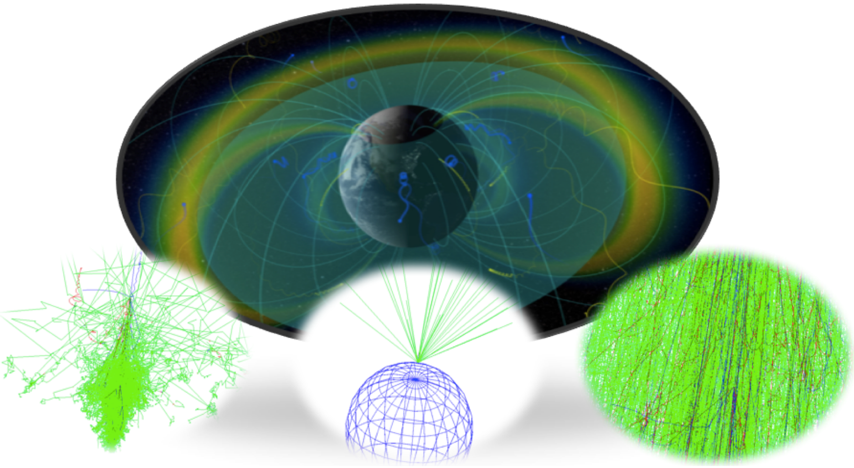
Inaugural Workshop on Applications of
Cosmic Ray Measurements

# Tracing the Temporal Variations of Effective Temperature in Earth's Upper Atmosphere with Cosmic Ray Measurements

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# Implications of Temperature Measurements

Georgia State University

- Investigate climate change
- Build modeling tools to enhance weather forecasting
- Public safety



nseypress.com/news/uk-news/2018/02/21/in-pictures-england-
-white-after-fresh-snow-falls-overnight/#Ct6RQqkvelzvWqgK.99

Buffalo New York SNOW STORM November 2014

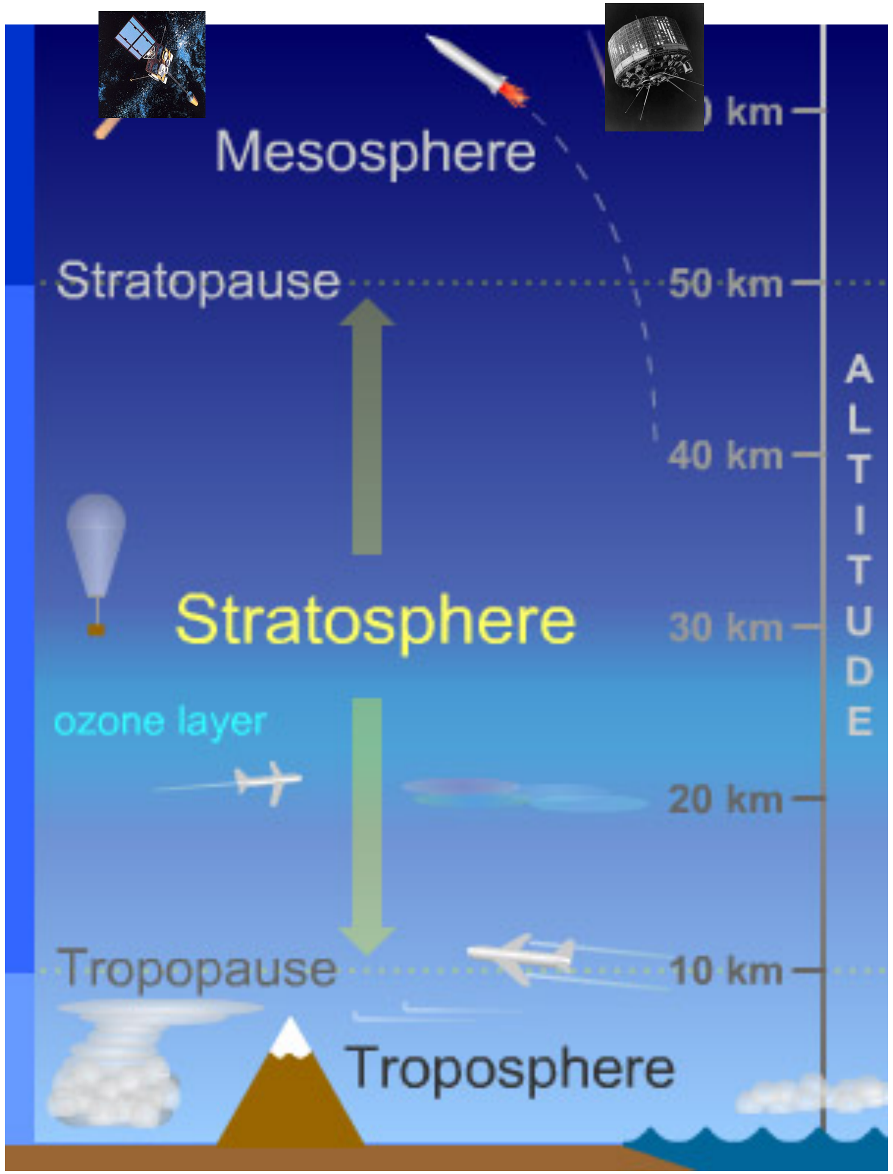

http://www.zeebiz.com/india/news-266-districts-in-11-different-states-are-drought-affected-in-2015-16-995

# Traditional Methods of Temperature Measurements

**Remote Sensing: Weather Satellites (Infrared/microwave radiometer)**

**Upper air soundings (Radiosonde)**

**Atmospheric LIDAR**




*http://scied.ucar.edu/shortcontent/stratosphere-overview*

# Limitations:

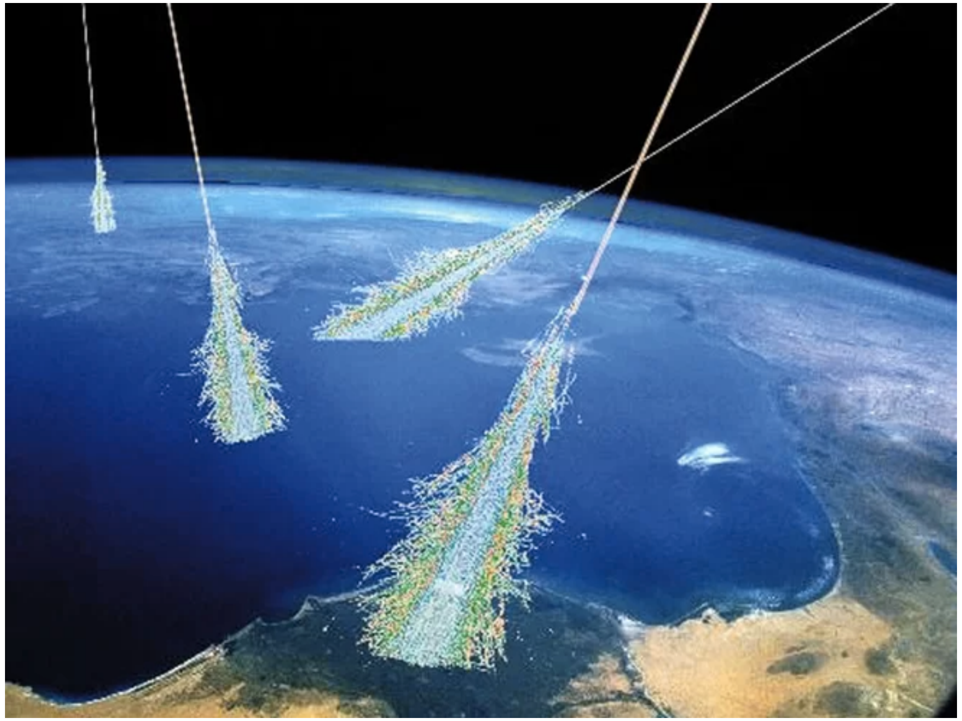
- Sensor performance can be affected by severe weather conditions
- No continuous temporal measurements available

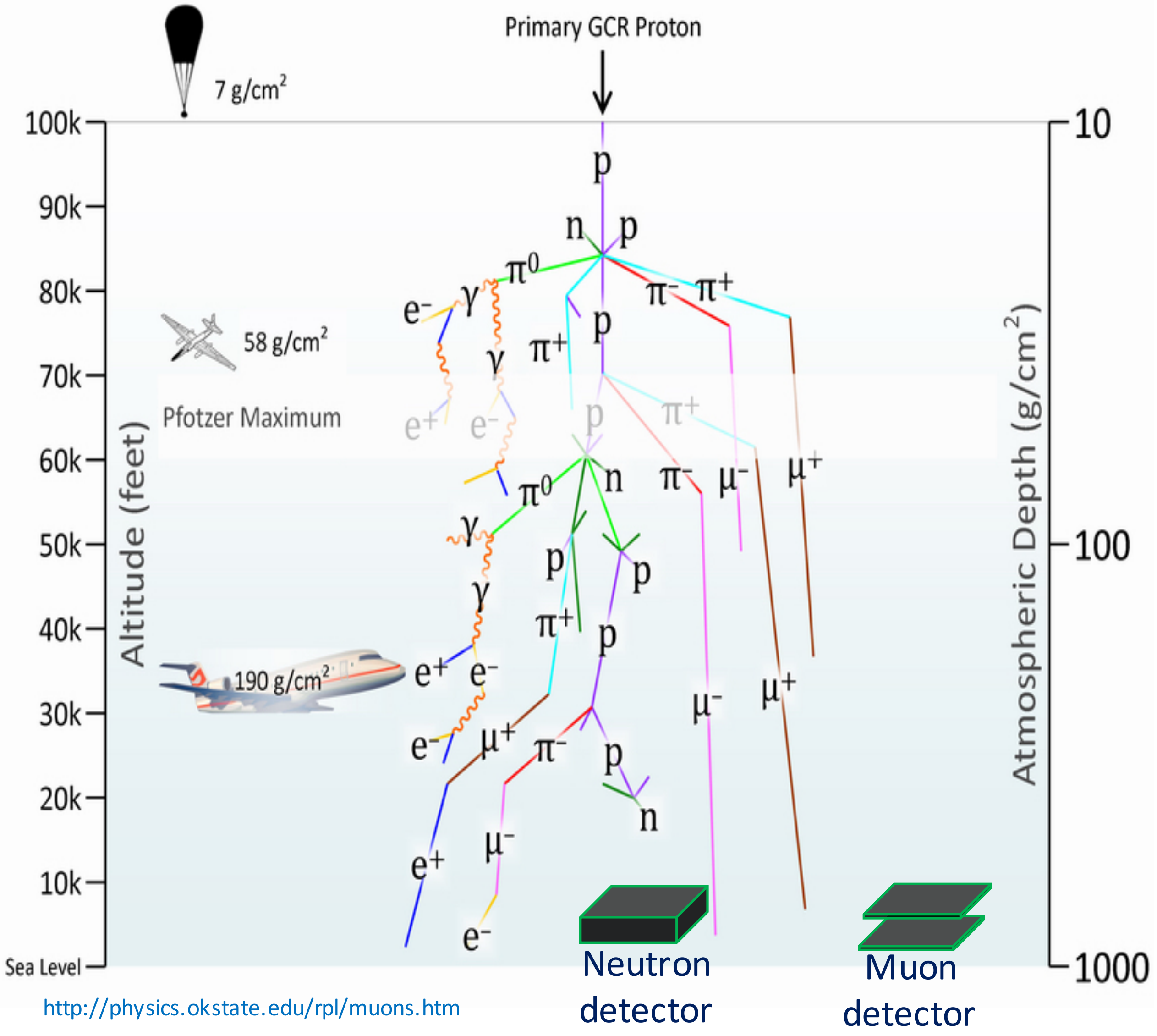
# Motivation

To develop reliable and efficient tools to monitor the dynamical changes of the earth's atmosphere in real – time using cosmic rays.

