Stratospheric warmings and their effects in the ionosphere

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Motivation

- Unexplained behavior of the upper thermosphere and ionosphere
- Large day-to-day variability, in particular at low latitudes
- Forcing from below (e.g. "meteorological" forcing) accounts for 20-30% of ionospheric variability (*Forbes et al*., 2000, *Mendillo et al*. 2002) on average; case studies of much larger variations
- Forcing from below is comparable to ionospheric changes related to geomagnetic activity [e.g., *Fuller-Rowell et al*., 2000; *Rishbeth and Mendillo*, 2001; *Forbes et al*., 2000]

How can we find a good approach to study lower atmospheric forcing?

Timeline

There is such a phenomenon as sudden stratospheric warming…

First ISR World day campaign;
First evidence of ionospheric variations during SSW

ISR campaign every winter

Record strong SSW

"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" – *Wang et al.*, 2011

2006 2007 2008 2009 2010 2011 2012 ?

Papers rejected → Papers cited 25-45 times

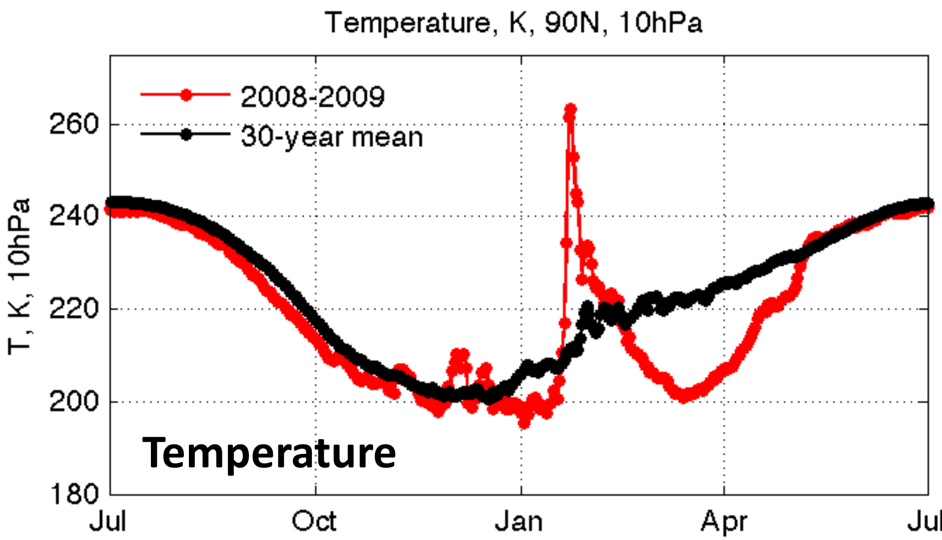
Special issue of JGR;
joint between JGR-Atmospheres and JGR-Space Physics

We've made only first steps in this journey…

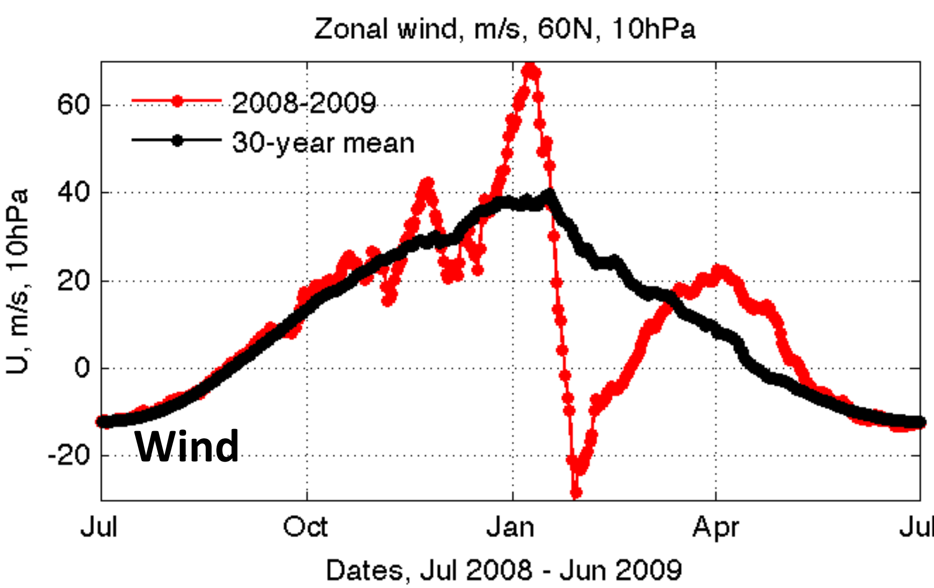
This lecture is about…

- Sudden stratospheric warming as meteorological event
- Known ionospheric responses associated with sudden stratospheric warmings
- Interpretation of the observed and modeled phenomena
- Where do we go from here?

Sudden stratospheric warming – what is it?

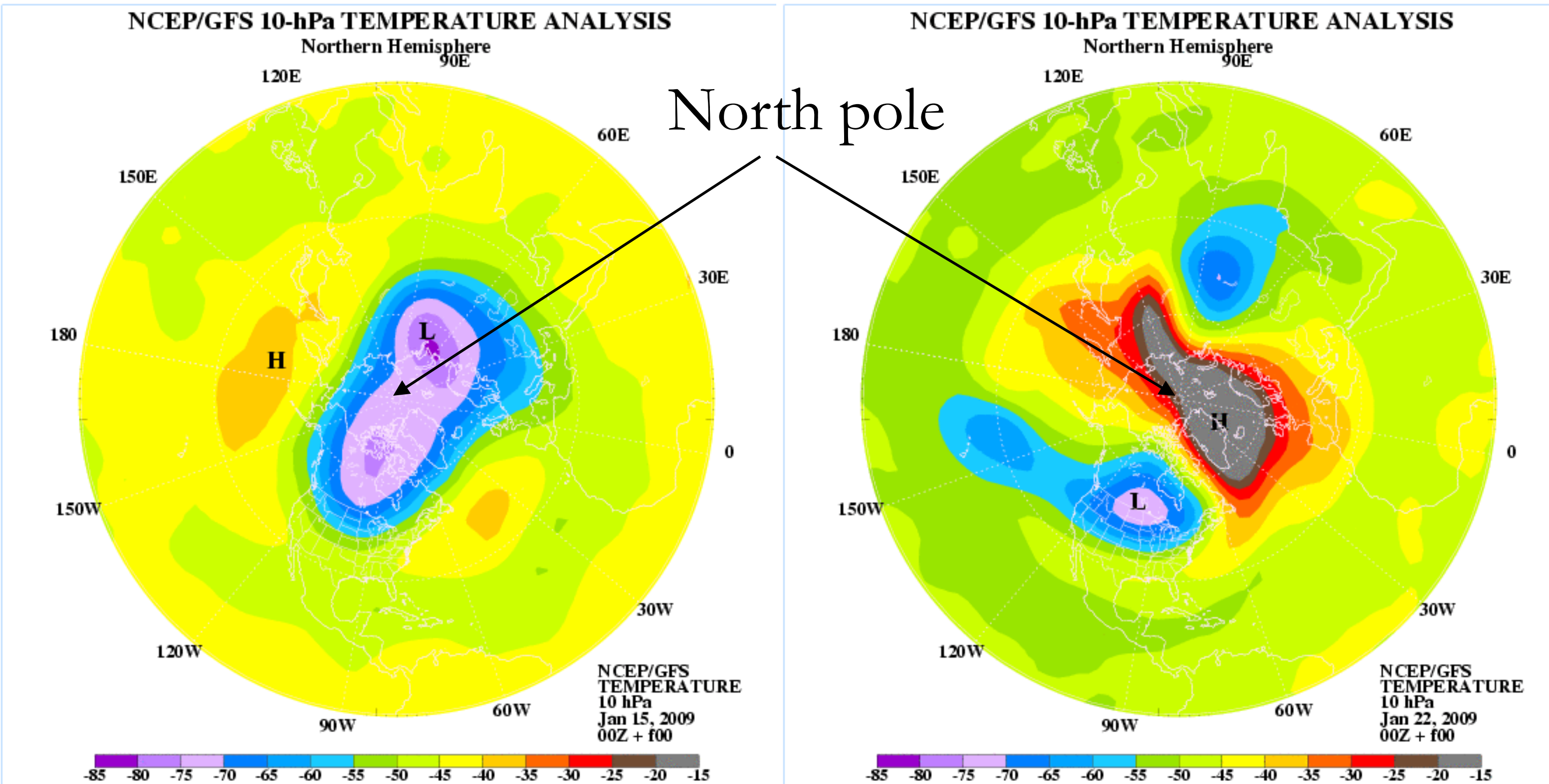


- Largest known meteorological disturbance
- Rapid increase in temperature in the high-latitude stratosphere (25K+); from winter-time to summer-time
- Accompanied by a change in the zonal mean wind



Stratospheric temperature at 10hPa (~32km)

Before warming	During warming



- 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

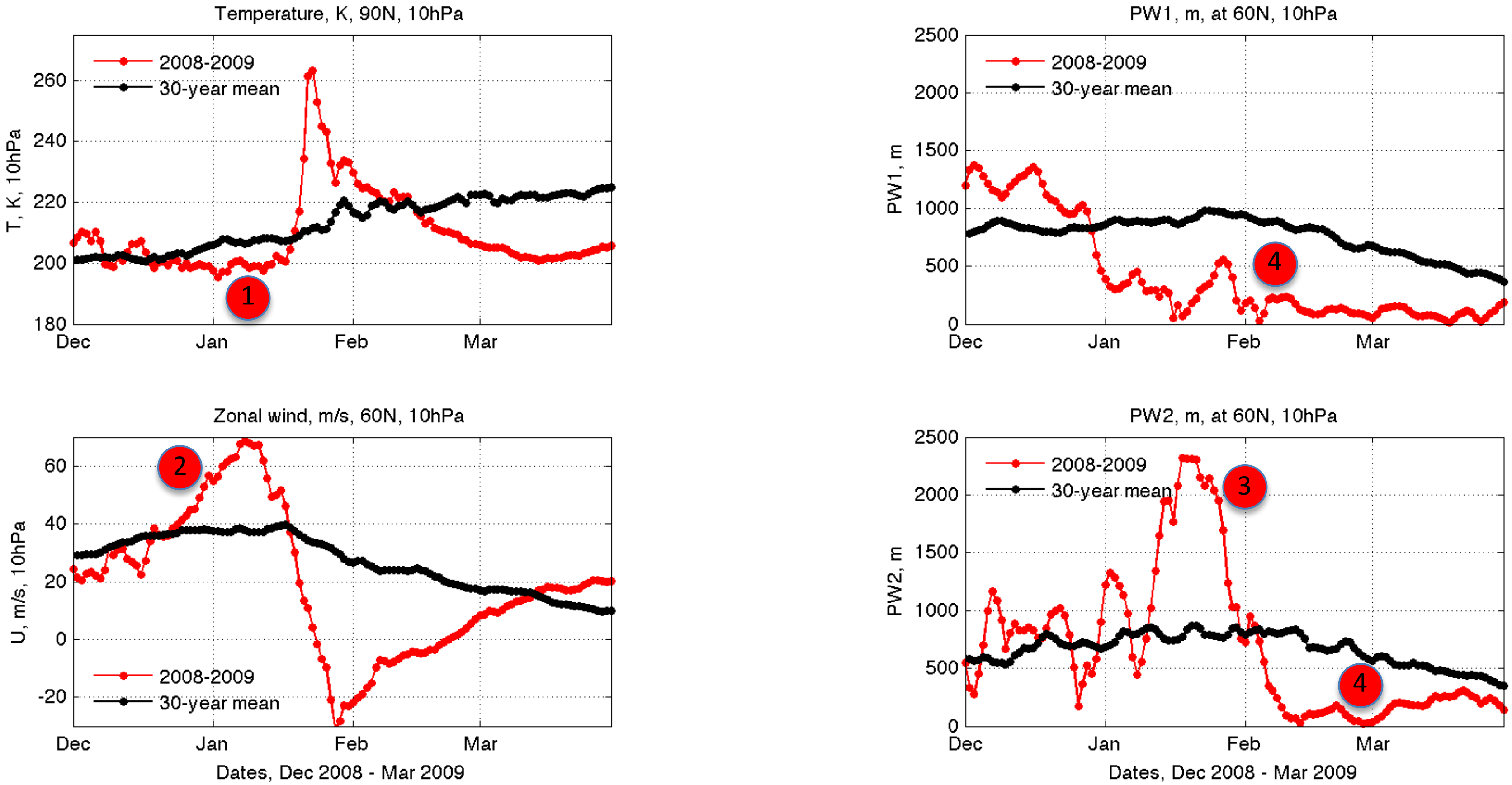
What I’ve learned about sudden stratospheric warmings:

- They are not sudden
- They are not only stratospheric
- They are not only warmings

