APPLICATION OF ISR TECHNOLOGY TO THE UPPER ATMOSPHERIC LONG-TERM TREND STUDY

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With contributions from John Holt

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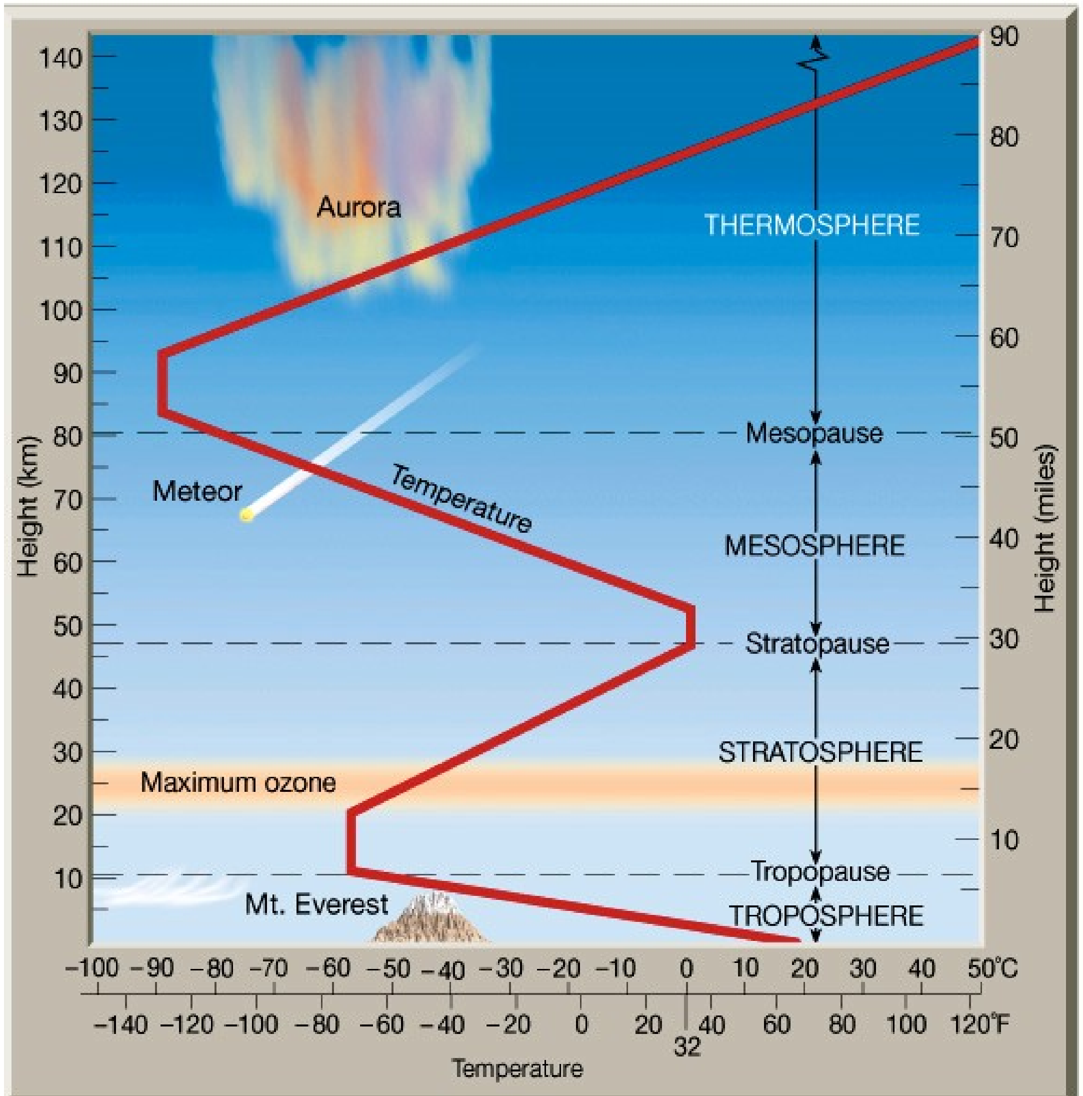
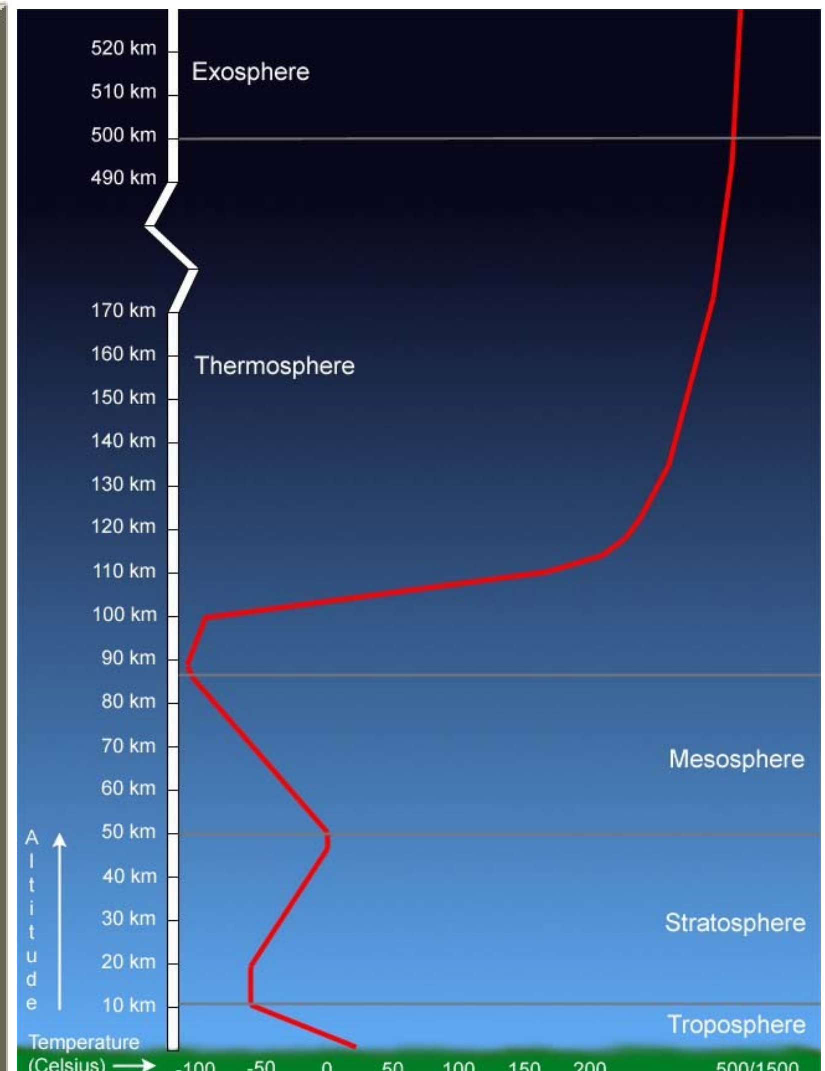
Outline

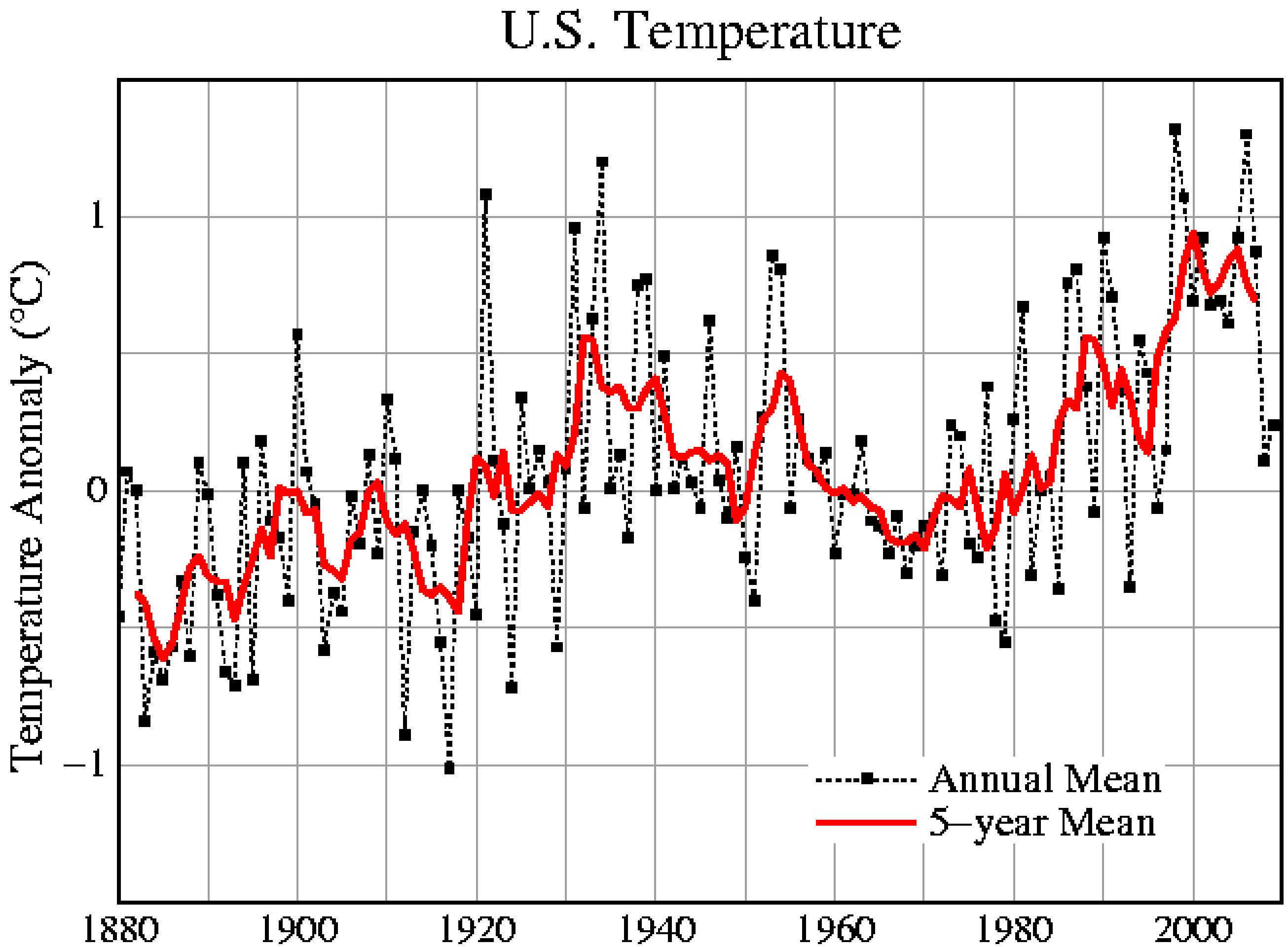
- Introduction -- Temperature efforts
- ISR observations of ion temperature trends at different heights of the upper atmosphere
- Results of the thermospheric parameters
  - Exospheric temperature
  - $[O]_{400}$
- ISR results compared to other data
- Summary

Atmospheric temperature





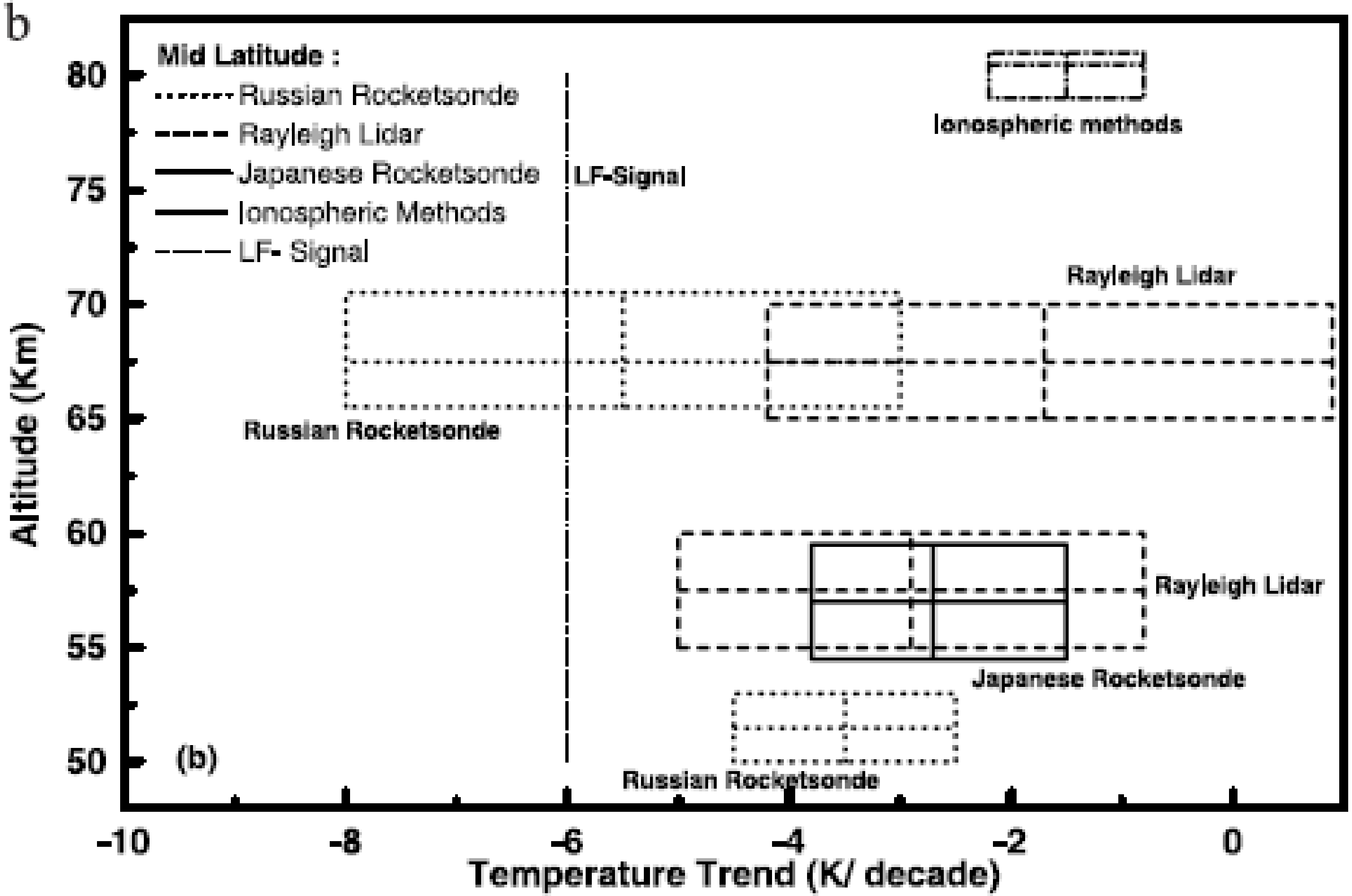
Annual Mean Temperature Change in the US