# Cosmic Ray Production in Earth's Atmosphere

Simon Swordy (U. Chicago), NASA

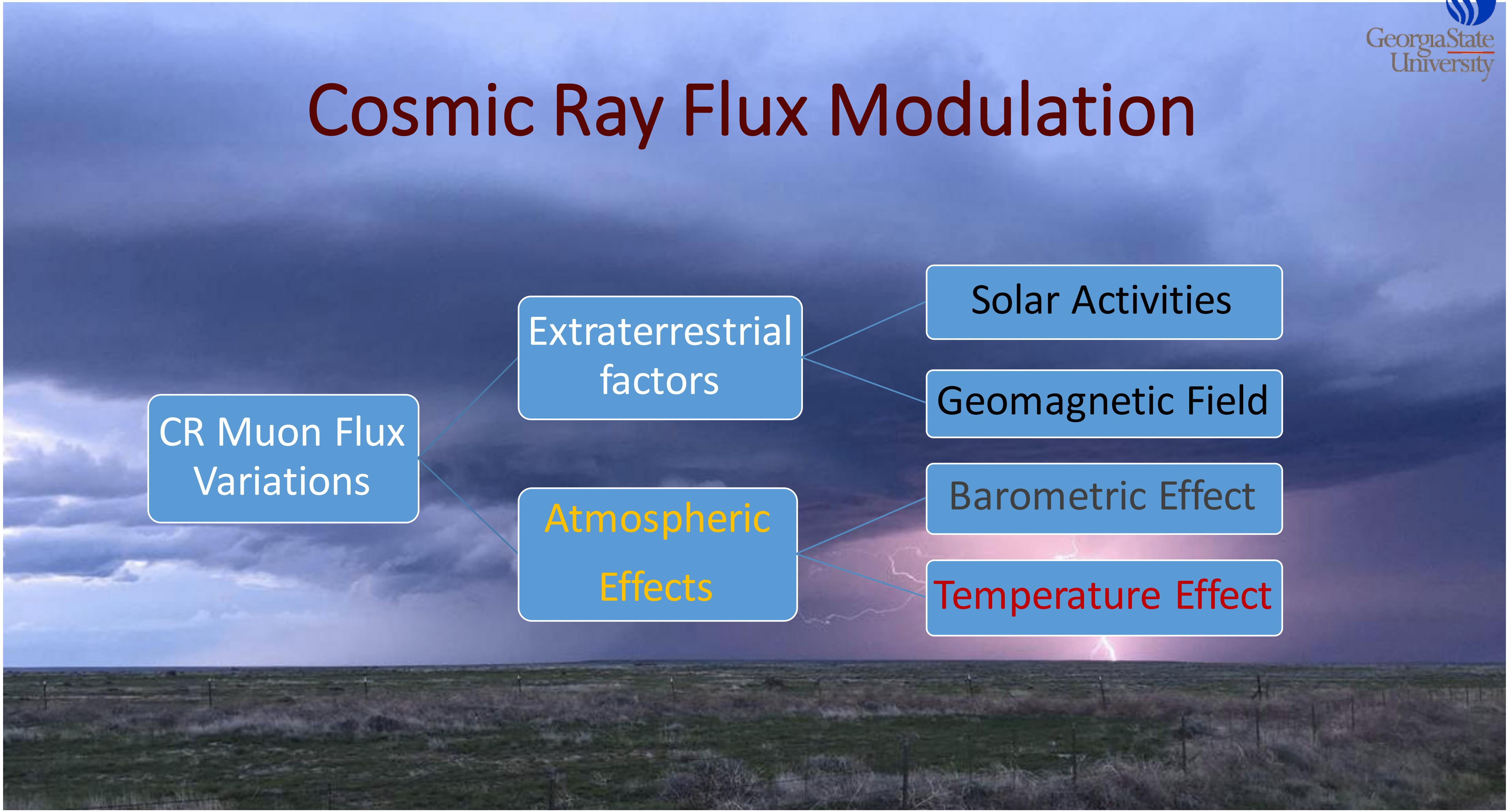




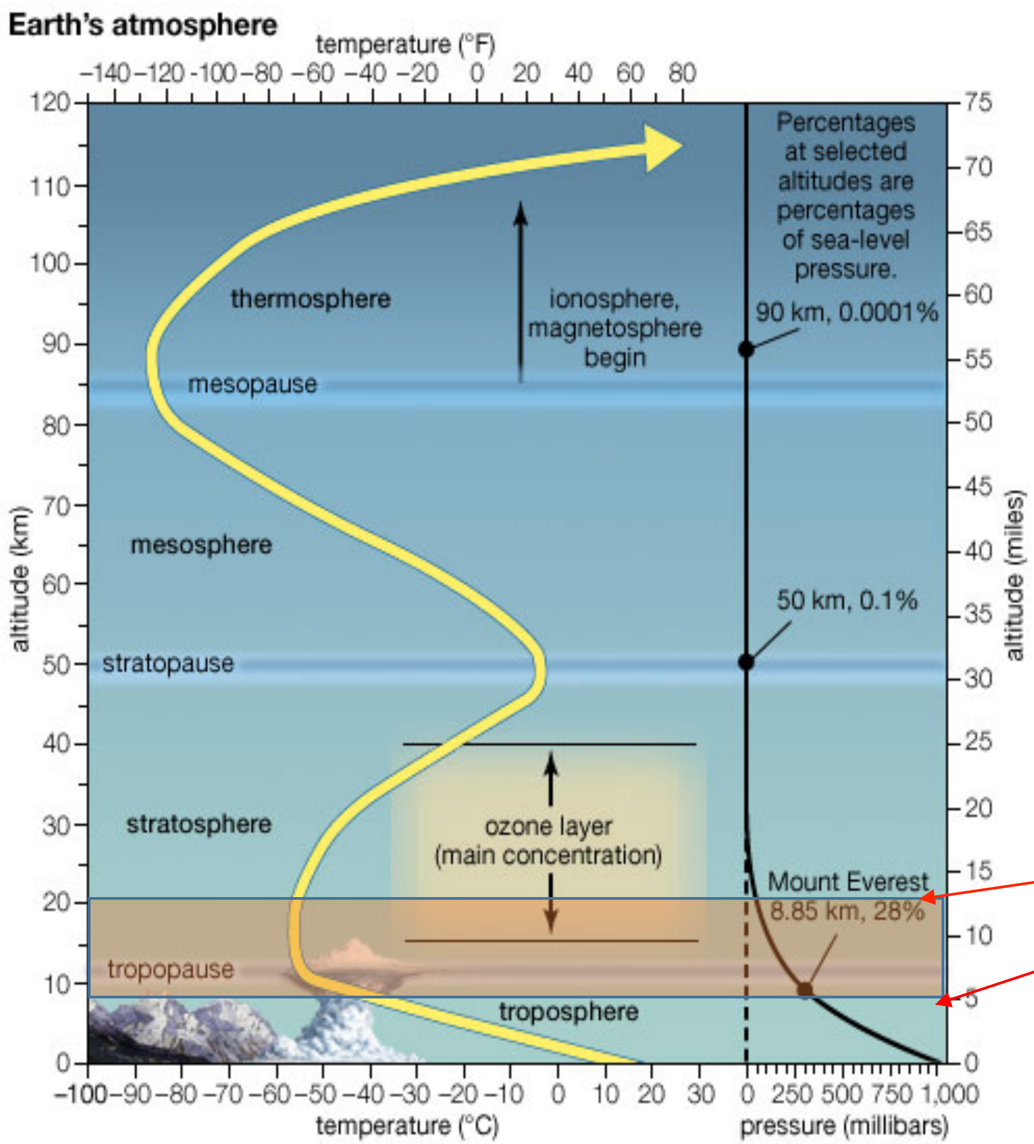

http://physics.okstate.edu/rpl/muons.htm

- High energy protons (90%), alpha particles (9%), and heavier nuclei (1%)
- Energies of ($10^9$ – $10^{20}$) eV

# Cosmic Ray Flux Modulation

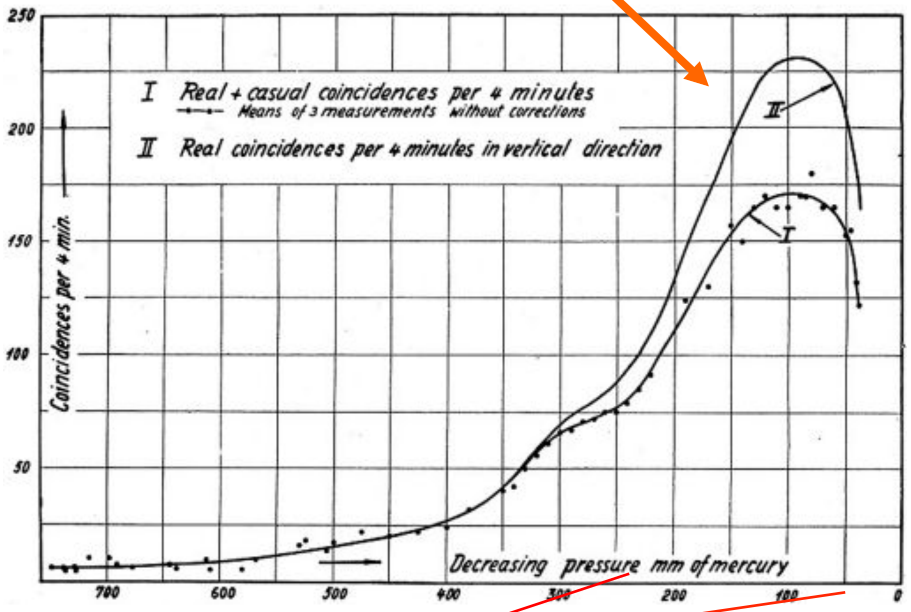


# Atmospheric profile and Muon Production Level




© 2007 Encyclopædia Britannica, Inc.

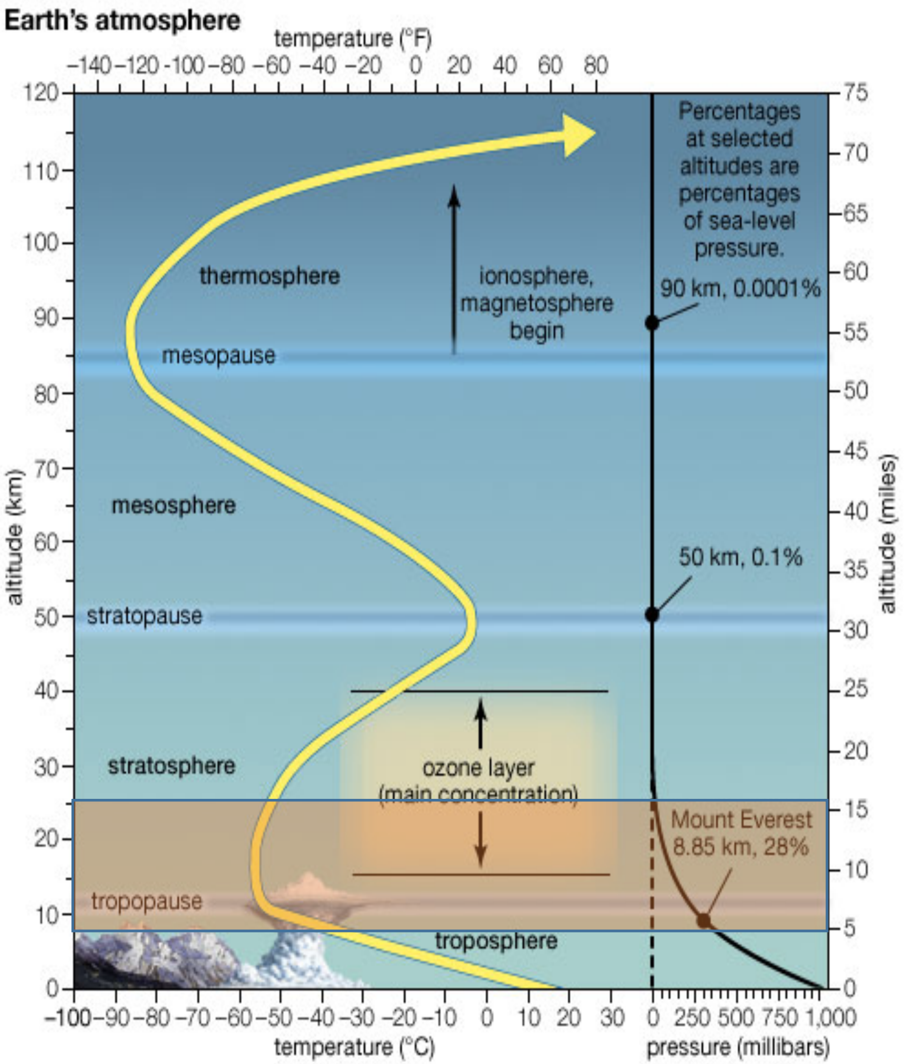
**maximum between ~100 - 200 hPa**




Pfotzer, 1936

- Most of the muons are produced in upper troposphere - lower stratosphere region **[UT-LS]**
- **Change in temperature→ Change in air density →Muon flux variation**

# Effective Temperature






$$T_{eff} = \frac{\int_{x=0}^{\infty} T(X)W(X)dX}{\int_{x=0}^{\infty} W(X)d(X)}$$

T(x): Temperature at atmospheric depth X

W(x): Weight of atmospheric depth X

depends on particle production at that depth

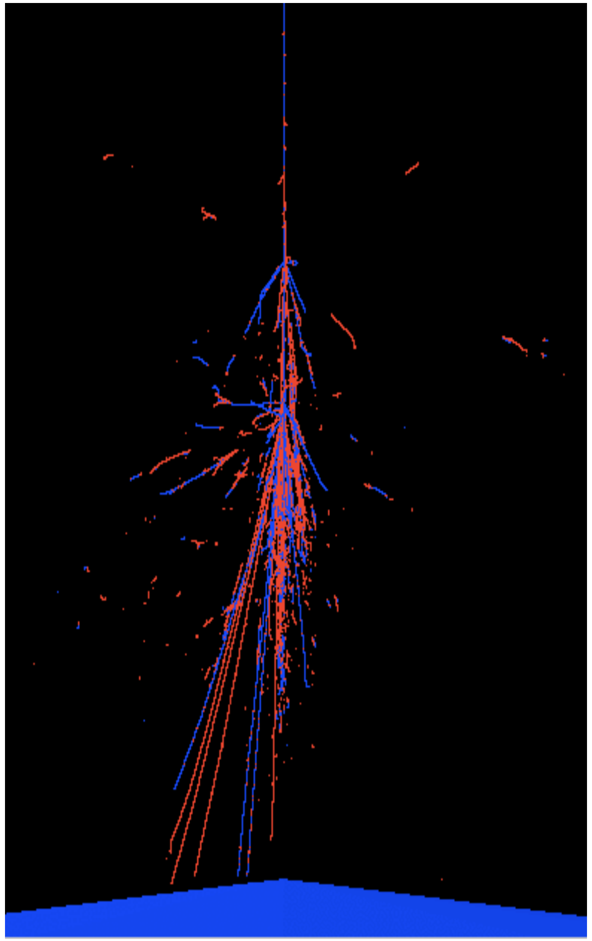
$$\frac{\delta I_\mu}{I_\mu^0} = \alpha_T \frac{\delta T_{eff}}{T_{eff}}$$

$\alpha_T$ =Temperature Coefficient:

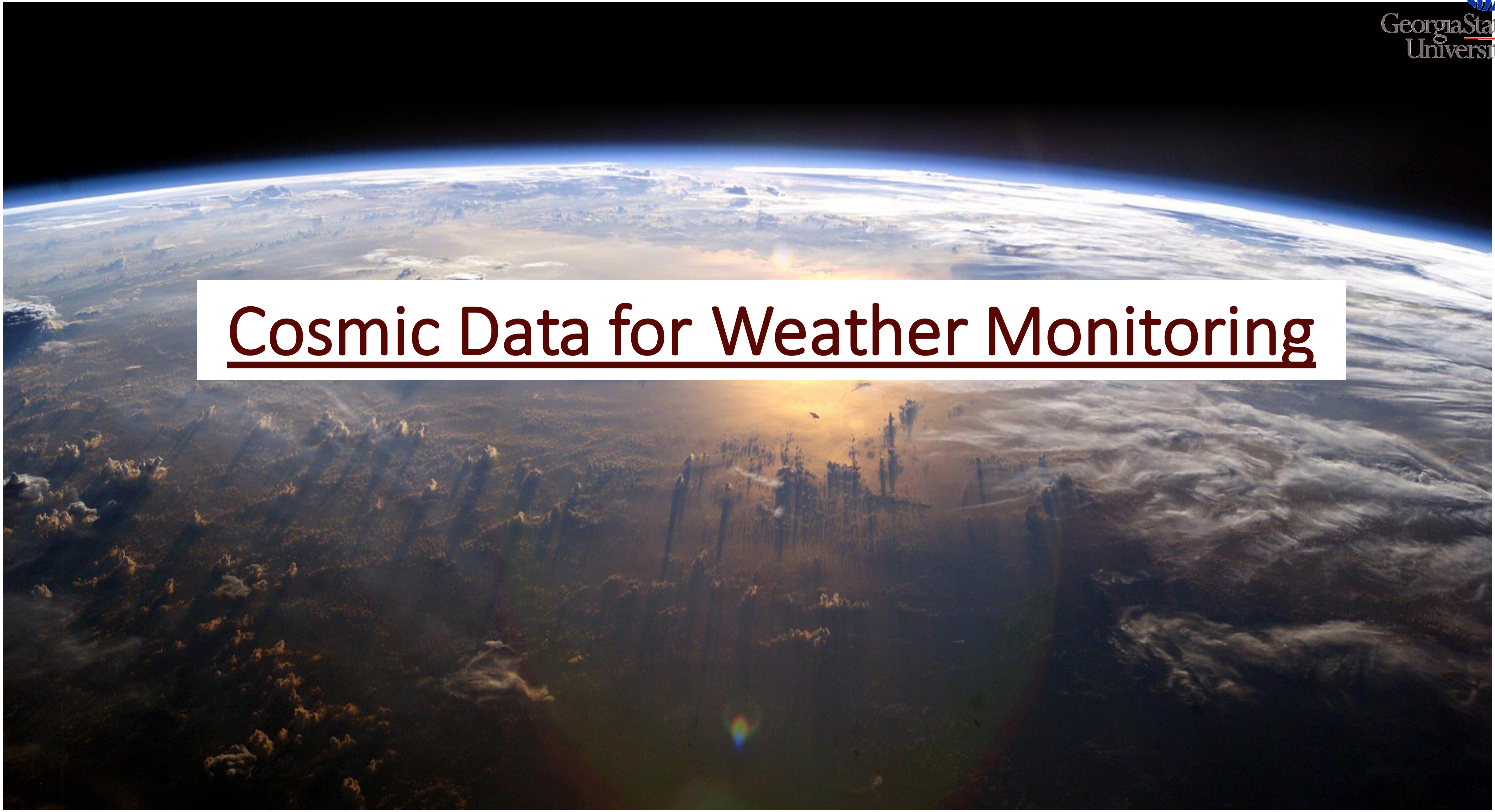
20Km

15Km

0Km



# Cosmic Data for Weather Monitoring



# Cosmic Rays as Temperature Gauge

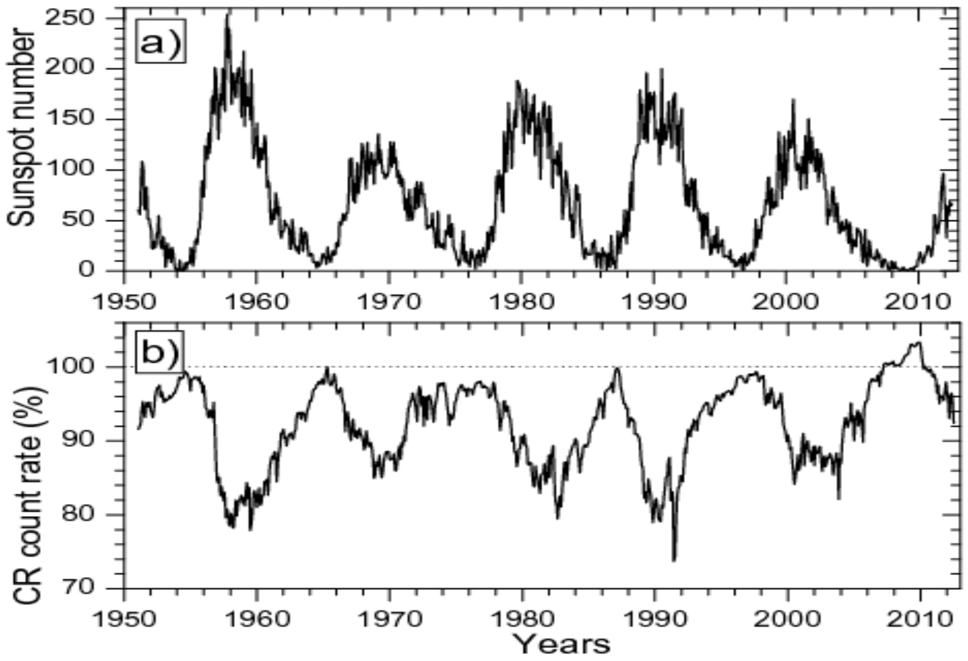
## Procedure:

$$\delta I\mu = f(\delta Teff, \delta P, \delta IN) \Rightarrow \delta Teff = g(\delta I\mu, \delta IN, \delta P)$$

