Specification of the Near-Earth Space Environment using Data Assimilation Techniques

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Currently on Sabbatical at GFZ

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"Bringing The Pieces Together"

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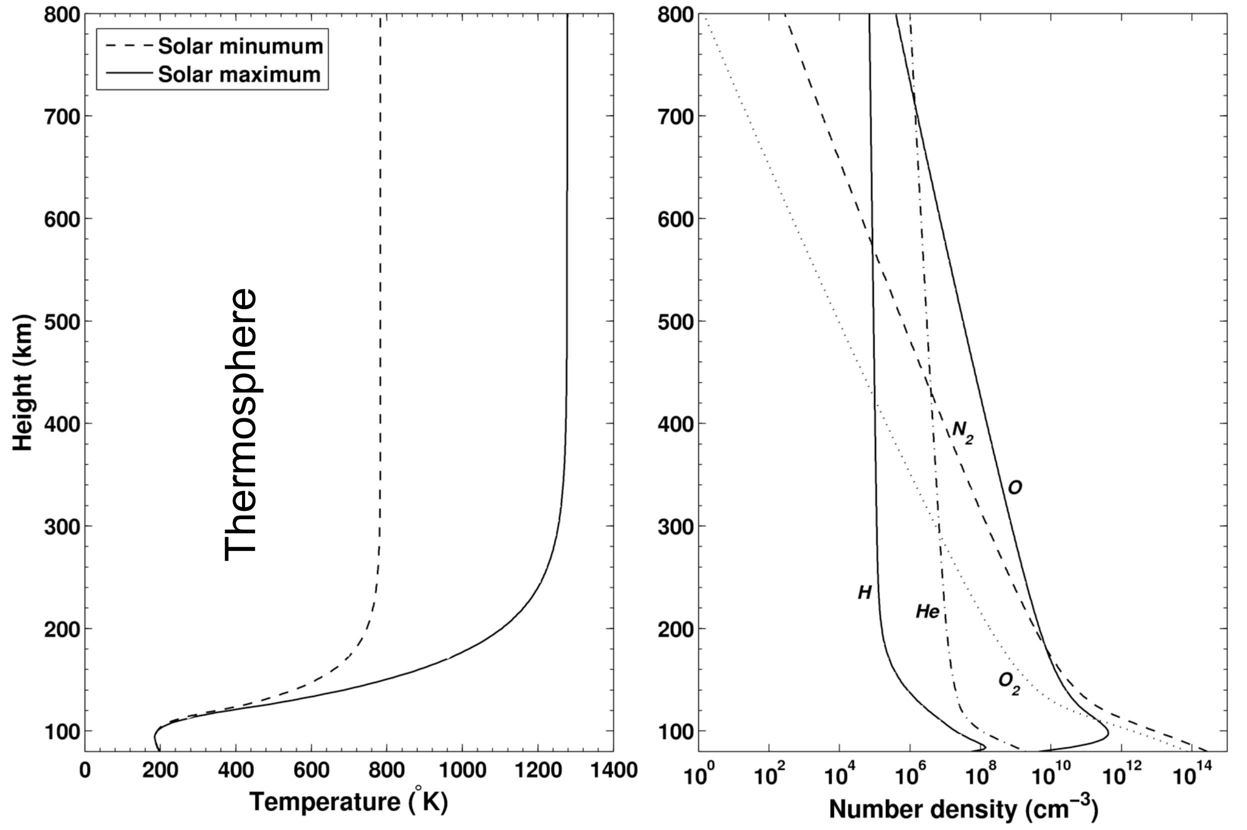
The Earth Upper Atmosphere

At about 100 km altitude the temperature of the atmosphere strongly increases and the gas species will begin to separate according to their mass.



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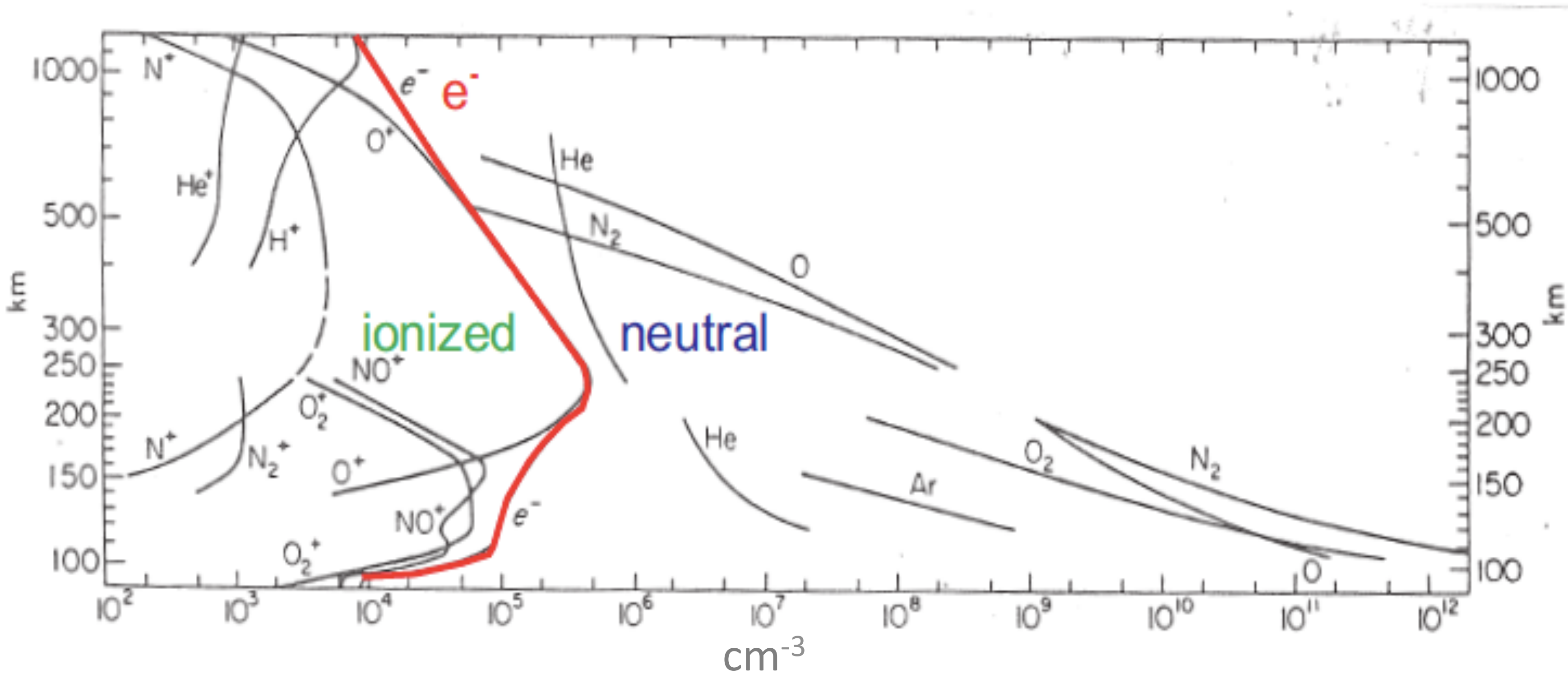
The Ionosphere

- Embedded in the neutral gas is the ionosphere.
- Ionosphere consists of electrically charged particles (ions and electrons).



After Kelley 2009

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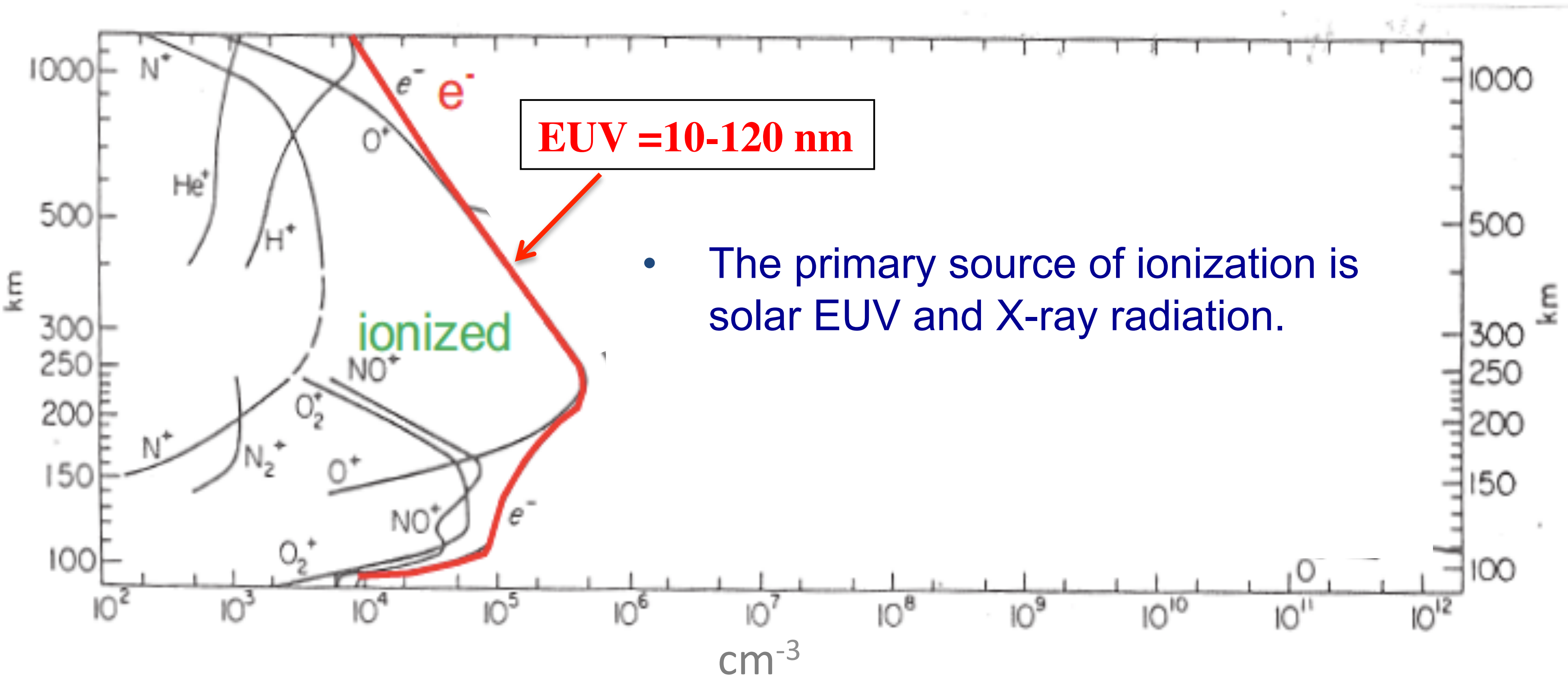

- The primary source of ionization is solar EUV and X-ray radiation.

After Kelley 2009

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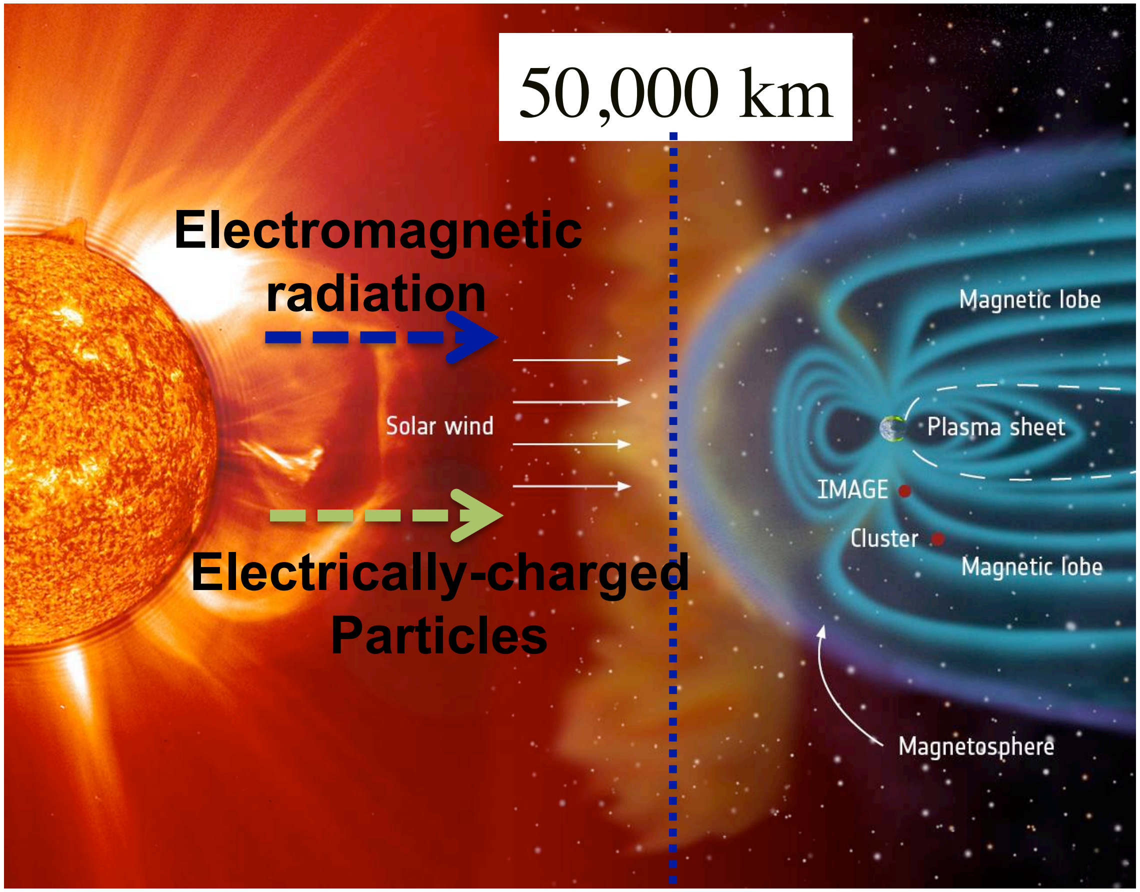
The Solar Wind

Electromagnetic radiation and **electrically-charged particles** stream outward from the Sun and **engulf the Earth**.

The particles interact with the Earth's magnetic field and change the atmosphere.



