# Spatial and temporal extent of ionospheric anomalies during sudden stratospheric warmings in the daytime ionosphere

Larisa Goncharenko, Shunrong Zhang, Anthea Coster, Leonid Benkevitch,
*Massachusetts Institute of Technology, MIT Haystack Observatory*
Ivan Galkin, Bodo Reinisch,
*Lowell Digisonde International,Univ Massachusetts Lowell*
*Nestor Aponte, SRI International,*
*Mary Spraggs, Western Kentucky University*

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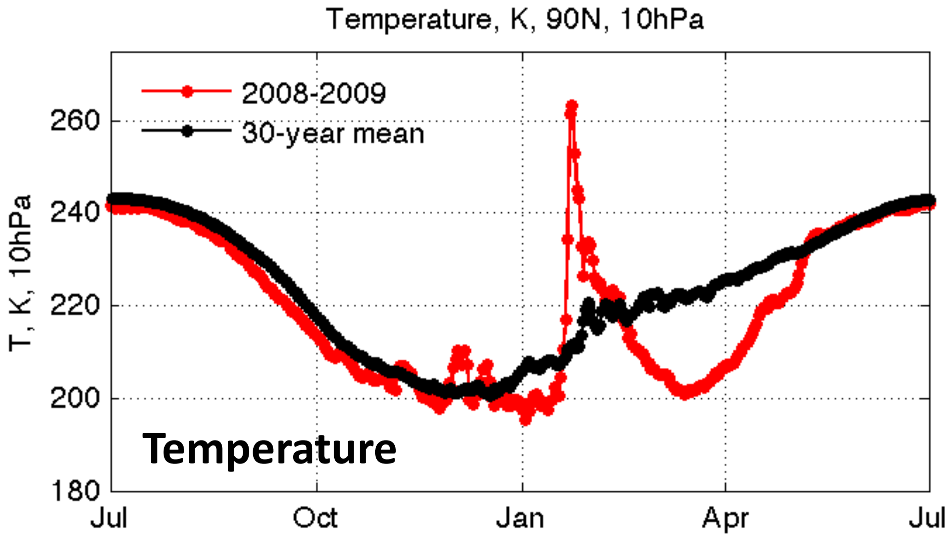
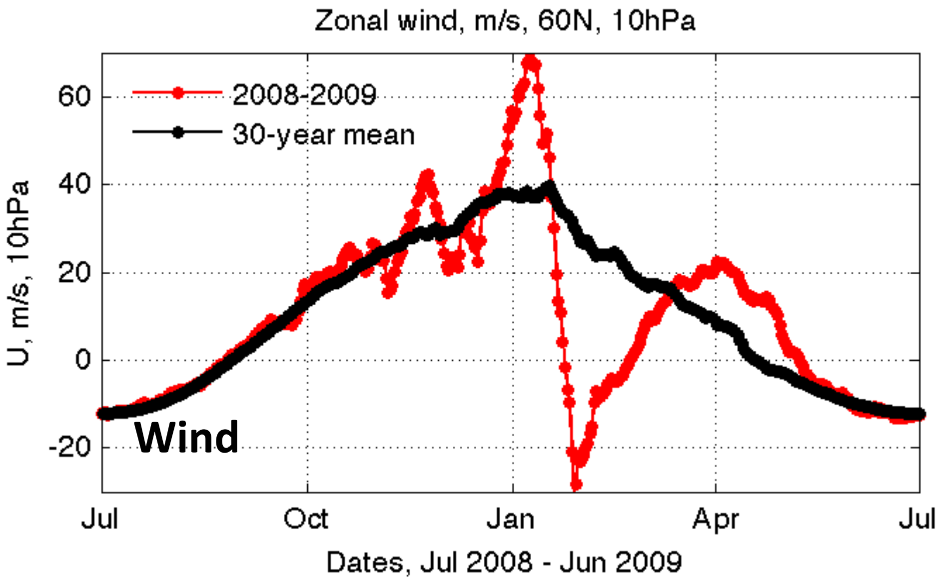
# Outline

- Background
  - What is sudden stratospheric warming (SSW)?
    - Anomaly in the polar stratosphere (~30km)
  - Why do we care about it?
  - What is known about SSW effects in the ionosphere?
- Motivation for this study
  - What is not known and not known?
- Results of this study - ionospheric anomalies at:
  - Magnetic equator
  - EIA crest
  - Tropical latitudes
  - Mid-latitudes
  - High-latitudes, Southern Hemisphere
- Conclusions and implications

# Background
# 1. Sudden stratospheric warming – what is it?




- Largest known meteorological disturbance
- Rapid increase in temperature in the high-latitude stratosphere (25K+); from winter-time to summer-time
- Accompanied by a change in the zonal mean wind
- **Anomalies last for a long time in the stratosphere (2 weeks +)**