[Atmospheric effects]

$\delta P$: Change in air pressure

$\delta IN: Neuton\ Flux\ variation$ (to correct the solar effects and primary particle fluctuation) [Extraterrestrial effects]




Ilya G. Usoskin, Living Rev. Solar Phys., 10 (2013)

# Regression Method

Dr. Xiohang Zhang,
https://scholarworks.gsu.edu/phy_astr_diss/85/

$$\delta T_{eff} = a\delta I_{\mu} + b\delta I_{N} + c\delta I_{\mu}^{2} + d\delta I_{N}^{2} + e\delta I_{\mu}\cdot\delta I_{N}$$

Independent Variable
(Observed Data)

Dependent variables
(Model parameters)

Model parameters = 5

$$_{n}C_{k} = \frac{n!}{k!(n-k)!}$$

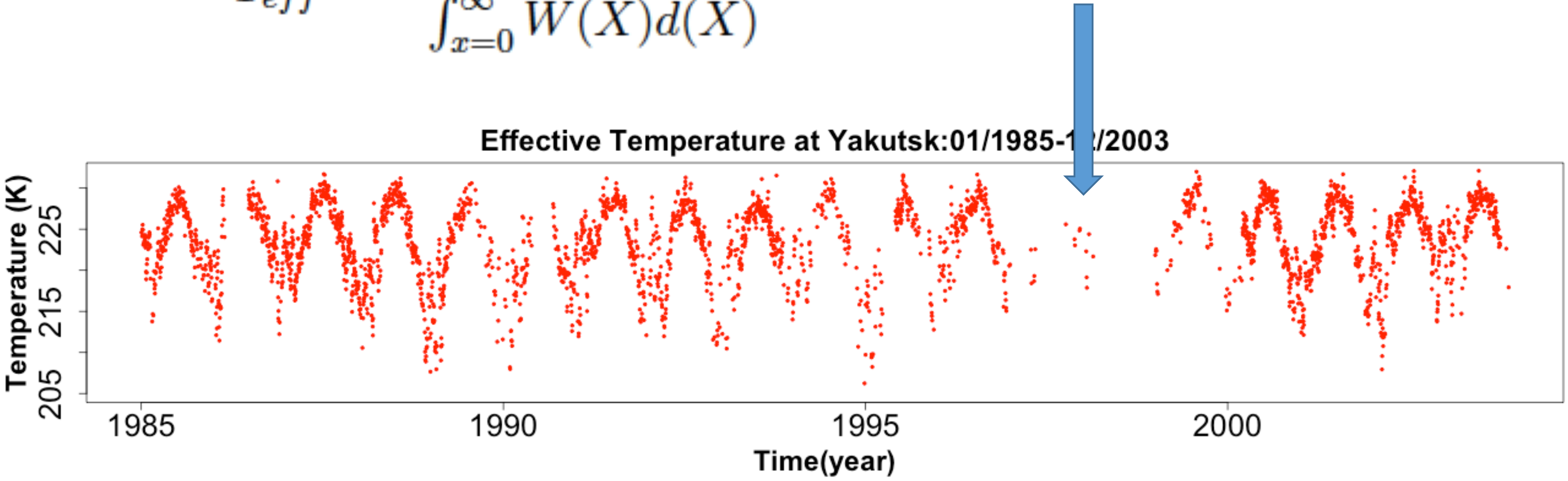
Possible combination: 31
(Model candidates)

- Partial Least Square technique to compare predictive power (RMSE) using cross validation of different models
- Best fit model: Least error

# Effective Temperature: using Radiosonde measurements

$$T_{eff} = \frac{\int_{x=0}^{\infty} T(X)W(X)dX}{\int_{x=0}^{\infty} W(X)d(X)}$$

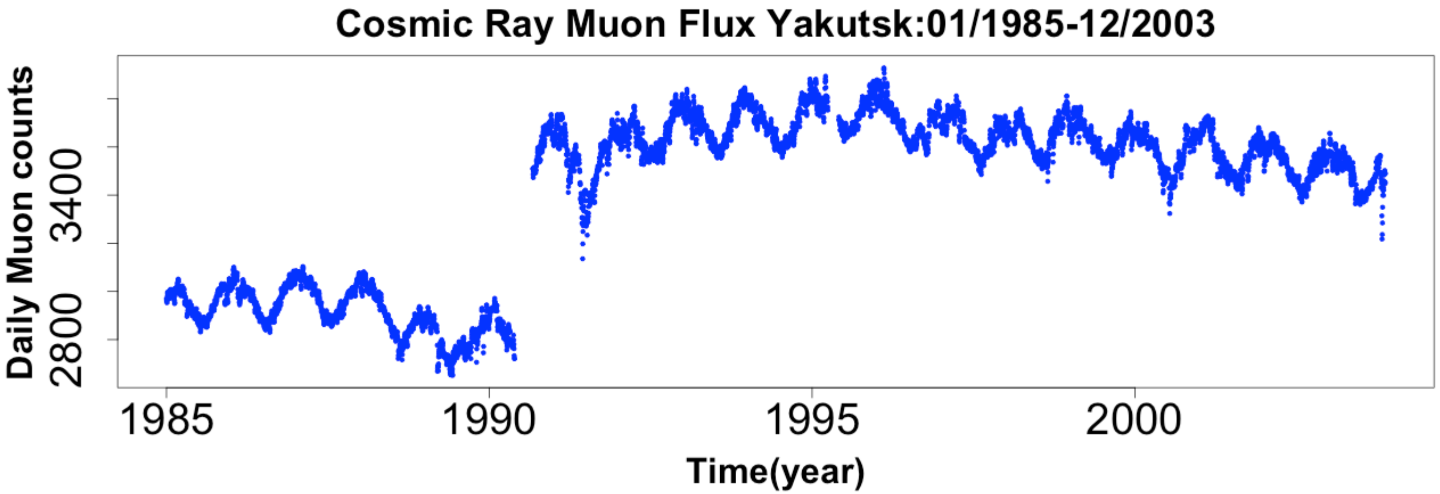
**Missing Radiosonde Data**

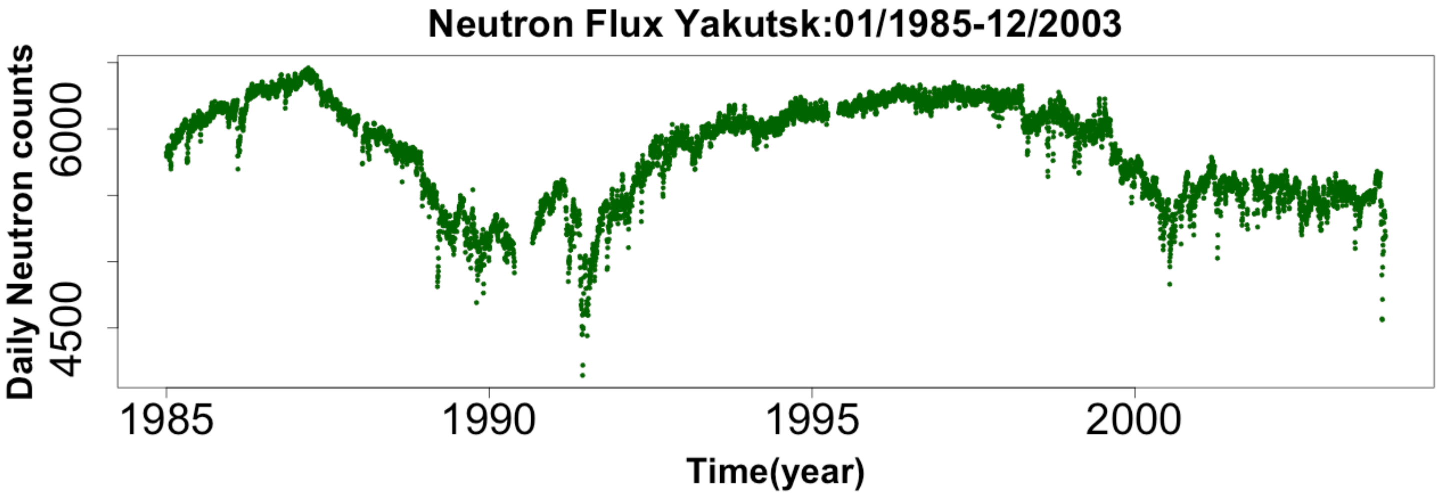



- Department of Atmospheric science, Wyoming University

# Cosmic Ray Muon and Neutron Counts

Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy,
Yakustk- Russia



# Regression analysis and Predictive Power

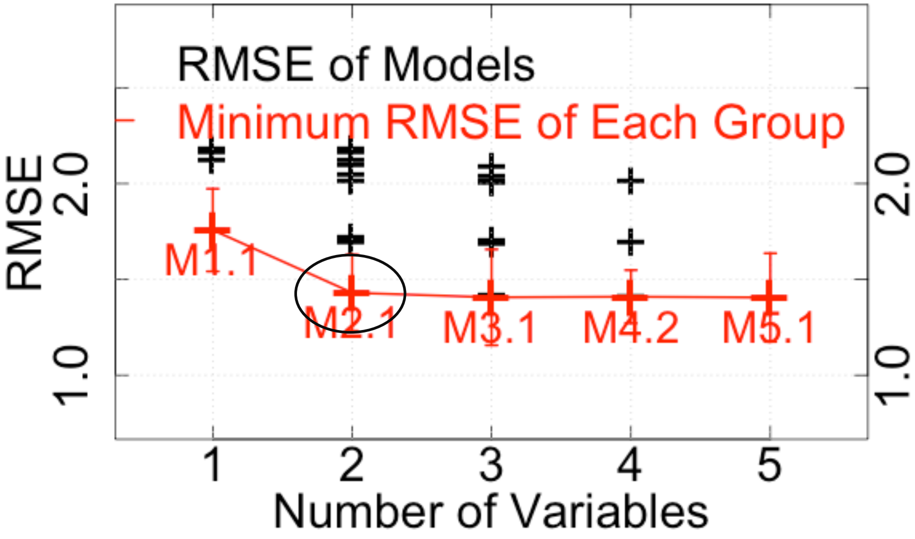
$$\delta T_{eff} = a\delta I_{\mu} + b\delta I_N + c\delta I_{\mu}^2 + d\delta I_N^2 + e\delta I_{\mu}\cdot\delta I_N$$

- Total number of model candidates: 31
- Model representation: Ma.b

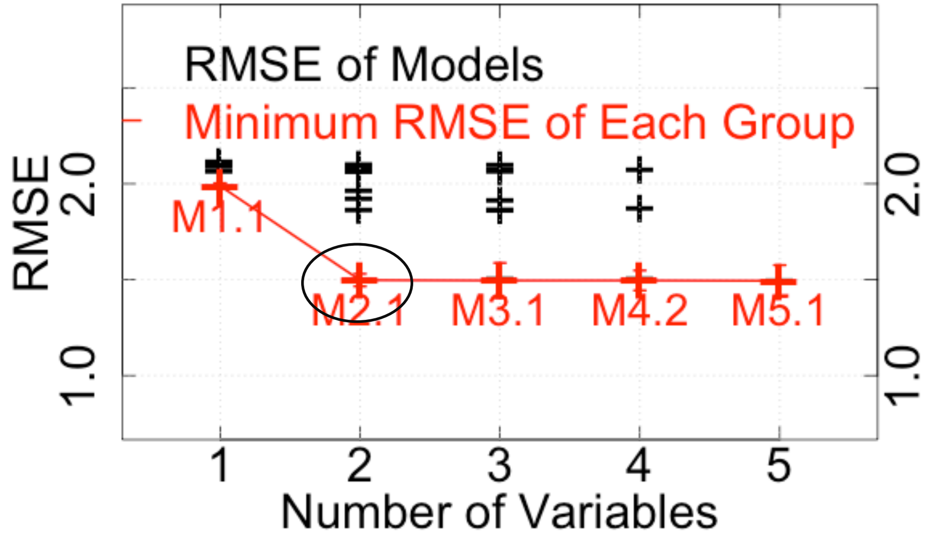
  a: number of predictors (group number)