Past the moon →

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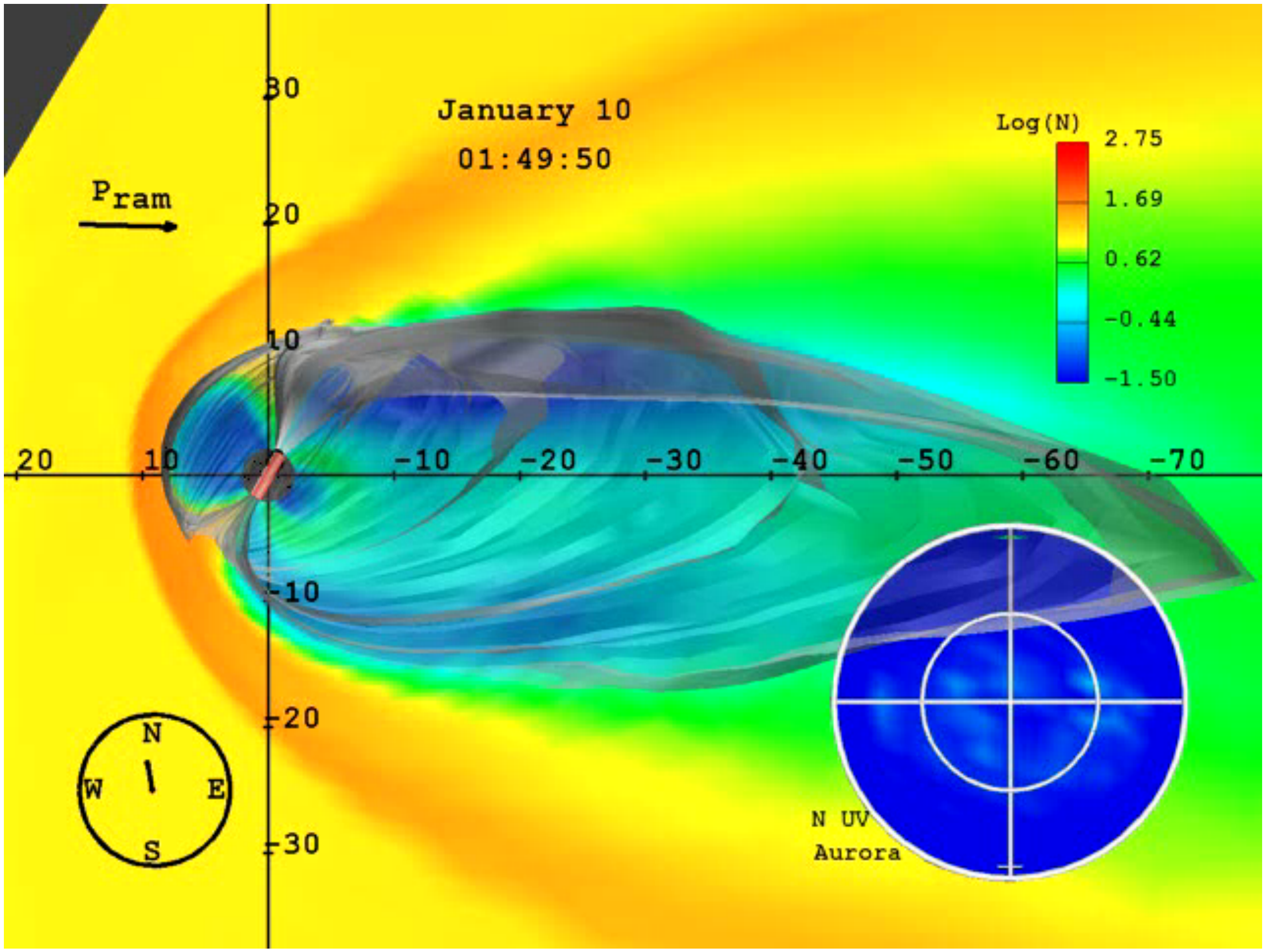
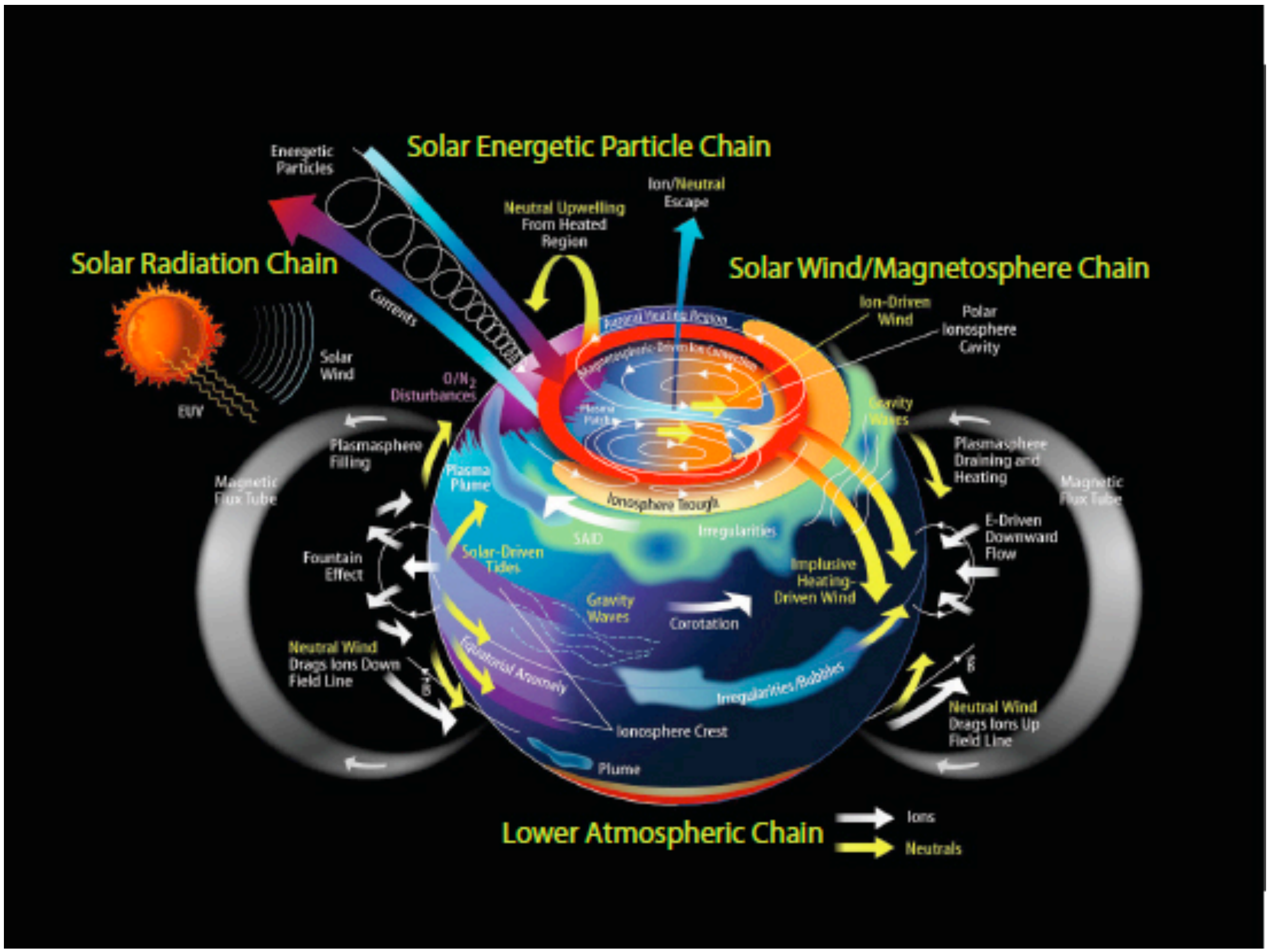
Solar Wind Buffeting the Magnetosphere



Video Courtesy NASA

Interactions with the Upper Atmosphere

Solar variability strongly affects the upper atmosphere through a chain of processes



National Academy of Sciences

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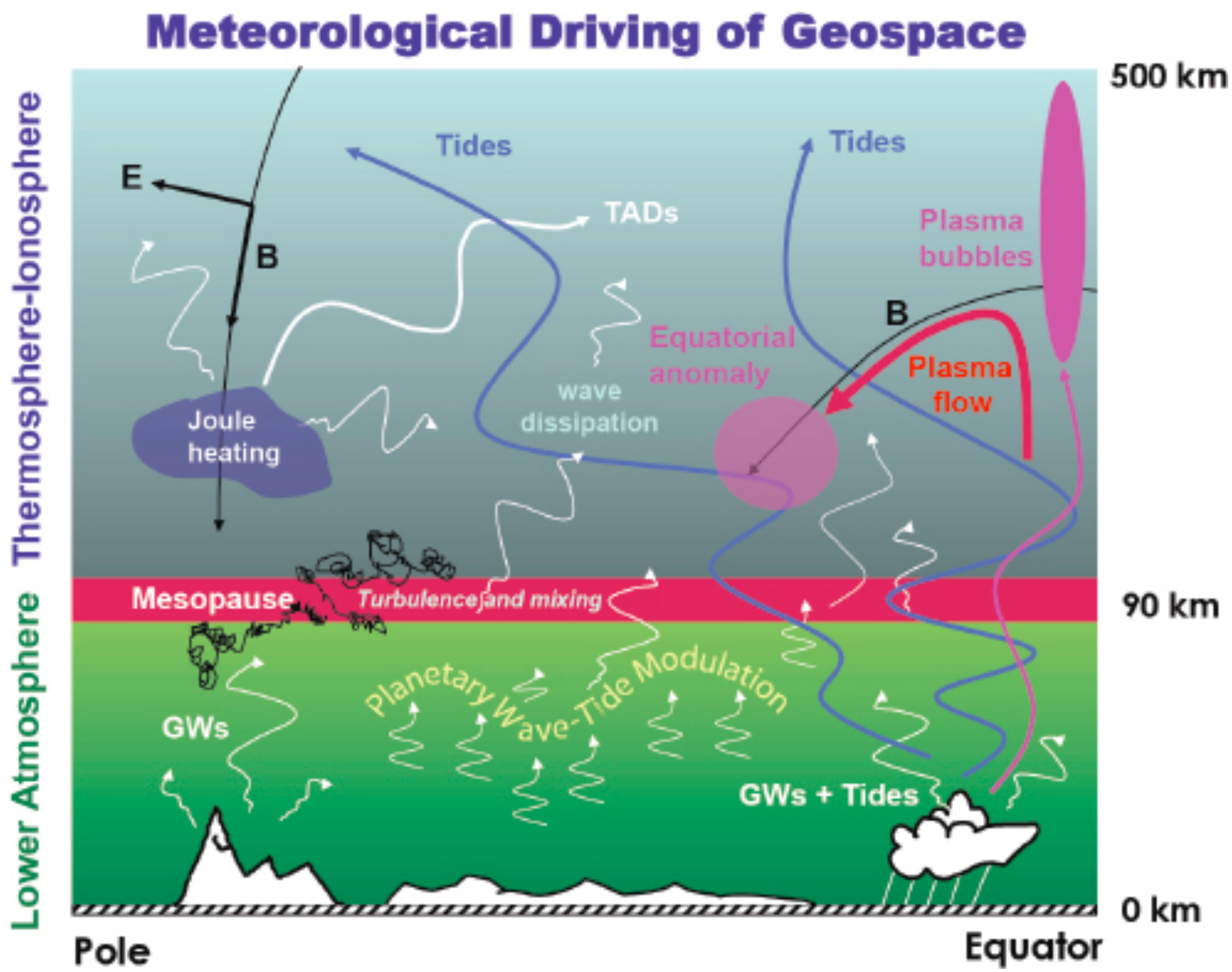
The Earth's Upper Atmosphere is also Driven from Below



National Academy of Sciences

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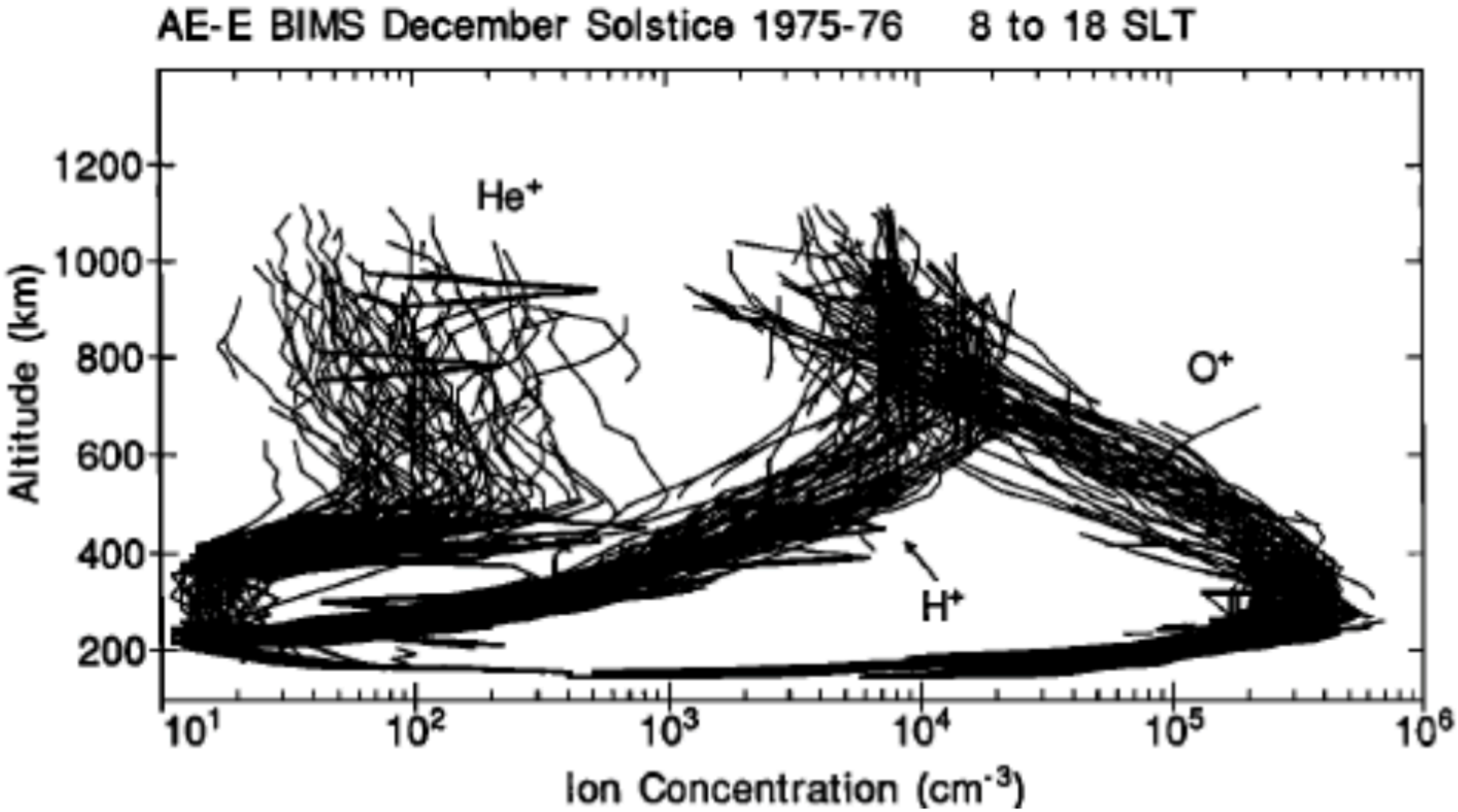
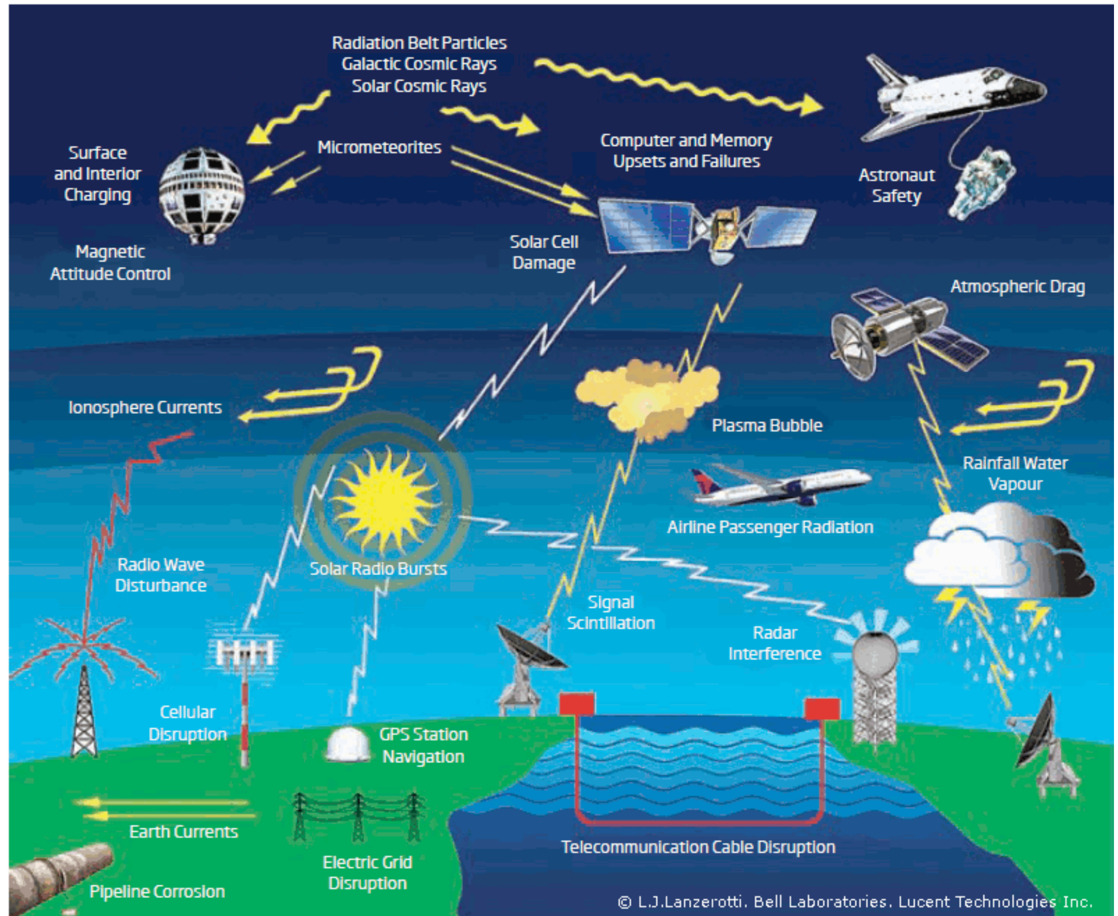
The ionosphere exhibits strong variability



Gonzales et al., 1992

How does the near-Earth space environment affect us?