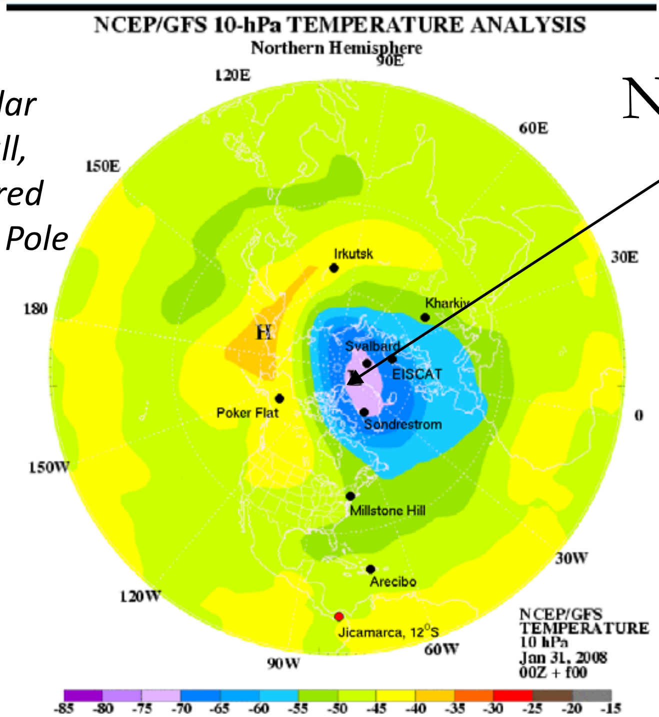


# Background

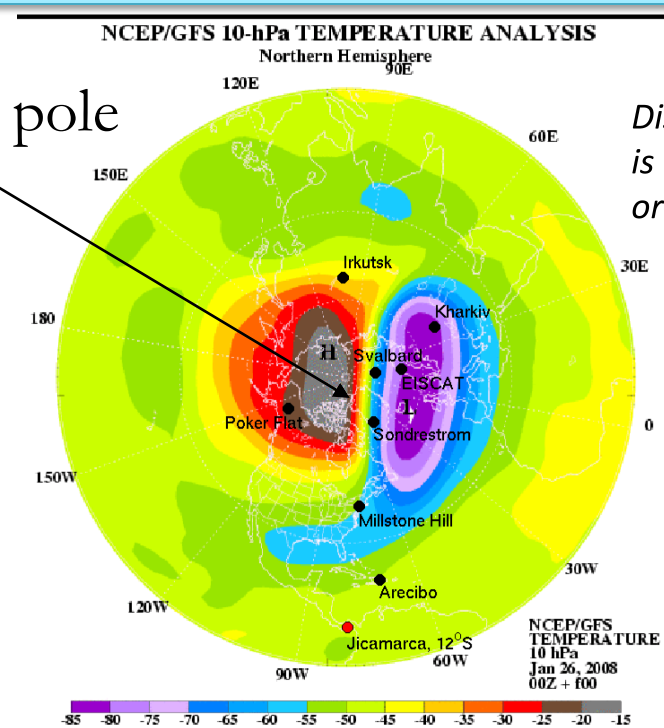
# 2. Change in the polar vortex

| Before warming | During warming |
| --- | --- |

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




North pole

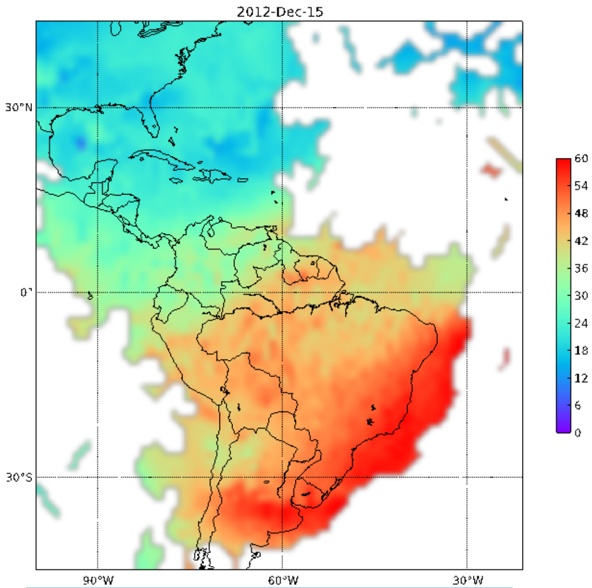



*Disturbed vortex is broken into 2 or more cells*

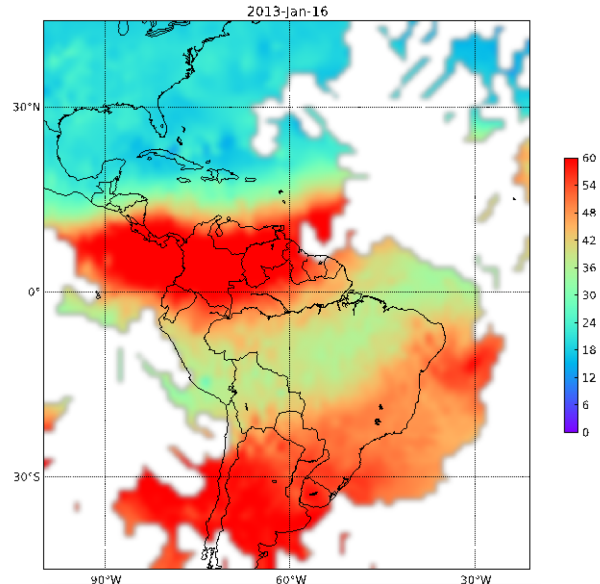
- Stratospheric sudden warming is a large-scale dramatic coupling event in the **winter** polar atmosphere
- Results from interaction of planetary waves with zonal mean flow
- Largest planetary waves recorded in nature
- Involves changes in temperature, wind, gravity wave activity

# Background

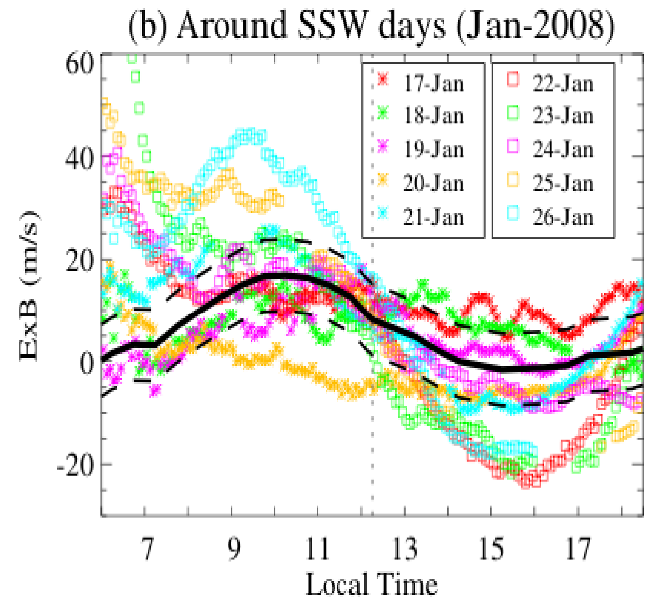
# 3. Why are we interested in SSW?




TEC Before SSW




TEC During SSW



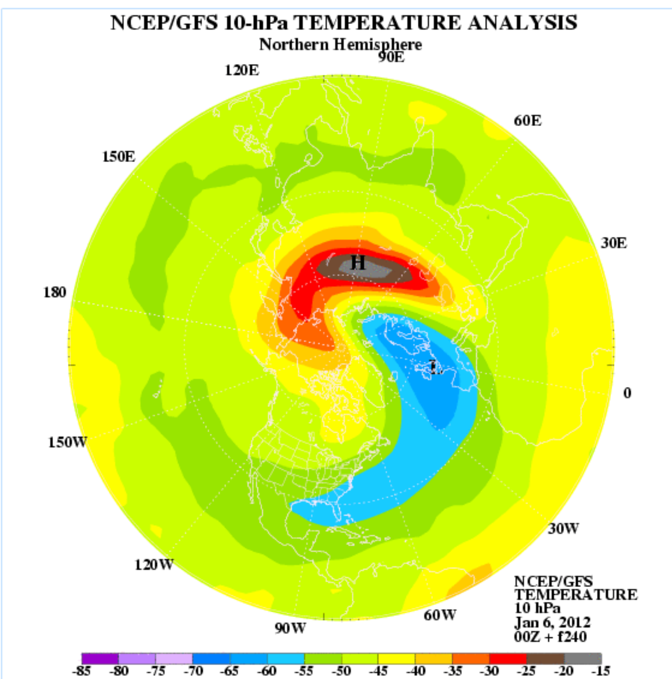

**SSW drives super-fountain in the low latitude ionosphere**

- **Strong experimental evidence of dramatic ionospheric variations during SSW (~100%) in the low-latitude ionosphere (Chau et al., 2012)**
- Multiple mechanisms connecting lower and upper atmosphere
- SSW events are long-lasting ( > 2 weeks), cover large geographic area (> 1000km), and occur 1-3 times per winter
  - existing observational networks can be successfully used

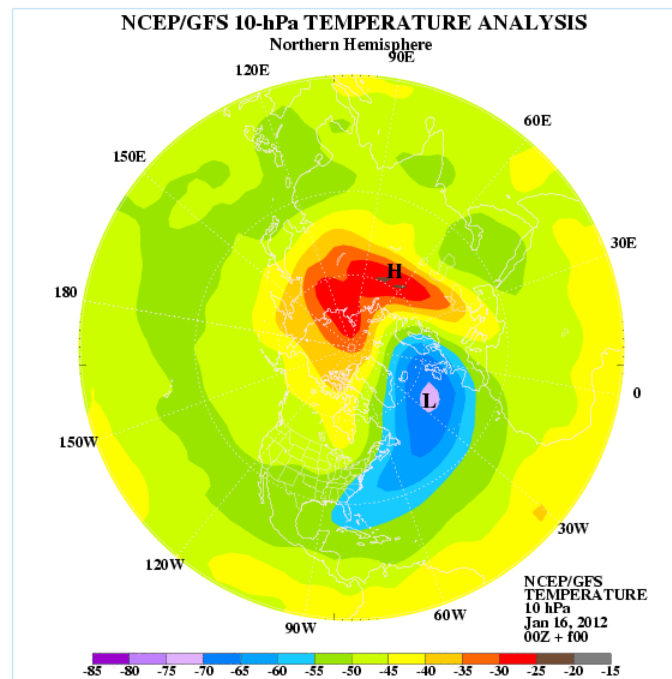
# Background
# 4. Implications for ionospheric research

- **Highlights importance of lower atmospheric drivers in ionospheric variability**
  - Need solar EUV + geomagnetic drivers + meteorological forcing
- **Provides direct pathway to multi-day ionospheric forecast**
  - Stratospheric parameters can be predicted 8-10 days in advance