  b: sequence in the group

Solar cycle 22 09/1990 - 03/1995



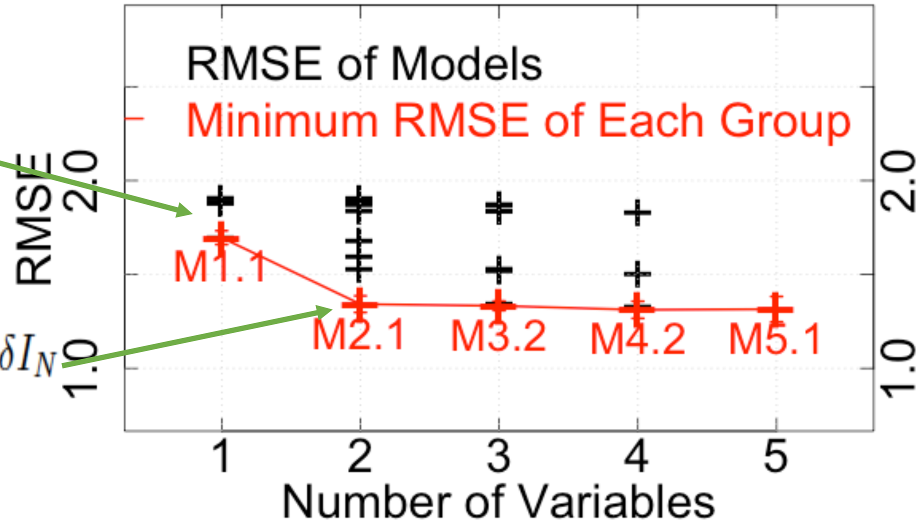

Solar cycle 22 01/1985 - 05/1990



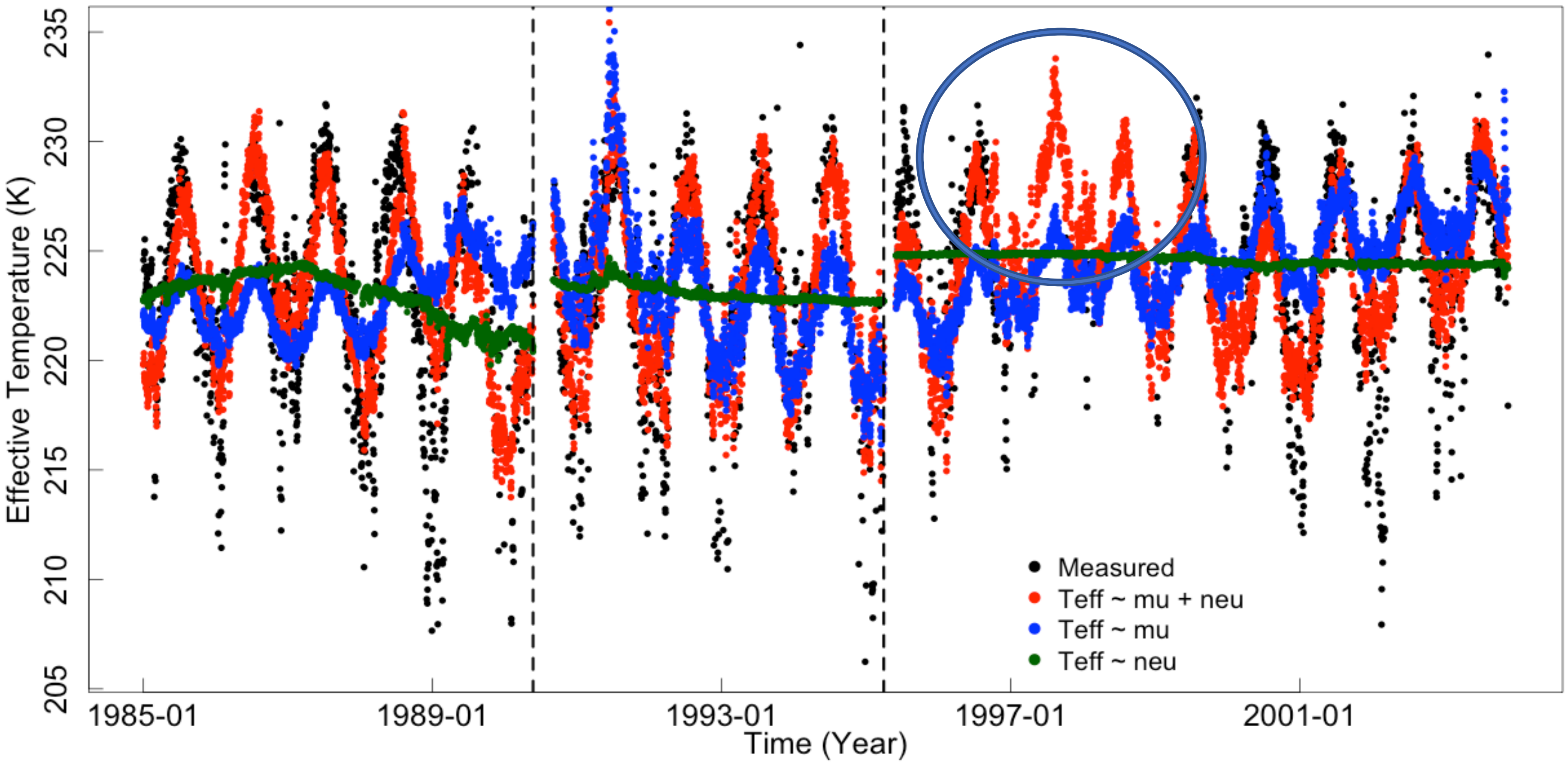

Solar cycle 23 06/1995 - 11/2003

$$\delta T_{eff} = \alpha \cdot \delta I_{\mu}$$

$$\delta T_{eff} = \alpha \cdot \delta I_{\mu} + \beta \cdot \delta I_N$$



# Reconstruction of Effective Temperature Using CR Data



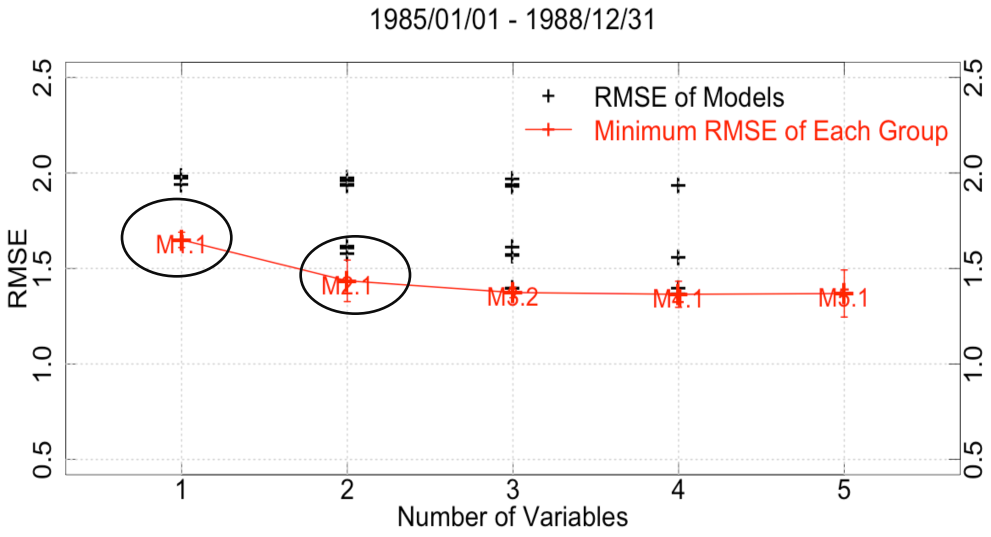

- Regression was performed and $T_{eff}$ was constructed separately on three different datasets corresponding to three time periods to compare the results and plotted together.

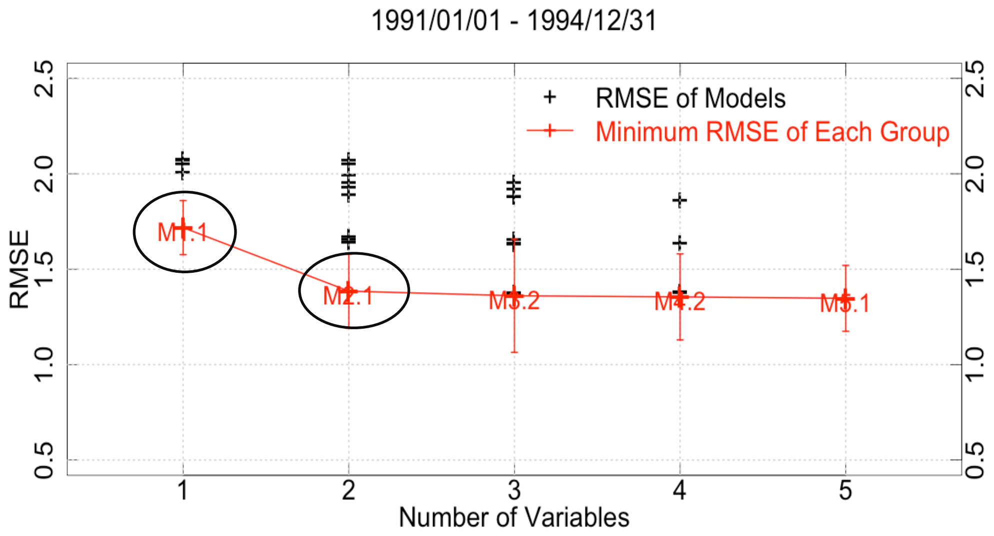
# Effect of Short-term Analysis

- Do we still get the same results (Predictive Models) for shorter time period
- Role of neutrons?

# Predictive Power Comparison

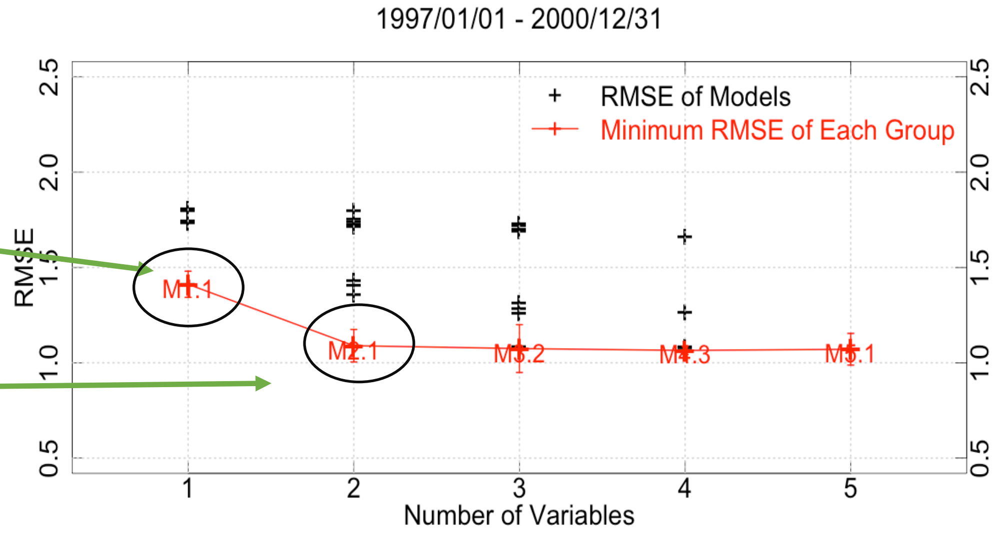
## Periodic analysis: 4 years data



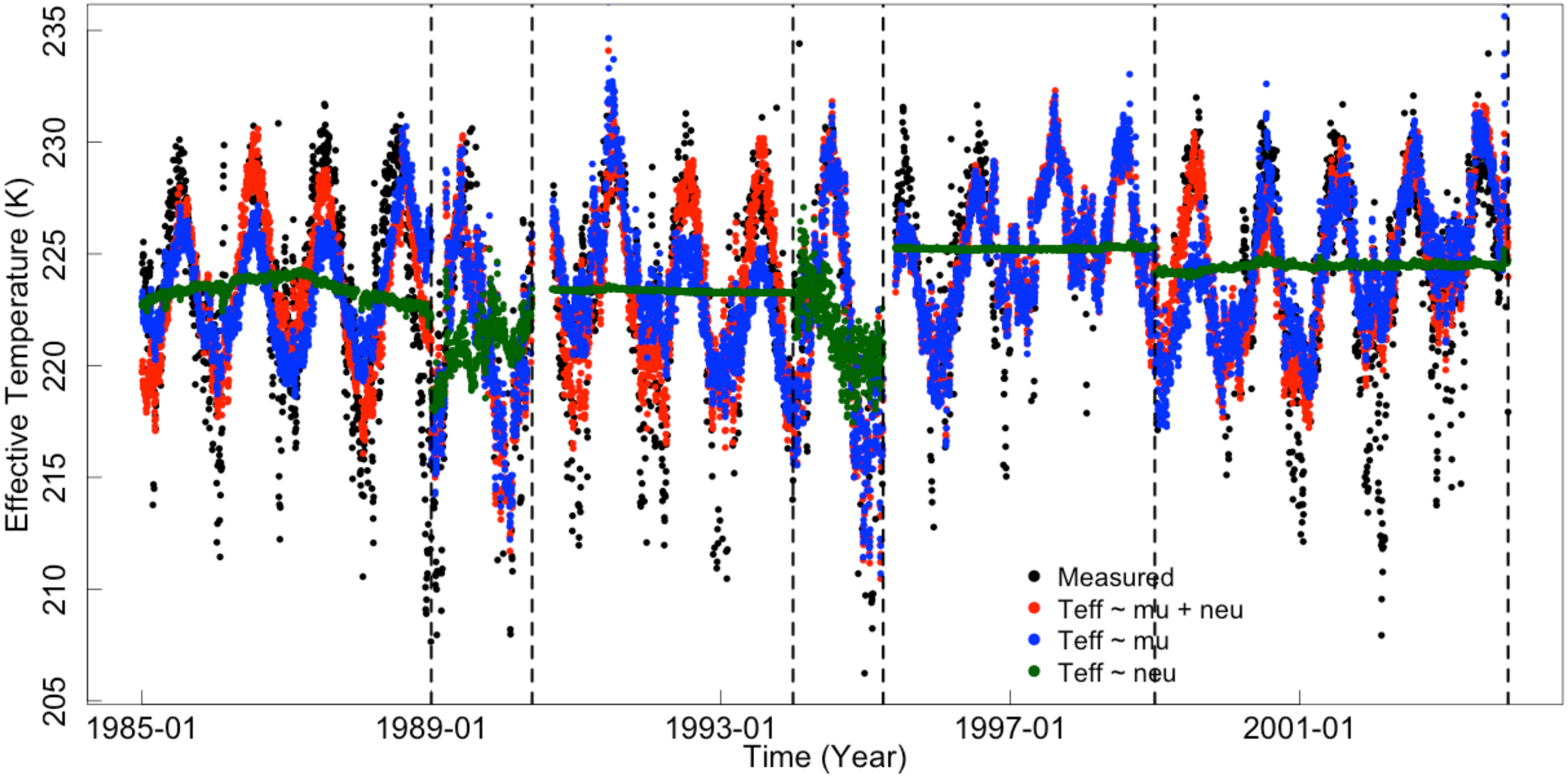




$$\delta T_{eff} = \alpha \cdot \delta I_{\mu}$$

$$\delta T_{eff} = \alpha \cdot \delta I_{\mu} + \beta \cdot \delta I_N$$



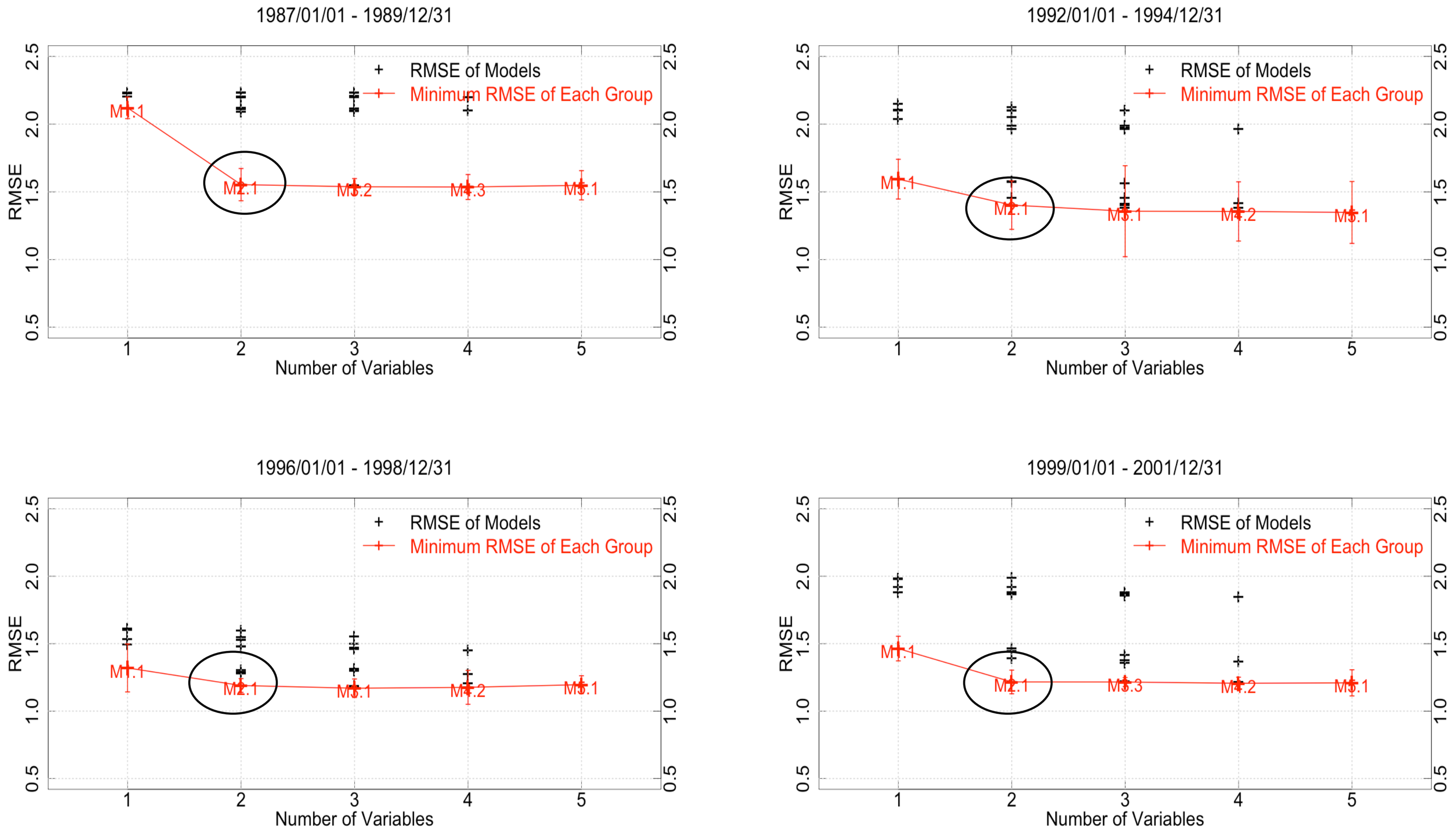
# Reconstruction of Effective Temperature (Regression analysis on every 4 years of CR data)