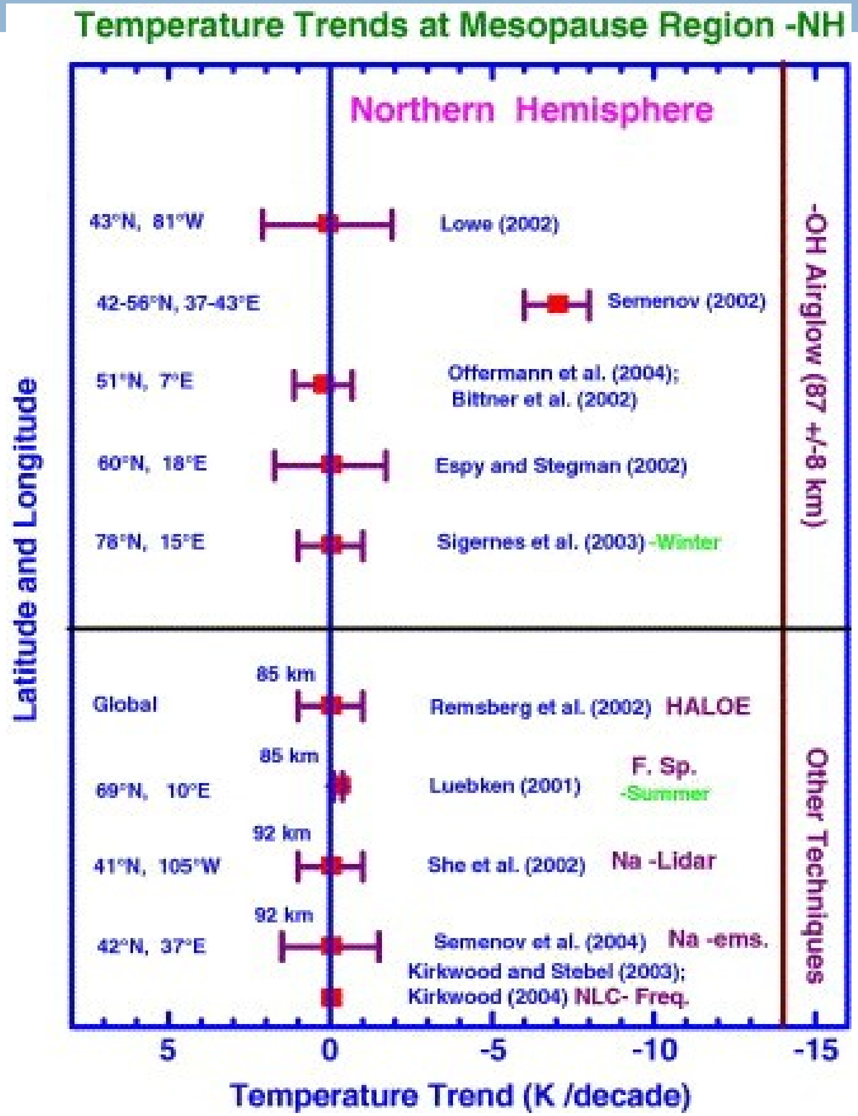
Annual and five-year running mean surface air temperature in the contiguous 48 United States (1.6% of the Earth's surface) relative to the 1951-1980 mean.

Observed cooling in the mesosphere

b



Mesopause



Temperature Trends at Mesopause Region -NH
Northern Hemisphere
43°N, 81°W
Lowe (2002)
42-56°N, 37-43°E
Semenov (2002)
51°N, 7°E
Offermann et al. (2004);
Bittner et al. (2002)
60°N, 18°E
Espy and Stegman (2002)
78°N, 15°E
Sigernes et al. (2003) -Winter
-OH Airglow (87 +/-8 km)
85 km
Global
Remsberg et al. (2002) HALOE
85 km
69°N, 10°E
Luebken (2001)
F. Sp.
-Summer
92 km
41°N, 105°W
She et al. (2002)
Na -Lidar
92 km
42°N, 37°E
Semenov et al. (2004)
Na -ems.
Kirkwood and Stebel (2003);
Kirkwood (2004) NLC- Freq.
Other Techniques
Latitude and Longitude
5
0
-5
-10
-15
Temperature Trend (K /decade)

Thermosphere: theoretical modeling

Roble and Dickinson: Trace Gases and the Upper Atmosphere

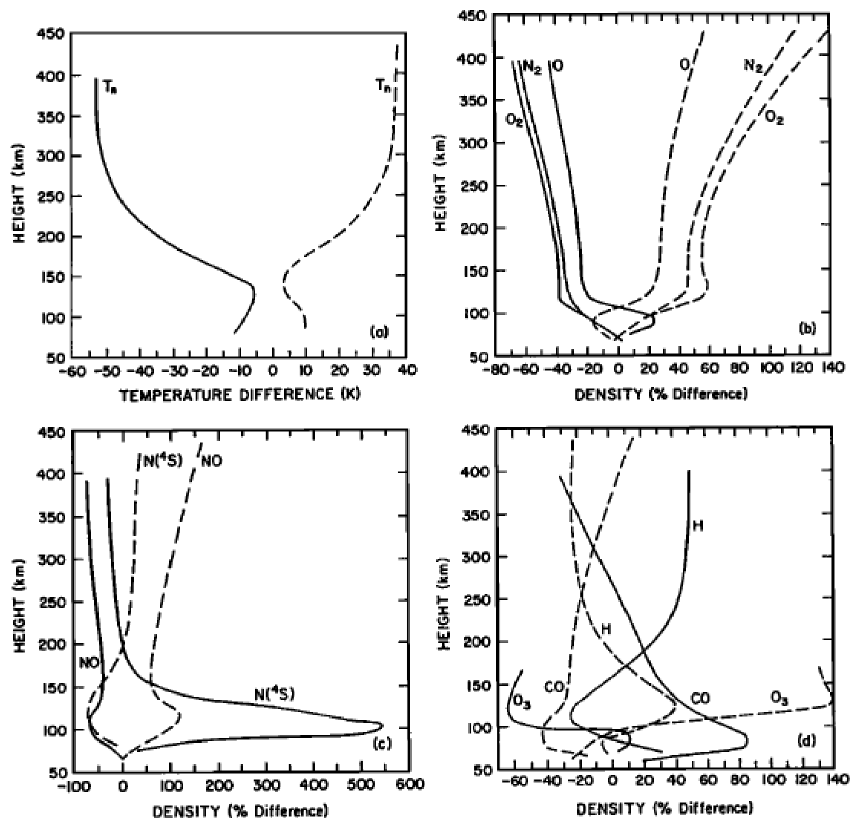


Fig. 2. Calculated (a) neutral gas temperature difference profile from the base case for the case where trace gases are doubled (solid lines) and halved (dashed lines), (b) density difference profiles (%) for O, O_2 and N_2 for the case where trace gases are doubled (solid lines) and halved (dashed lines), and (c) same as (b) except for NO and $N(^4S)$ and (c) same as (b) except for O_3, H and CO.

Roble and Dickinson (1989)

CO_2 at 60 km was doubled or halven

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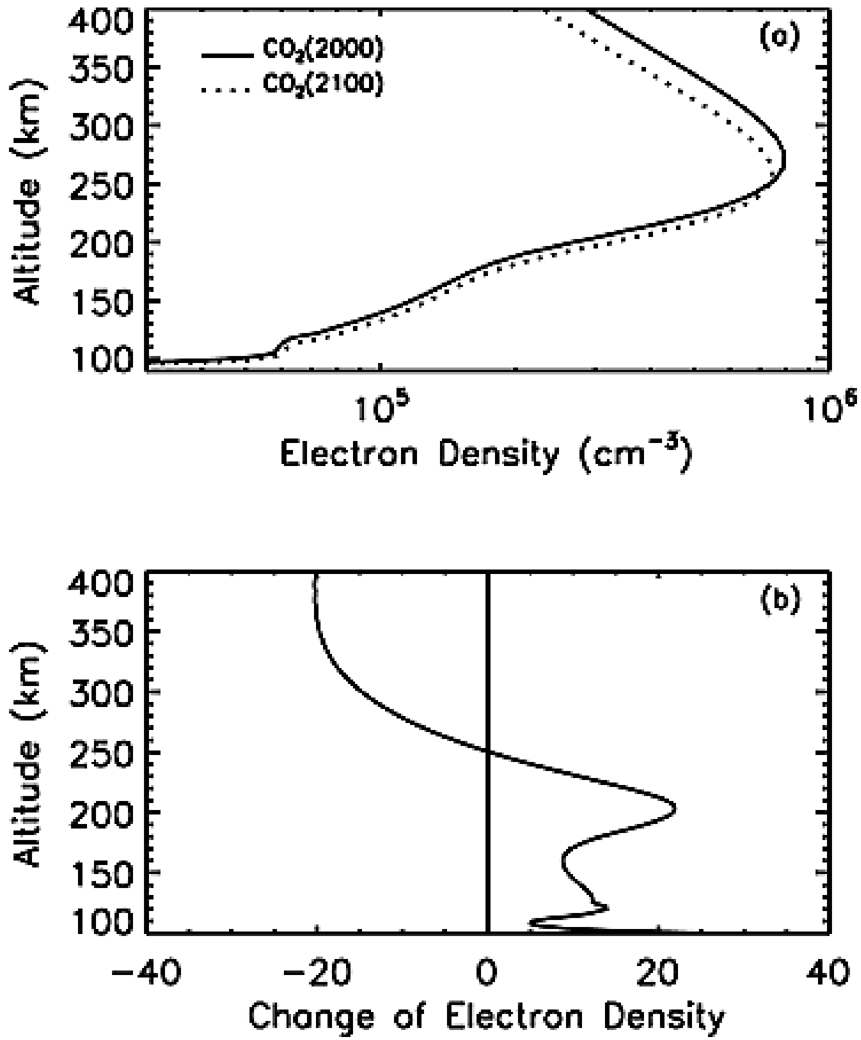
Ionospheric responses



Qian et al. (2008)

