Coupling of atmospheric regions from equatorial to middle latitudes

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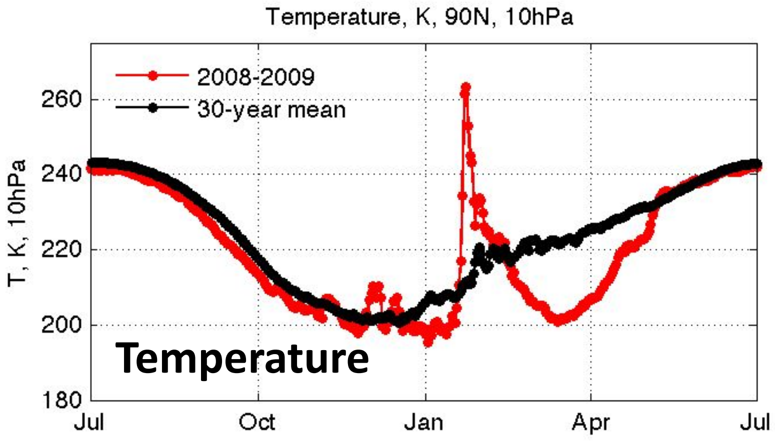
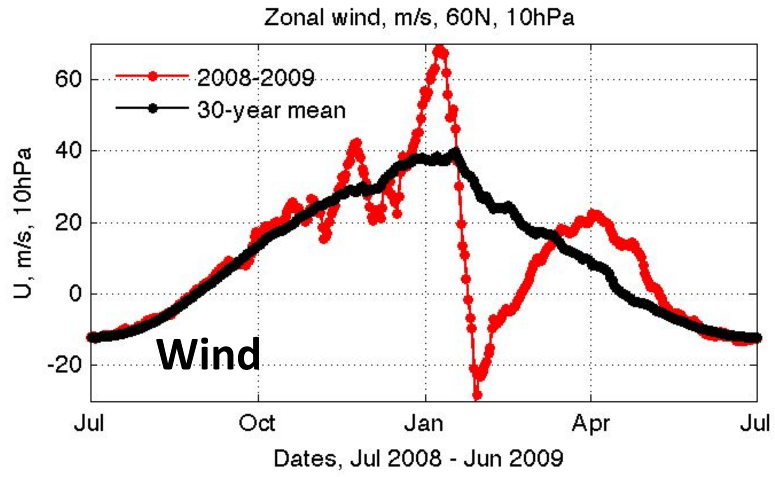
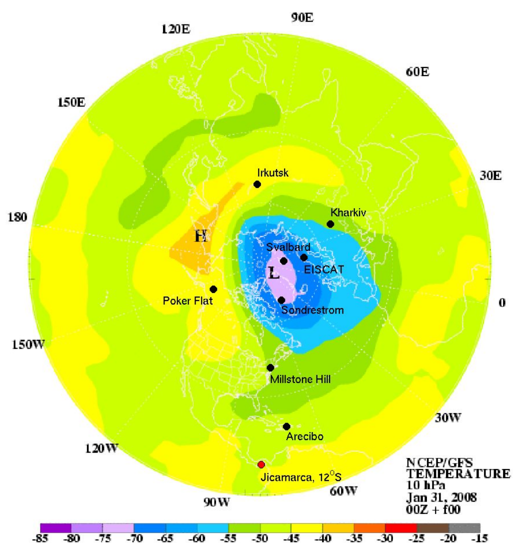
60th Anniversary Jicamarca Radio Observatory Workshop, July 24-27, 2022

Background: sudden stratospheric warming – what is it?



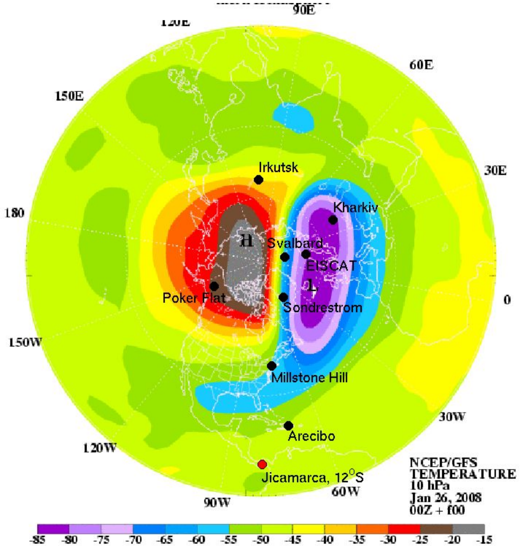


- Largest known meteorological disturbance in the **wintertime polar stratosphere**
- Rapid increase in temperature in the high-latitude stratosphere (25K+); from winter-time to summer-time
- Accompanied by a change in the zonal mean wind
- Driven by interaction of planetary waves with zonal mean wind
- **Anomalies last for a long time in the stratosphere (2 weeks +)**
- **Dedicated ISR campaigns since 2007**



Before warming

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

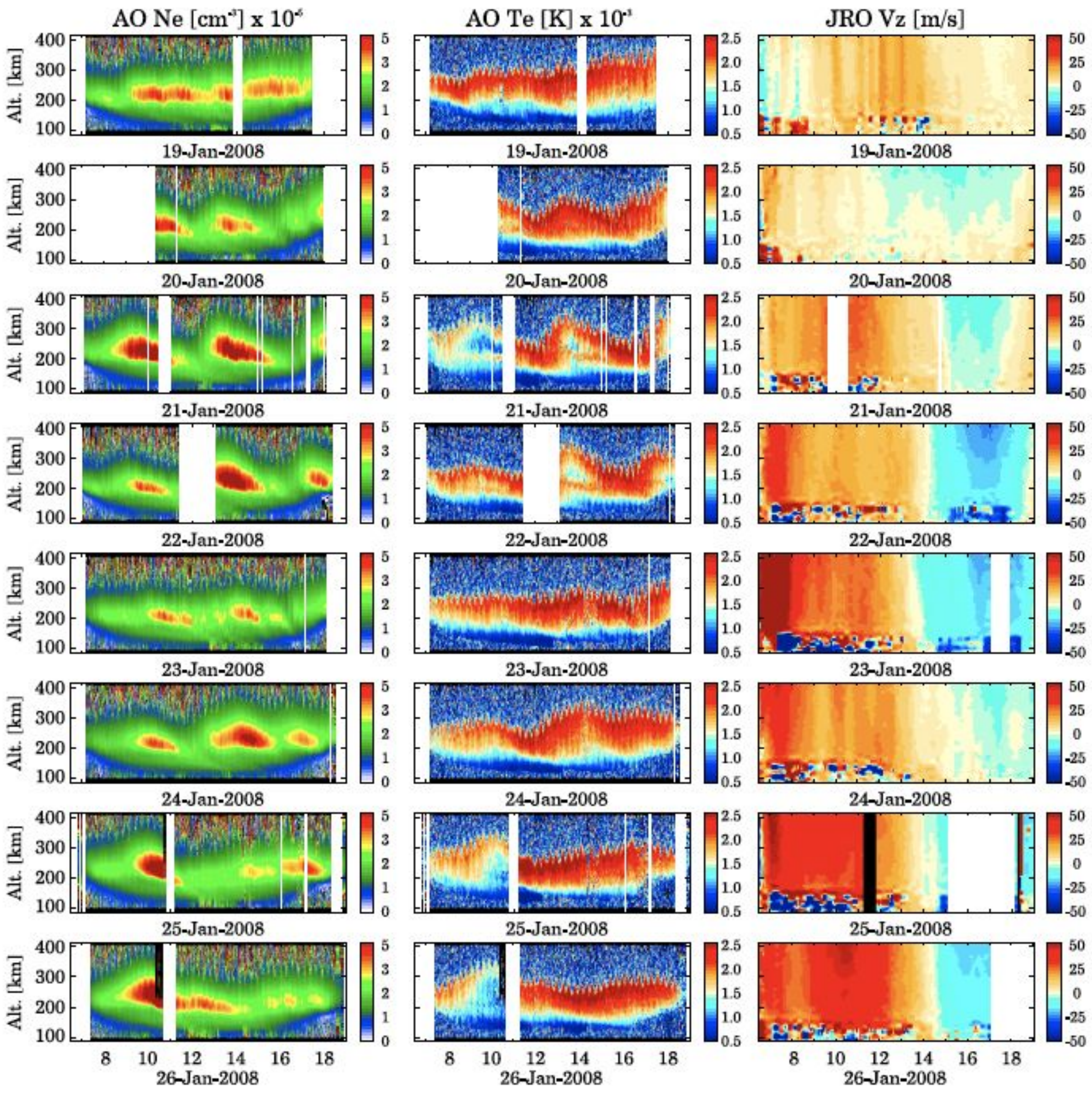


During warming

Disturbed vortex is broken into 2 or more cells

Major progress in studies of coupling between different atmospheric regions was achieved through studies of SSW effects