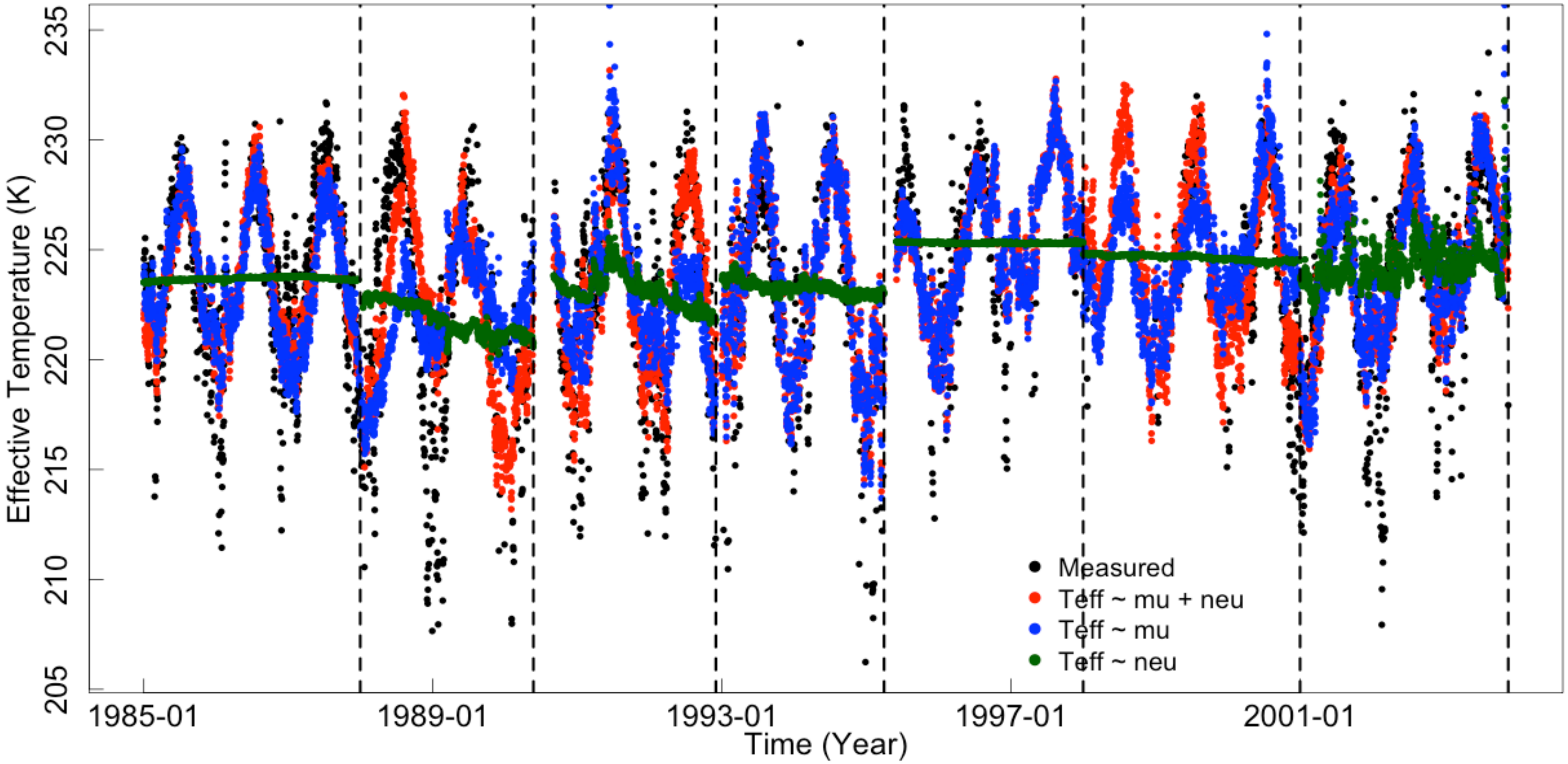

- Regression was performed $T_{eff}$ was reconstructed separately for each sub dataset.
- Model $T_{eff} = f(I_{\mu} + I_{N})$ gives best fit for most subsets.

Periodic analysis: 3 years data

# Predictive Power Comparison



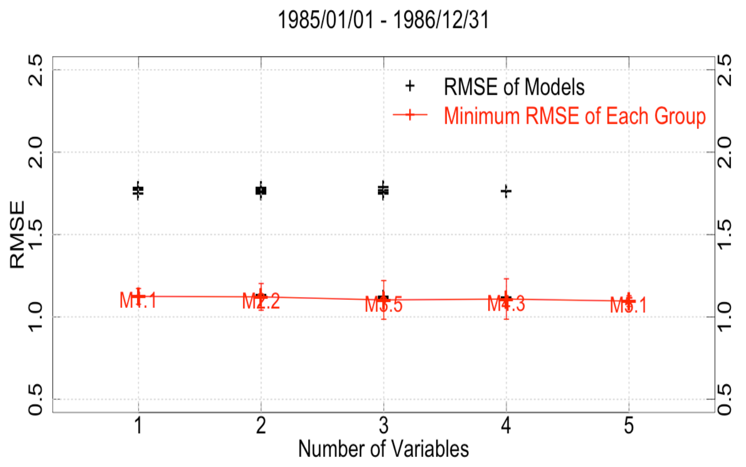
# Reconstruction of Effective Temperature (Regression analysis on every 3 years of CR data)

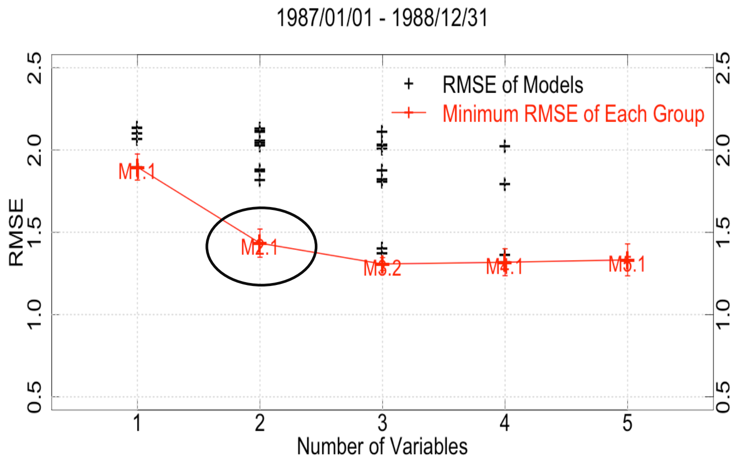


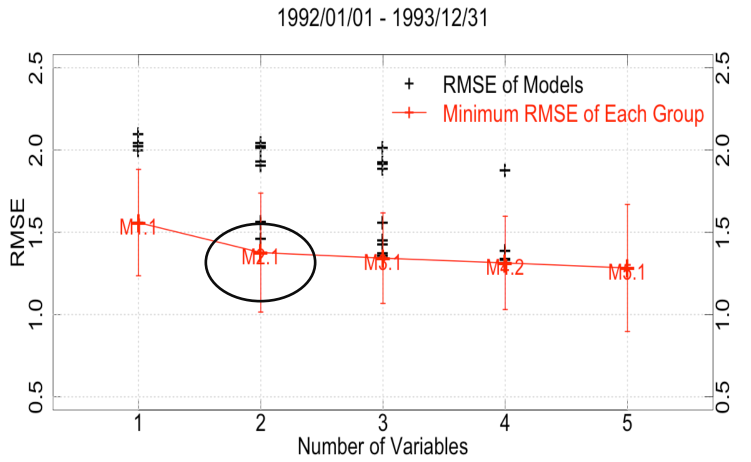

- Regression was performed $T_{eff}$ was reconstructed separately for each sub dataset.
- Model $T_{eff} = f(I_{\mu} + I_N)$ gives best fit for most subsets.

