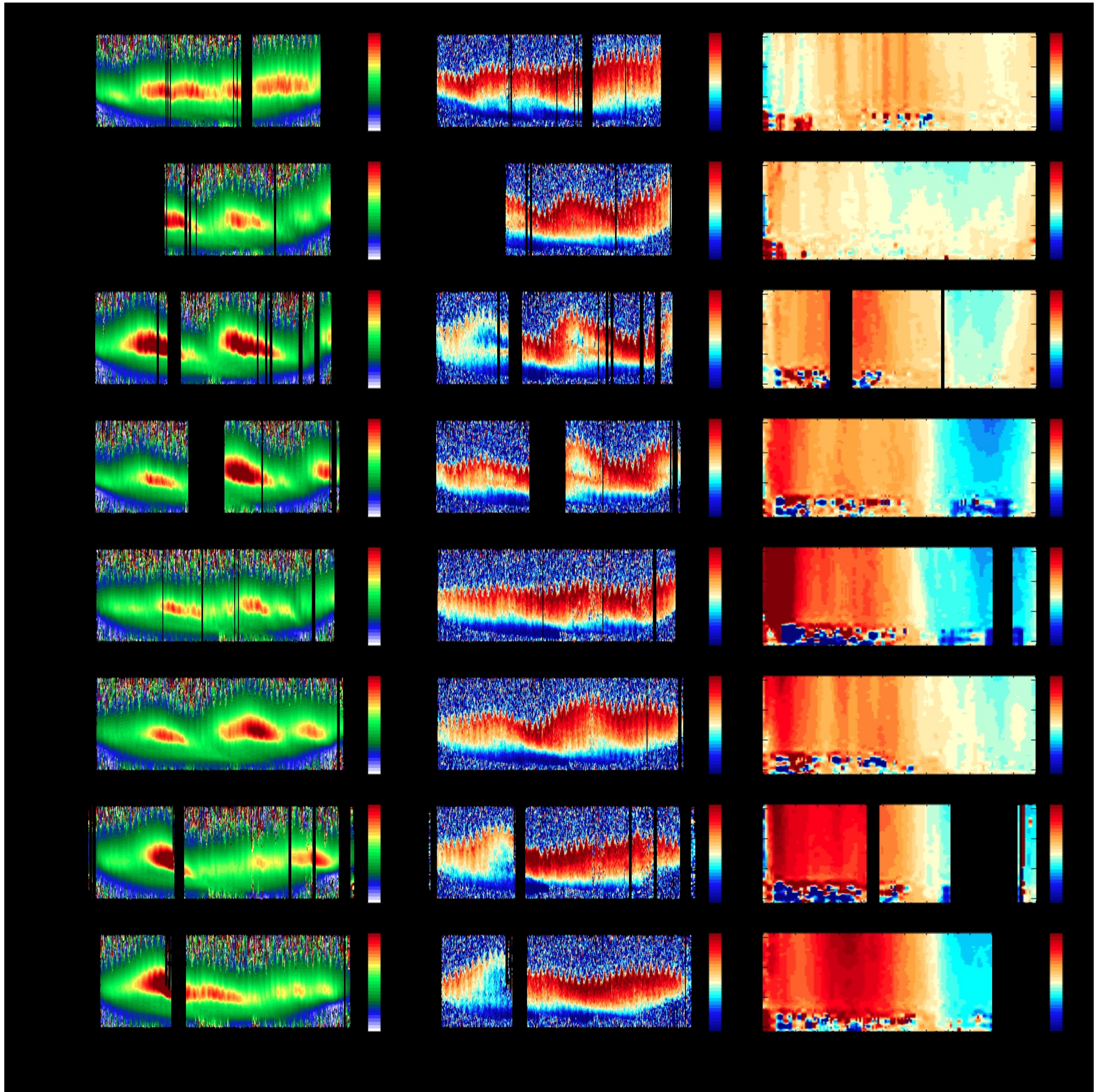
Total Electron Content map.
Goncharenko et al., 2010



- Upward drift in the morning, downward in the afternoon – evidence of electric field via enhanced 12-h tide
- Related increase and decrease in electron density
- Total Electron Content **change 50-150%** from the background

- Entire daytime low to mid-latitude ionosphere is affected during SSW
- **Major motivation for coupling studies**
- **Major motivation for model development**