Terminology is arbitrary; physics is not

Sudden stratospheric warmings are not sudden…

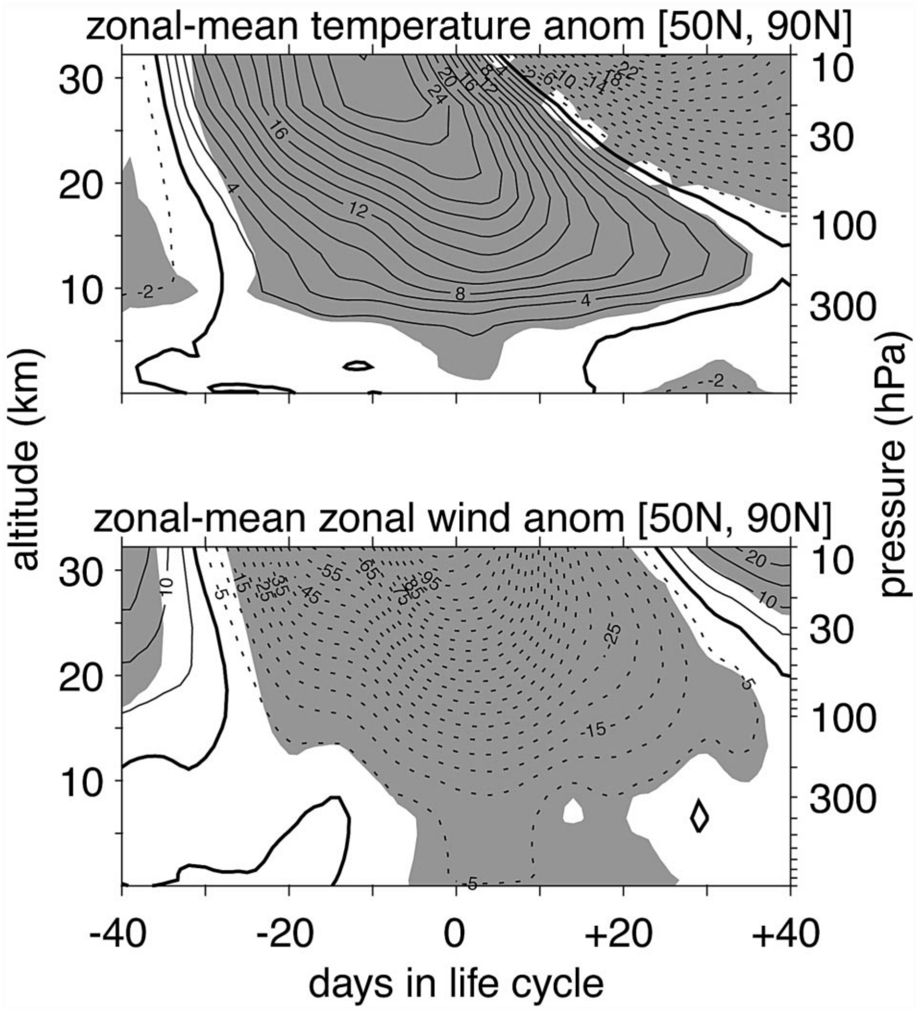
Part 1: 2009 case



Anomalous behavior in multiple stratospheric parameters prior to and after the SSW:

1. Cold polar vortex prior to the peak in temperature
2. Strong eastward wind prior to SSW
3. High planetary wave activity prior to SSW
4. Collapse of PW activity after the peak in SSW

Sudden stratospheric warmings are not sudden… Part 2: composite study

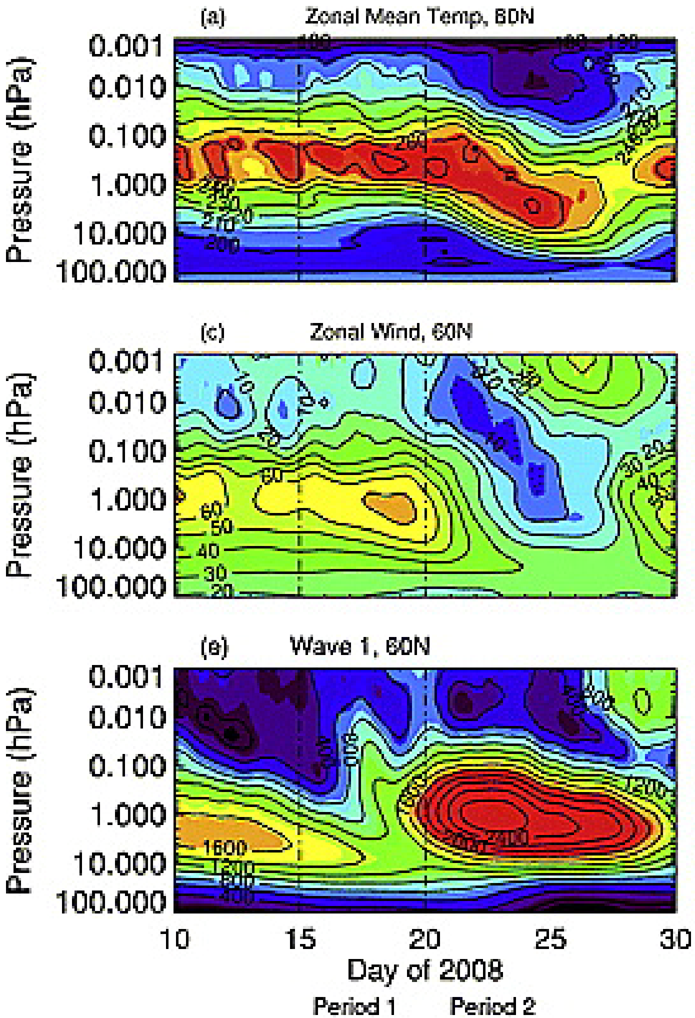


Limpasuvan et al., 2004

- Several stages of SSW with regards to the central day:
  - Onset (days -37 to -23)
  - Growth (days -22 to -8)
  - Maturity (days -7 to 7)
  - Decline (days 8 to 22)
  - Decay (days 24 to 37)
- Preconditioning includes anomalously strong zonal flow at high latitudes and weak flow below 60°N; warm pole above 30hPa
- During growth and mature stages, anomalies descend to the lower stratosphere
- Wind and temperature peaks in the mature stage; anomalously low PW begins

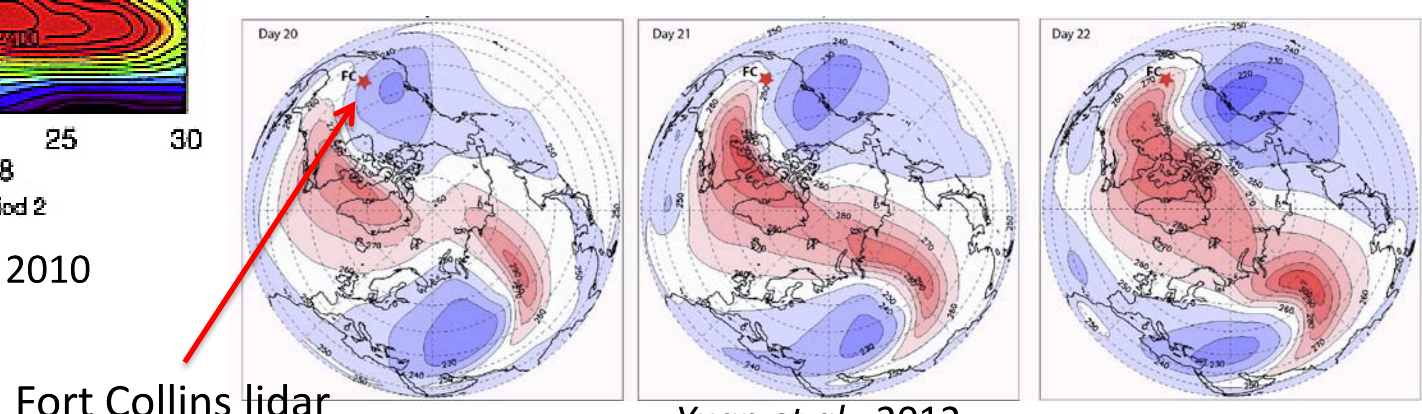
Mature stage is ~2 weeks; significant anomalies +/-40 days from central date

SSW is not only stratospheric event…



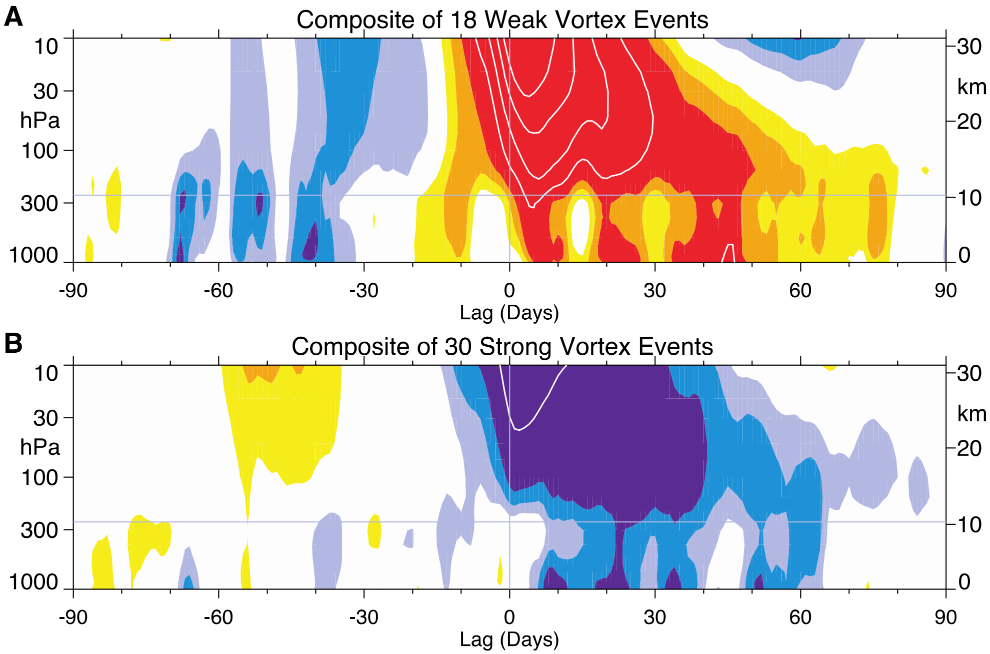
Siskind et al., 2010

- First discovered 60 years ago
- Mesospheric effects are known since 1970s
  - cooling of the polar mesosphere (*Labitzke* 1972, 1981, *Walterscheid* 2000, *Azeem* 2005, changes in gravity waves, zonal mean flow, PW, tides (*Hoffmann* 2007, *Yamashita* 2010)
  - Complex variations at middle and low latitudes (*Pancheva* 2008, *Shepherd* 2007, *Sridharan and Sathiskumar*, 2008, *Lima* 2011)



Yuan et al., 2012

SSW is not only stratospheric event…



Baldwin and Dunkerton, 2001

- *Anomalies in stratospheric circulation descend to the troposphere and create tropospheric anomalies*
- *Can be used as a predictor of tropospheric weather up to 2 months in advance*

- Tropospheric effects are known since ~2001 (*Quiroz* 1977, *Baldwin and Dunkerton*, 2001, *Thompson* 2002, *Charlton* 2004); accepted only recently
  - include locations of storm tracks and the likelihood of mid-latitude storms
  - Active research area; >200 publications

Weather changes after 2009 SSW

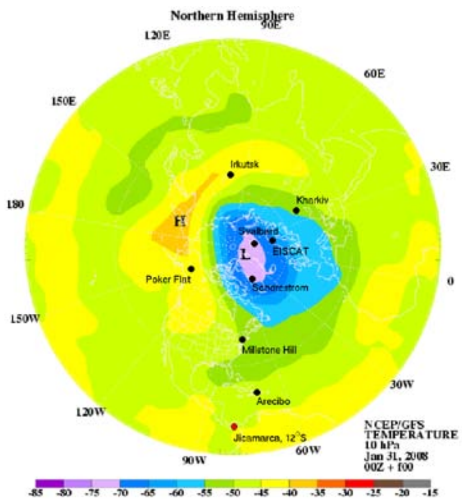
London, February 2, 2009

- A bitter cold snap over much of the United States; temperatures below -22 F in Midwest
- 8 inches of snow in London; 12 inches in other areas
- Heaviest snowfall southeastern England had seen in nearly 20 years
- All London buses, trains and subway out of service

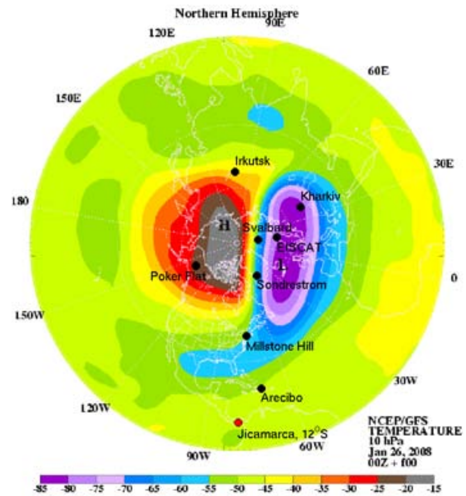
Atmospheric scientists use studies of stratospheric anomalies to transition to the long-term weather forecast and address critical needs in the society

Sudden stratospheric warmings are not only "warmings"

NCEP temperature, 10hPa (~32 km)

