Thermospheric Dynamics as Observed Through the Lens of Networked FPIs

Jonathan J. Makela

This talk is based on work supported by a variety of funding agencies through a myriad of funding vehicles. The **National Science Foundation**, **Air Force Office of Sponsored Research**, **NASA**, **Office of Naval Research**, and **Illinois Strategic International Partnerships** are gratefully acknowledged (although any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of these agencies).

ECE ILLINOIS

ILLINOIS

From **operations**, to **data analysis**, to **scientific collaborations**, the results presented in this talk would not be possible without the help of many colleagues, students, and mentors from around the world.

Importance of wind measurements

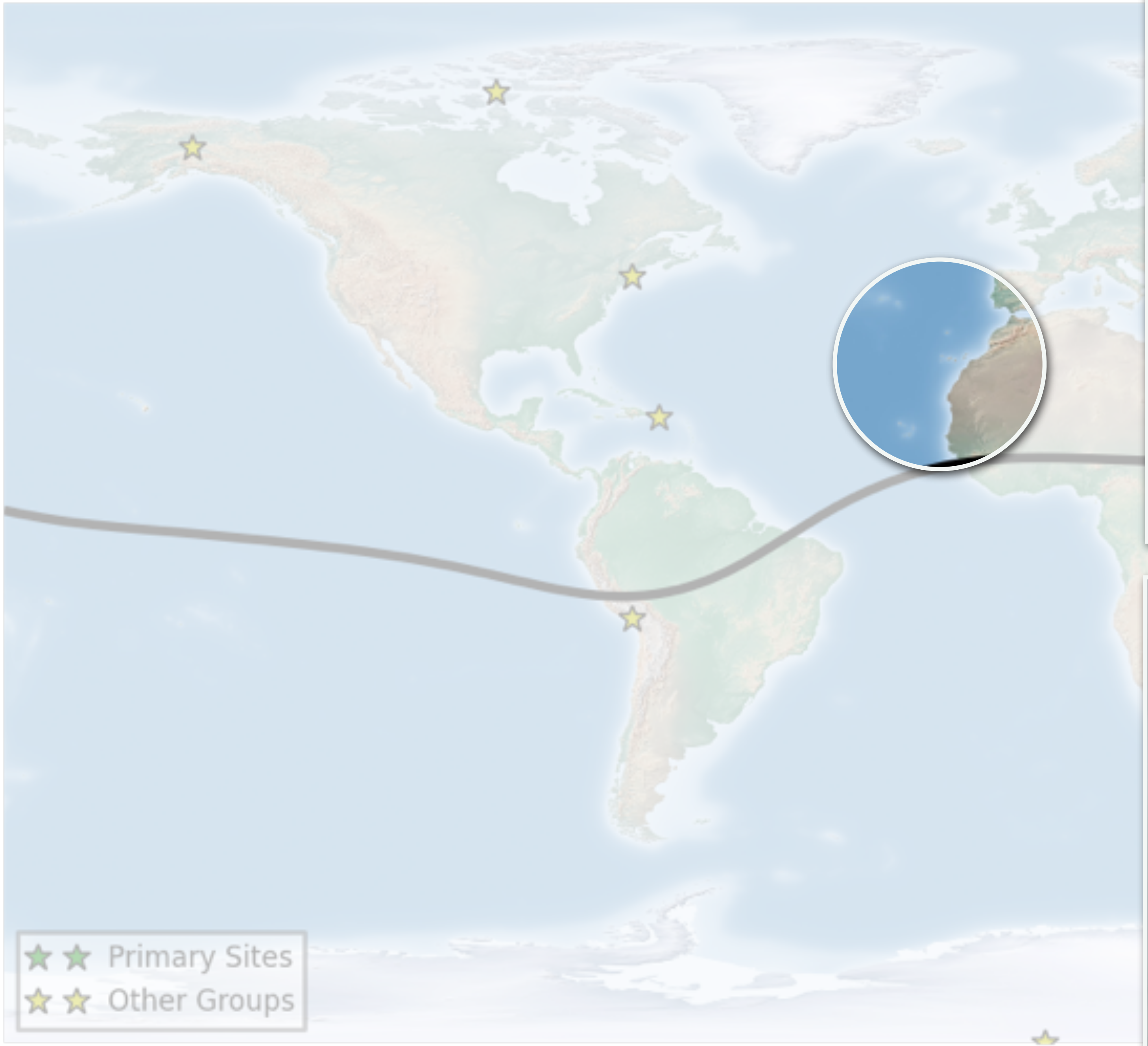
- The winds transport (or advect) mass, momentum, composition, and energy throughout the atmosphere system
- Winds also move plasma through drag/collisions and can induce currents and electric fields
- Despite importance of neutral winds, they are vastly under sampled (historically <1K global observations per day; except during a satellite mission)
    - Much of our current understanding of the wind field is based on global climatologies developed through satellite missions or from low-temporal resolution measurements made from single-site FPI experiments
    - Misses much of short spatial/temporal scale physics
- This limits our ability to model and understand the coupling/driving effects of the thermosphere on space weather

Motivations for an FPI network

- Characterization of the base state of thermospheric dynamics
  - Indications that climatological models did not correctly specify thermospheric neutral winds
  - Need to validate first-principles models
- Understand thermosphere-ionosphere coupling at low-latitudes
  - Neutral winds play a role in the development of ionospheric irregularities
  - Study the F-region dynamo in detail through simultaneous observations of plasma drift velocity and neutral winds
- Study spatial-temporal dynamics using multi-site observations
  - Need a larger field-of-view to unravel spatial-temporal dynamics
- Understand the mid-latitude thermospheric response to geomagnetic disturbances

2005

2005-2007



2009: Deployment of RENOIR to Brazil

2011: NATION deployment

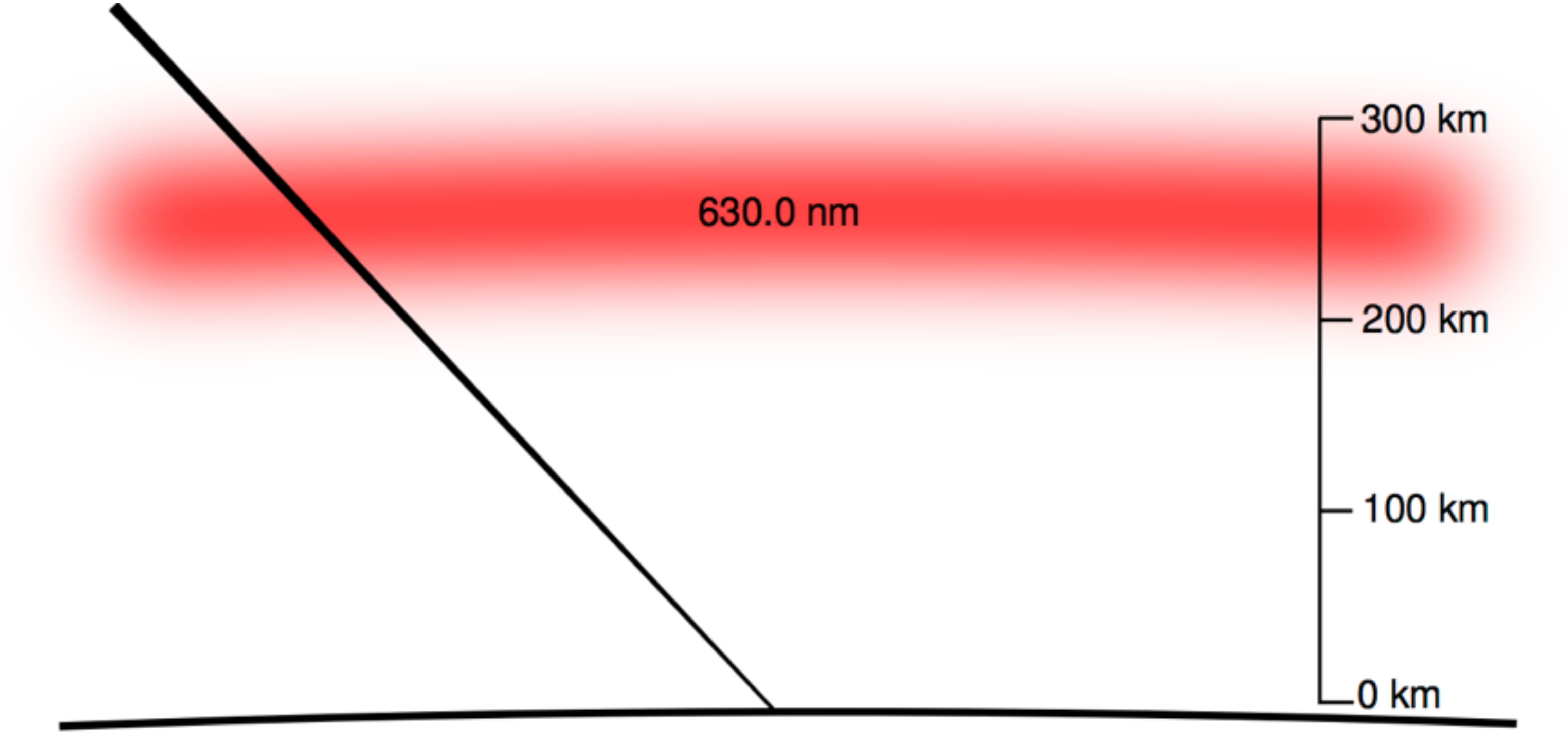
2012: NATION deployment

2013: NATION deployment

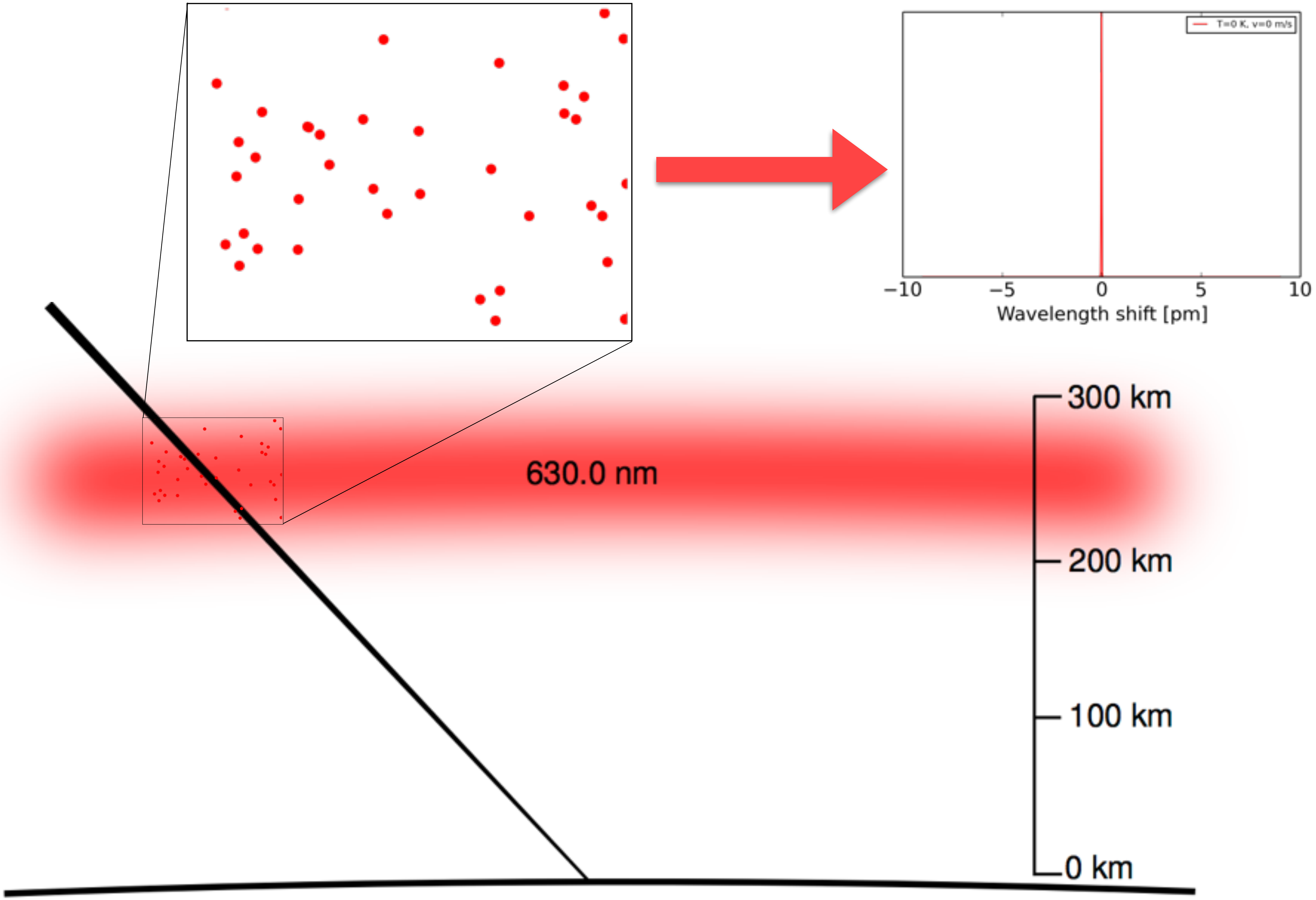
2013: Deployment to Morocco

Current deployments

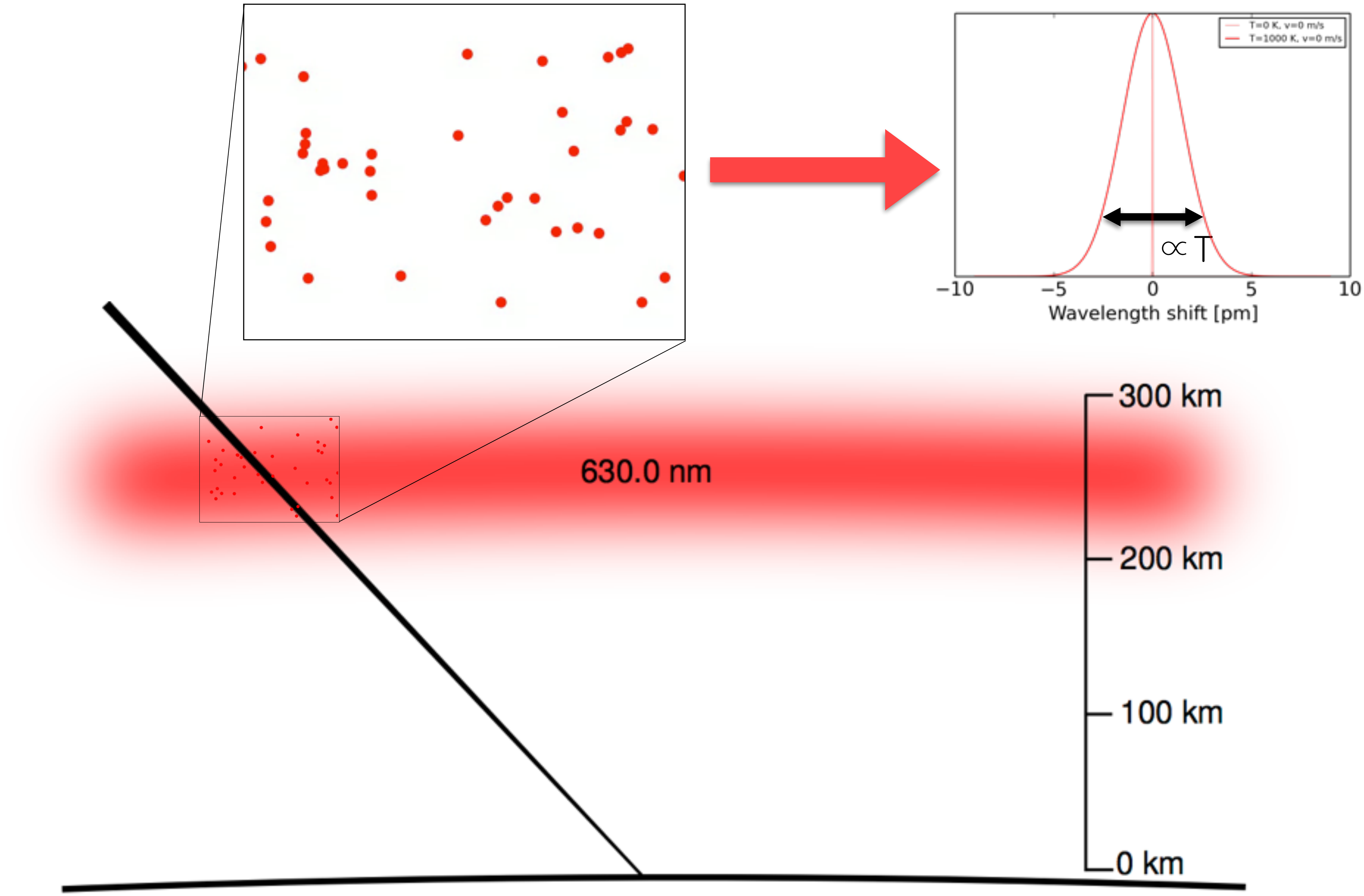
Remote sensing of thermospheric neutral winds



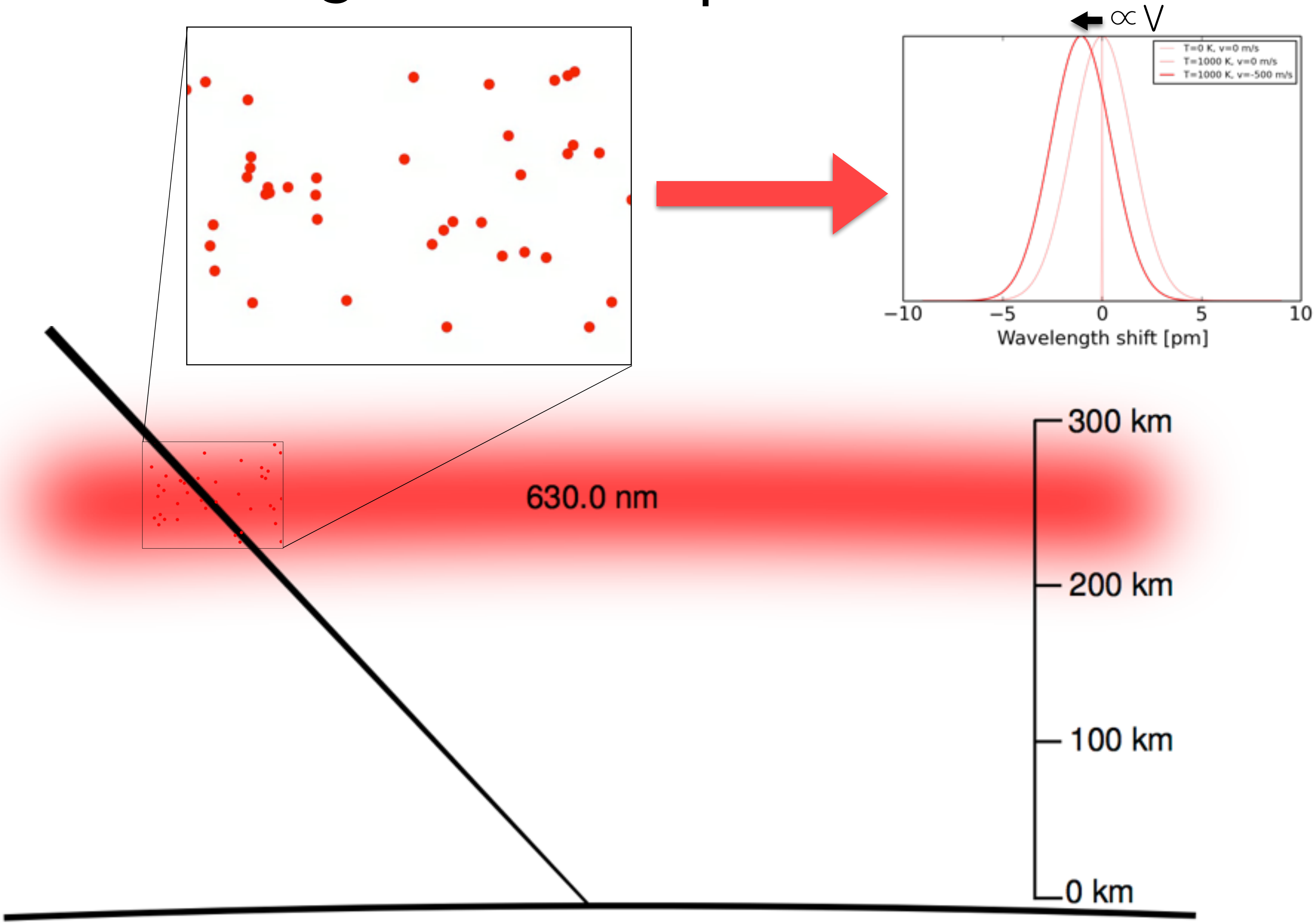
Remote sensing of thermospheric neutral winds