- Environment where many satellites and the ISS operate ☹
- Region that navigational system signals (Galileo, GPS, Beidou, …) cross and get (eventually strongly) affected ☹
- Protection against extreme solar EM and particle radiation ☺



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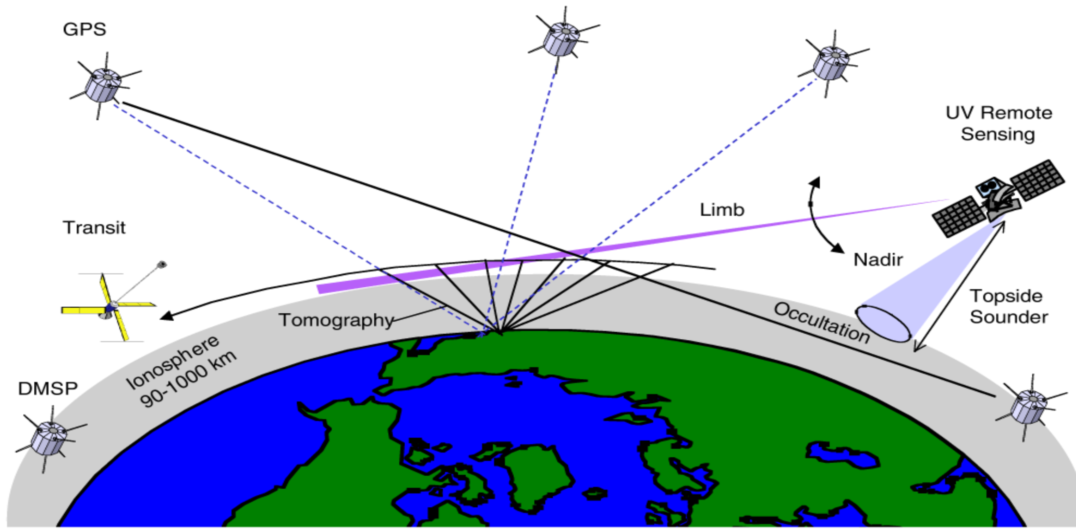
A Whole Suite of Data Sources to Observe the Ionosphere



- **Bottomside *Electron Density* Profiles from Ionosondes**
- **Integrated Electron Density from Ground/Space GNSS Receivers**
- ***Electron Density* Along Satellite Tracks**
- **Integrated UV Emissions from satellites**
- **Occultation Data**
- **…**

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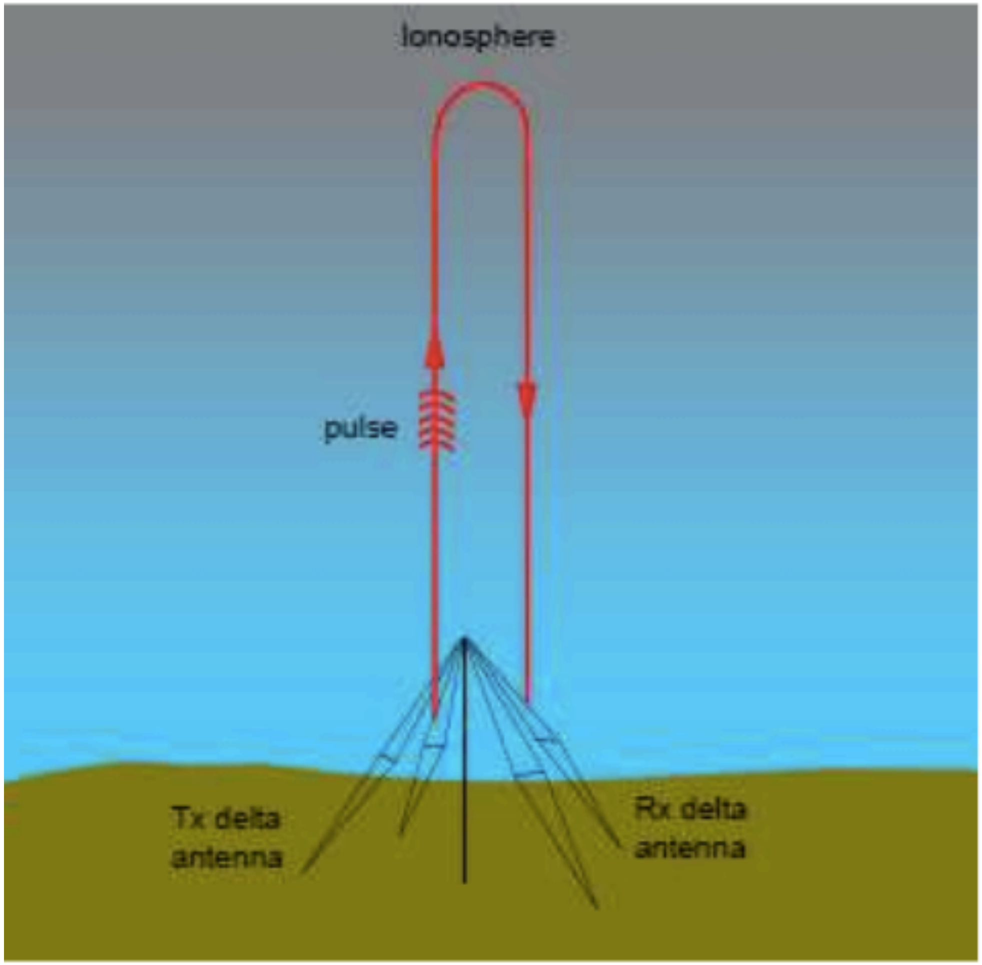
Ionosonde



Transmitter sends a short pulse High-frequency (HF) signal into the ionosphere.

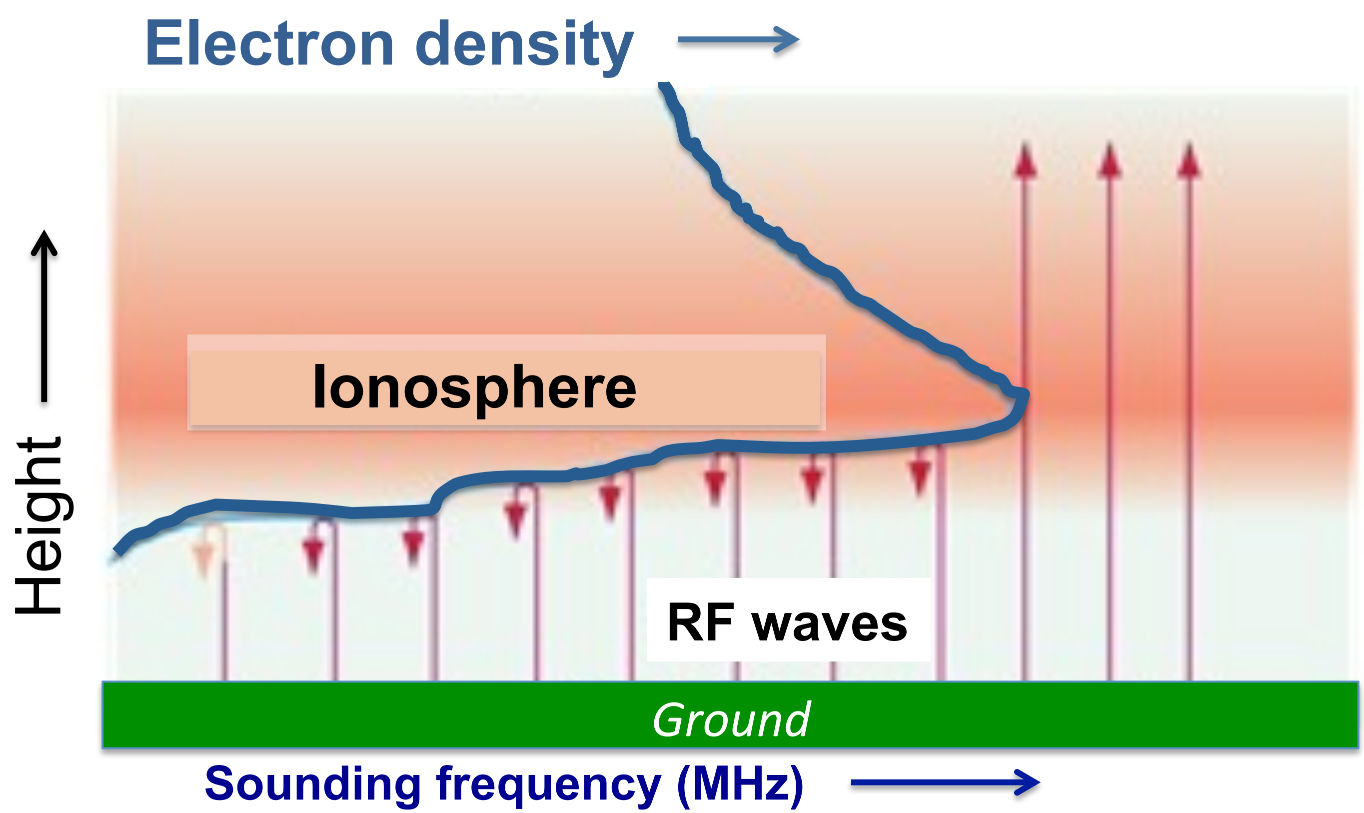
HF signal is reflected back to the ground by the ionosphere.

Reflection occurs at an altitude where the natural frequency of the plasma matches the frequency of the signal.

Ionosonde records the time delay between the transmission and reception of the pulse.

Ionosonde

Repeat transmission over a range of different frequencies!



Measurements can be obtained only to the peak density!

→ Ionosonde measures the bottomside ionosphere.

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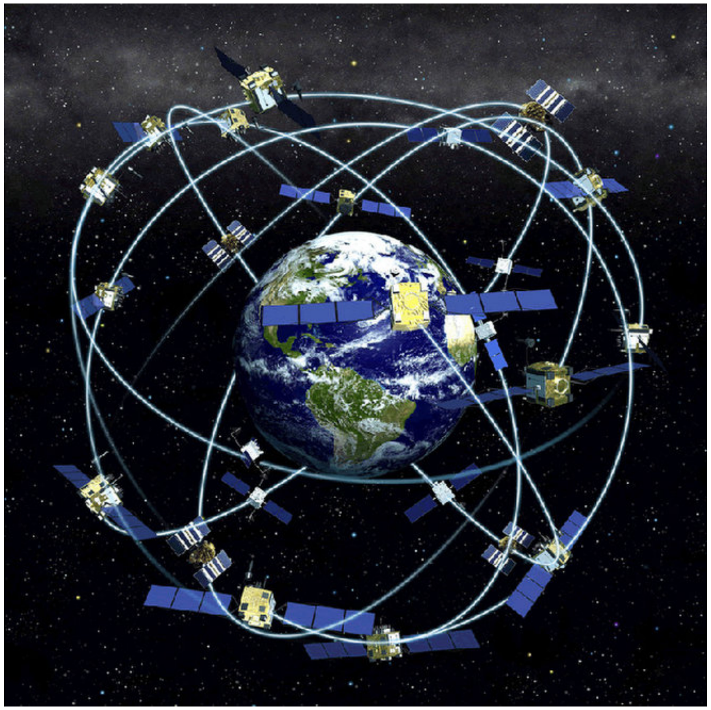
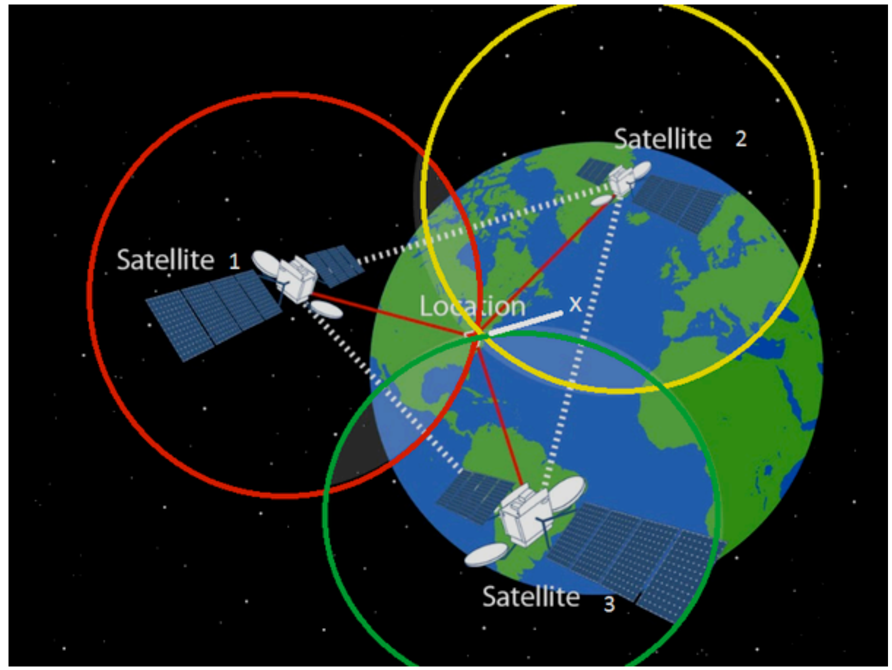
The GPS Navigation System

GPS satellite constellation
31 operational transmitter satellites





Large boom in ionospheric observations came with the advent of the GPS system.

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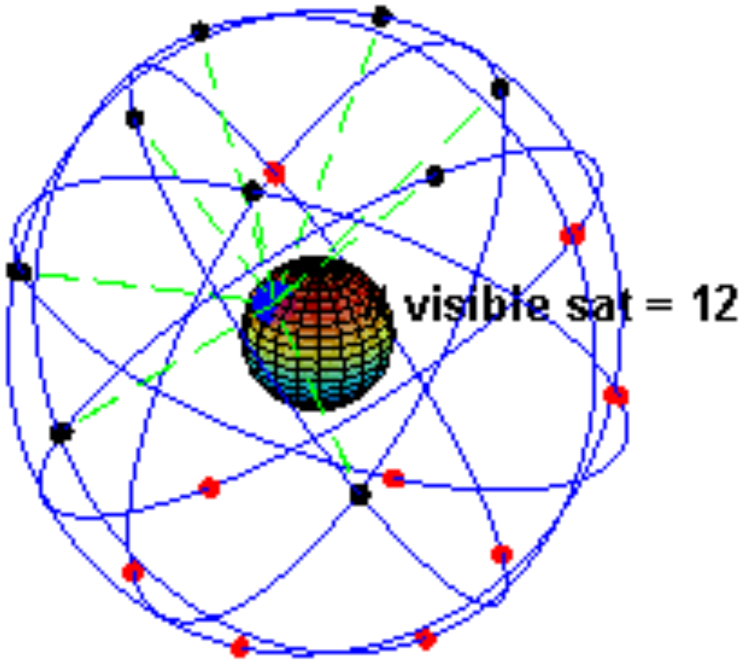

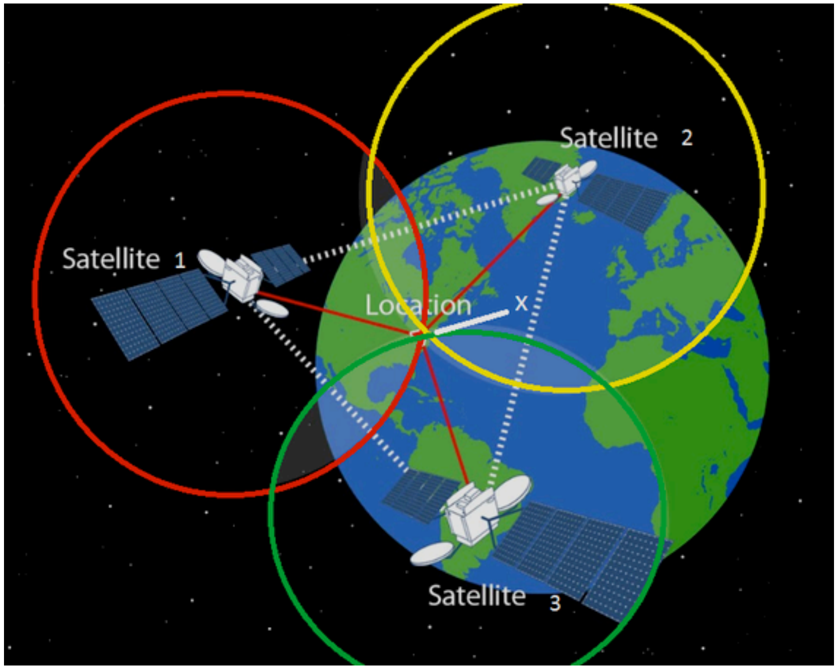

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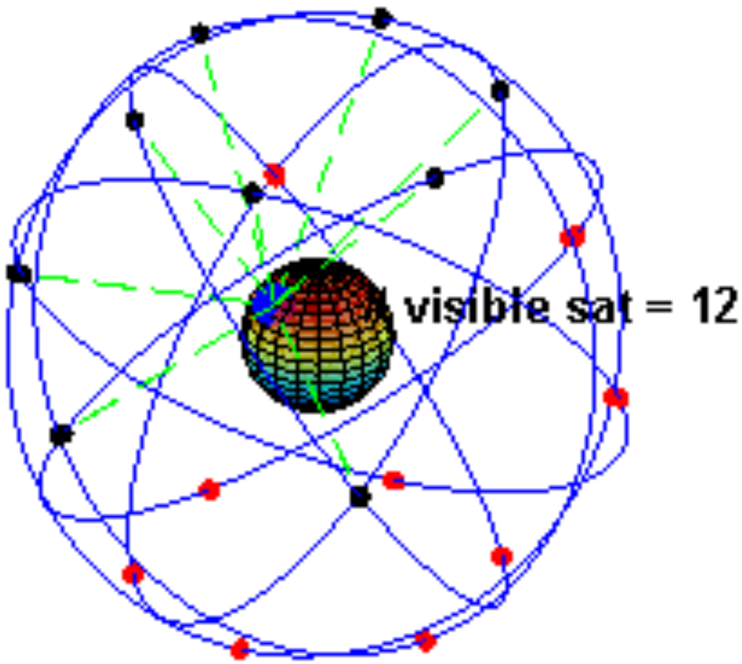