SSW effects in ionosphere – early years: 2007-2009

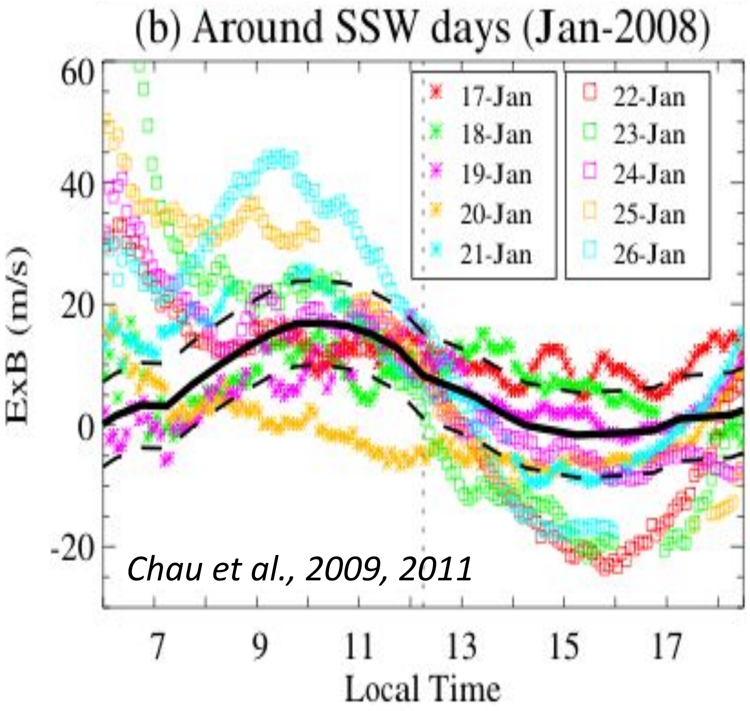


Chau et al., 2010

- Concept and plans since 2006
  - SSW effects in stratosphere – since 1960s
  - SSW effects in mesosphere – since 1970s
  - SSW effects in ionosphere – since 2008-2009
- First ISR World Day campaigns: 2007, 2008, 2009
  - Unexpected results: strong anomalies in Jicamarca vertical drift

- Jicamarca Observatory played a fundamental role in the discovery of SSW effects in ionosphere
  - Jicamarca instruments (ISR, JULIA, magnetometers, ionosonde)
  - Jicamarca people

SSW of 2008 and 2009: Jicamarca ISR and GPS TEC



- Upward drift in the morning, downward in the afternoon -12-h wave
- Interpreted as evidence of enhanced 12-tide & E-region dynamo

Entire daytime low to mid-latitude ionosphere is affected during stratwarming; Total Electron Content change 50-150%