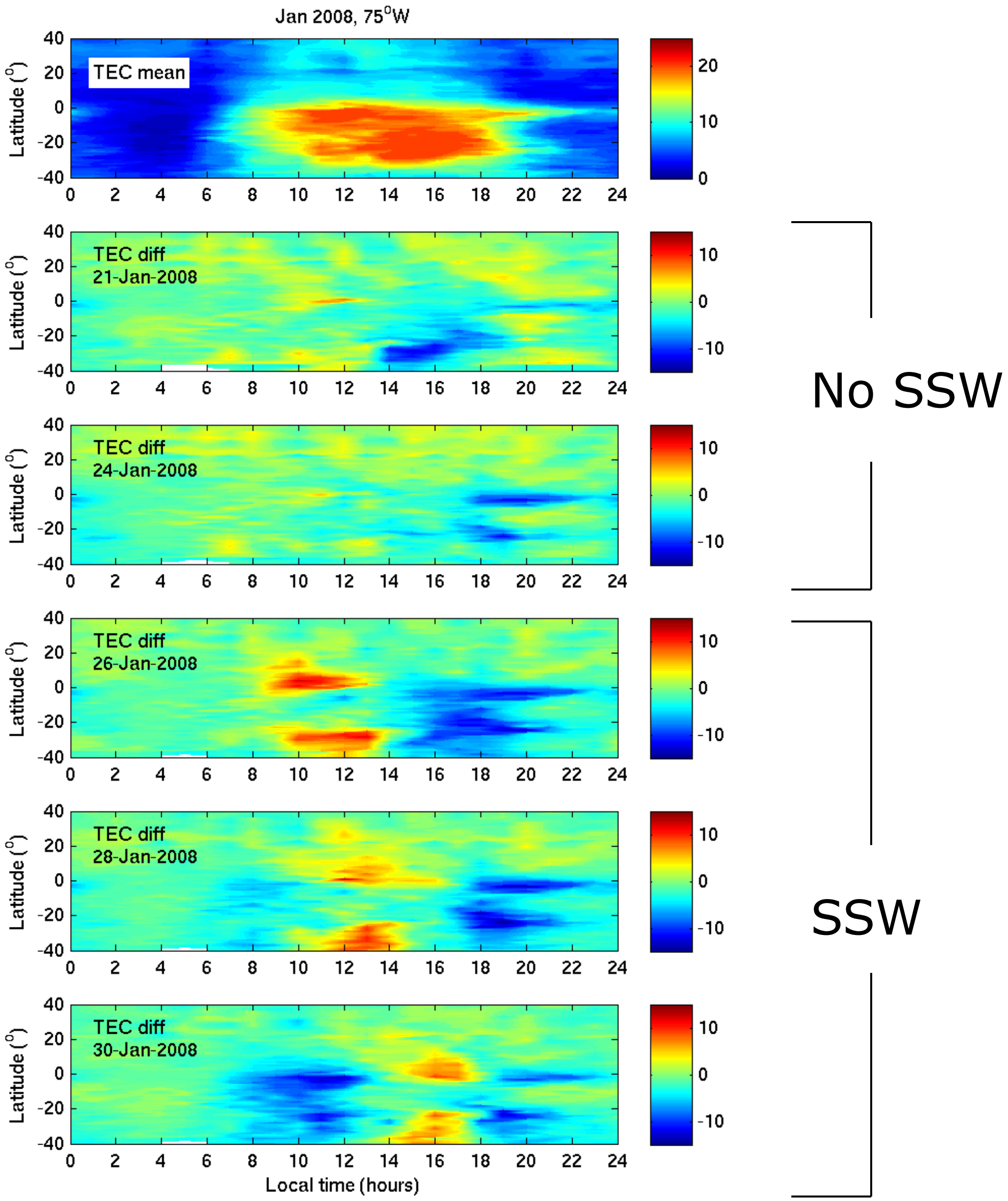
ISR Parameters: Arecibo and Jicamarca



- Change in Ne at Arecibo corresponds to the change in vertical drift at Jicamarca
- Anti-correlated change in electron temperature
- **Persistent multi-day disruption of all ionospheric parameters**

Chau et al., 2010

GPS TEC at 75°W, Jan 2008

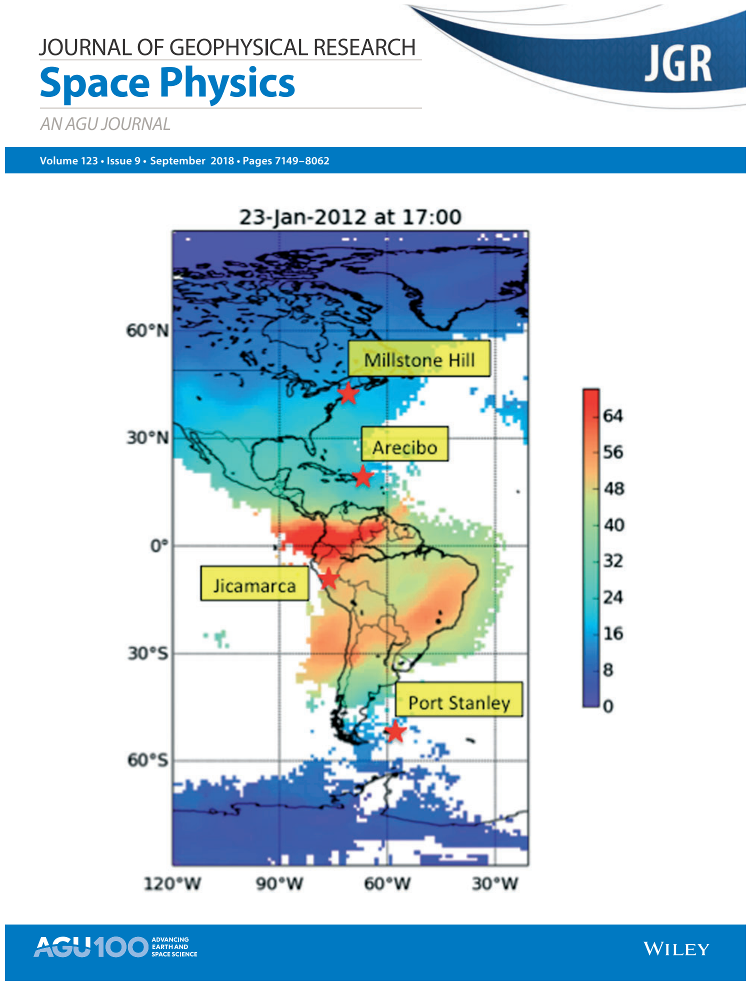


- No clear pattern prior to SSW
- Variation in TEC during stratwarming: semidiurnal wave, ~5-12 TEC
- Progressive shift to later local times – evidence of lunar tide
- Both high amplitude of the wave and rapid phase change lead to large variability in TEC

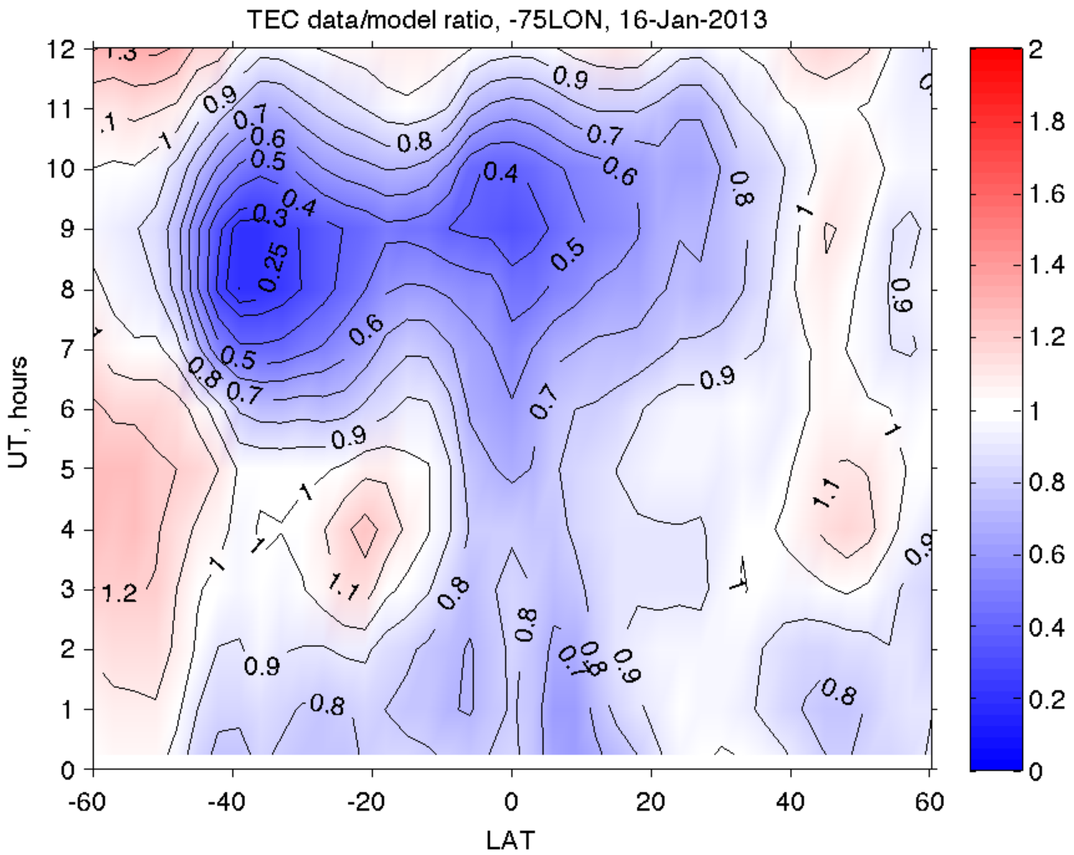
Availability of continuous, high-resolution datasets is essential (GNSS, magnetometers, ionosondes, …)

