Future Use and Challenges of Physics-Based Space Weather Data Assimilation

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Modern technological systems like GPS and Galileo, HF communications, and radar ranging are affected by geomagnetic storms and can become unreliable during large events. Geomagnetic storms are caused by large increases, often associated with changes in the spatial distribution, of the high-latitude energy deposition from the magnetosphere. The changes in energy input have global consequences with undesirable effects on technological systems and they cannot be adequately modeled at the present time. For operational purposes these changes can only be specified and perhaps modeled using data assimilation schemes .

OUTLINE

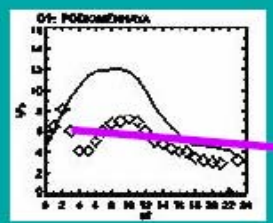
- Introduction
- The System
- The Need for Data Assimilation
- Example of Data Assimilation
- Status and Challenges

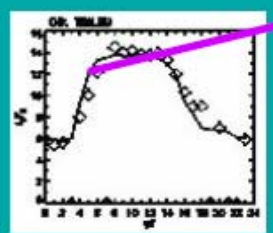
Why modeling the space environment?

Negative Ionospheric Storm Tracks Region of Low O/N_2

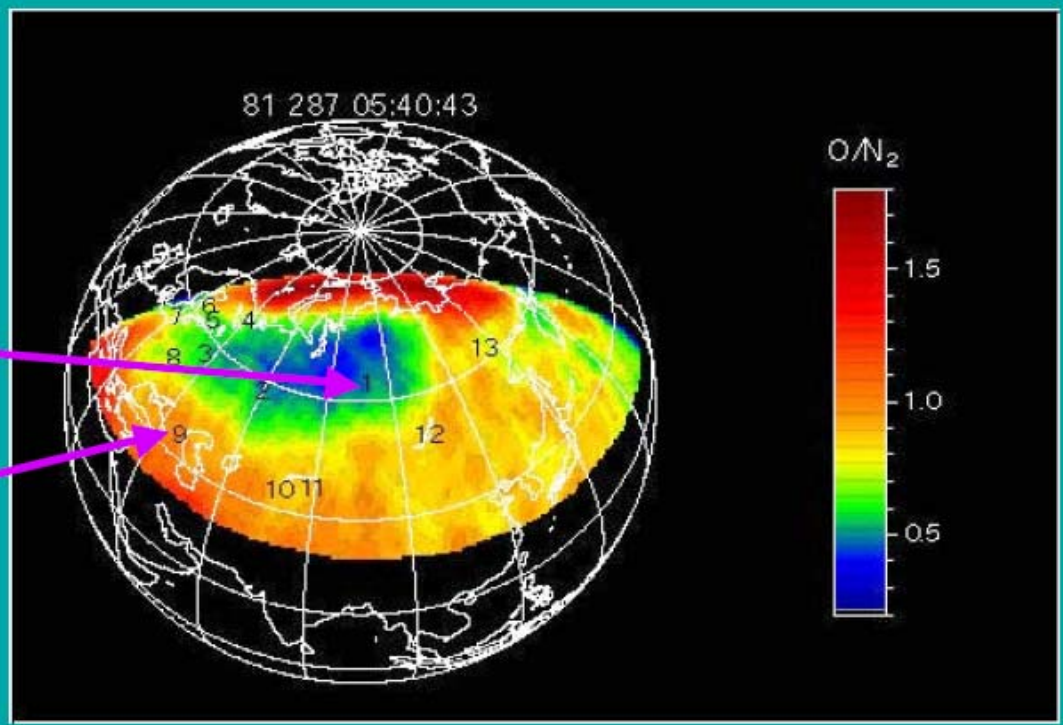
Ionosonde
24 hr data
14 Oct. 1981

Monthly Mean ——
Daily Data ◆◆◆

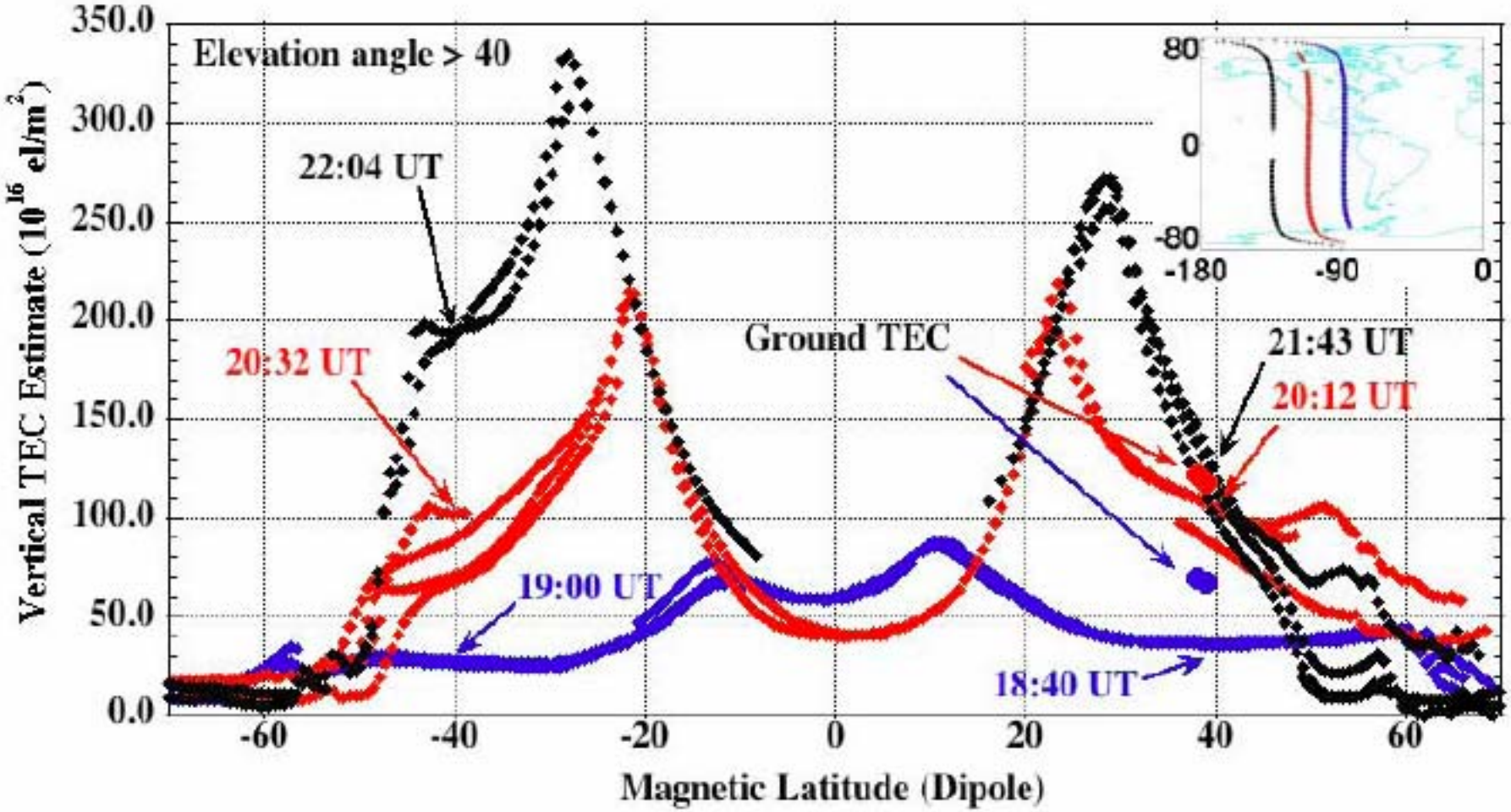




f_oF_2 follows O/N_2 inferred from DE-1 FUV image



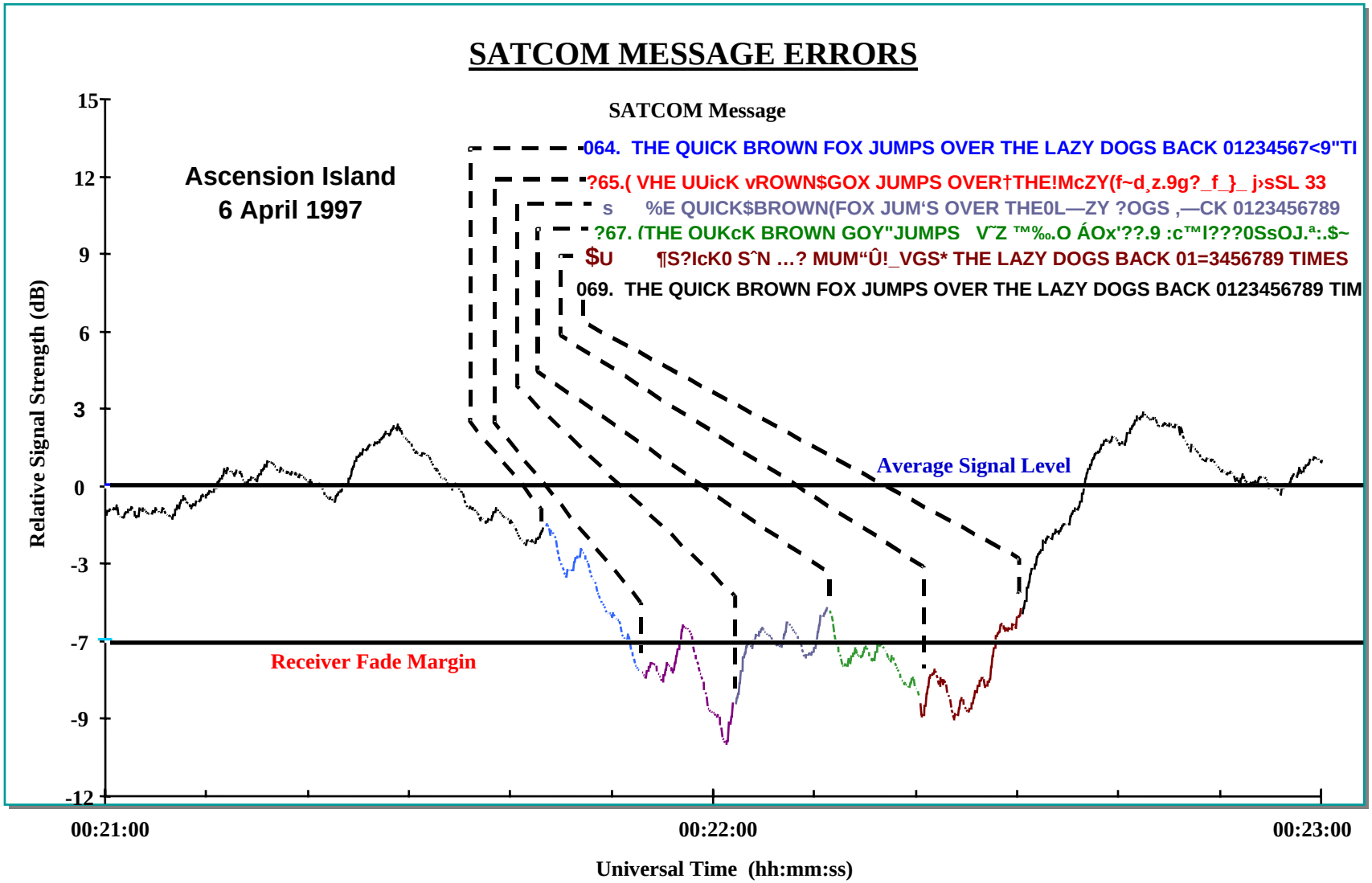
TEC above the CHAMP satellite altitude of 400 km on October 30, 2003