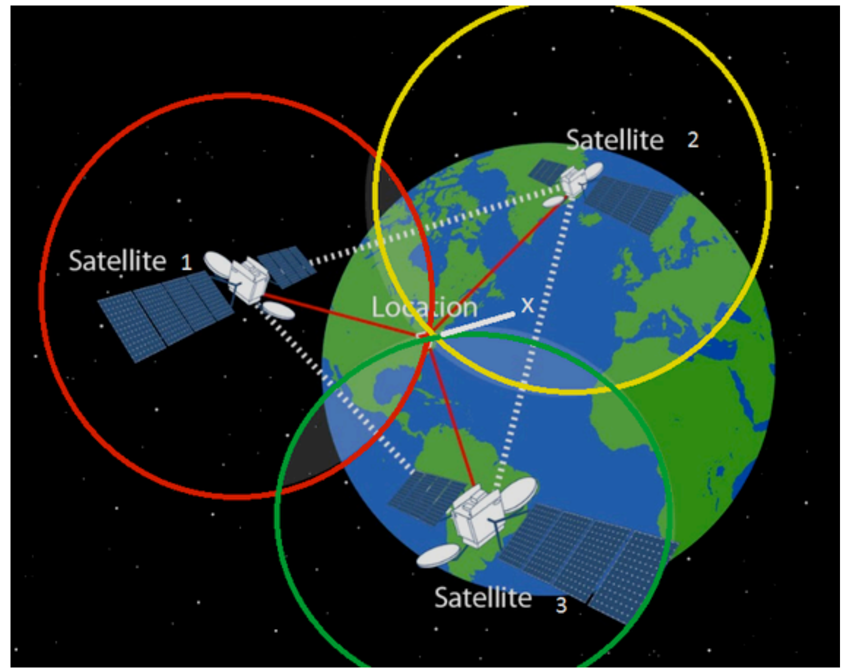

The carrier phase measurements are affected by several quantities:

$$L = R_{Geo} + c\,\Delta t \pm \Delta_{ion}(f) - \varepsilon$$

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GPS: Trans-ionospheric electromagnetic waves

$$L = R_{Geo} + c\,\Delta t \pm \Delta_{ion}(f) - \varepsilon$$

Geometric distance between transmitter and receiver

Timing differences between transmitter and receiver

Other disturbances: Tropospheric delay, Phase cycle slips, multi-path ambiguities, noise, instrumental transmitter and receiver calibration parameters

Frequency independent terms

GPS: Trans-ionospheric electromagnetic waves

$$L = R_{Geo} + c\,\Delta t \pm \Delta_{ion}(f) - \varepsilon$$

Ionospheric effect

✓ Frequency dependent

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$$L = R_{Geo} + c\,\Delta t \pm \Delta_{ion}(f) - \varepsilon$$

Ionospheric effect

✓ Frequency dependent

Dual frequency receivers observe GPS signals at 2 frequencies L1 and L2

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GPS: Trans-ionospheric electromagnetic waves

$$L_{1,2} = R_{Geo} + c\,\Delta t \pm \Delta_{ion}(f_{1,2}) - \varepsilon$$

Ionospheric effect

✓ Frequency dependent

Dual frequency receivers observe GPS signals at 2 frequencies L1 and L2

→ Elimination of non-frequency dependent terms by subtraction of observables at both frequencies

GPS: Trans-ionospheric electromagnetic waves

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Ionospheric effect

✓ Frequency dependent

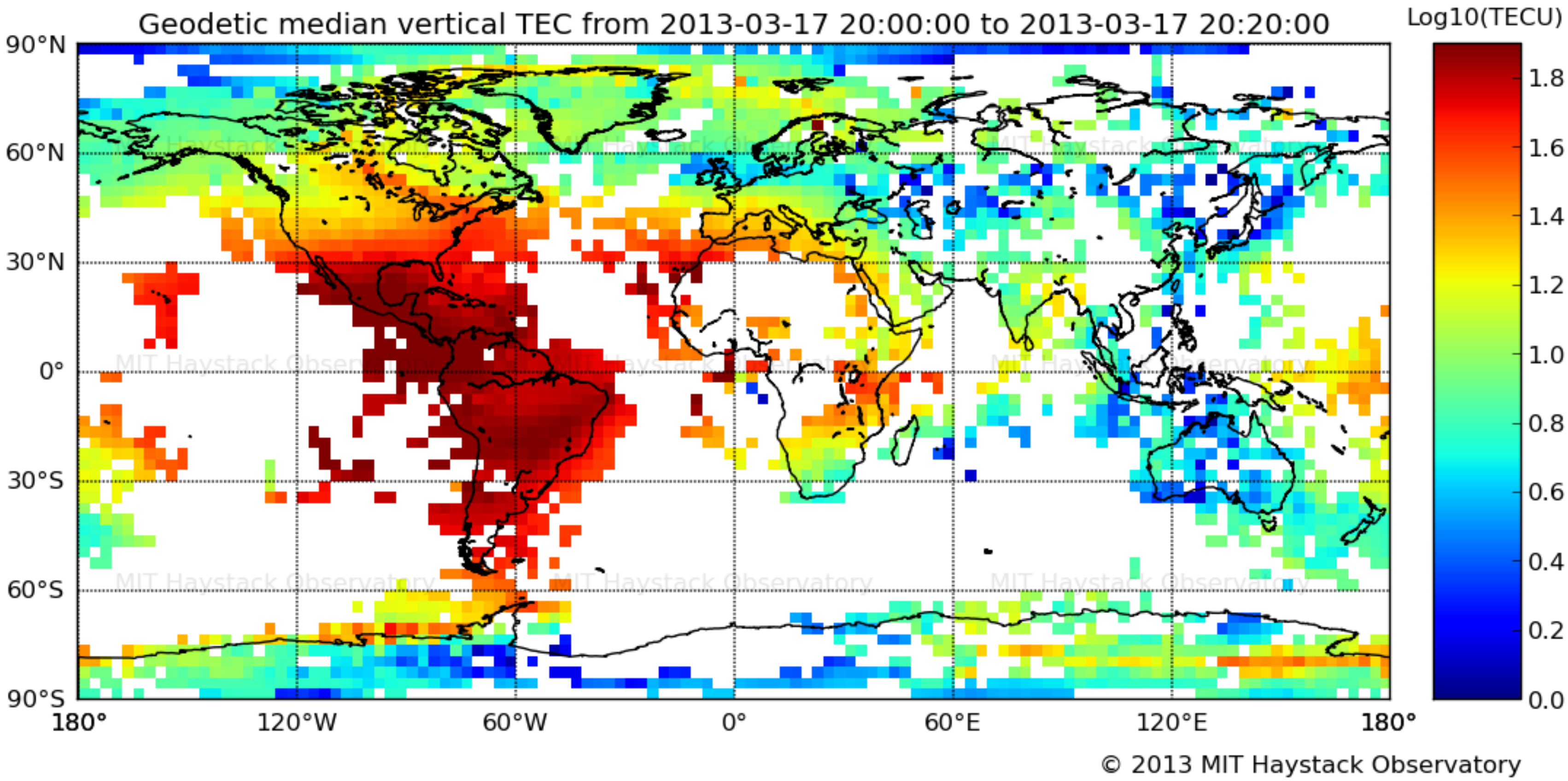
Dual frequency receivers observe GPS signals at 2 frequencies L1 and L2

→ Elimination of non-frequency dependent terms by subtraction of observables at both frequencies

$$L_1 - L_2 \propto \int_{Transmitter}^{Receiver} Ne\,dl \quad = \text{TEC}$$

Ne: electron density   ***TEC***: Total Electron Content

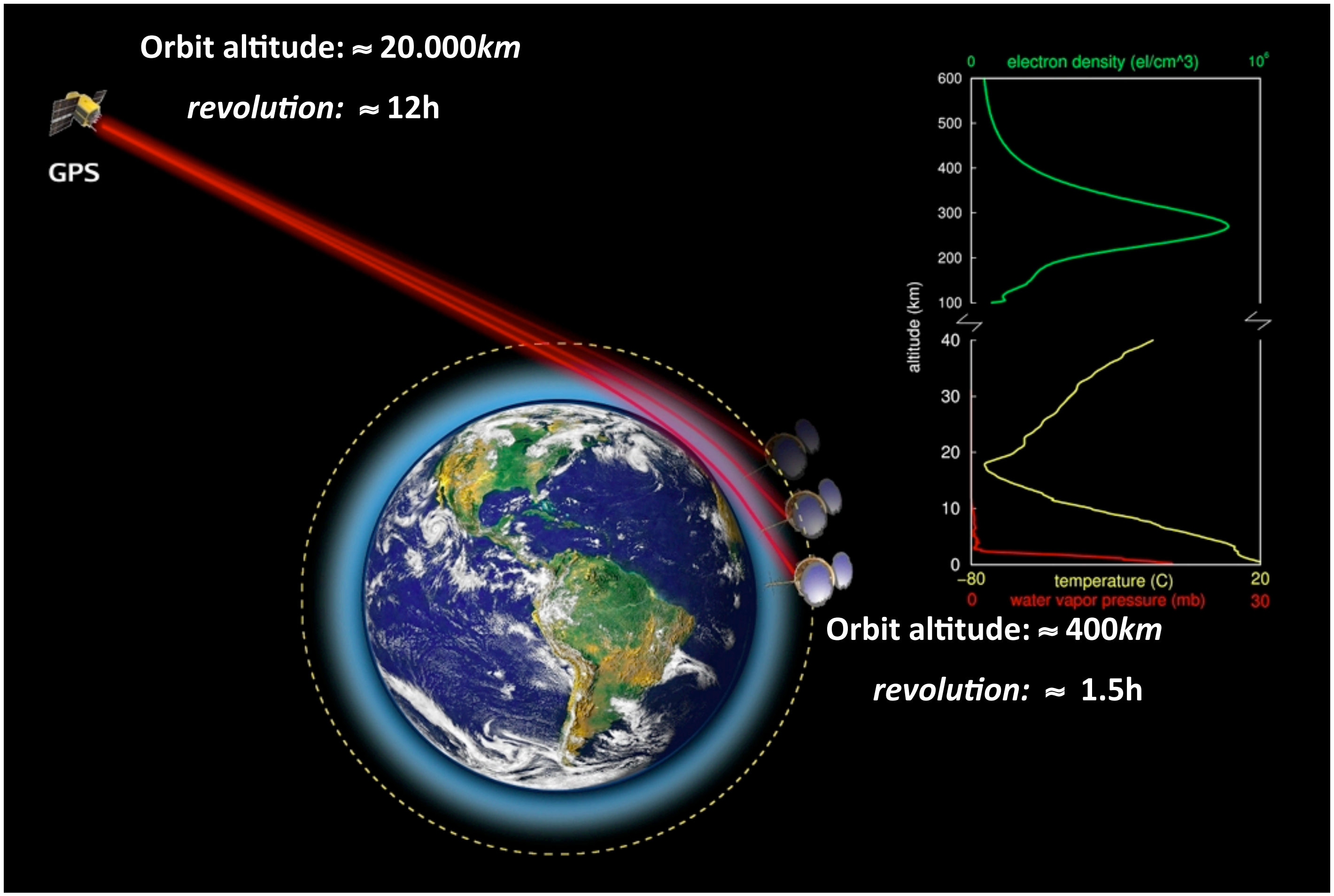
TEC from thousands of dual-frequency receivers are available around the globe.



- Sparse observations over the oceans
- TEC data provide only very limited height profile information

GPS in Space

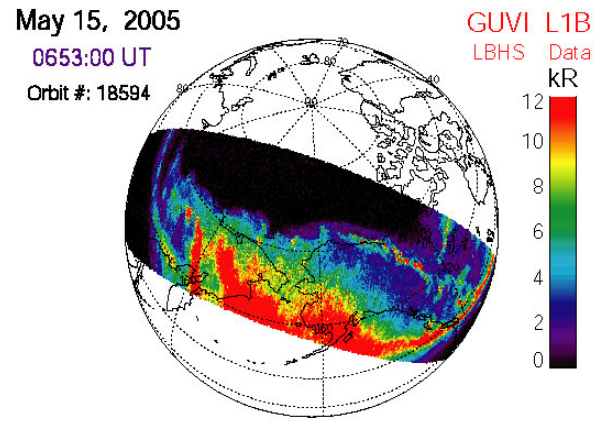
Radio Occultations

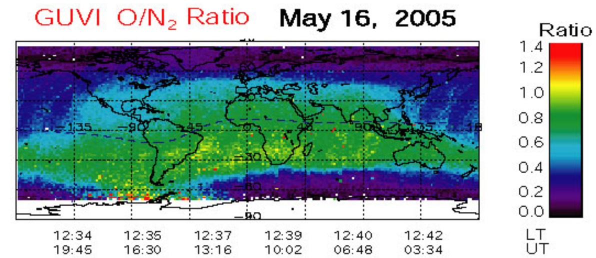


Yue et al. [2014]

On the One Hand, we have large Quantities of Data

- Different kinds of instruments measuring different quantities (apples and oranges)
- Observations are in different places
- Observations have different cadence and availability
- Observations have different error statistics





http://guvi.jhuapl.edu

Difficult to create coherent Picture

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On the Other Hand, we have Mature Theoretical/Numerical Models

➡ Models contain our 'knowledge' of the physics

Continuity Equation:

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j \boldsymbol{u}_j) = P_j - L_j$$

Momentum Equation:

$$n_j m_j \frac{\partial \boldsymbol{u}_j}{\partial t} + \nabla p_j - n_j m_j \boldsymbol{G} - e_j n_j \left[\boldsymbol{E} + \boldsymbol{u}_j \times \boldsymbol{B} \right] = n_j m_j \nu_{jn} (\boldsymbol{u}_n - \boldsymbol{u}_j)$$

Energy Equation:

$$\frac{D}{Dt}\left(\frac{3}{2} p_j\right) + \frac{5}{2} p_j \left(\nabla \cdot u_j\right) = Collisions + Heating - Cooling$$

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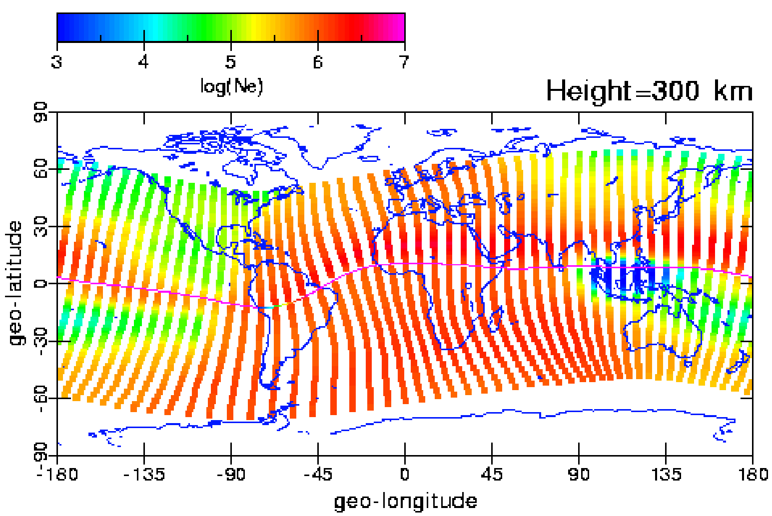
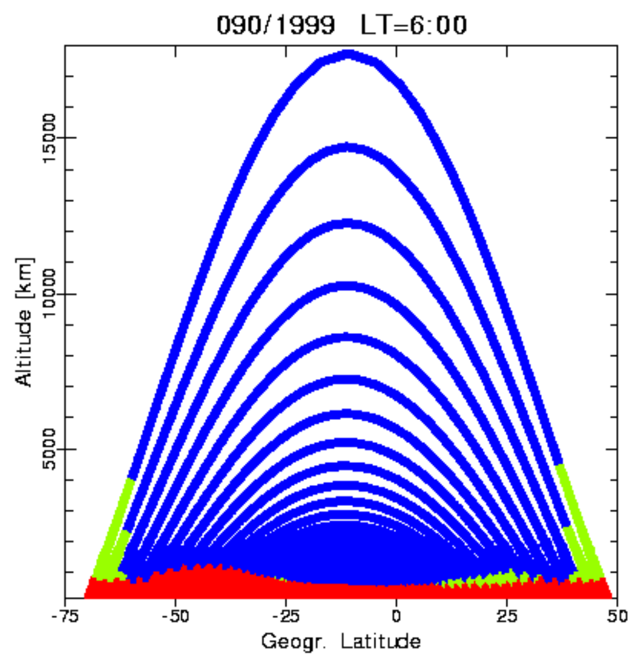
Numerical Models for the Ionosphere

These equations are generally solved in a **magnetic coordinate system** given by the Earth’s magnetic field

Motion perpendicular to the geomagnetic field is result of **ExB** force.