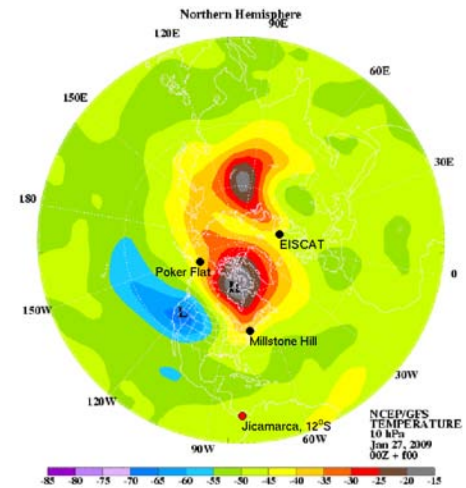


Pre-SSW vortex



January 2008 SSW

Vortex displacement event



January 2009 SSW

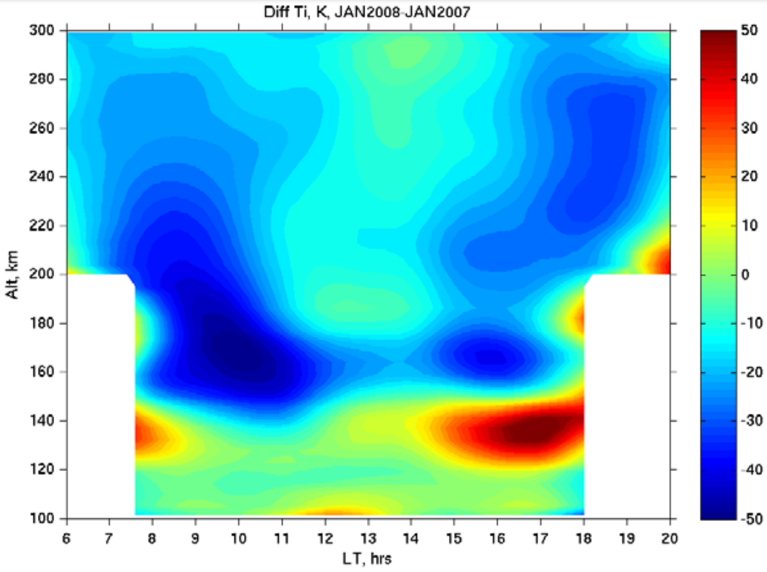
Vortex split event

- Warming in the polar stratosphere is accompanied by a cooling in the polar mesosphere and a cooling of tropical stratosphere
- Areas of warm and cold cells develop in the polar stratosphere
- The event is inherently asymmetric; variations at a particular location (ground-based observer) can depend on location with regards to the disturbed polar vortex

What do we see in the ionosphere?

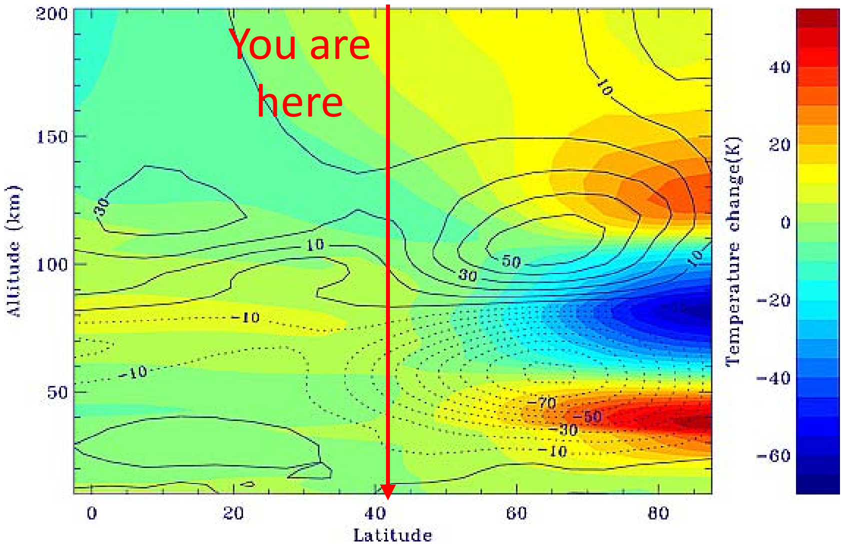
Ionospheric response to SSW: Temperature "sandwich"

Data: Millstone Hill ISR, 42ºN



Goncharenko and Zhang, 2008

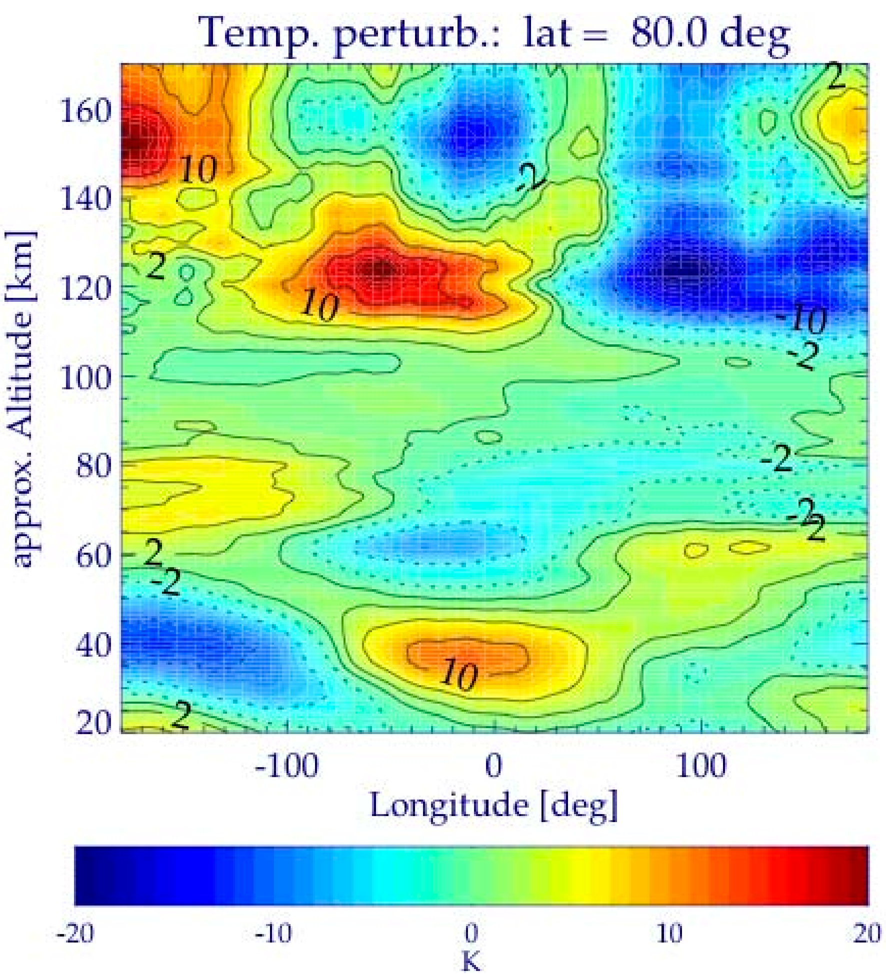
Model: TIMEGCM



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 experimental evidence of temperature change during SSW

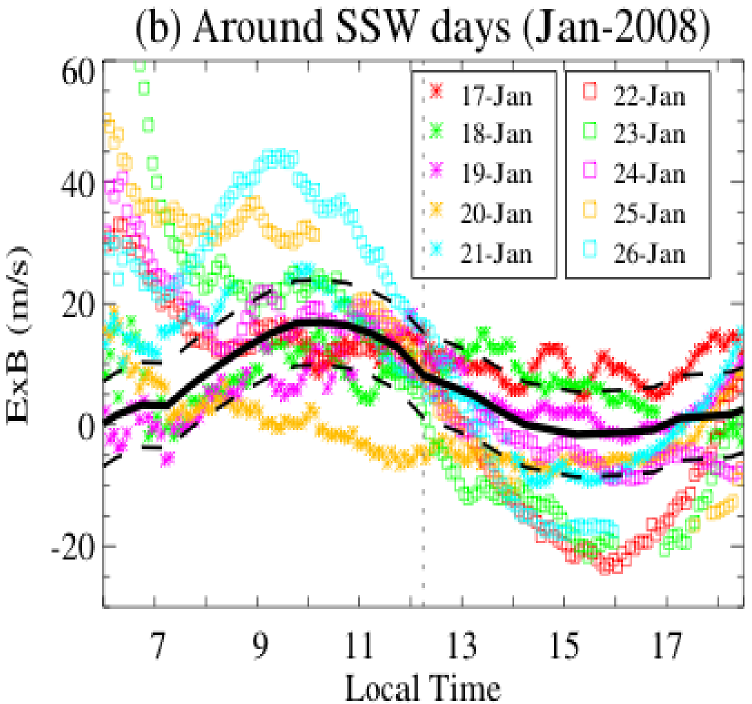


Funke et al., 2010

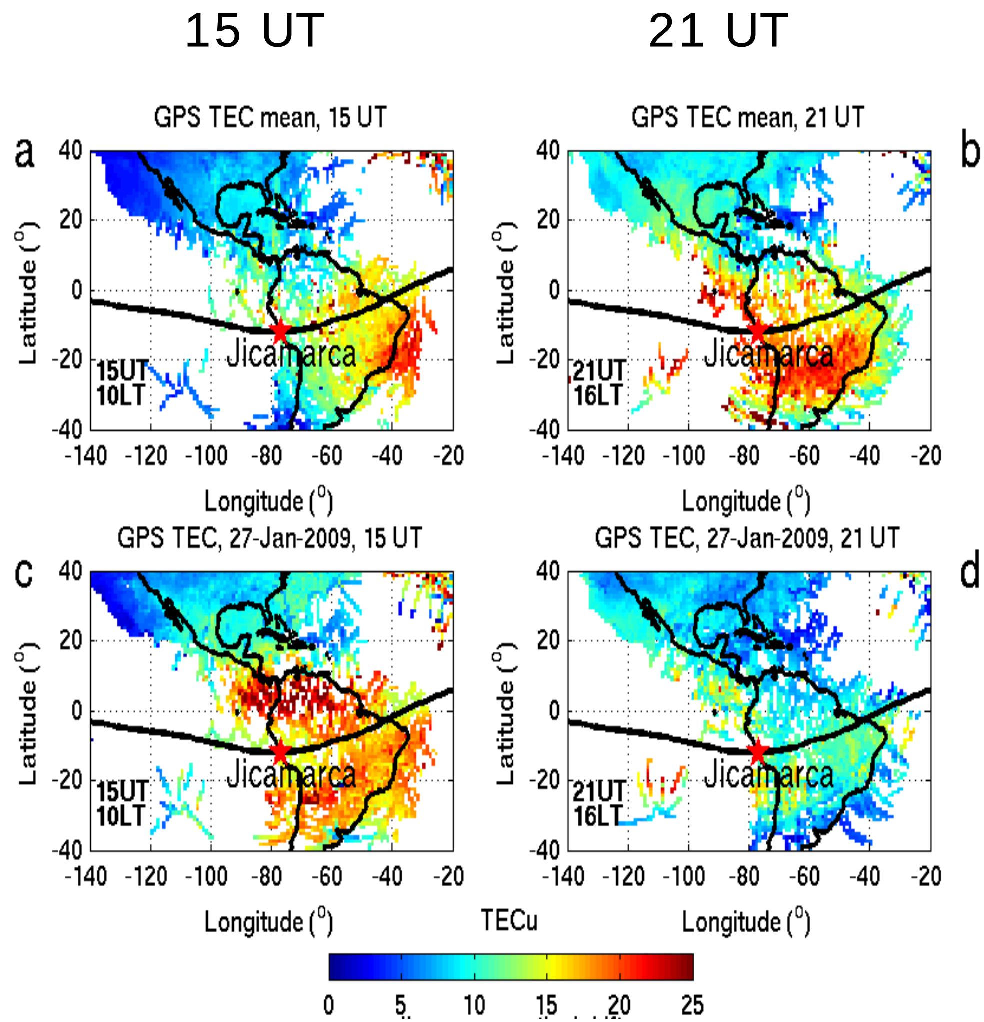
- MIPAS on ENVISAT – Tn increase at 120-140 km during Jan 2009 SSW
  - Wave 1 pattern
  - Stronger in the stratosphere and thermosphere; weaker in the mesosphere
- Ti increase at 120-142 km in EISCAT data (*Kurihara et al, 2010*)
- Tn and Ti decrease in the F-region at Poker Flat – FPI and ISR data (*Conde and Nicolls*, 2010)
- Ongoing debate on the relative importance of geomagnetic activity and SSW forcing highlights the complexity of this topic [*Liu et al*., 2011, *Fuller-Rowell et al*., 2011]

Several studies demonstrate high-latitude warming at 120-150 km or cooling in the F – region related to SSW; response at low latitudes is a matter of a debate