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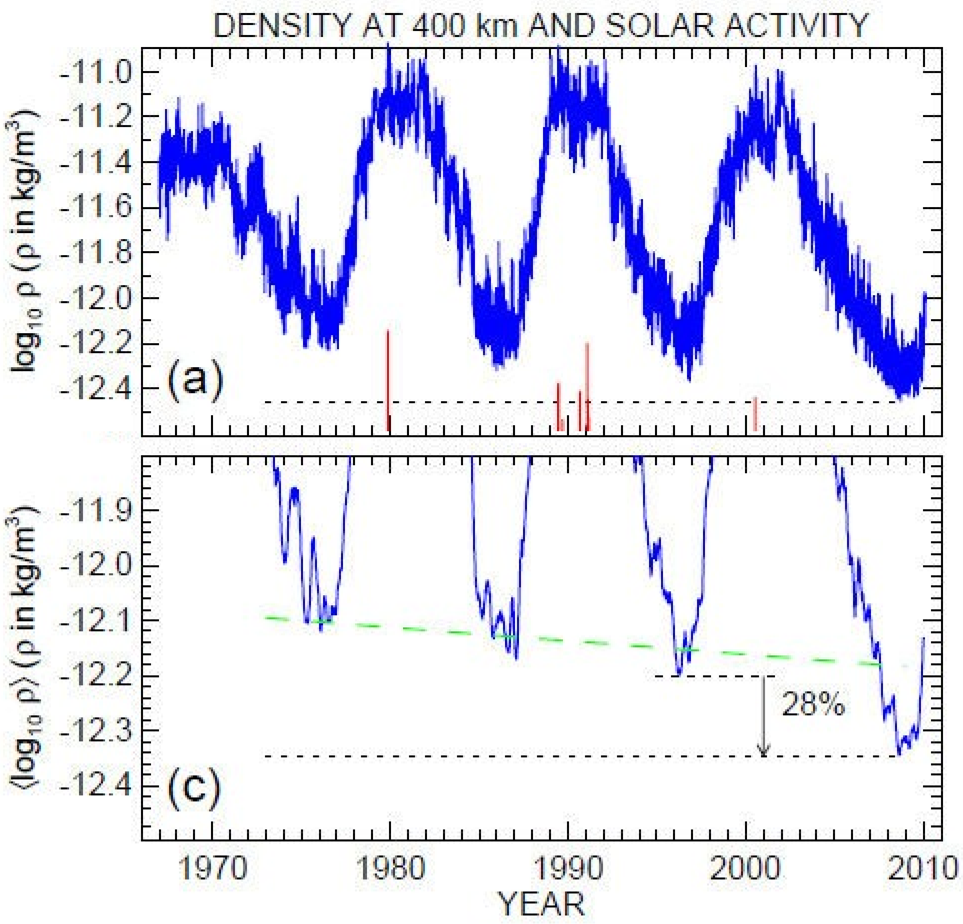
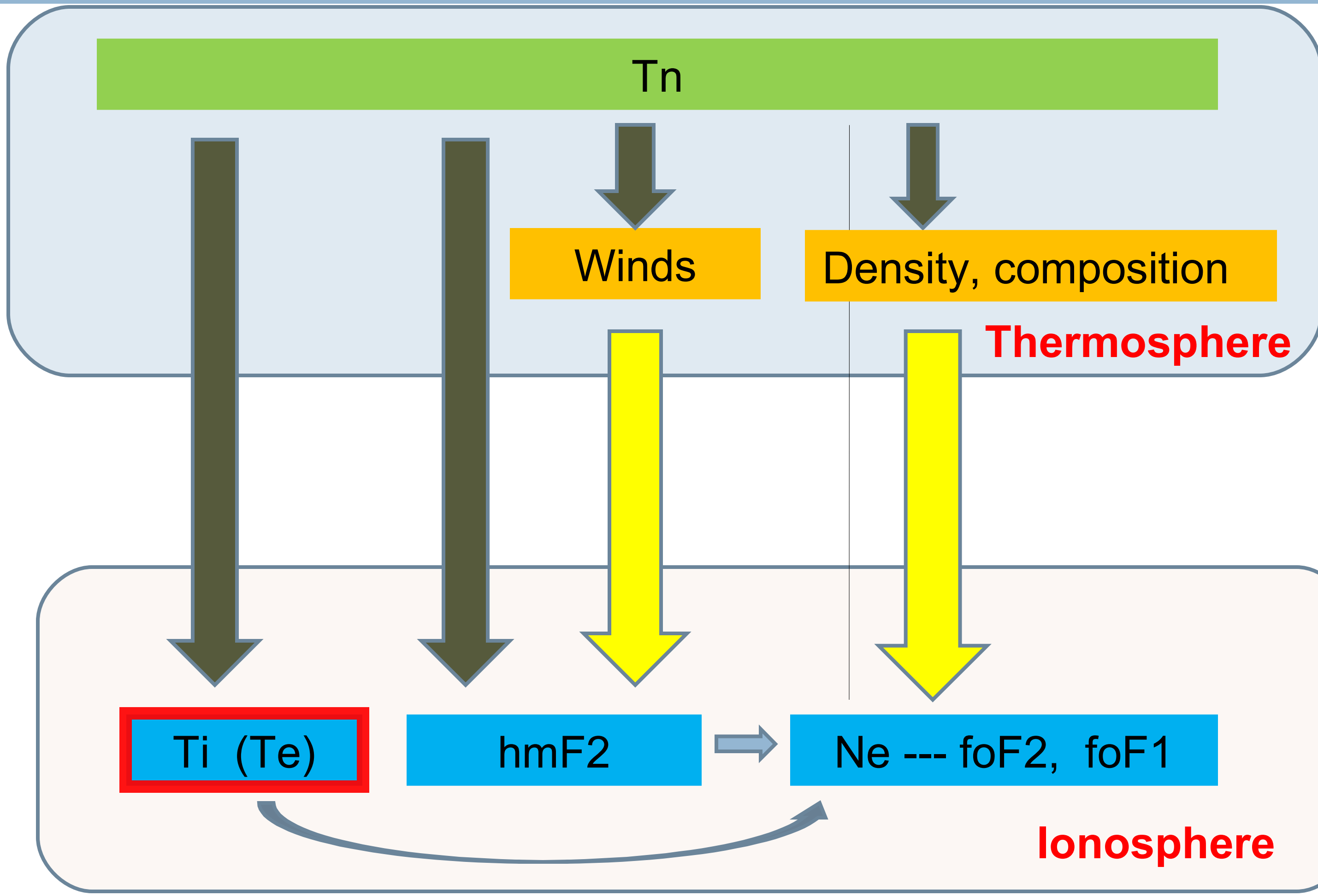
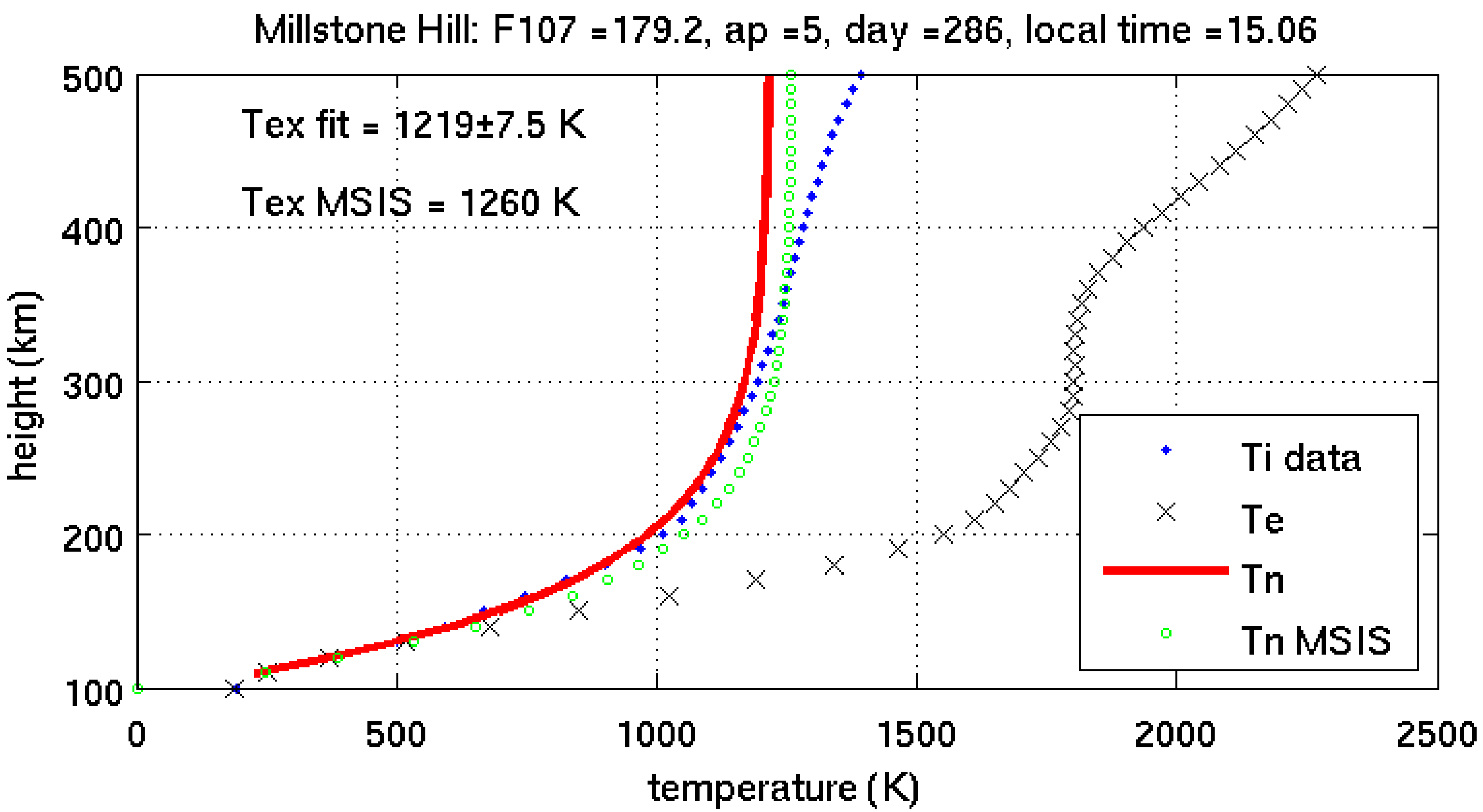
Observed thermospheric density change



Temperature effects



Ti, Te, Tn



Millstone Hill: F107 =179.2, ap =5, day =286, local time =15.06
Tex fit = 1219±7.5 K
Tex MSIS = 1260 K
height (km)
temperature (K)
Ti data
Te
Tn
Tn MSIS
500
400
300
200
100
0
500
1000
1500
2000
2500

Advantages of using ISR data

- Direct measure of thermal status
  - Ti, Te, Tn
  - Ti dependency on solar activity and season is much easy to be determined.
- Large height coverage
  - Topside, bottomside
  - Height dependency
- Multiple parameters

Millstone Hill ISR

N_e

T_e

T_i

V_0

Ion composition

$T_n \leftarrow\rightarrow T_{ex}$

EXB

U

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MADRIGAL -- Long-term ISR Database

Documentation
Empirical
Ionospheric Models
CVS
Mailing Lists
Download/Update
Madrigal
Madrigal Sites

- Millstone Hill, USA
- EISCAT, Norway
- SRI International, USA
- Cornell University, USA
- Jicamarca, Peru
- ISTP, Russia
- Wuhan, China

The Open Madrigal Initiative

MIT Haystack Observatory, home of the Millstone Hill Incoherent Scatter Radar, has supported an on-line incoherent scatter database since 1980. This early database evolved into both the CEDAR Database at the National Center for Atmospheric Research (NCAR) and the Madrigal Database at Millstone Hill. The CEDAR and Madrigal Databases have very different user interfaces and capabilities, but use the same basic data format, and data files are easily exchanged between the two systems.

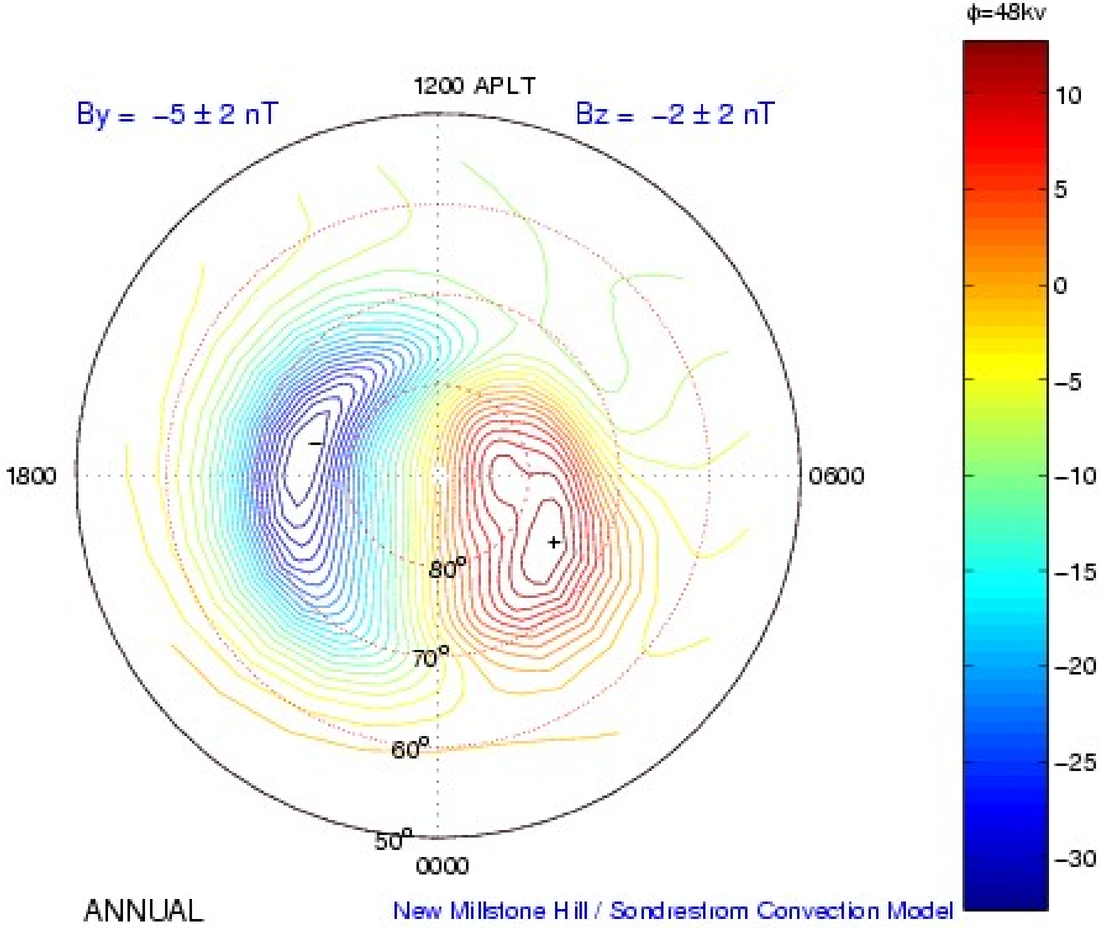
Madrigal is a robust, World Wide Web based system capable of managing and serving archival and real-time data, in a variety of formats, from a wide range of instruments. Data can be accessed from the Madrigal sites at Millstone Hill, USA, EISCAT, Norway, SRI International, USA, Cornell University, USA, Jicamarca, Peru, The Institute of Solar-Terrestrial Physics, Russia, and Wuhan Ionospheric Observatory, the Chinese Academy of Sciences, using standard Web browsers; and directly, using APIs which are available for several popular programming languages.

The distributed Madrigal Database has been recognized by a Sun Microsystems Academic Excellence Award which included the Haystack Observatory server which hosts the Open Madrigal project.

POWERED BY Sun microsystems

http://www.openmadrigal.org/

Ionospheric climatology study based on ISR observations at Millstone Hill



ISRIM: Incoherent Scatter Radar Ionospheric Model

Model Millstone Hill **Output Parameter** NeI

Day Number (day)	Start 30	End 345	Interval 45	between 1-365
Local Time (hour)	Start 0	End 24	Interval 1	between 0-24
Altitude (km)	Start 100	End 500	Interval 20	between 100-600 [ESR,Tromso, St. Santin,Arecibo], 200-500[MUR], 100-1000[MH]; also used for IEC calculation
Geodetic Latitude (degree)	Start 45	End 65	Interval 4	for regional model only; between 18-70 [EastAmerica], 33-55[MH], or 45-78[Europe]
Solar Activity	F107 135			previous day's index; between 70-300
Magnetic Activity	ap index 15			3-hourly index for the previous 3hours; between 0-100