1TECU = 16 cm of delay at L1

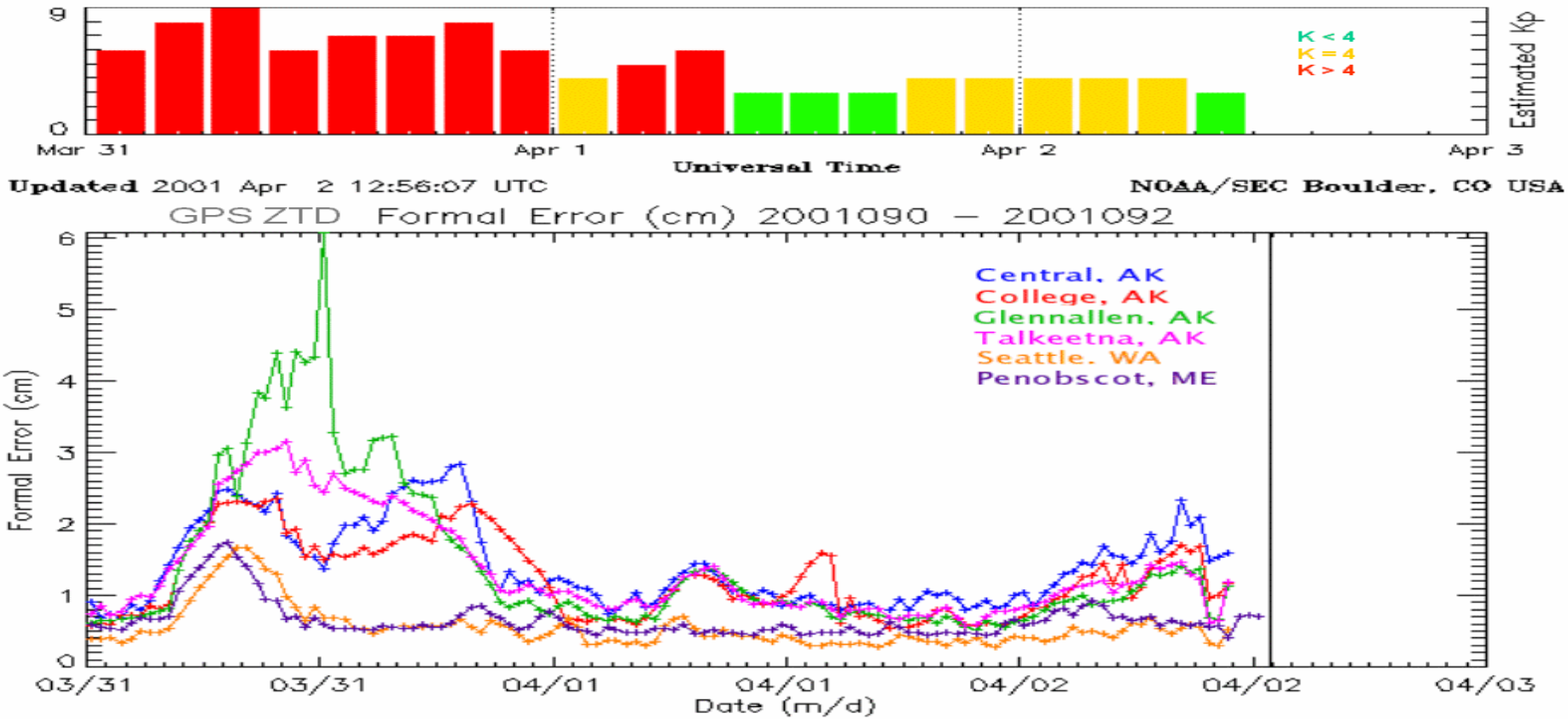
Mannucci, private communication, 2005

ACTUAL SATCOM MESSAGES



S. Basu, private communication

Geomagnetic Storm of 31 March 2001



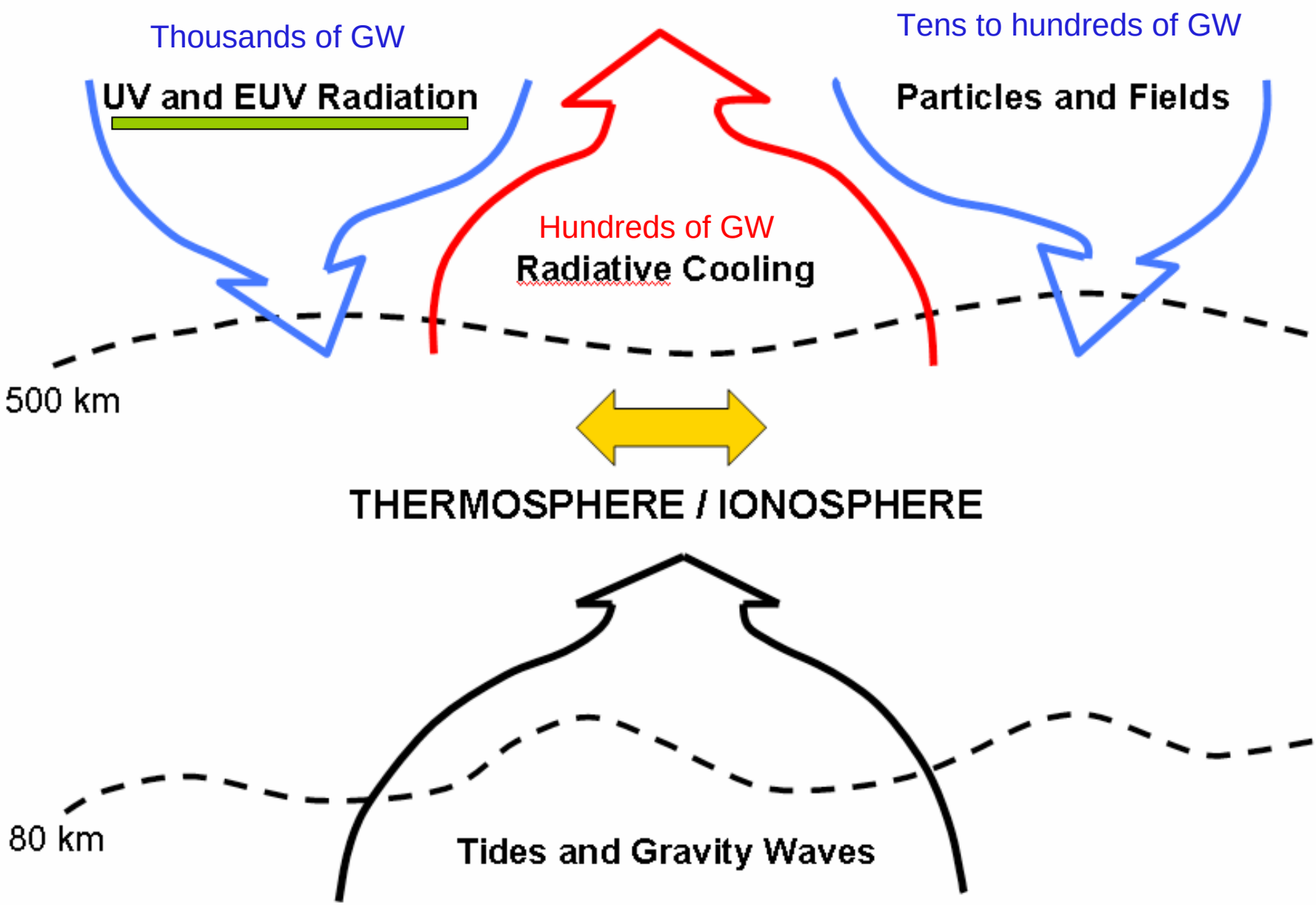
Comparison of estimated planetary K-index and formal error (i.e. RMS scatter) in GPS zenith tropospheric delay estimates. ZTD formal error estimates derived from data acquired at NOAA/FSL GPS-Met sites at Central, AK, College, AK, Glennallen, AK, Seattle, WA; and Penobscot, ME. The Kp index is derived at the U.S. Air Force Space Forecast Center using data from ground-based magnetometers at Meanook, Canada; Sitka, AK; Glenlea, Canada; Saint Johns, Canada; Ottawa, Canada; Newport, WA; Fredericksburg, VA; Boulder, CO; and Fresno, CA.