Goncharenko et al., 2010b

Observations of nighttime decrease in Ne during SSW

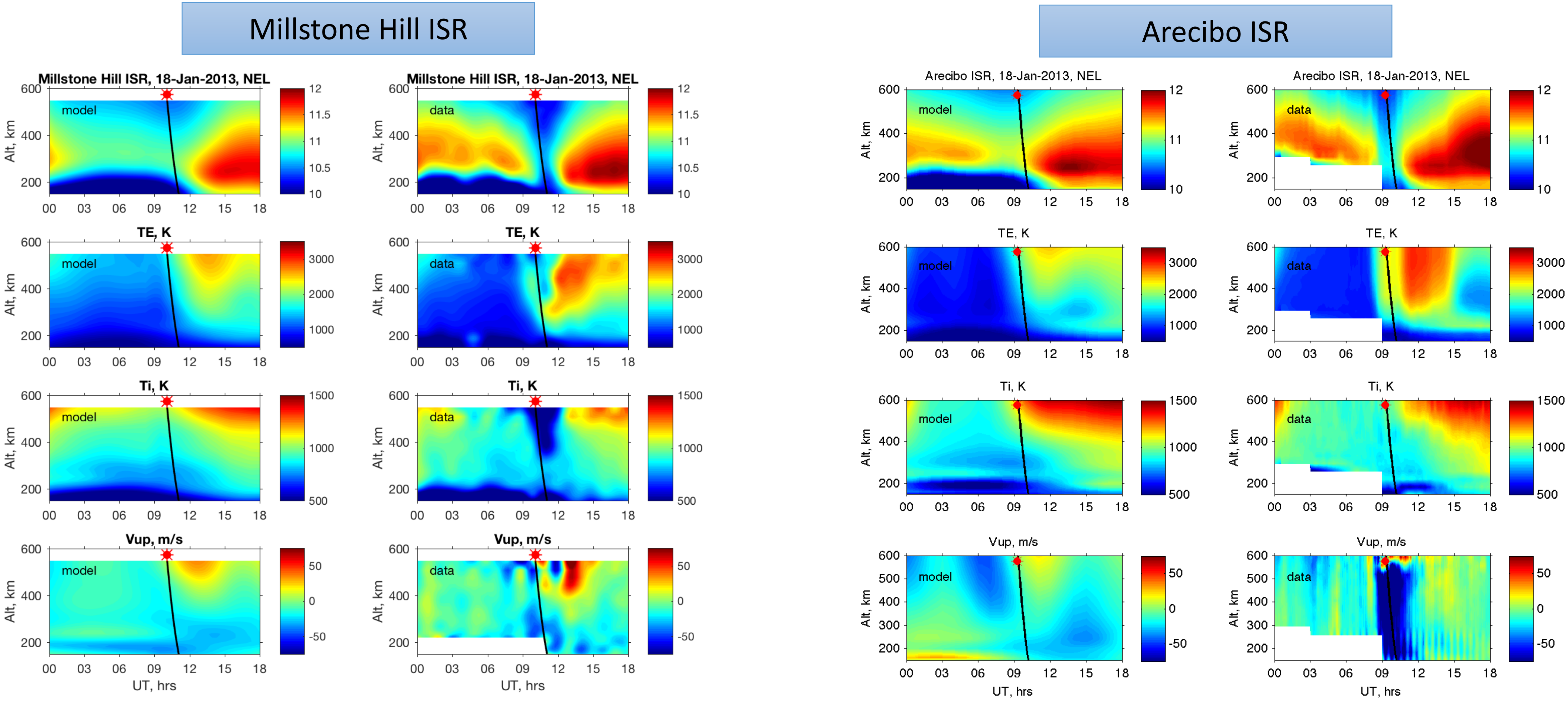


Goncharenko et al., 2018



- Deep ionospheric hole developed during SSW in the nighttime – TEC and NmF2 decrease by a factor of 2-4 [*Goncharenko et al., 2018]*