RUN Reset

Method

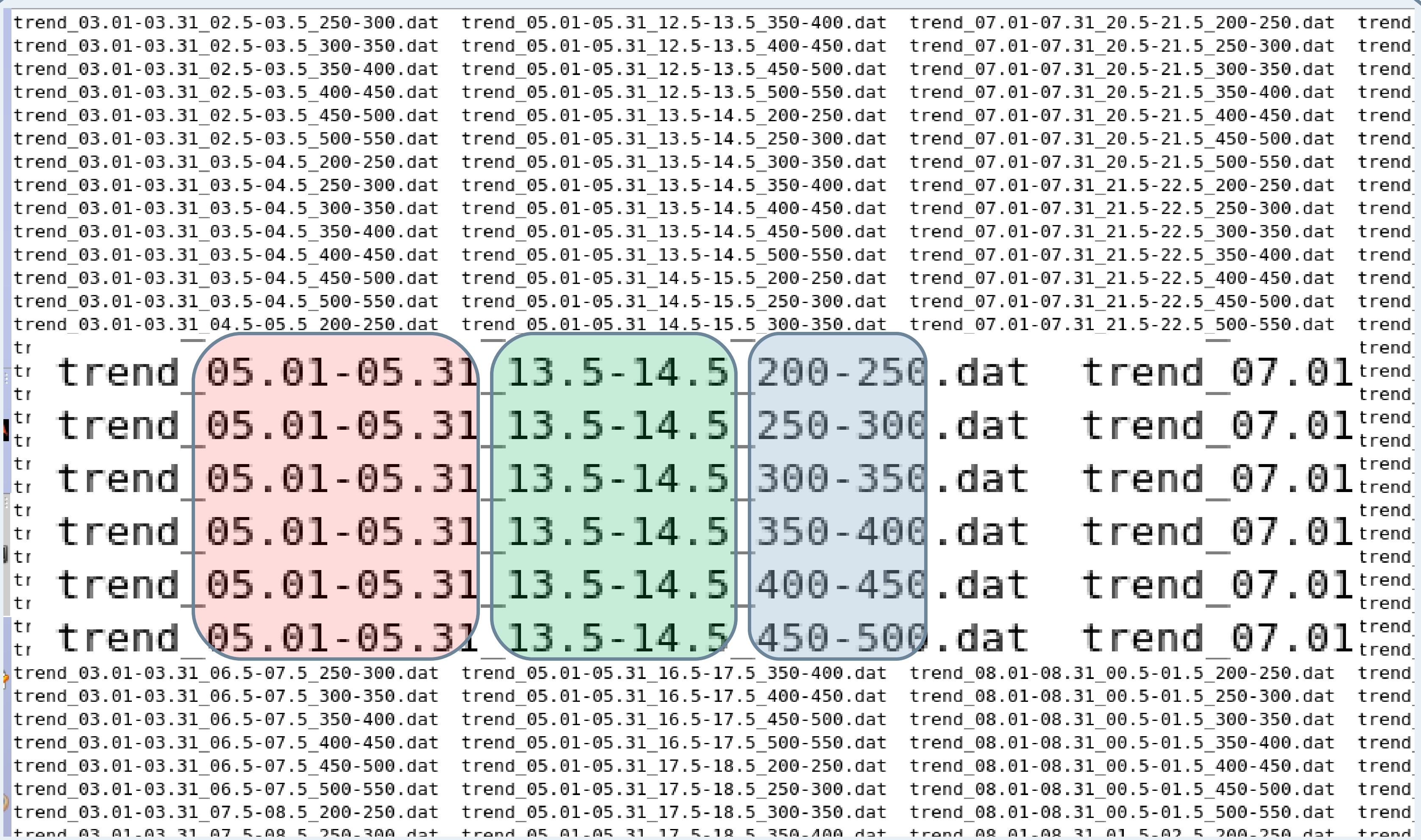
- Getting data
- Binning
- Fitting / modeling
- Determining the trend
- Error estimate
- Derived parameters

Madrigal: global search

```
ngtze:/modelspace/Trends/Millstone > more globalIsprintMH.py
/opt/madrigal/bin/python


"This script runs a global search through Madrigal data from a given URL.

  This script is a stand-alone application, and can be run from anywhere with a connection to the internet.
  It runs on either unix or windows.  It requires only the MadrigalWeb python module to be installed.

 Usage:

      globalIsprint --url=<Madrigal url> --parms=<Madrigal parms> --output=<output file> [options]

      where:

      --url=<Madrigal url> - url to homepage of site to be searched
                             (ie, http://www.haystack.mit.edu/madrigal/)
                             This is required.

      --parms=<Madrigal parms> - a comma delimited string listing the desired Madrigal parameters
                               in mnemonic form.  (Example: gdalt,dte,te).  Data will be returned
                               in the same order as given in this string.

      --output=<output file name> - the file name to store the resulting data.

      --user_fullname=<user fullname> - the full user name (probably in quotes unless your name is Sting or Madonna)

      --user_email=<user email>

      --user_affiliation=<user affiliation> - user affiliation.  Use quotes if it contains spaces.

      and options are:

      --startDate=<MM/DD/YYY> - start date to filter experiments before.  Defaults to allow all experiments.

      --endDate=<MM/DD/YYY> - end date to filter experiments after.  Defaults to allow all experiments.

      --inst=<instrument list> - comma separated list of instrument codes or names.  See Madrigal documentation
```

Data binning

```
yangtze:/modelspace/Trends/Millstone > m exeGetDataMHFregion
#!/bin/sh
# The madtclsh path is longer than 32 characters. So, we take advantage
# of the fact that a backslash continues a comment line in tcl \
exec /opt/local/bin/tclsh "$0" ${1+"$@"}
#exec /usr/bin/tclsh "$0" ${1+"$@"}

for {set h1 200} {$h1 <550} {incr h1 +50} {
set h2 [expr {$h1 + 50}]
set num 0
for {set t1 -00.5} {$t1 <1} {incr num +1} {
set t1 [expr {$t1+1}]
set t2 [expr {$t1+1}]
for {set mth 01} {$mth <13} {incr mth +1} {exec /opt/madrigal/bin/python globalI
sprintMH.py --filter=year,1960,2009 --seasonalStartDate=$mth/01 --seasonalEndDat
e=$mth/31 --filter=ut,$t1,$t2 --filter=gdalt,$h1,$h2
}
}
}

yangtze:/modelspace/Trends/Millstone >
```


trend_03.01-03.31_02.5-03.5_250-300.dat
trend_03.01-03.31_02.5-03.5_300-350.dat
trend_03.01-03.31_02.5-03.5_350-400.dat
trend_03.01-03.31_02.5-03.5_400-450.dat
trend_03.01-03.31_02.5-03.5_450-500.dat
trend_03.01-03.31_02.5-03.5_500-550.dat
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trend_03.01-03.31_03.5-04.5_400-450.dat
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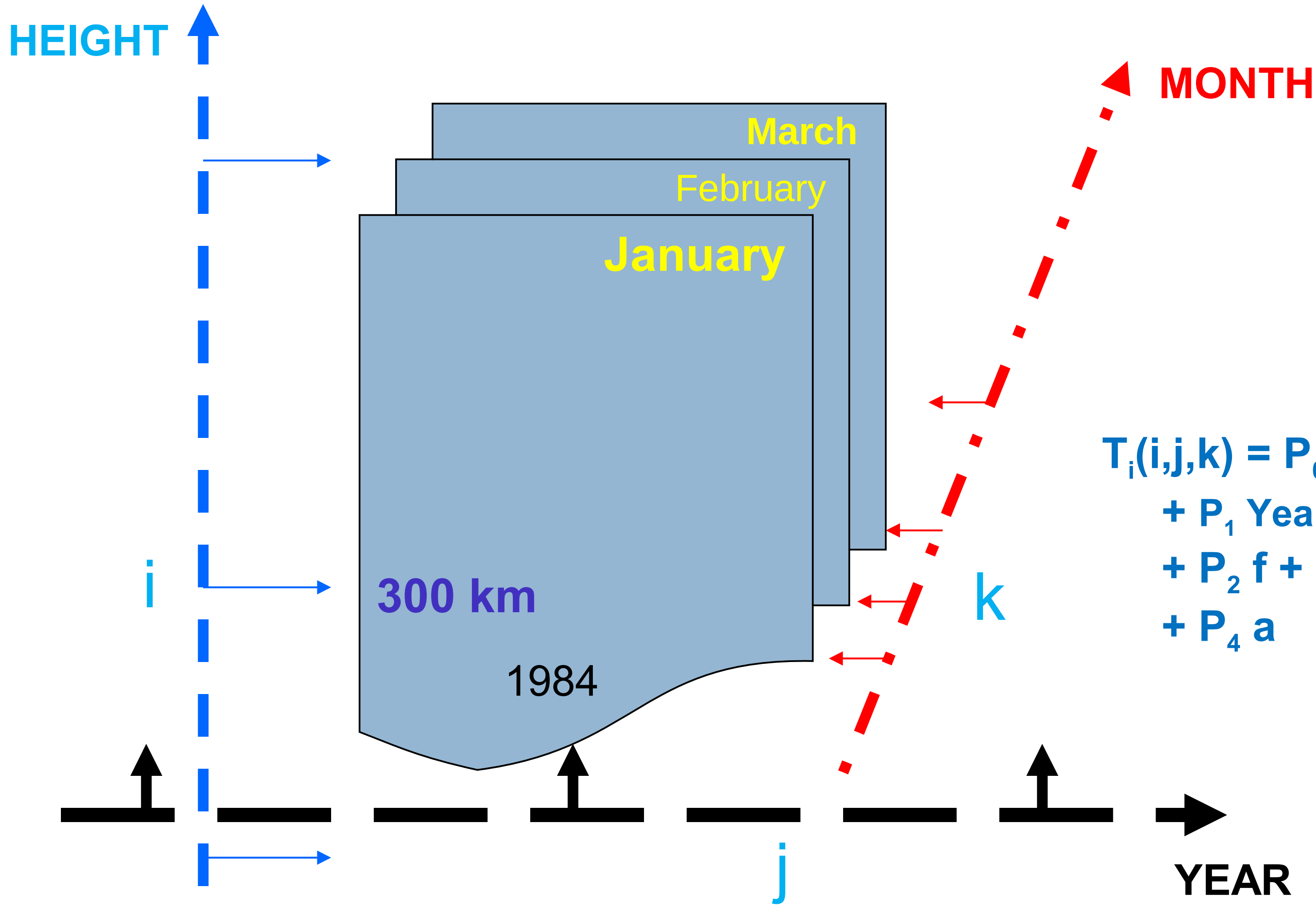
trend_05.01-05.31_16.5-17.5_400-450.dat
trend_05.01-05.31_16.5-17.5_450-500.dat
trend_05.01-05.31_16.5-17.5_500-550.dat
trend_05.01-05.31_17.5-18.5_200-250.dat
trend_05.01-05.31_17.5-18.5_250-300.dat
trend_05.01-05.31_17.5-18.5_300-350.dat
trend_08.01-08.31_00.5-01.5_200-250.dat
trend_08.01-08.31_00.5-01.5_250-300.dat
trend_08.01-08.31_00.5-01.5_300-350.dat
trend_08.01-08.31_00.5-01.5_350-400.dat
trend_08.01-08.31_00.5-01.5_400-450.dat
trend_08.01-08.31_00.5-01.5_450-500.dat
trend_08.01-08.31_00.5-01.5_500-550.dat

Data Binning: noontime



$$T_i(i,j,k) = P_0 + P_1\,\text{Year} + P_2\,f + P_3\,f^2 + P_4\,a$$

Model

T_i =

P_0 + (background)

P_1 Year + (long-term trend)

P_2 f + P_3 f^2 + (solar flux)

P_4 a (magnetic activity)