Tropospheric wet delay =7.5 cm

Seth Gutman, FSL

How can one do a better modeling job?

THE SYSTEM


Thousands of GW
UV and EUV Radiation
Tens to hundreds of GW
Particles and Fields
Hundreds of GW
Radiative Cooling
500 km
THERMOSPHERE / IONOSPHERE
80 km
Tides and Gravity Waves

Solar EUV Heating

We use a proxy (F10.7) for the solar flux.

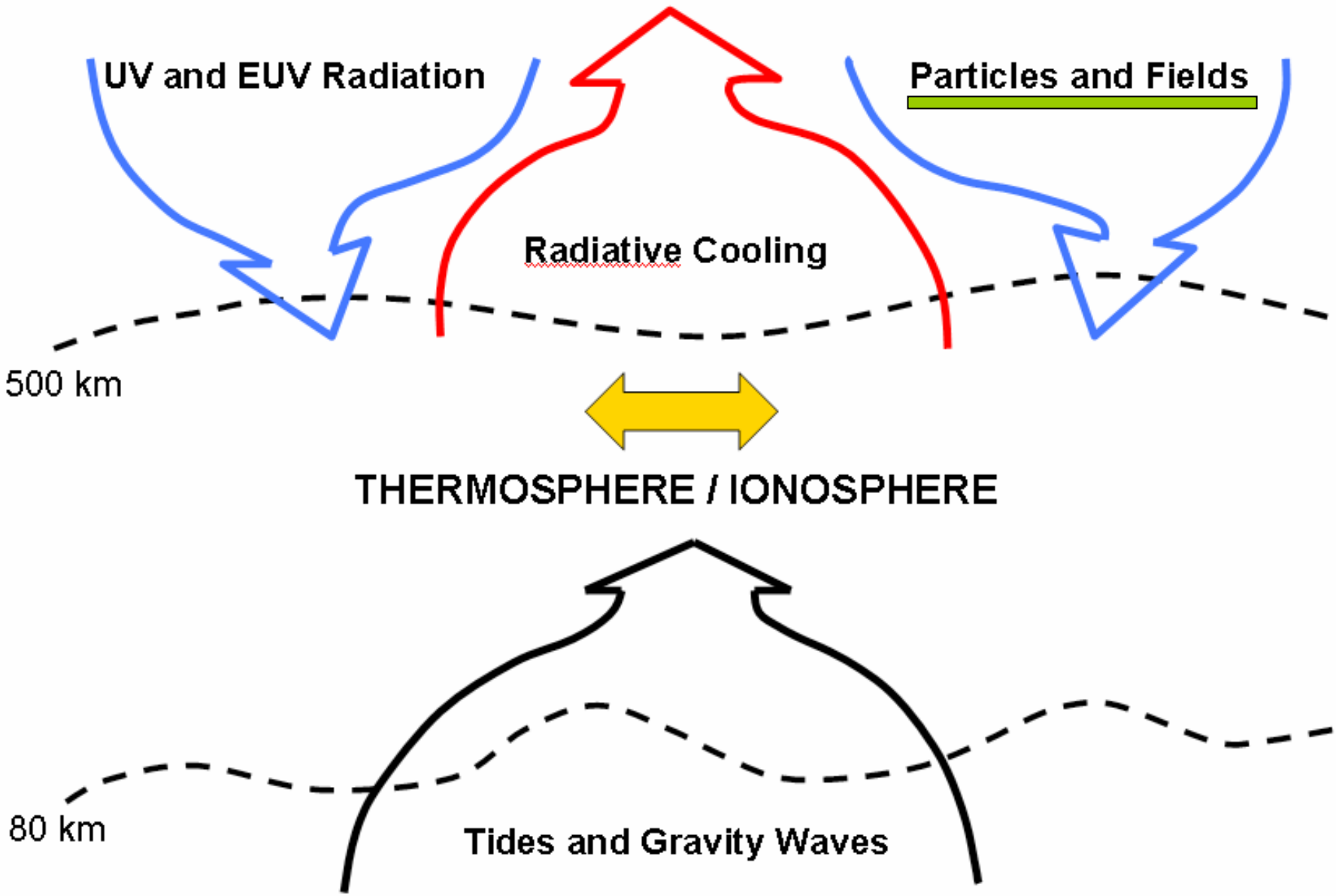
F10.7 correlates well with the solar flux over long time scales but not so well over short time scales.

The use of a proxy combined with uncertainties in heating efficiencies combine to produce uncertainties of at least 50% in the thermosphere heating.

Chemical heat transport complicates the picture even more.