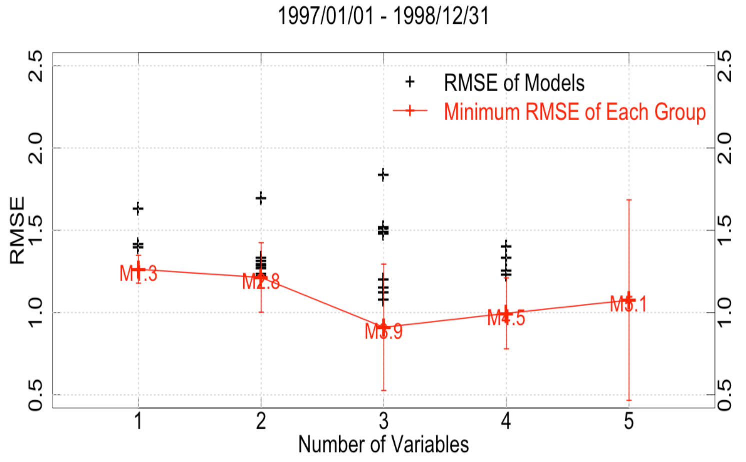
# Predictive Power Comparison

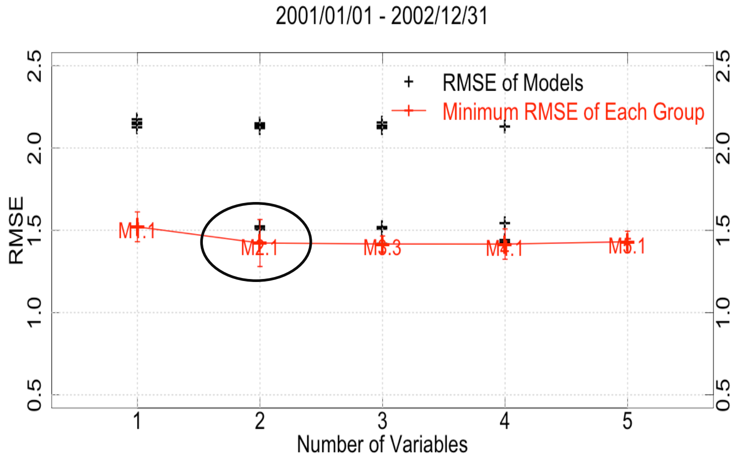
## Periodic analysis: 2 years data

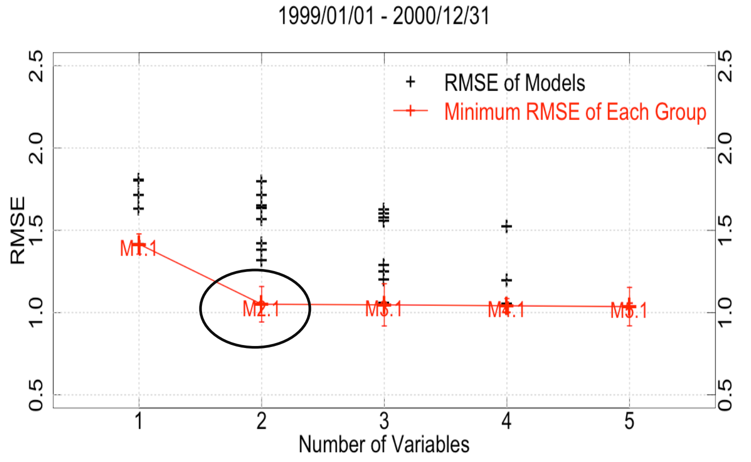


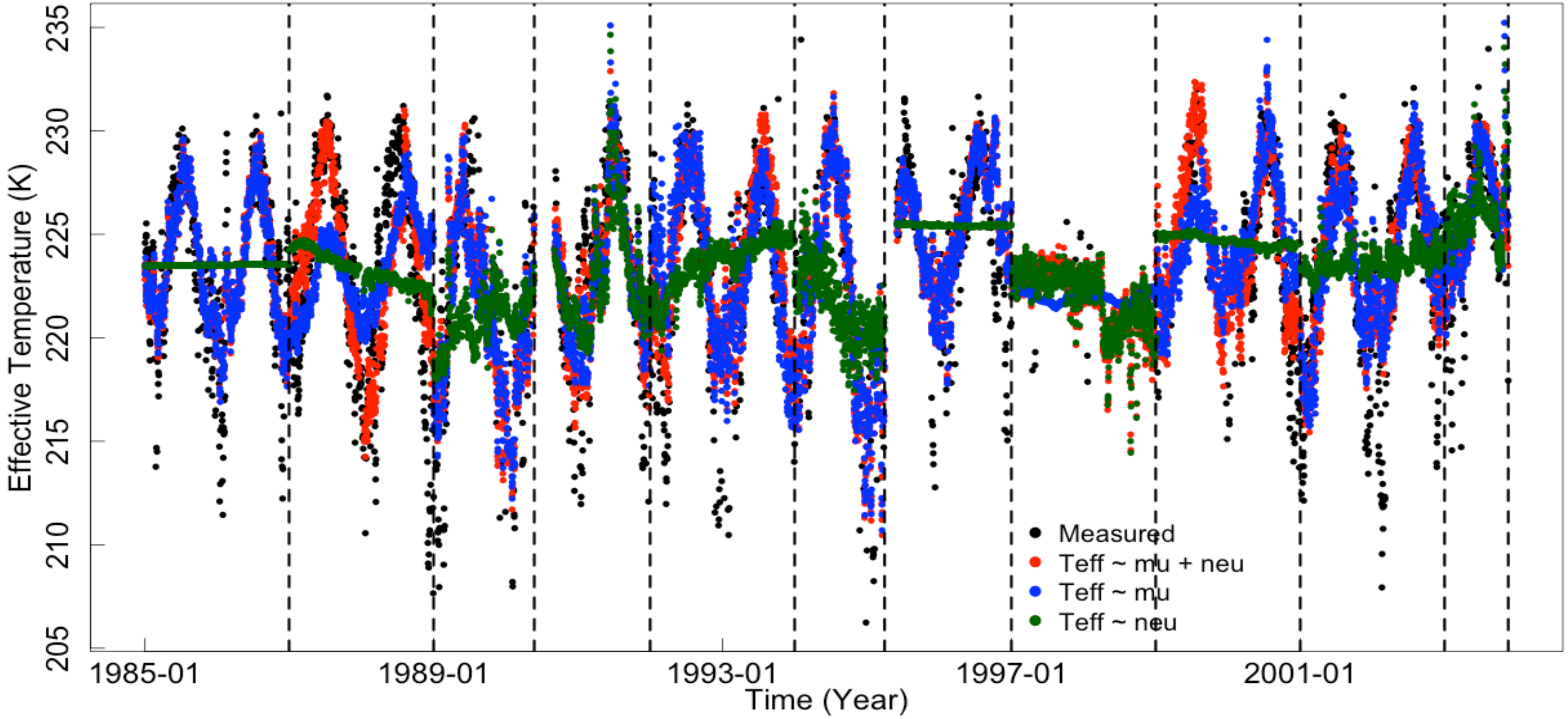



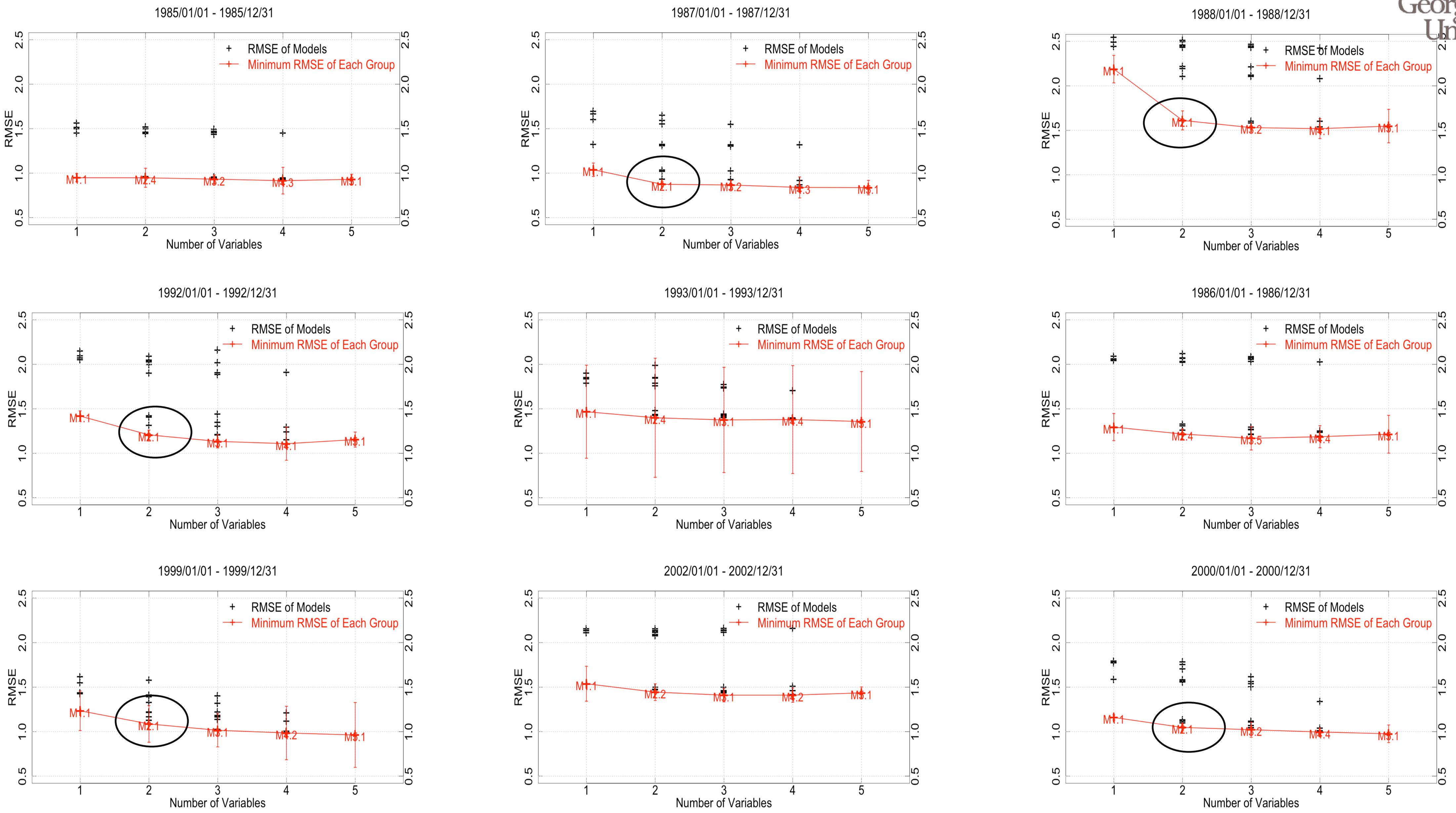



# Reconstruction of Effective Temperature (Regression analysis on every 2 years CR data)

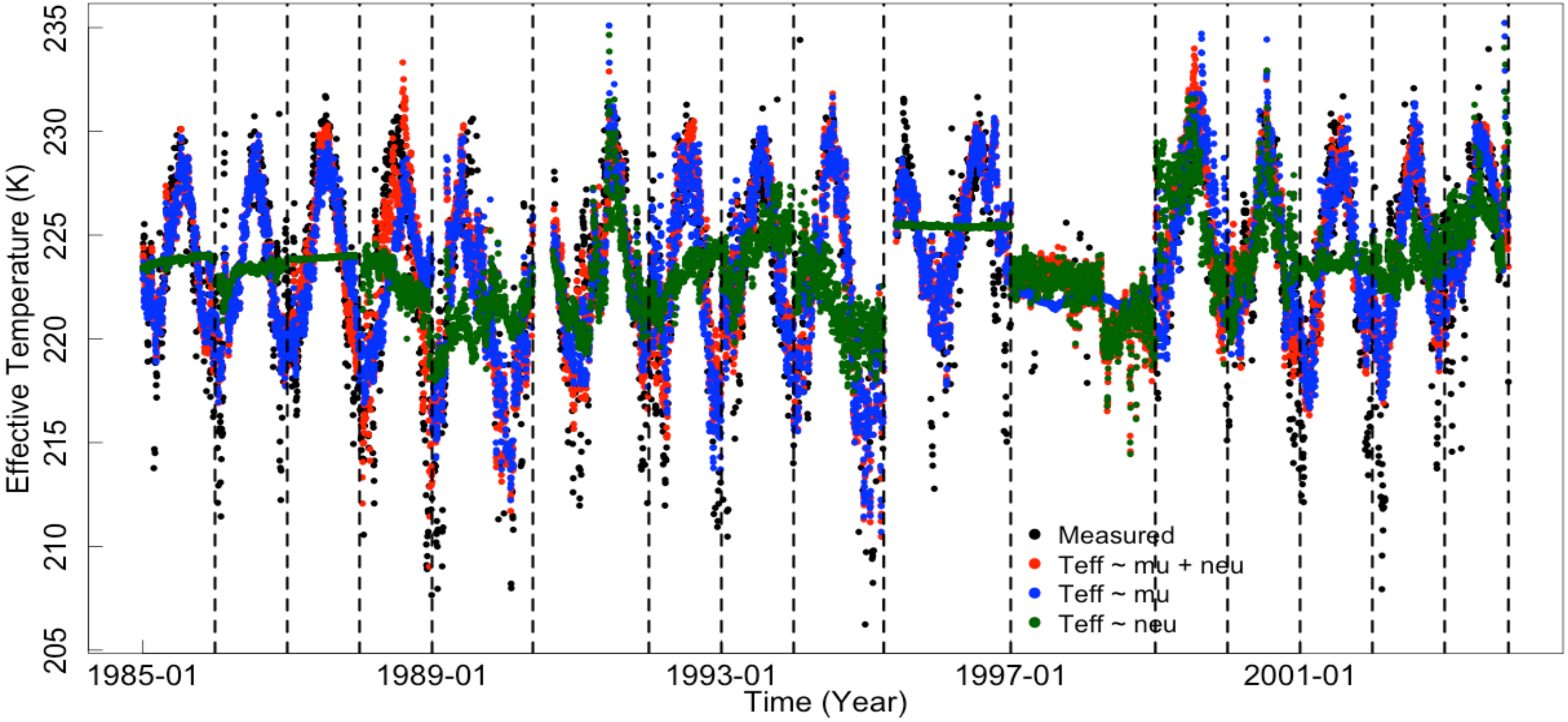



- Regression was performed $T_{eff}$ was reconstructed separately for each sub dataset.
- Model $T_{eff} = f(I_{\mu})$ gets better to capture $T_{eff}$ values for most time intervals.

# Predictive Power Comparison



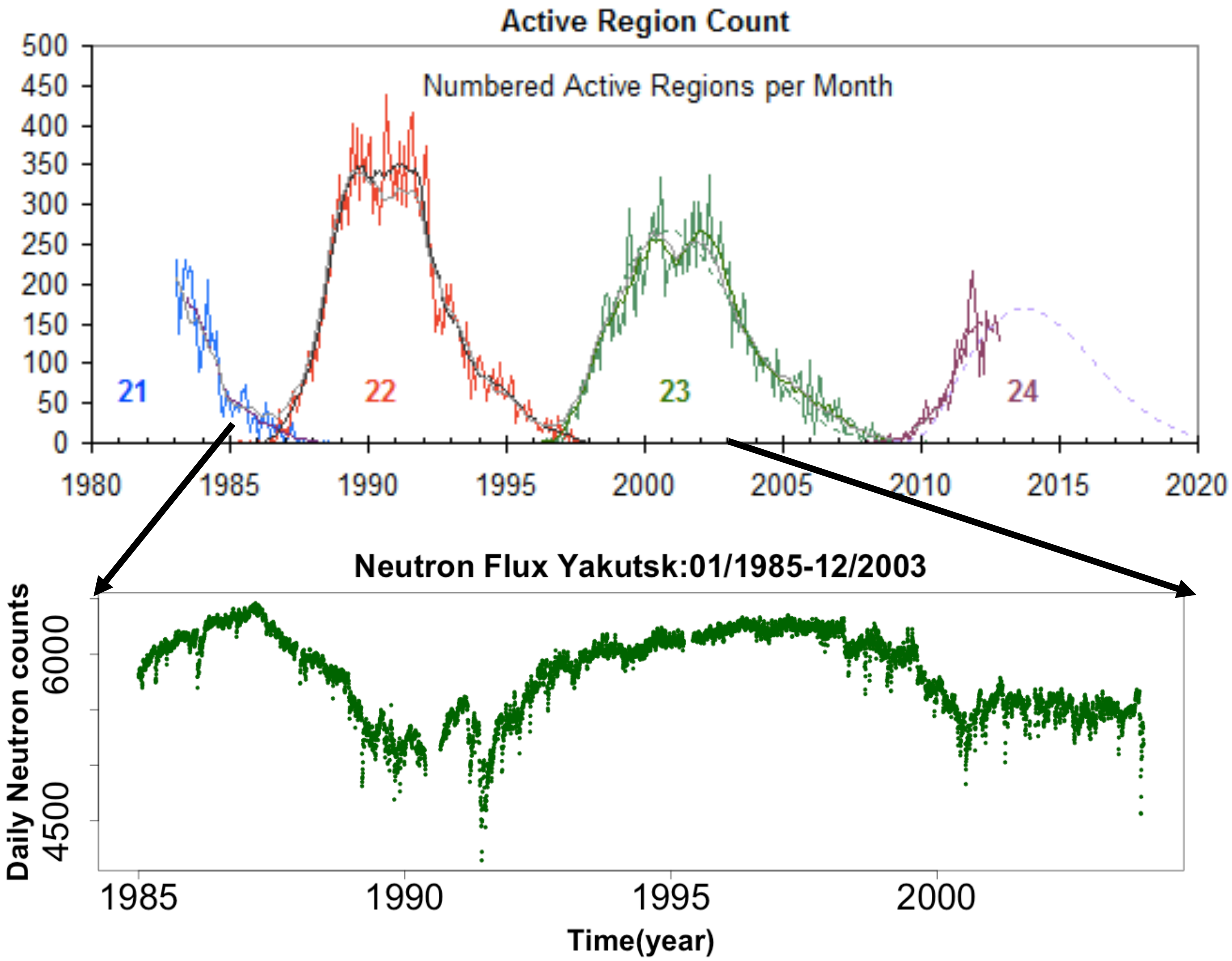
# Reconstruction of Effective Temperature (Regression analysis on yearly CR data)




- Regression was performed $T_{eff}$ was reconstructed separately for each sub dataset.
- Model $T_{eff} = f(I_{\mu})$ gets as good as the model $T_{eff} = f(I_{\mu} + I_N)$.

# Effect of Solar Cycle and Neutron Variation

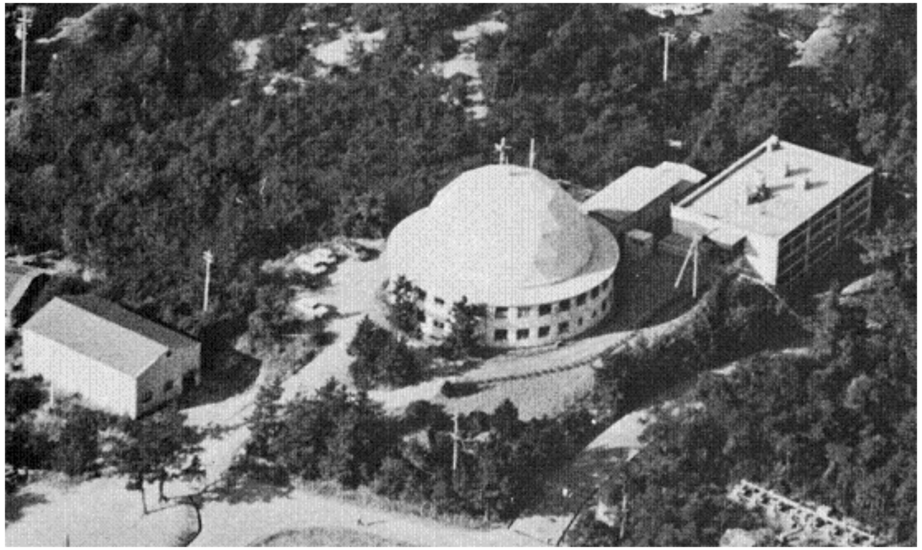
Leif Svalgaard, Dec 2013




Neutron plays role in the long term analysis (modelling) of effective temperature due to 11 solar cycle modulation

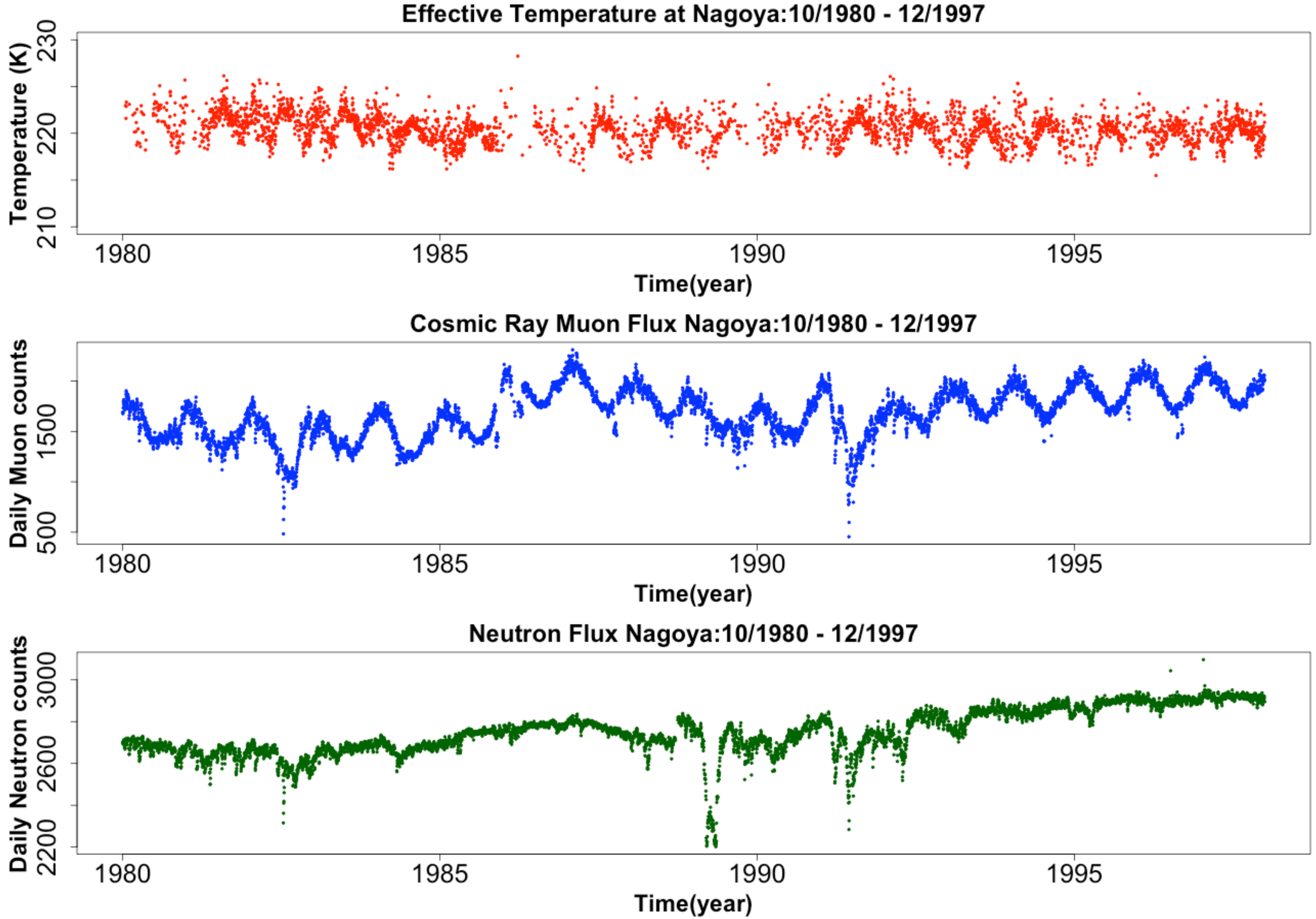
# Effective Temperature calculation for Nagoya, Japan

NAGOYA UNIVERSITY, NAGOYA JAPAN



- ➢Muon Telescope (Nagoya, Japan)
- ➢Neutron monitor (Mt. Norikura, Japan)
- ➢Radiosonde data was obtained for nearest station: Hamamatsu

# Effective Temperature, Muon And Neutron Data: Nagoya (1980-1997)

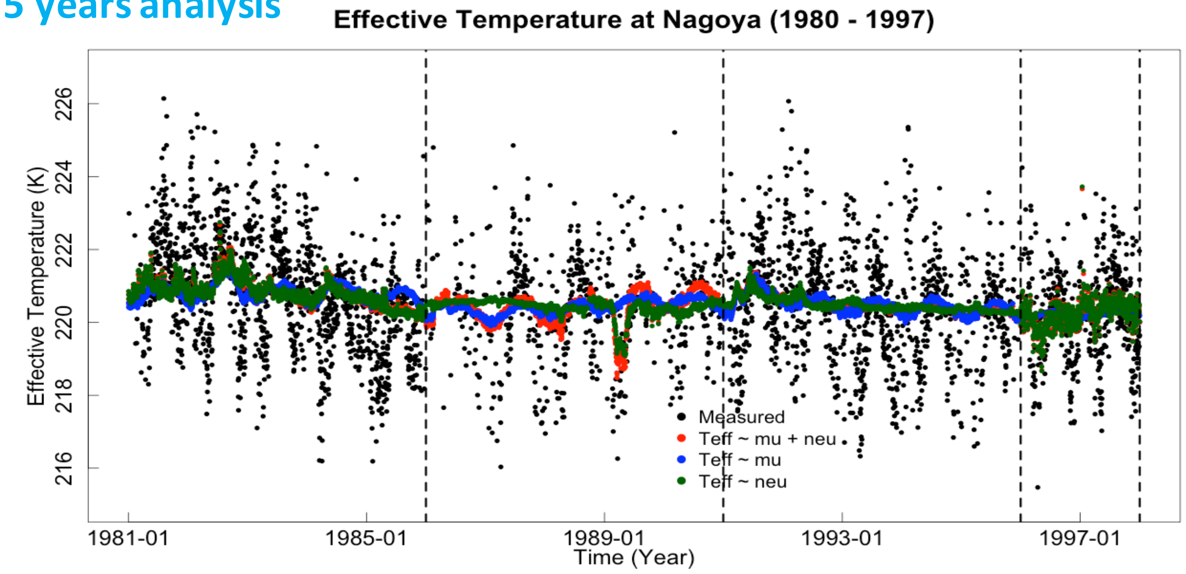



- Regression was performed for datasets corresponding different time durations.
- $T_{eff}$ was reconstructed separately for each dataset
- $T_{eff}$ was reconstructed for three models:

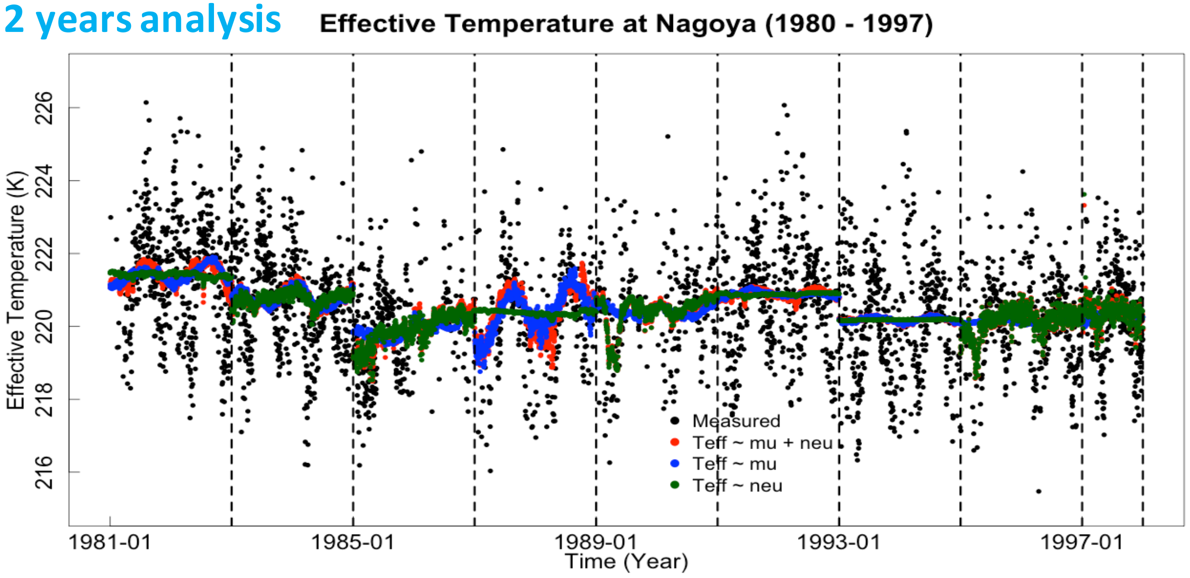
$$T_{eff} = f(I_{\mu} + I_N)$$
$$T_{eff} = f(I_{\mu})$$
$$T_{eff} = f(I_N)$$

# Reconstruction of Effective Temperature using CR data

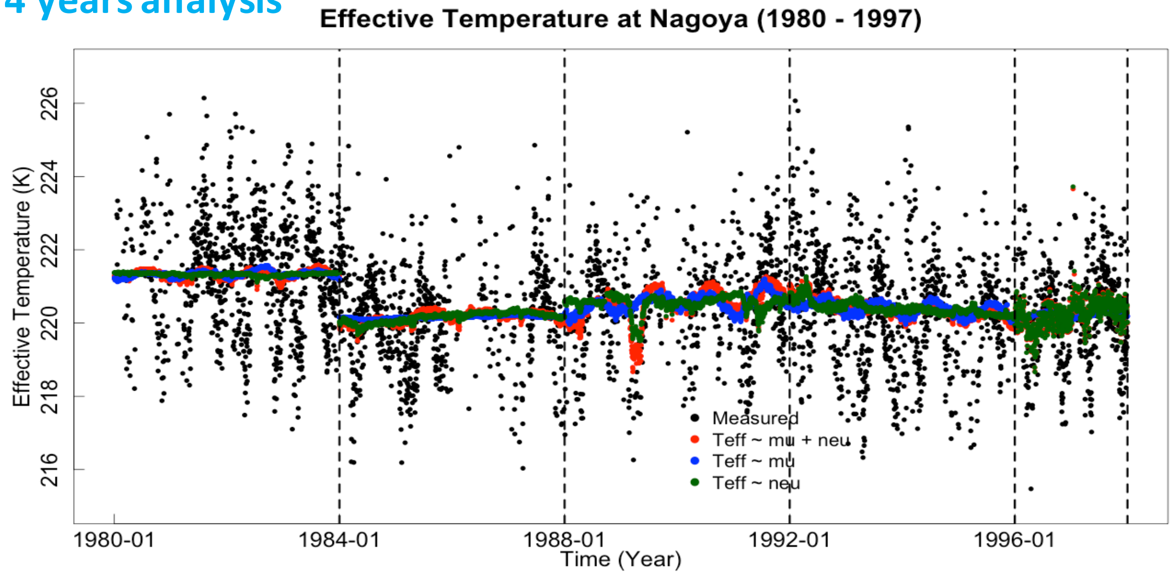
## 5 years analysis



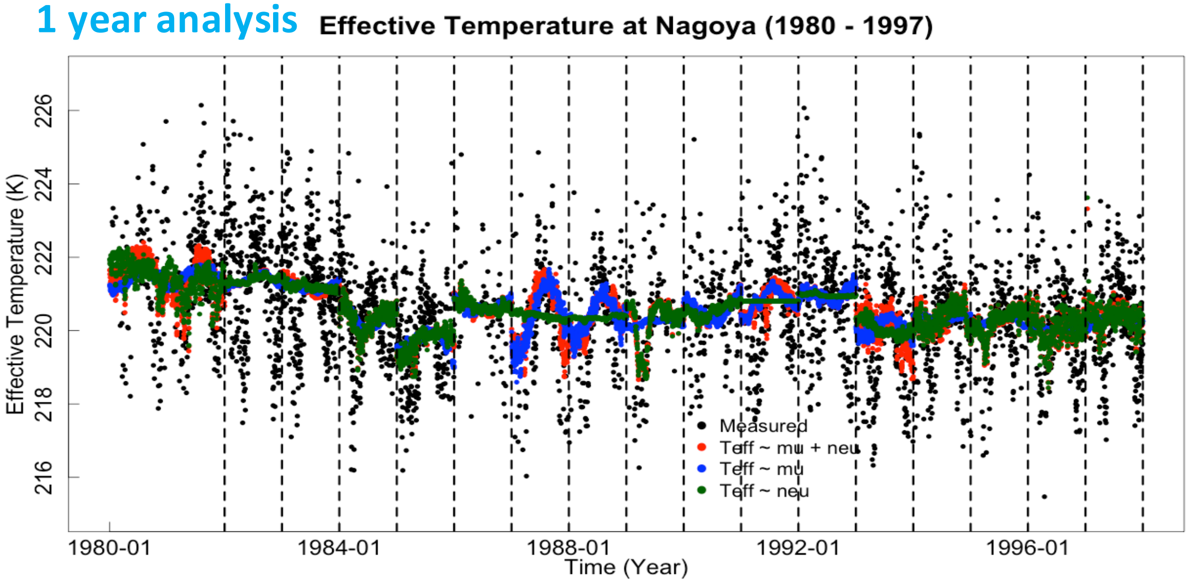

## 2 years analysis




## 4 years analysis




## 1 year analysis



# Unsuccessful mapping of Teff at Nagoya

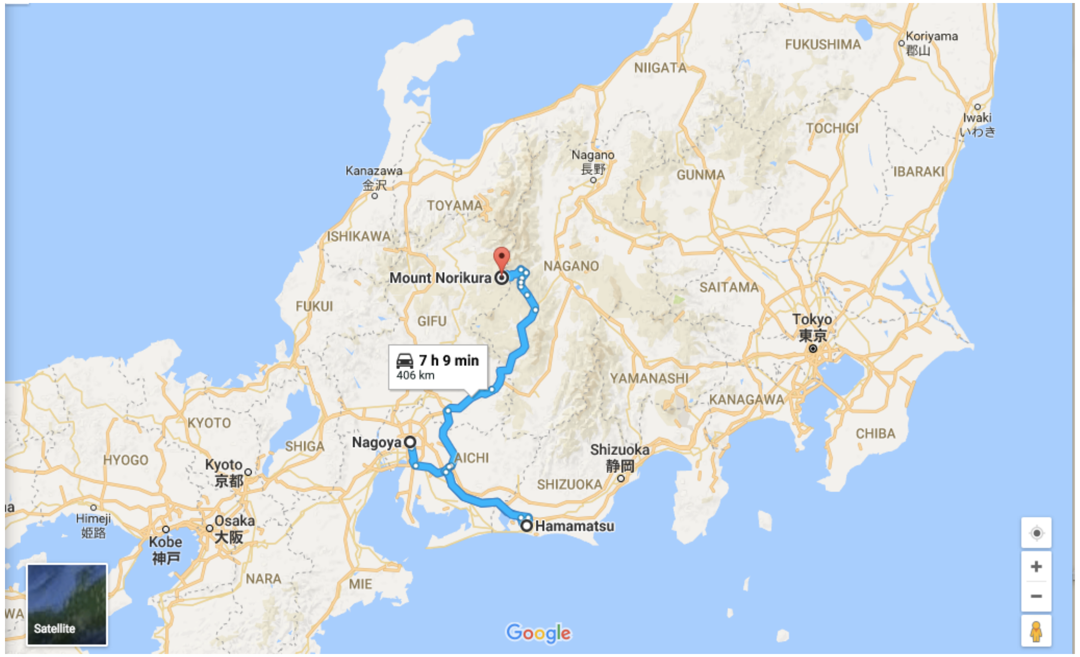
## Reason:

➢The Radiosonde temperature measurements were taken at Hamamatsu

➢Distance from Nagoya to Hamamatsu = 112Km

➢Distance from Nagoya to Mt. Norikura = 241Km

In order to find a statistical model to calculate Effective Temperature, both Cosmic ray data and radiosonde information shall be available at same location.



# Summary

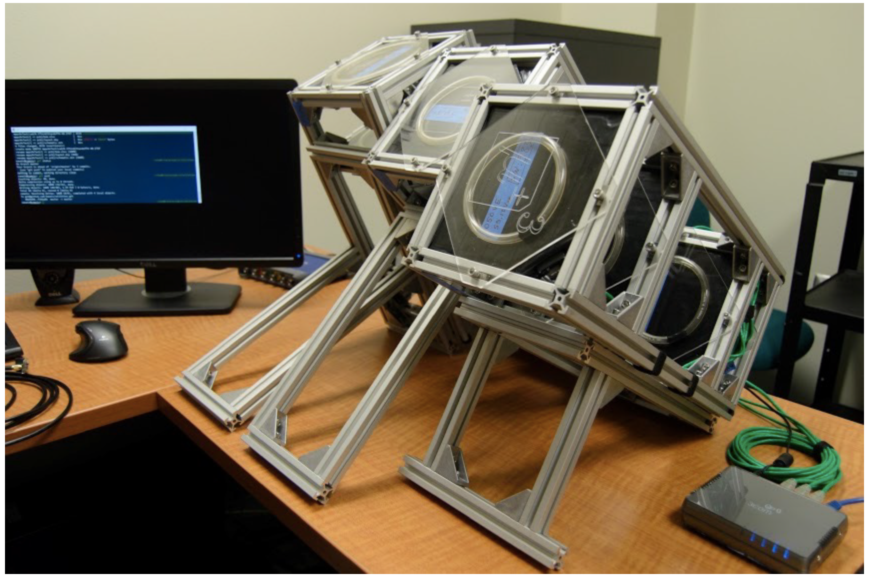
- Effective Temperature was reconstructed using cosmic ray (muon and neutron) data: Cosmic ray behaving as long distance thermometer!!
- $T_{eff}$ can be predicted (past events) using available CR records.
- To model Effective temperature, both Radiosonde and CR needs to be available at the same location.
- For short term weather prediction, Muon flux is sufficient but neutrons are needed to correct long term solar modulation.

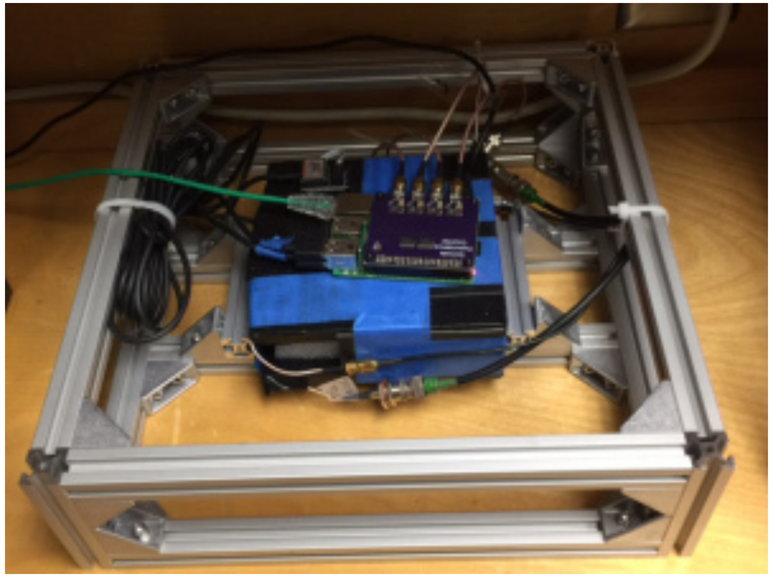
# Acknowledgement

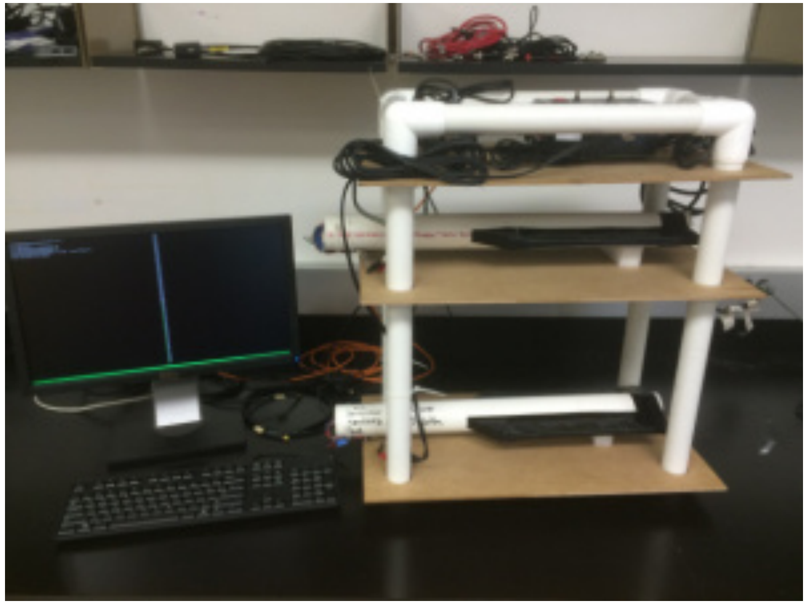

- Cosmic ray muon and neutron data: Institute OF COSMOPHYSICAL RESEARCH AND AERONOIMY RUSSIAN ACADEMY OF SCIENCES
- Department of Atmospheric science, Wyoming University