Remote sensing of thermospheric neutral winds

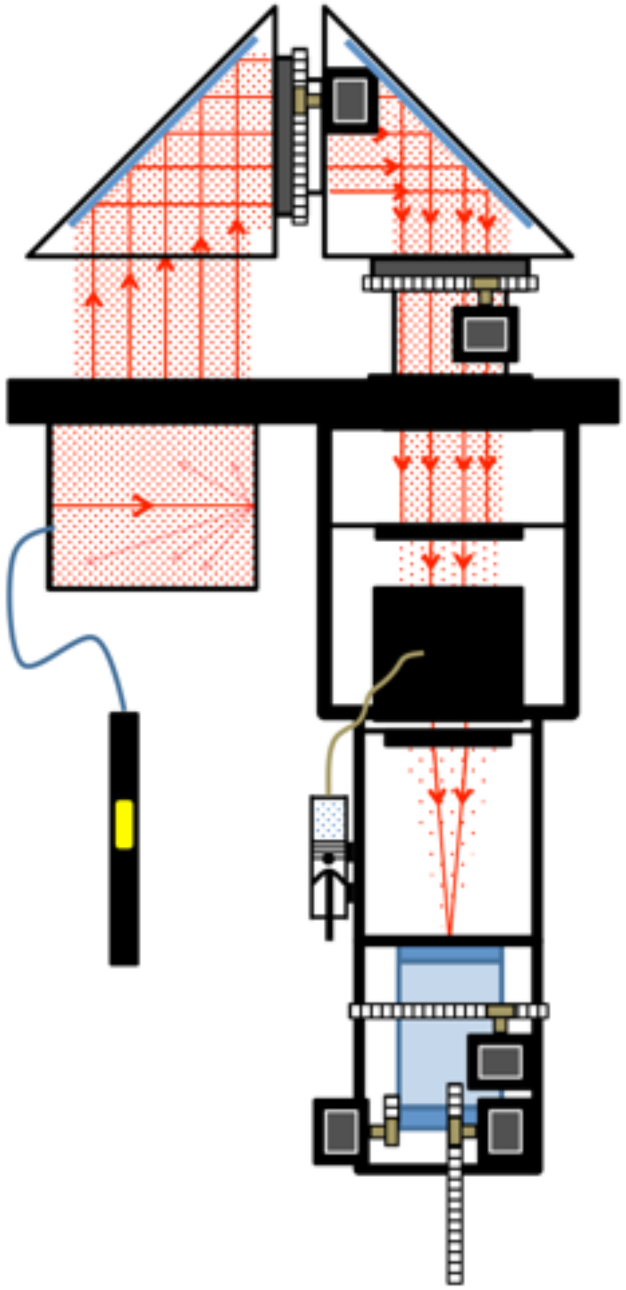


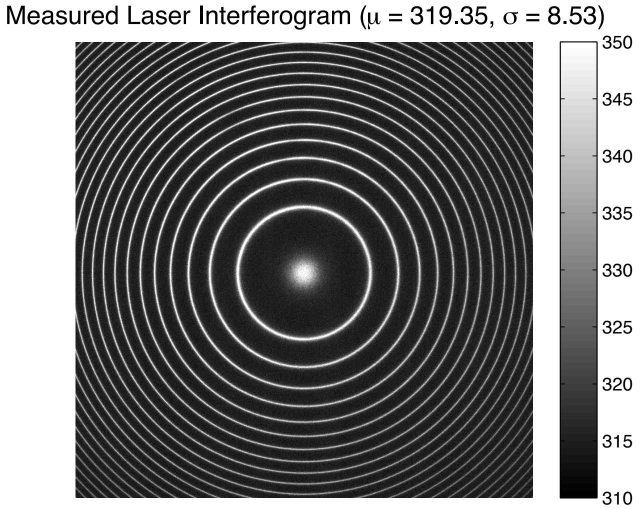
Remote sensing of thermospheric neutral winds



Imaging FPIs

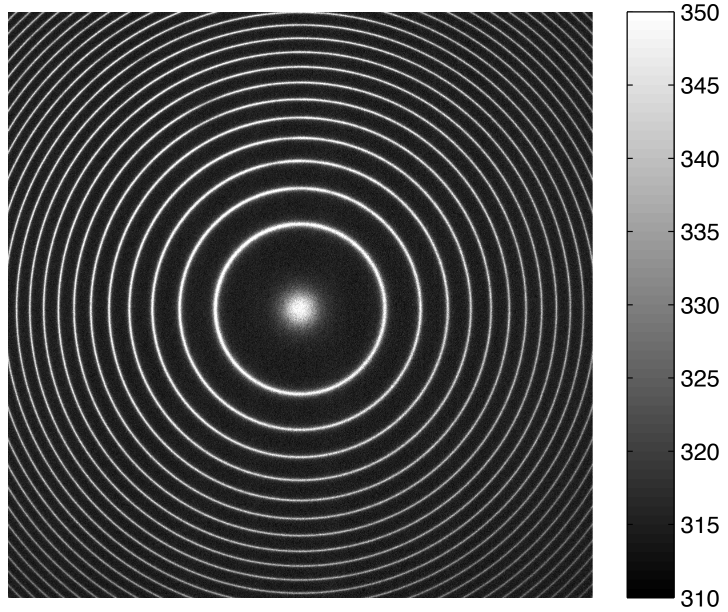
- Redesigned FPI initiated by Meriwether **reduced** the etalon aperture of the system to make the instrument smaller
    - Compensated by **increasing** the instrument's field-of-view allowing additional orders of the interference pattern to be imaged by a CCD
    - Imaging fringe pattern removed need to pressure scan the etalon
    - Increased SNR allowing for shorter integrations while maintaining small uncertainties (5 m/s; 20 K)
- A dual-mirror sky scanning system allows the instrument to look in arbitrary directions
- A frequency-stabilized HeNe laser allows monitoring of the instrument function and its stability

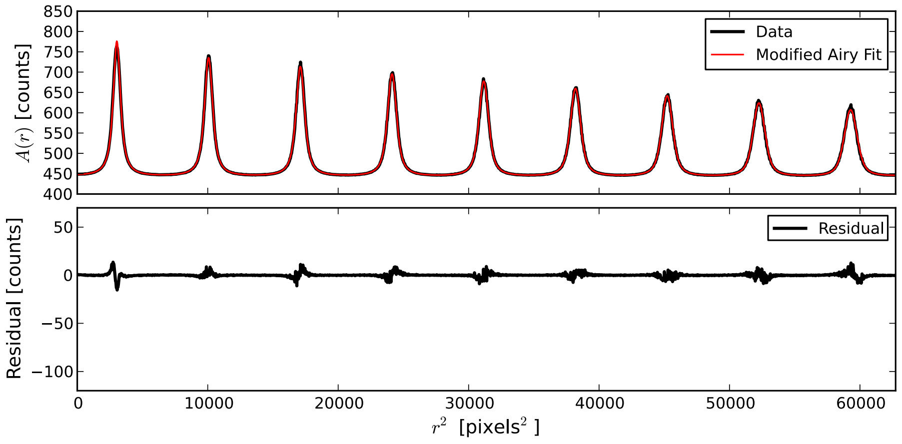




Analysis

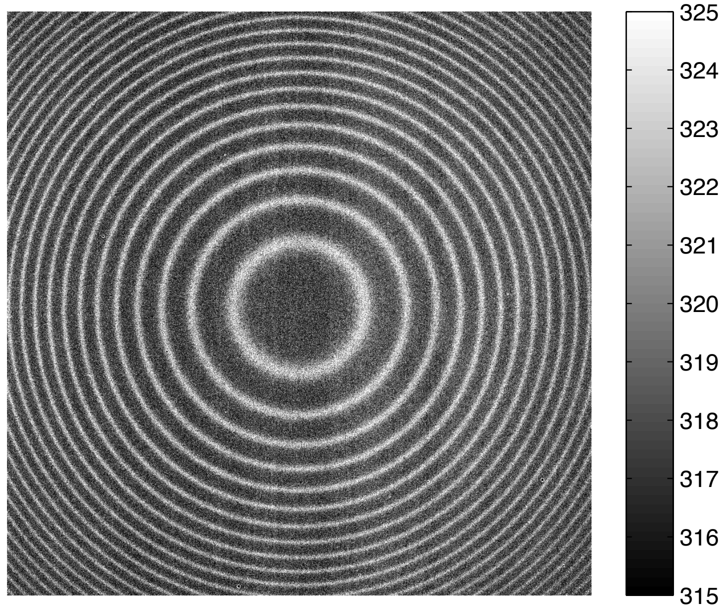
Measured Laser Interferogram (μ = 319.35, σ = 8.53)

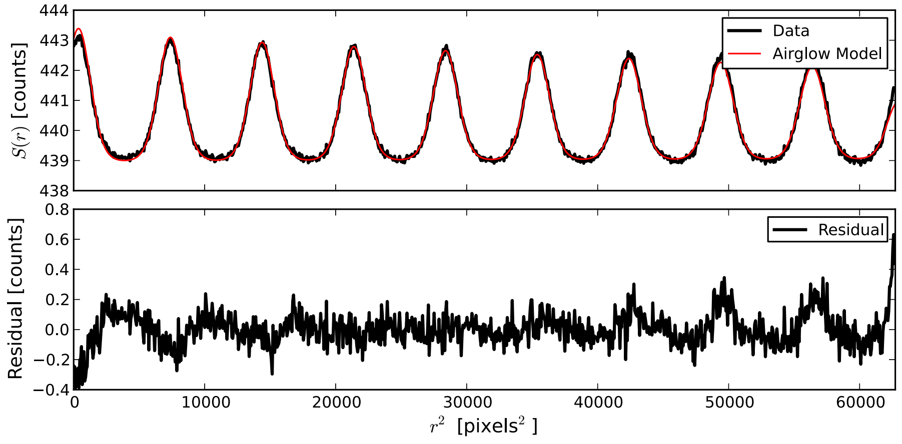




- Images of frequency-stabilized HeNe laser provides estimate of the FPI instrument function
    - Levenberg-Marquardt method used to estimate reflectivity, gap separation, laser wavelength, and optical defects

Measured Emission Interferogram (μ = 319.22, σ = 2.51)





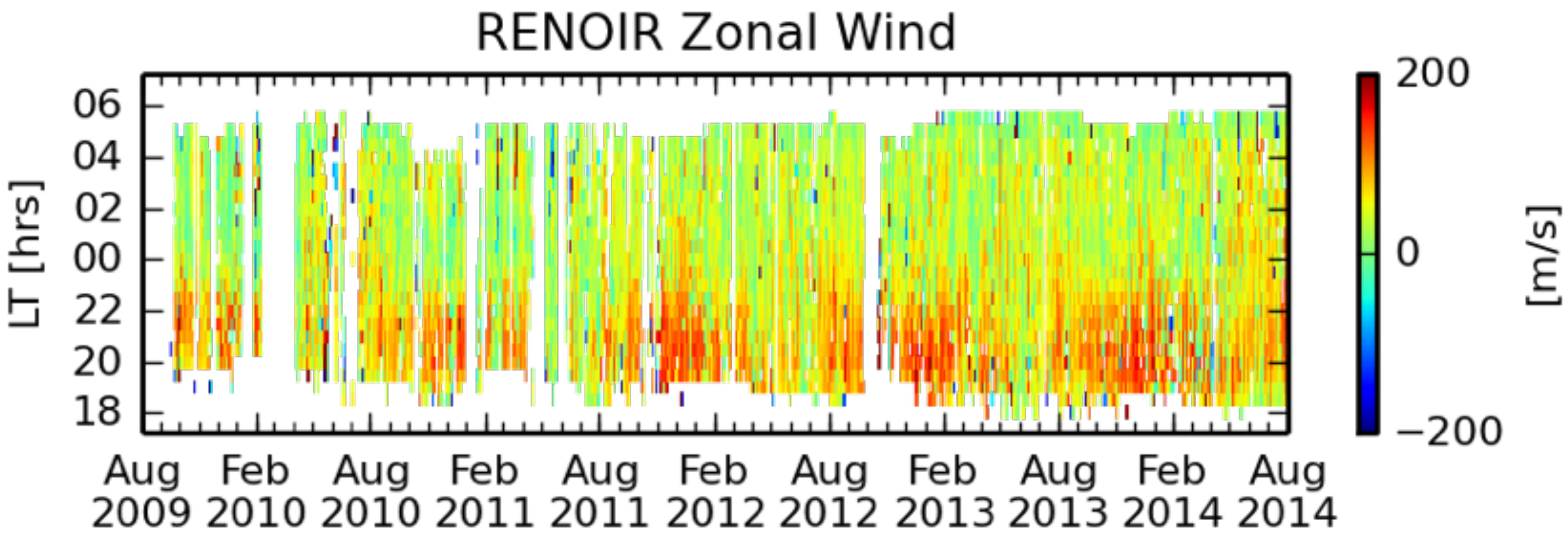
- Sky images are analyzed using instrument parameters derived from laser observations
    - Levenberg-Marquardt method used to estimate Doppler shift (winds) and broadening (temperature) effects

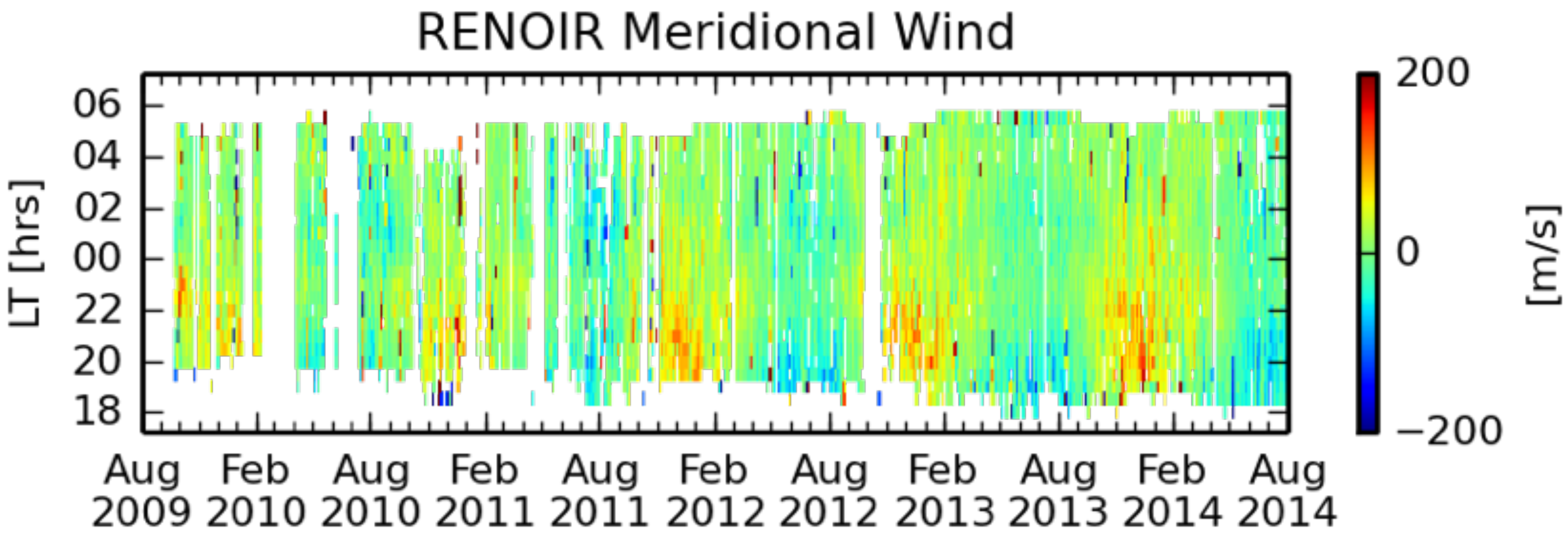
Details in Harding, B. J. , T. W. Gehrels, and J. J. Makela (2014), Nonlinear regression method for estimating neutral wind and temperature from Fabry–Perot interferometer data, *Appl. Opt.*, 53(4), 666, doi:10.1364/AO.53.000666.