January 2009 SSW: Jicamarca ISR and GPS TEC



Chau et al., 2009, 2011

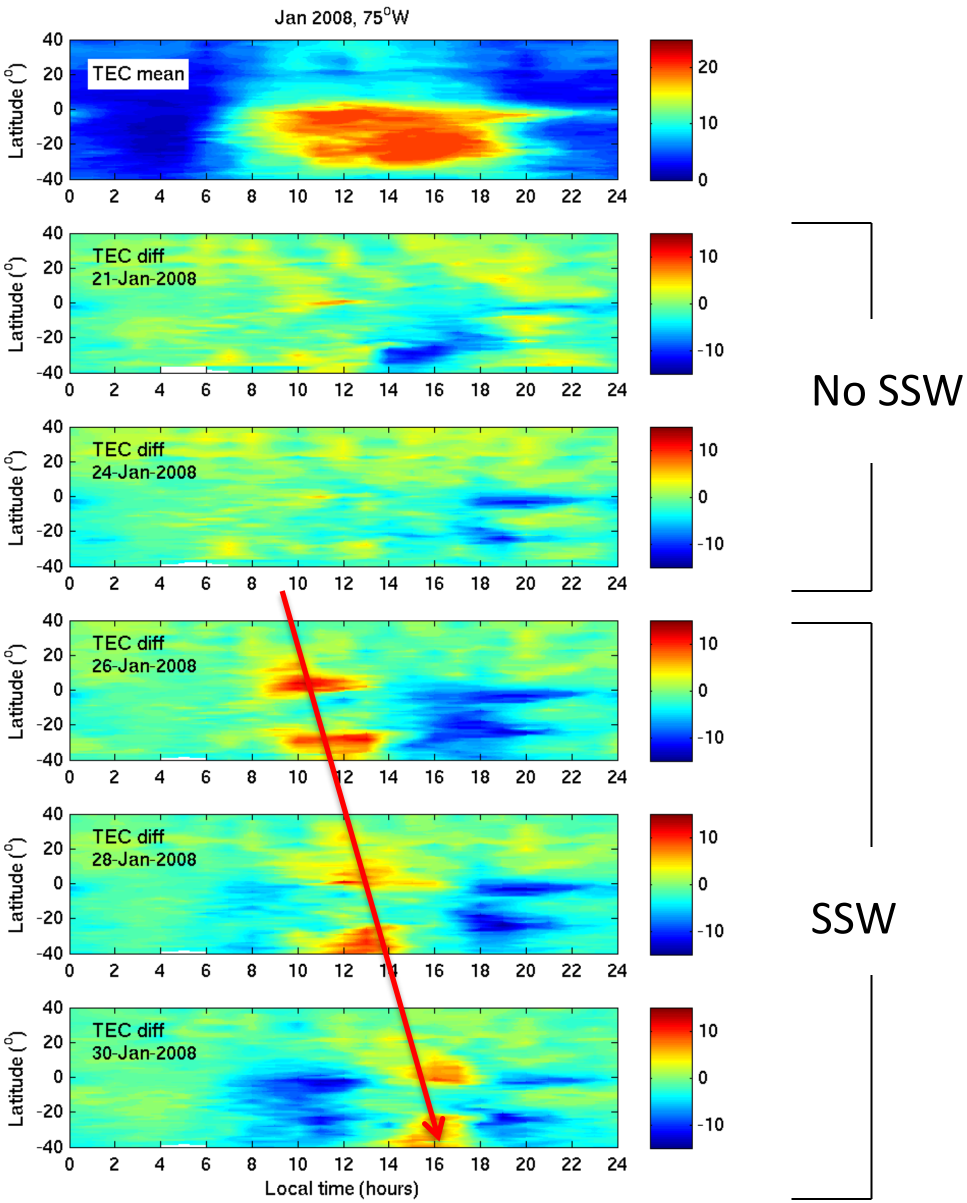


- Upward drift in the morning, downward in the afternoon -12-h wave
- Interpreted as evidence of enhanced 12-tide & E-region dynamo

Goncharenko et al., 2010a

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

GPS TEC at 75ºW, Jan 2008



- Peak daytime TEC: 15 TECu
- No clear pattern prior to SSW
- Variation in TEC during stratwarming: semidiurnal wave, ~5-12 TEC
- Progressive shift to later local times
- Both high amplitude of the wave and rapid phase change lead to large variability in TEC

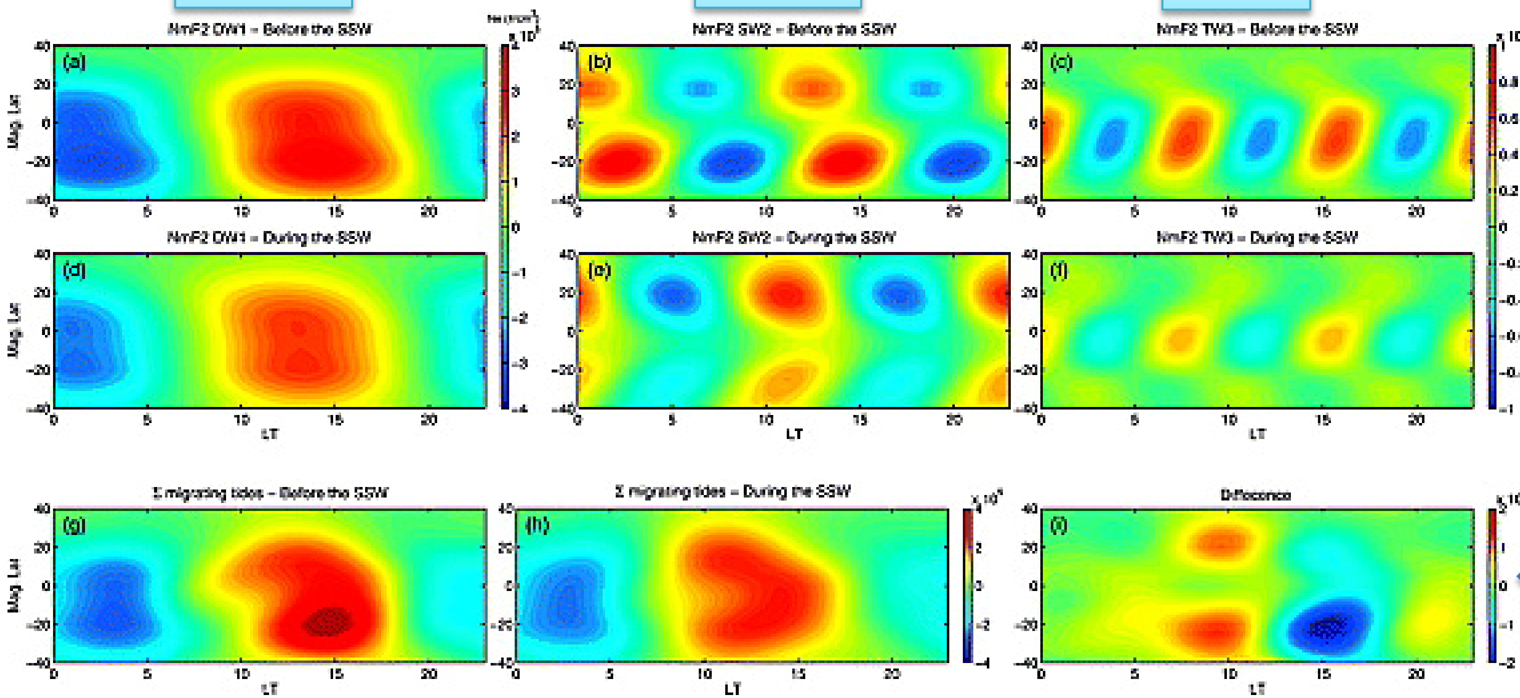
Goncharenko et al., 2010b

COSMIC/FORMOSAT, Jan 2009 SSW

DW1 | SW2 | TW3

No SSW

SSW



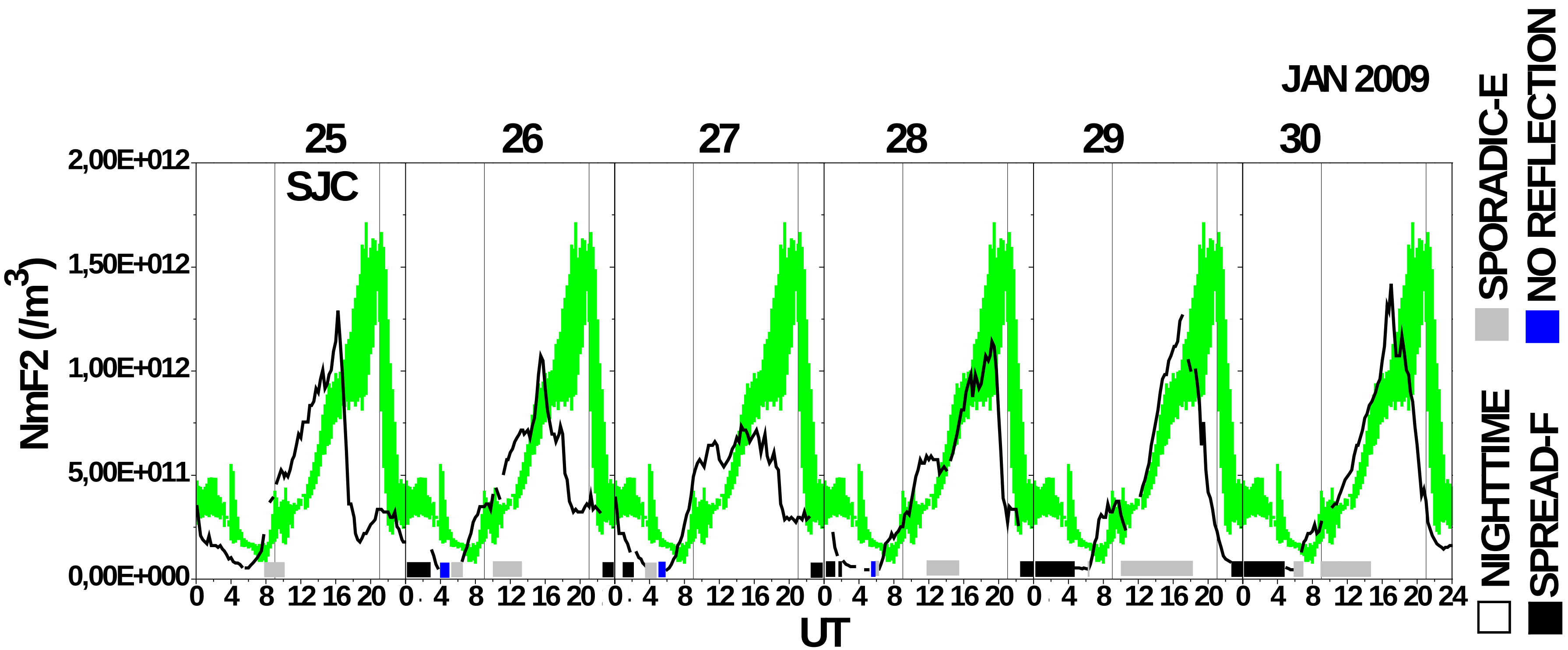
All migrating before SSW | All migrating during SSW | Difference

Lin et al., 2012

- Roles of different tides is a matter of a debate
- COSMIC analysis indicates migrating tides are major drivers
- Non-migrating tides responsible for ~20% of response

COSMIC results perfectly agree with GPS TEC results

South America:
Variations in NmF2 during stratwarming



Green – baseline

Black - SSW

Courtesy of Y. Sahai and R. de Jesus

- São José dos Campos digisonde (23.2 S, 45.9 W)
- January 2009 SSW event
- Decrease in NmF2 by a factor of 4 at sunset; persistent for several days

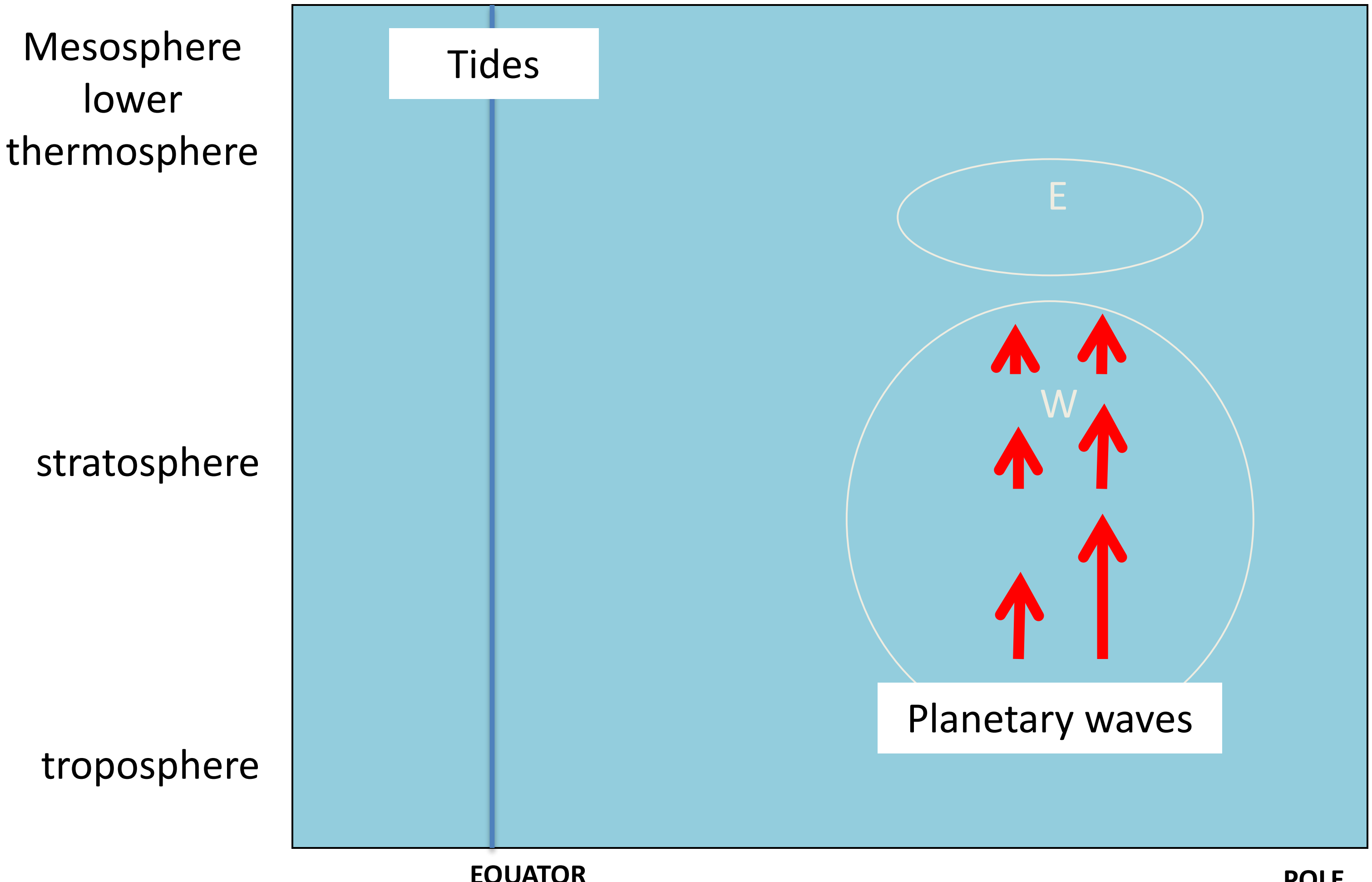
Question: If ionospheric response is so strong, how come scientists did not see it earlier?