Important for global dynamics and electrodynamics

THE SYSTEM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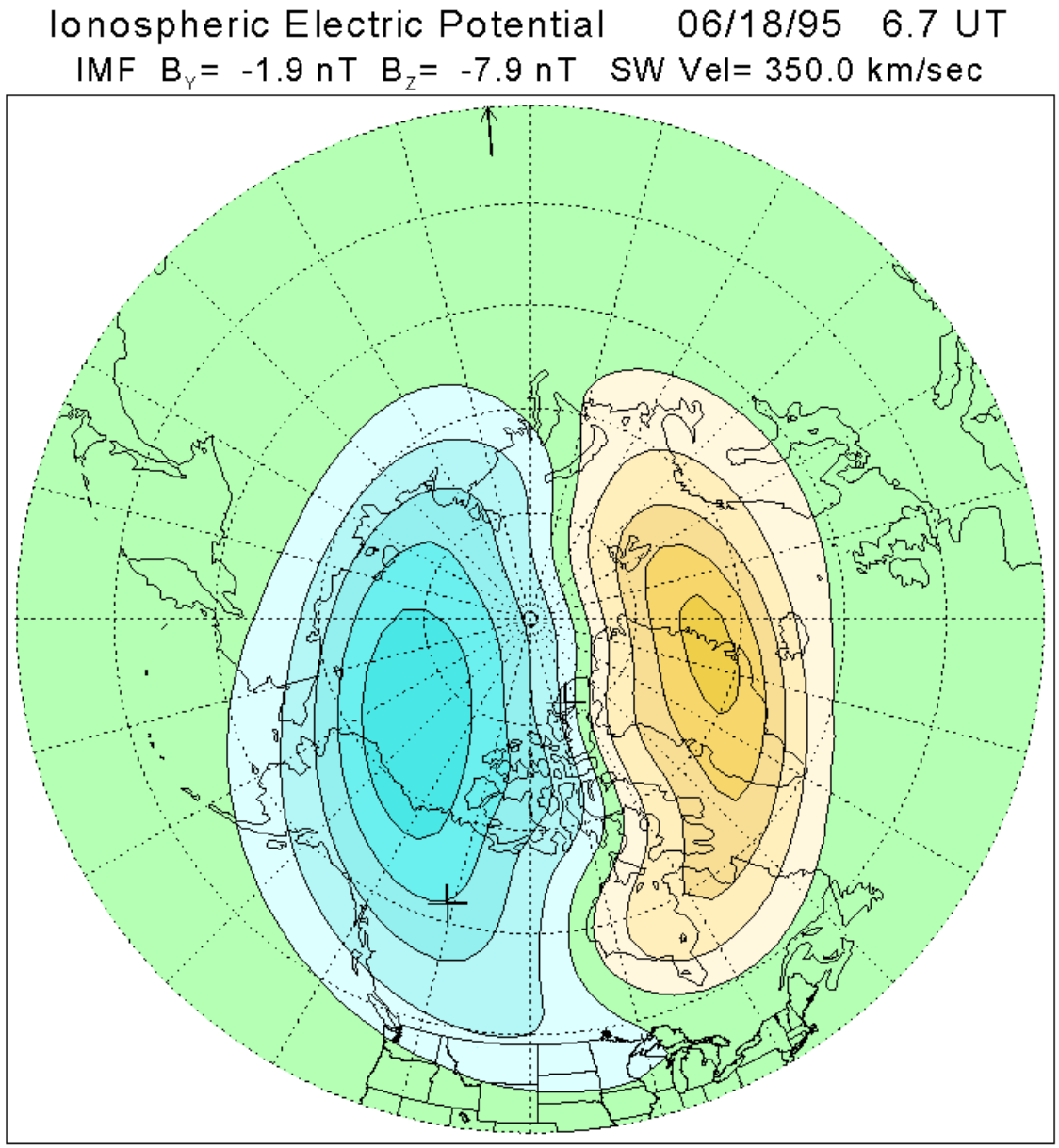
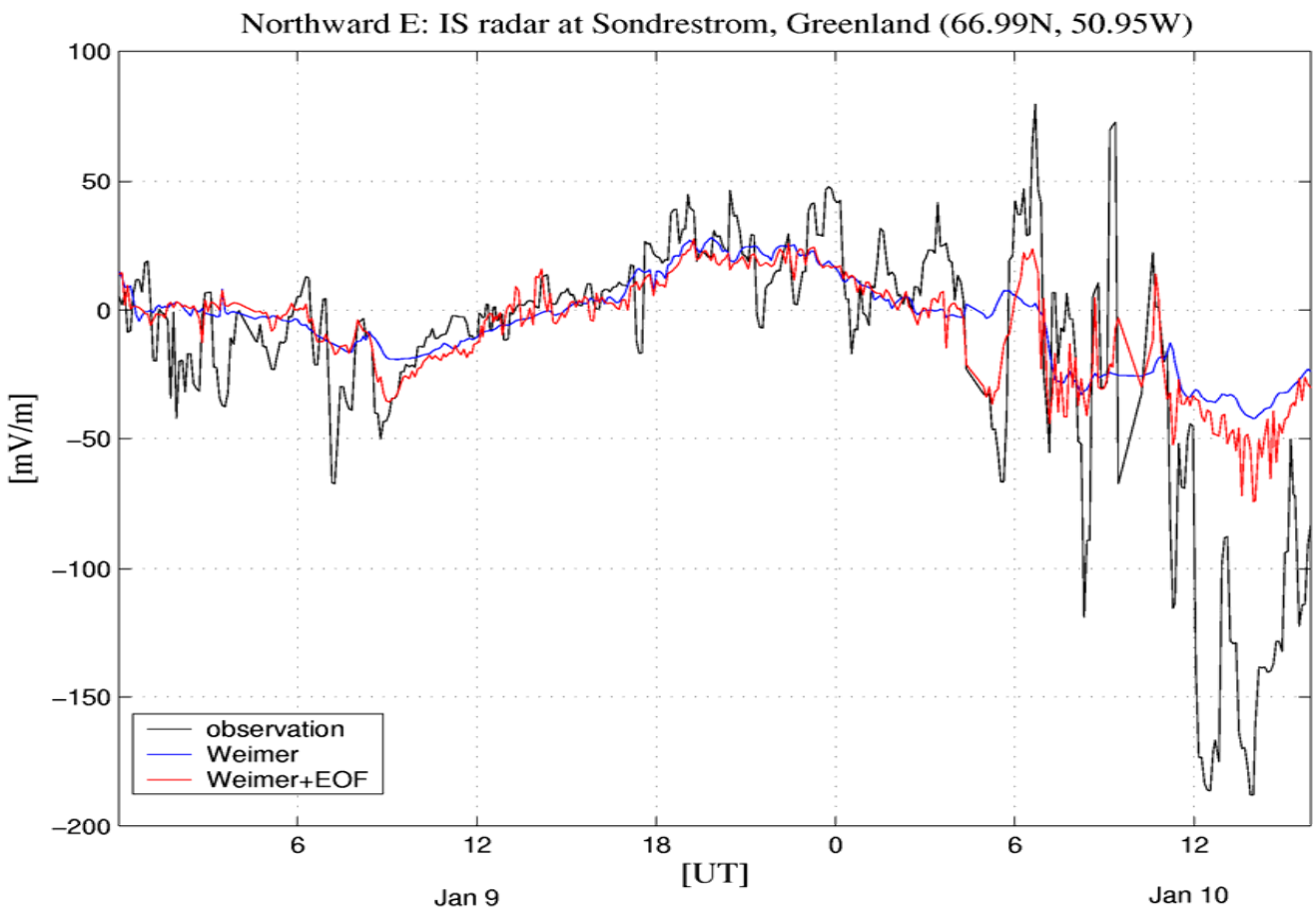
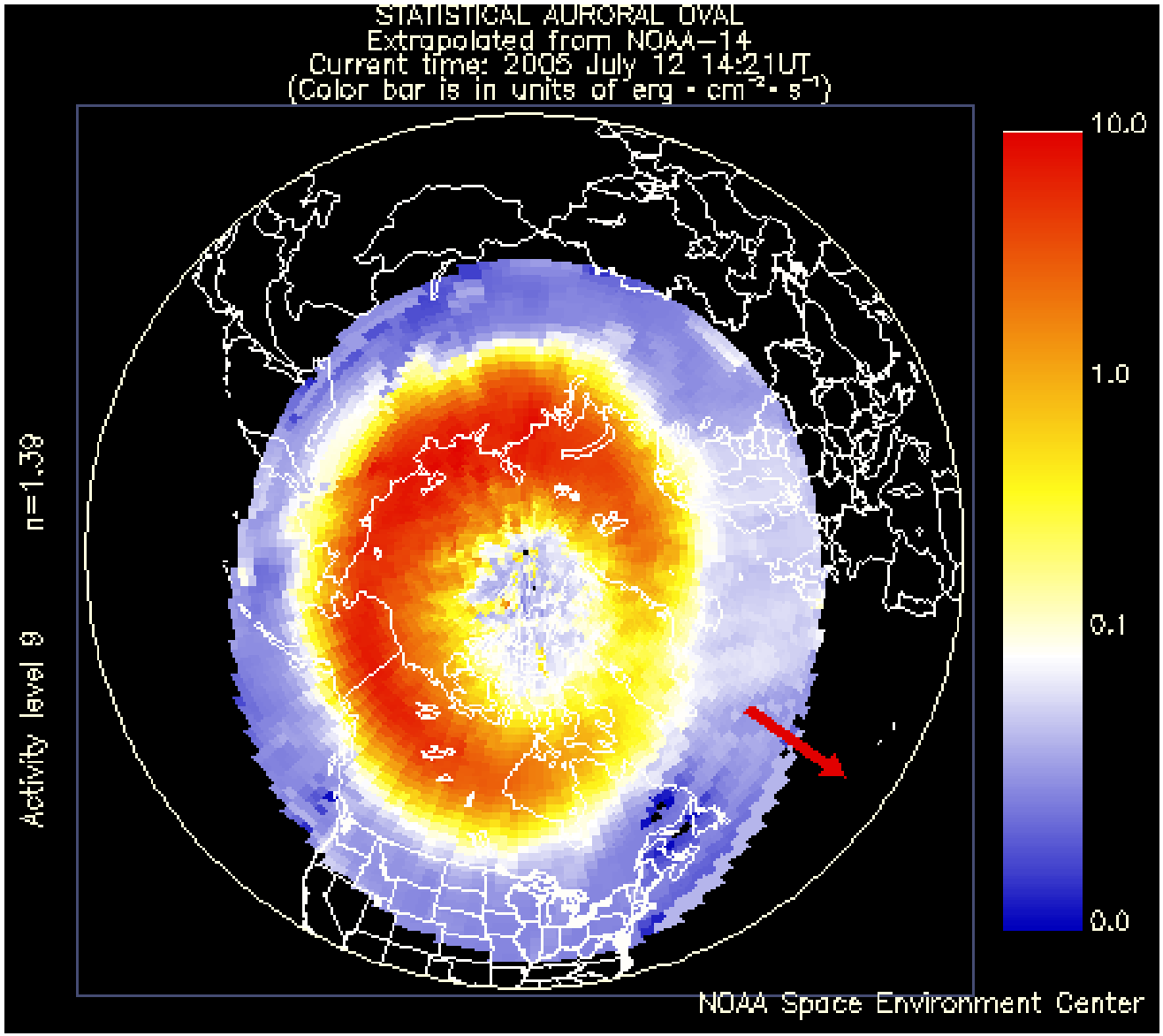


Weimer pattern

January 9-10, 1997



T. Matsuo Private Communication, 2004



http://www.sec.noaa.gov/pmap/

Particles and Fields

E-field patterns are statistical and consequently smooth

Conductivity calculations are based on statistical precipitation patterns that are extrapolated from one orbit insitu measurements

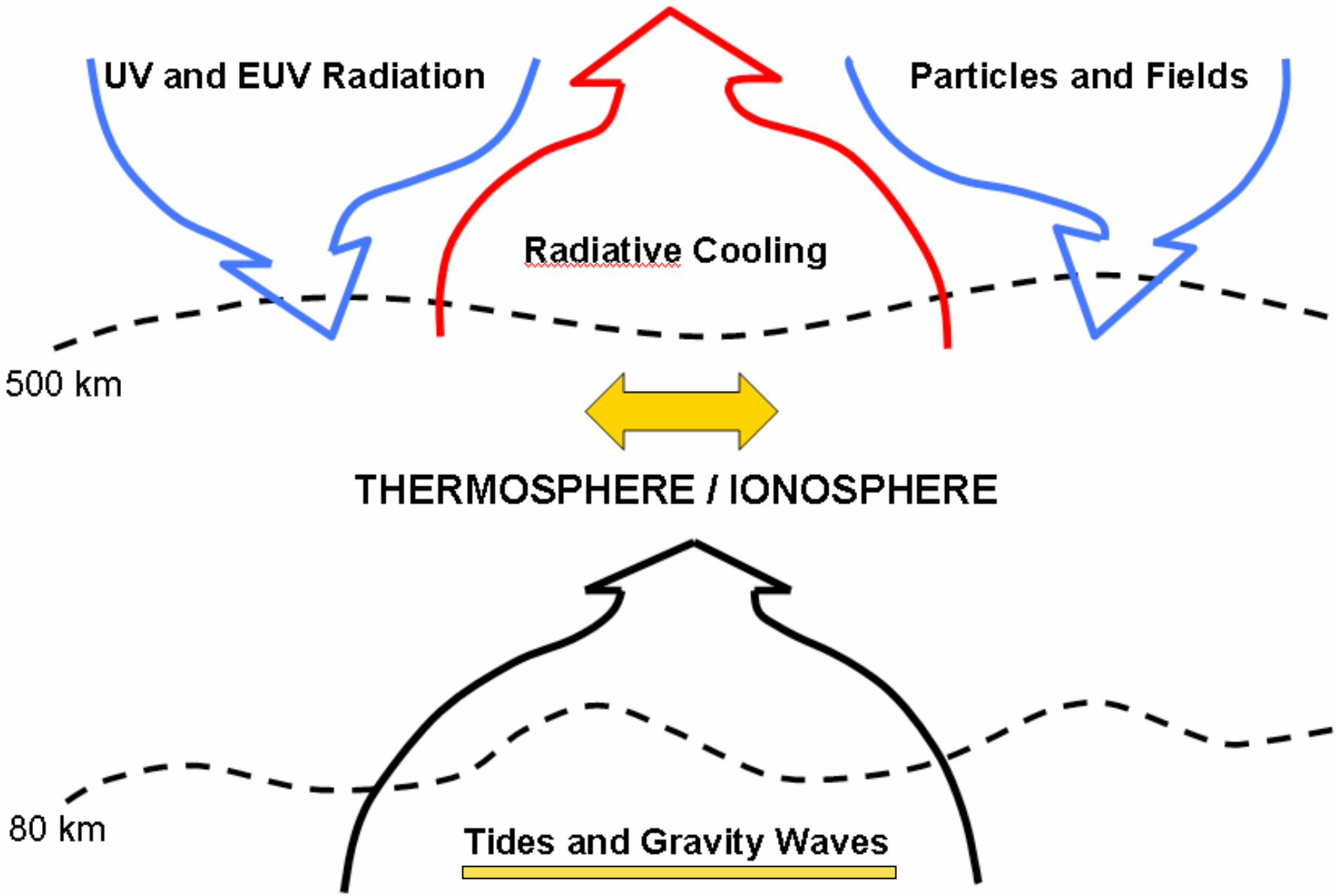
=> Joule heating calculations based on statistical patterns have large uncertainties:

50% globally

factor of ten locally

Important for global circulation, neutral composition, and electrodynamical processes

THE SYSTEM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500 km
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80 km
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Millstone Hill ISR Measurements

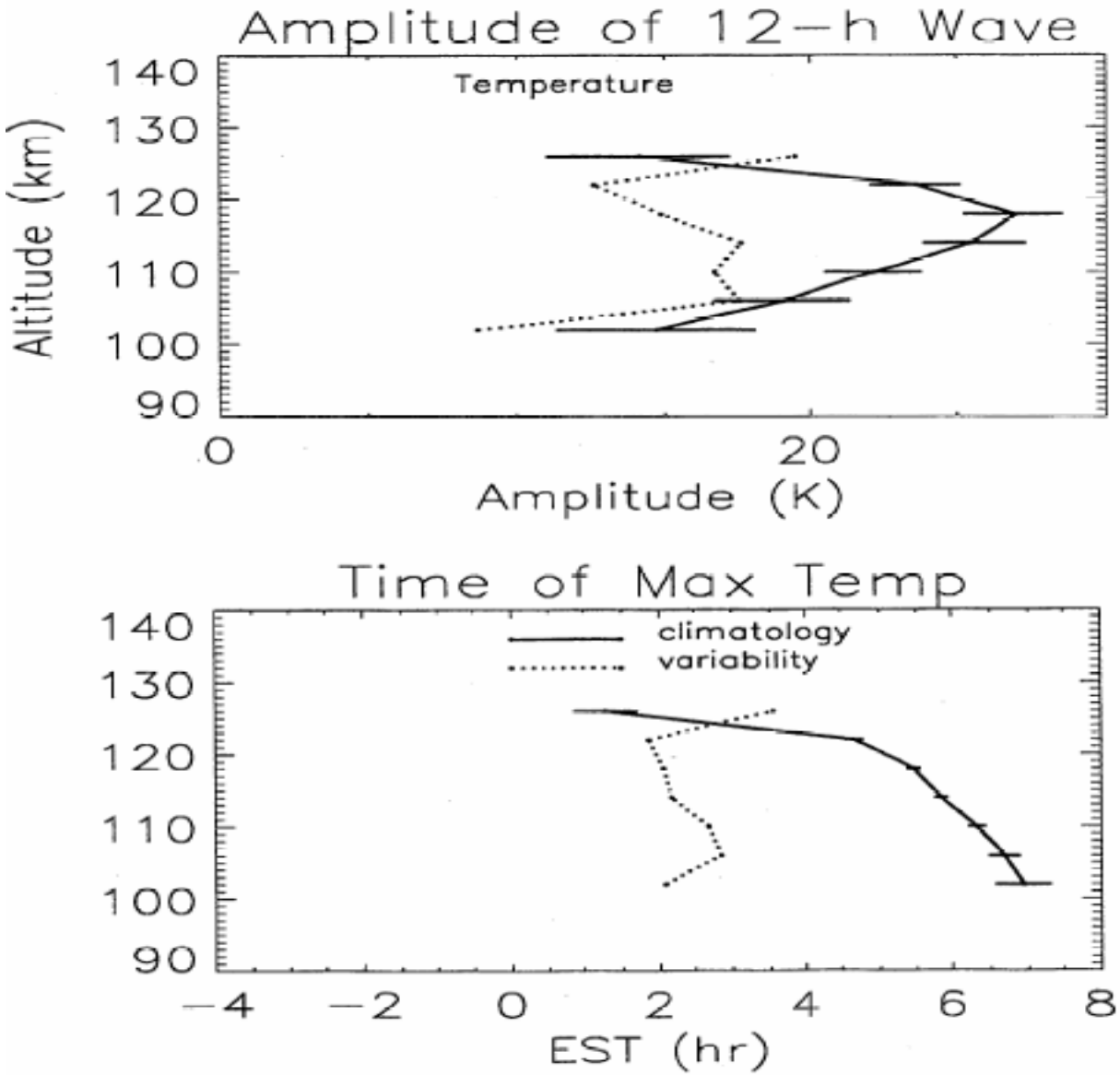


Figure 9. Altitude profile for climatologically mean temperature. Variability (dashed line) is determined as standard deviation from the climatological mean.

Goncharenko and Salah, JGR, 1998

Tides from below

Only propagating tides included in most models (active research)

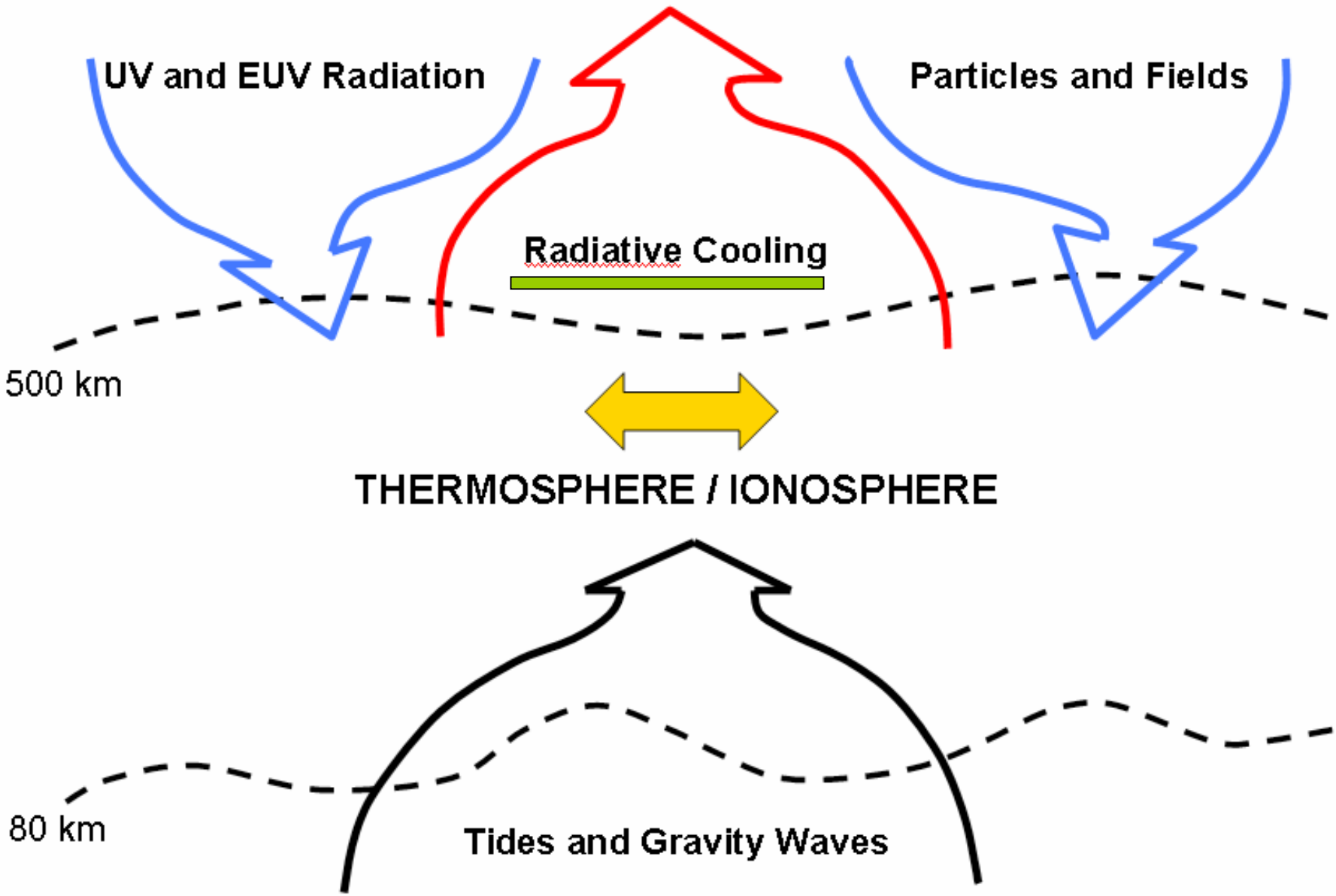
No planetary waves included yet (active research)

Amplitudes and phases are uncertain by at least 50%

Very important for the D- and E-regions (80-150 km)