15 UT mean

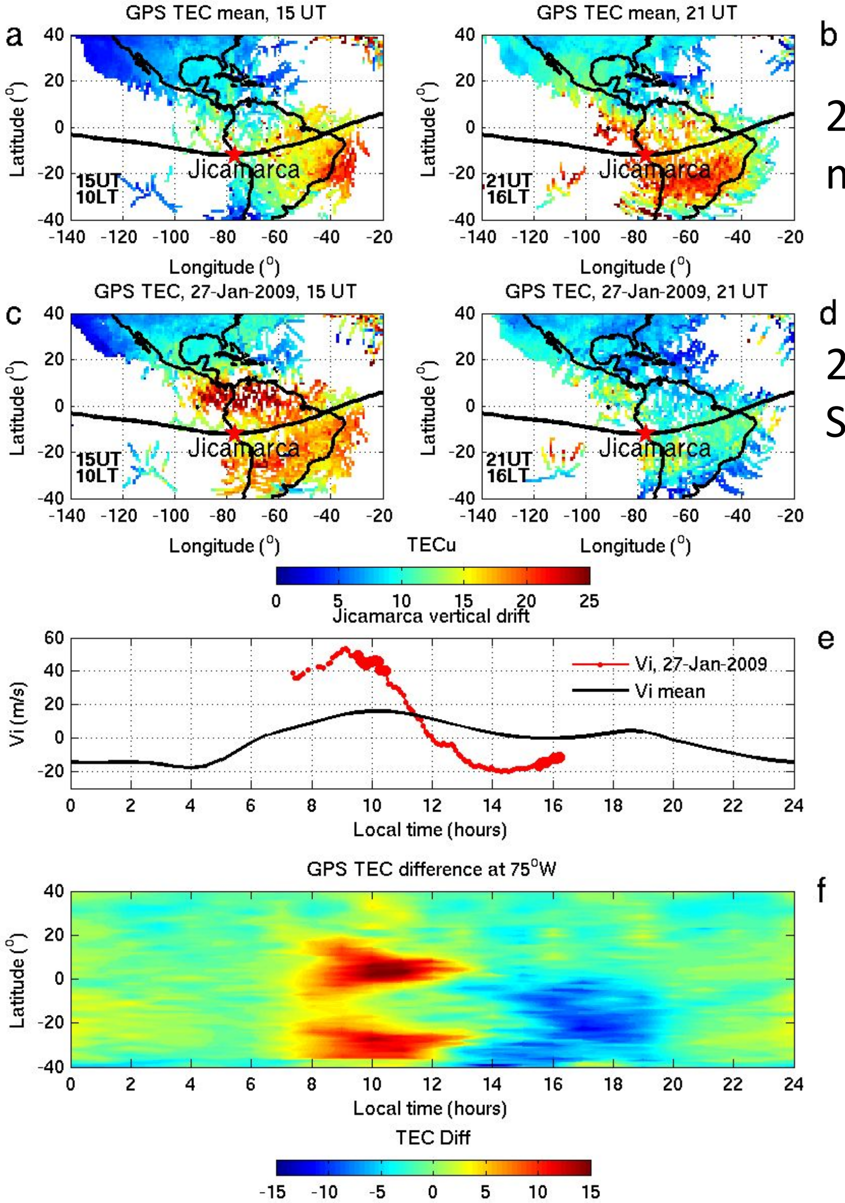
21 UT mean

15 UT SSW

21 UT SSW

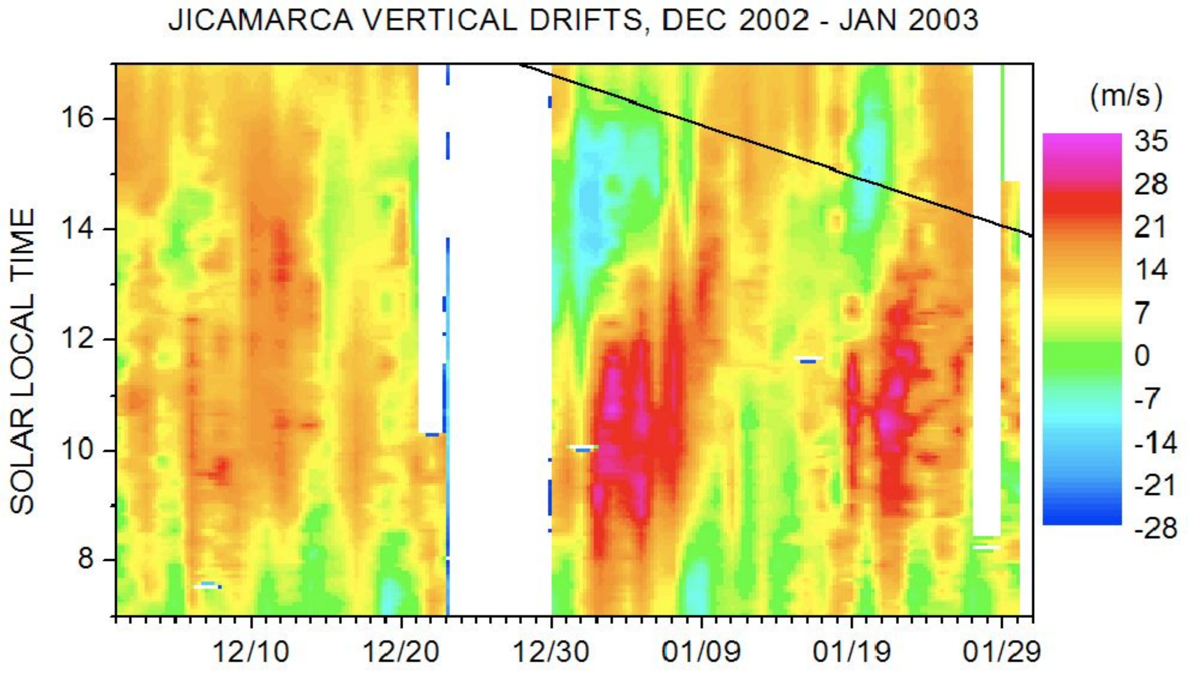
Jicamarca drift

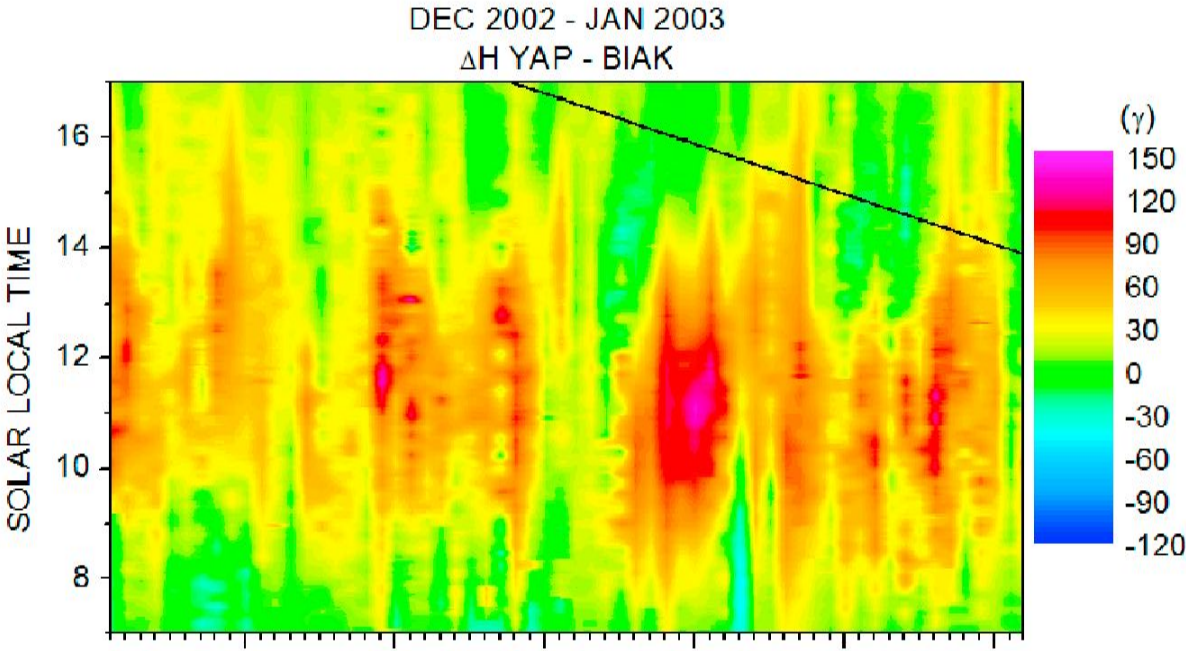
TEC change



Goncharenko et al., 2010

Another big surprise: lunar tide is important!





Fejer et al., 2010

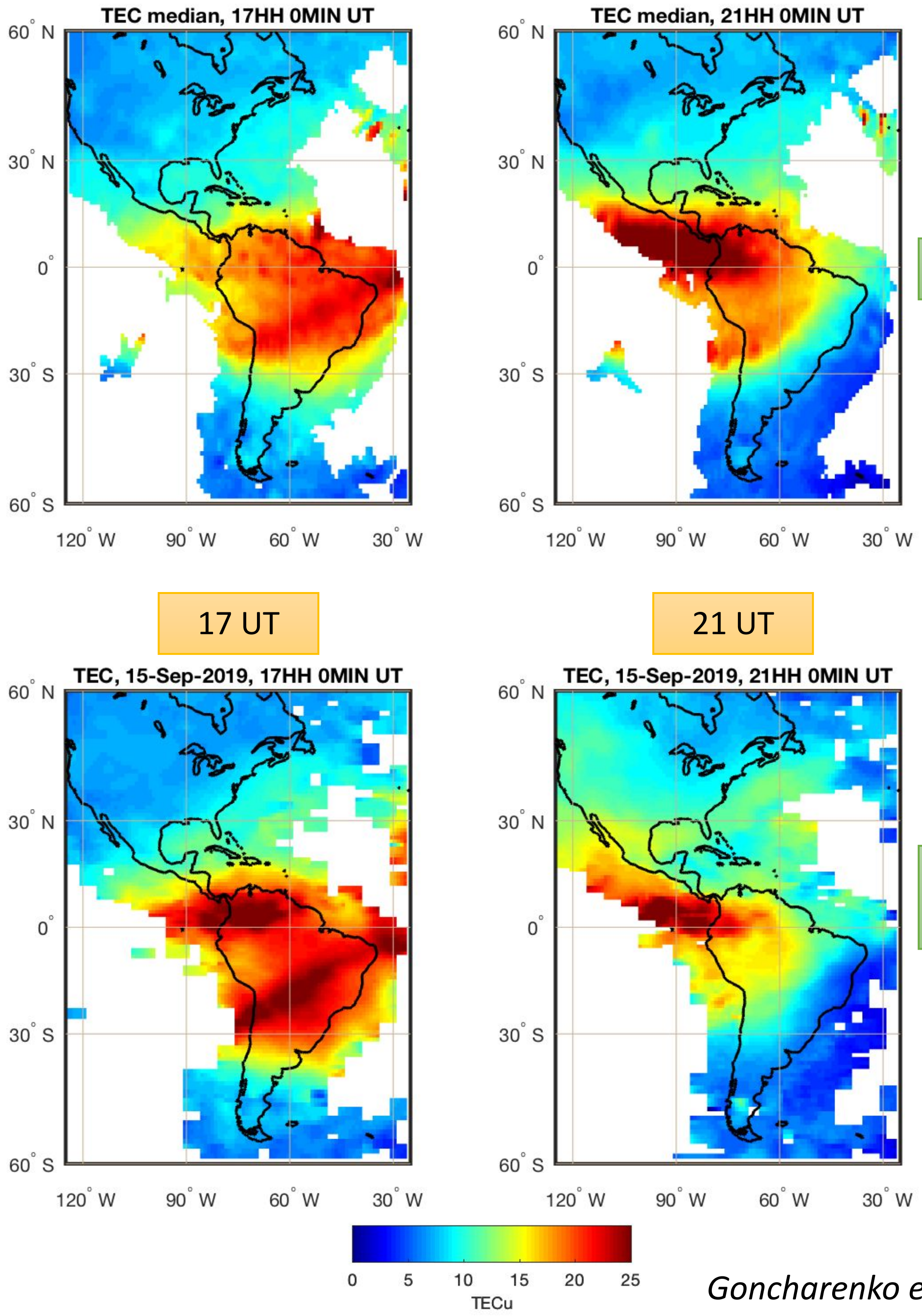
- Gradual shift in quasi-semidiurnal perturbations in Jicamarca drift or dH to later local times – enhancement of lunar semidiurnal tide
- Dozens of studies since than
- Led to understanding and appreciation of impact of lunar tide on the IT variability

SSW & coupling studies now: major growth in variety of topics

Wang et al., 2011: "These new results 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"

- Several selected topics:
  - Effects of Antarctic SSW
    - Southern hemisphere SSW occur much less frequently than northern hemisphere SSW
  - Variation in thermospheric composition
  - Nighttime I-T system
  - Polar vortex and TIDs

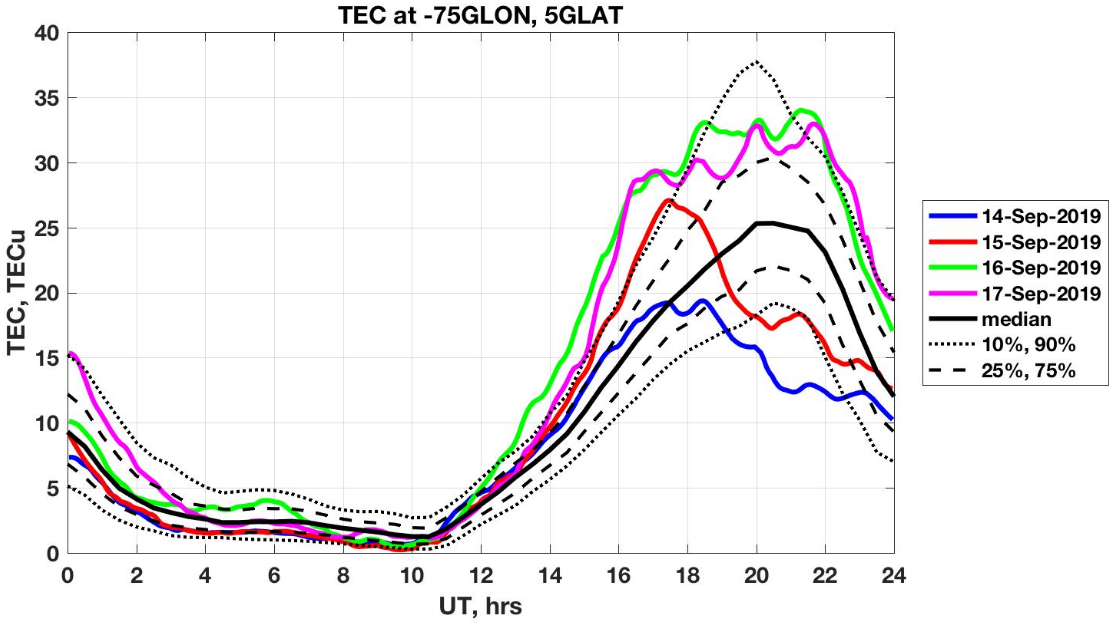
Topic #1: Ionospheric changes during Antarctic SSW of Sep 2019



baseline

Antarctic SSW event

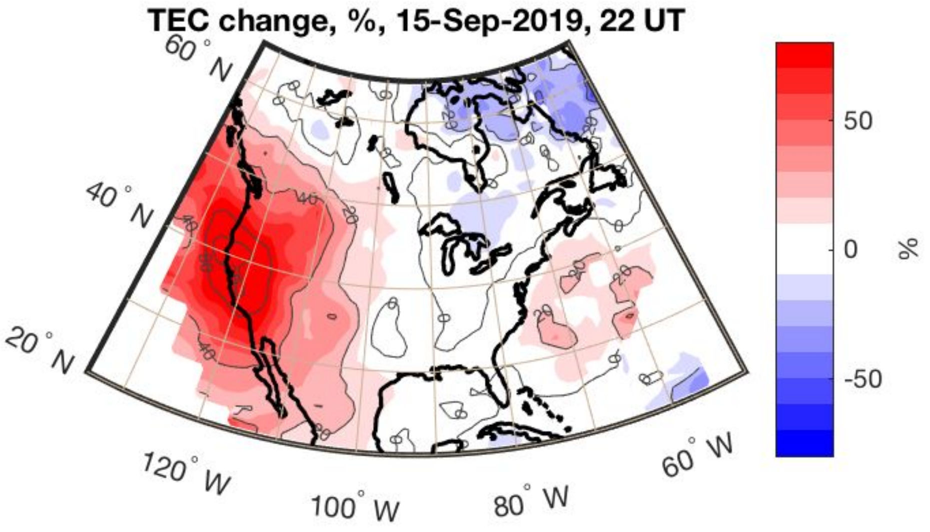
SSW effect: stronger EIA in the morning, weaker in the afternoon – similar to Arctic SSWs (Goncharenko et al., 2010; Chau et al., 2009)