Motion along the magnetic field results in a diffusion equation.





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Equatorial Anomaly

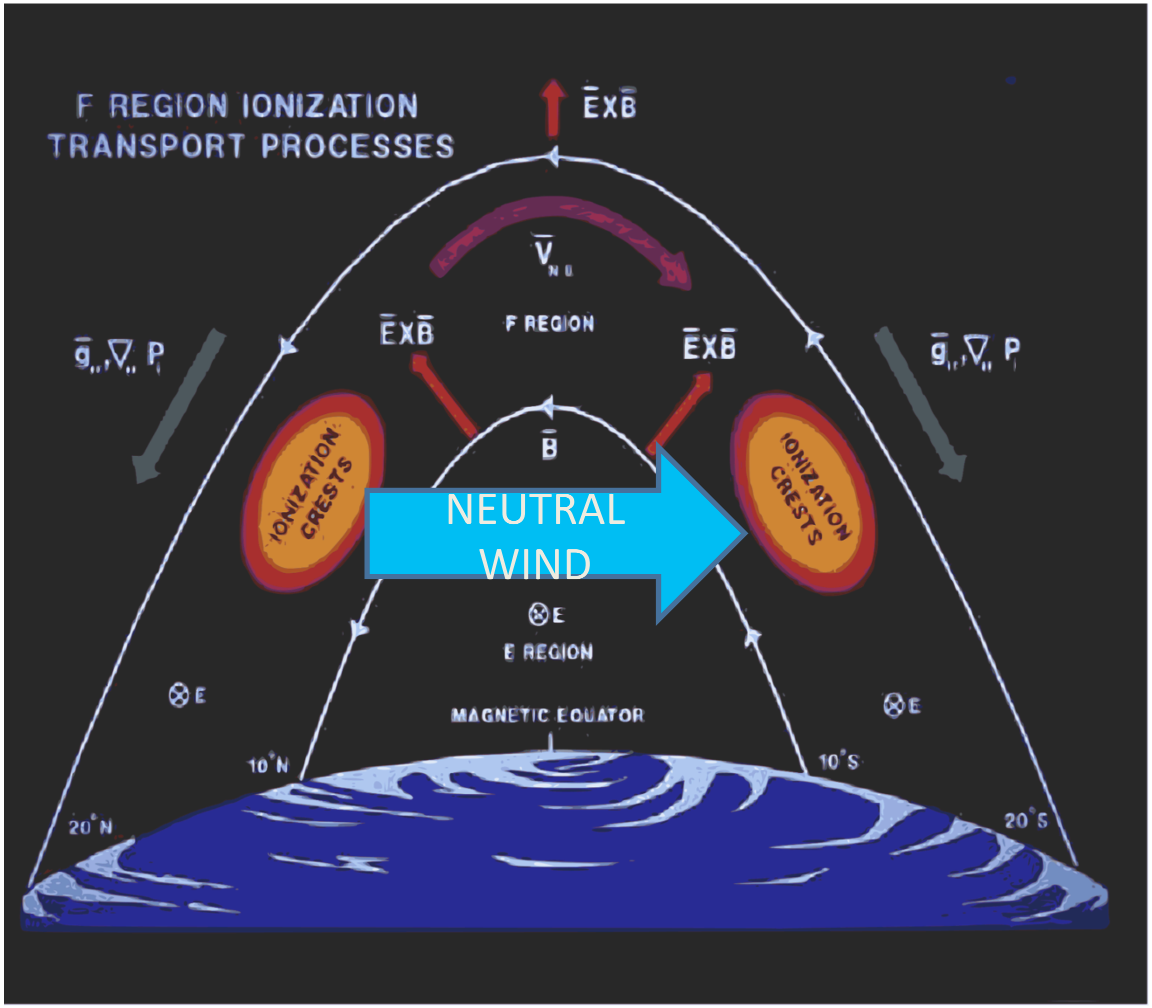


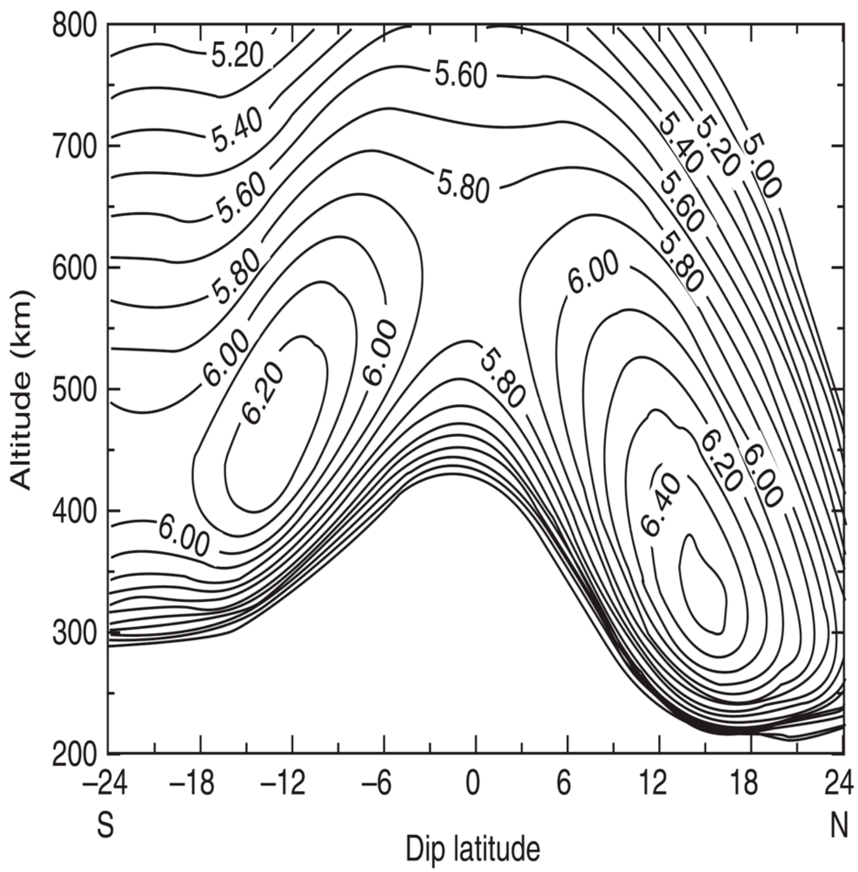
Image credit: Air Force Research Laboratory

- Eastward electric field produced by ions being dragged by neutral winds

  → upward ExB drift

- Plasma then diffuses along field lines due to gravity and pressure grad

Thermospheric Winds - Effects on the ionosphere



- Asymmetry in the Appleton anomaly.
- Northward meridional wind pushes plasma up the field lines in the southern hemisphere and down the field lines in the northern hemisphere.

Image from: Schunk and Nagy, *Ionospheres: Physics, Plasma Physics, and Chemistry,* 2009, 2nd edition.

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Uncertain Parameters in Physics-Based Model

- External Forcing
  - Electric Fields
  - Neutral Wind
  - Neutral Composition
  - Etc…
- Initial Conditions

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Objective of Data Assimilation

➡ Optimally combine the Observations and the Model to create a coherent Picture of the Space Environment

Ionospheric Data Assimilation Models

Over the past years several data assimilation models have been developed that employ various assimilation schemes:

- **Band-Limited Kalman Filter**
- **Gauss-Markov Kalman Filter**
- **Reduced State Kalman Filter**
- **Ensemble Kalman Filter**
- **4D-Variational**

→ Specifications for ionospheric plasma densities and **unobserved** parameters (Electric Field, Neutral Wind, Neutral Composition, etc.).

Gauss-Markov Kalman Filter Model

The Gauss-Markov Model uses a simplified Kalman Filter

- **Ionospheric Physics is contained in physics-based numerical background model (IFM)**
- **Kalman filter solves for deviation from background field**
- **Kalman filter is based on a statistical process**

  → **Diagonal state transition matrix**
- **Model does not provide information about driving forces**

Can easily be run on 1-2 CPUs

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Elimination of Background Biases

- **IFM TEC Compared to TOPEX TEC**
- **TOPEX Measures Vertical TEC Over Oceans (1340 km)**
- **10 - Year TOPEX Data Base (1992-2003)**
- **18-Sec Averaged Data = 11 Million TEC Values**
- **Comparisons Covered Different Seasonal, Solar Cycle, and Magnetic Activity Conditions**
- **Uncertain Parameters in the IFM Adjusted to Bring IFM into better Agreement with TOPEX TEC**

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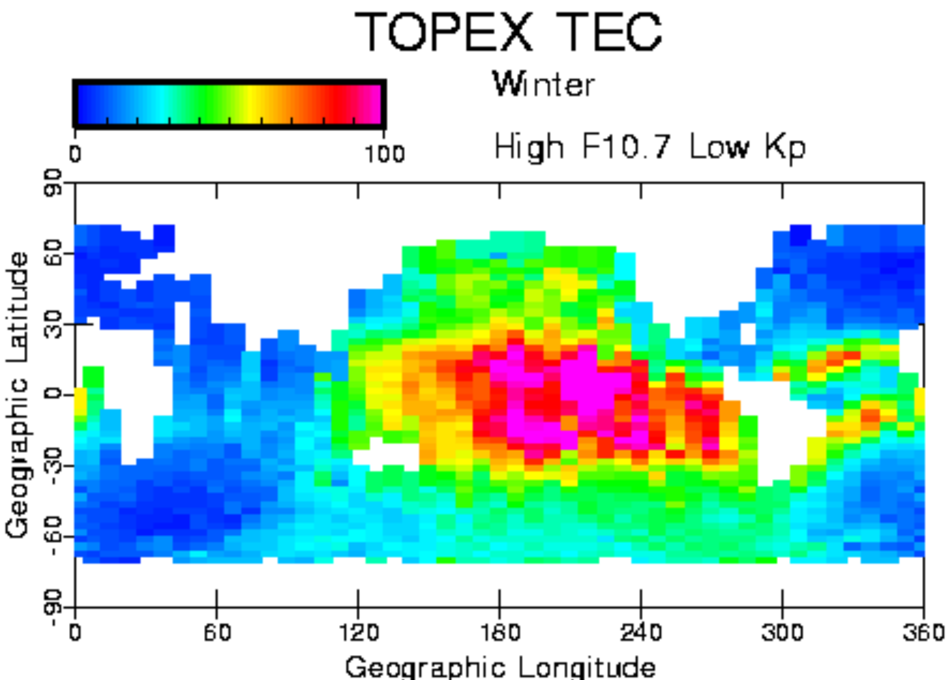
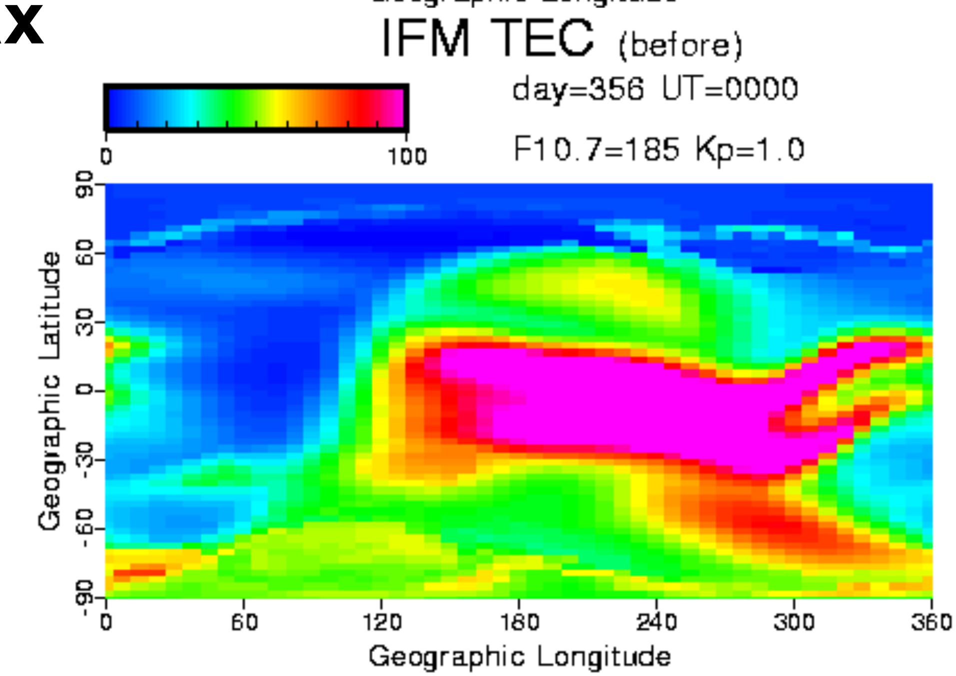
Winter

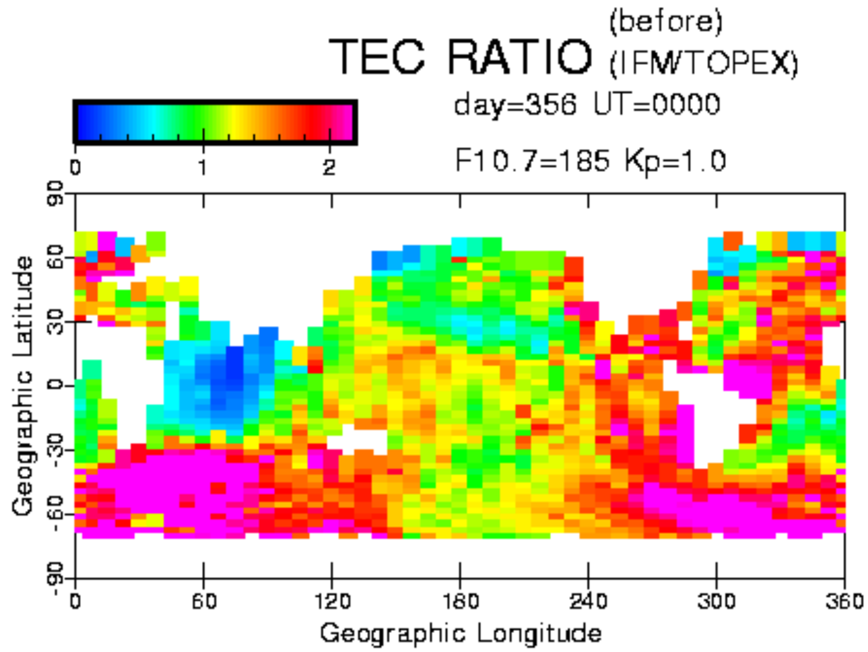
Low Kp

Solar Max

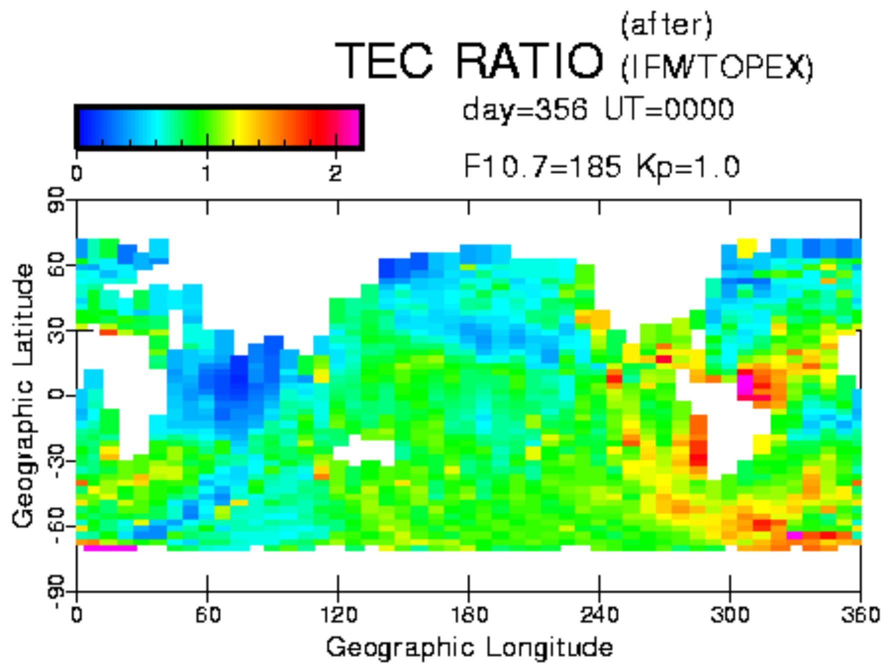




Before Adjustment



After Adjustment



Kalman filter solves for deviation from background field

Kalman filter is based on a statistical process

What to Use for Process Noise?