Motivations for an FPI network

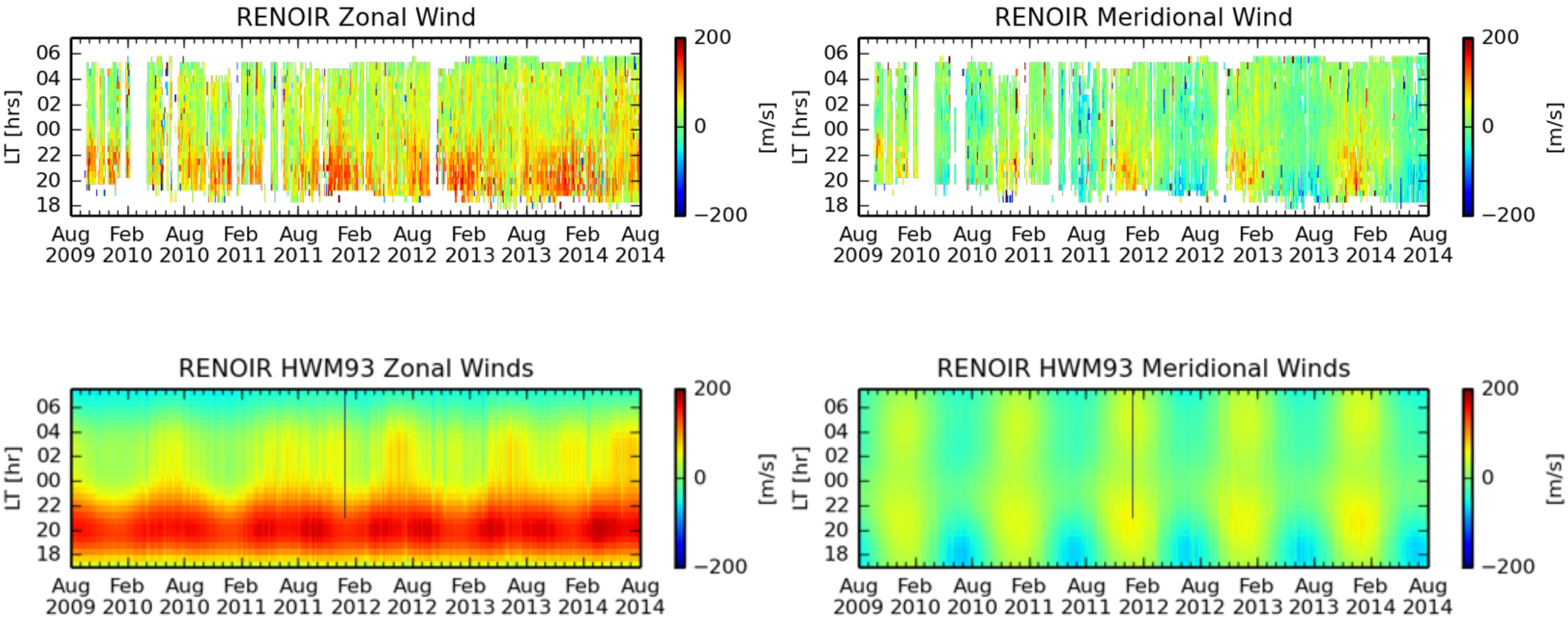
- Characterization of the base state of thermospheric dynamics
    - Indications that climatological models did not correctly specify thermospheric neutral winds
    - Need to validate first-principles models
- Understand thermosphere-ionosphere coupling at low-latitudes
    - Neutral winds play a role in the development of ionospheric irregularities
    - Study the F-region dynamo in detail through simultaneous observations of plasma drift velocity and neutral winds
- Study spatial-temporal dynamics using multi-site observations
    - Need a larger field-of-view to unravel spatial-temporal dynamics
- Understand the mid-latitude thermospheric response to geomagnetic disturbances

Long-term measurements

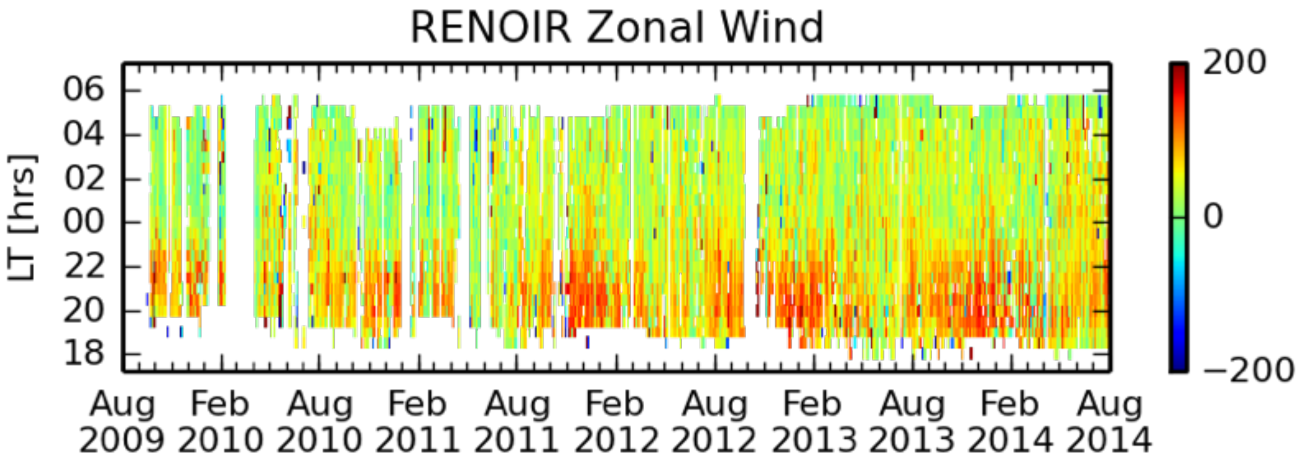

RENOIR Zonal Wind

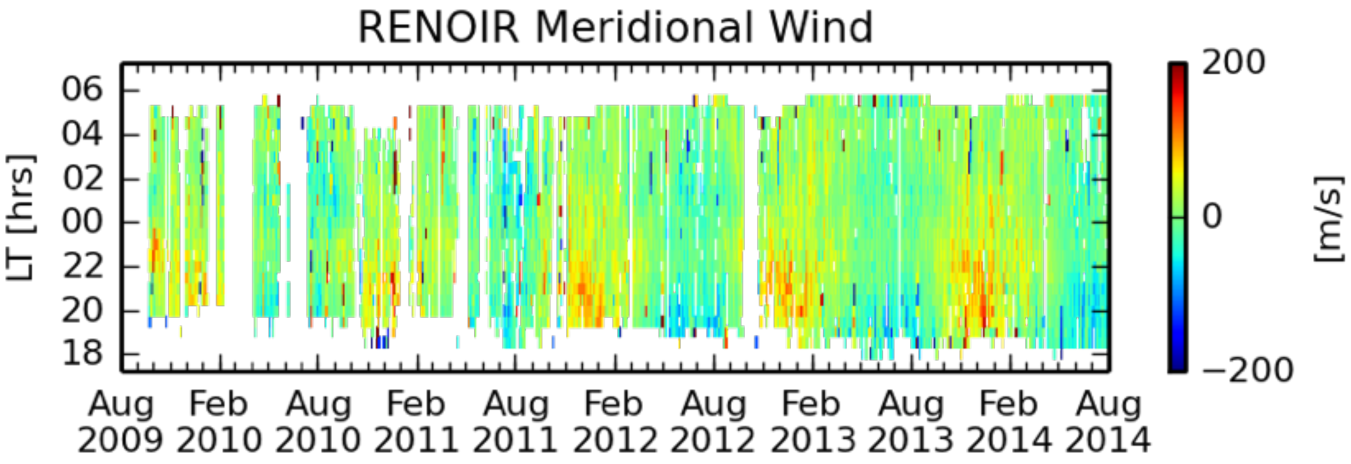

RENOIR Meridional Wind

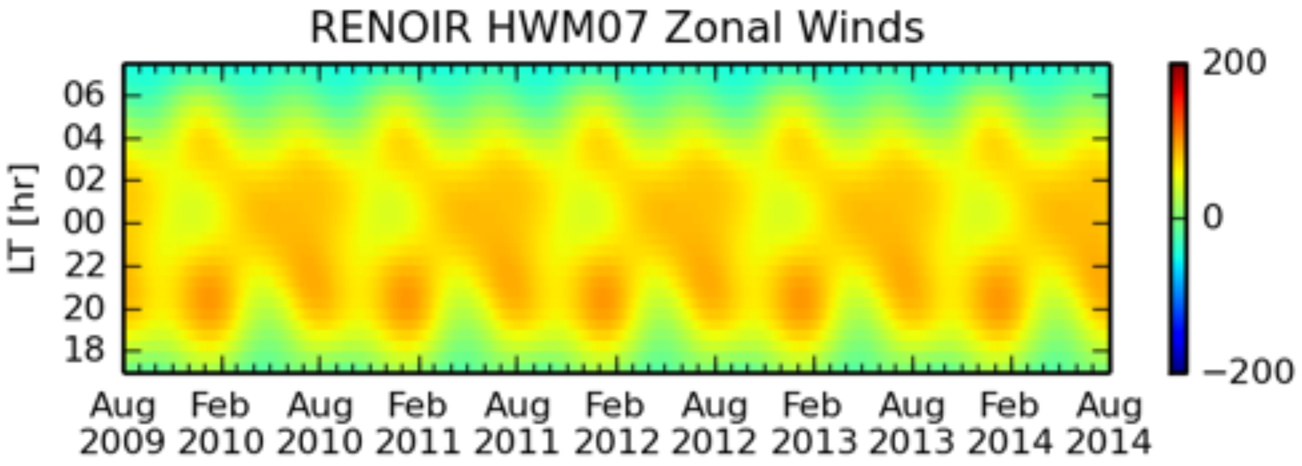
HWM93 validation (Brazil)

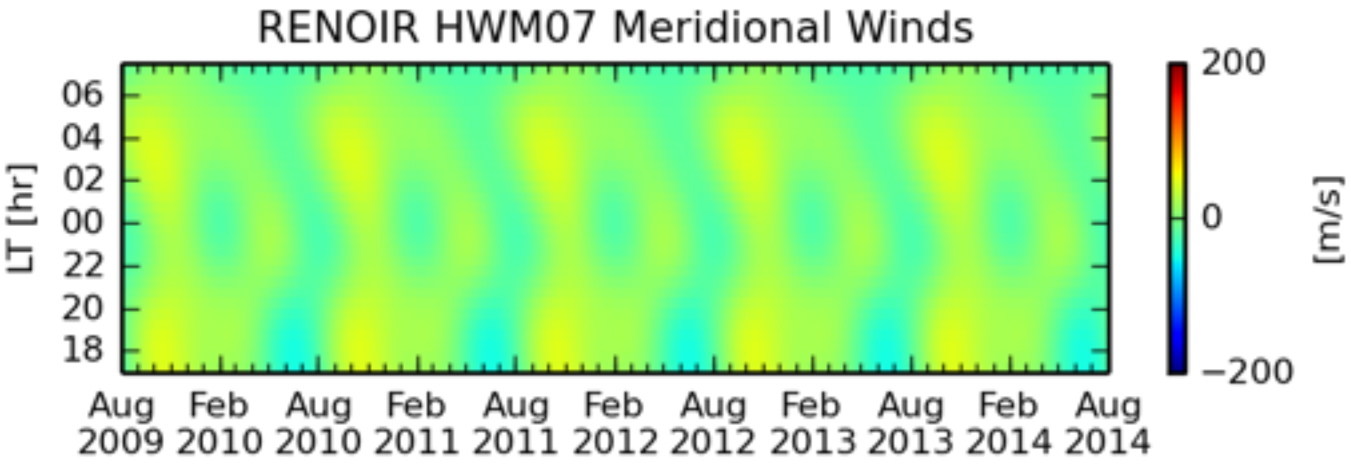


HWM07 validation (Brazil)

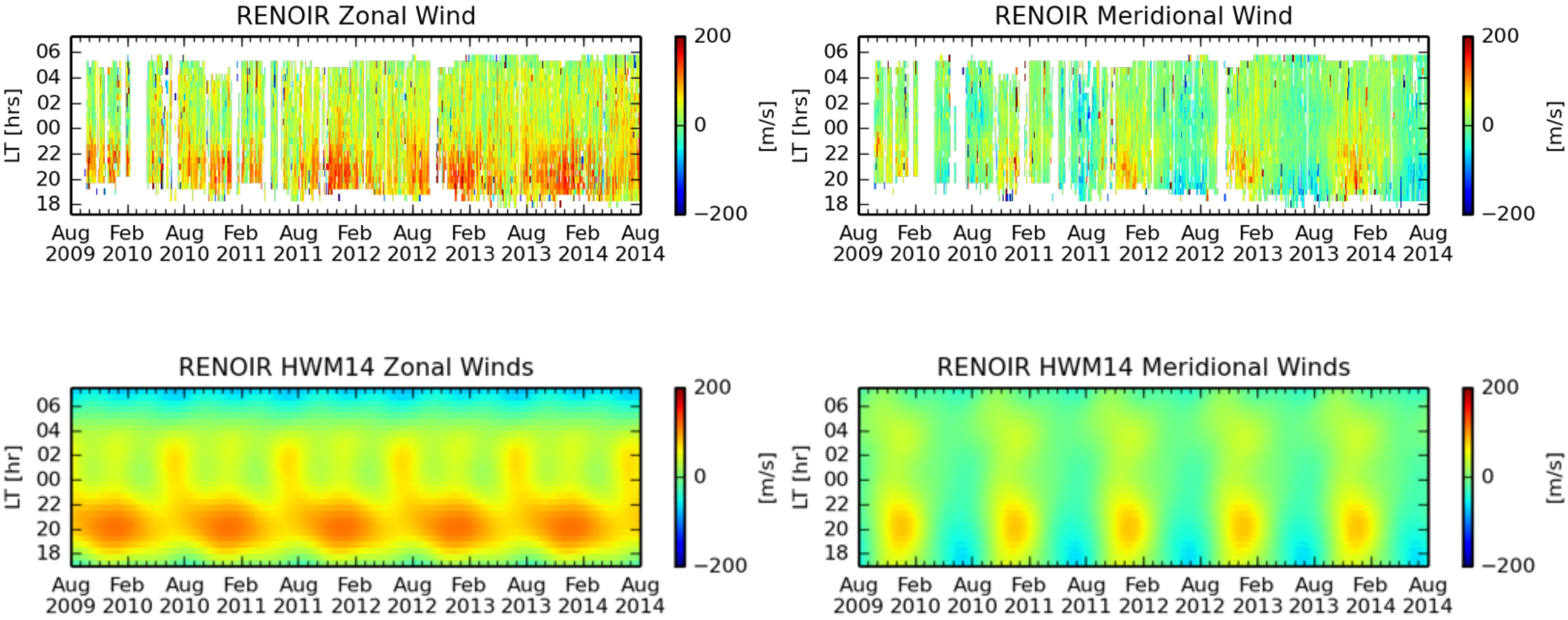




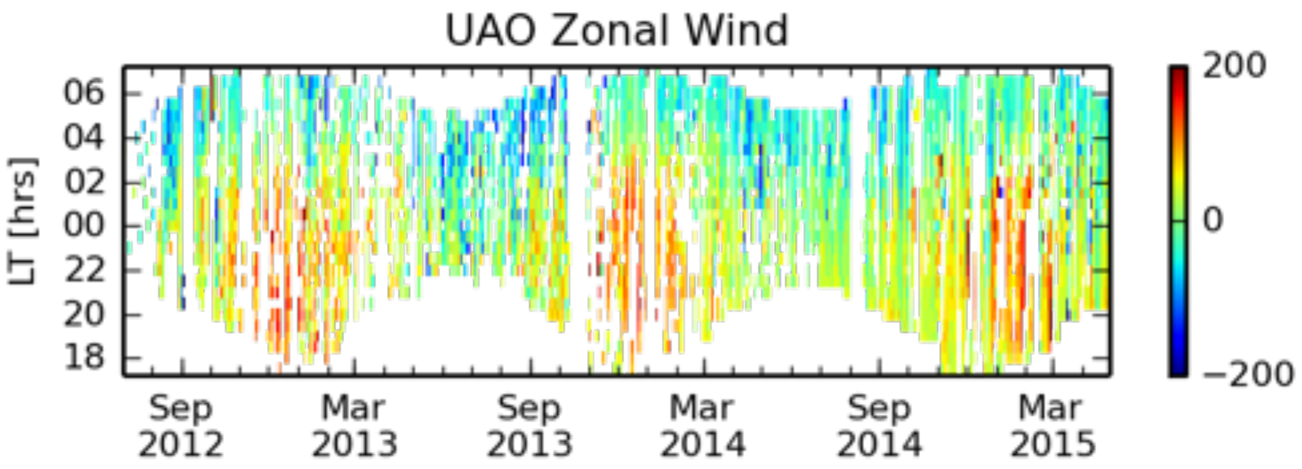


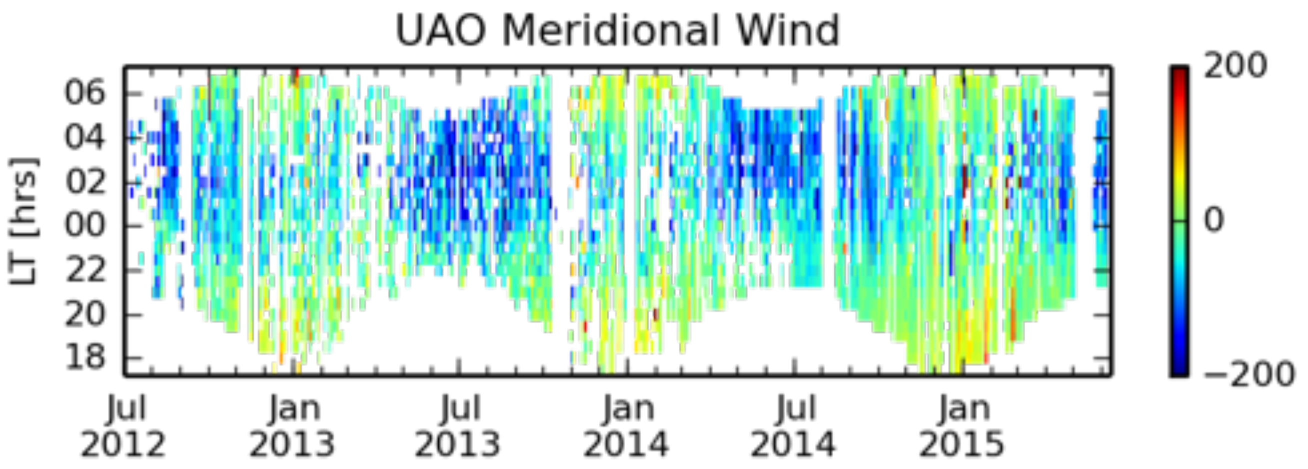


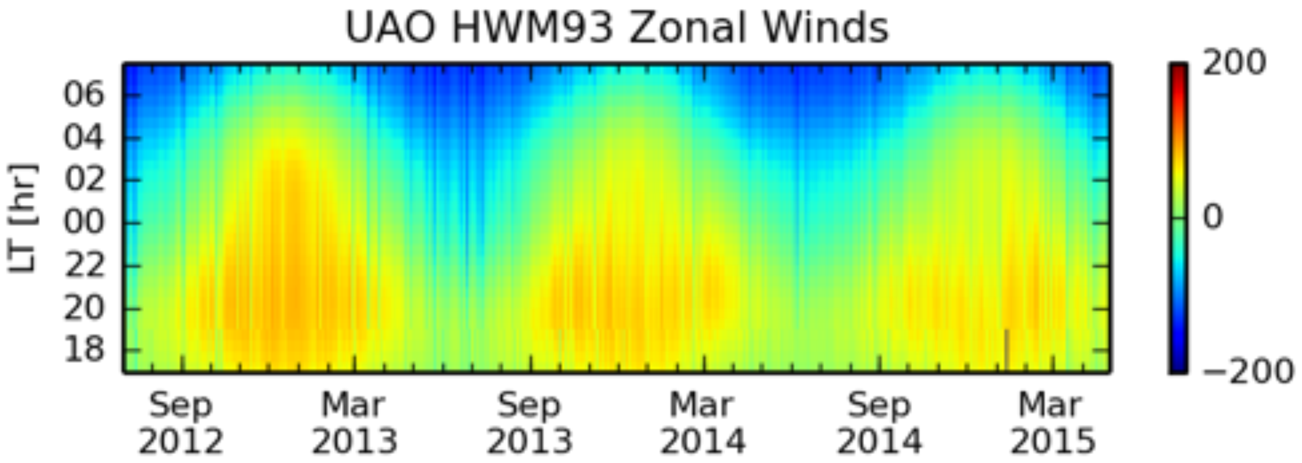
HWM14 validation (Brazil)