ISR observations of deep ionospheric hole

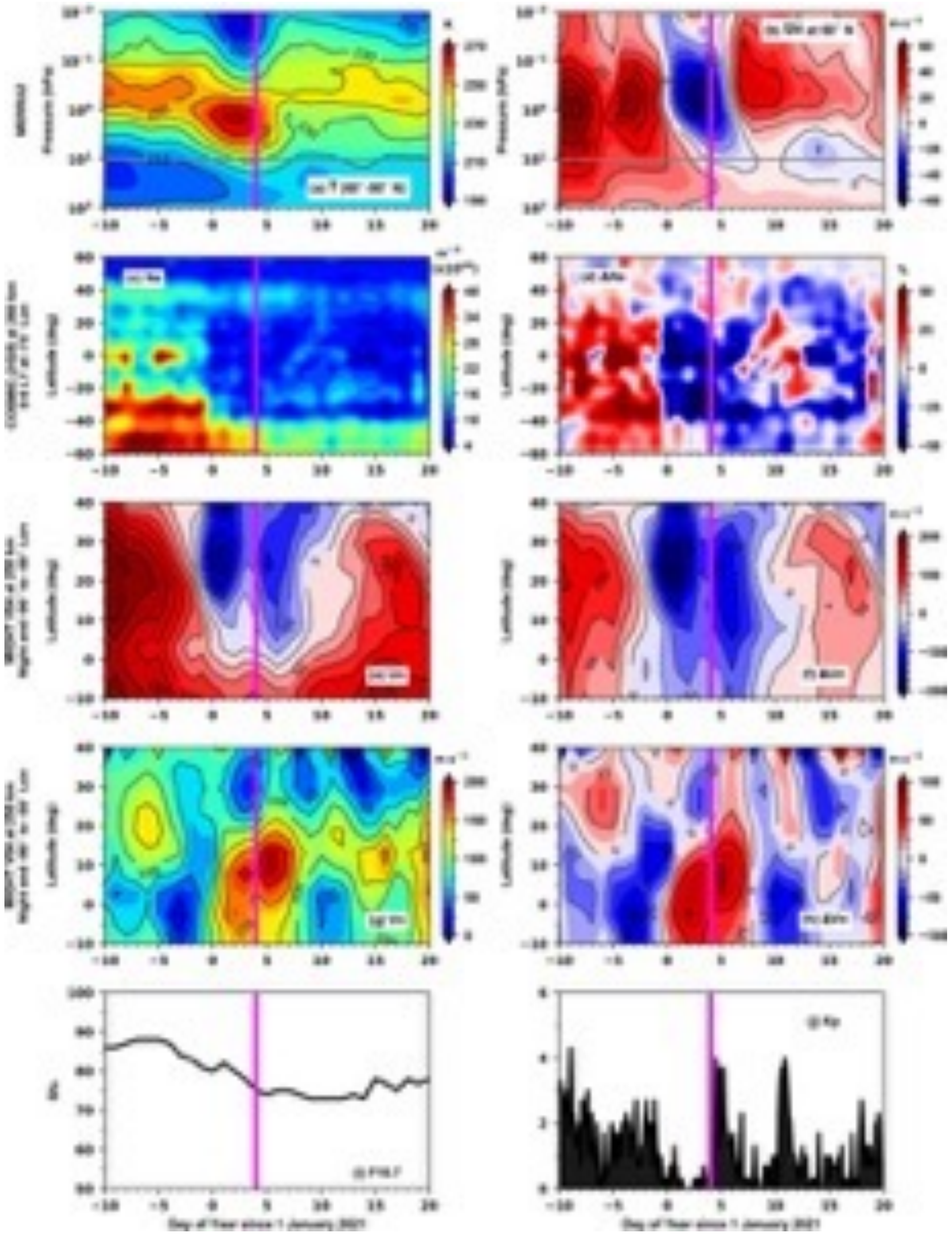


- Decrease in Ne is accompanied by Spread-F
- Suggested mechanism: SSW-induced change in thermospheric winds

Goncharenko et al., 2018

Simulations and observations: SSW of Jan 2021

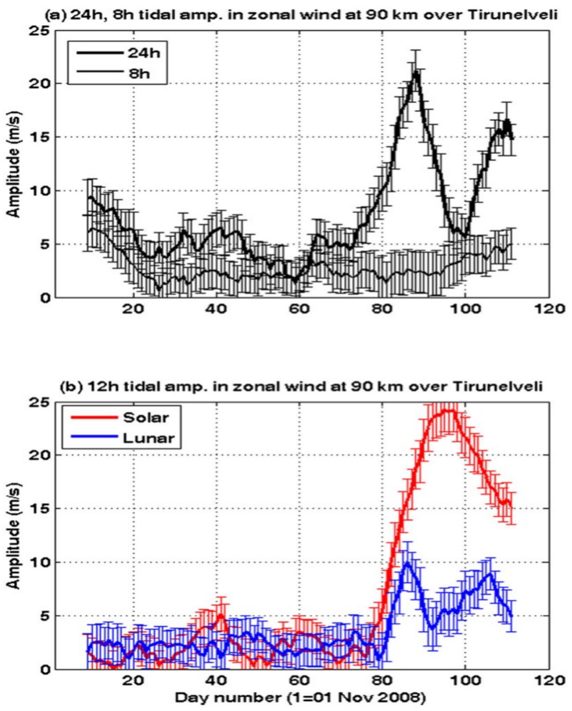
- Comprehensive data during SSW Jan 2021 – MERRA, COSMIC2, ICON MIGHTI
- COSMIC2 shows 50-70% decrease in Ne
- ICON/MIGHTI zonal wind residuals reach 50-100 m/s at 250 km
- Meridional wind is more poleward (divergent)
- TIMEGCM/NAVGEM simulations: deep ionospheric hole in the nighttime ionosphere during SSW is caused by tidally modified meridional winds
- **Implications: spread-F, irregularities, plasma bubbles**



Jones et al., 2023

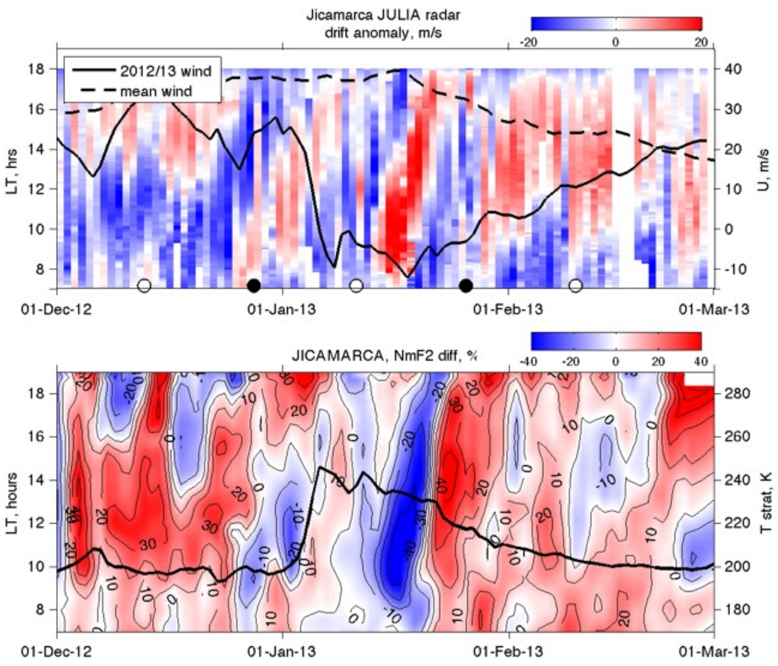
Upward impacts of SSW: current status

Tidal amplifications in MLT winds during SSW



Sathiskumar and Sridharan, 2013

Anomalies in ionospheric vertical plasma drift and peak electron density during SSW