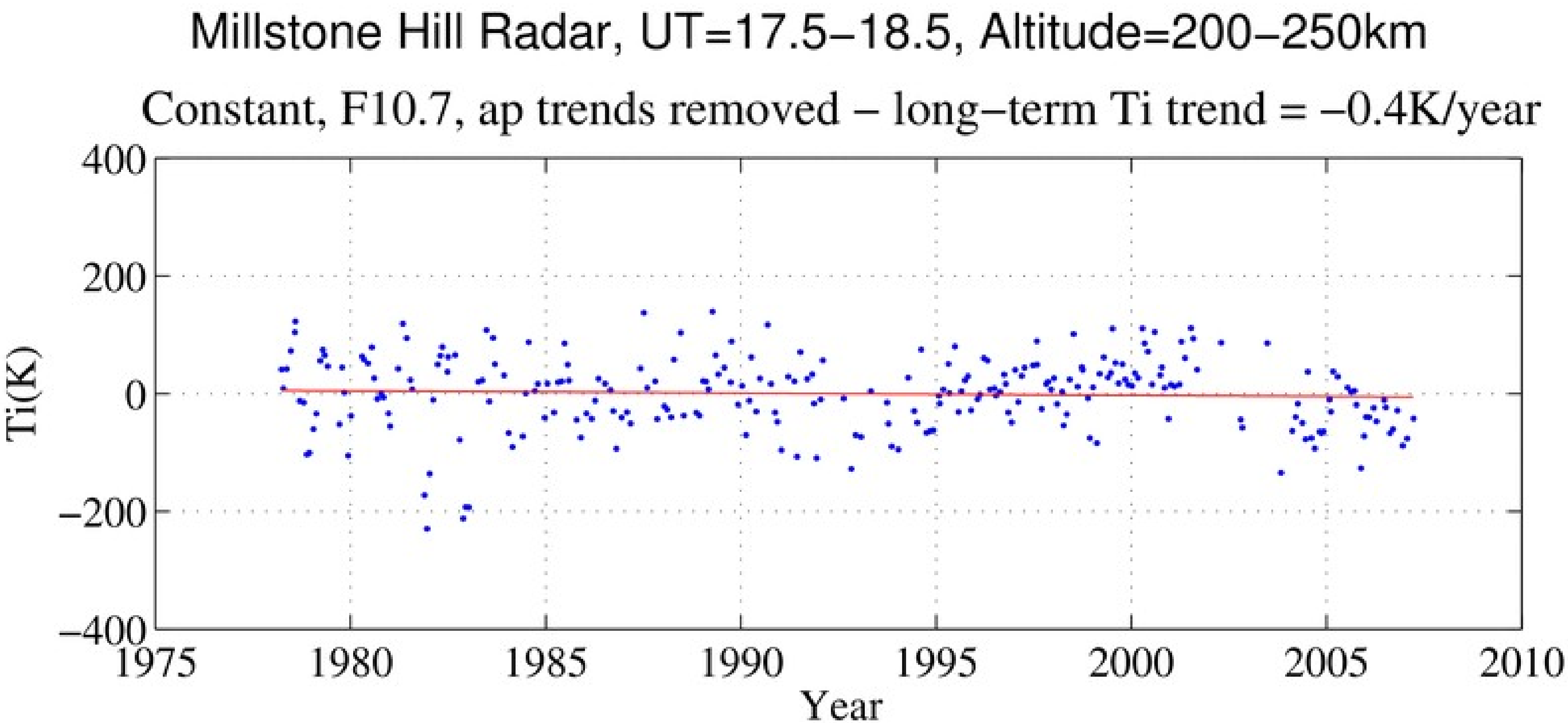
$f = F107 - \overline{F107}$

$a = ap3 - \overline{ap3}$

Results

- Ti trends at different heights
- Confidence levels
- Derived parameters

200-250 km



DATA - P_0

- P_2 f - P_3 f^2

- P_4 a

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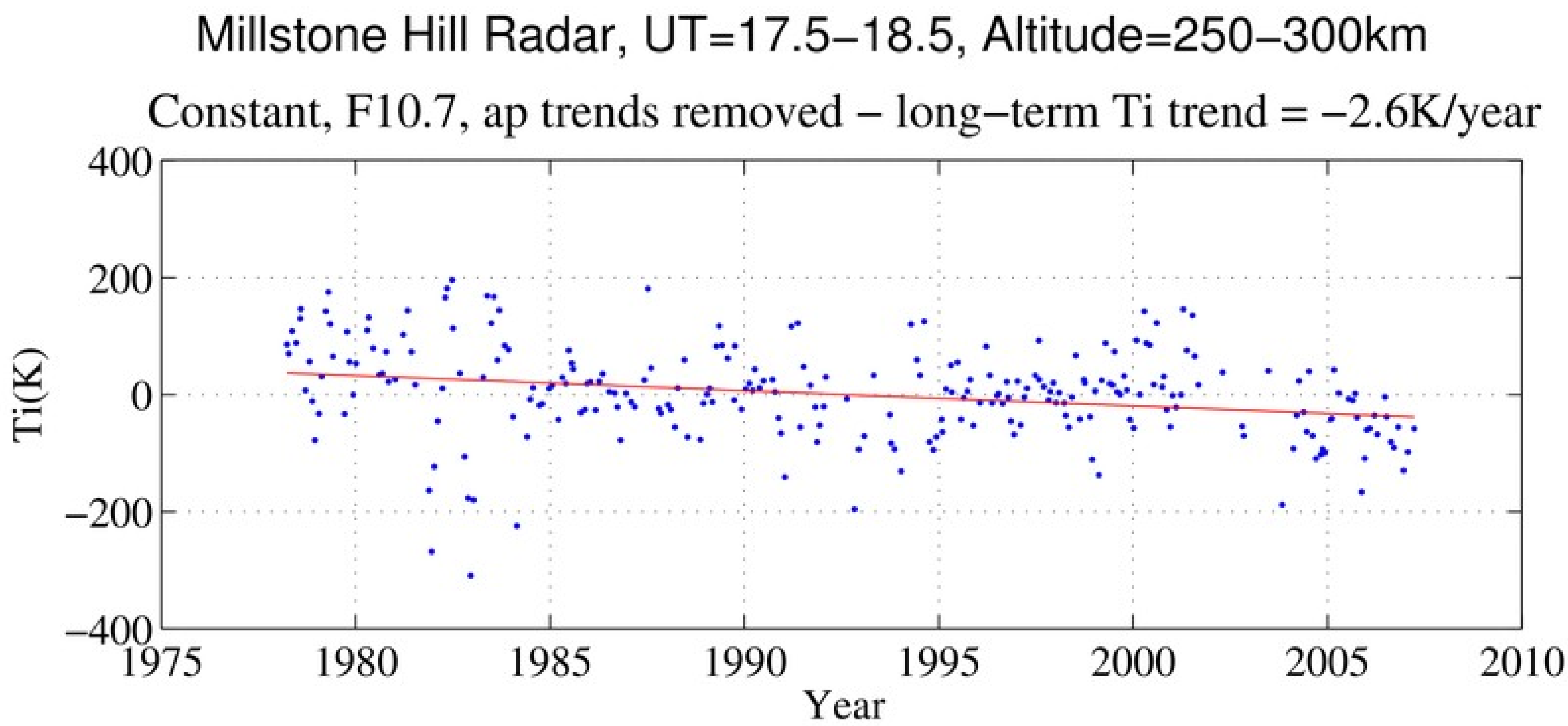
250-300 km



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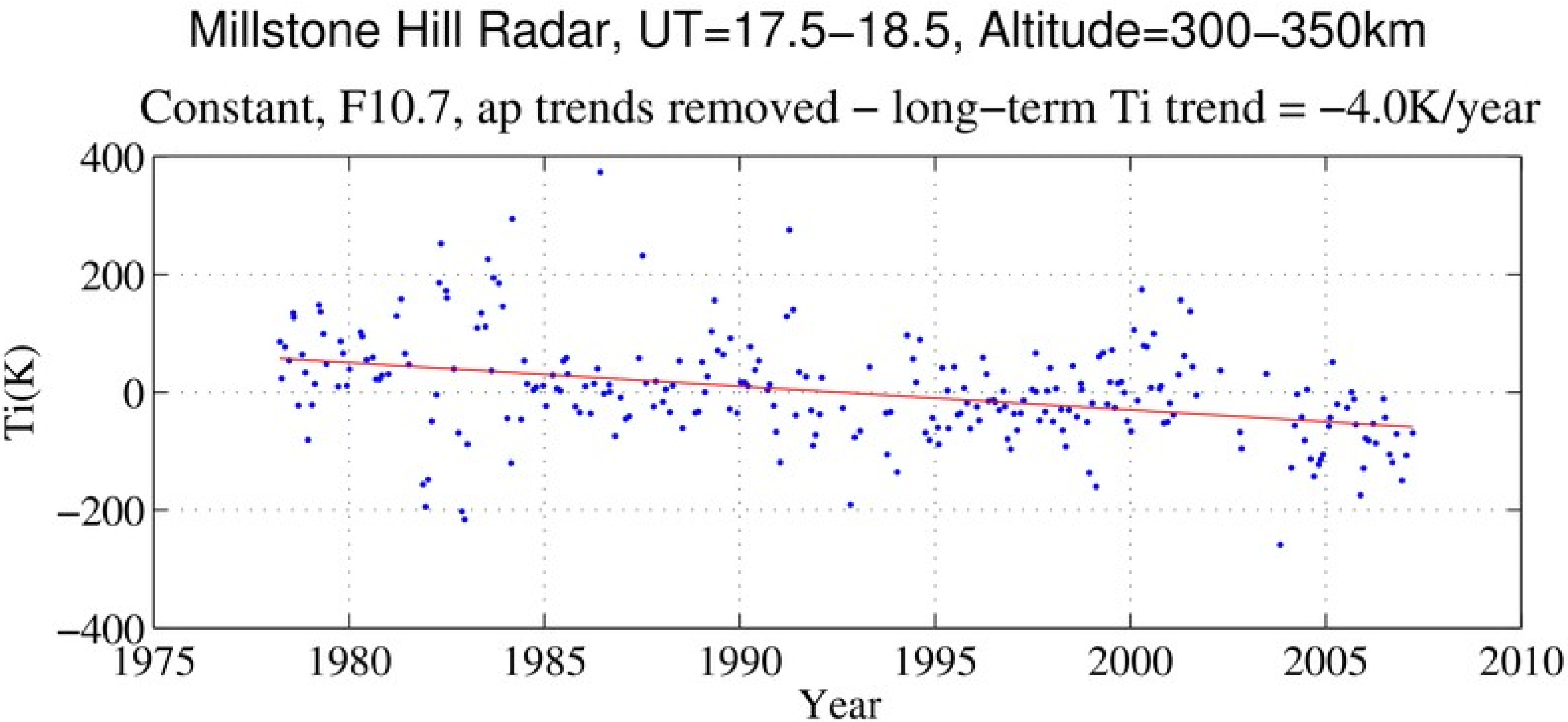
300-350 km



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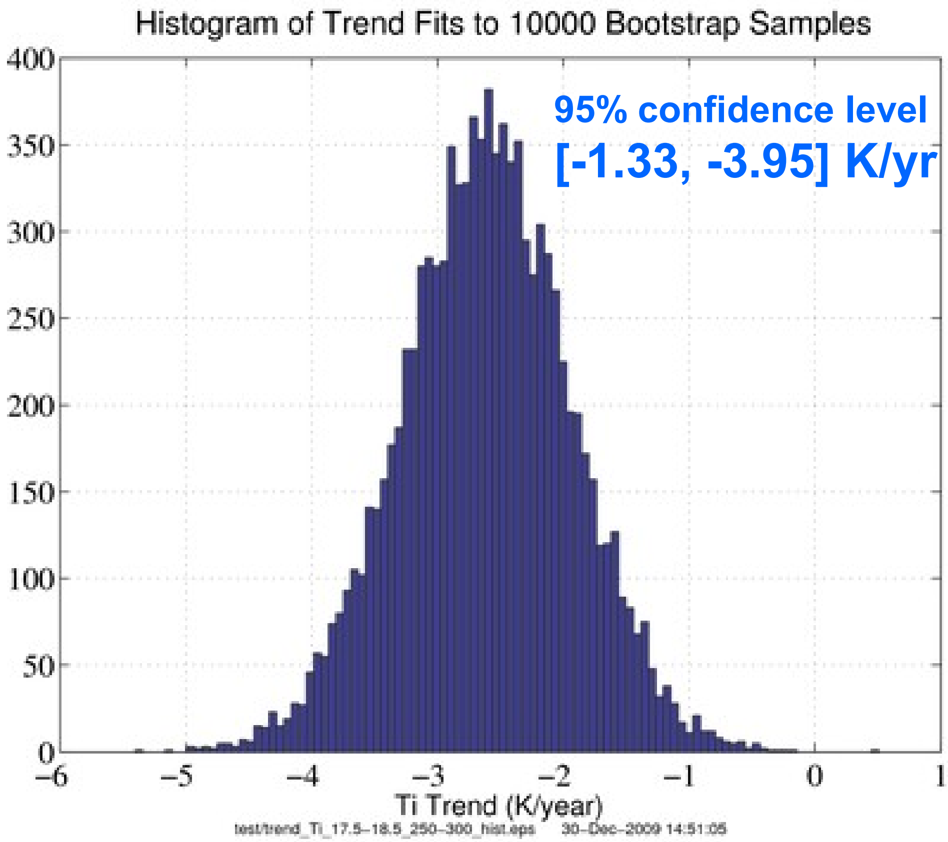
Confidence level – Bootstrap method



Bootstrapping is a modern, computer-intensive, general purpose data resampling approach.

It is implemented by constructing a number of resamples of the observed dataset (and of equal size to the observed dataset), each of which is obtained by random sampling with replacement from the original dataset.

250-300 km; noon time

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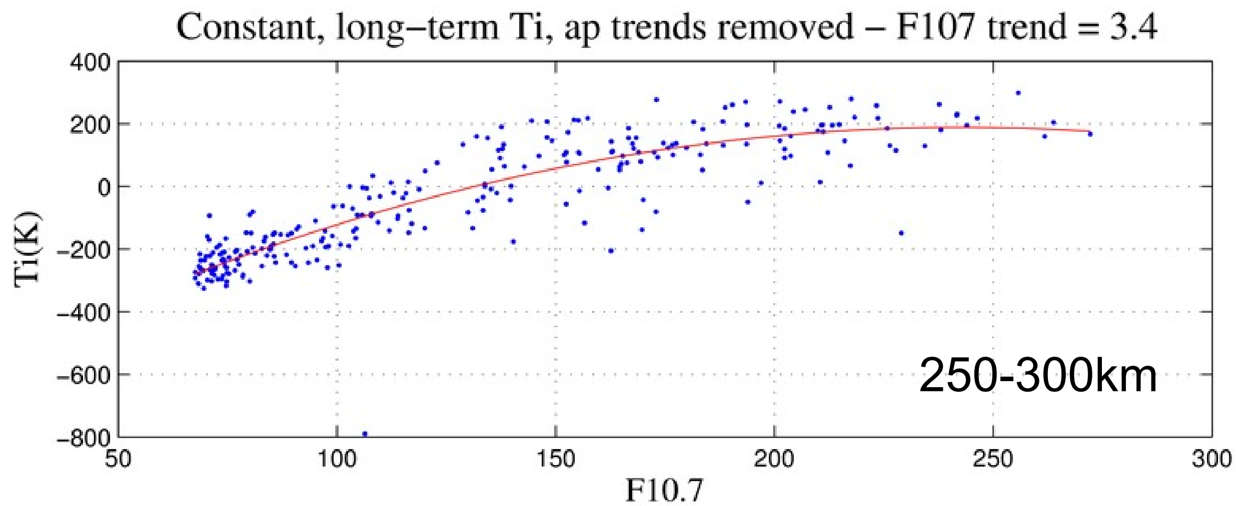
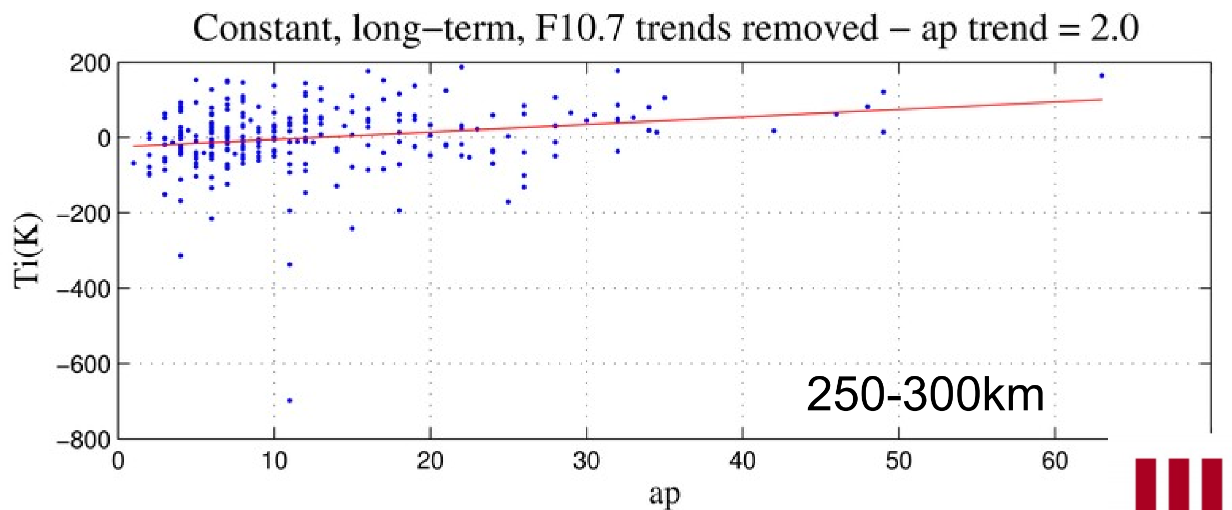
f and a dependency