Important for the F-region (300-500 km) variability

THE SYSTEM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500 km
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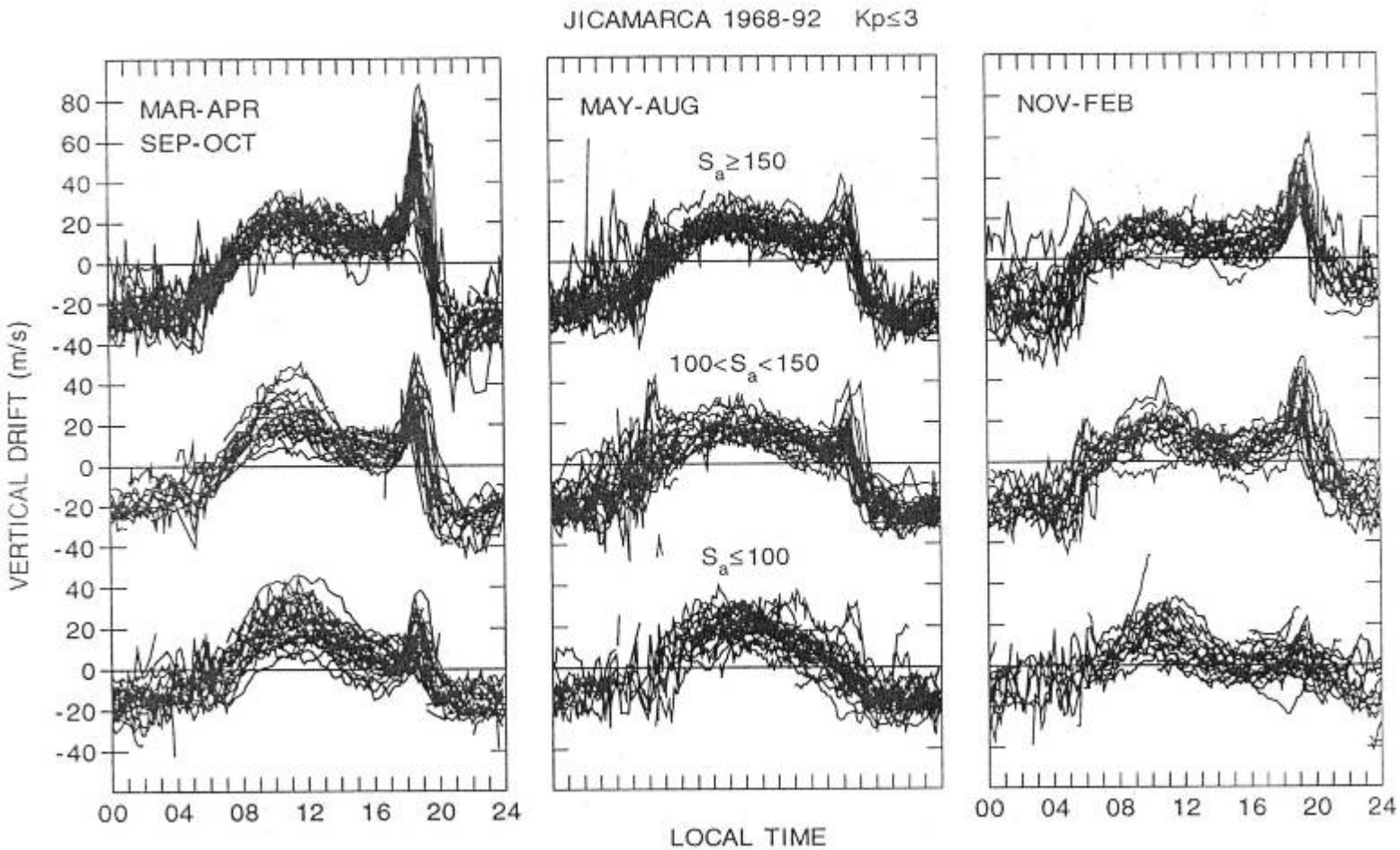
Work on resolving these uncertainties in the energy inputs and sinks is made more difficult by the large variability present in the system.

Large Variability



Fejer and Scherliess, 2001

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

A Modeling Problem

• Variability in high-latitude convection and particle precipitation produce large variability in Joule heating.

• Joule Heating changes the global neutral temperature structure, neutral circulation, and neutral chemical composition.

• Neutral changes affect production, loss and transport of ionization and have dramatic effects on global electron density and TEC structures.

• Global Joule heating cannot be satisfactory modeled at this time because both the convection E-field and the particle precipitation patterns used in the models are statistical.

=> We can model generic storms but not specific ones

One possible solution is data assimilation.

Data Assimilation

Combine model and data based on their statistical errors

Challenges

Find the best model representation for state evolution in time

Obtain accurate statistical error estimations for model and data

Availability of quality data

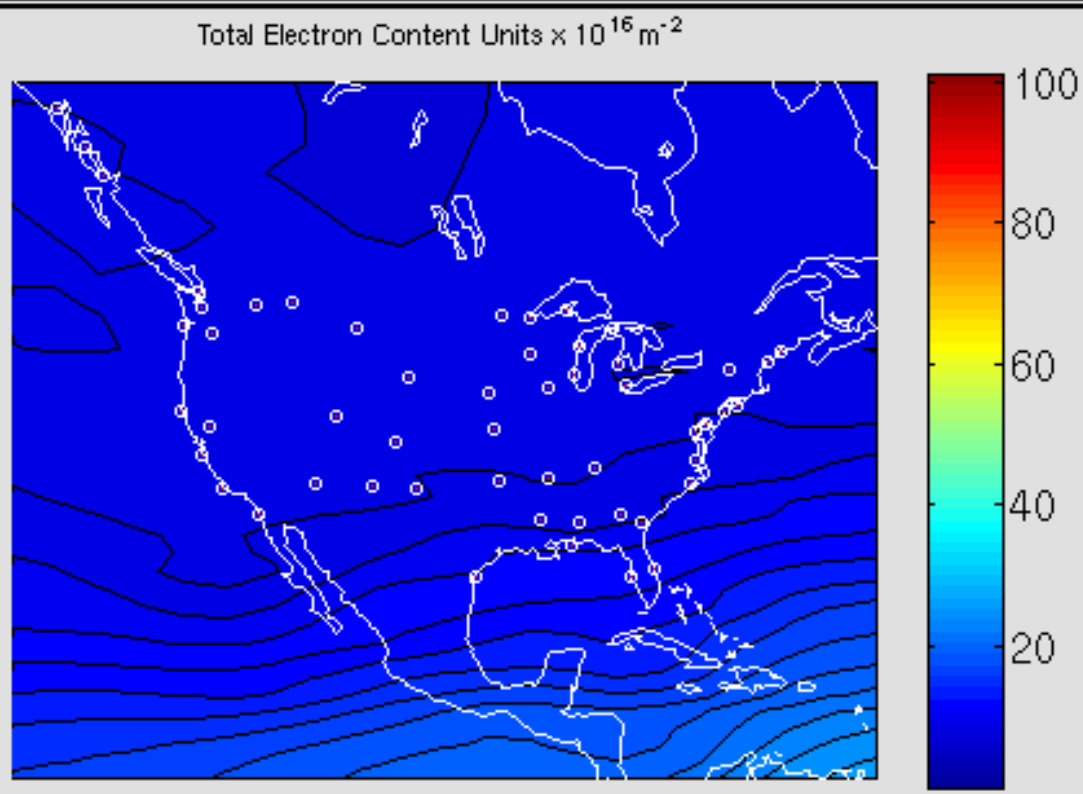
- latency
- spatial coverage
- statistical errors

Presented by the NOAA/Space Environment Center

Vertical TEC	TEC uncertainty	Recent trend	All Plots

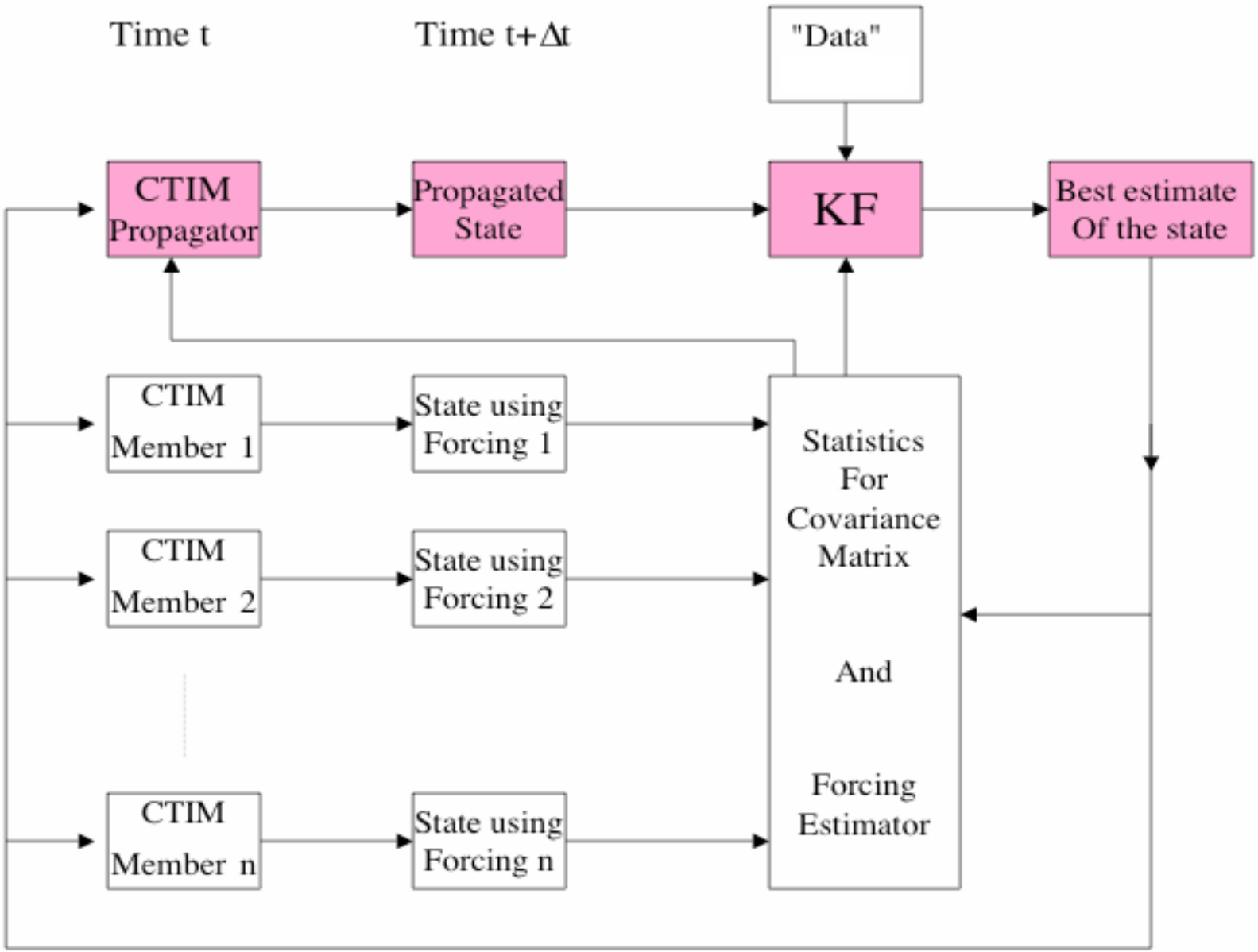
Vertical Total Electron Content

2005 Jul 12 1715 - 1730 UTC



Today	Java movie	Javascript movie	Data files
Yesterday	Java movie	Javascript movie	Data files