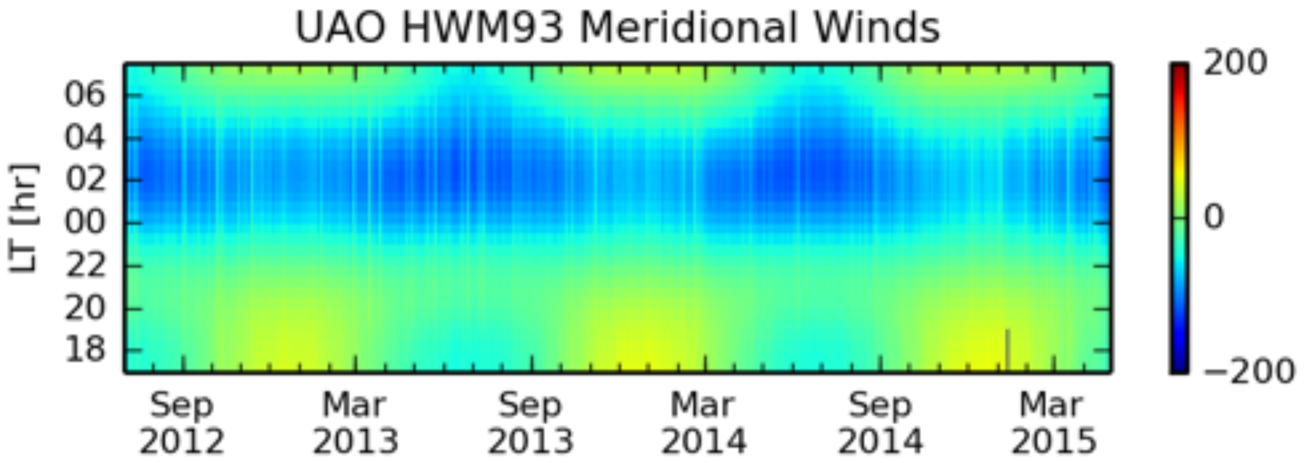


HWM93 validation (Illinois)

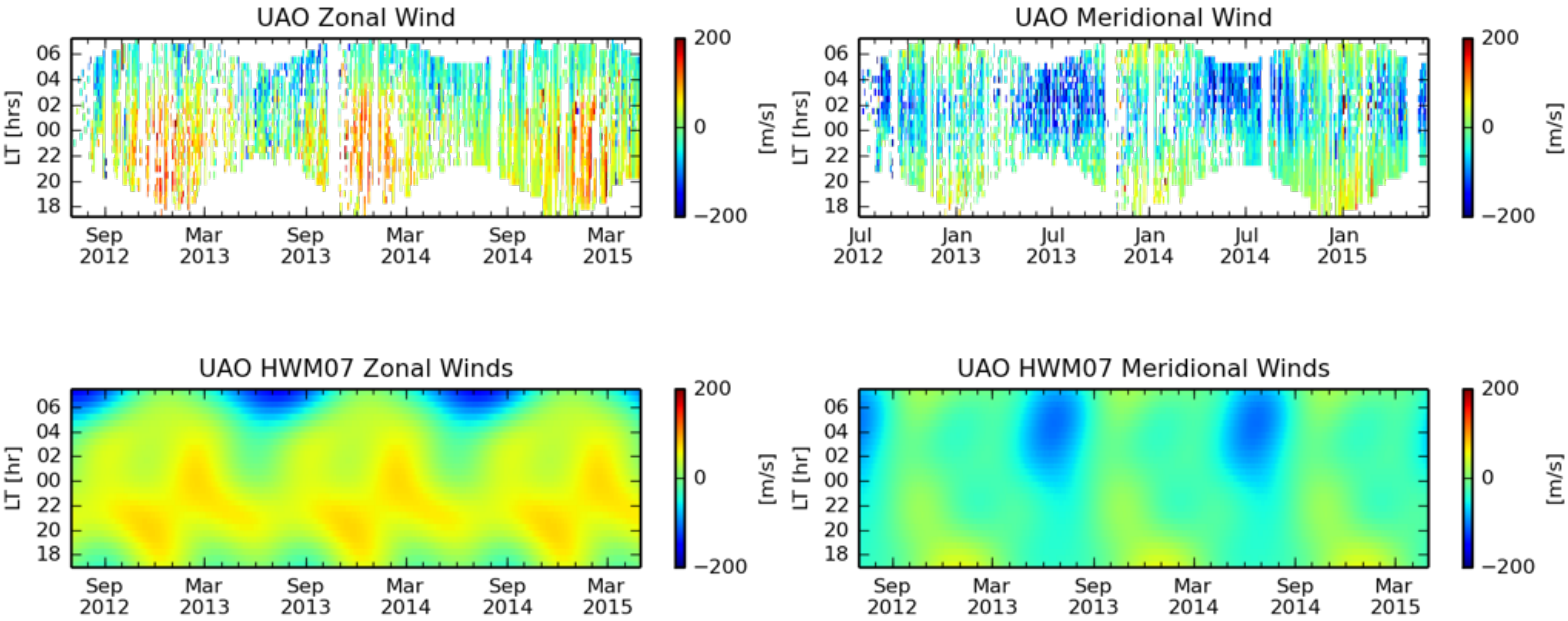




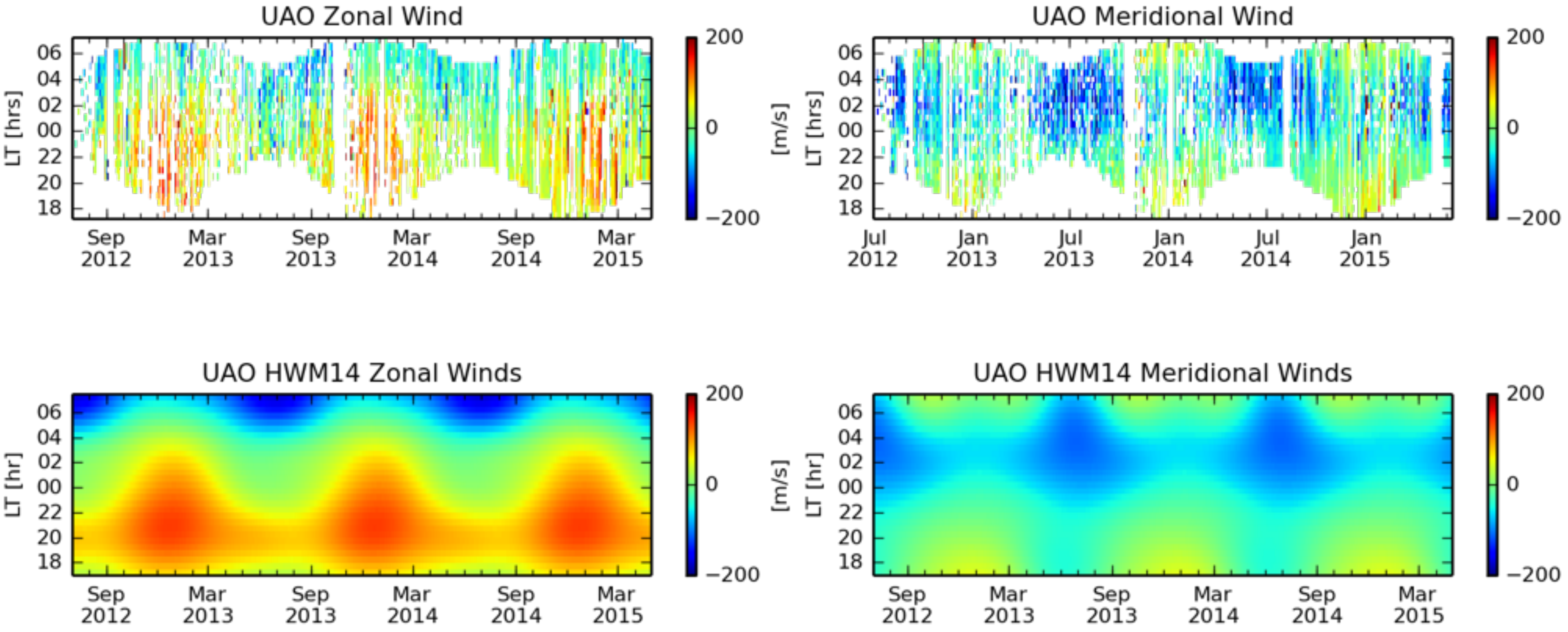




HWM07 validation (Illinois)



HWM14 validation (Illinois)

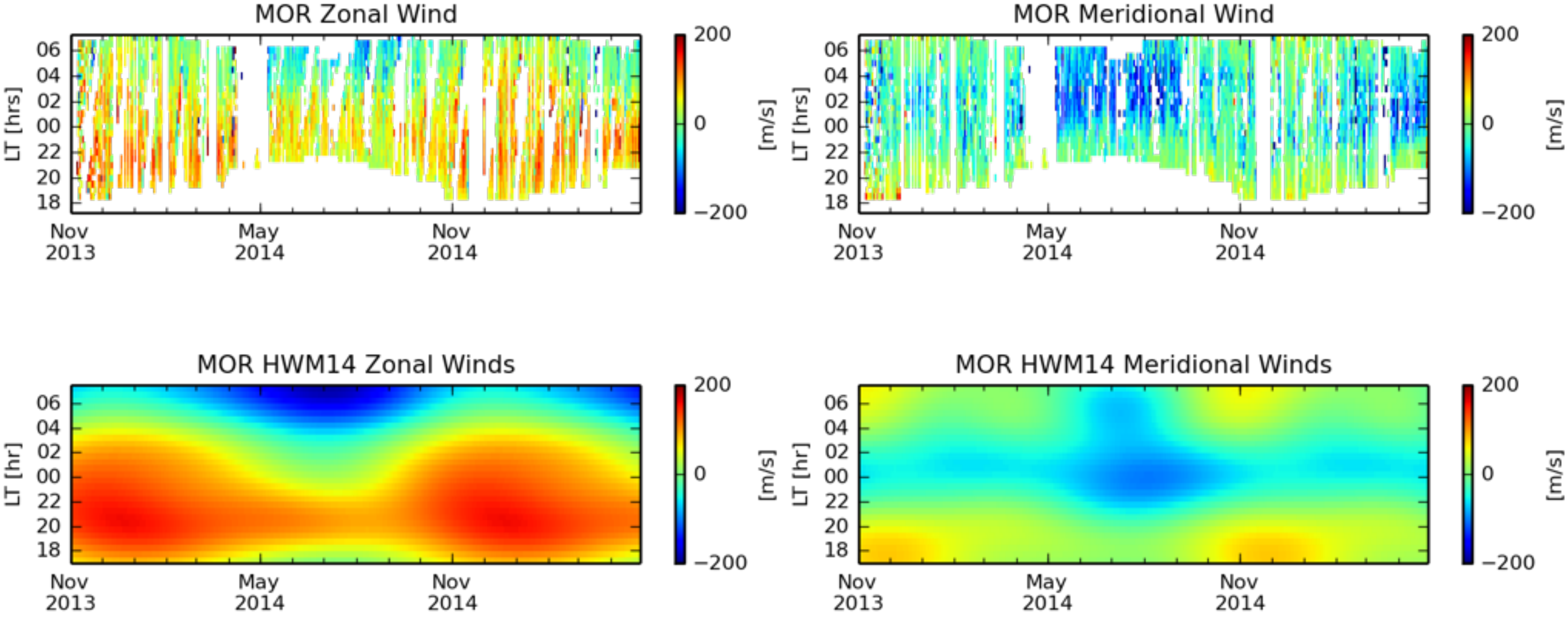

UAO Zonal Wind

UAO Meridional Wind

UAO HWM14 Zonal Winds

UAO HWM14 Meridional Winds

HWM14 validation (Morocco)

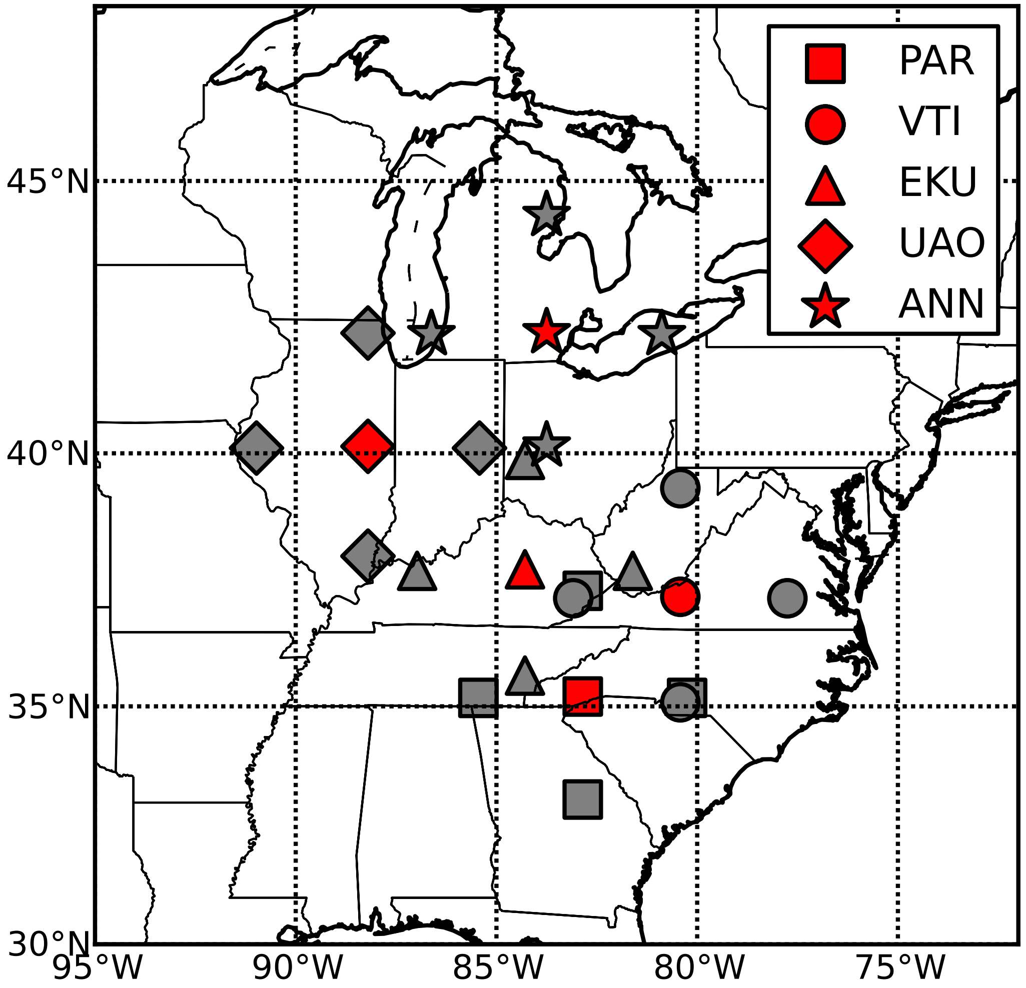


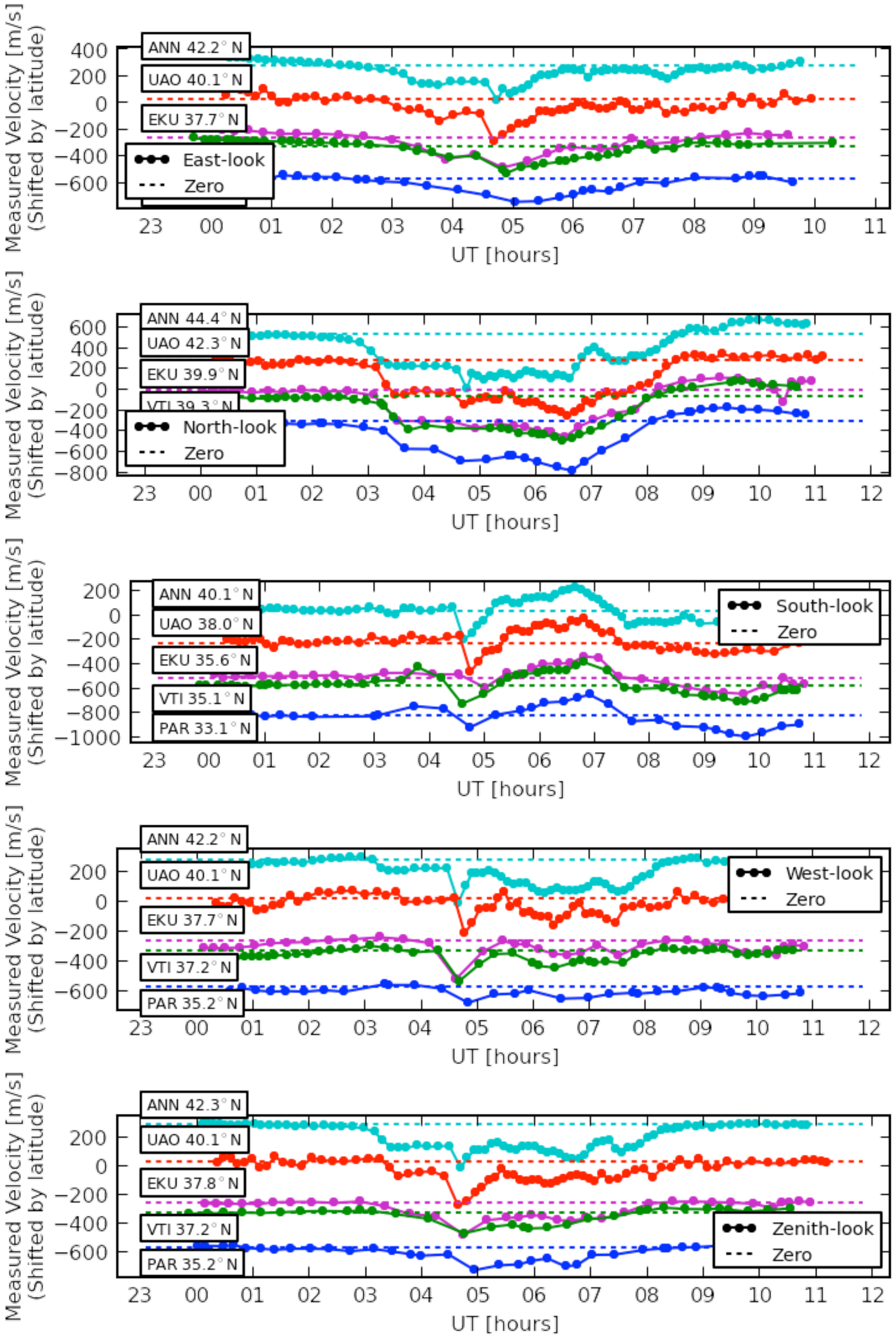
Motivations for an FPI network

- Characterization of the base state of thermospheric dynamics
  - Indications that climatological models did not correctly specify thermospheric neutral winds
  - Need to validate first-principles models
- Understand thermosphere-ionosphere coupling at low-latitudes
  - Neutral winds play a role in the development of ionospheric irregularities
  - Study the F-region dynamo in detail through simultaneous observations of plasma drift velocity and neutral winds
- Study spatial-temporal dynamics using multi-site observations
  - Need a larger field-of-view to unravel spatial-temporal dynamics
- Understand the mid-latitude thermospheric response to geomagnetic disturbances

Data interpretation

- Wealth of data can make interpretation difficult
  - Measurement is actually projection of a vector quantity onto a line-of-sight
  - We are interested in the vector quantity!