10-day forecast




observations



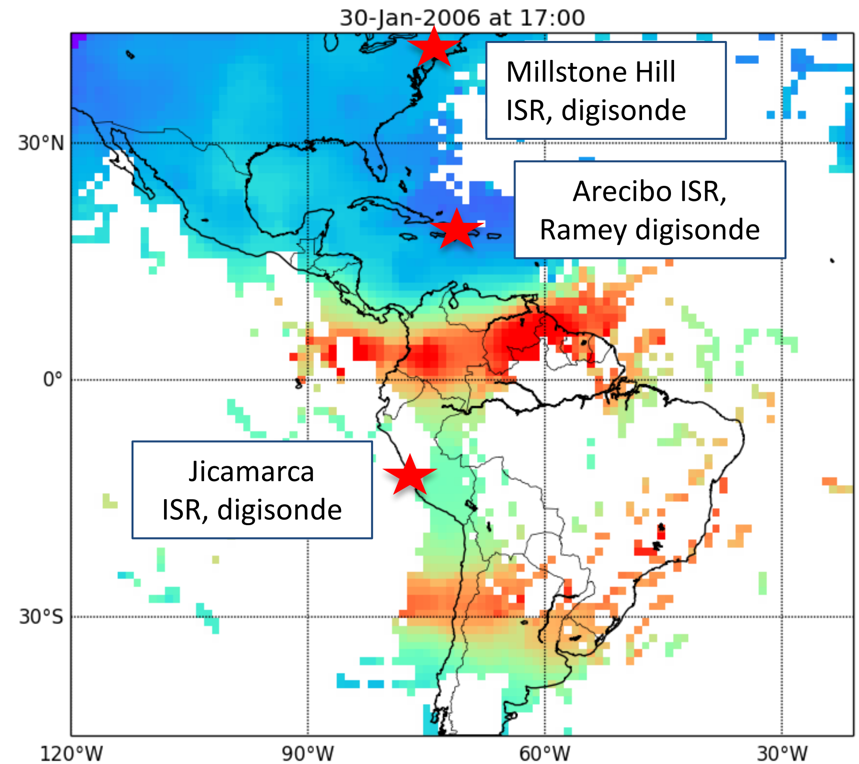
# Objective of study

- Motivation
  - Dramatic ionospheric disturbances associated with SSW reported at low latitudes
    - Mostly limited to case studies
  - Several mechanisms suggested:
    - Amplification of solar migrating semidiurnal tide (SW2)
    - Amplification of solar non-migrating semidiurnal tide (SW1)
    - Amplification of lunar semidiurnal tide
    - Change in middle atmosphere dynamics
    - Anomalies in stratospheric ozone
    - Change in composition due to tidal dissipation
    - Wind dynamo due to high-latitude heating
- Objective:
  - To provide comprehensive, rigorous examination of ionospheric experimental data to isolate ionospheric anomalies associated with SSW
  - To extend studies to higher latitudes

**This study identifies several types of ionospheric anomalies in connection with SSW**

# Data used

- GPS TEC – 2000-2014, American sector, 75$^o$W
- Digisondes:
  - Jicamarca, 1993-2014
  - Ramey, 1999-2014 (without 2008-2010)
  - Millstone Hill, 1997-2014
- Incoherent scatter radars:
  - Aresibo ISR, Jan 2013
  - Millstone Hill ISR, Jan 2013
- Nov 1 – Mar 31 data (150 days)




Leveraging multiple observational techniques:

- GPS TEC – continuous coverage in latitude
- Ionosondes/digisondes – long historic records
- IS radars – multiple ionospheric parameters in a large altitude range

# How do we separate SSW effects?

- Model terms:

$$TEC_m = TEC_o +$$

$$b_1 PF107 + b_2 PF107^2 +$$

solar activity

$$b_3 Ap_3 + b_4 Ap_3^2 + b_5 Ap_{3-3} + b_6 Ap_{3-6} + b_7 Ap_{3-9} +$$

geomagnetic activity

$$b_8 \sin(2\pi DOY/365) + b_9 \cos(2\pi DOY/365) +$$
$$b_{10} \sin(4\pi DOY/365) + b_{11} \cos(4\pi DOY/365) +$$

season

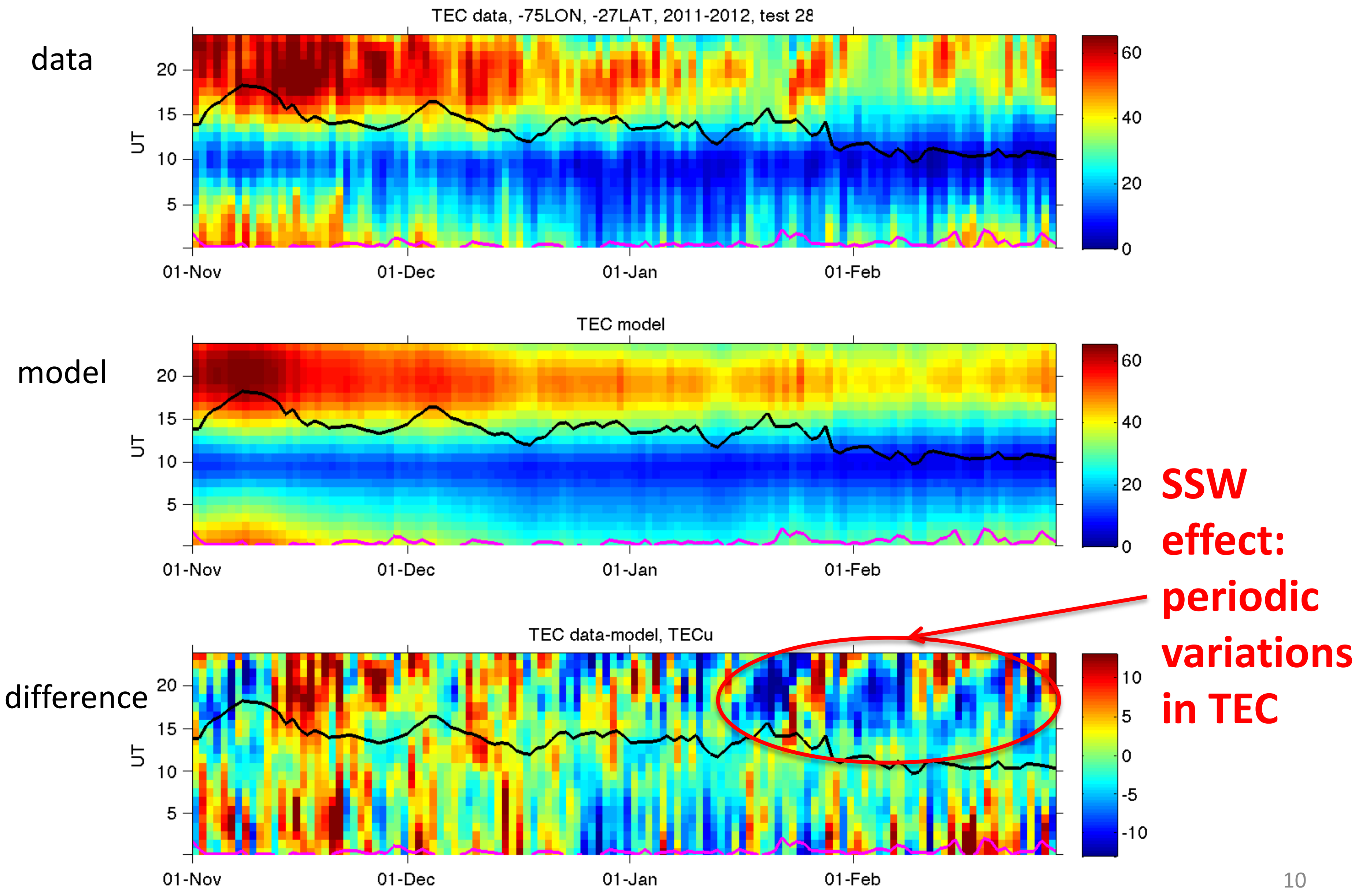
$$b_{12} PF107 \sin(2\pi DOY/365) +$$
$$b_{13} PF107 \cos(2\pi DOY/365)$$

F10.7 & season cross-terms

- $PF107 = (F10.7 + F10.7_{81ave})/2$
- Fit to the data for every latitude; 3 deg. resolution
- Fit to the data for every UT bin

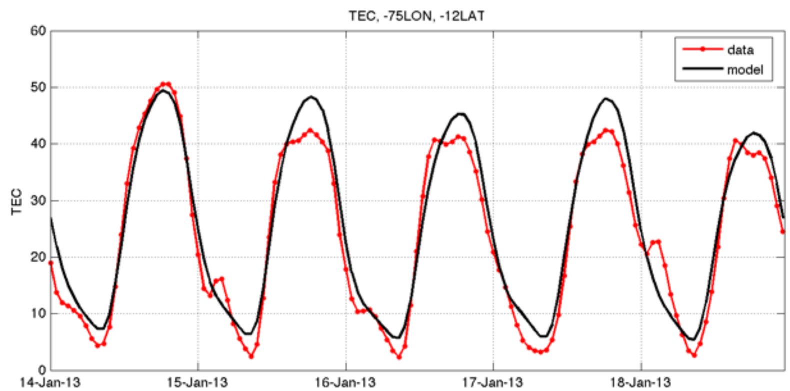
**We develop empirical models to describe background**