In the absents of data the model error covariance should relax to the error covariance of the background model

Database of ensemble of IFM model runs

- Ensemble of global 3-D Ne distributions produced by a physics-based ionospheric model (IFM) in terms of various geophysical conditions and variability of model drivers, including wind, E-field, and neutral atmosphere (1107 2-day IFM runs).

Used to estimate the process noise used in the calculation of the model error covariances

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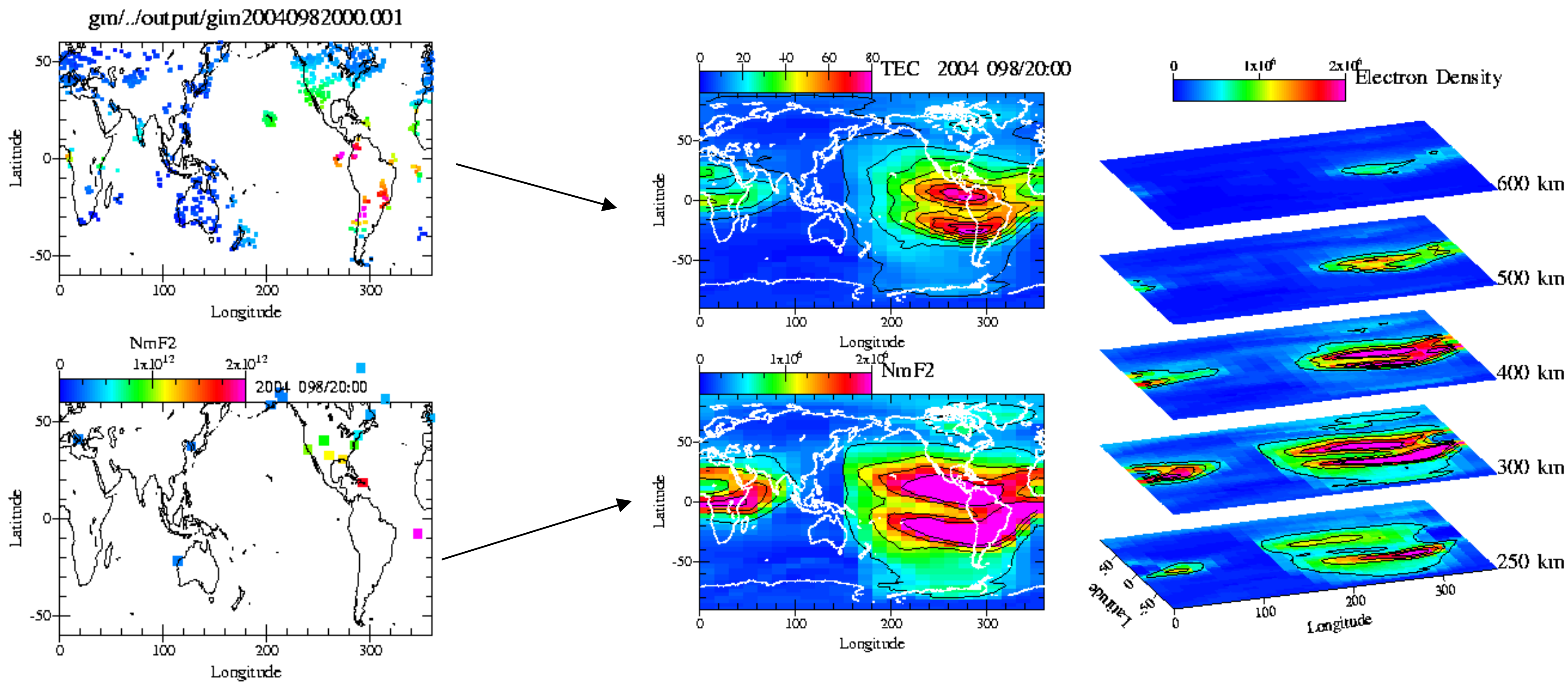
The 3-D Gauss-Markov Filter N_e Density Field

GPS TEC at 300 km Pierce Point (mapped to vertical)

Slant TEC used in this assimilation



Squares show NmF2 from Ionosondes

Bottomside profiles used in this assimilation

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Ensemble Kalman Filter Basic Approach

Ensemble Kalman filter is a Monte Carlo approximation.

It samples the probability density function of forecast and analysis using ensemble model runs

Allows to **incorporate ionospheric physics** in data assimilation

Uses a physics-based numerical ionosphere-plasmasphere model

Provides both specifications for the ionospheric plasma densities and drivers:

- Electric Field
- Neutral Wind
- Neutral Composition

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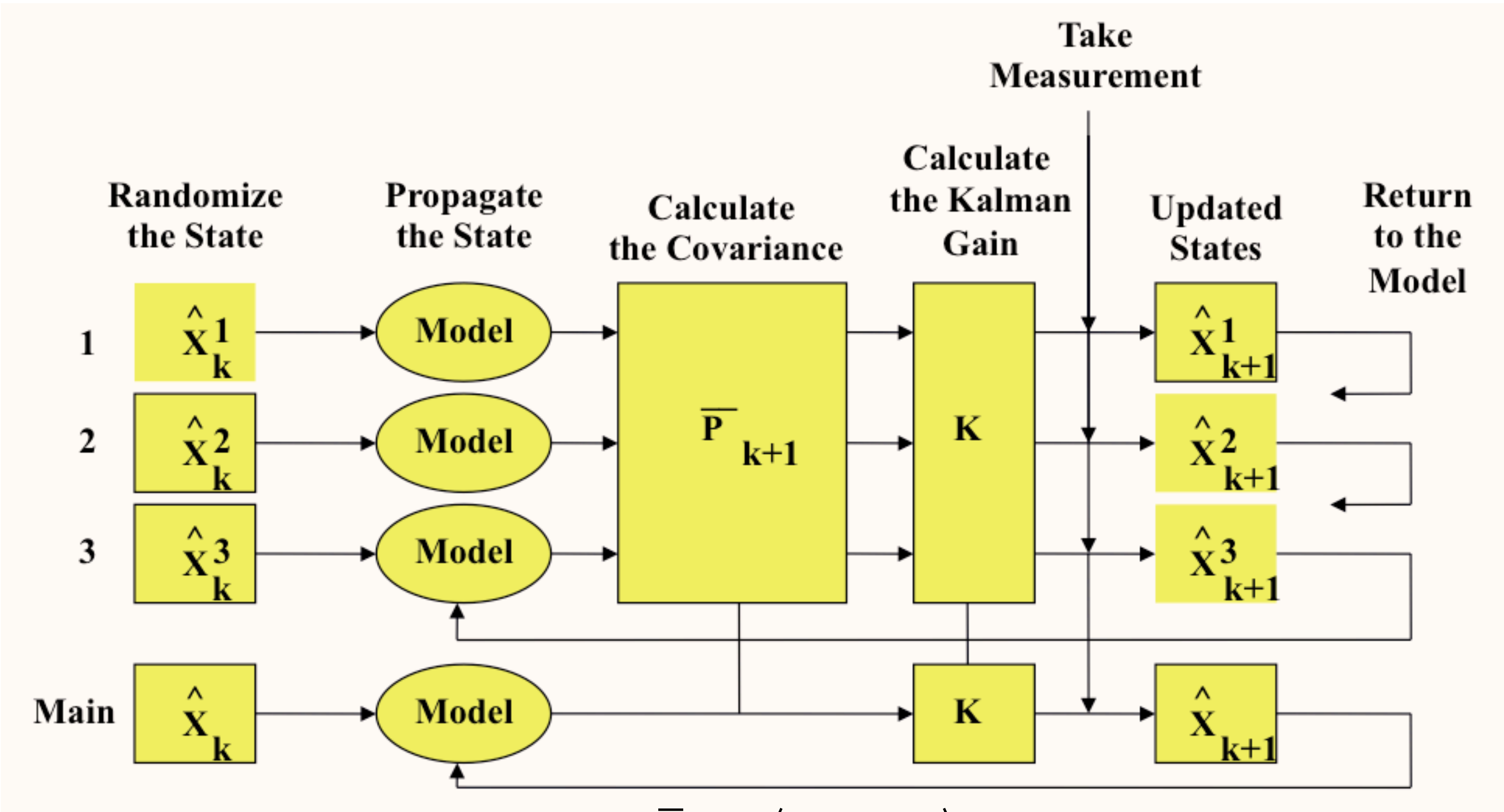
Ensemble Kalman Filter Example

With three Ensemble Members

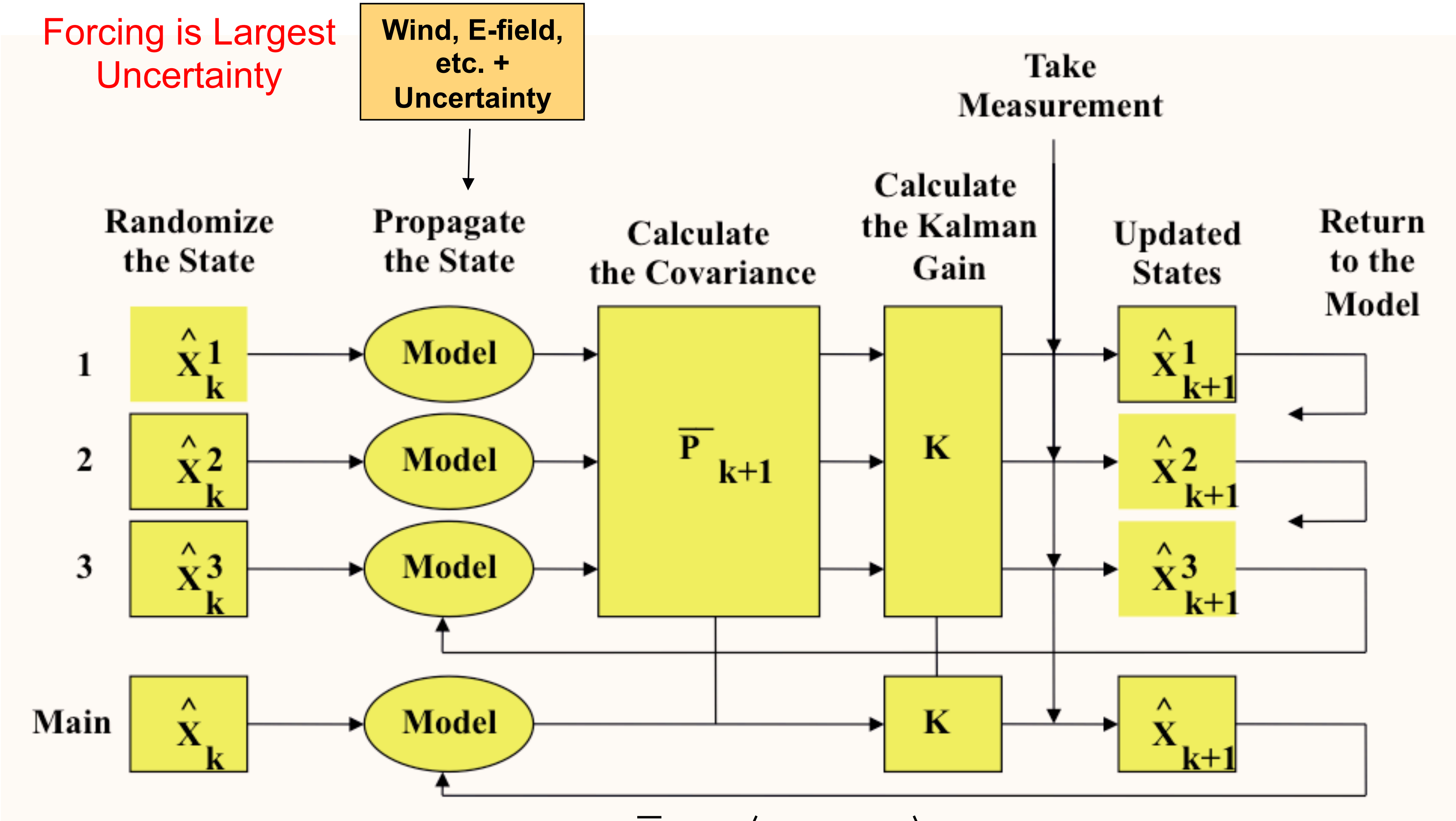


$$P_{k+1} \approx \bar{P}_{k+1} = \langle x_{k+1}, x_{k+1} \rangle$$

Ensemble Kalman Filter Example

With three Ensemble Members

Forcing is Largest Uncertainty



$$P_{k+1} \approx \overline{P}_{k+1} = \langle x_{k+1}, x_{k+1} \rangle$$

Augmentation of State

Include Driving Forces into State Vector

State consists of

Electron density on a *lat x lon x alt* grid

+ **Neutral density** (O, N_2)
+ **Electric field** in equatorial plane
+ **Neutral wind**
+ …

Driving forces become part of the estimation problem!

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Localization

Eliminate spurious covariances

May be required for realistic applications when the system dimension exceeds the ensemble size (Oke et al., 2006)

- Use Gaussian localization function.
- It is applied to the state error covariance matrix by means of a Schur product.
- Multiplying each element P_{ij} of the covariance matrix by the factor $\rho_{ij} = \exp(-0.5\, r^2_{ij} / r^2_0)$, where r_{ij} is the horizontal distance between elements i and j in grid space, and r_0 is the localization radius.

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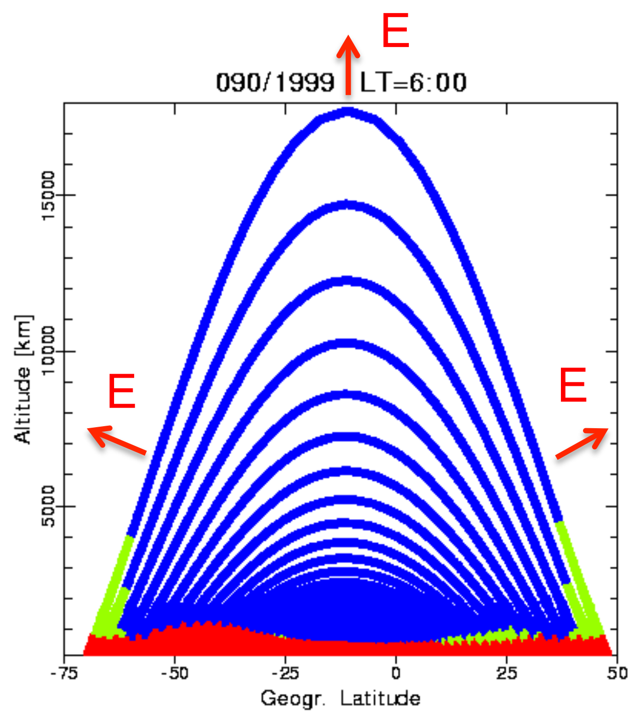
However

- Electric fields play an important role in the dynamics of the ionosphere.
- Electric fields map from one hemisphere to the other via magnetic fields.