NATION Observing Geometry

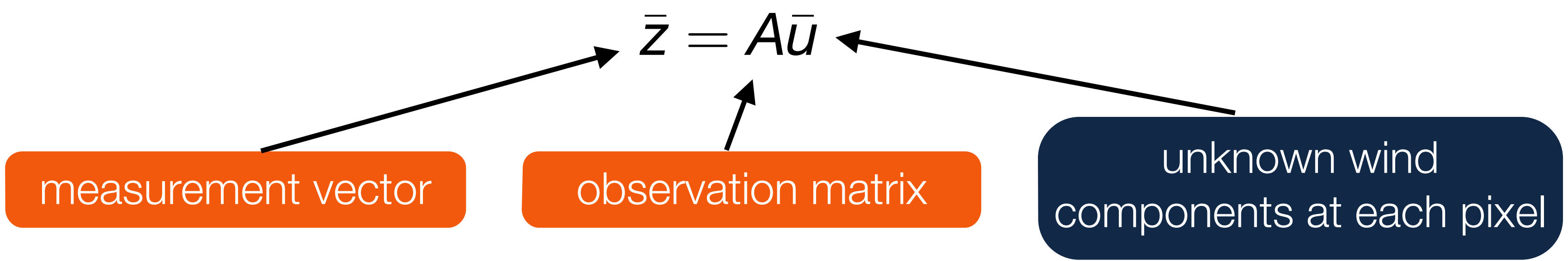


Regional wind field estimation

- Projection of wind vector (*u*, *v*, *w*) onto line of sight:

$$z_i = u_i \sin\theta \cos\phi + v_i \sin\theta \sin\phi + w_i \cos\theta$$

- Stack all observations into a single matrix equation:



$$\bar{z} = A\bar{u}$$

measurement vector

observation matrix

unknown wind components at each pixel

- At least two challenges:
  - *A* is sparse and (severely) underdetermined
  - Measurements are noisy
- Assume field is smooth and regularize

minimize $\|G\bar{u}\|_2^2 + \lambda_1 \|C\bar{u}\|_2^2$

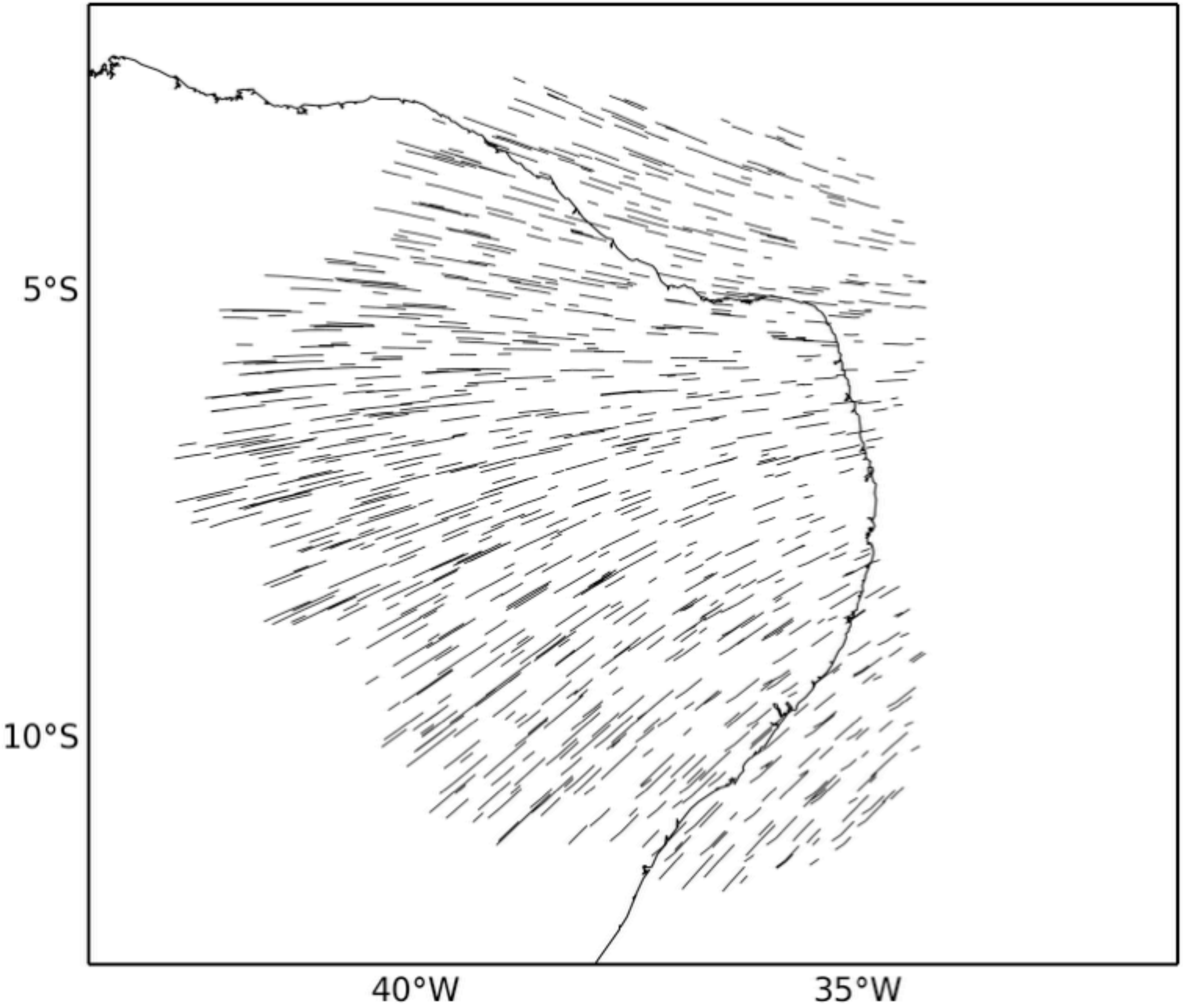
such that $\|\Sigma^{-\frac{1}{2}} \left(A\bar{u} - \bar{z}\right)\|_2^2 \leq \varepsilon$

$$\bar{u}^* = \left[A^T\Sigma^{-1}A + \lambda_0 \left(G^TG + \lambda_1 C^TC\right)\right]^{-1} A^T\Sigma^{-1}\bar{z}$$

C	second derivatives of wind vector components
G	first derivatives of wind vector
Σ	measurement covariance matrix
λ0	regularization parameter
λ1	tuning (balance) parameter

Details in Harding, B. J., J. J. Makela, and J. W. Meriwether (2015), Estimation of mesoscale thermospheric wind structure using a network of interferometers, *J. Geophys. Res. Space Physics*, 120, doi:10.1002/2015JA021025.

2013-02-02 02:31:30 UT



Dynamics and the MTM

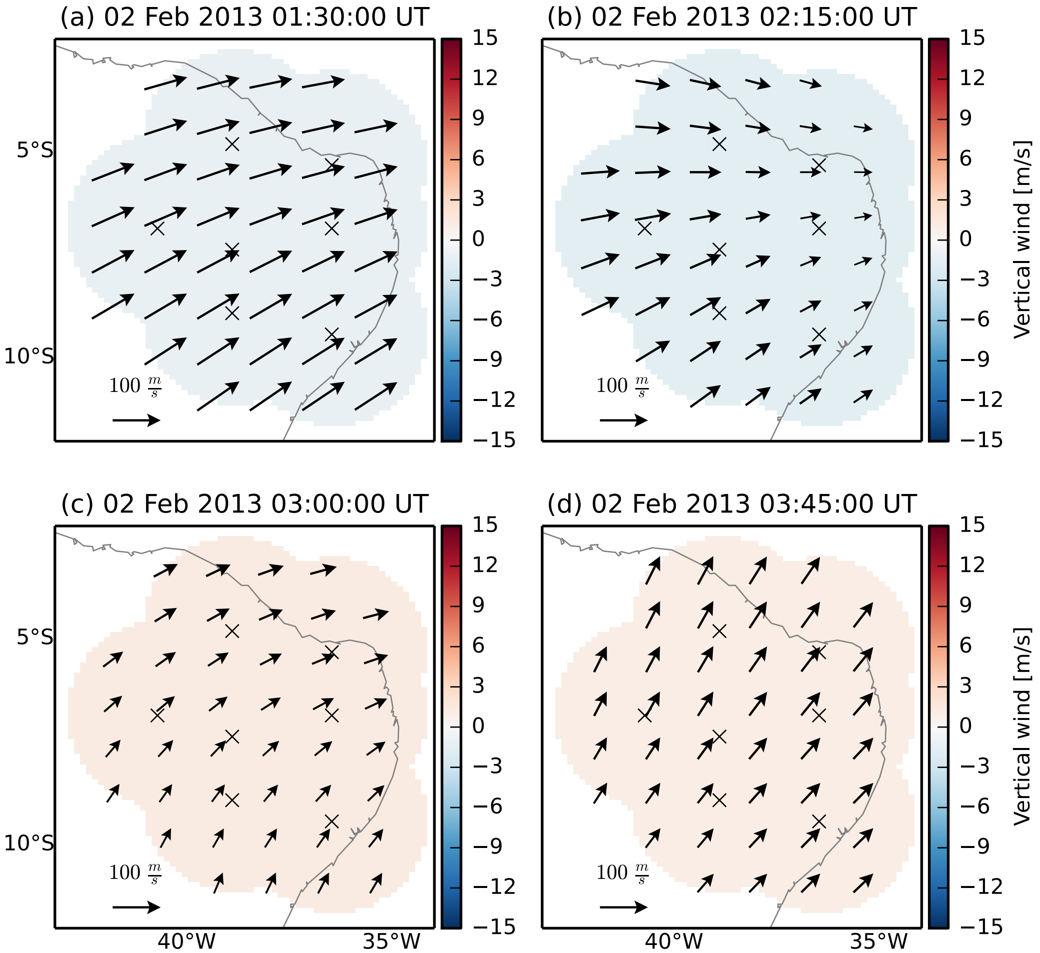
- Times of local wind convergence can be seen in estimated wind field on nights exhibiting a midnight temperature maximum (MTM)

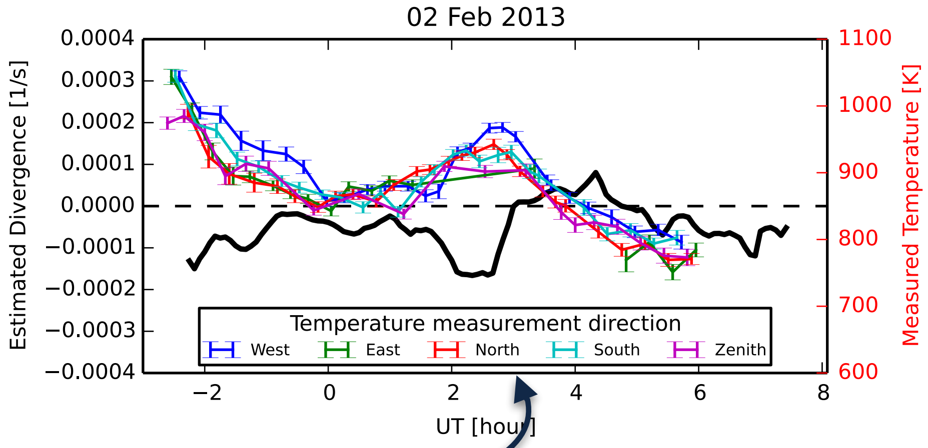
- Divergence of the wind field can be calculated:

$$\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$$

- Strong convergence of wind beginning at 0145 UT coincident with beginning of MTM

- Return to slight divergence/zero at 0245 UT coincident with temperature reduction





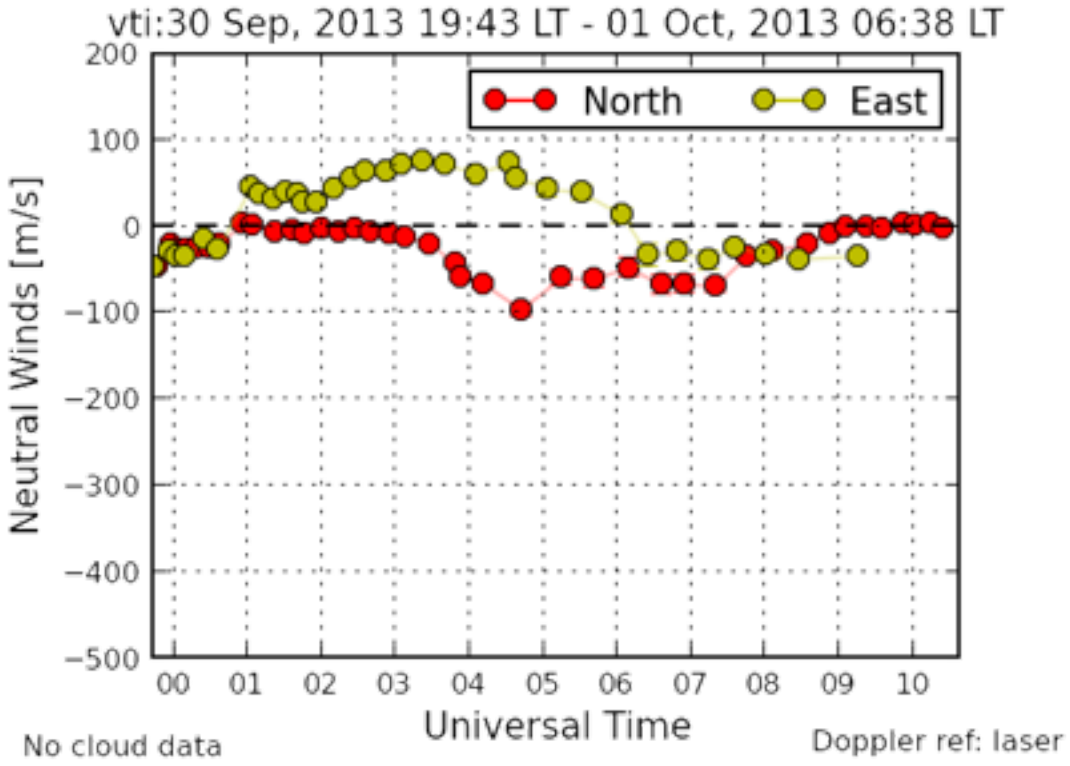
Local midnight

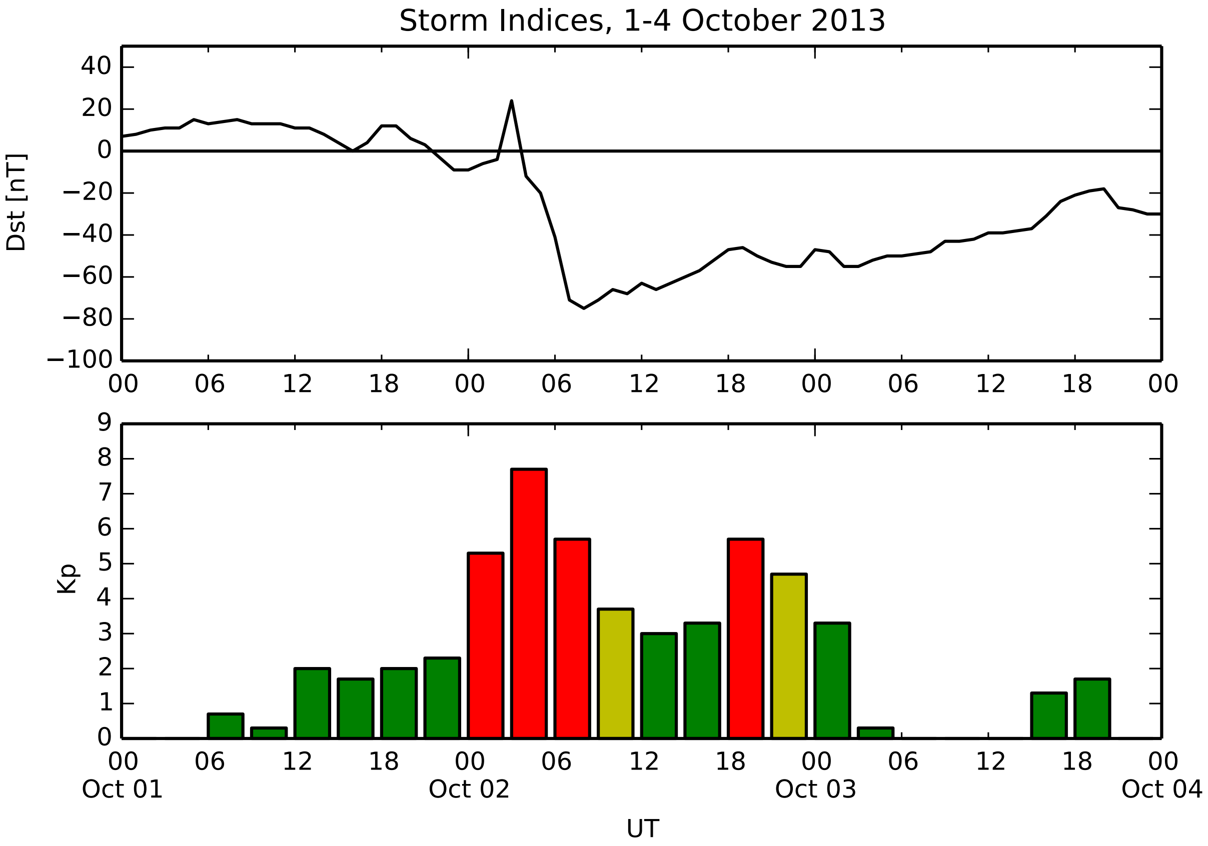
Motivations for an FPI network

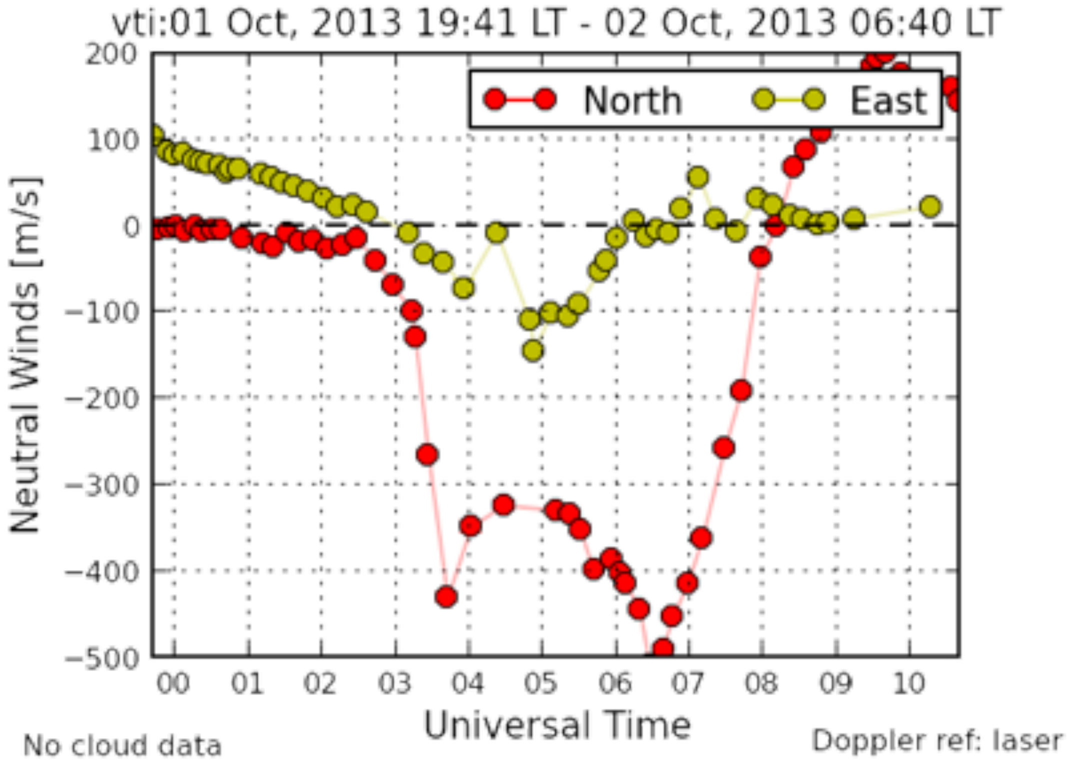
- Characterization of the base state of thermospheric dynamics
    - Indications that climatological models did not correctly specify thermospheric neutral winds
    - Need to validate first-principles models
- Understand thermosphere-ionosphere coupling at low-latitudes
    - Neutral winds play a role in the development of ionospheric irregularities
    - Study the F-region dynamo in detail through simultaneous observations of plasma drift velocity and neutral winds
- Study spatial-temporal dynamics using multi-site observations
    - Need a larger field-of-view to unravel spatial-temporal dynamics
- Understand the mid-latitude thermospheric response to geomagnetic disturbances