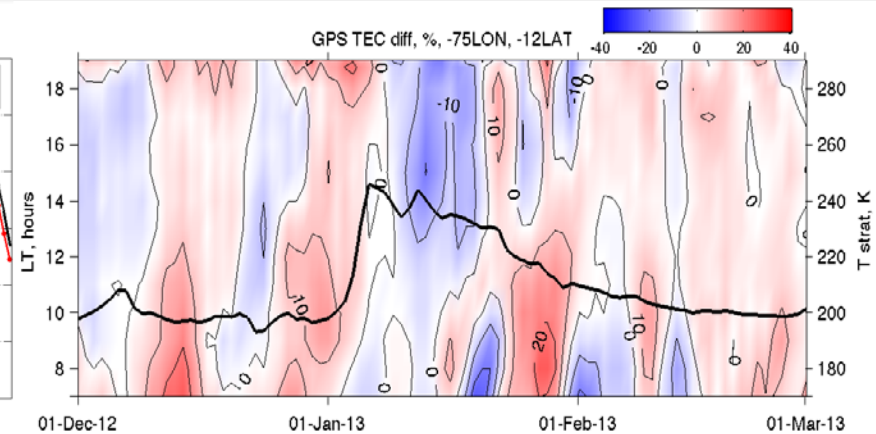
# Defining anomalies



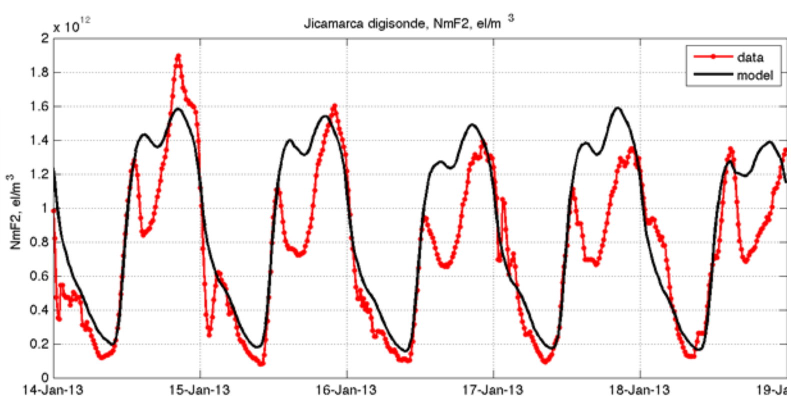
# Comparison of GPS TEC and digisonde NmF2, Jicamarca