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Localization Lengths

- **Spatial Correlations of Day-to-Day TEC Variability**
- **1000 GPS Ground-Based Receivers**
- **150 Million ΔTEC**
- **Correlation Lengths Determined for:**
  - **Mid & Low Latitudes**
  - **Daytime & Nighttime**
  - **Season**
  - **Meridian & Zonal Directions**

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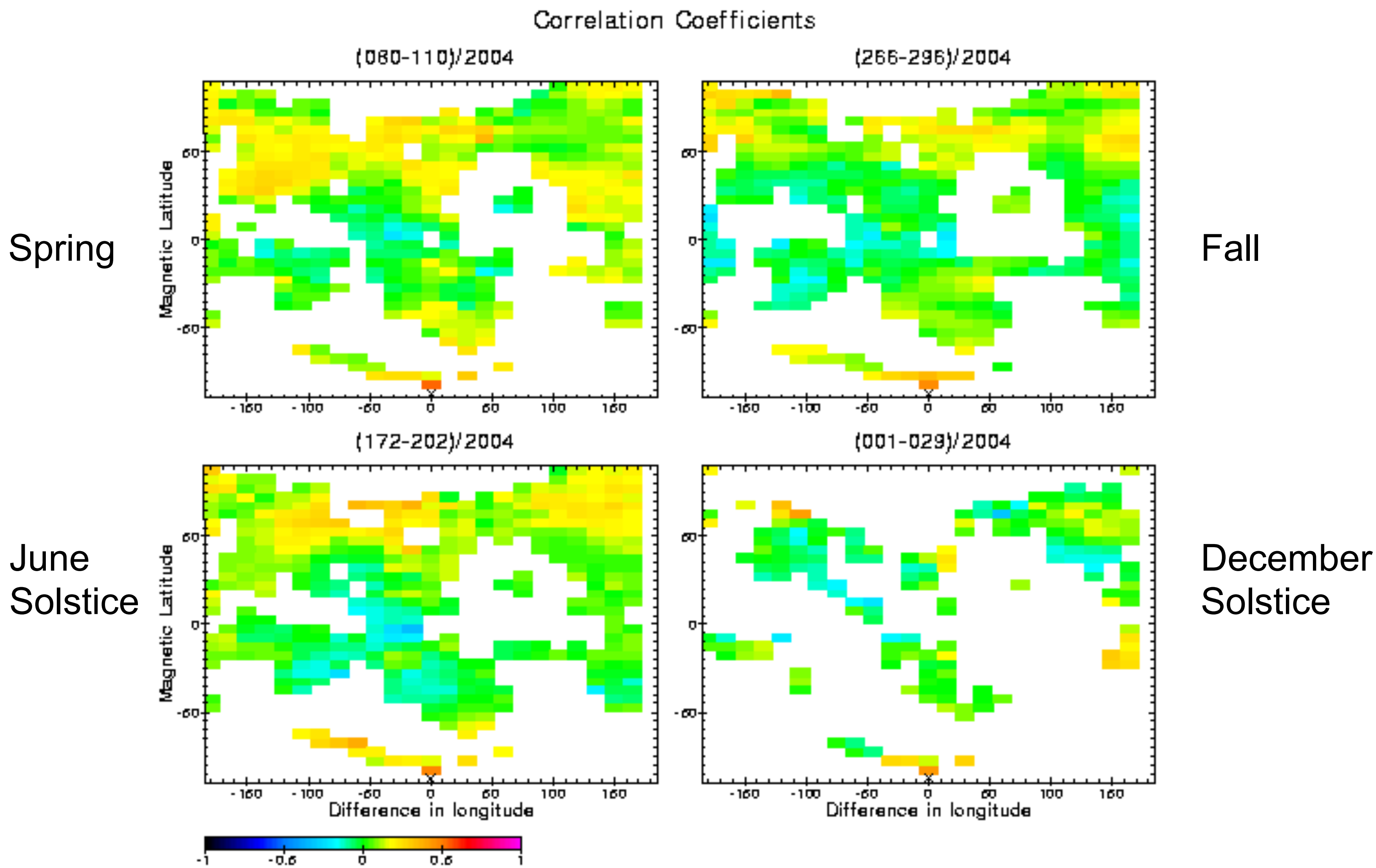
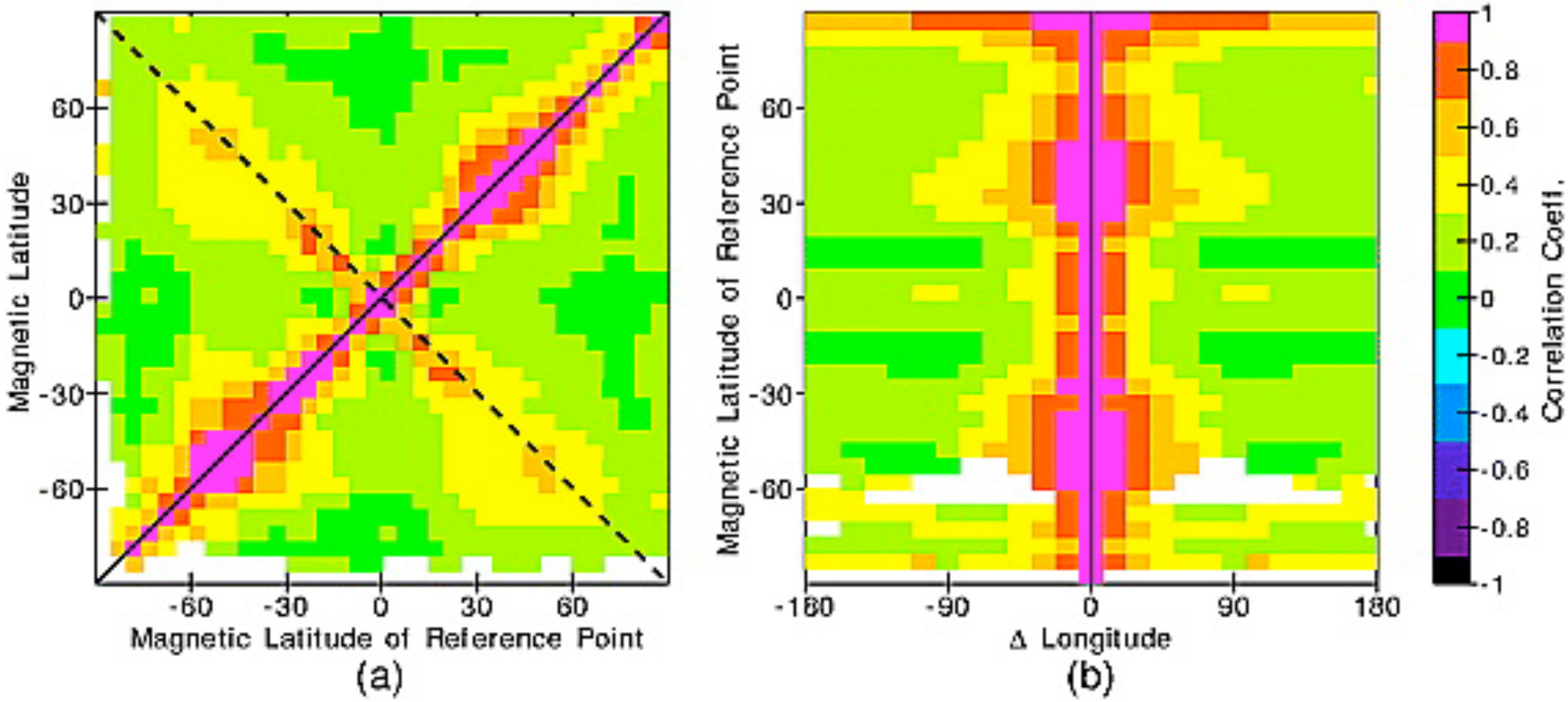


Correlation Coefficients
(080-110)/2004
(266-296)/2004
(172-202)/2004
(001-029)/2004
Spring
Fall
June Solstice
December Solstice
Magnetic Latitude
60
0
-60
-160
-100
-60
0
60
100
160
Difference in longitude
-1
-0.6
0
0.6
1

Correlation Coefficients/Length



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Example of Ensemble Kalman Filter Model

- Several Days in March/April of 2004
- Geomagnetically Quiet Period
- Data Assimilated
  - o Slant TEC from 162 GPS Ground Receivers
- Use Ionosonde Data for Validation

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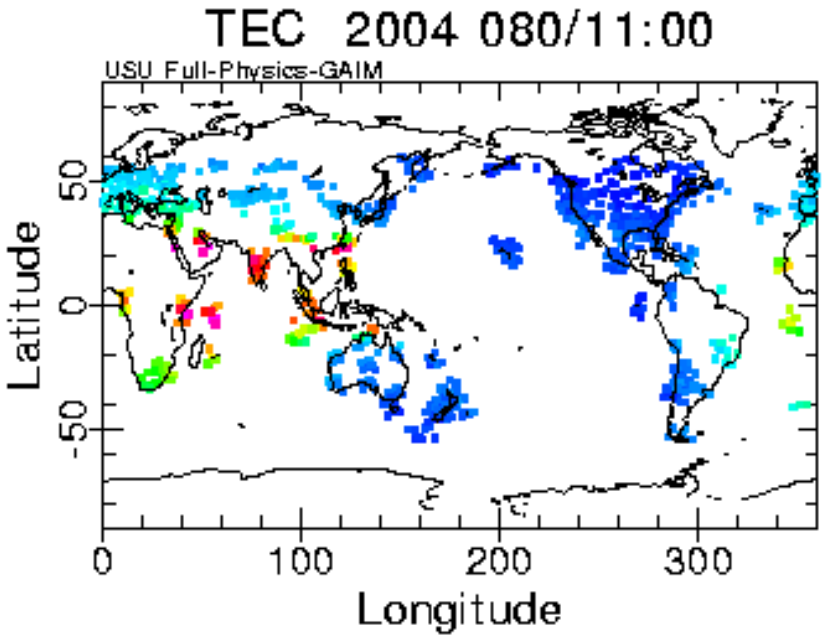
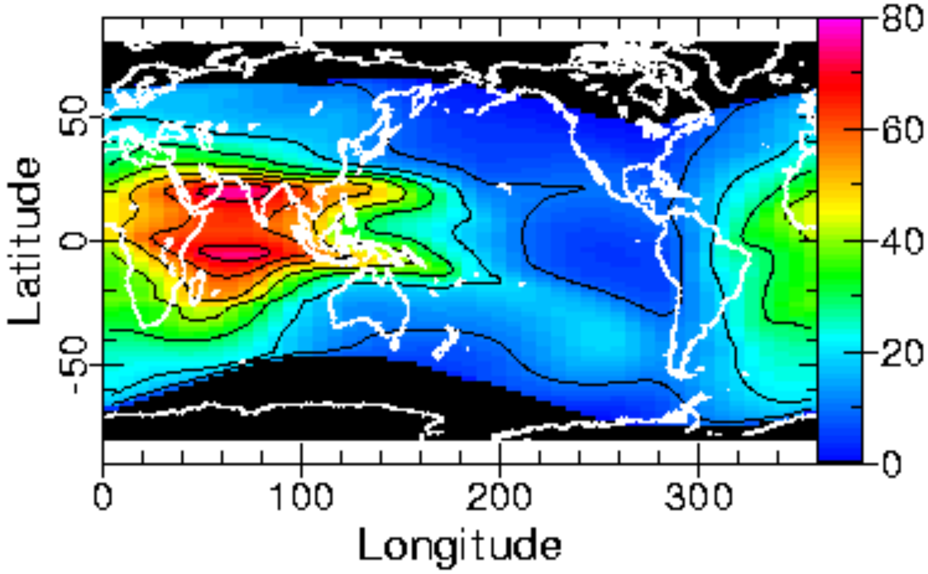
Example Model Output (TEC)



Slant GPS/TEC from about 160 ground GPS receivers are assimilated every 15 min.

For illustration purposes the Figure shows vertical TEC at 300 km pierce point.



Ensemble Kalman Filter TEC Model Output.

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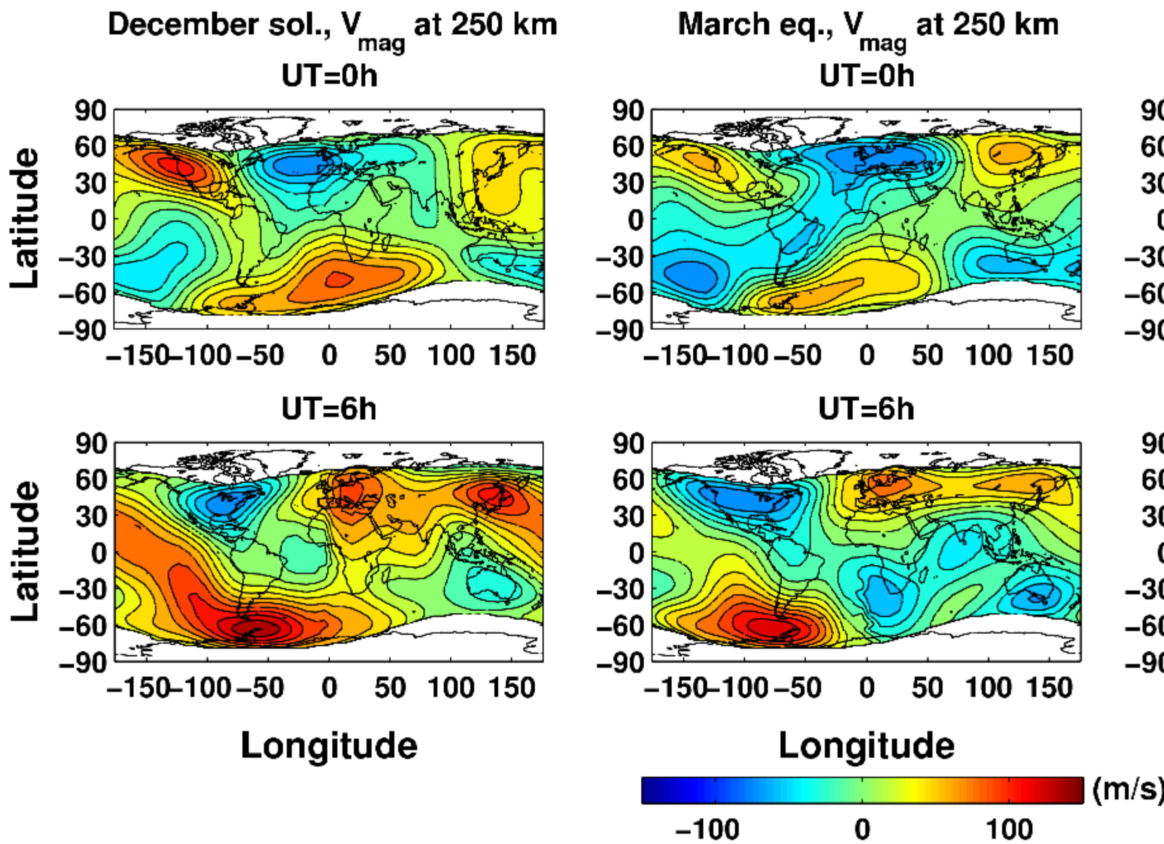
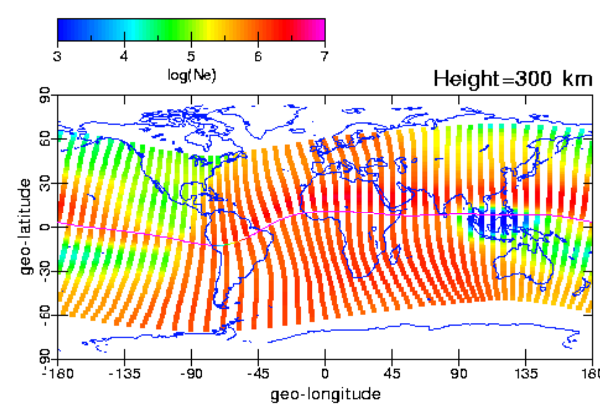
Derived Global magnetic meridional winds