Stormtime thermospheric dynamics

- Distributed measurements allow us to study the response of the thermosphere to storms
- Storm time thermospheric flows consistently show significant equatorward winds (400 m/s) and a reversal of the zonal winds towards the west





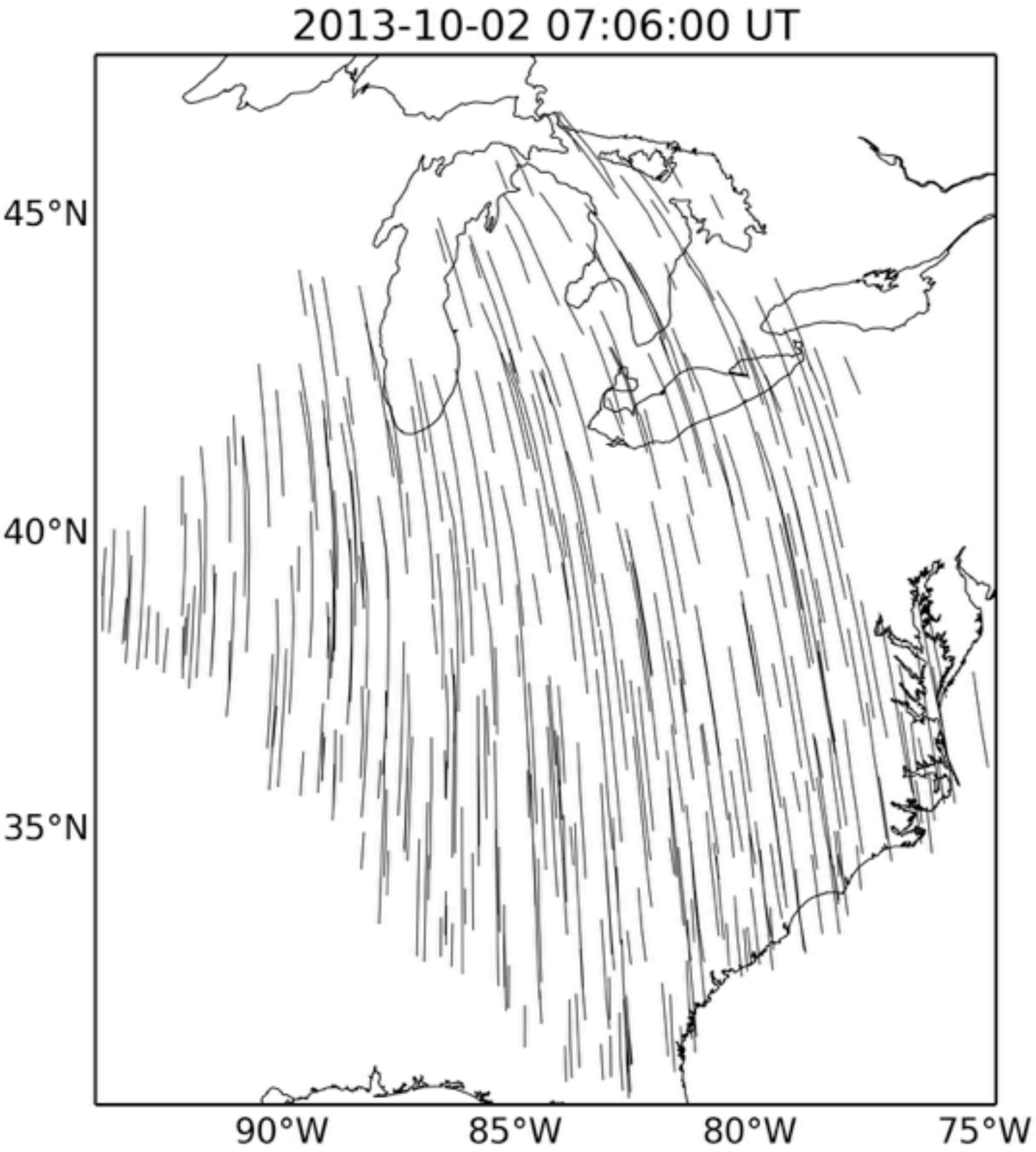


Stormtime wind field

- Using the mapping strategy, the horizontal wind field can be reconstructed

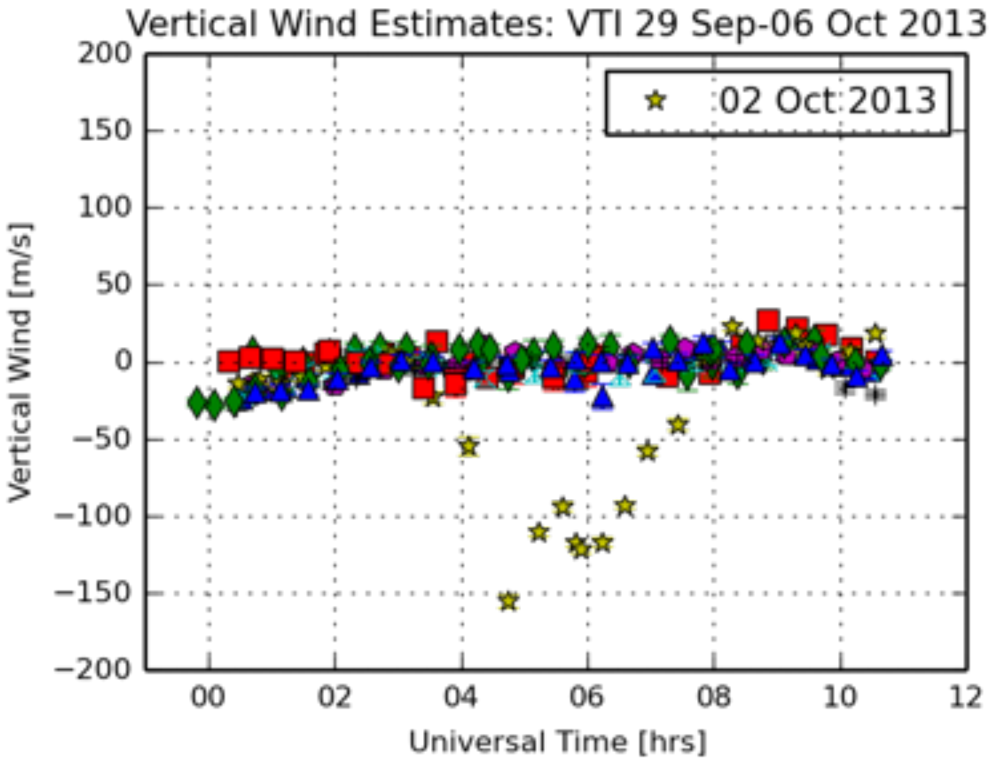
  - The "typical" equatorward surge is seen to begin around 03 UT

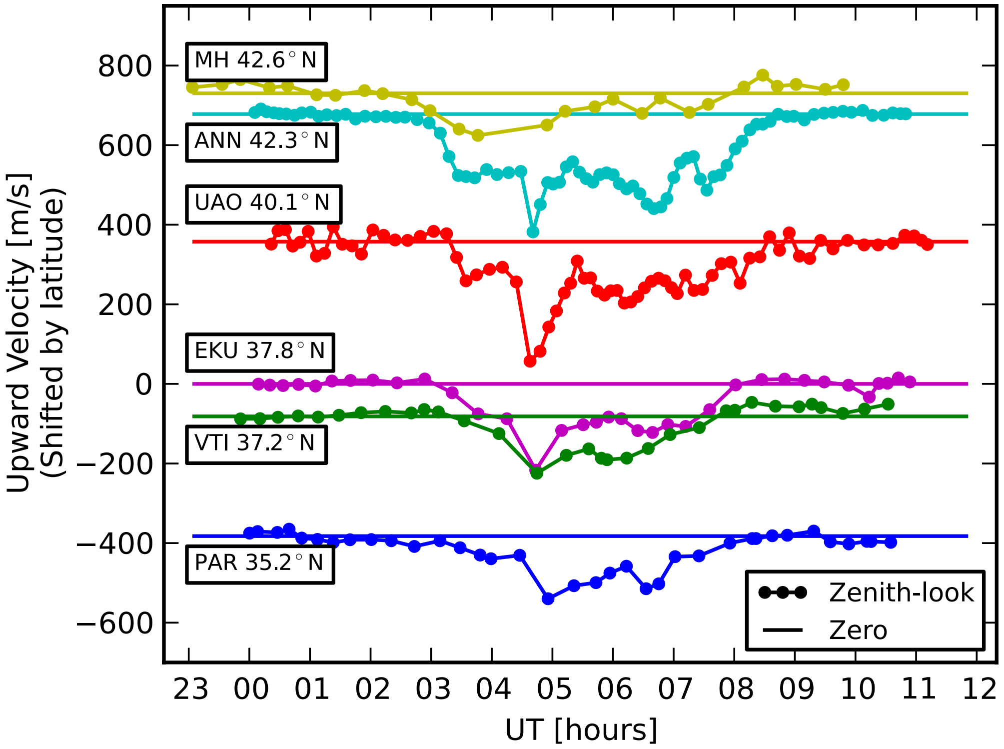
  - It reverses from 08-09 UT (south to north)



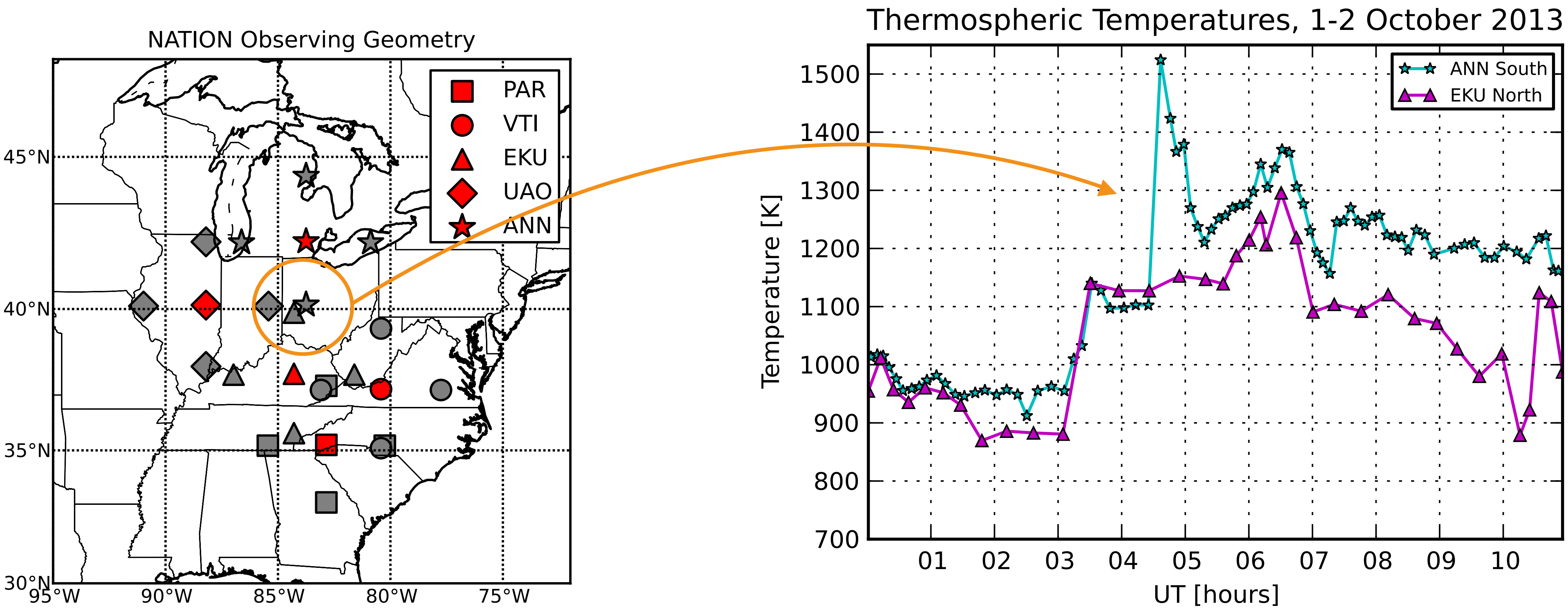
The network advantage

- NATION FPIs use a frequency stabilized laser to monitor the instrument stability
  - Allows for estimation of the vertical neutral wind using zenith measurements
  - Clear departure from zero vertical wind seen on 02 October 2013
- Use of multiple, independent instruments gives confidence that the perturbation seen on the storm day is not instrumental



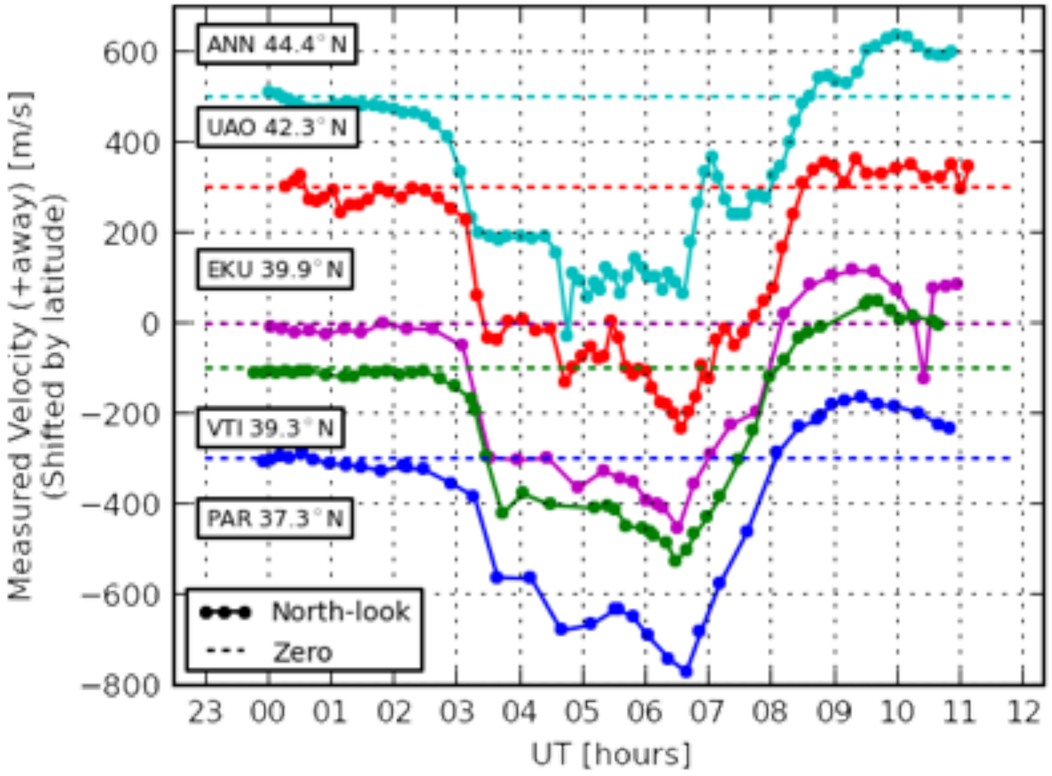


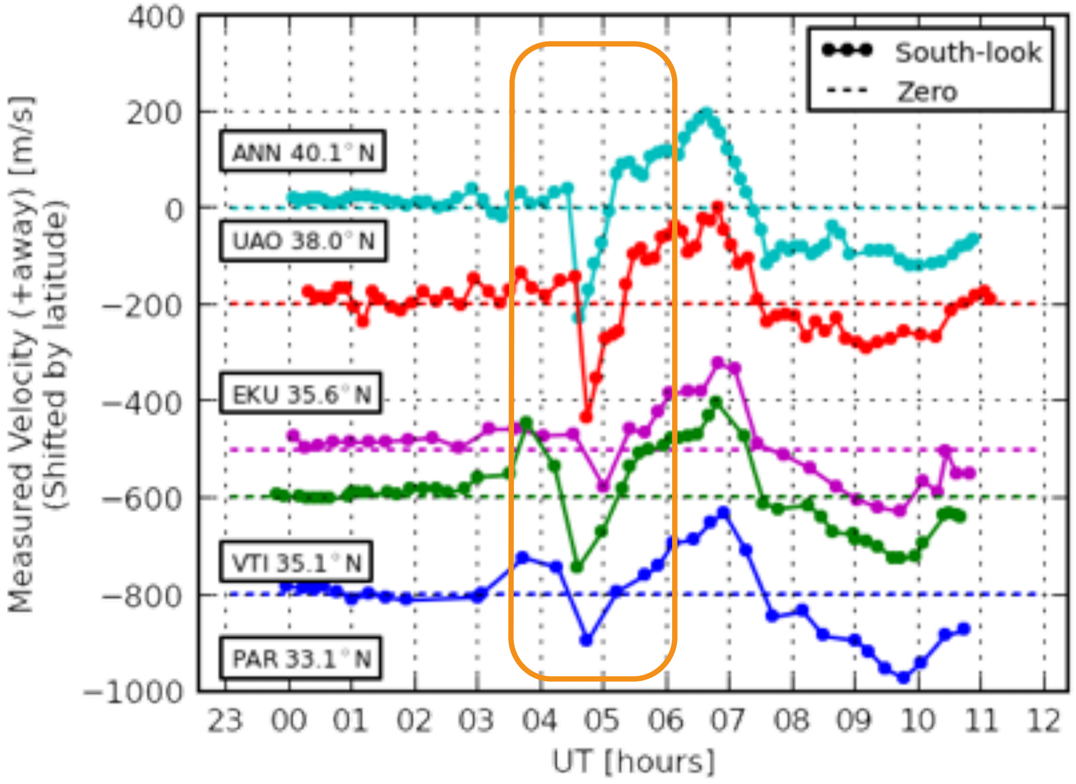
Temperature discrepancies



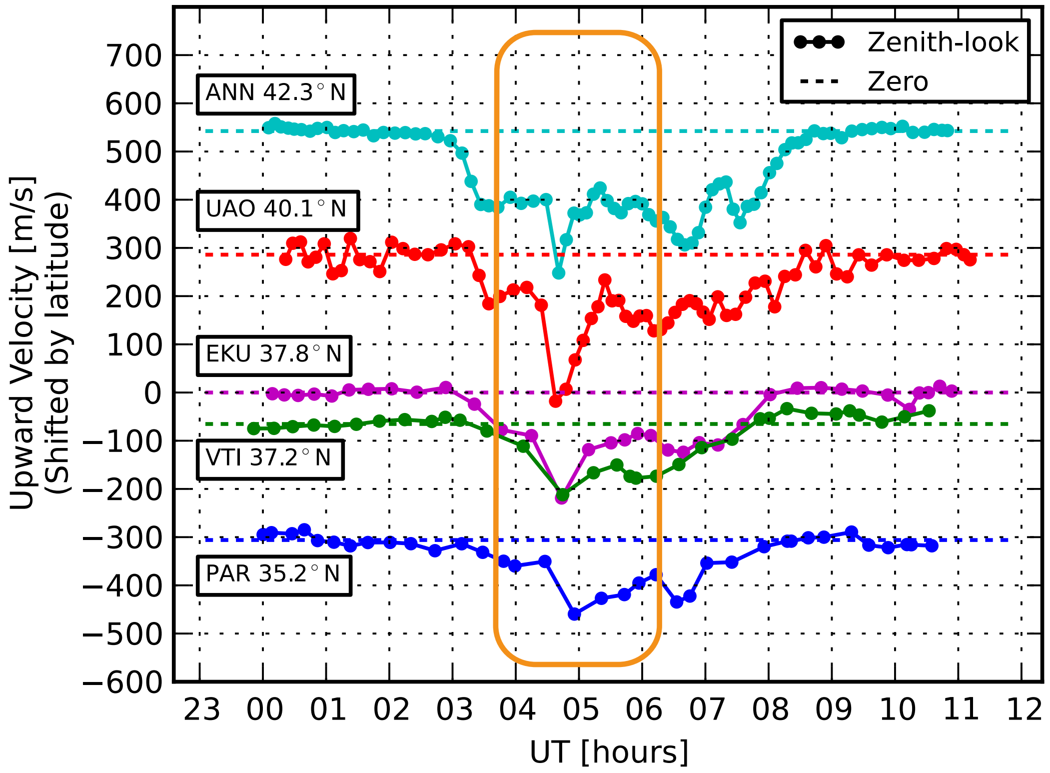
- Temperatures measured in the same thermospheric volume along the magnetic field (ANN South) and perpendicular to the magnetic field (EKU North) are different
  - Typically (during non-storm conditions), differences are quite small (<20 K)