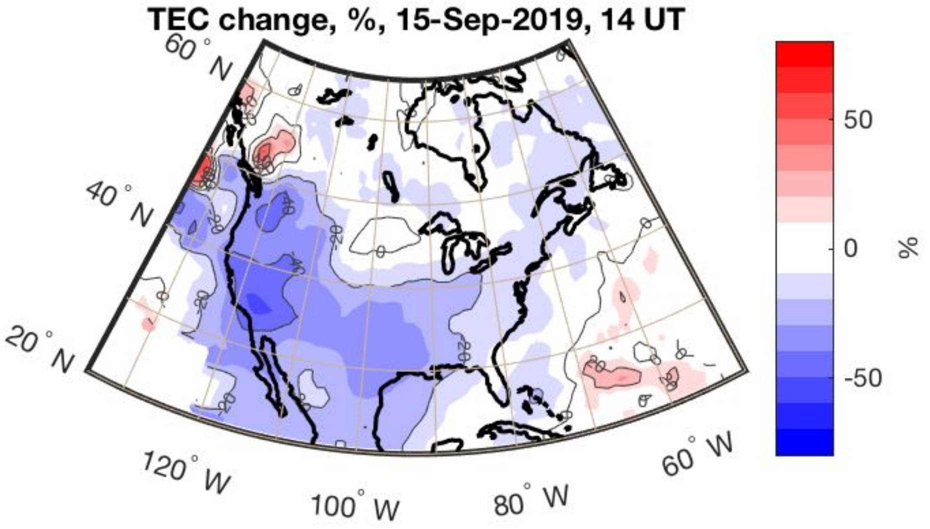


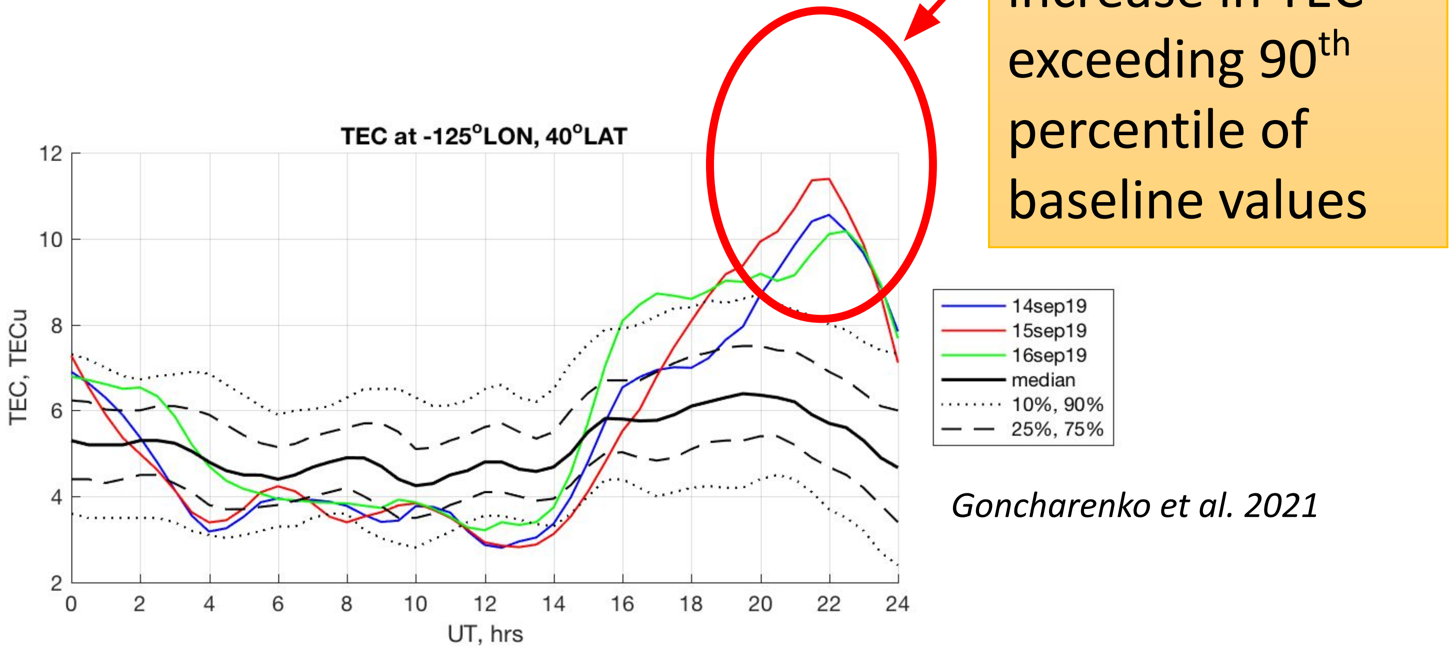
- Anomalies in the crests of EIA – increase or suppression of TEC by up to a factor of 2
- Anomalies last for multiple days

Goncharenko et al., JGR 2020

Effects of Antarctic SSW over continental USA: 50-100% change in TEC





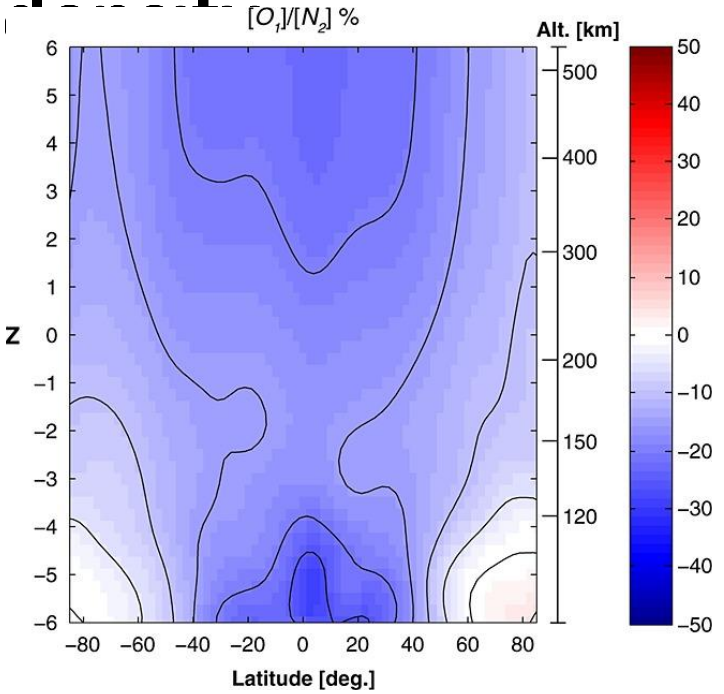


Goncharenko et al. 2021

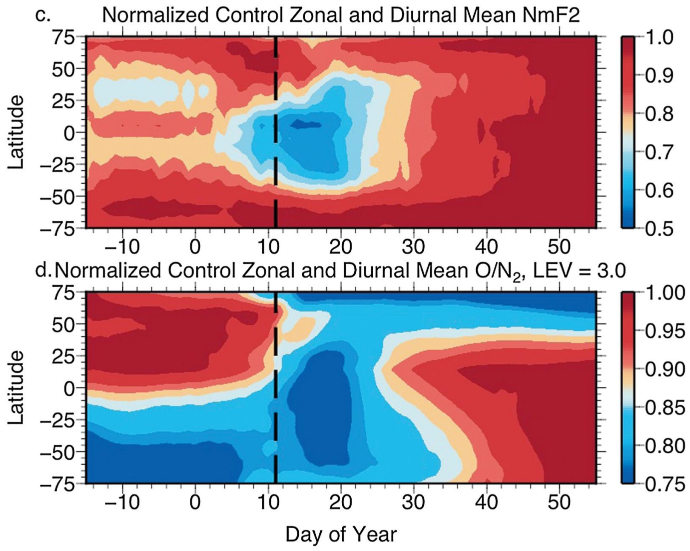
- Persistent quasi-semidiurnal TEC changes are observed in September in the **Western USA only**
- TEC increase reaches **80-100%**; decrease reaches **20-40%**
- Why only Western USA? Regional differences in TEC response could be related to modulation of thermospheric winds by SSW and large declination angle over Western US
- Vincent et al, 2022: 37 Antarctic SSW in 1994-2019; peak in August-October and April-May

