Stratospheric warmings and their effects in the ionosphere

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• 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?
There is such a phenomenon as sudden stratospheric warming...

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

Record strong SSW

ISR campaign every winter

“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

Papers rejected

Papers cited 25-45 times

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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 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
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

- 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...

- First discovered 60 years ago
- Mesospheric effects are known since 1970s
SSW is not only stratospheric event...

- 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

- 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

Baldwin and Dunkerton, 2001
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)

- 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, 42°N

Model: TIMEGCM

Goncharenko and Zhang, 2008

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
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.

- 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)

*Funke et al., 2010*
Entire daytime low to mid-latitude ionosphere is affected during stratwarming; TEC change 50-150%

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
GPS TEC at 75°W, 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 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
• 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

Courtesy of Y. Sahai and R. de Jesus
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


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

Induced meridional circulation?

Altered Rossby wave transmission?

Altered gravity wave transmission?

Altered tide transmission?

Altered tide generation?
Suggested mechanisms: Interaction of planetary wave and tide

- 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

Pedatella and Forbes, 2010
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;
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 semidurnal migrating tide.
Change in the longitudinal distribution of ozone

- Longitudinal distribution of ozone becomes strongly asymmetric during SSW

Implications: Amplified semidiurnal 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

- 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

- 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?

- 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**

- Quasi-stationary planetary waves
- SSW
- Equatorial $ExB$ drift
- TEC gradients
- Irregularities

**Link A - Demonstrated**

**Link B - Demonstrated**

**Link C - Proposed**

Predictable up to 8-10 days

Predictable ???

- Planetary waves can modify background ionosphere and provide preconditioning 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.
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”:
  – 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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• To many people who said “I do not understand everything you are talking about, but this is what I can do”