Wind discrepancies

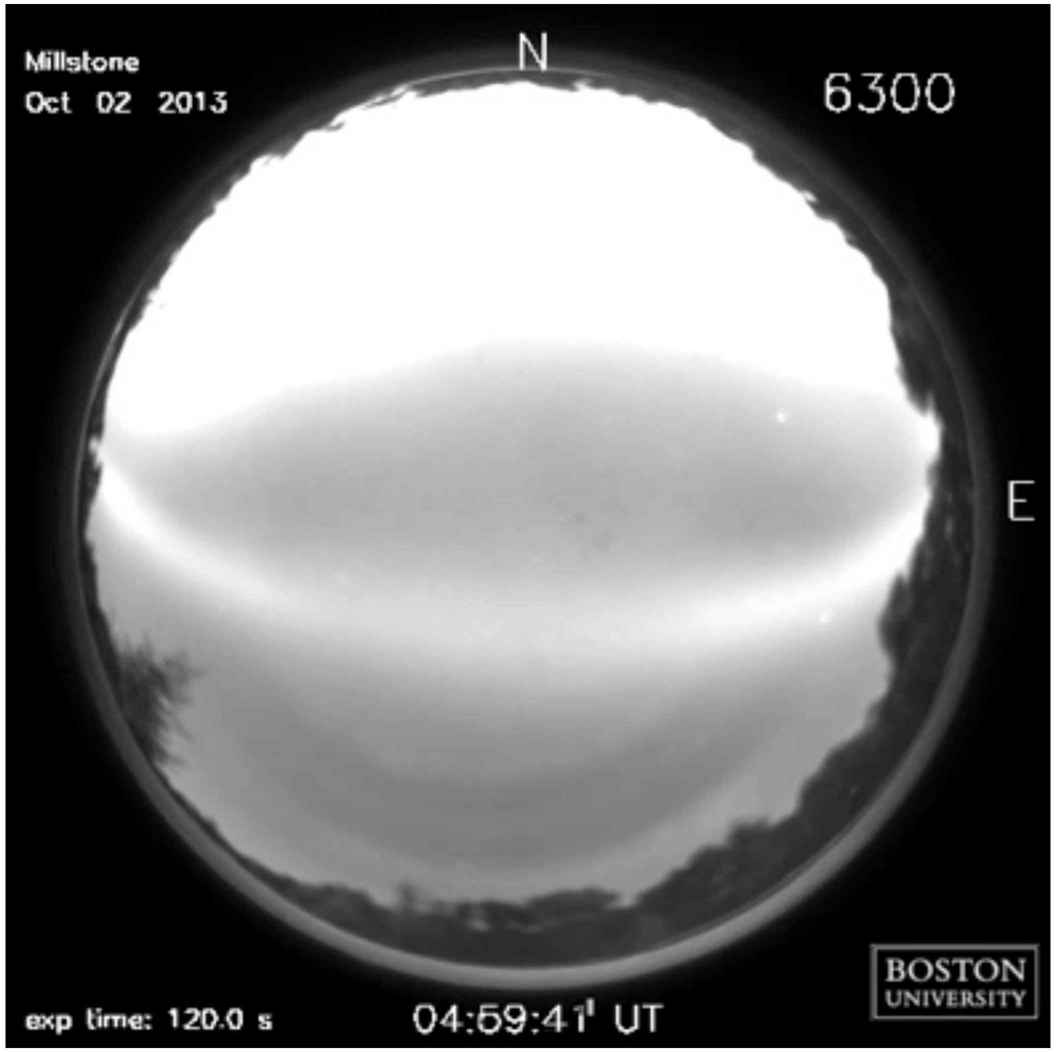


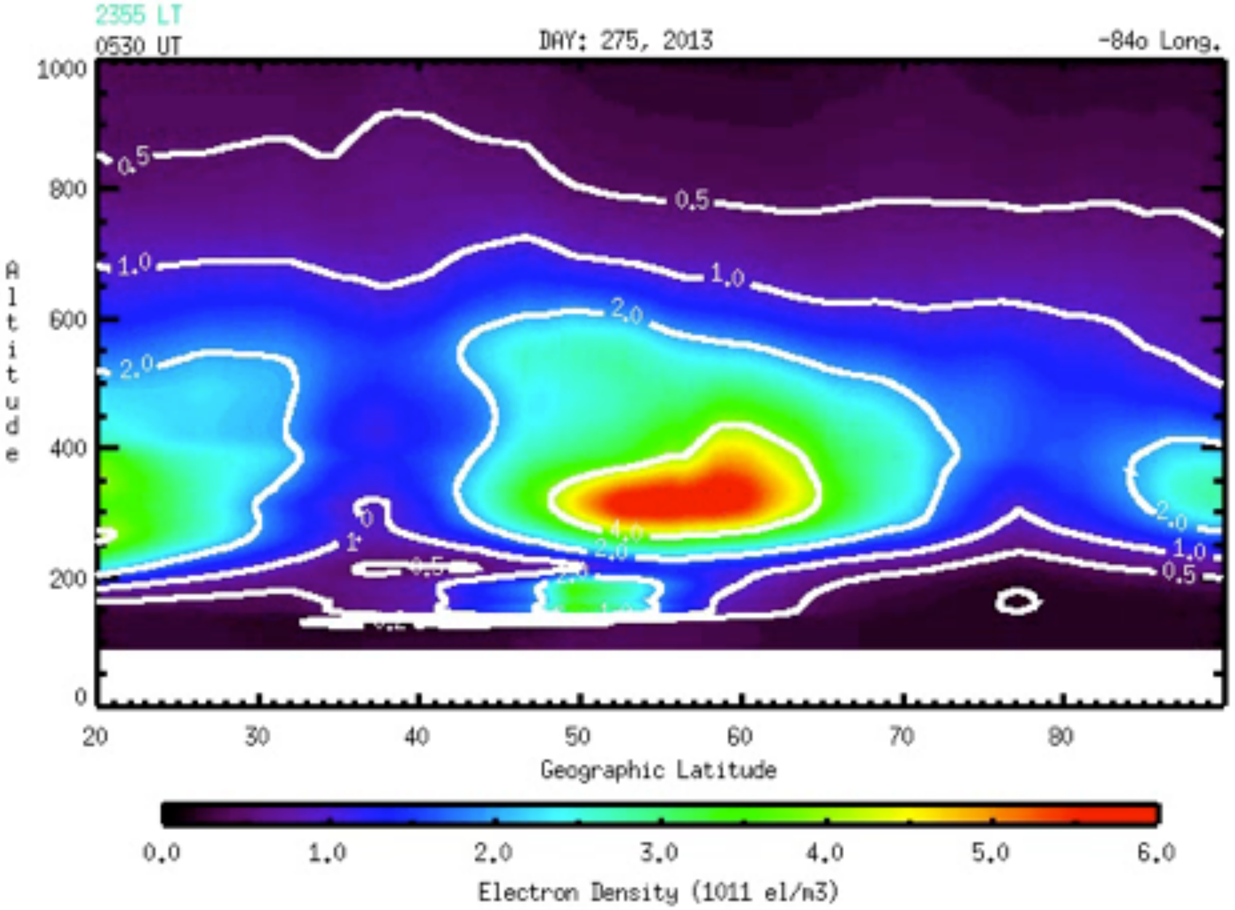


- Significant discrepancies between line-of-sight velocities measured looking to the north and south
- “Pulse” at 0430 UT seen looking up and to the south with increasing amplitude as a function of latitude



Corollary measurements





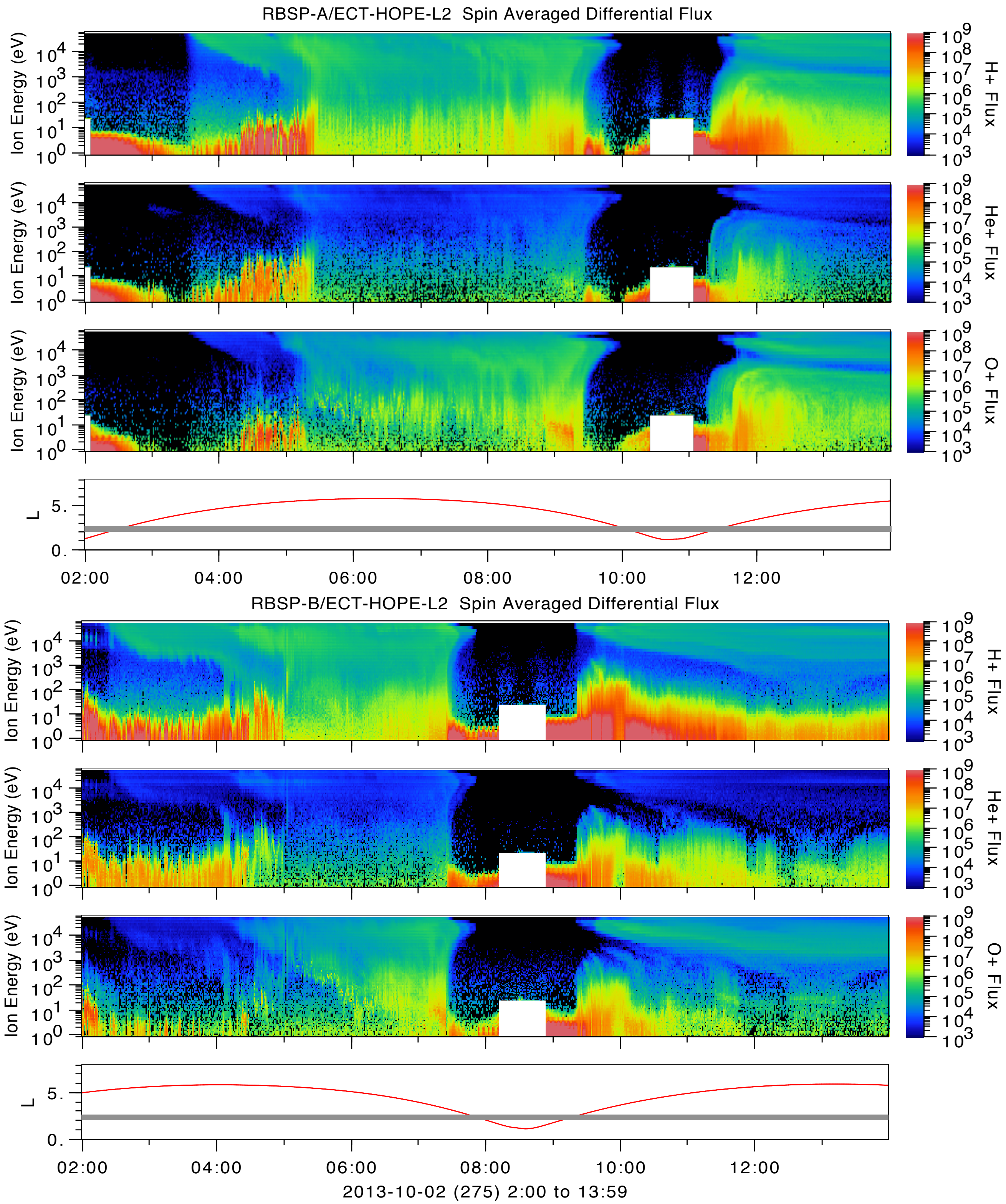
- Appearance of blue shift in the 630.0-nm observations (apparent downward wind) are coincident with
  - Appearance of a SAR arc (C. Martinis; Millstone ASI)
  - Increased electron density at low altitudes (G. Bust; IDA4D)

A connection to the inner magnetosphere

- NATION measurements also coincident with enhanced O^+ populations (ECT-HOPE)

- These types of features appear to be present during times of apparent storm time downward winds

Details in Makela, J. J., et al. (2014), Storm time response of the midlatitude thermosphere: Observations from a network of Fabry-Perot interferometers, *J. Geophys. Res. Space Physics*, 119, 6758–6773, doi:10.1002/2014JA019832.



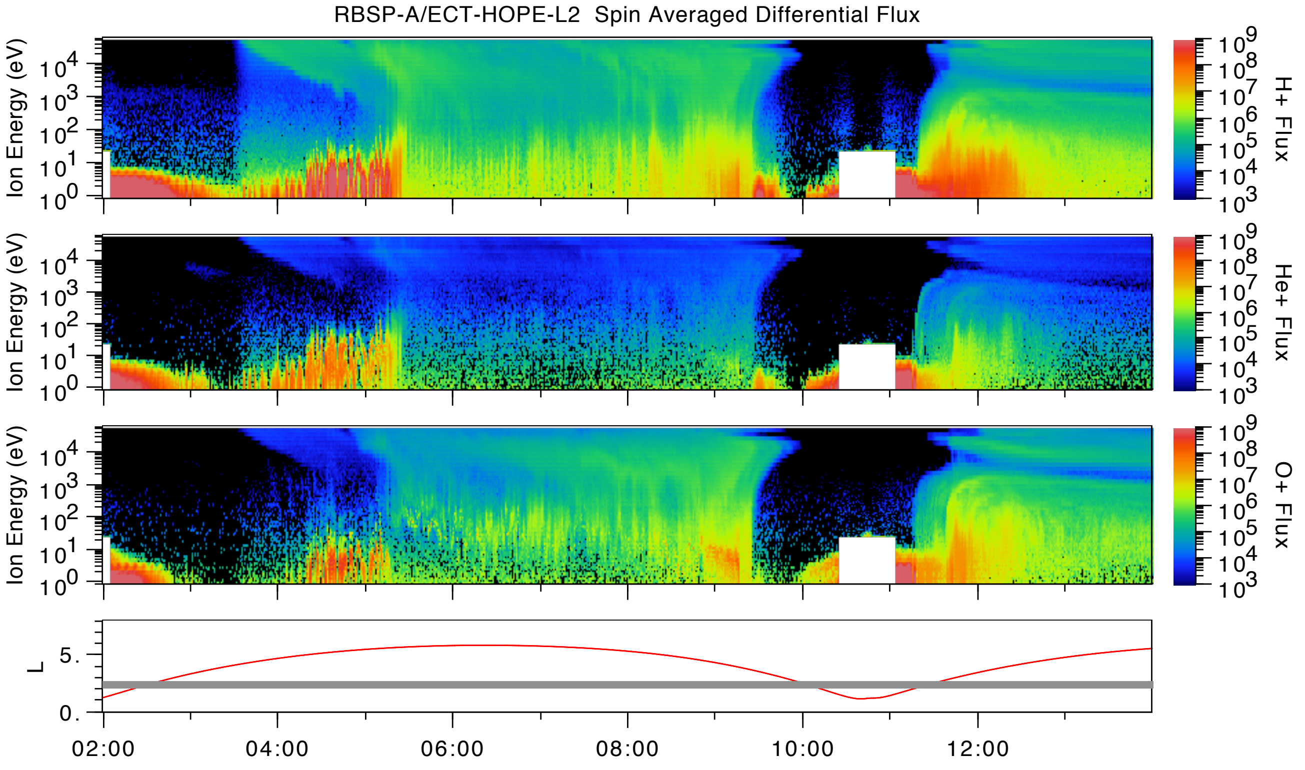
Data from the Van Allen Probes ECT-HOPE instrument

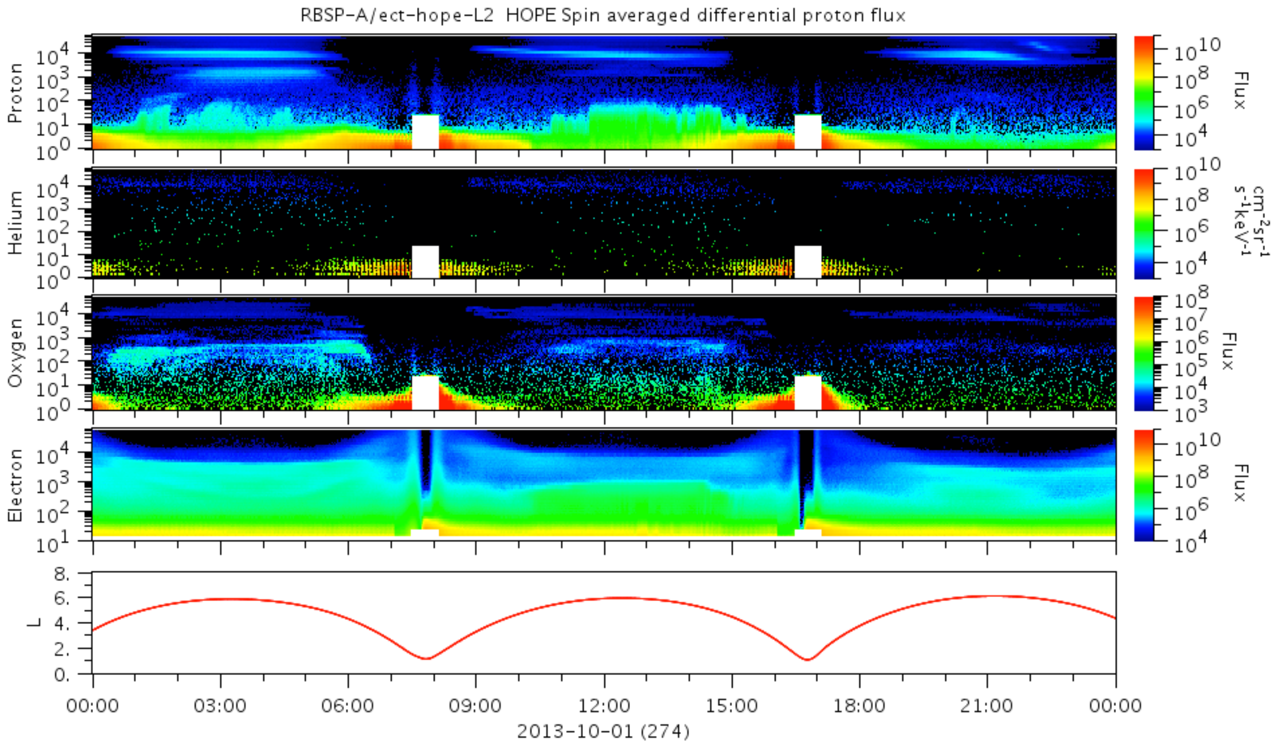
A connection to the inner magnetosphere

- NATION measurements also coincident with enhanced O^+ populations (ECT-HOPE)

- These types of features appear to be present during times of apparent storm time downward winds

Details in Makela, J. J., et al. (2014), Storm time response of the midlatitude thermosphere: Observations from a network of Fabry-Perot interferometers, *J. Geophys. Res. Space Physics*, 119, 6758–6773, doi:10.1002/2014JA019832.