Strong ionospheric disturbances could be driven by stratospheric weather during different seasons: Dec-Feb, Apr-May, Aug-Oct

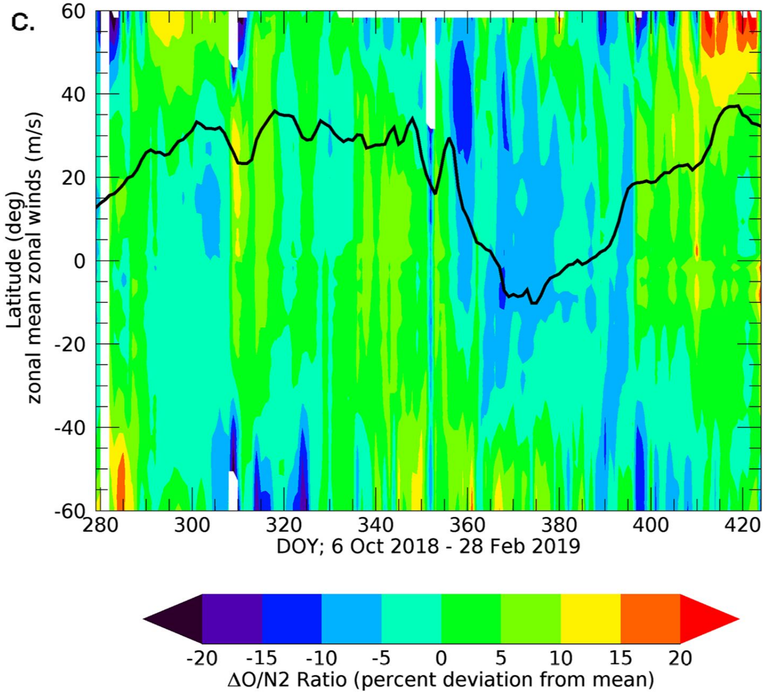
Topic #2: Wave dissipation effects: change in thermospheric composition and electron



Yamazaki and Richmond, 2013



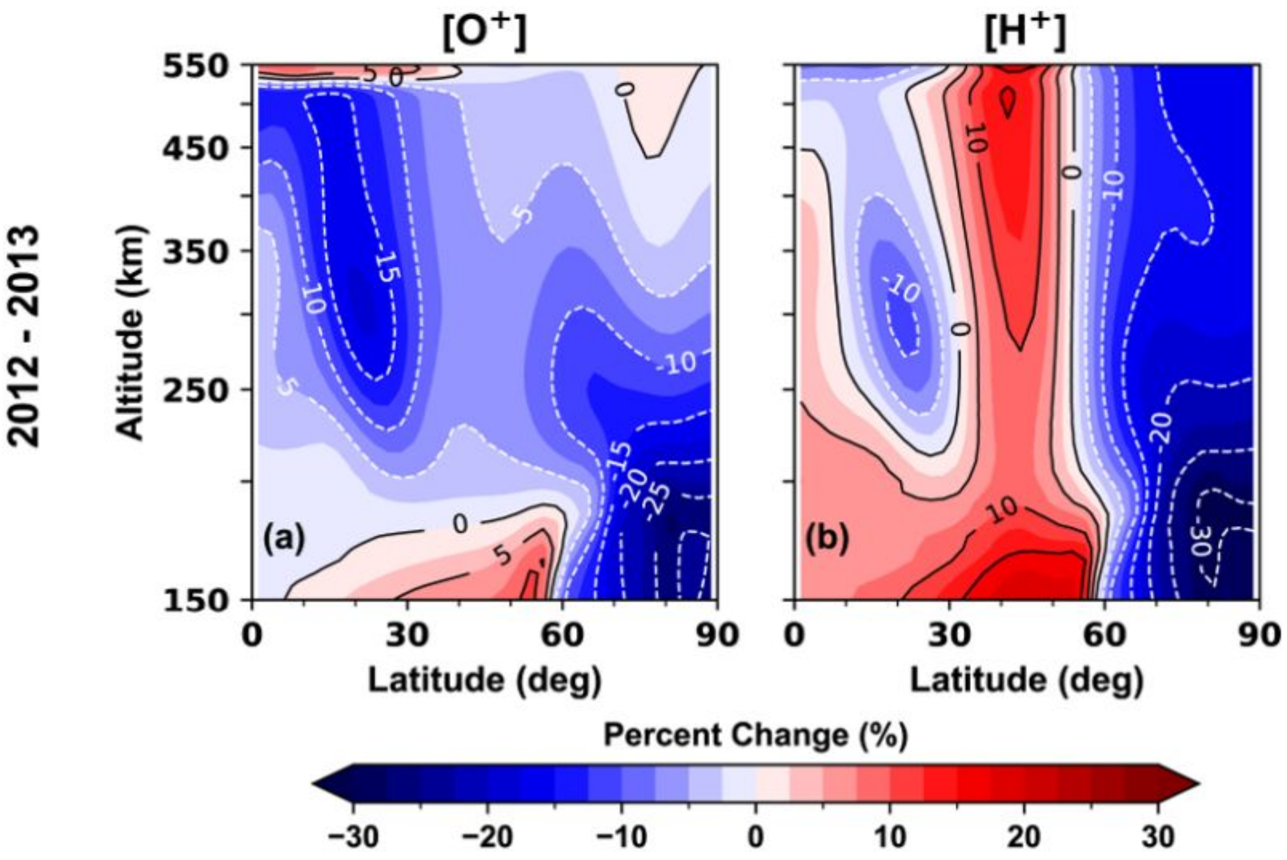
Pedatella et al., 2016



Oberheide et al., 2020

- Simulations: tidal dissipation changes residual circulation and enhances downward transport of [O] -> increase in zonal wind; 20-30% decrease in O/N2, ~25% decrease in Ne (Yamazaki and Richmond, 2013; Jones et al., 2014a,b, 2016, Pedatella et al., 2016)
- Simulations: dissipation of Q2-day wave leads to 16-20% decrease in O/N2 and 16-32% decrease in NmF2 (Yue and Wang, 2014)
- Observations: 5-10% decrease in O/N2 during SSW (Oberheide et al., 2020)
- **New and promising area of research**

Can stratospheric warming effects extend to the magnetosphere?

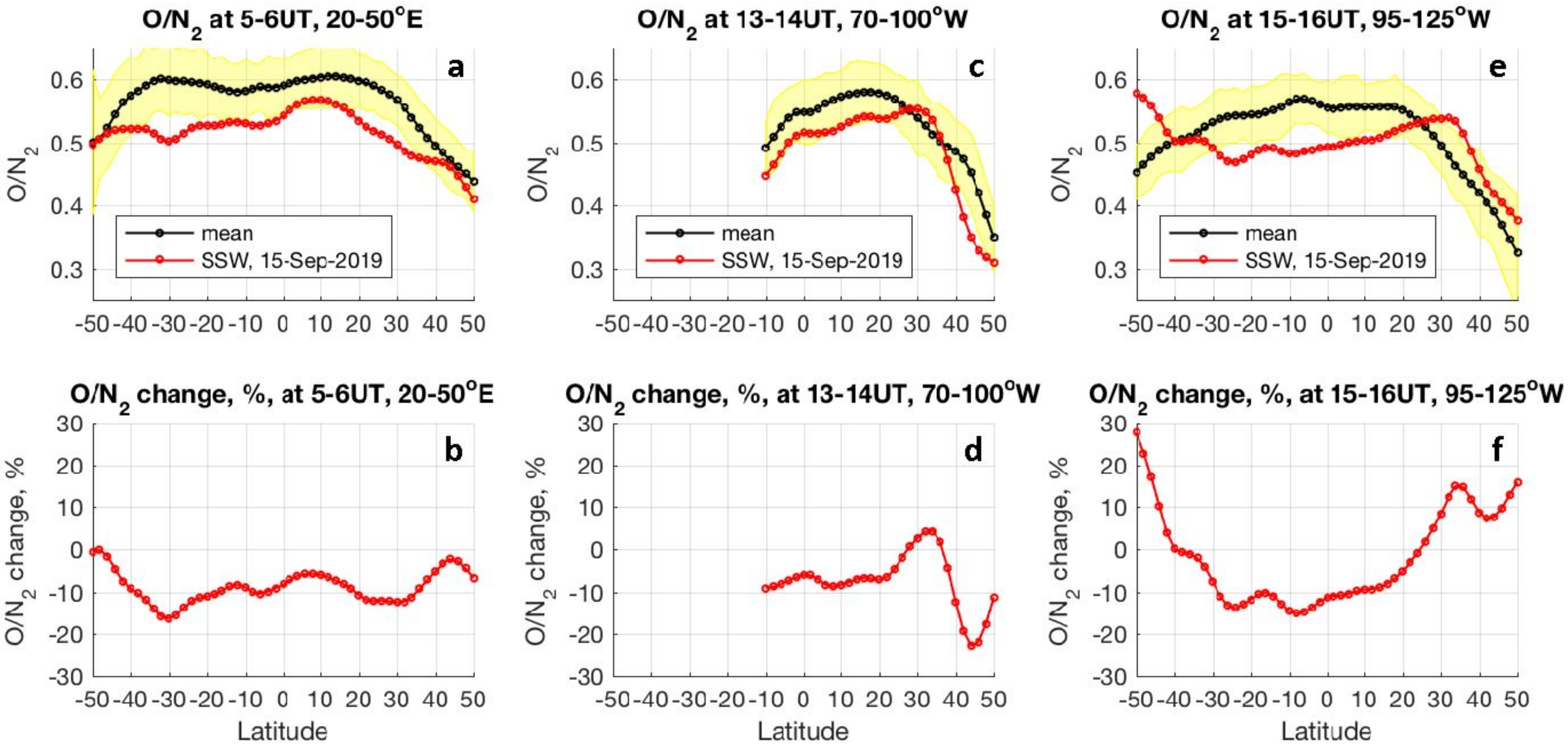


Jones et al, 2020

- TIME-GCM simulation: enhanced small-scale GW and tidal activity drive enhanced meridional residual circulation
- Large reduction at 500 km in light species - ~8% decrease in [He], ~17% decrease in [H]
- 5-7% decrease in globally averaged mass density at ~500 km
- **SSW-associated variability in [He] and [H] may potentially affect the plasma population in the topside ionosphere and plasmasphere**