Low- and mid-latitude magnetic meridional winds derived from



The obtained wind pattern agrees well with its well-established

Night → Equatorward

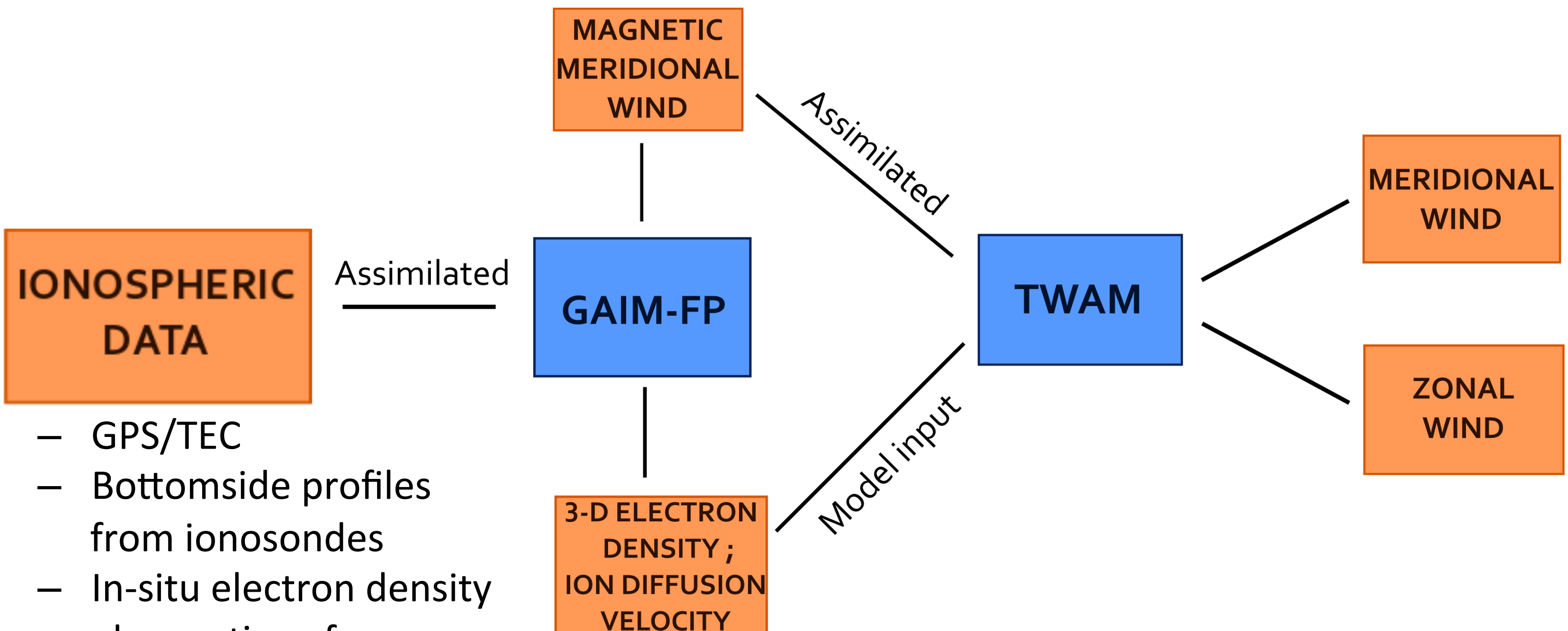
Day → Poleward

Solstices → Predominantly summer-to-winter flow

Equinox → Symmetric pattern about the geographic equator

Thermospheric Wind Assimilation Model (TWAM)

Use a separate Data Assimilation Model for the thermospheric wind together with ensemble Kalman filter (GAIM-FP) output to **obtain neutral wind components**



- GPS/TEC
- Bottomside profiles from ionosondes
- In-situ electron density observations from satellites
- …

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Thermospheric Wind Assimilation Model (TWAM)

Physics-based Model:

The equation of motion of the neutral air

GRAVITY VISCOSITY

$$\frac{d\boldsymbol{u}}{Dt} = -2\boldsymbol{\Omega}\times\boldsymbol{u} + \boldsymbol{g} - 1/\rho\boldsymbol{\nabla}p + \mu/\rho\nabla^2\boldsymbol{u} - \nu_{ni}(\boldsymbol{u}-\boldsymbol{u}_i)$$

CORIOLIS PRESSURE COLISSIONS

Where:

Data:

The global magnetic meridional wind data from GAIM-FP.

Output:

The solution for zonal (*u*) and meridional (*v*) winds are obtained in 110-600 km altitude using an implicit Kalman filter technique.

Implicit Kalman Filter Equations

$$\mathbf{M}_1(k+1)\,\mathbf{x}(k+1) = \mathbf{M}_2(k+1)\,\mathbf{x}(k) + \mathbf{U}(k+1) + \mathbf{q}(k+1)$$ *- Implicit form of dynamic system*

$$\mathbf{z}(k+1) = \mathbf{H}(k+1)\,\mathbf{x}(k+1) + \mathbf{r}(k+1)$$ *- Measurement equation*

Introduce Auxiliary Variables:

$$\mathbf{y}(k+1) = \mathbf{M}_1(k+1)\,\mathbf{x}(k+1)$$

$$\mathbf{H}_1\mathbf{M}_1(k+1) = \mathbf{H}$$

Rewrite equations using auxiliary Variables:

$$\mathbf{y}(k+1) \equiv \mathbf{y}^f = \mathbf{M}_2(k+1)\,\mathbf{x}(k) + \mathbf{U}(k+1) + \mathbf{q}(k+1)$$ *- Predicted state*

$$\mathbf{z}(k+1) = \mathbf{H}_1(k+1)\,\mathbf{y}(k+1) + \mathbf{r}(k+1)$$ *- Measurement equation*

$$\mathbf{P}_y^f = \mathbf{M}_2\mathbf{P}_x\mathbf{M}_2^T + \mathbf{Q}$$ *- Forecast error covariance*

Calculate Kalman Gain:

$$\mathbf{K}_y = \mathbf{P}_y^f\mathbf{H}_1^T\left(\mathbf{R} + \mathbf{H}_1\mathbf{P}_y^f\mathbf{H}_1^T\right)^{-1}$$ *- Kalman gain*

Update State and Error Covariances:

$$\mathbf{x}^a = \mathbf{M}_1^{-1}\left[\mathbf{y}^f + \mathbf{K}_y\left(\mathbf{z} - \mathbf{H}_1\mathbf{y}^f\right)\right]$$ *- Updated state*

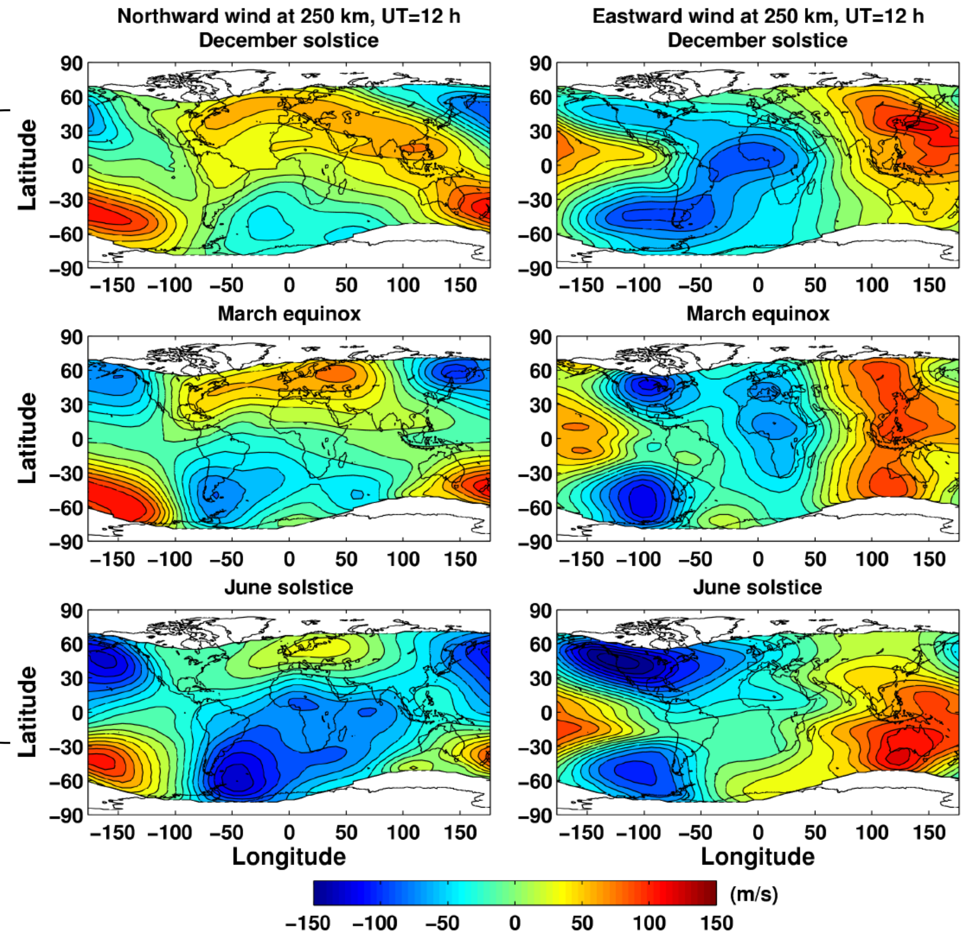
$$\mathbf{P}_x^a = (\mathbf{M}_1)^{-1}\left[(\mathbf{I} - \mathbf{K}_y\mathbf{H}_1)\,\mathbf{P}_y^f\right]\left(\mathbf{M}_1^T\right)^{-1}$$ *- Updated state error covariance*

The global pattern of TWAM winds

- Flow from the hottest part towards the coldest part.
- Modified by ion drag and Coriolis forces.

Positive = Northward wind

Meridional wind **Zonal wind**



Positive = Eastward wind

Meridional and zonal winds at 250 km from TWAM.

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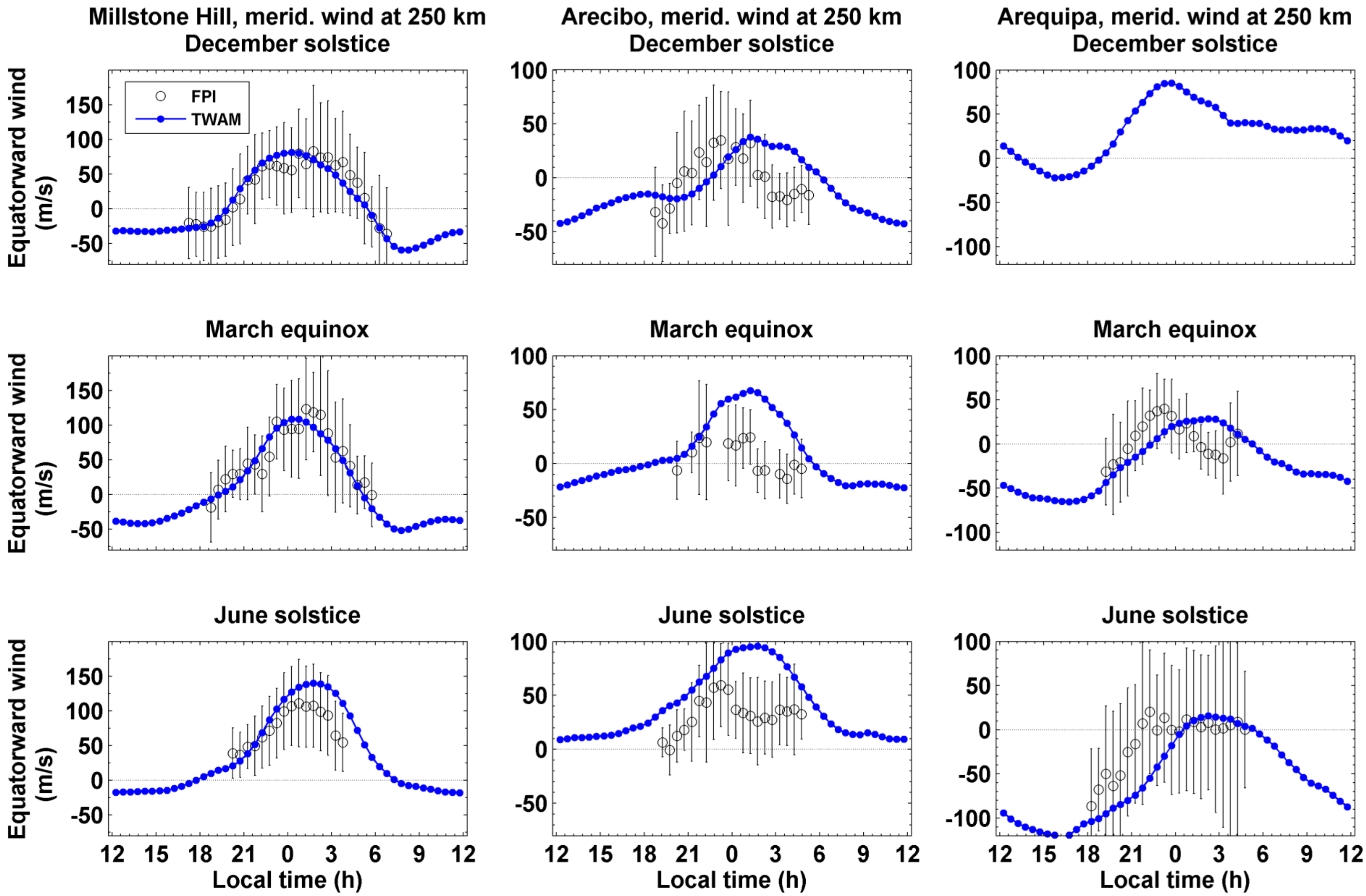
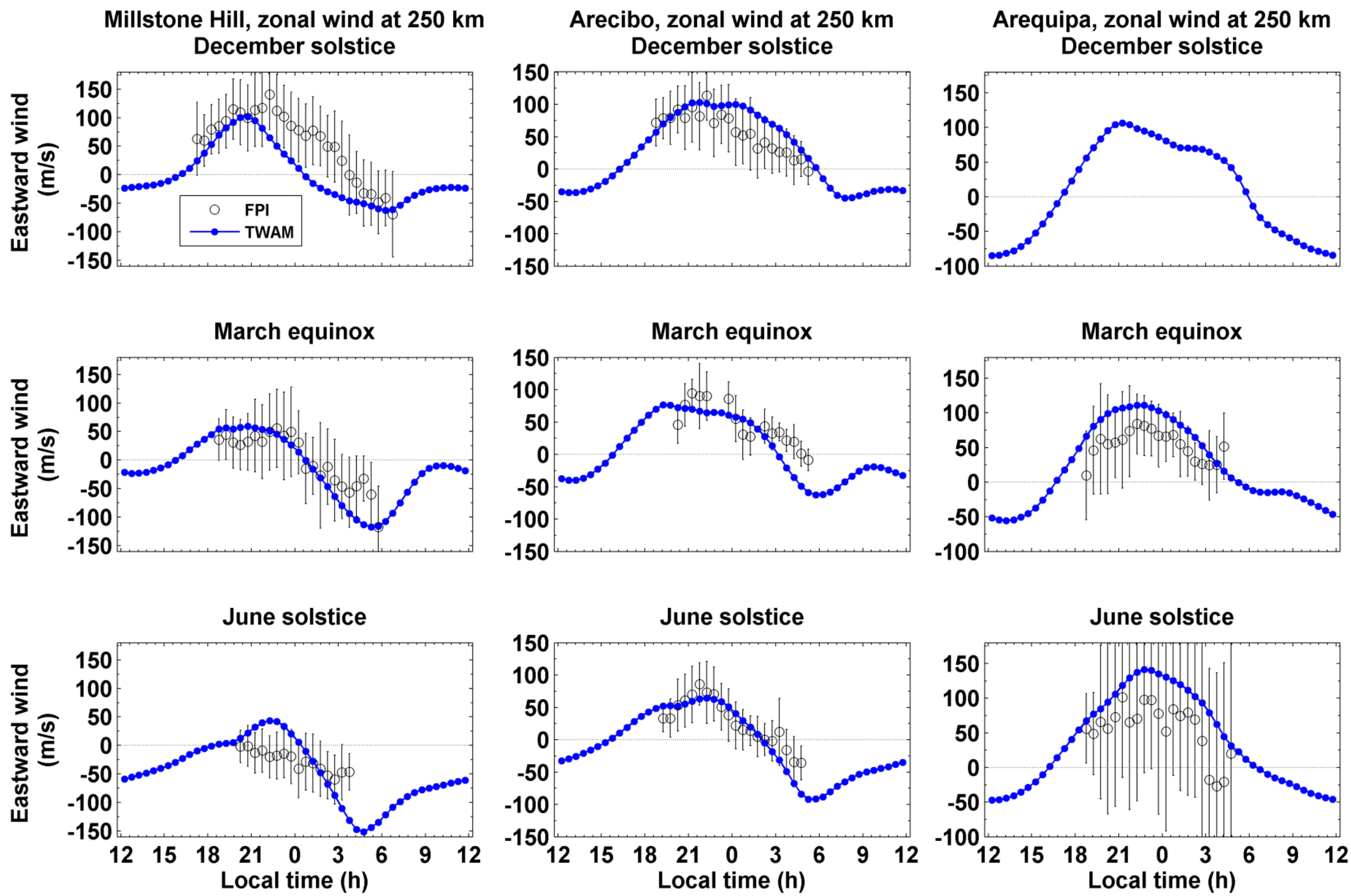
Comparison of TWAM geographic meridional winds with FPI data



LT variations of seasonal geographic meridional winds from FPI observations and TWAM. (Positive - equatorward).

Comparison of TWAM geographic zonal winds with FPI data



LT variations of seasonal geographic zonal winds from FPI observations and TWAM. (Positive - eastward).

Summary

- **The Ionosphere is highly variable**

- **For the Ionosphere a vast amount of Data is available**

- **Data Assimilation has become an Important Part of Ionospheric Sciences and Applications**

- **Data Assimilation has many Challenges and Rewards**
  - **Challenges**
    - **Data Quality & Distribution**
    - **Physics-Based Model Deficiencies**
    - **Assimilation Technique Approximations**
  - **Rewards**
    - **Reliable Specification & Forecast Models**
    - **Useful Scientific Tool**

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