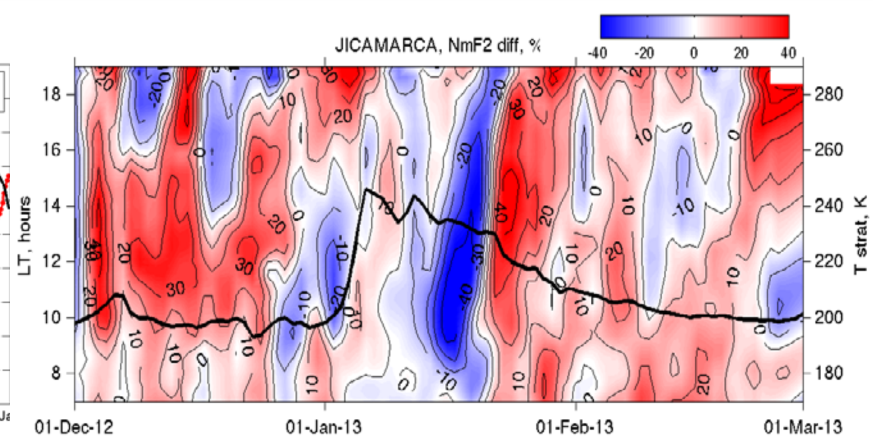
**GPS TEC**



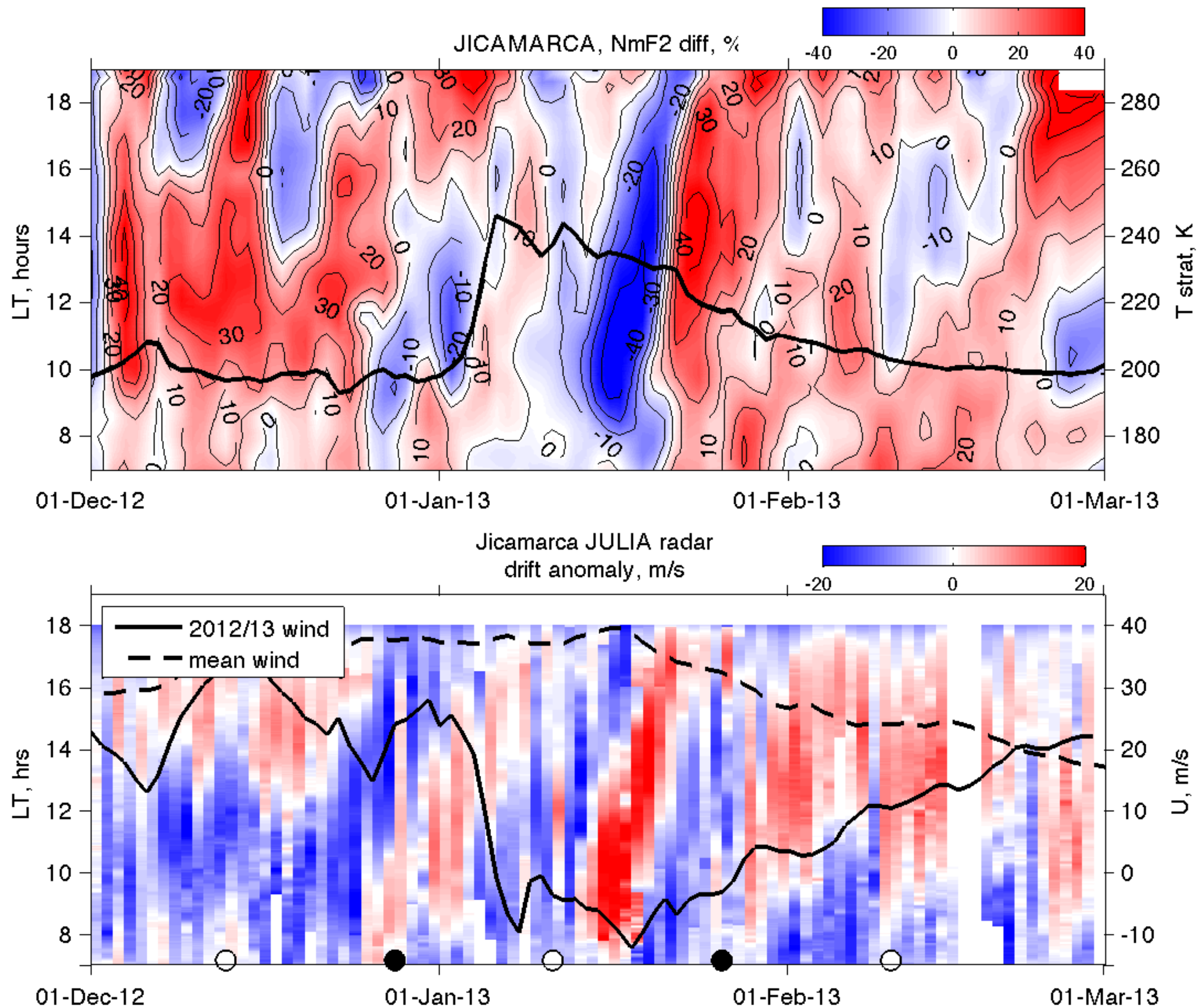

**Jicam. Digis.**



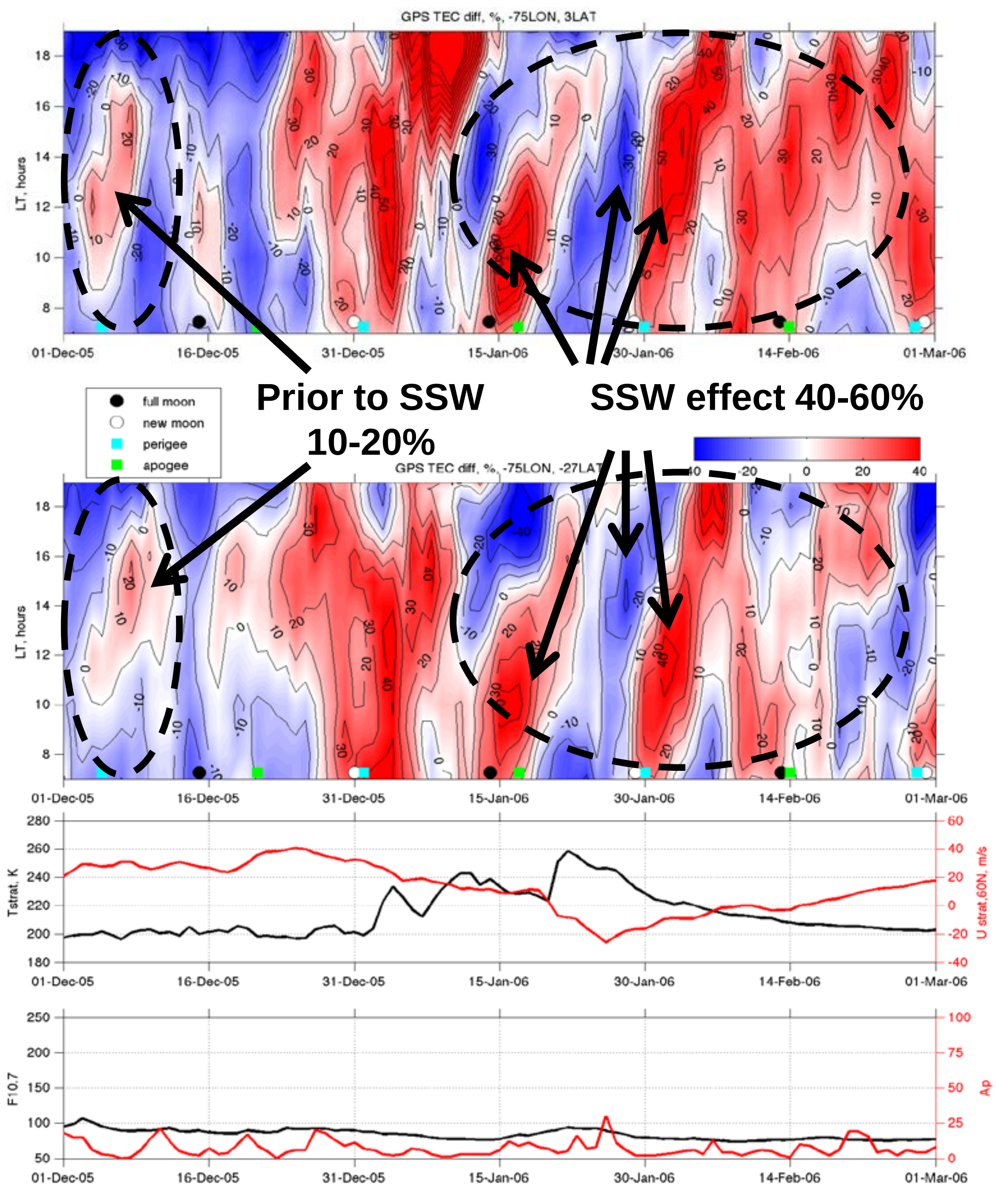




- **SSW-associated variations are stronger in NmF2 than in TEC**
- Data/model comparison is easier for NmF2
- Suggests complex electron density profile change

# NmF2 and vertical drift change at magnetic equator (Jicamarca)



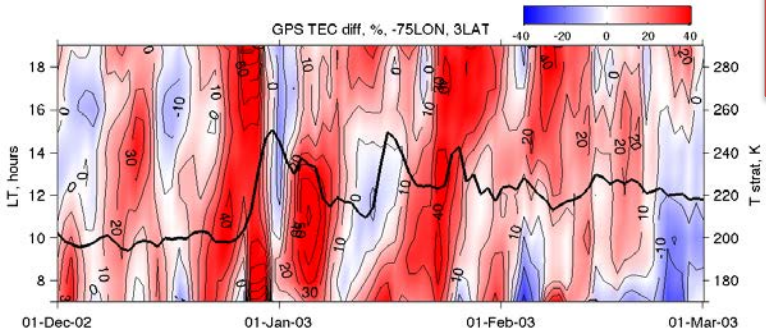
# EIA crests: Variety of anomalies in TEC

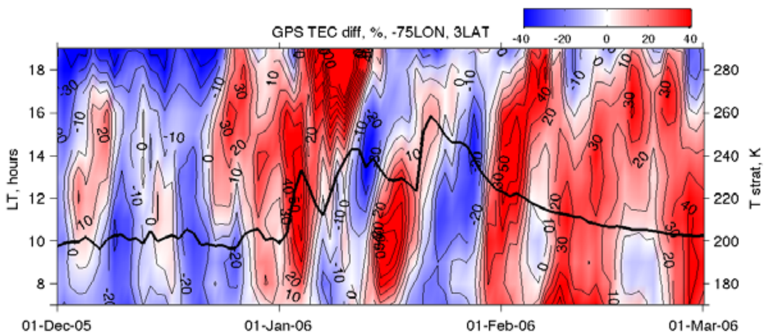


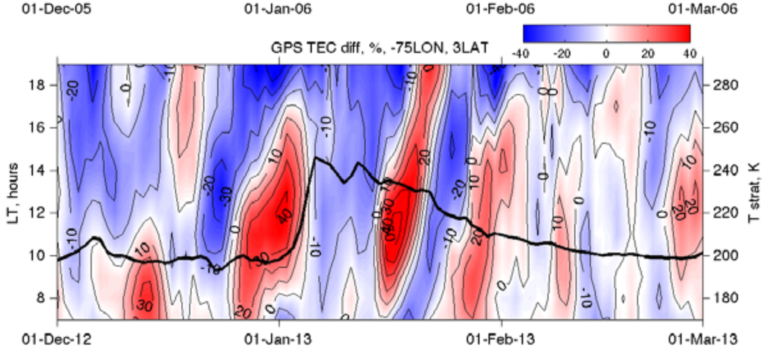

- Periodic enhancements in the EIA crests reach 40-60% during SSW event and last for over a month (~Jan 10 - Feb 20, 2006).
- Strongest positive variations are observed 2-4 days after the new or full moon.
- Similar but weaker variations within 10-20% of the background level are observed without SSW – lunar tide?
- The phase of variations during SSW is shifted to earlier local times.
- Multi-day increase in TEC in End of Dec-Jan