Ensemble type Kalman Filter



Codrescu et al., Space Weather, Nov. 2004

The classic Kalman filter equations can be written as:

$$x^F(t+1) = \Phi(t+1;t)x(t) + u(t) \tag{1}$$

$$P^F(t+1) = \Phi(t+1;t)\mathbf{P}(t)\Phi^T(t+1;t) + \mathbf{Q}(t) \tag{2}$$

$$y(t+1) = \mathbf{M}(t)x^F(t+1) + v(t) \tag{3}$$

$$\mathbf{K}(t+1) = \mathbf{P}^F(t+1)\mathbf{M}^T(t)[\mathbf{M}(t)\mathbf{P}^F(t+1)\mathbf{M}^T(t) + \mathbf{R}(t)]^{-1} \tag{4}$$

$$x(t+1) = x^F(t+1) + \mathbf{K}(t+1)[y(t+1) - \mathbf{M}(t)x^F(t+1)] \tag{5}$$

$$\mathbf{P}(t+1) = (\mathbf{I} - \mathbf{K}(t+1)\mathbf{M}(t))\mathbf{P}^F(t+1) \tag{6}$$

where,

$x(t)$ is the best estimate of the state vector (of length n) at time t,

$x^F(t+1)$ is the forecast value of the state vector at $t+1$, before new data are assimilated,

$\Phi(t+1;t)$ is the n by n transition matrix describing the evolution of the system from time t to time $t+1$,

$u(t)$ is a vector of length n realization of the process noise, assumed gaussian random with zero mean,

$\mathbf{P}(t)$ is the n by n covariance matrix at time t,

$\mathbf{P}^F(t+1)$ is the forecast value of the covariance matrix at time $t+1$, before data is assimilated,

$\mathbf{Q}(t)$ is the diagonal n by n covariance matrix of the process noise, $E(uu^T)$,

$y(t+1)$ is the measurement vector (of length m) at time $t+1$,

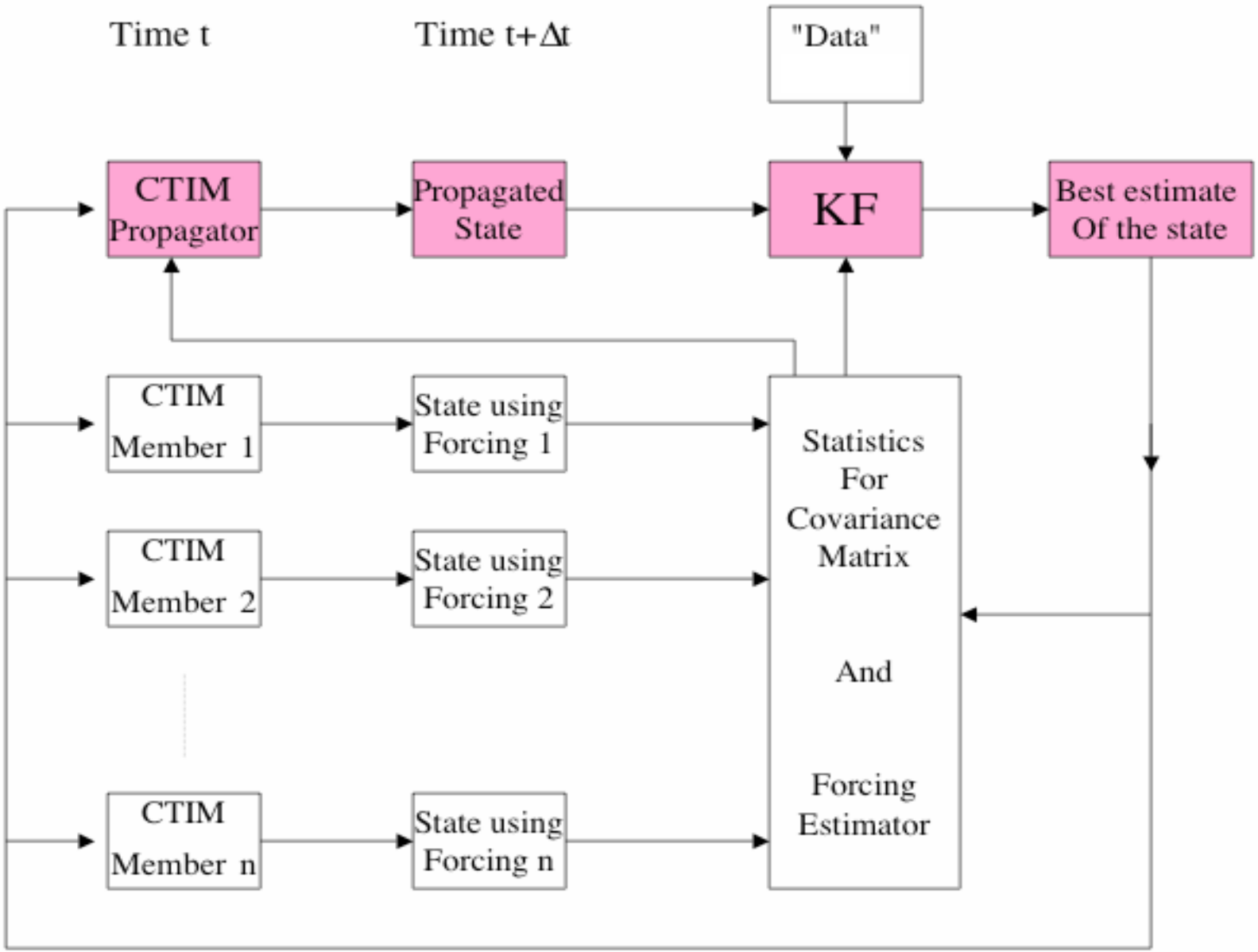
$\mathbf{M}(t)$ is the m by n measurement matrix, relating the measured values to the state vector $x^F(t+1)$,

$v(t)$ is a vector realization (of length m) of the measurement noise, assumed gaussian random with zero mean,

$\mathbf{K}(t+1)$ is the n by m Kalman gain matrix, and

$\mathbf{R}(t)$ is the m by m observation error covariance matrix, i.e. $E(vv^T)$.