- **Answer 1**: Better data availability and better global models
- **Answer 2**: Solar minimum conditions + record strong stratwarmings enabled identification of SSW effects
- **Answer 3**: They did. Nobody believed them:
  - Manson et al., ~1970s; Kazimirovskiy et al., 1970-1980s, Pancheva, 1980s, Stening, 1990s

Answer #4: selective attention effect

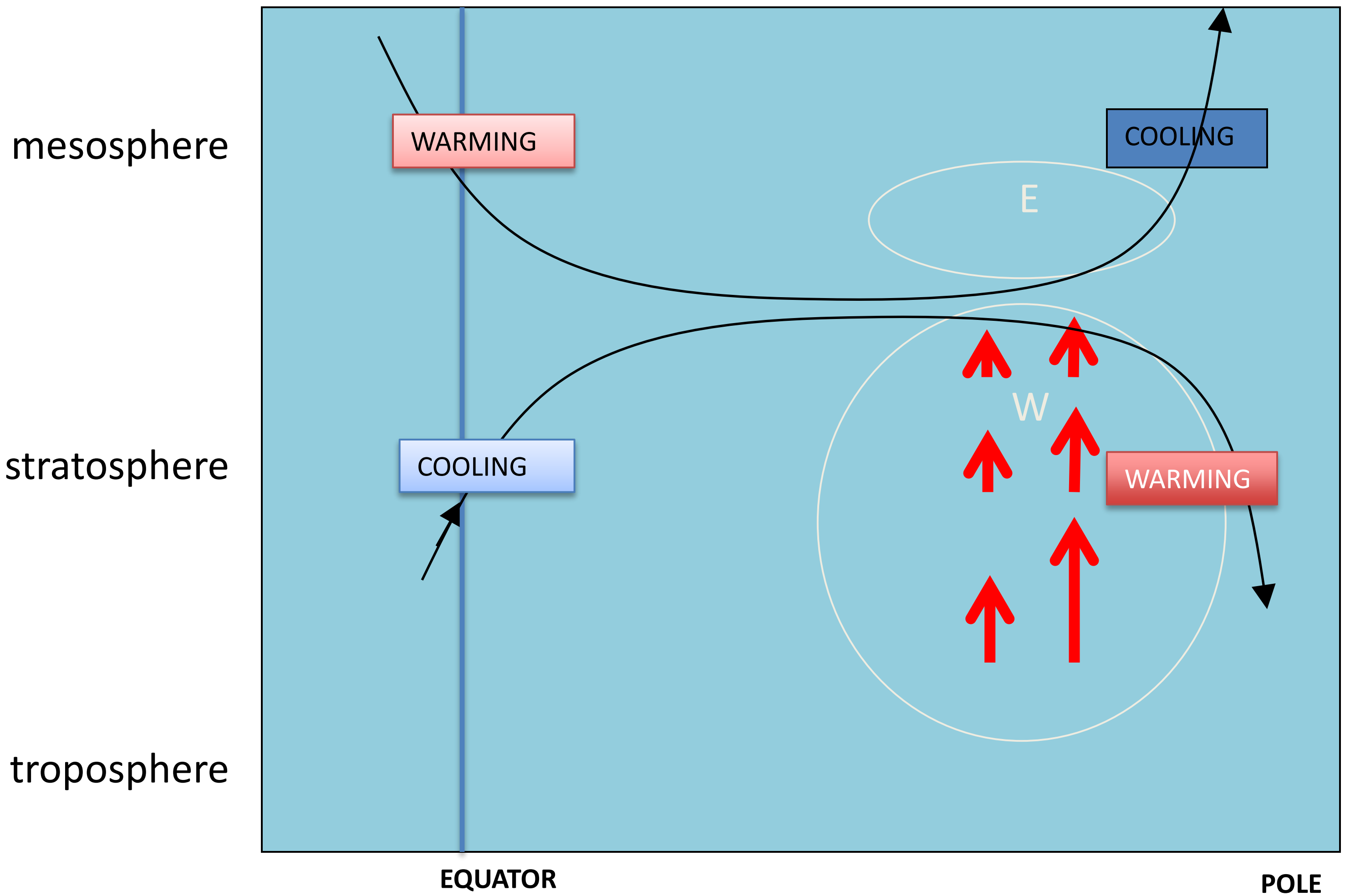
- Unintentional blindness phenomenon
- ~50% of busy audience does not see obvious objects
- Our prior beliefs, interests and expectations shape the way we perceive the world

Main challenge: **How** high-latitude planetary waves modify low-latitude ionosphere?



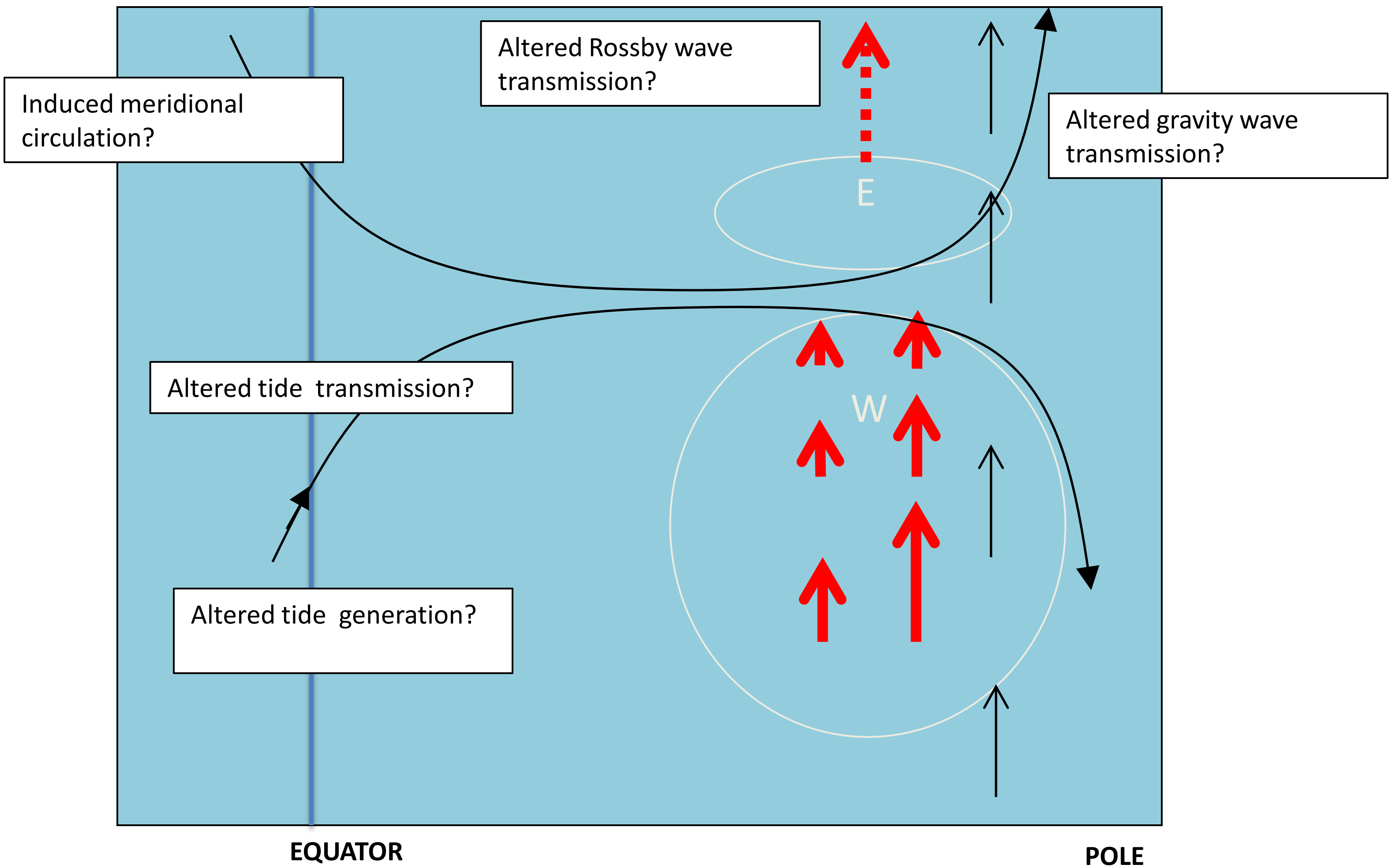
- Planetary waves do not propagate to MLT altitudes
- Amplitude of planetary waves decreases with latitude
- Need to explain how signature is carried in both vertical and horizontal directions

Coupling mechanism
(*Matsuno*, 1971, *Plumb*, 1986, *Garcia*, 1987)

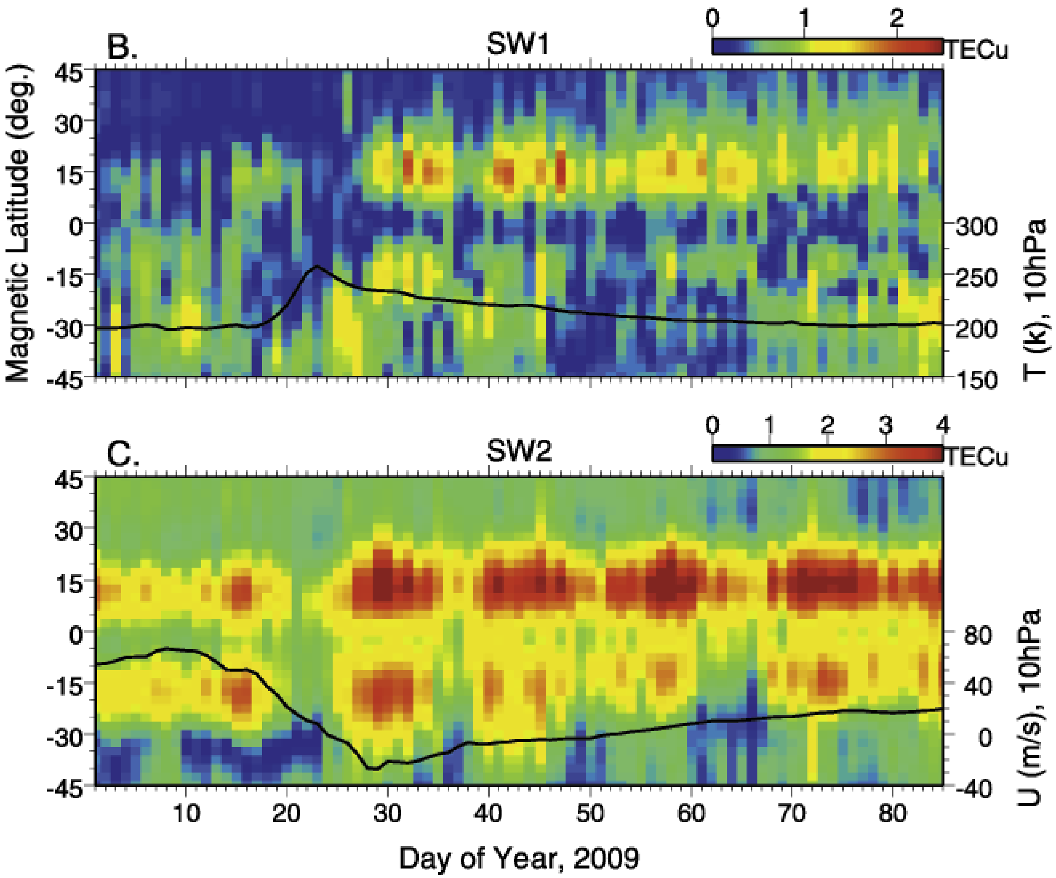


Planetary wave forcing drives a global circulation with a clockwise lower cell (<40km) and a counterclockwise upper cell (>40km)