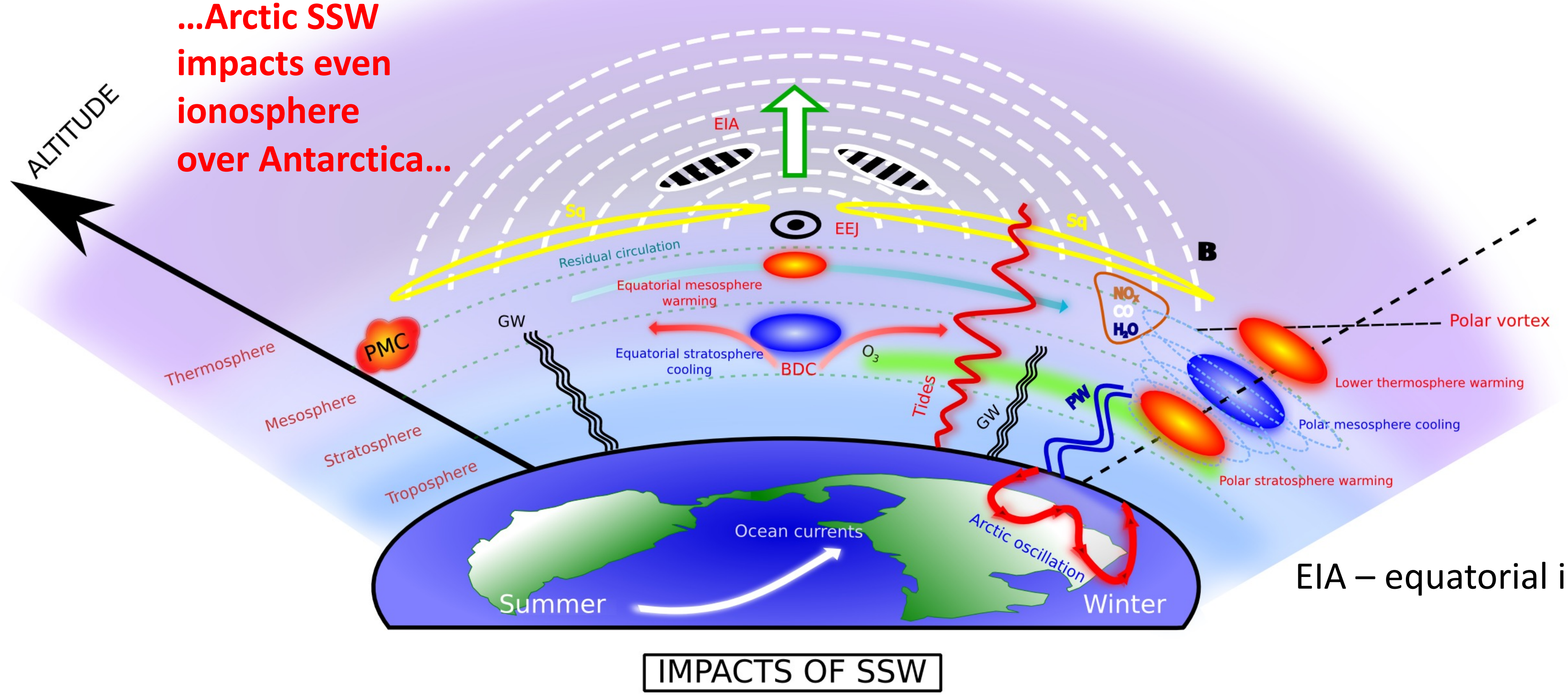
Goncharenko et al., 2021

- Profound ionospheric and thermospheric disturbances are documented during **Arctic** SSW events at ***low and middle latitudes*** (reviews by Chau et al., 2011; Goncharenko et al., 2021)
- **Main features:**
  - Amplified tides (~12hr, 24hr) in MLT winds
  - ~12hr anomalies in ionospheric plasma drift, electron density and total electron content
  - Anomalies can persist for up to ~30 days
- **Main mechanisms:**
  - Modification of electric field by amplified tidal winds in MLT region
  - Propagation of modified winds to the upper thermosphere (Pedatella and Maute, 2015)
  - Other thermospheric changes – composition change due to dissipation of tides and GW

Focus on SSW has been a proven strategy to vastly improve our understanding of mechanisms coupling the lower and upper atmosphere

Variety of known effects during SSW: from Arctic stratosphere to low, mid-latitude and high-latitude ionosphere (over Antarctica)

...Arctic SSW impacts even ionosphere over Antarctica...



EIA – equatorial ionization anomaly

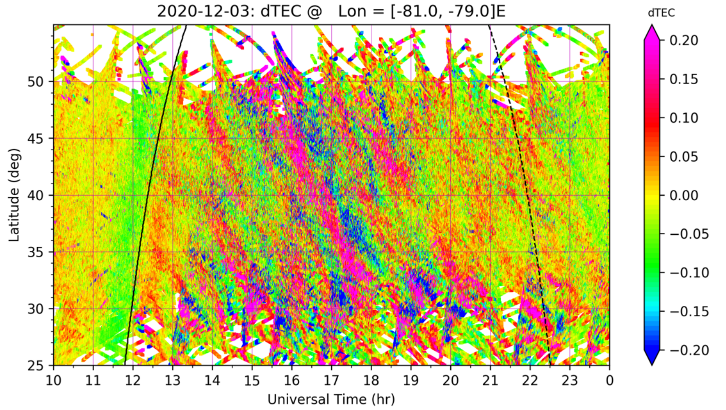
Pedatella et al., 2018

What’s next: future research areas

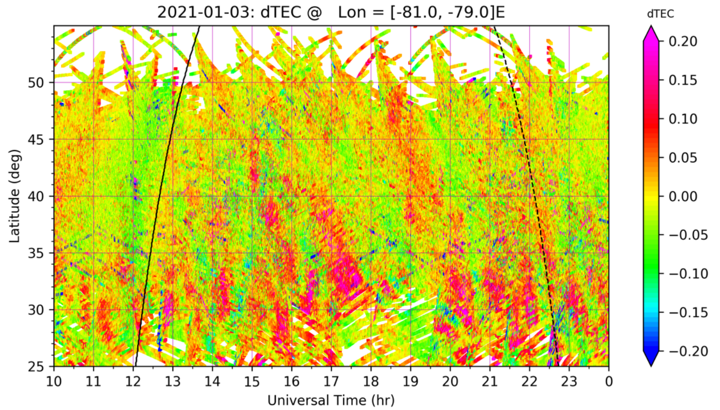
- **Area 1: variety of temporal scales**
  - **Topic #1 - Impacts of weak (SSW) and strong polar vortex on shorter time scales (gravity waves and traveling ionospheric disturbances)**
  - Topic #2 - Studies of SSW impacts on ionosphere on longer time scales (planetary waves)
  - Topic #3 - post-SSW ionospheric disturbances
  - Topic #4 – contribution of weak/strong polar vortex to understanding long-term effects in the I/T system
- **Area 2: variety of tropospheric and stratospheric states**
  - **Topic #5 - effects of strong polar vortex on the ionosphere-thermosphere-mesosphere system**
  - Topic #6 - Other significant lower atmospheric phenomena (QBO, MJO)
- **Area 3: variety of spatial scales**
  - Topic #7 – effects of strong and week PV on high-latitude ionosphere & thermosphere
  - Topic #8 – mechanisms driving longitudinal differences in the I/T system for weak (SSW) and strong polar vortex conditions
- **Area 4: societal impacts**
  - Topic #9 – links between weak/strong polar vortex and ionospheric irregularities, scintillations and plasma bubbles
  - Topic #10 – impact on HF communication