# Can we see TEC perturbations during every SSW?

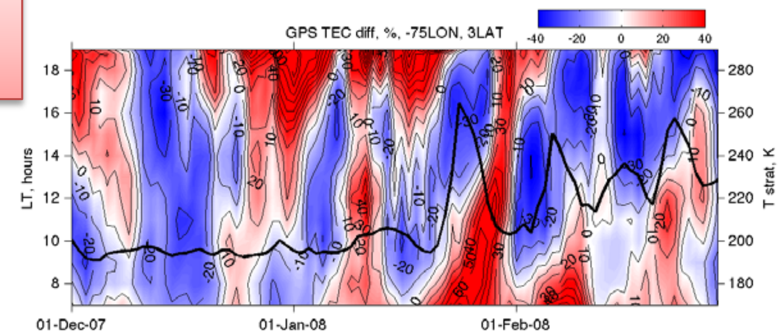
GPS TEC, 3°N

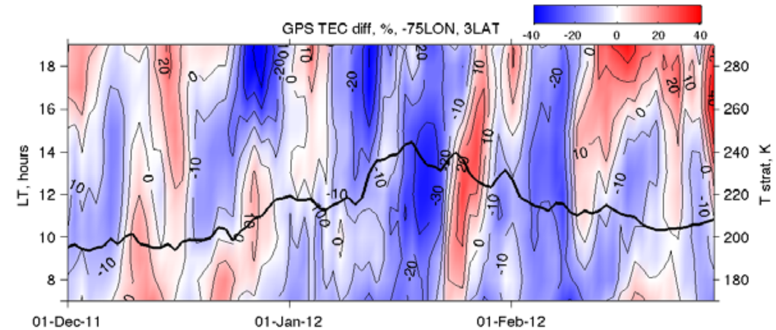


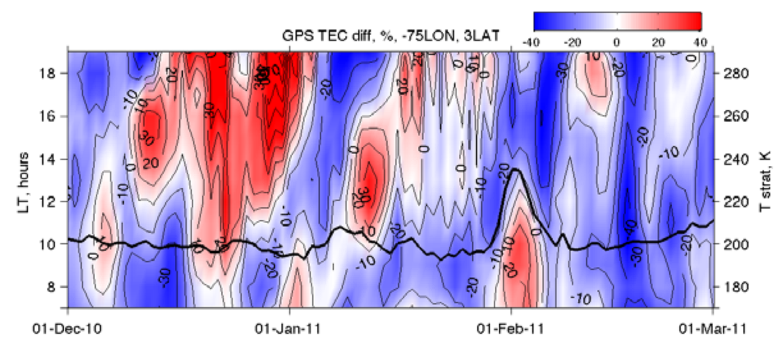




Major SSWs: 50-100% peak-to-peak



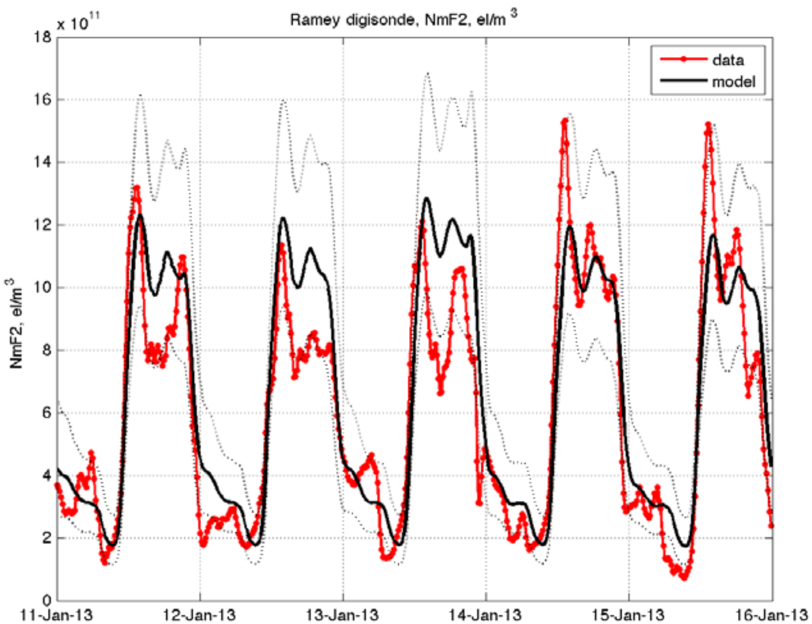



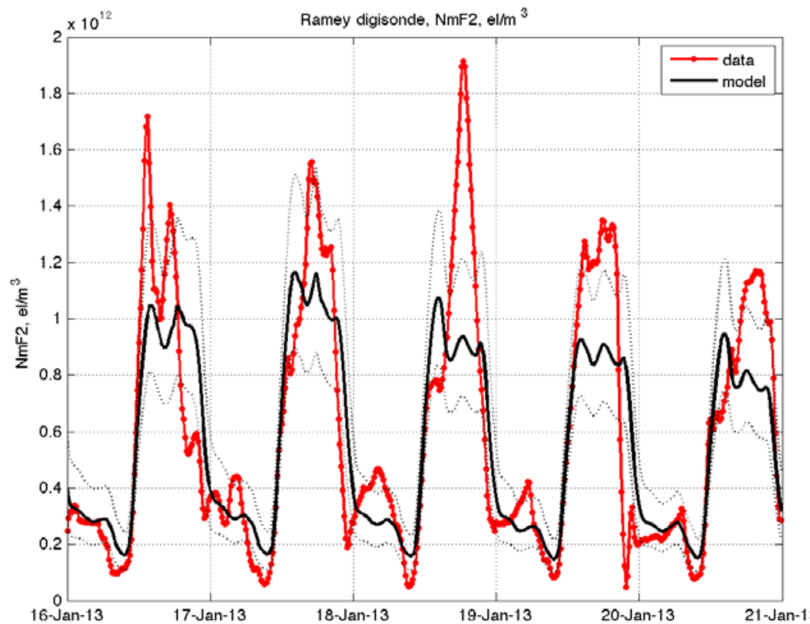



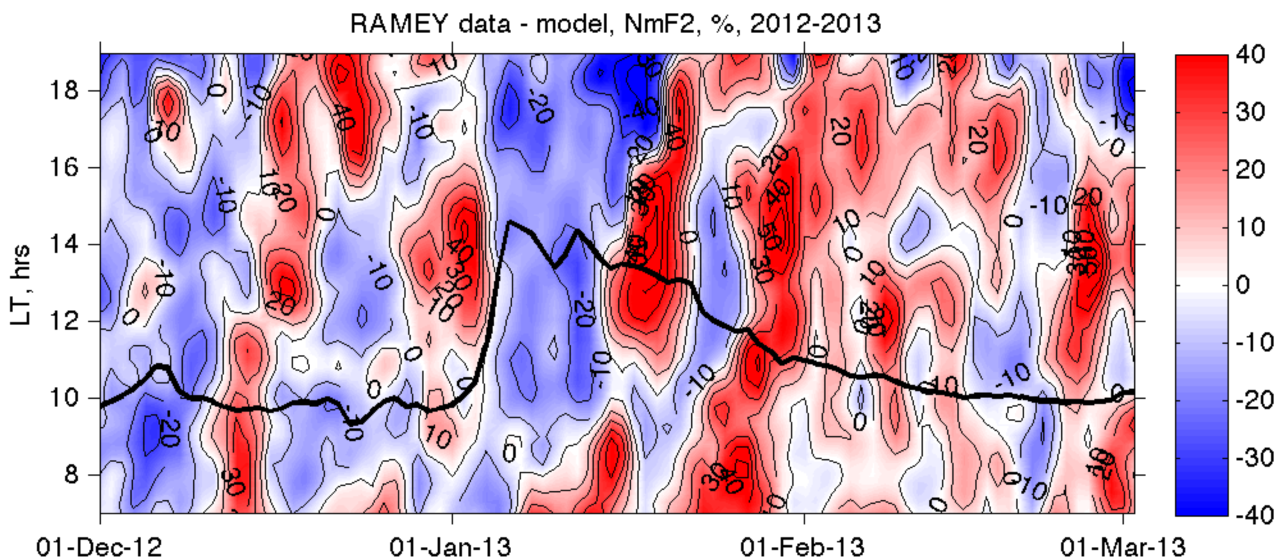

Minor SSWs: 30-60% peak-to-peak

**Yes. They are observed every winter**

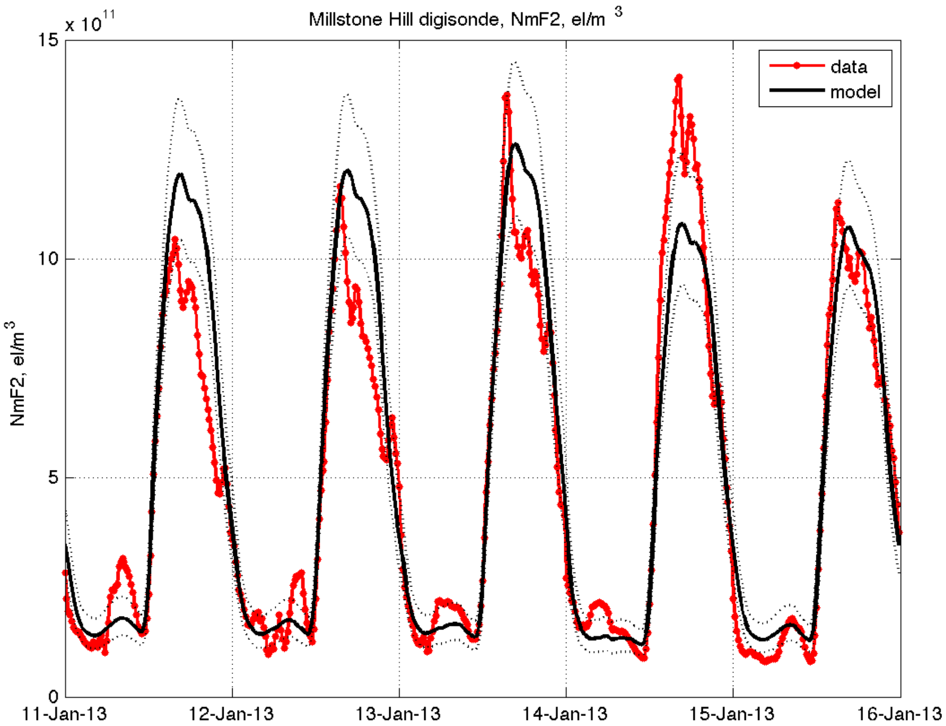
# Poleward of EIA: Ramey digisonde, 18°N