Possible influences on the upper atmosphere



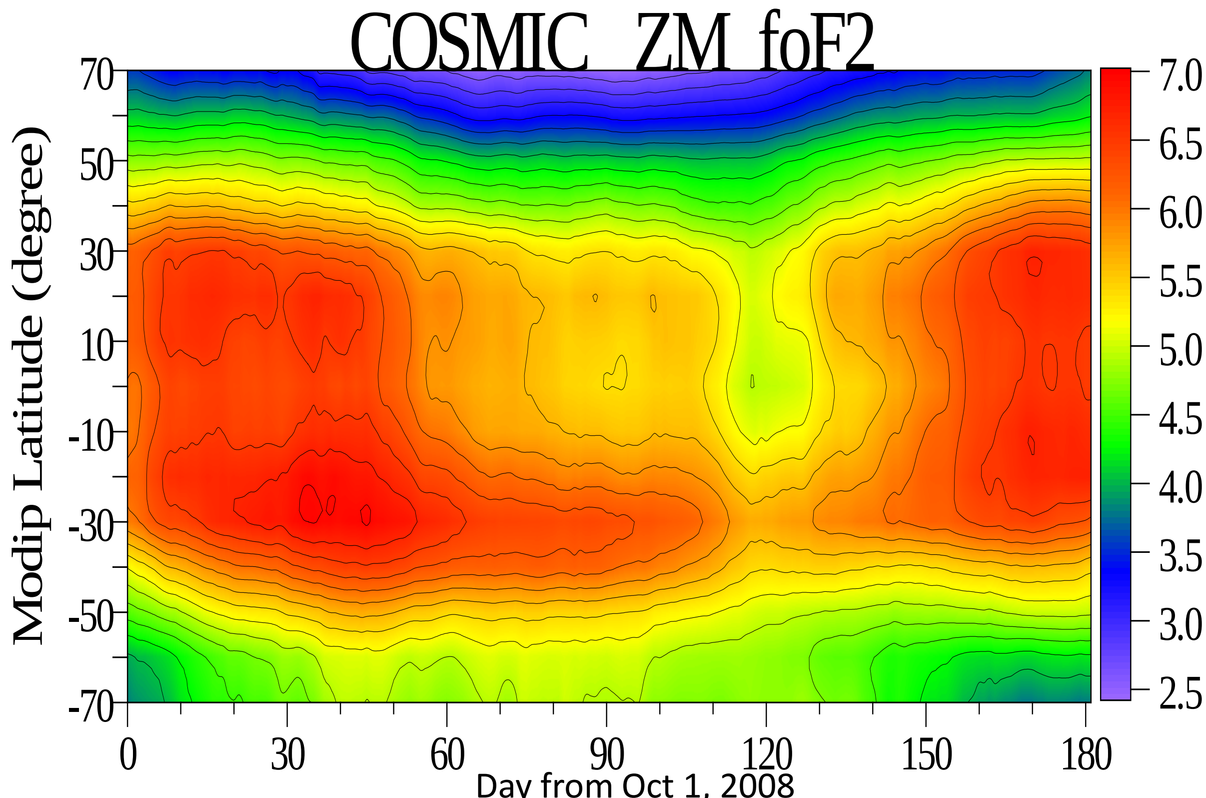
Suggested mechanisms: Interaction of planetary wave and tide



Pedatella and Forbes, 2010

- Non-linear interaction of planetary wave 1 and migrating semidiurnal tide generates non-migrating semidiurnal tide
- JPL TEC data; 2009 SSW
- Increase in both migrating and non-migrating semidiurnal tide
- Partial explanation

Suggested mechanisms: disturbed wind dynamo



Pancheva and Muhtarov, 2011

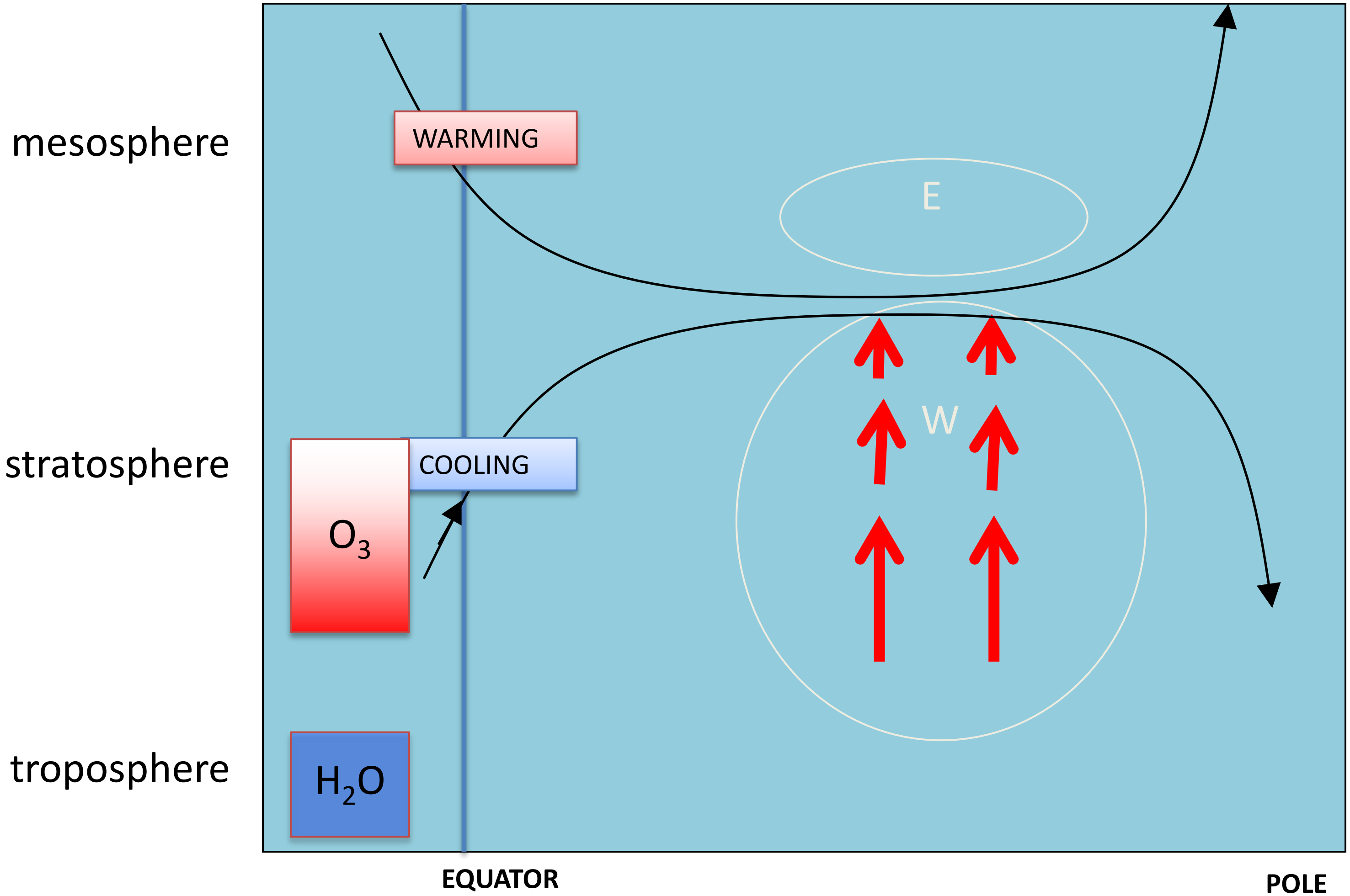
- Decrease in hmF2 and NmF2 in COSMIC data
- Thermospheric warming reported by *Goncharenko and Zhang*, 2008, *Funke et al.*, 2010, *Kurihara et al.*, 2010
- Similar to the disturbed wind dynamo due to geomagnetic storms

Suggested mechanisms: lunar tide

- Supporting experimental evidence found by *Fejer et al*., 2011, *Park et al*., 2012, *Yamazaki et al.*, 2012a,b
- Regular lunar tide ~5m/s
- Amplified during SSW by a factor of 2
- Lunar tide could be influenced by propagation through the altered middle atmosphere (zonal wind, temperature)

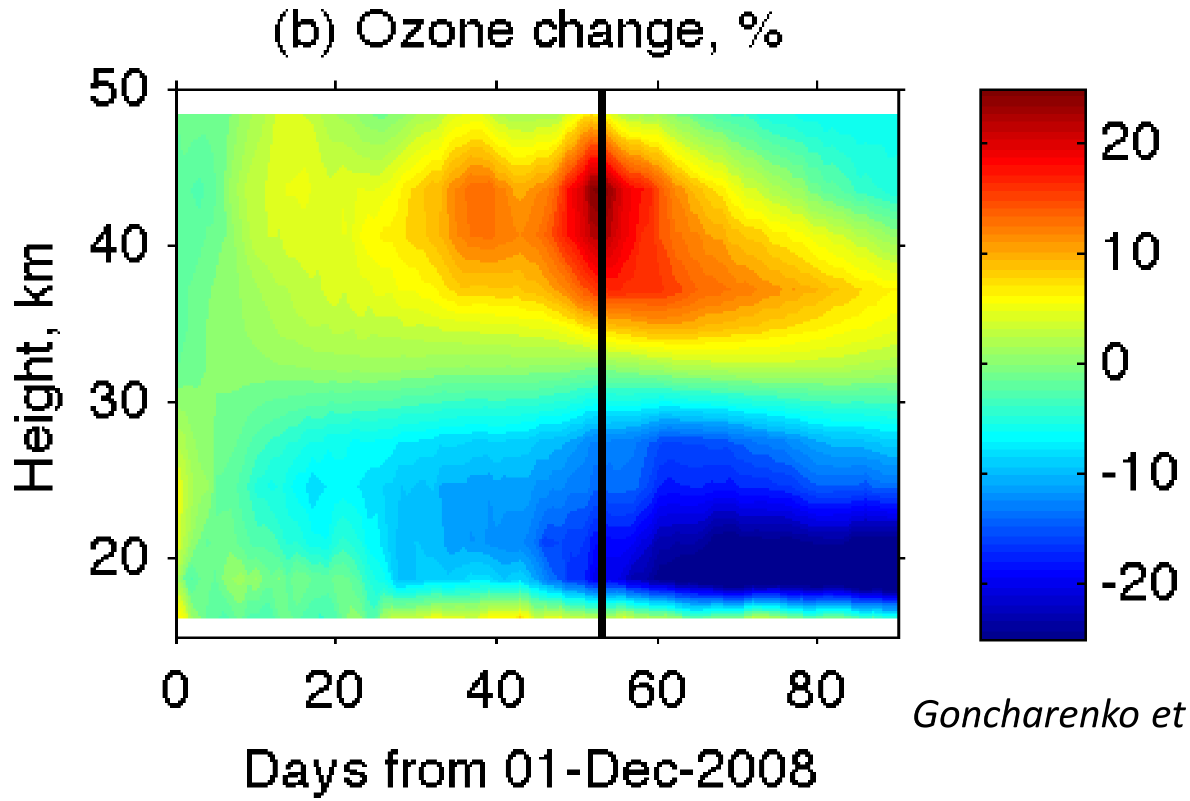
Fejer et al., 2010

Suggested mechanisms: altered generation of tides



- Cooling and circulation changes lead to ozone anomalies in the stratosphere
- Convection changes can lead to water vapor anomalies in the troposphere;