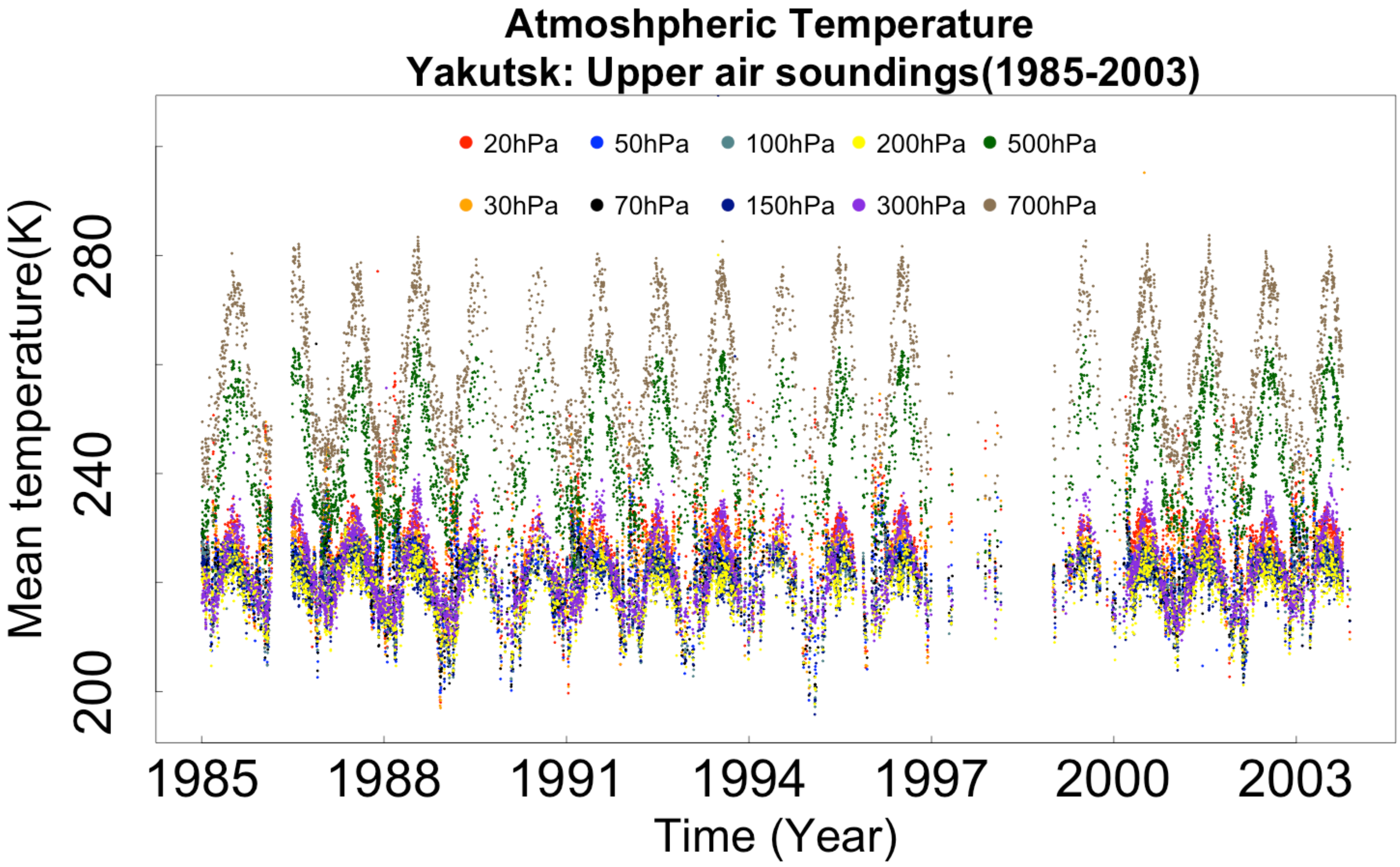
# BACK-UP SLIDES

# Cosmic Ray Detectors at GSU



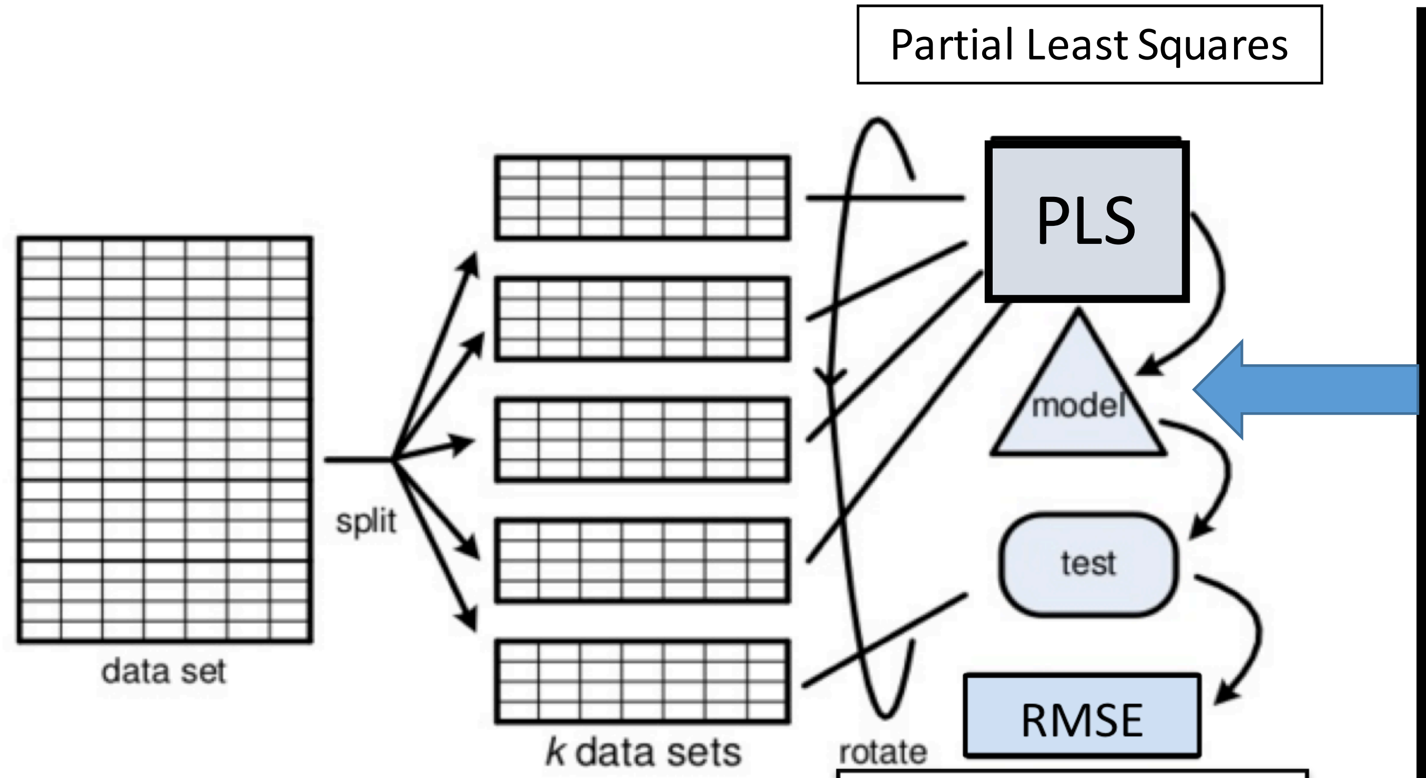







- Downloaded from Wyoming University upper air soundings records.
- Weather station: Yakutsk (24959)

# Evaluate Predicting Performance of Models – K-fold Cross Validation

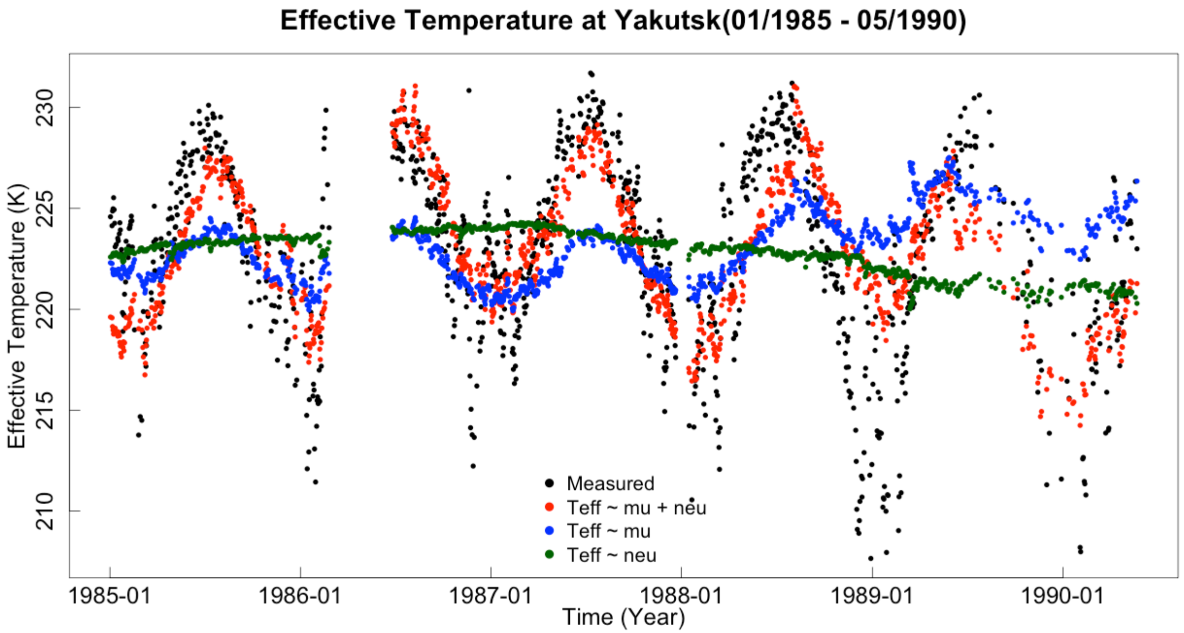


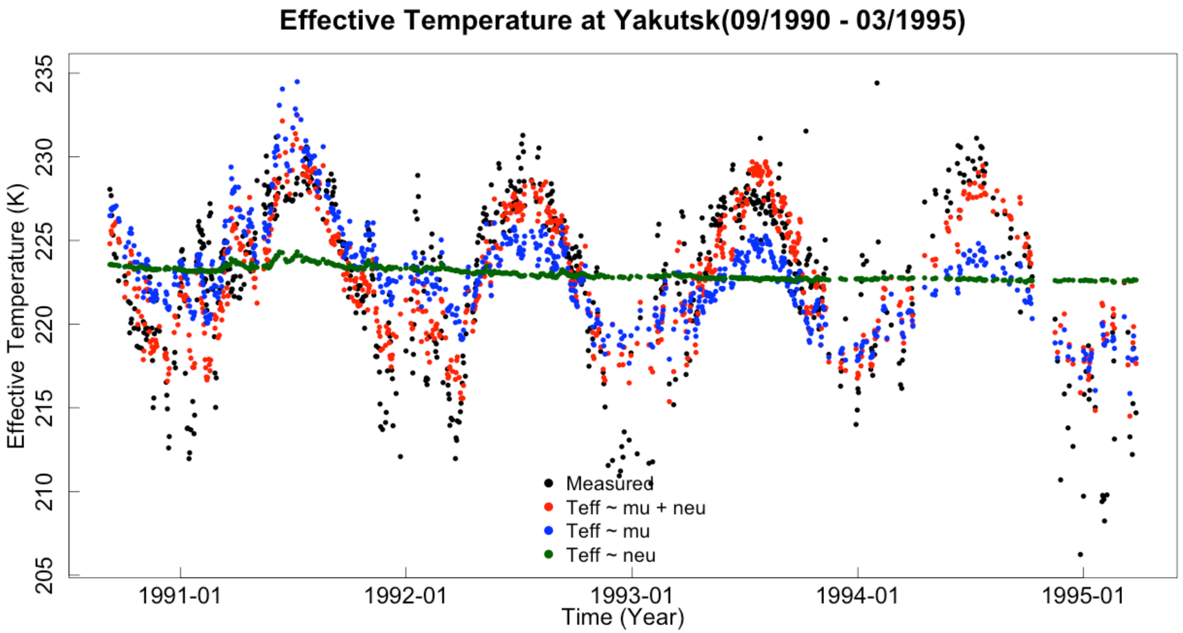

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{n}}$$

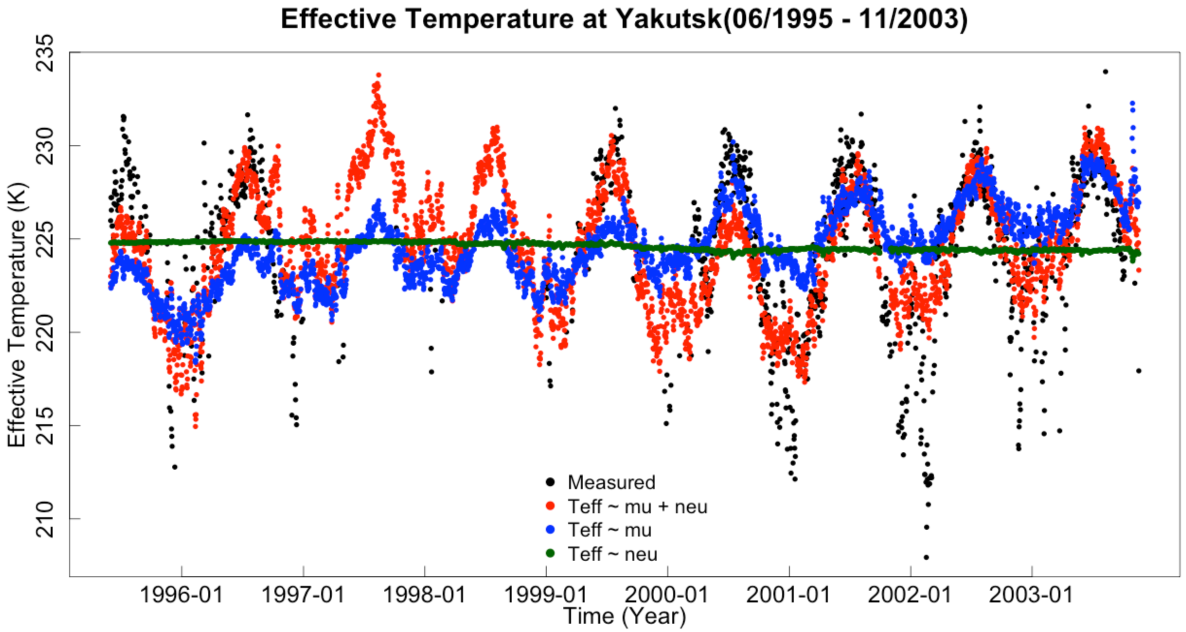
M1.1 : TE ~ mu
M1.2 : TE ~ neu
M1.3 : TE ~ mu2
M1.4 : TE ~ neu2
M1.5 : TE ~ neumu
M1.6 : TE ~ mu3
M1.7 : TE ~ neu3
M1.8 : TE ~ n2m
M1.9 : TE ~ nm2
M2.1 : TE ~ mu + neu
M2.2 : TE ~ mu + mu2
M2.3 : TE ~ mu + neu2
M2.4 : TE ~ mu + neumu
M2.5 : TE ~ mu + mu3
M2.6 : TE ~ mu + neu3
M2.7 : TE ~ mu + n2m
M2.8 : TE ~ mu + nm2
M2.9 : TE ~ neu + mu2
M2.10 : TE ~ neu + neu2
M2.11 : TE ~ neu + neumu
M2.12 : TE ~ neu + mu3
M2.13 : TE ~ neu + neu3
M2.14 : TE ~ neu + n2m
M2.15 : TE ~ neu + nm2
M2.16 : TE ~ mu2 + neu2
M2.17 : TE ~ mu2 + neumu
M2.18 : TE ~ mu2 + mu3
M2.19 : TE ~ mu2 + neu3
M2.20 : TE ~ mu2 + n2m
M2.21 : TE ~ mu2 + nm2
M2.22 : TE ~ neu2 + neumu
M2.23 : TE ~ neu2 + mu3
M2.24 : TE ~ neu2 + neu3
M2.25 : TE ~ neu2 + n2m
M2.26 : TE ~ neu2 + nm2
M2.27 : TE ~ neumu + mu3
M2.28 : TE ~ neumu + neu3
M2.29 : TE ~ neumu + n2m

## Model Selection Principles:

- Choose the one that has the least RMSE
- choose the simplest one




## Regression Coefficients

| mu | mu , neu | neu |
|---|---|---|
| -0.2212119 | -0.6046357, 0.2853218 | 0.0697698 |
| -0.4678745 | -0.8353385, 0.2255857 | -0.02592697 |
| -0.3140509 | -0.6880383, 0.2573893 | 0.01623815 |