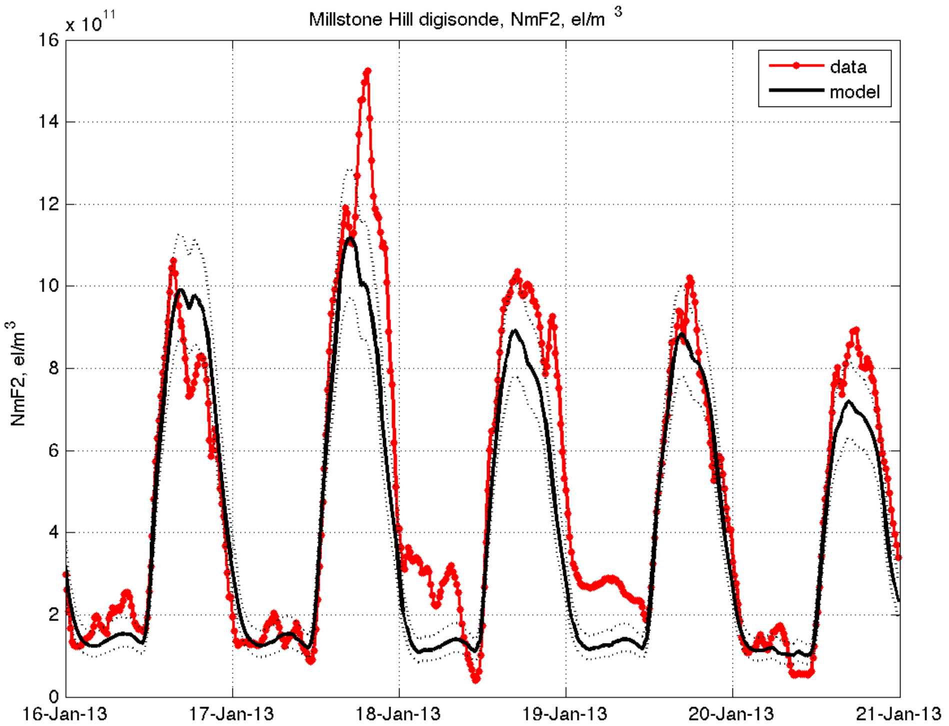


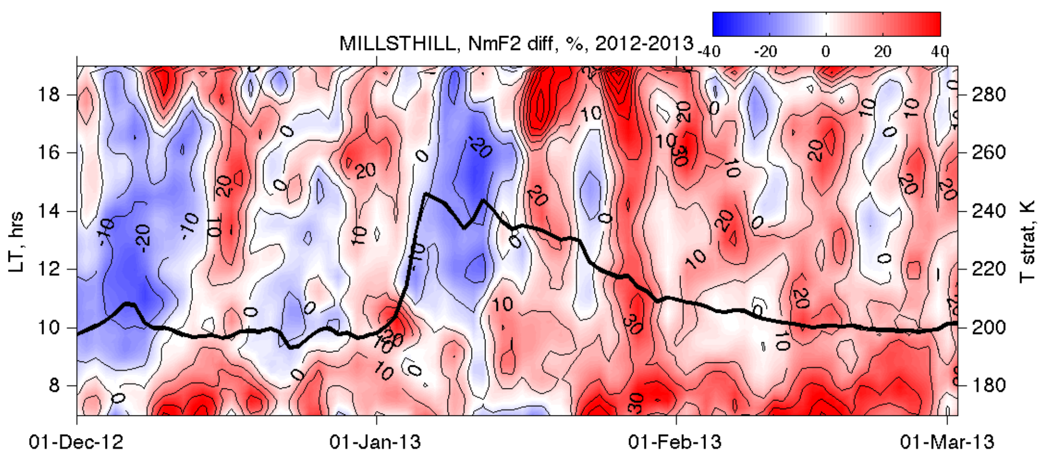



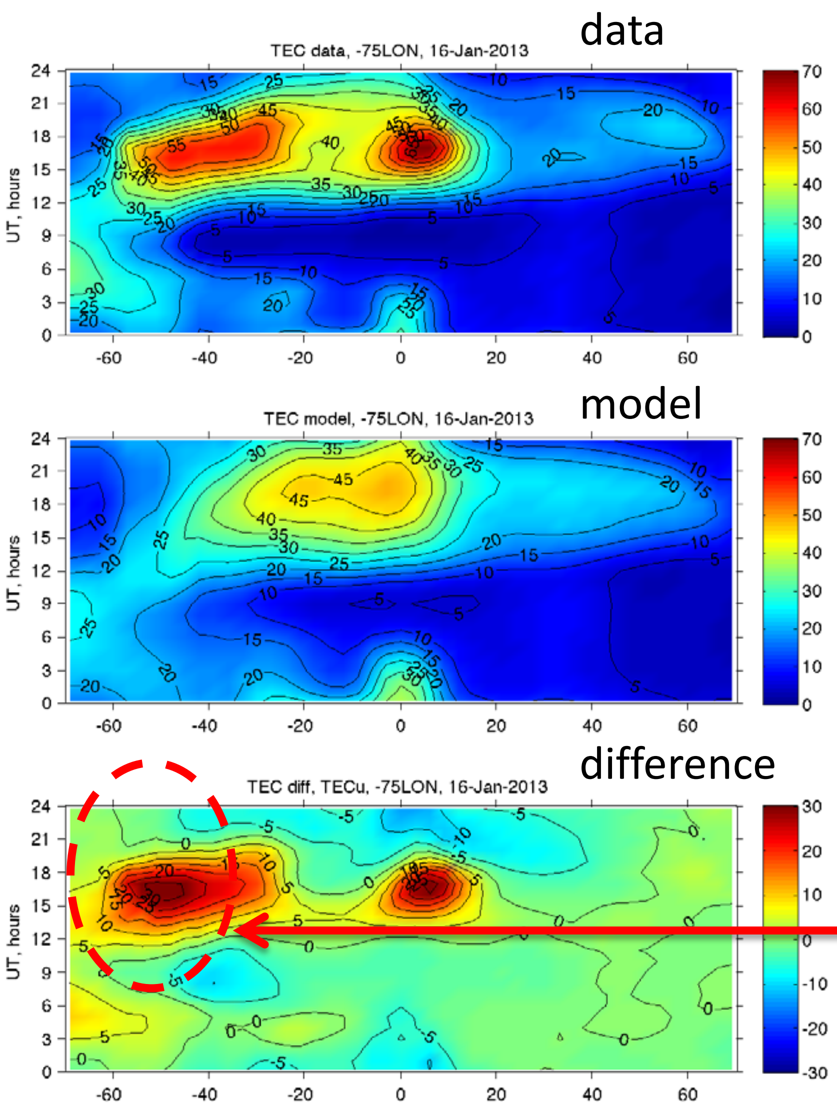
# Middle latitudes: Millstone Hill digisonde, 42ºN