Change in the zonal mean ozone

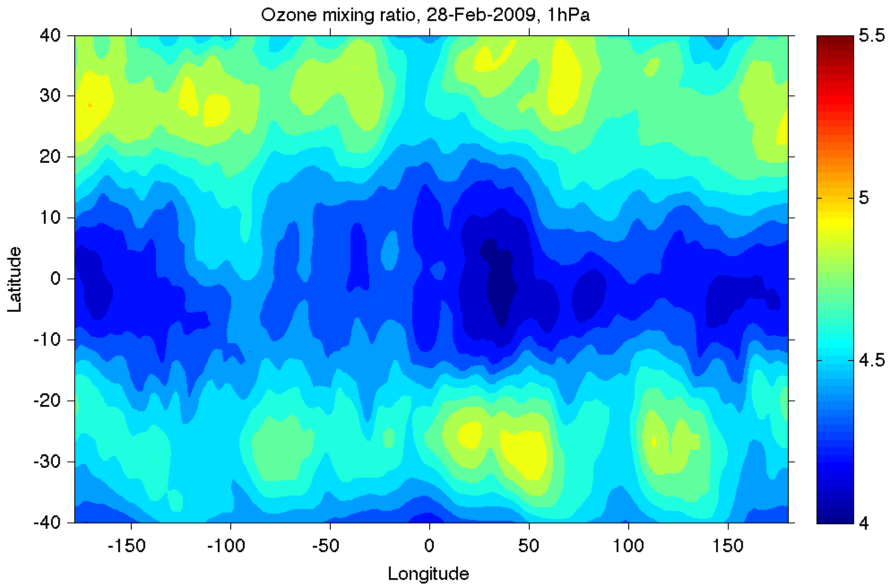


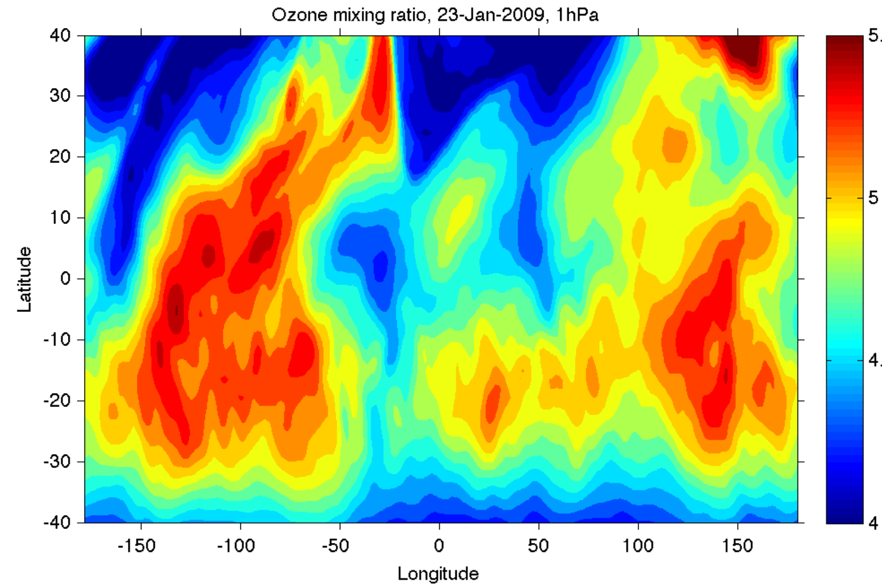
Goncharenko et al., 2012

- Perturbations in the ozone mass mixing ratio reach 25% in the upper stratosphere
- The increase in the low-latitude ozone density between 30-50 km is driven by:
  1) upward transport of ozone from the ozone-rich lower stratosphere,
  2) meridional transport from the Southern to the Northern hemisphere,
  3) longer ozone lifetime due to the tropical cooling

Implications: Amplified semiduirnal migrating tide

Change in the longitudinal distribution of ozone





Low PW activity

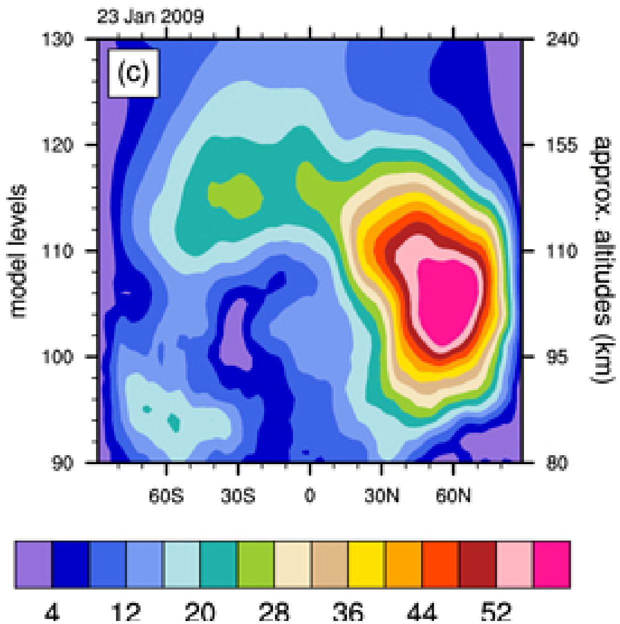
SSW peak

- Longitudinal distribution of ozone becomes strongly asymmetric during SSW

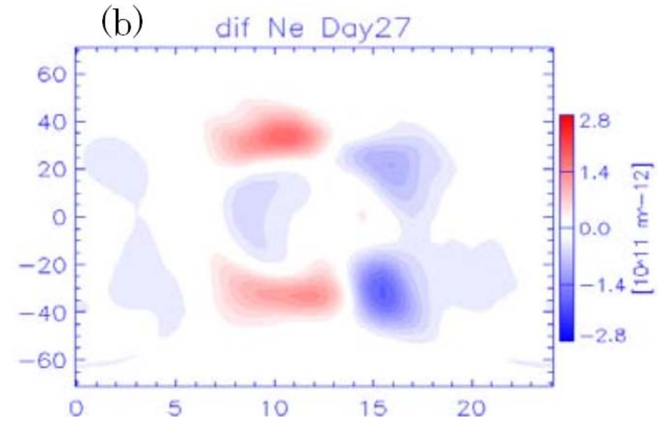
Implications: Amplified semiduirnal non-migrating tide of *stratospheric* origin (in addition to non-migrating tides of *tropospheric* origin)

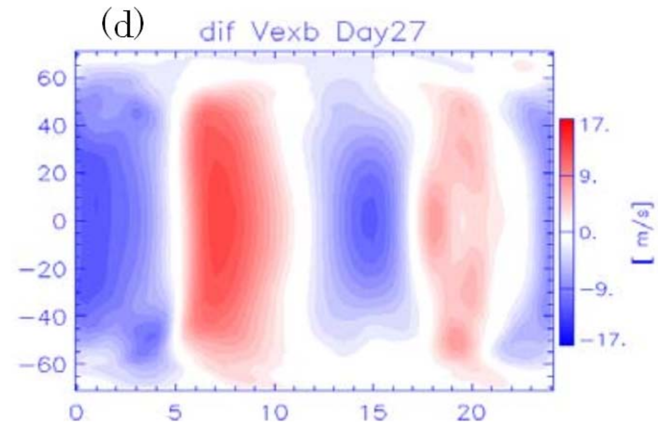
Concept: Planetary waves can indirectly drive short-term variability in tides through variations in the source region

Modeling and simulations of SSW events



Wang et al., 2012
WAM model
SW2 tide





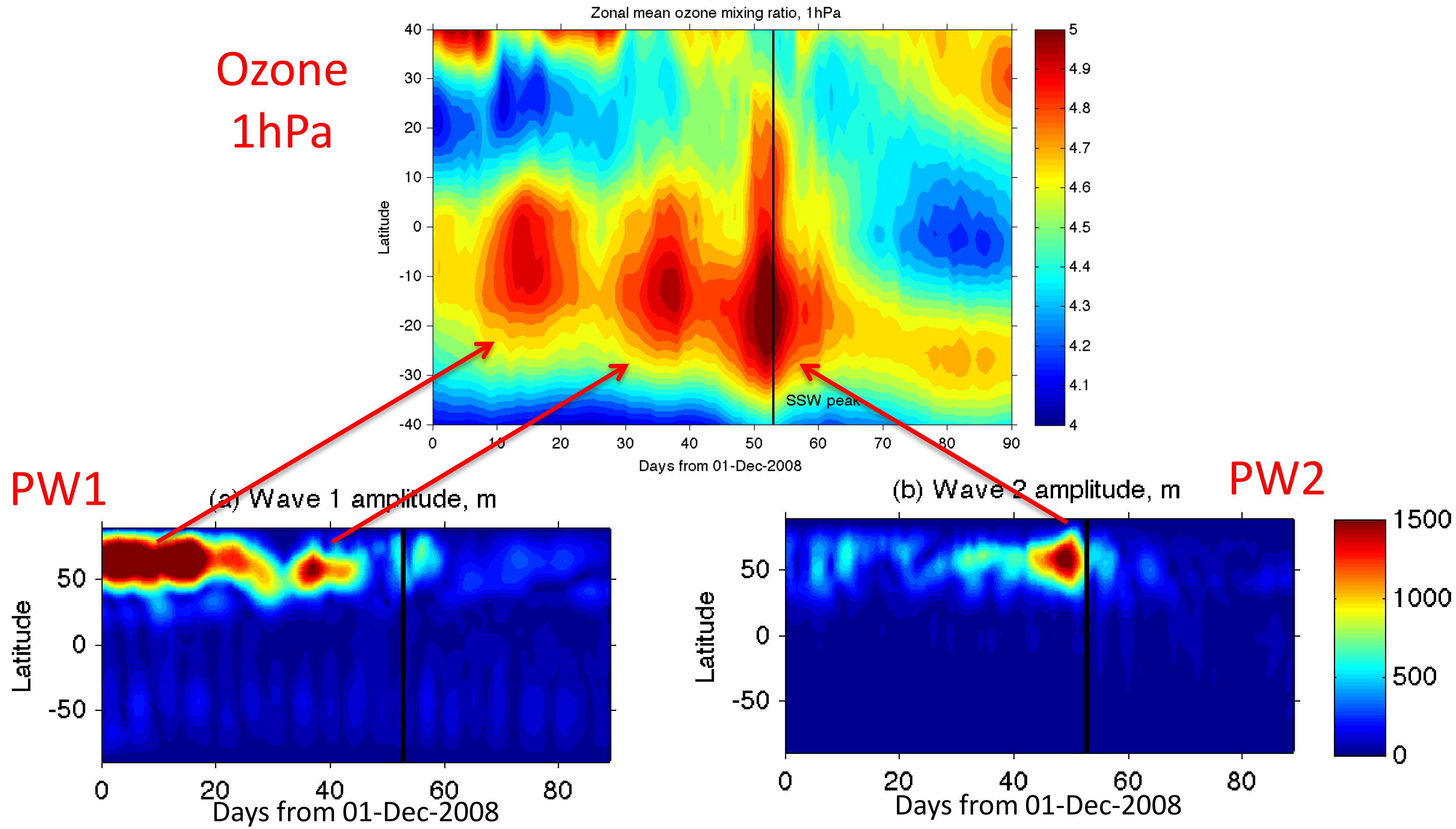
Jin et al., 2012
GAIA model
Variations in Ne and ExB drift

- WACCM simulates well dynamical features of SSW in the stratosphere/mesosphere(*Chandran* 2011, *Kvissel*, 2011, *de la Torre*, 2012)
- Tidal changes in migrating and non-migrating tides in WACCM and GAIA due to PW+tides, ozone changes, and change in propagation conditions (*Jin* 2012, *Pedatella* 2012)
- Models predict the electrodynamic response (*Liu et al.*, 2010, *Fuller-Rowell et al.*, 2010, 2011, *Fang et al.*, 2012, *Jin et al.*, 2012)
- WAM forecasts the response several days ahead (*Fuller-Rowell*, 2011, *Wang et al.*, 2011)

Initial conclusions

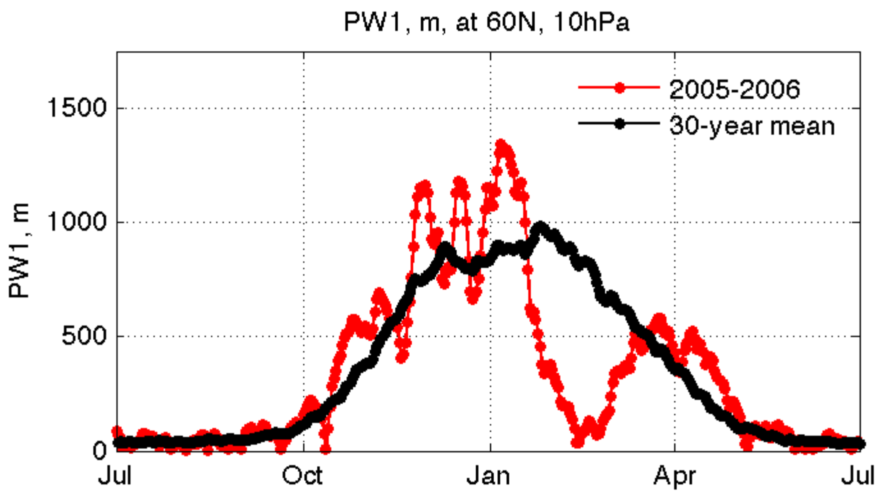
- Solid experimental evidence of profound ionospheric disturbances associated with stratwarming events
- Several mechanisms have been suggested to explain ionospheric anomalies during SSW
- Importance of most mechanisms is not known
- Superposition of effects from different mechanisms can be constructive or destructive; will vary with time, latitude, altitude

Going beyond SSW…

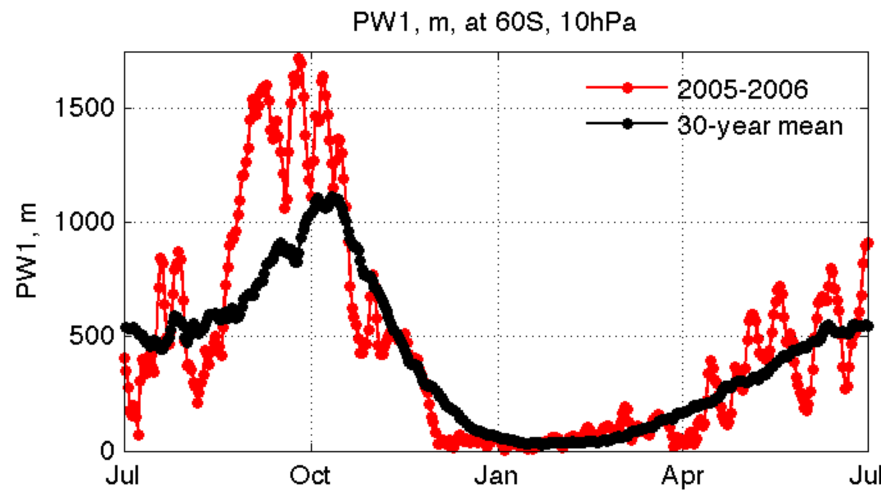


- Other amplifications in planetary waves generate similar variations in ozone
- Consistent with ideas of *Coughlin and Gray* [2009] about continuum of SSW