Transient stratospheric disturbances potentially can affect magnetospheric weather

O/N2 changes during SSW: strong longitudinal dependence

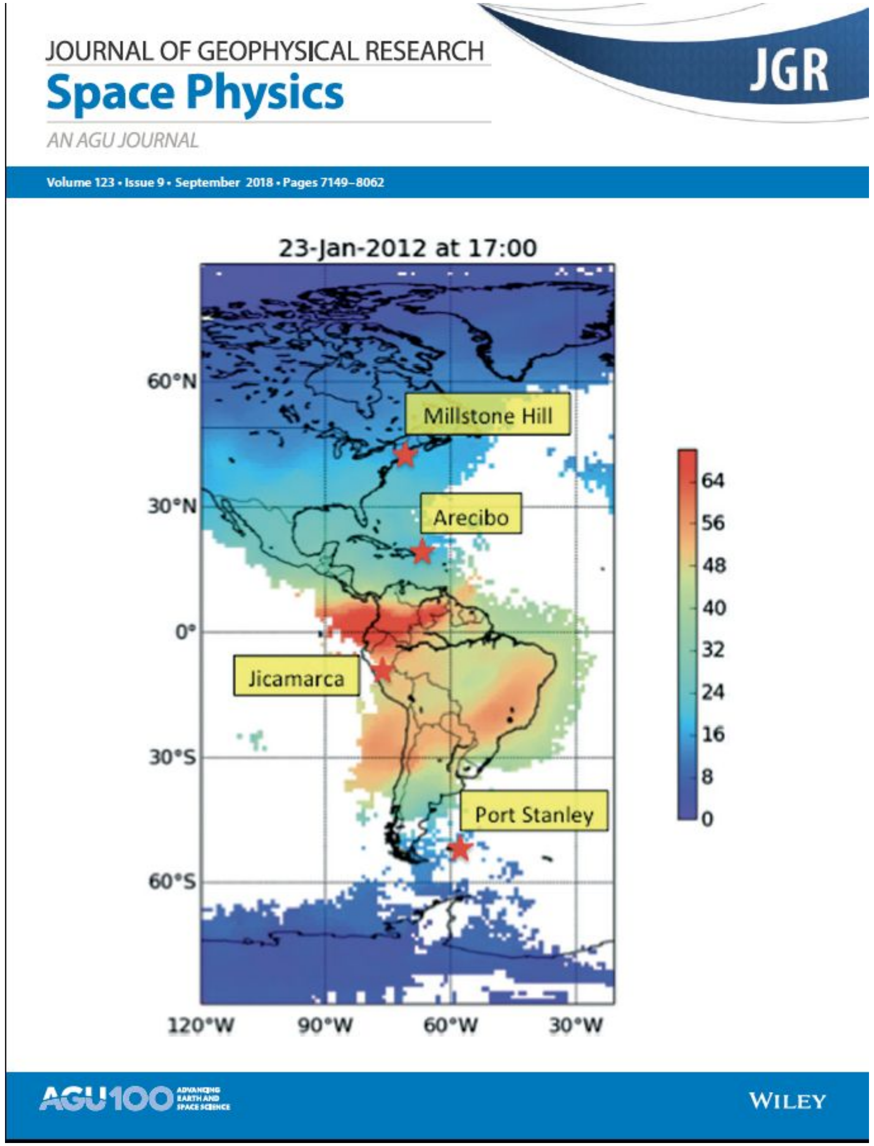


Goncharenko et al., 2021

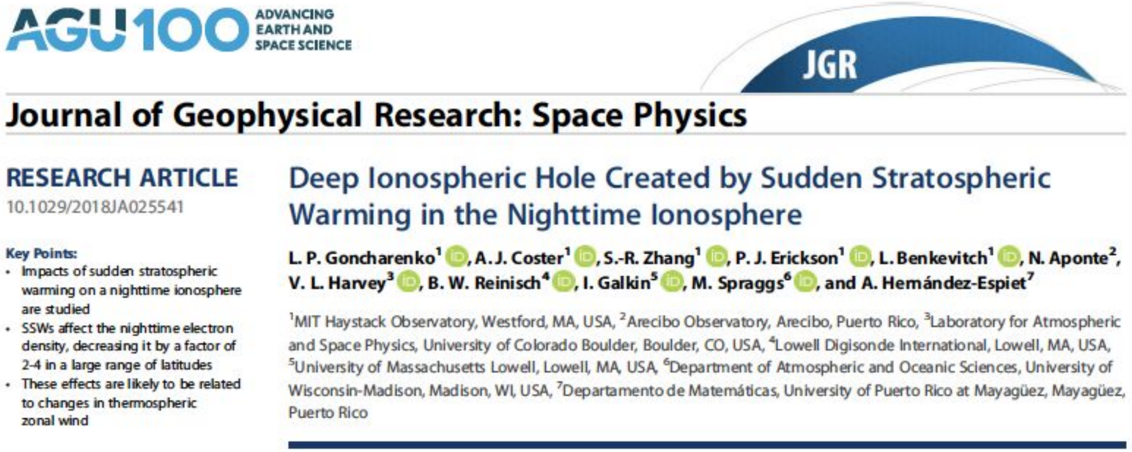
Latitudinal and longitudinal perturbations in O/N2 are not currently understood

- Simulations focused on zonal mean effects so far
- Observations reveal more complex picture, with significant longitudinal difference in O/N2 perturbations
- **Availability of TIMED, GOLD, and ICON data opens opportunities for novel I/T studies**

Topic #3: SSW effects in the nighttime ionosphere



Goncharenko et al., 2018



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Key Points:

- Impacts of sudden stratospheric warming on a nighttime ionosphere are studied
- SSWs affect the nighttime electron density, decreasing it by a factor of 2-4 in a large range of latitudes
- These effects are likely to be related to changes in thermospheric zonal wind

Deep Ionospheric Hole Created by Sudden Stratospheric Warming in the Nighttime Ionosphere