Data - P_0
- P_1 Year
- P_4 a



Data - P_0
- P_1 Year
- P_2 f - P_3 f^2

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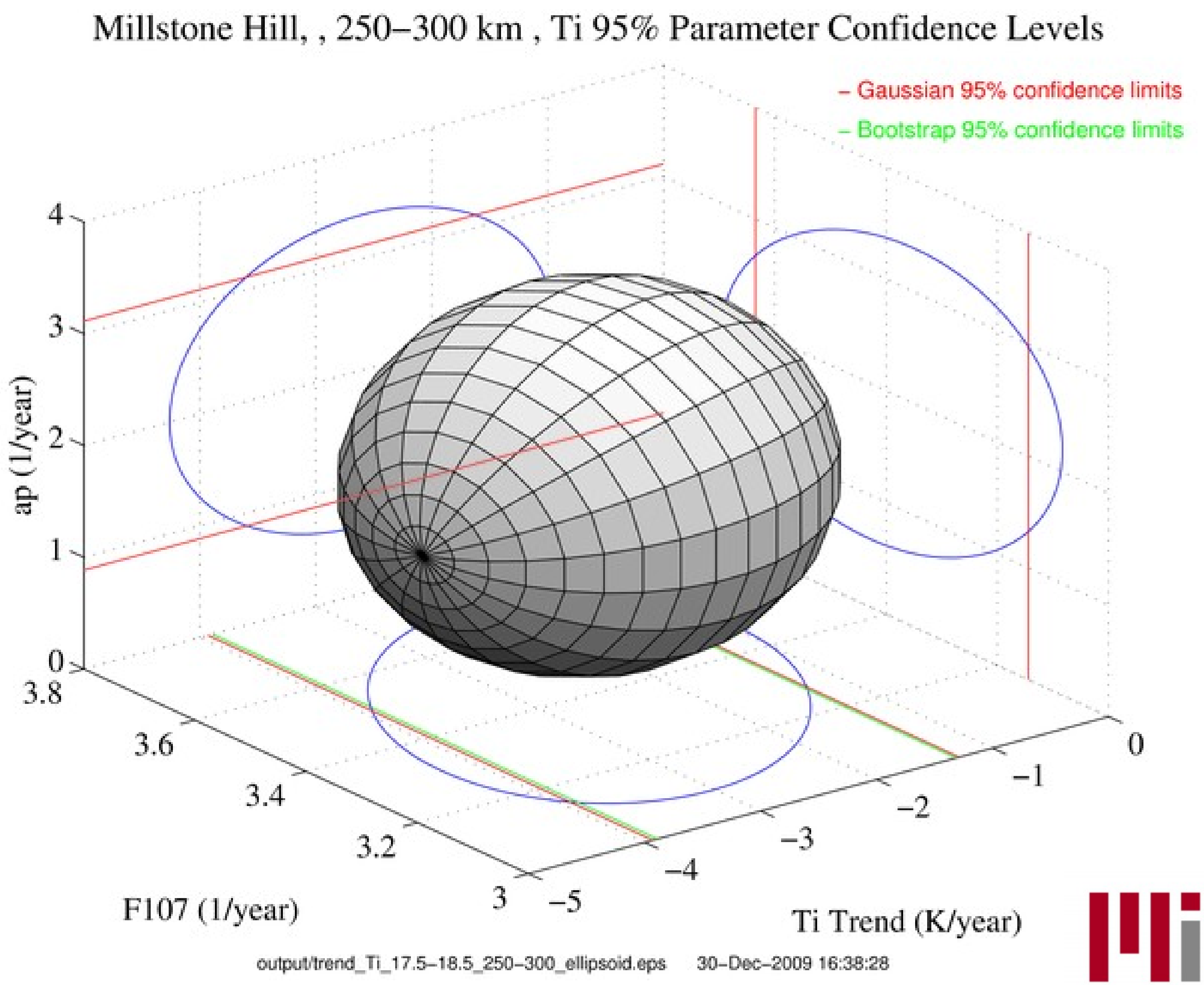
Confidence levels



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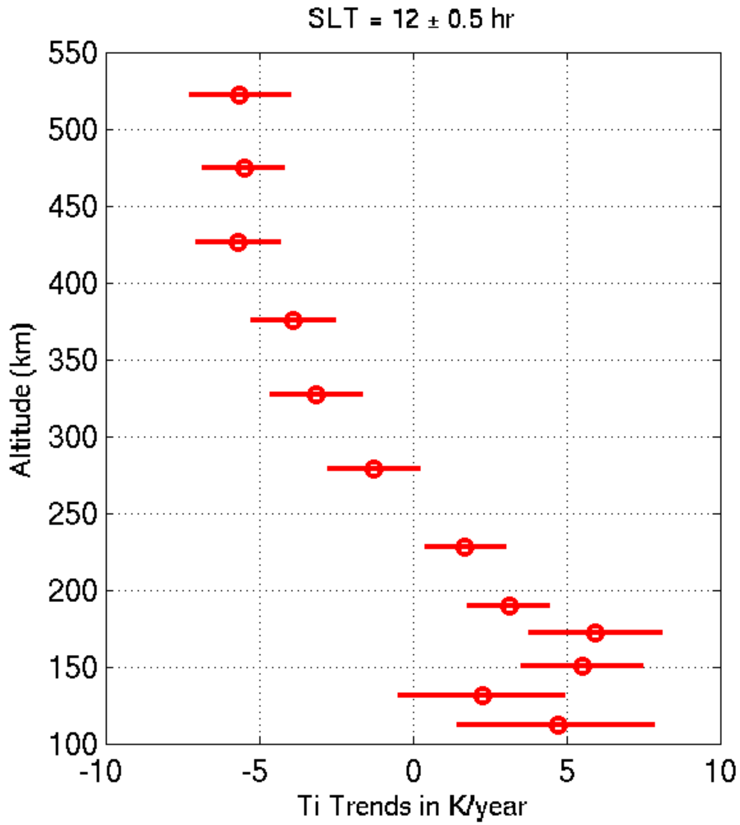
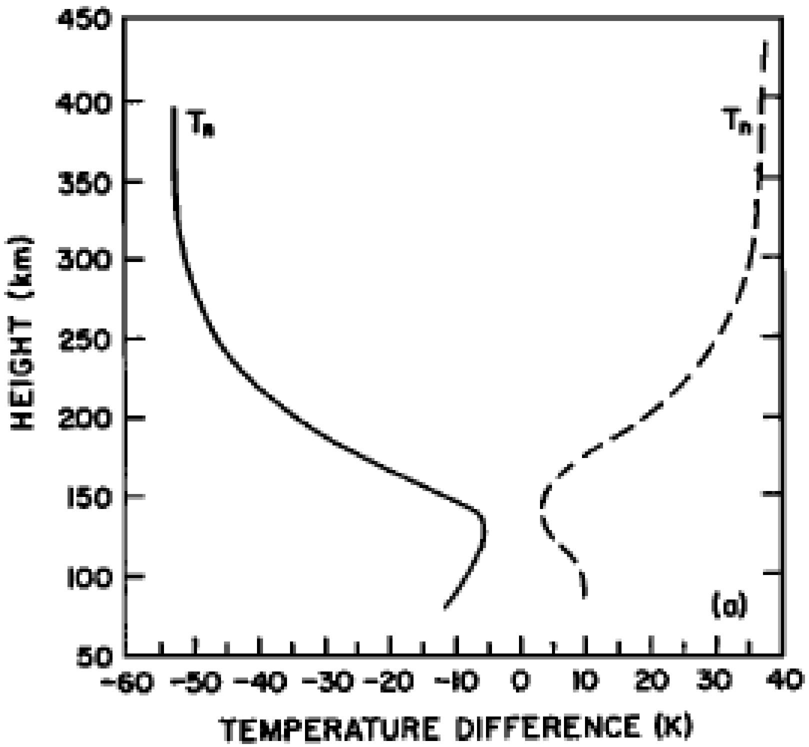
Height distribution





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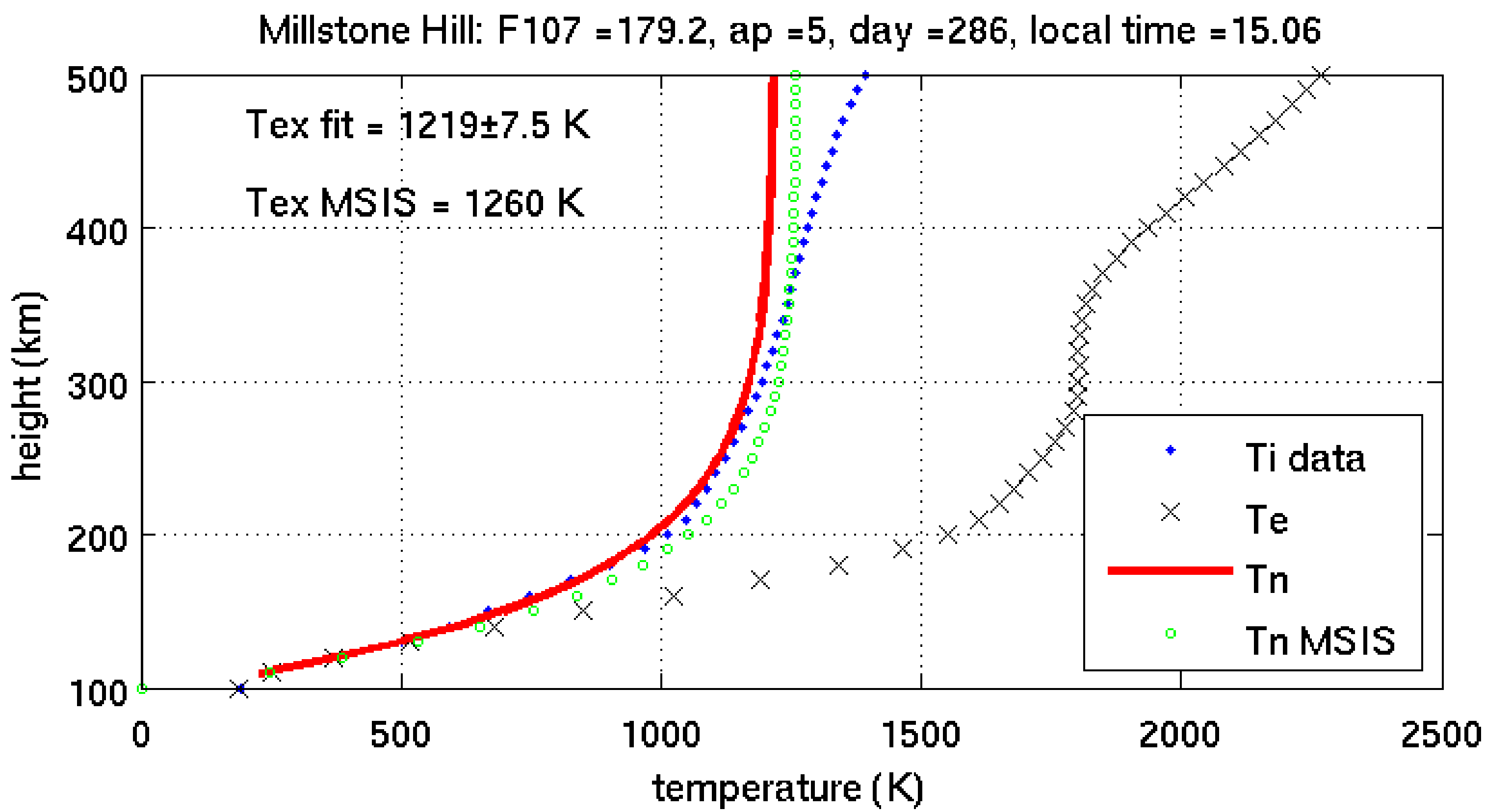
Ti, Te, Tn

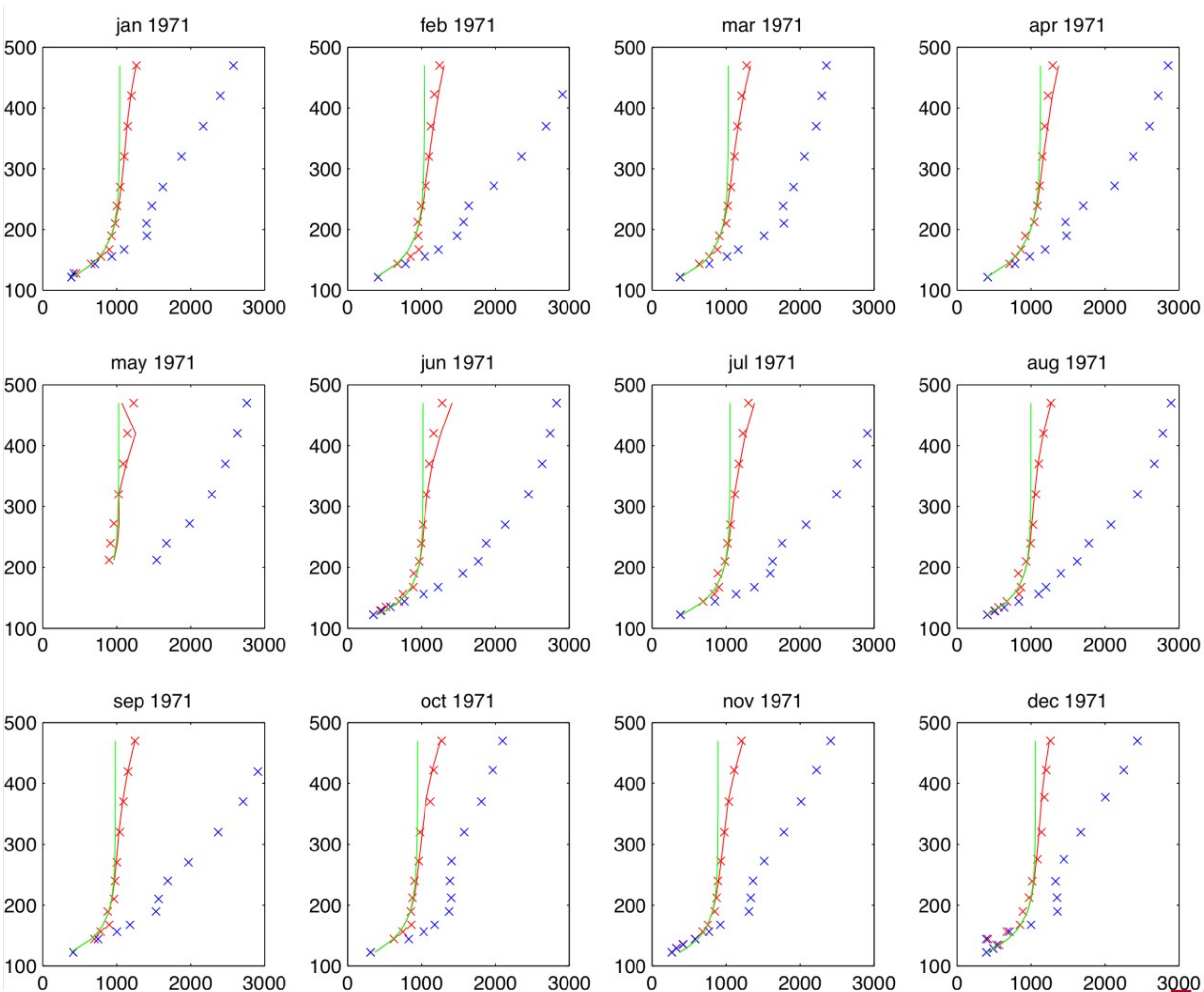


a (Te-Ti) = b (Ti-Tn)

a = $7.6\times10^{20}\, N_i N_e T_e^{-3.2}$ Wm^{-3} , the coefficient of energy transfer from electrons to ions

b = $3.36\times10^{-28}\, F\, N_i [O]\, (T_i+T_n)^{1/2}$ Wm^{-3} the coefficient of energy transfer from ions to neutrals.