Going beyond SSW: planetary wave activity



Northern Hemisphere

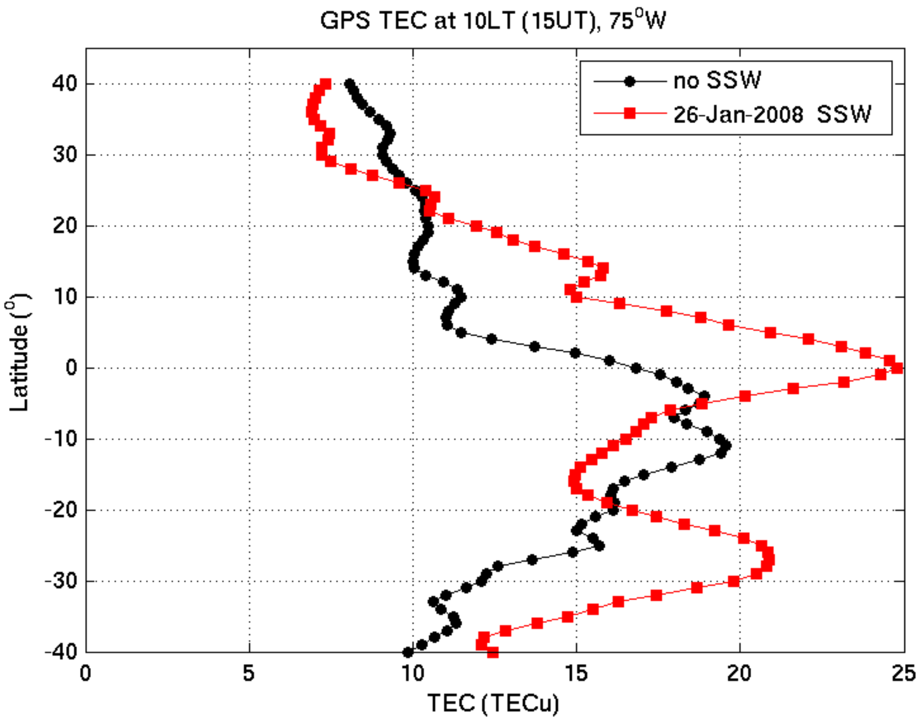


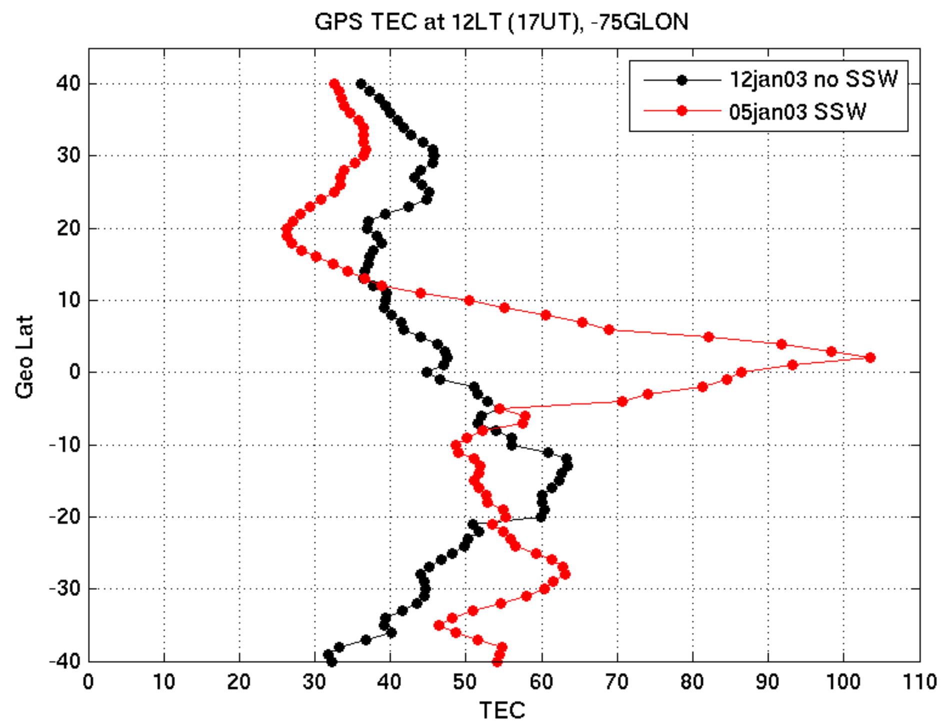
Southern Hemisphere

- PW are amplified in Nov-Mar in the Northern Hemisphere; May-Nov in the Southern Hemisphere
- Anomalies in the equatorial ionosphere can be expected throughout the year

Suggested strategy: use stratwarmings to understand the mechanisms of lower/upper atmosphere coupling; apply knowledge throughout the year

What can we expect for higher solar activity?



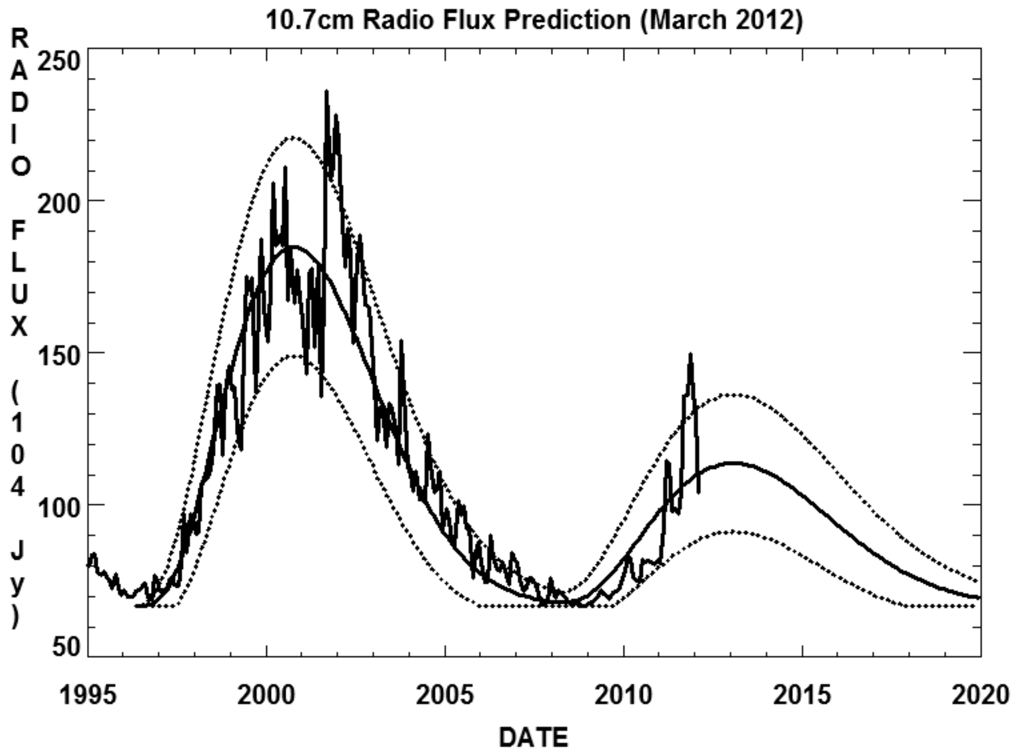


Solar min, F10.7 = 72:
Minor SSW Jan 2008
Max TEC = 25

Solar max, F10.7 = 148:
Minor SSW Jan 2003;
Max TEC = 100

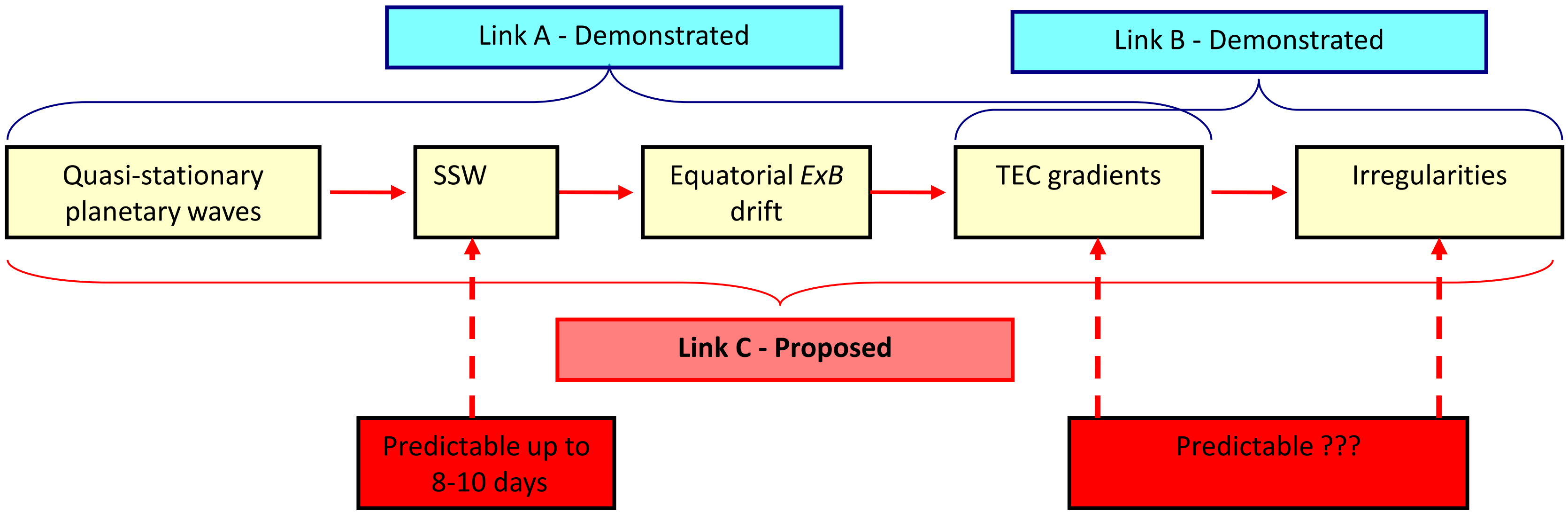
- Increased probability of stratwarmings
- Measurable ionospheric effects (*Fejer et al*., 2010, 2011, *Yamazaki*, 2012); smaller amplitudes in lunar tides, but large phase shift

Outlook for the future



- Low solar flux simplifies studies of lower/upper atmosphere coupling
- During lower solar flux, ionosphere is sensitive to **both** geomagnetic activity and lower atmospheric forcing

Possible implications



- Planetary waves can modify background ionosphere and provide pre-conditioning important for variety of mechanisms affecting irregularities

- Multiple evidence that PW-tide interaction leads to increased tidal variability in the MLT region; implications for F-region are not fully understood
- SSW is a "proof of concept"; applicable to other planetary waves
- Path to the multi-day ionospheric forecast

Focused studies of SSW have the potential of bringing transformative change to ionospheric research and address critical societal need

Why I am optimistic (Part 1)

- We have build a tremendous momentum in studies of lower/upper atmosphere coupling
  - New understanding of ionospheric variability due to migrating and non-migrating tides
  - Overwhelming experimental evidence of strong coupling between the stratosphere and the thermosphere/ionosphere during stratwarmings
- Rapidly developing modeling capabilities (Akmaev, 2011):
  - WAM effort, *Fuller-Rowell et al*., 2010, 2011, *Wang et al*, 2011, *Fang et al*., 2012;
  - WACCM/WACCM-X (*Liu et al*., 2010, *De la Torres et al*., 2011)
  - GAIA (Jin et al., 2011, 2012)
- Rapid advances in the quality of data assimilation products: NASA MERRA, NOGAPS/ALPHA, ECMWF, UKMO
  - 20+ parameters, global, high temporal and spatial resolution
- Current and anticipated advances in ionospheric data availability
  - New missions - SWARM, RBSP, FORMOSAT-7/COSMIC-II, ICON)
  - Major improvements in CEDAR instruments (IS radars, lidars, LISN, FPIs)
- The nature is on our side (solar flux relatively low)

We have the means to address many questions

Why I am optimistic (Part 2)

- Lower atmospheric community: "Raising the roof", *Shaw and Shepherd*, 2008:
  - Only lowermost 10km was thought to be responsible for weather and climate
  - Quality of the atmospheric models improves when upper boundary increased to 50km
  - It took 10-20 years to recognize
- Upper atmospheric community - "lowering the floor":
  - Acceptance of the role of migrating & non-migrating tides - < 10 years (*Hagan and Forbes*, 2002, 2003, *Immel et al*., 2006, *Kil and Paxton*, 2011, *England*, 2011)
  - Growing understanding of the role of planetary waves and stratwarming – 4 years

Rapid acceptance of recent advances is a tribute to the entire CEDAR community

What we will achieve in the next 5-10 years will become a matter of textbooks

These discoveries will be made by you.

My most sincere thanks

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