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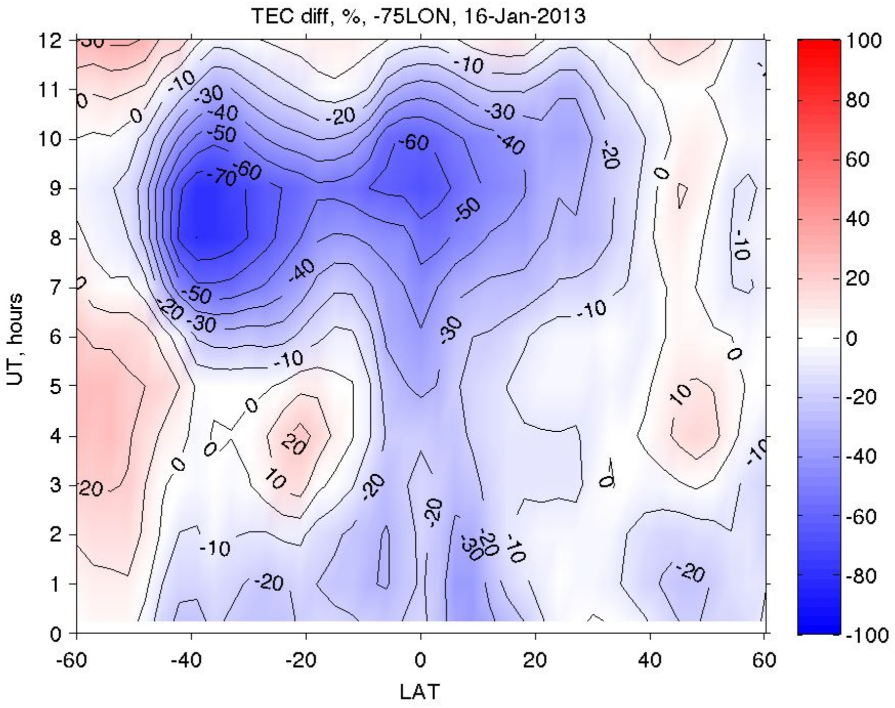
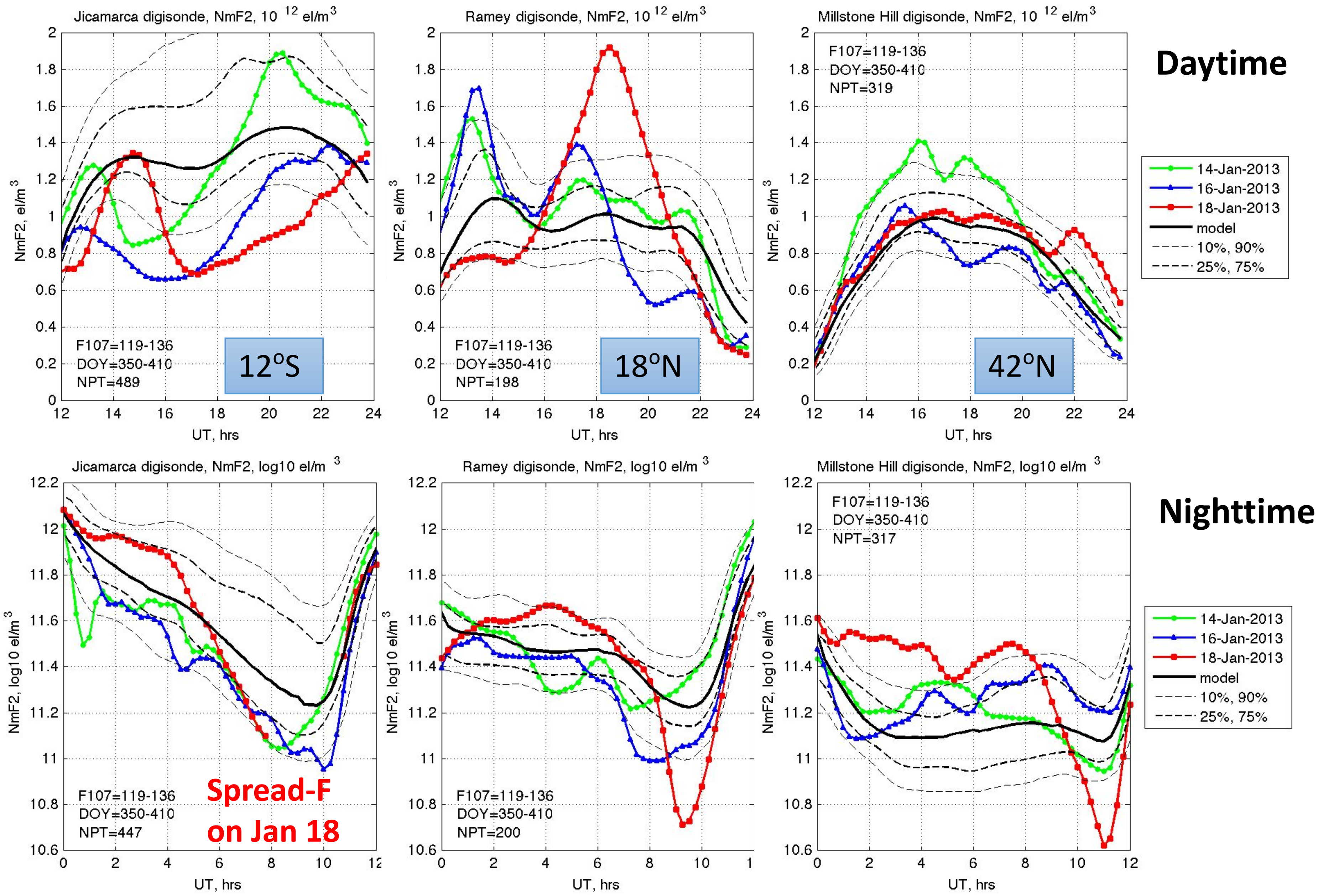


- During SSW, nighttime TEC is strongly decreased by a factor of 2 to 4
- Decrease extended from ~50°S to 40°N