dTEC in the American sector, 80^{o}W

Pre-SSW



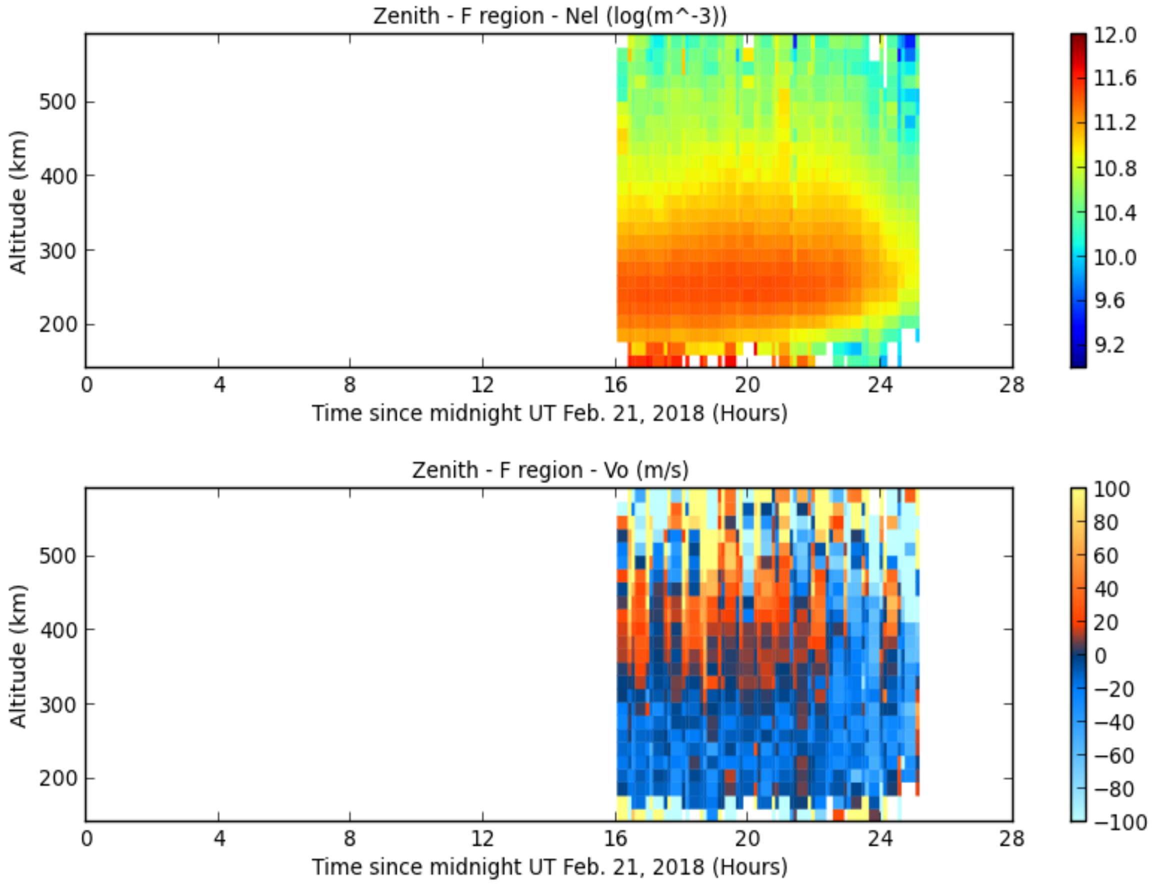
SSW



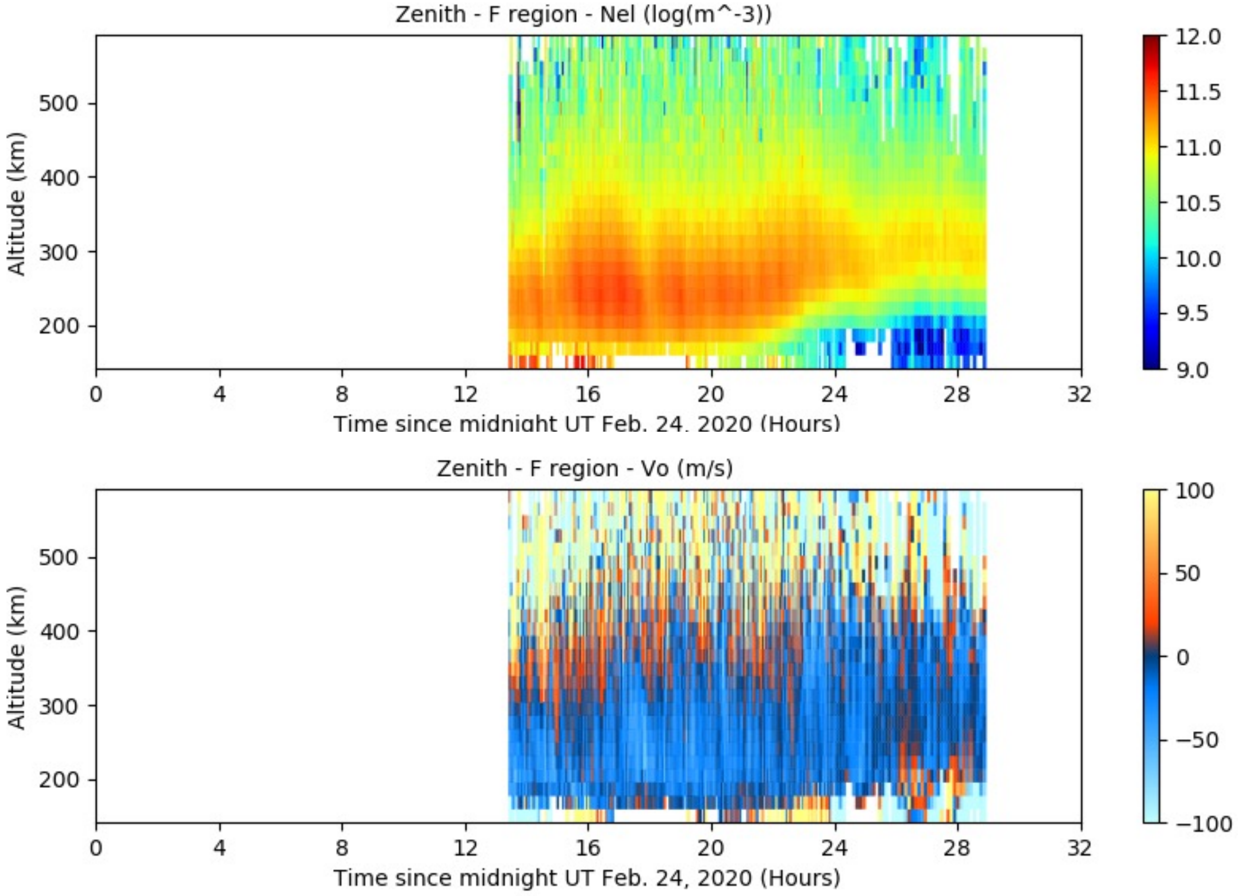
Harvey et al., 2023

Millstone Hill ISR: large Ne differences for weak & strong polar vortex

Weak vortex: Feb 21, 2018; F107=68; Ap=2



Strong vortex: Feb 24, 2020; F107=70; Ap=4



My vision

- **In N years (N ~30?) from now, we will look at the weather forecast on the ground and in the stratosphere to predict what happens in near-Earth space**
- **We will link stratospheric predictability to multi-day space weather forecast**
  - Geomagnetically quiet conditions (Kp < 4+) occur ~95% of the time
- **Scientific challenges emphasize needs for investments in research infrastructure: we need to keep developing observational networks**
  - We need continuous, high-quality and high spatial resolution observations of mesospheric, thermospheric and ionospheric parameters
  - Critical for the robust identification of essential features and understanding physical mechanisms