Ensemble type Kalman Filter

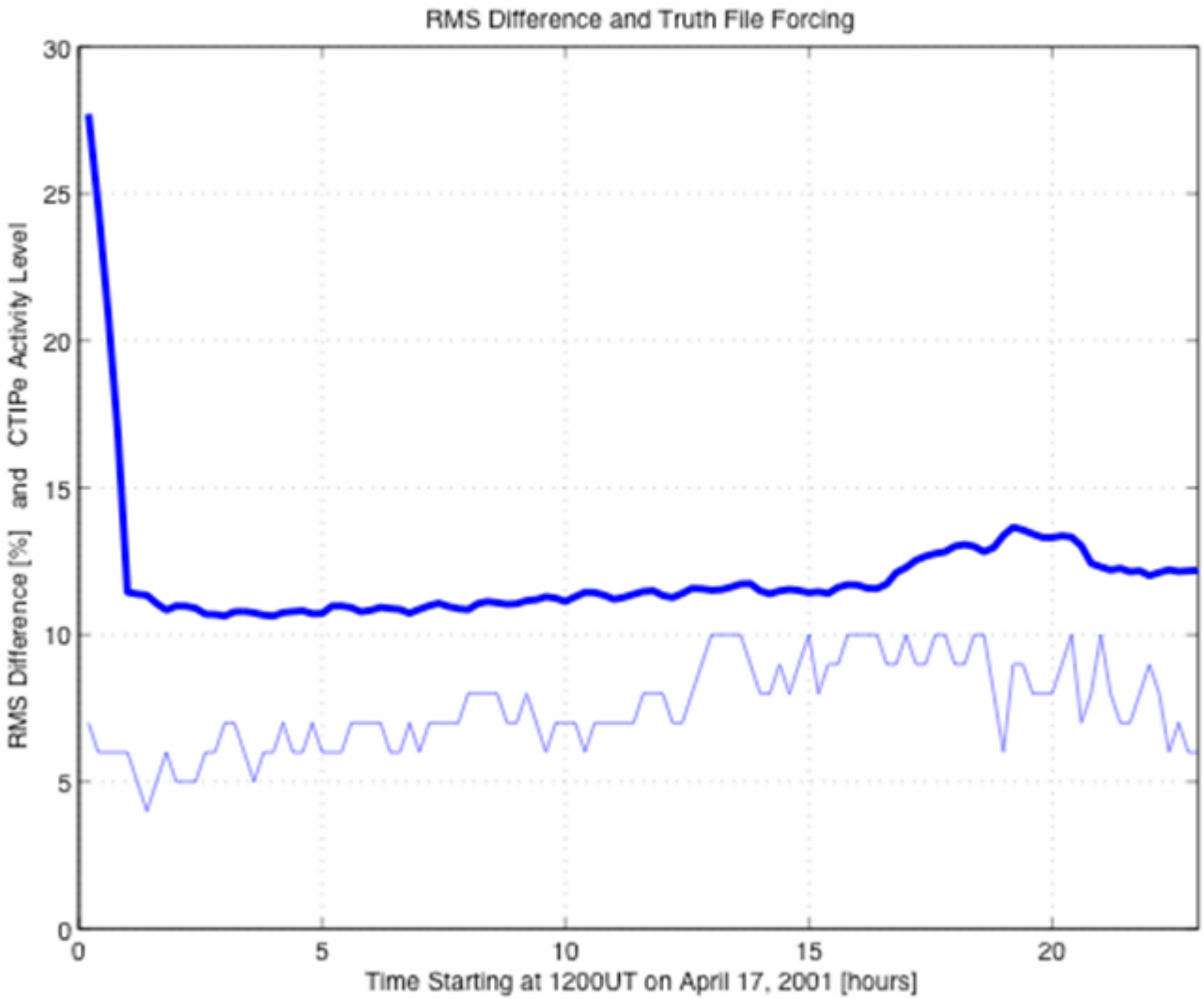


Codrescu et al., Space Weather, Nov. 2004

Global height-integrated O/N_2 ratio

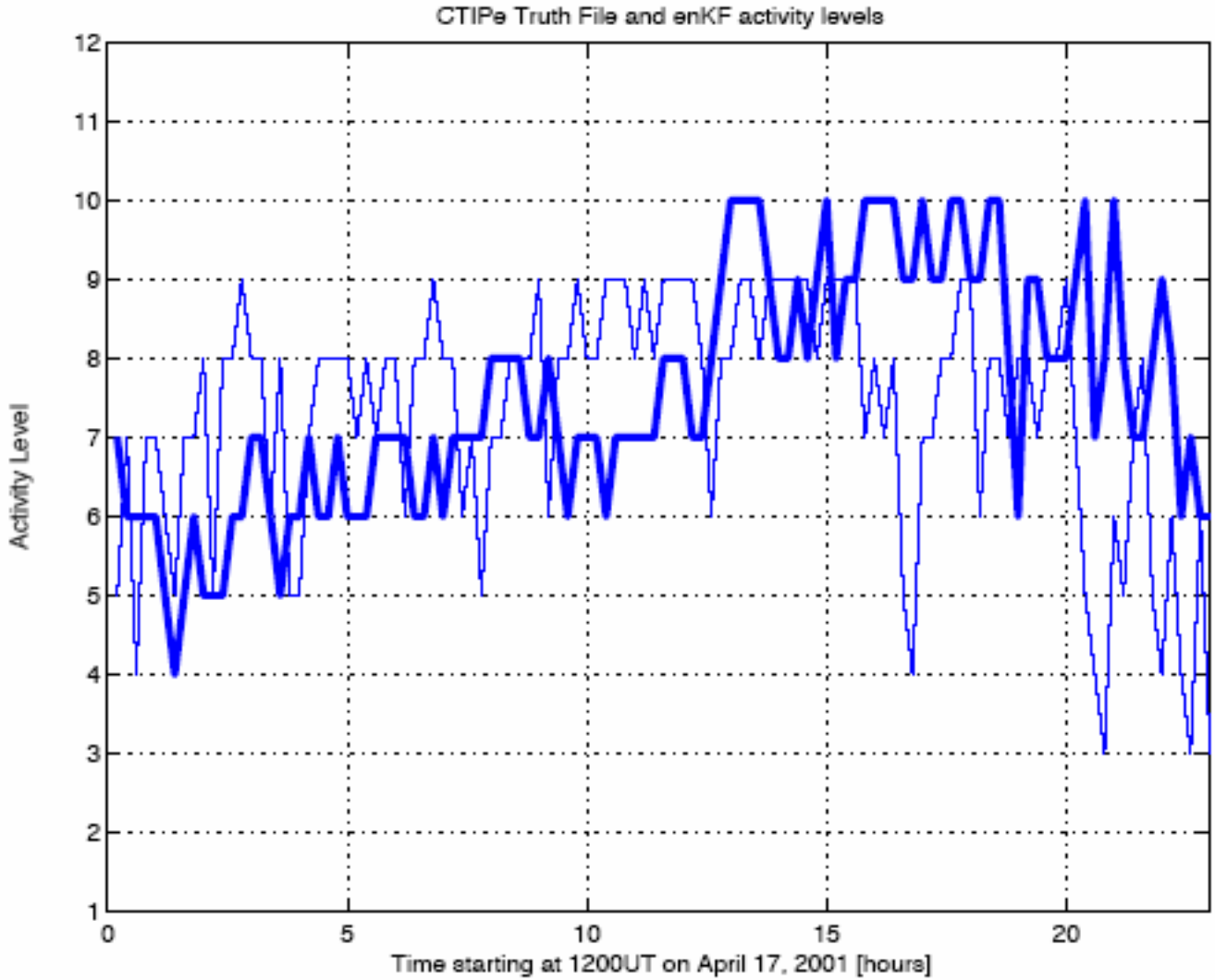
QuickTime™ and a
decompressor
are needed to see this picture.

Global O/N2 ratio difference



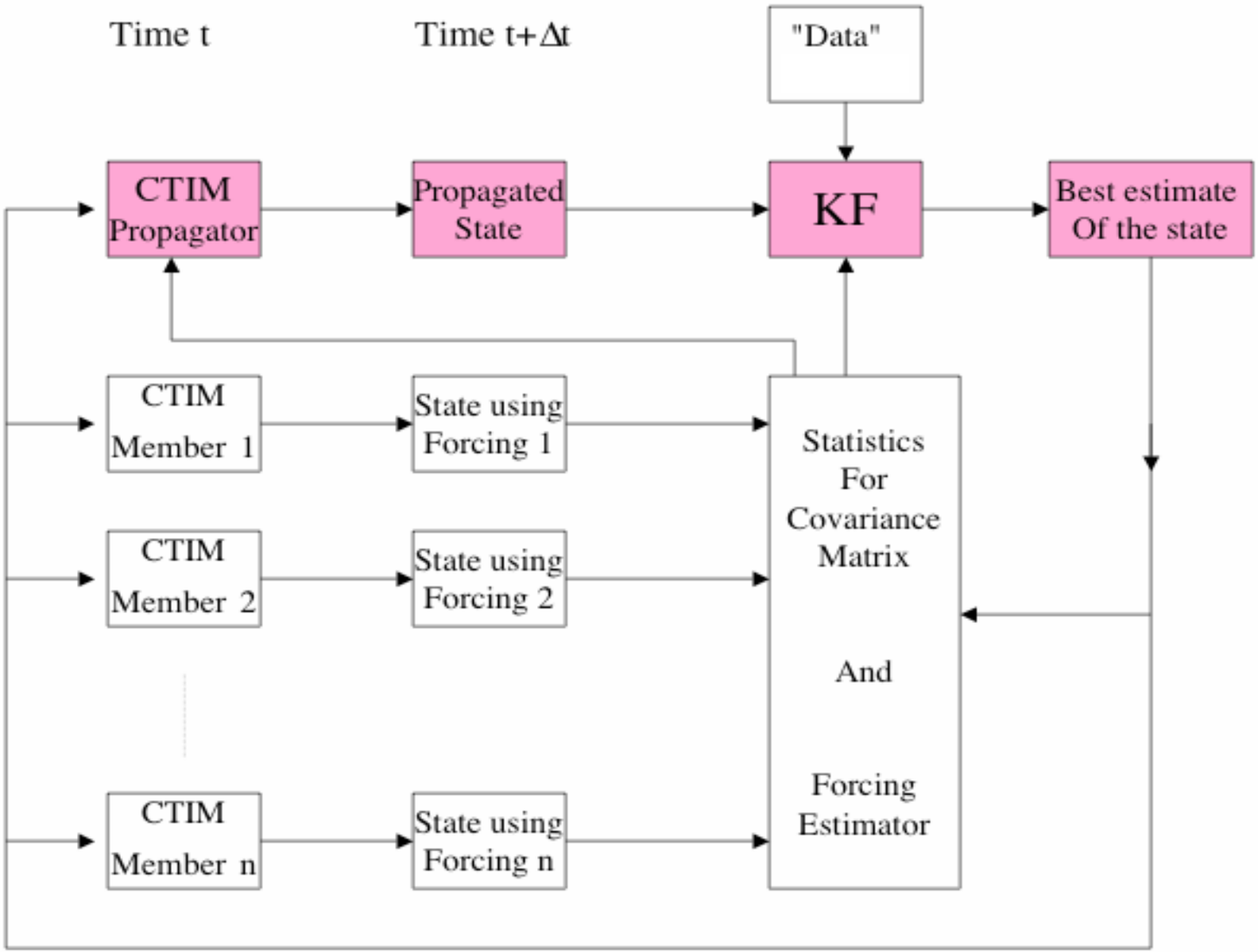
(Codrescu et al. Space Weather, Nov. 2004)

Inferred vs true forcing for April 17, 2001 storm



(Codrescu et al. Space Weather, Nov. 2004)

Ensemble type Kalman Filter



Codrescu et al., Space Weather, Nov. 2004

Data Assimilation and the future

Ensemble Kalman filters offer the best hope for data assimilation for large strongly forced dynamical systems.

One can do a "good" modeling job without knowing the forcing. Here it was done based on assimilation in only one field (neutral chemical composition).

One could do assimilation in multiple fields and combine the results for much more accurate forcing patterns.

One could derive forcing patterns based on EOFs. Successive orders of EOFs can be determined from different assimilated fields using better data and physical understanding. At this time we use the equivalent of only two or three EOFs.

The accuracy of the forcing patterns can increase with the amount of available data, physical understanding, and the sophistication of the schemes. This will lead to better specification and forecast of the space environment.

Near Future Challenges

Operational Global TEC product (USTEC and GAIMs)

Run GCMs in semi-operational environment + data assimilation

Specify variability and its sources from reanalysis fields

Coupling with the lower atmosphere in one seamless model (IDEA)

Scintillation modeling and prediction nested grid models + data assimilation

TEC response to storms

SED produced by SAPS

UV and EUV specification and effects

Importance of Te in NmF2 and TEC flare response

High-latitude forcing specification now from ACE
- Solar wind structure influence on high-latitude forcing
- Solar wind-magnetosphere-ionosphere coupling + data assimilation

Proposed Data Assimilation Definition

(For Space Sciences)

Data assimilation is a method in which observations of the current (and possibly, past) state of a system are combined with the results from a <u>mathematical</u> simulation <u>model</u> to produce an *analysis*, which is considered as 'the best' estimate of the current state of the system.