Ionosonde data

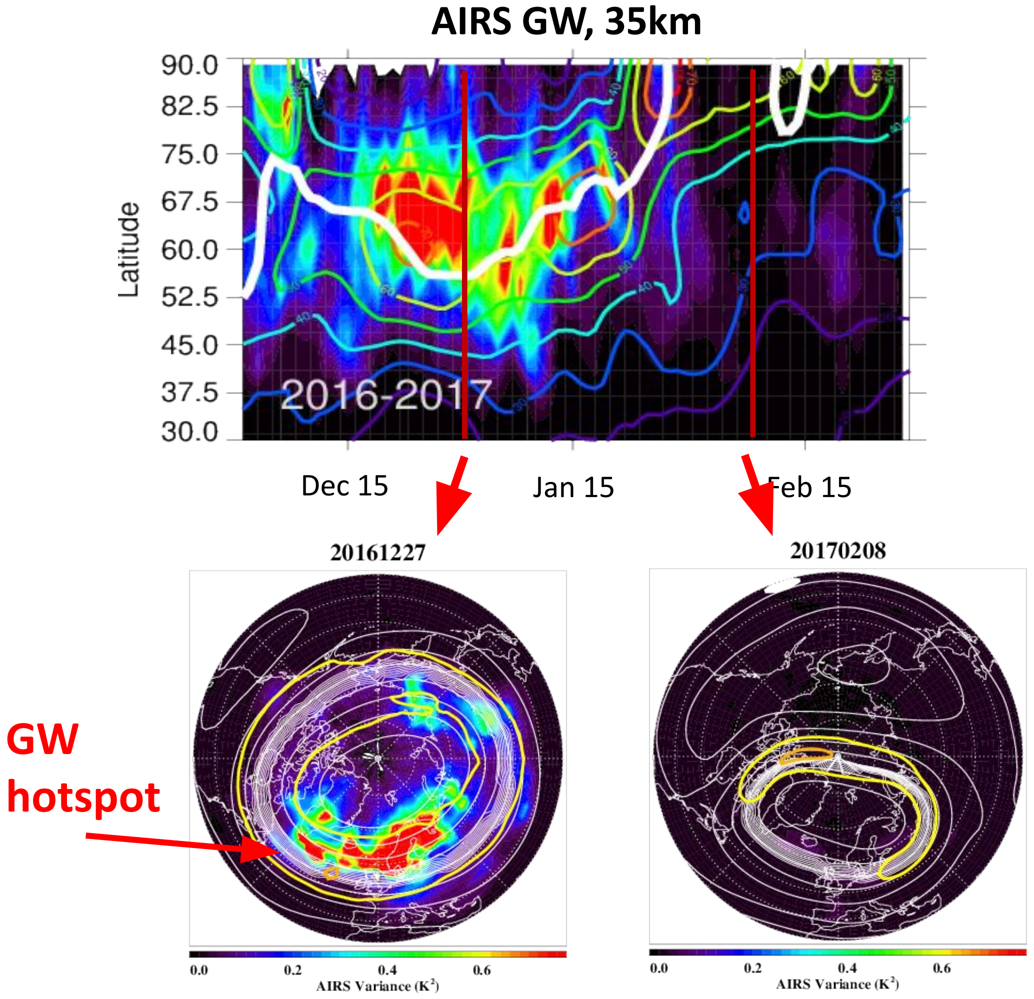


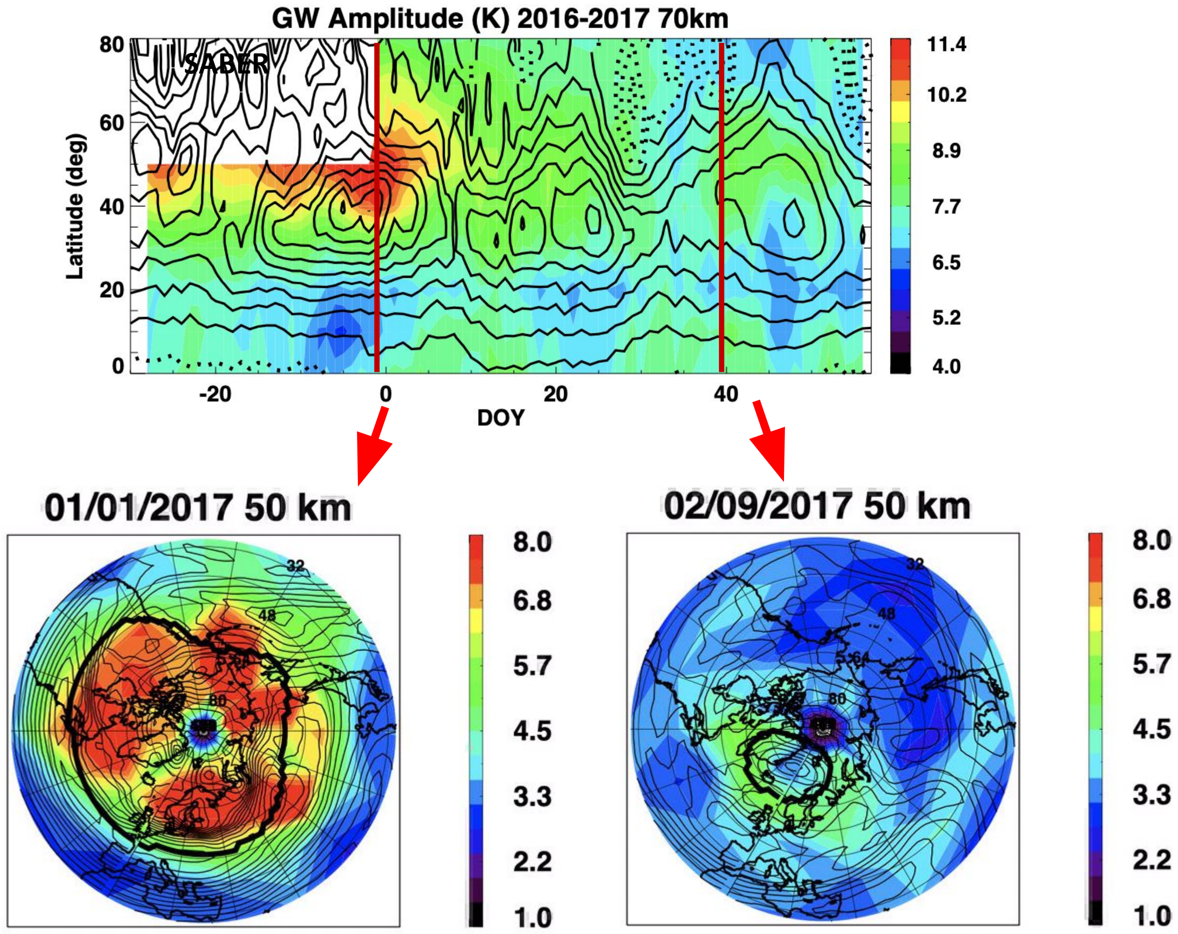
- **Spread-F is seen at Jicamarca**
- This study suggested SSW effects in the thermospheric zonal winds as driver of nighttime changes
- Simulations with SAMI3 show larger roles of perturbations in meridional wind

We need high-resolution observations of thermospheric winds at different locations to understand these changes

Having variety of instruments at Jicamarca Observatory (and other places) is of major importance

Topic #4: Polar vortex, stratospheric GW hotspot and TIDs

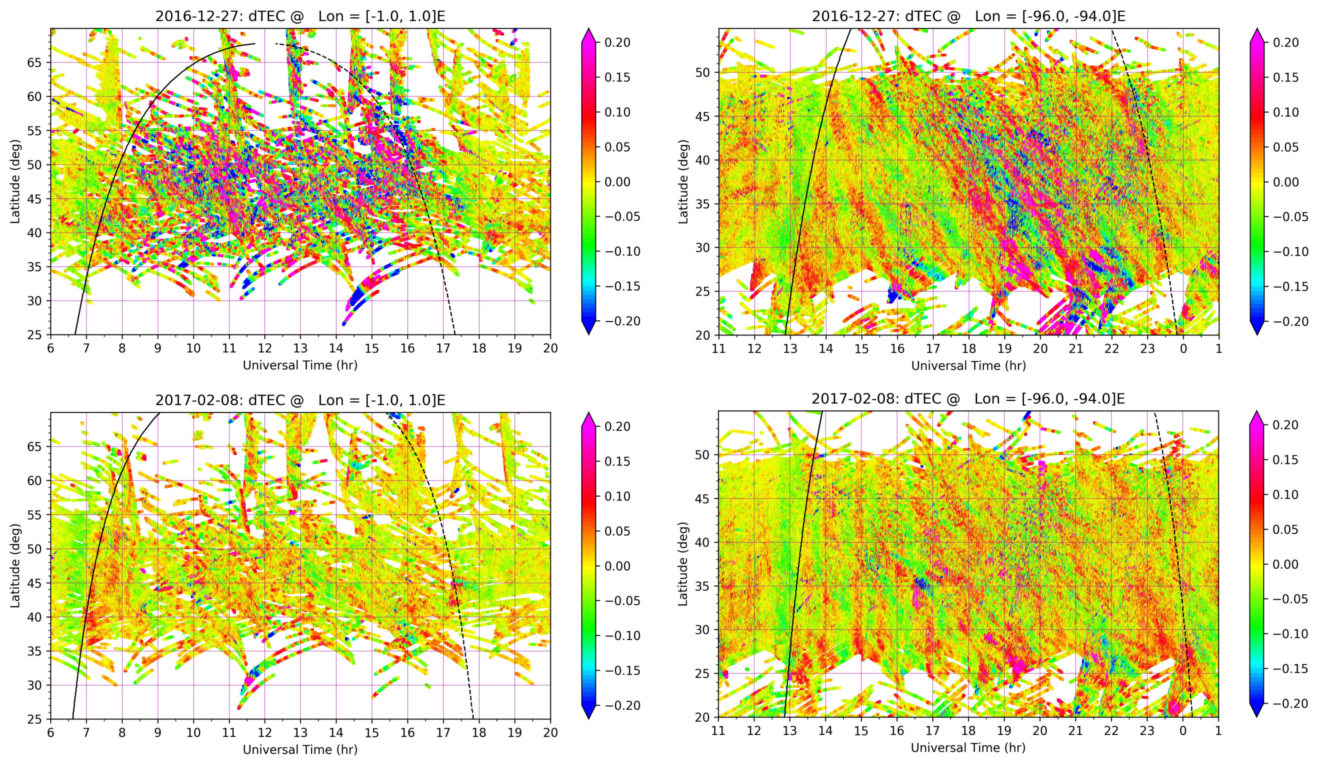


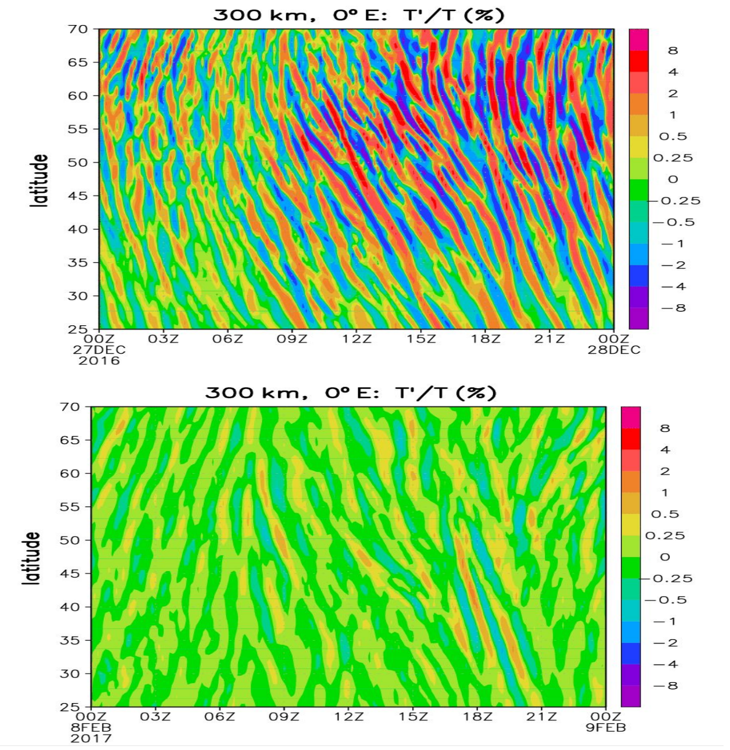


- Winter 2016-2017: strong polar vortex from mid-Dec to mid-Jan; minor sudden stratospheric warming in the end of Jan
- Aqua satellite, AIRS data (35 km): peak stratospheric GW activity at **55-75^{o}N, GW hotspot over Europe**
- TIMED satellite, SABER data: enhanced GW activity in Dec down to **35-40^{o}N**; extended **range of longitudes**

TIDs and GW in the ionosphere/thermosphere are amplified during high GW activity in the stratosphere

GNSS dTEC, Europe, 0^{o}E | **GNSS dTEC, central US, 95^{o}W** | **HIAMCM simulations, Europe, 0^{o}E**





High stratospheric GW activity Dec 2016

Low stratospheric GW activity Feb 2017

- GNSS TEC data shows amplification of **daytime small and medium-scale TIDs** in Dec as compared to Feb
- TIDs are amplified in a large range of latitudes (**25-60^{o}N**) and longitudes (Europe, Asia, eastern and central US)
- Simulations with HIAMCM model show excellent agreement with observations

Gravity waves evolve with altitude, latitude, and longitude and are imprinted on ionosphere in a large range of latitudes and longitudes

Summarizing thoughts

- Jicamarca Observatory played a critical role in the discovery of SSW effects in the ionosphere in 2008-2012
  - Strategic location, cluster of instruments, strong collaborative culture
  - SSW studies paved the way for understanding major vertical coupling mechanisms
- Future outlook:
  - **Deep content**: few locations with a cluster of multi-instrument 'big' facilities to provide multiple parameters
  - **Wide content**: networks of DASI-like instruments
    - Crucial for data assimilation to obtain regional and/or global view
  - Need to understand multiple scales
- Promote infrastructure that can be used for multiple science objectives
- Clear understanding that we need all available observations to maximize science returns - need to leverage resources from NSF, NASA, DoD, industry
- Need reinvestment and community endorsement of 'big' facilities