Millstone Hill monthly median neutral temperature



Data for this study are monthly median Ne, Te, Ti.

Applied simplified ion energy equation to calculate Tn from measured Ne, Te, Ti profiles and neutral densities from modified MSIS model.

Modified MSIS model incorporated in non-linear least squares fit objective function.

Fit to Profiles yields Tx, $n(o)_{400}$.

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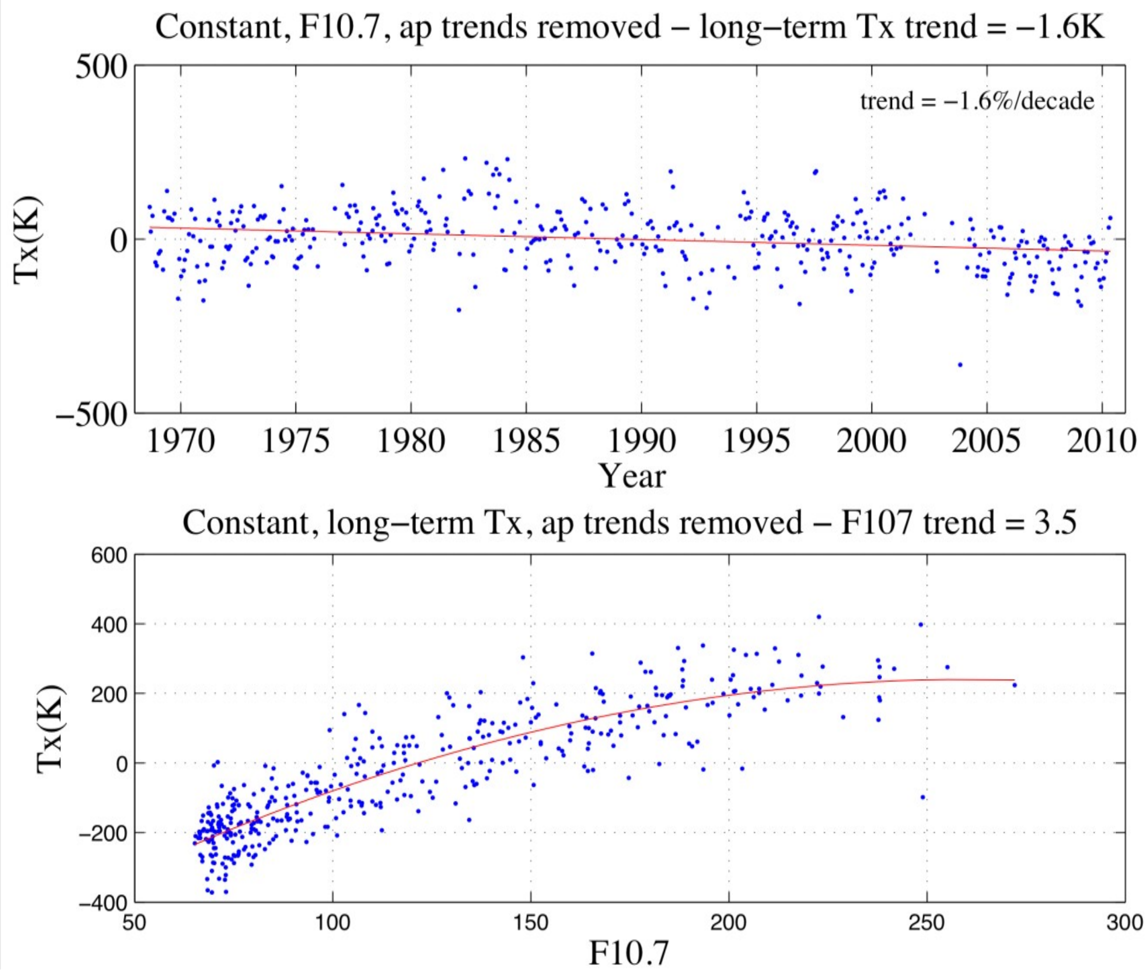
Exospheric temperature



T_x trend ~

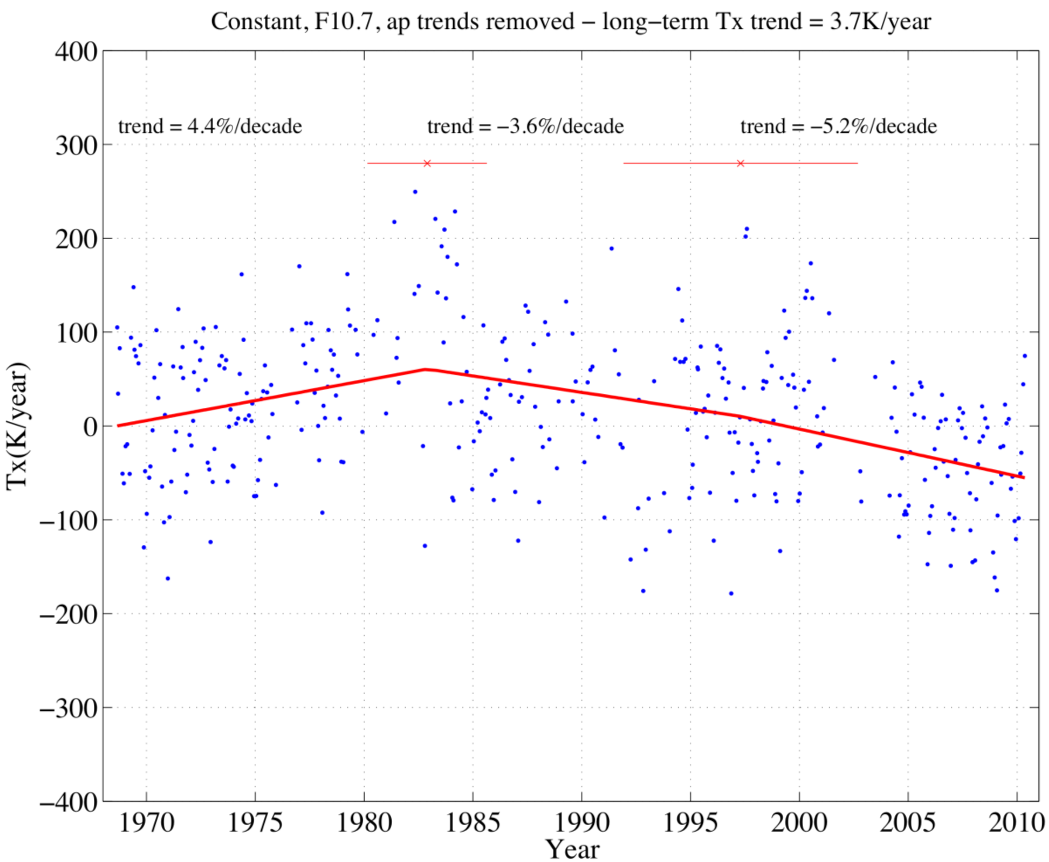
-1.6 K/year

i.e:

16K/decade

1.5%/decade

3-segment fit to Millstone Hill exospheric temperature



Find breakpoints around 1982 and 1997.

Bootstrap standard deviations are fairly large.

1982 breakpoint is similar to that seen in several earlier studies including in St. Santin ISR data (Oliver, submitted).

1997 breakpoint is well before the solar cycle 23 extended Minimum.

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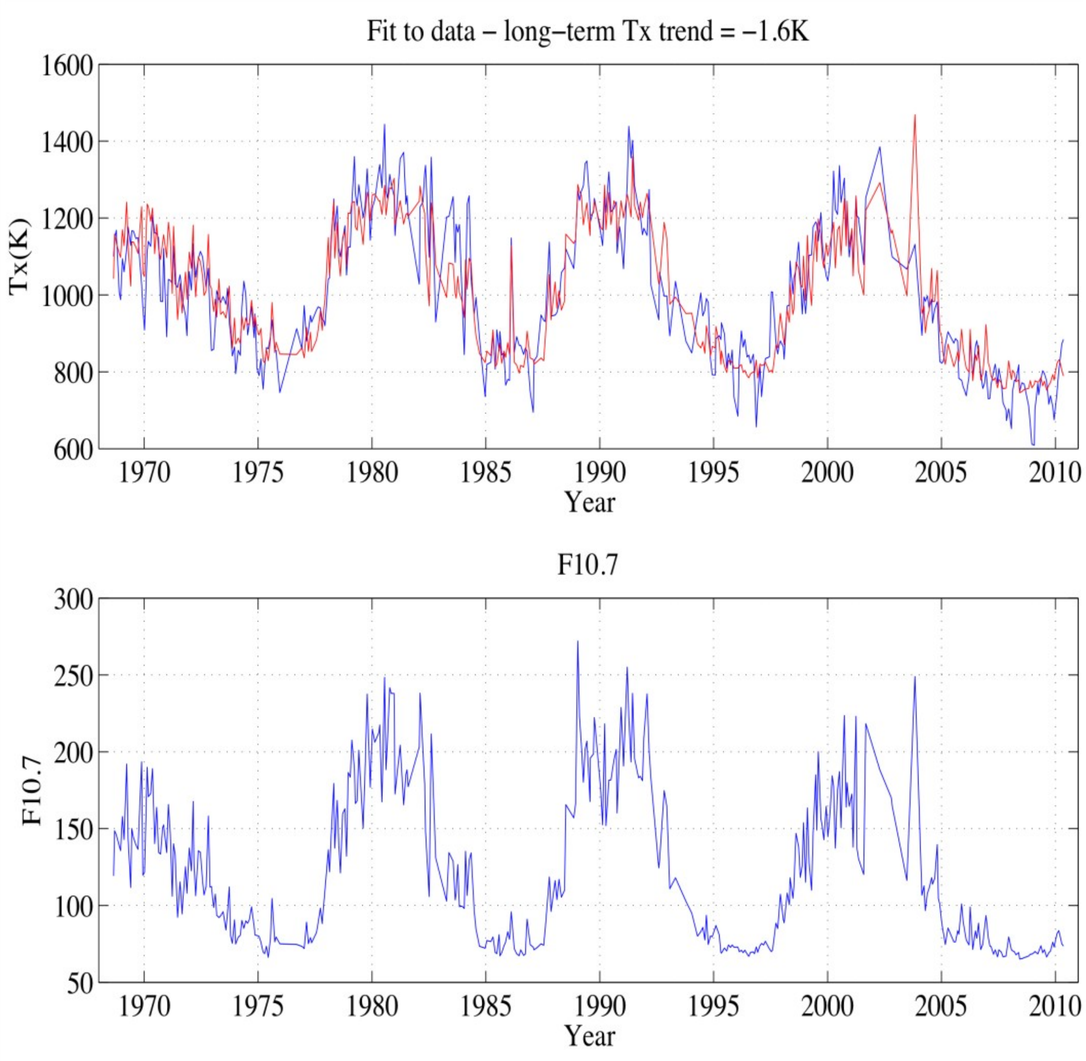
Exospheric temperature from July 1968 – March 2010



Extended time-series encompasses
4 solar minima.

Blue = data
Red = fit with linear trend

Decrease in Tx at solar minimum is very clear.

Fit does not capture full decrease of Tx at extended minimum of cycle 23.