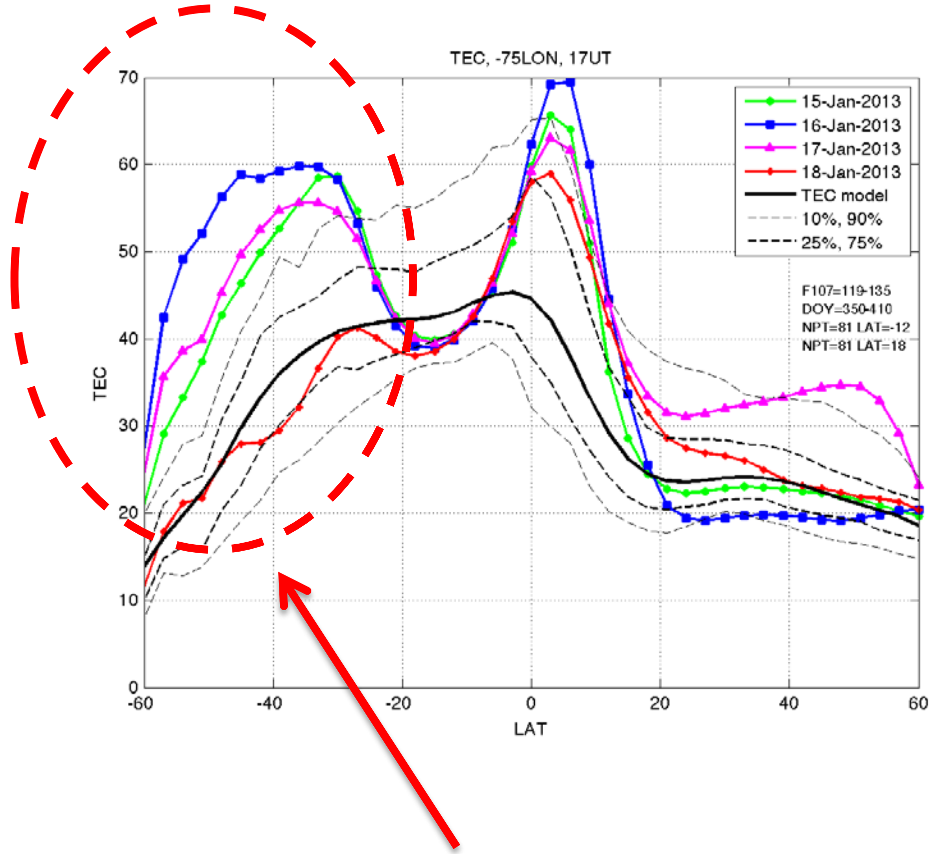


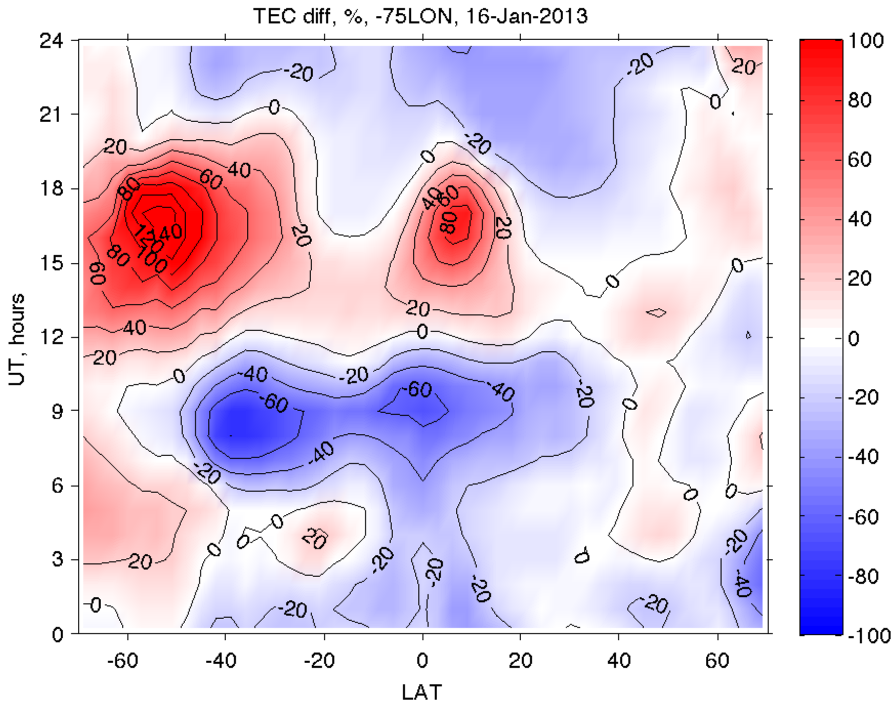



# Southern Hemisphere anomalies



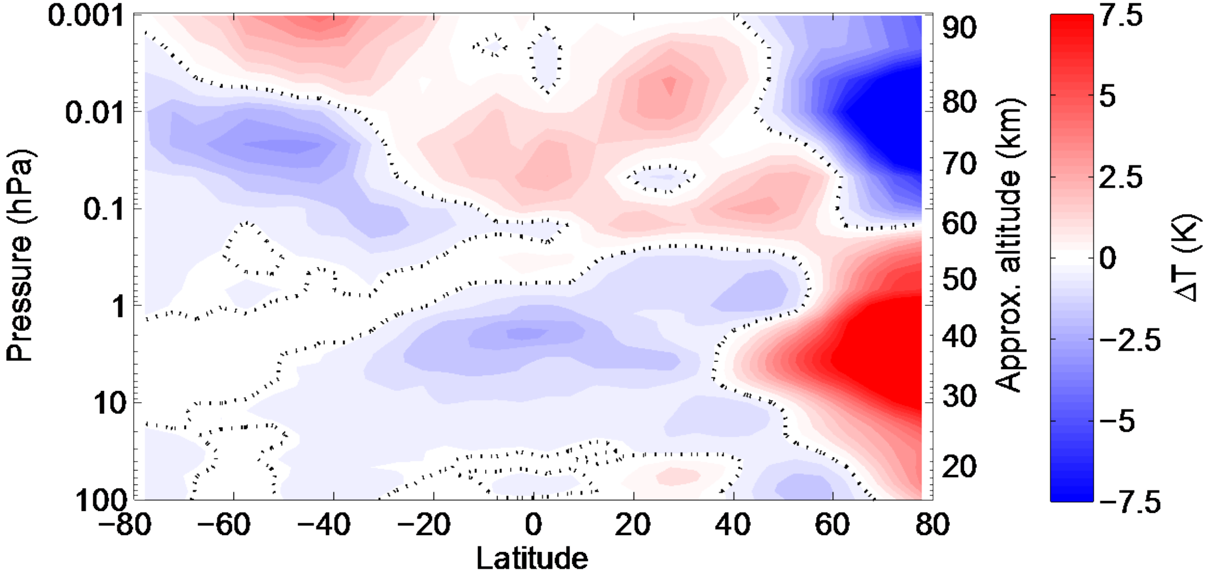




- Large positive TEC anomaly appears in the 40-60°S
- Not directly related to EIA




Ionospheric anomaly in TEC, 60-140 %, Jan 16, 2013
Modifies Weddel Sea anomaly

Are these anomalies connected?
Mechanisms of interhemispheric coupling?




Stratospheric and mesospheric anomaly in temperature
10 day ave, Jan 2013, Aura MLS data
*de Wit et al., GRL 2015*

# Summary

- We used multi-year observations from different techniques to identify variety of ionospheric anomalies due to meteorological processes (SSW)
- We identify periodic ionospheric perturbations in daytime TEC, NmF2 and vertical drift data:
  - **How often**: **every winter** during major and minor SSW;
  - **For how long**: for **1 month or longer**
  - **How large**: At low latitudes ~50-100% peak-to-peak amplitudes during major SSW and ~30-60% during minor SSW
  - **Where**: This type of ionospheric disturbance **extends at least to mid-latitude in the Northern Hemisphere and Southern Hemisphere**
  - **Why**: Most likely drivers are variations in lunar and solar semidiurnal tides (amplitude and phase)
- We identify additional strong ionospheric disturbance (60-140%) in the mid and high-latitude Southern Hemisphere

Lower atmospheric forcing can be responsible for strong, long lasting ionospheric disturbances

These studies reveal stratosphere to ionosphere and pole-to-pole connections

Understanding coupling mechanisms responsible for these effects will pave the way for multi-day ionospheric forecast