  - Future community observational systems:
    - Major missions for global coverage (USA - NASA GDC, DYNAMIC; Europe - Daedalus?)
    - **Networks of ground-based systems (ISR radars, GNSS receivers, MLT radars, HF systems,, FPIs, lidars, ASI, other) – most promising and attainable**

Multi-day stratospheric forecast (8-16 days)
\+ delay in ionospheric response (3-6 days)
= path to multi-day ionospheric forecast

So, what does it take to change a research paradigm?

- **A novel idea**
- Robust observational evidence: multiple techniques and cases
- Patience, persistence, resilience:
  - Multiple presentations at different meetings
  - Being prepared for rejections
  - First papers rejected
  - First proposals rejected
- A network of support (your own group, USA colleagues, international colleagues)
- Steady financial support
- Lots of luck (SSW of 2009 – deep solar min + largest SSW)

… and yet another impact of sudden stratospheric warming ☺…

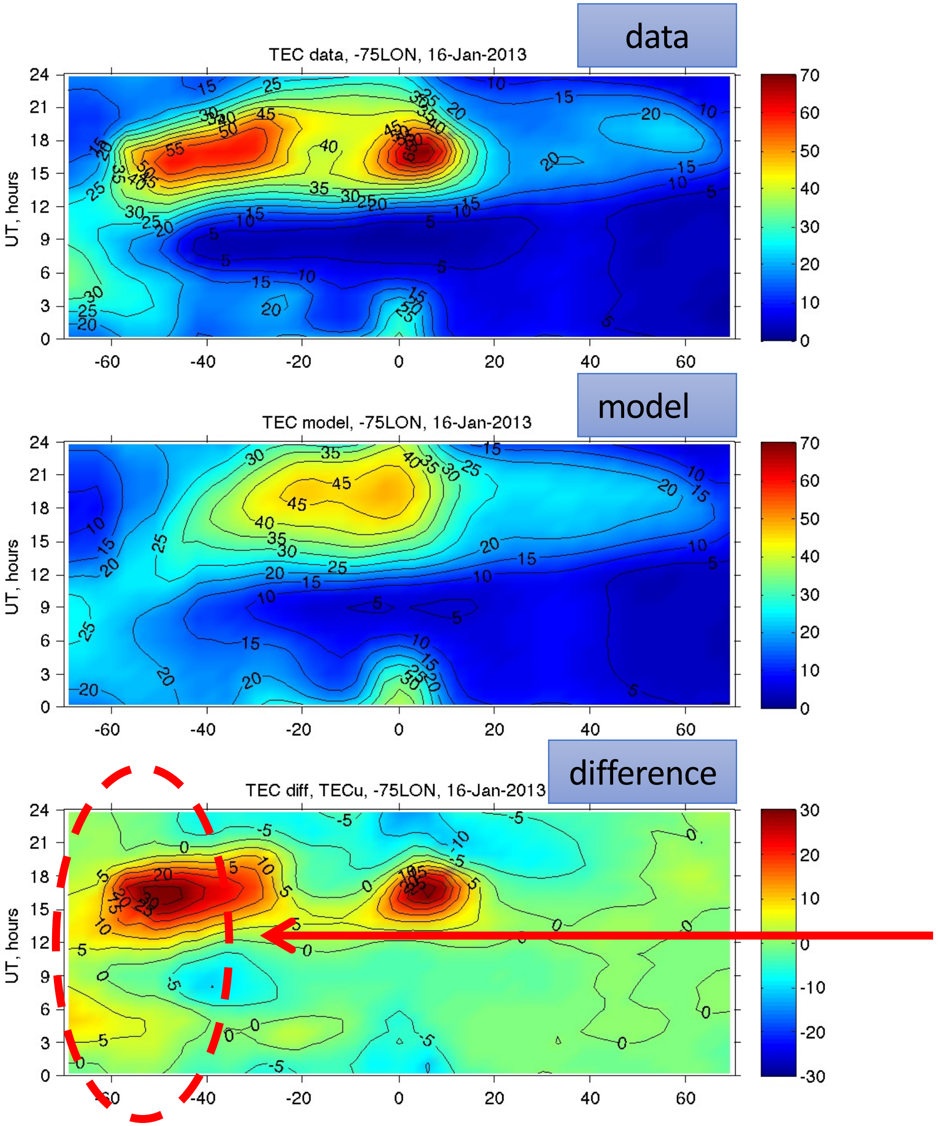
Thank you for your attention!