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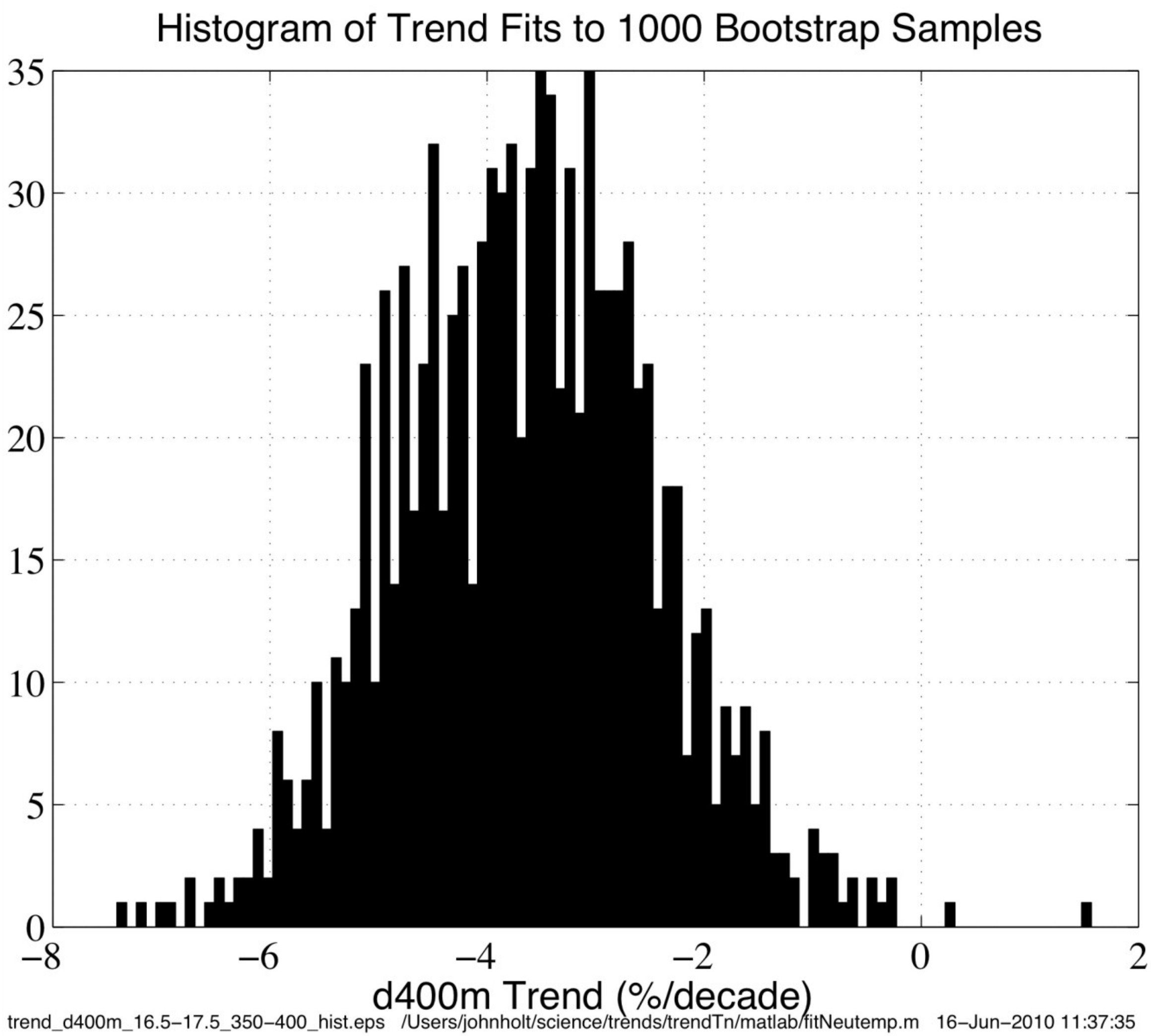
n(O) trend at 400 km, 1968-2010



Compute probability density Of $n(o)_{400}$ from 1000 bootstrap samples.

Mean is -3.6%/decade.

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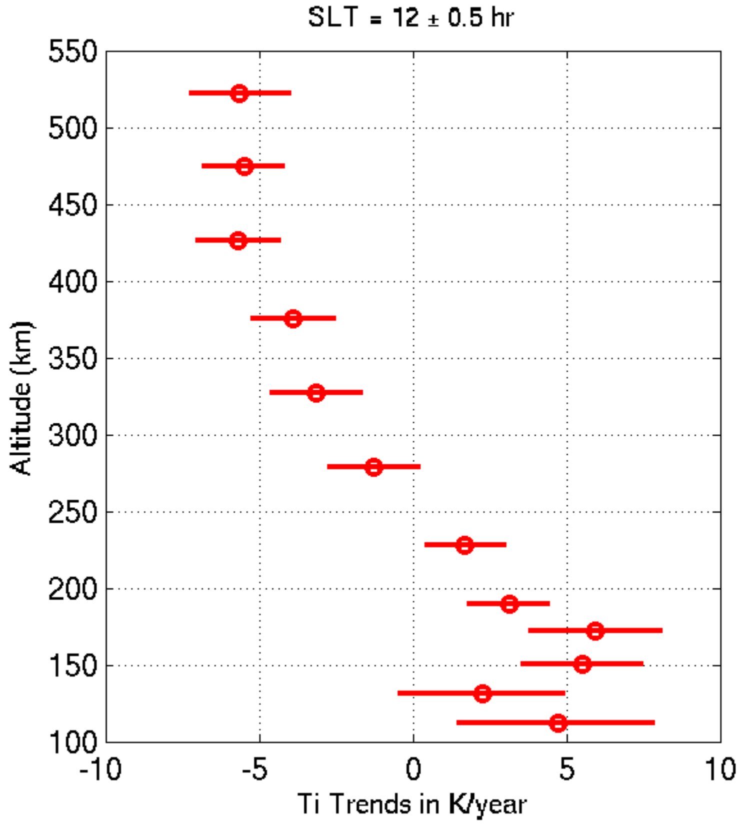
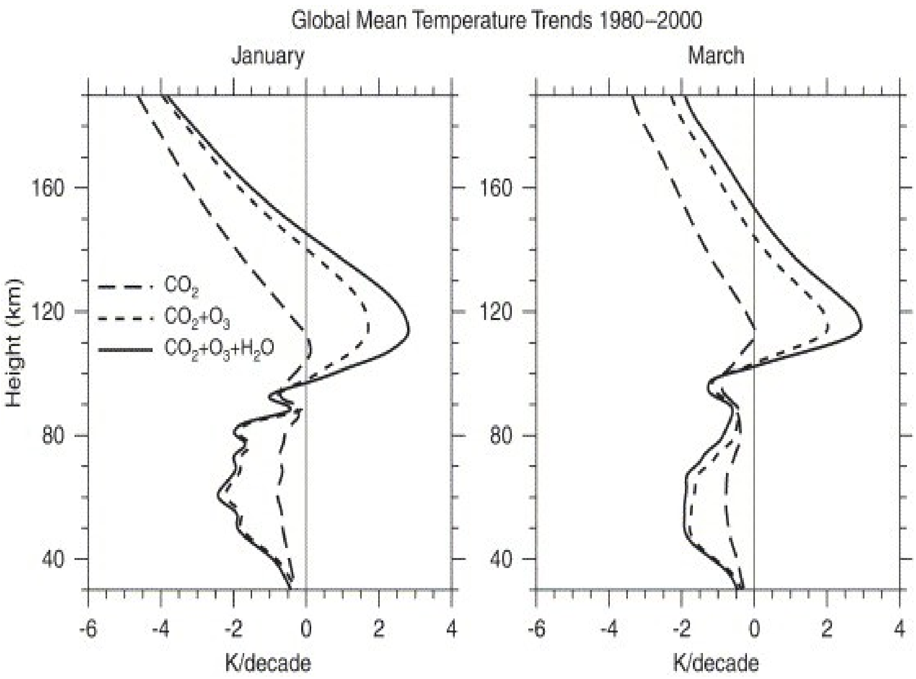
Why cooling in the thermosphere?

- Thermospheric enegy source
  - Solar EUV produces ionization and electrons, from which energy can be transported to neutral particles via the ions throught electron-ion and ion-neutral collisions.
  - Energy from chemical reactions
  - EUV energy at Schumann-Runge continuum can be directly absorbed by some neutral atoms
  - Heating from the blow; from auroal particles, Joule heating, etc
  - Effects of CO2 absorption of outgoing longwave radiation is weak, because CO_2 layer in the thermosphere is optically very thin.
- **Cooling agent**
  - CO2 at 15 μm and NO at 5.3 μm; IR (infrared radiative) radiation to the space
- Other possibilities
  - Decreasing magnetic activity
  - Long-term change in Earth's magnetic field

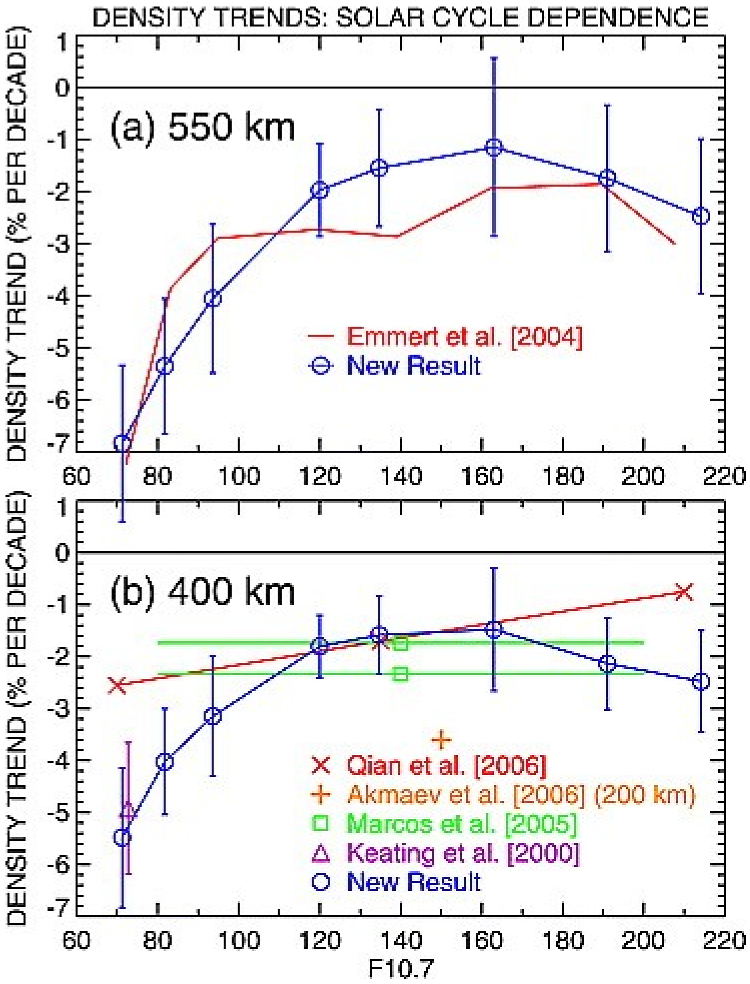
Comparisons with modeling



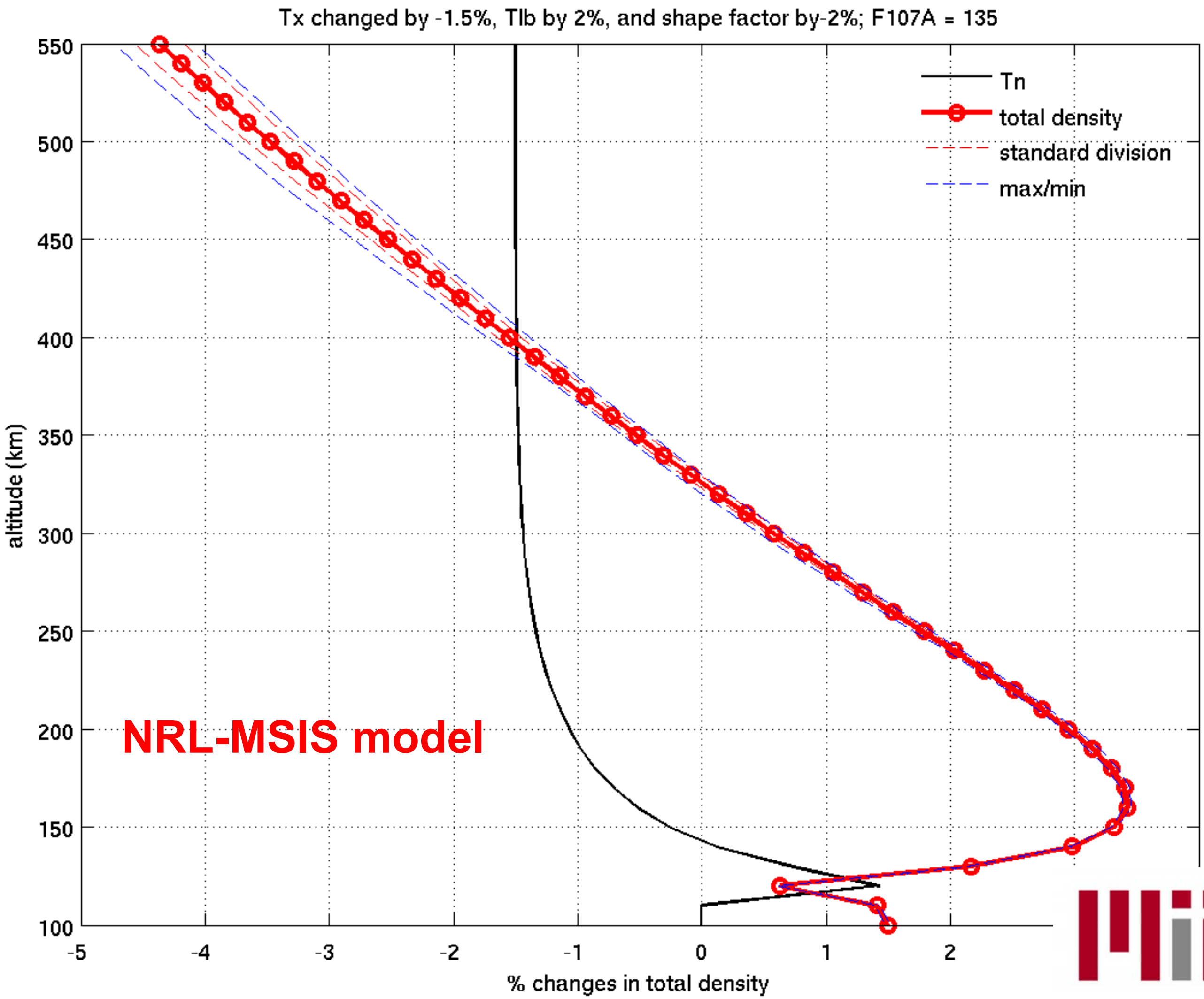
Akmaev et al. (2006)



Satellite observation: density



How much will neutral density change for a -1.5% T_{ex} decrease?



-1.5% density change may be expected. BUT …

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Conclusion

- A direct measure of upper atmospheric temperature indicates a clear cooling trend.
- The cooling trend increases with height within 200-500km height, in agreement with the modeling.
- Midday Tex trend is estimated to decrease at ~1.6% per decade over Millstone Hill.
- Tex trends can be location dependent, but overall Tex results are compatible with density trend results.
- Some breakpoints of the trend exist, some of which may be correlated with the ozone trends.

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Future work

- Dependencies
  - Height
  - Local time; Solar activity
- Other ISR directly measured and derived parameters
  - Tex; [O]; etc
- Data from other ISR sites

Table 1 A summary of datasets to be used in the proposed studies

Station	Geographic location	Available data	Number of experiments*
Millstone Hill	42.6N, 288.5E	1976- now	~1900
St. Santin	44.6N, 2.2E	1966-1987	~ 420
Sondrestrom	67.0N, 309.0E	1983-now	~ 1900
Chatanika	65.1N, 147.4E	1976-1982	~ 55
Poker Flat	65.1N, 147.4E	2007-now	~ 600

Note: * The number of experiments is based on a quick exam of the Madrigal/CEDAR databases. Each experiment can last from 1 to 30 days, but mostly 2-5 days.

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