Extra slides

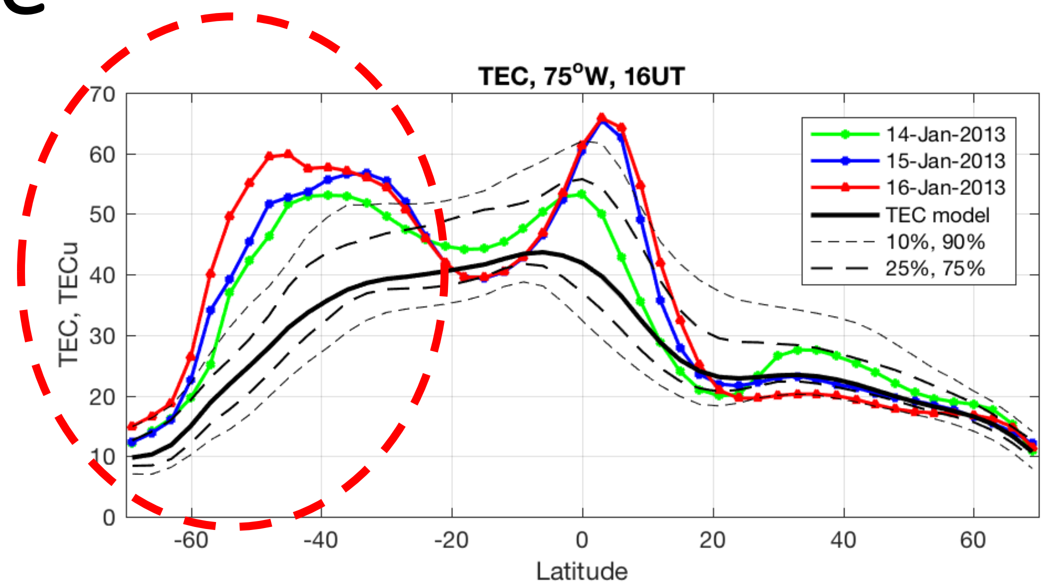
Pole-to-pole, stratosphere to ionosphere connections

Goncharenko LP, Harvey VL, Randall CE, Coster AJ, Zhang S-R, Zalizovski A, Galkin I and Spraggs M (2022) Observations of Pole-to-Pole, Stratosphere-to-Ionosphere Connection. *Front. Astron. Space Sci*. 8:768629. doi: 10.3389/fspas.2021.768629

Effects of Arctic SSW at middle and high latitudes of the Southern Hemisphere



Goncharenko et al., 2022

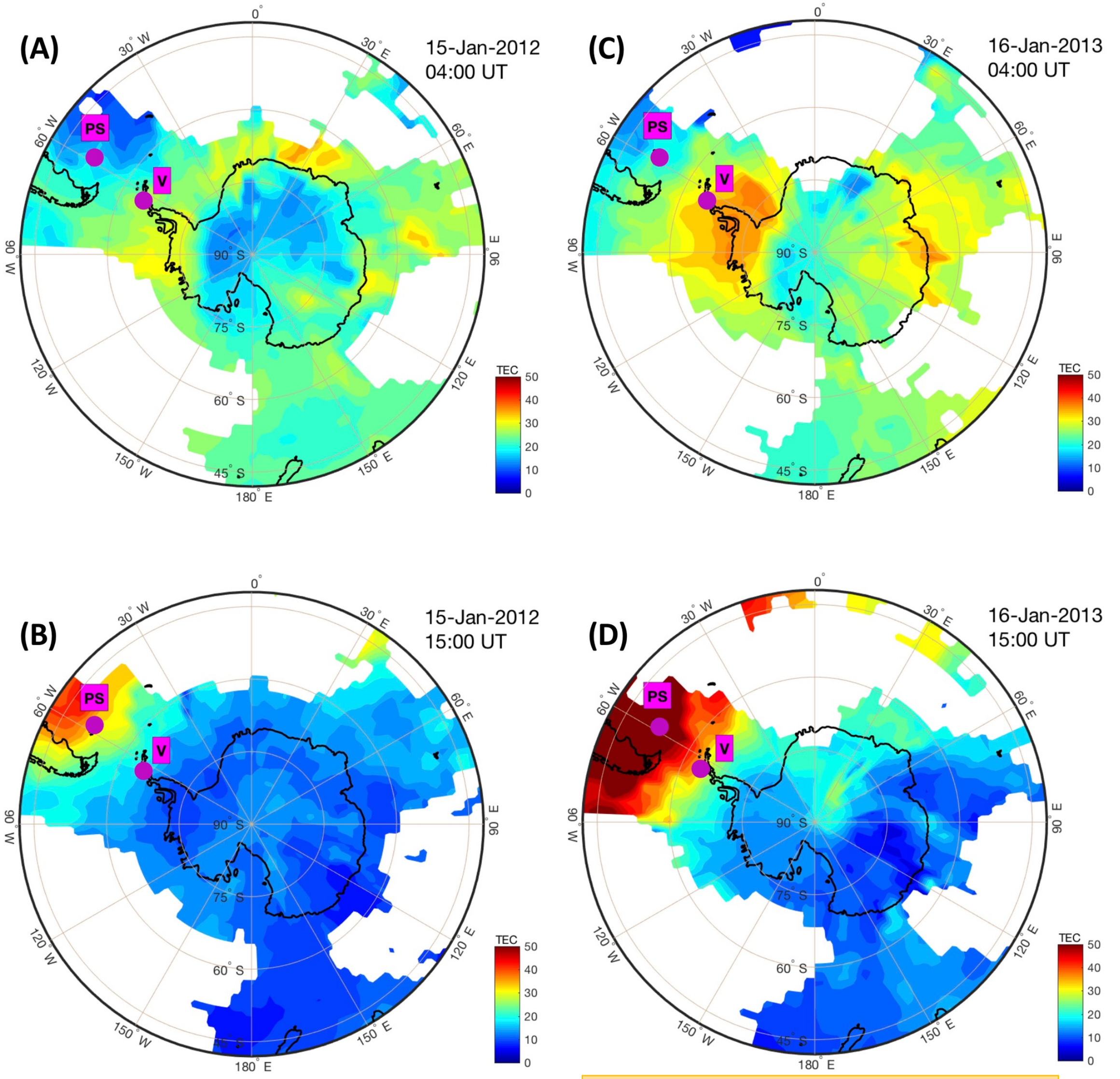


- Case study of Jan 2013 SSW
- Large positive TEC anomaly appears at 40-70°S
- Extends to high latitudes in the Southern Hemisphere and modifies Weddell Sea anomaly
- TEC model for 75°W is developed from 15+ years of TEC data (*Goncharenko et al.*, 2018)

TEC over Antarctica during SSW 2013

4 UT

15 UT



TEC control day
Jan 15, 2012
F10.7=133, Ap=4

TEC During SSW
Jan 16, 2013
F10.7=137, Ap=5

- Increase in TEC during SSW in the morning to afternoon sector and around local midnight
- Magenta dots indicate locations of ionosondes
- Increase in daytime NmF2 by a factor of ~2 at 51°S, Port Stanley and 65°S, Vernadsky

Goncharenko et al., 2022

Summary of interhemispheric study

- Main features of Arctic SSW of Jan 2013 over Antarctica (Goncharenko et al., 2022):
  - Persistent mesospheric and ionospheric anomalies over Antarctica
  - Consistent features in TEC and ionosonde observations
  - Increase in TEC & NmF2 by a factor of ~2
- Arctic SSW can create truly global disturbances that reach across the globe to high altitudes above Antarctica

We suggest that the concept of interhemispheric coupling should be extended to the thermosphere and ionosphere