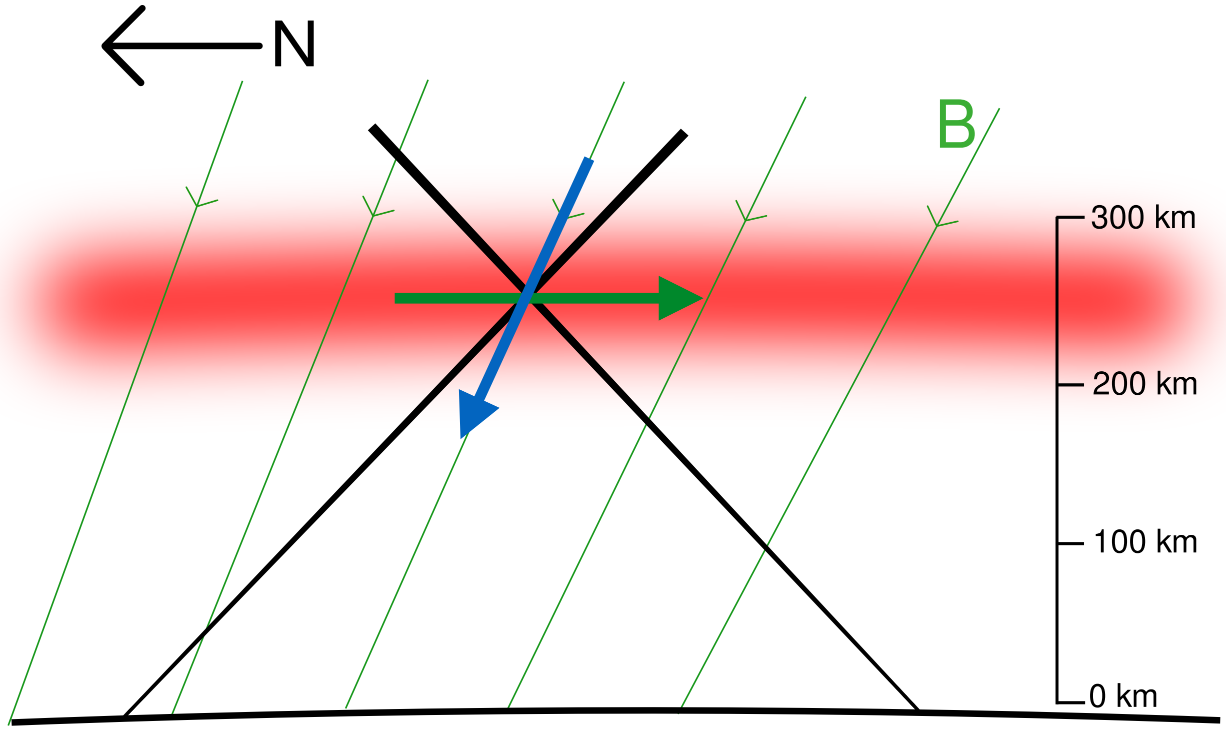




Data from the Van Allen Probes ECT-HOPE instrument

Stormtime contamination of 630.0-nm?

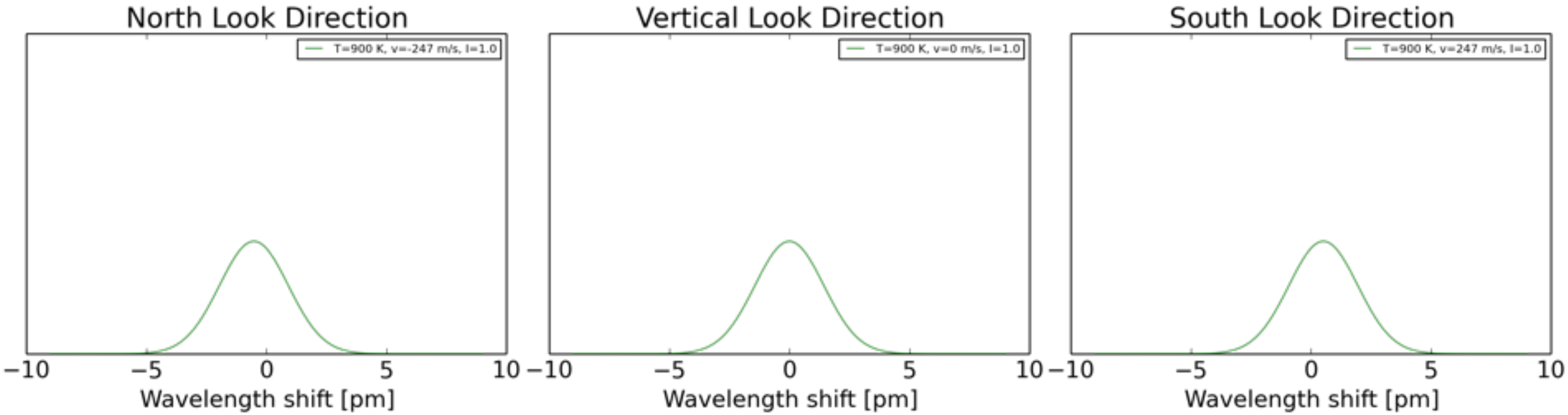
- *Torr et al.* (1974, 1982) suggest that charge and momentum exchange between these O+ ions and neutrals would produce fast O atoms
- *Ishimoto et al.* (1994) presented a model indicating collisional interaction between these fast O atoms with ambient atoms would produce Doppler-shifted 630.0-nm photons (500-7000 m/s)
- Fast O population would possibly have predominately field-aligned motion



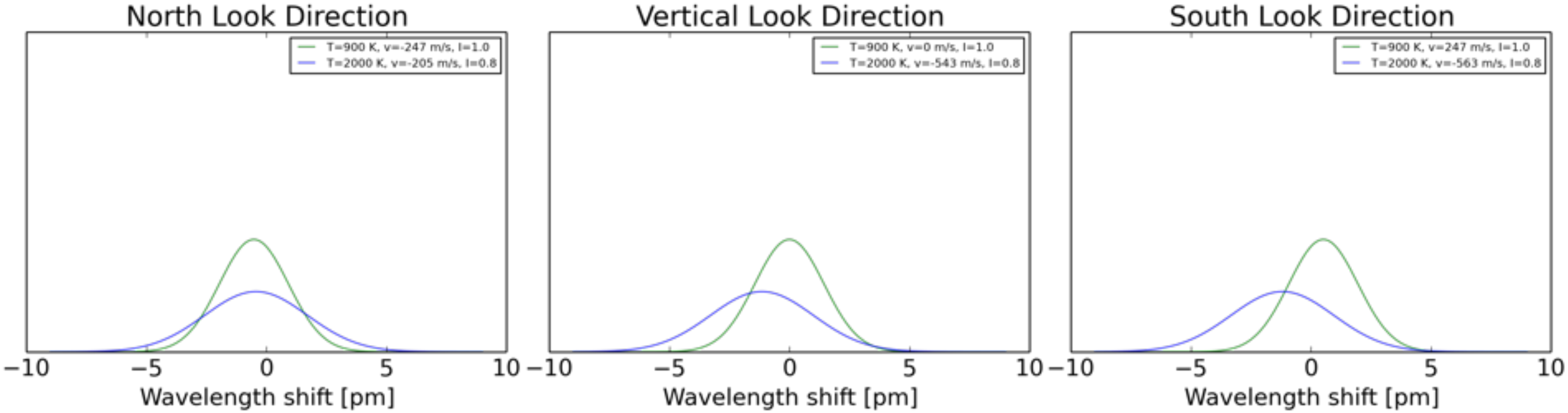
“Thermosphere”
w = -350 m/s
T = 900 K
I = 1.0

“Contamination”
$v_{B\|}$ = -600 m/s
T = 2000 K
I = 0.8

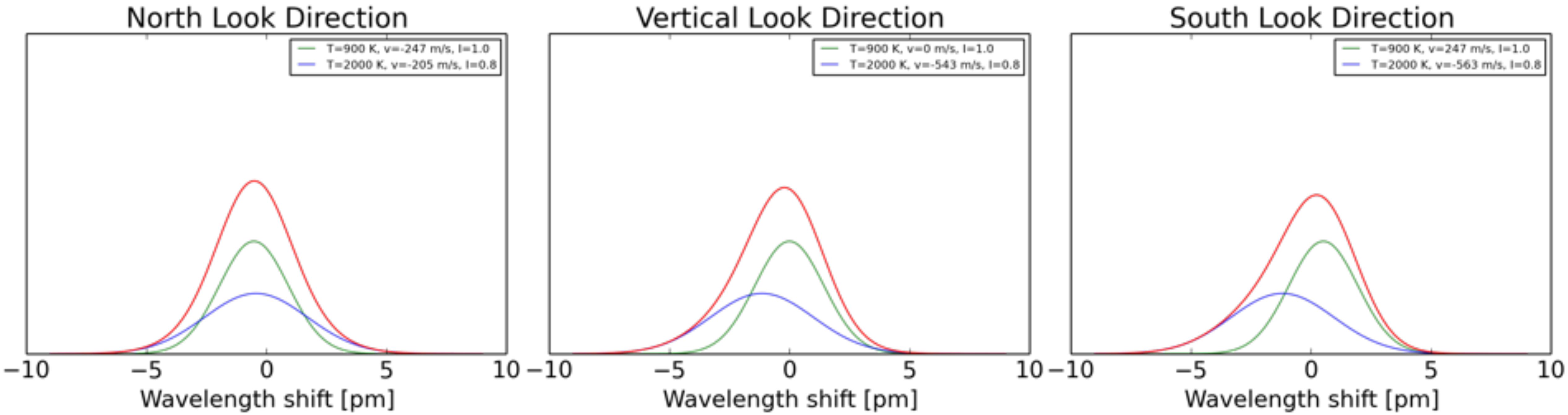
Effects of a second non-(or partially)-thermalized population



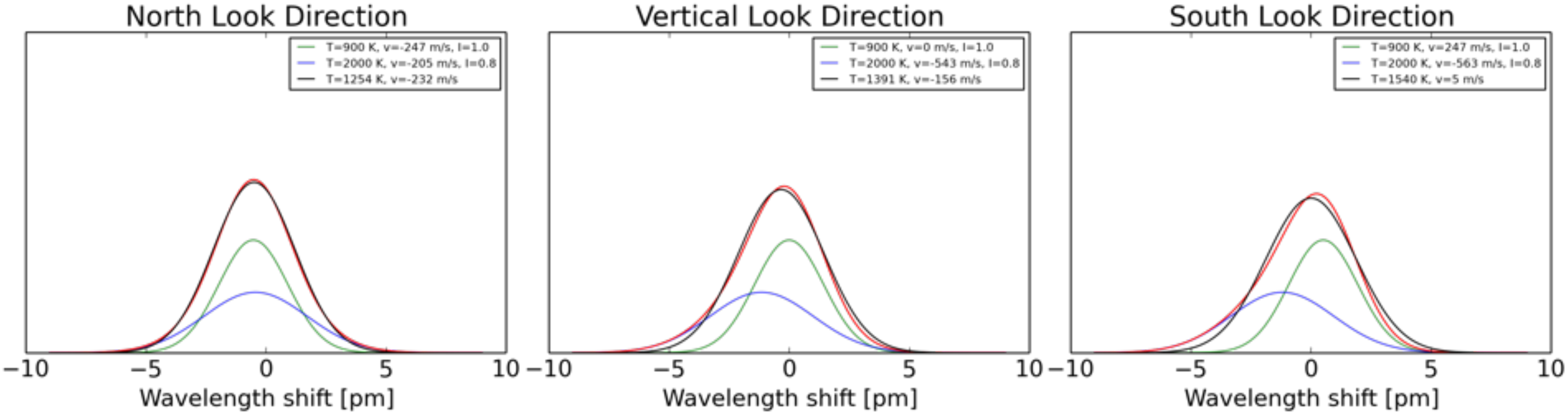
Effects of a second non-(or partially)-thermalized population



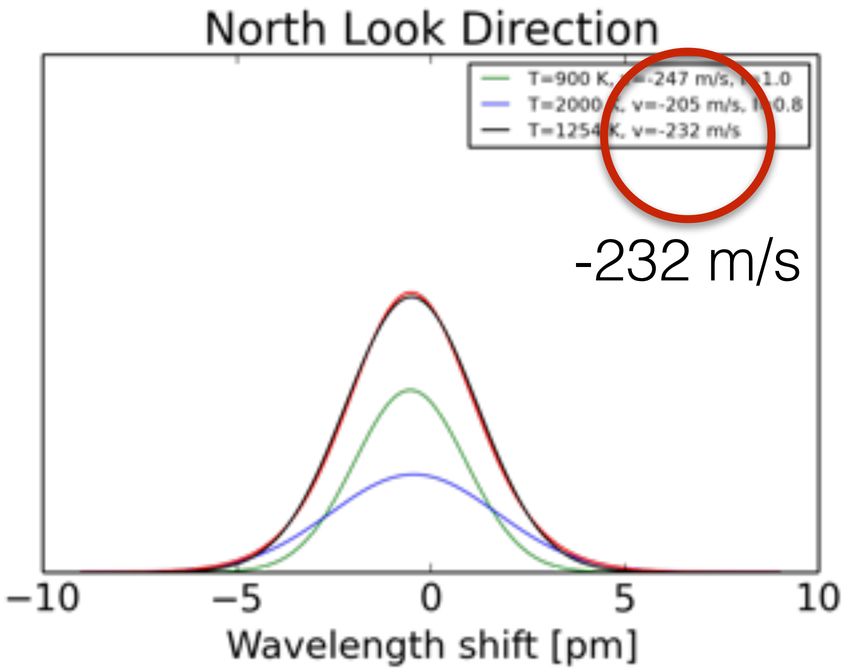
Effects of a second non-(or partially)-thermalized population



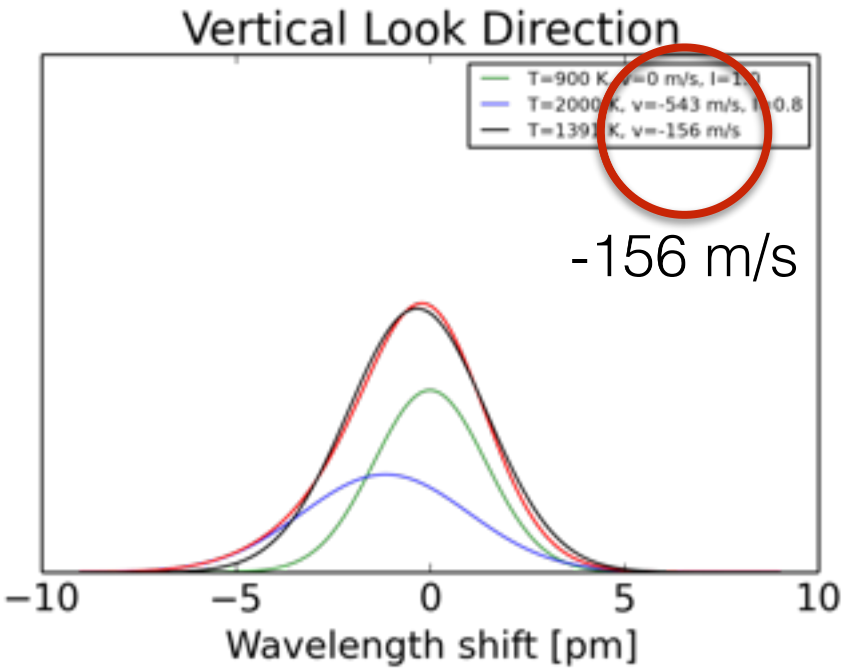
Effects of a second non-(or partially)-thermalized population



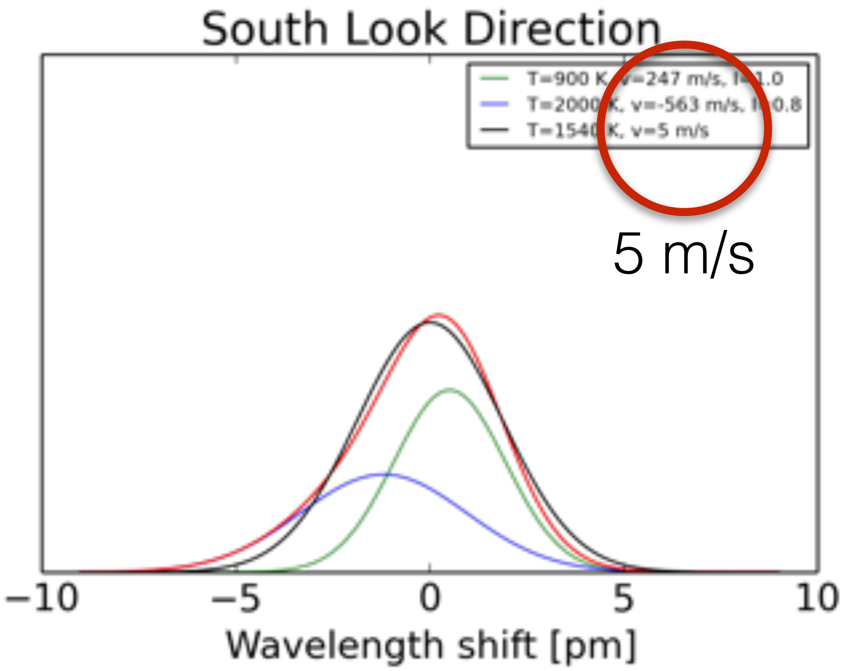
Effects of a second non-(or partially)-thermalized population



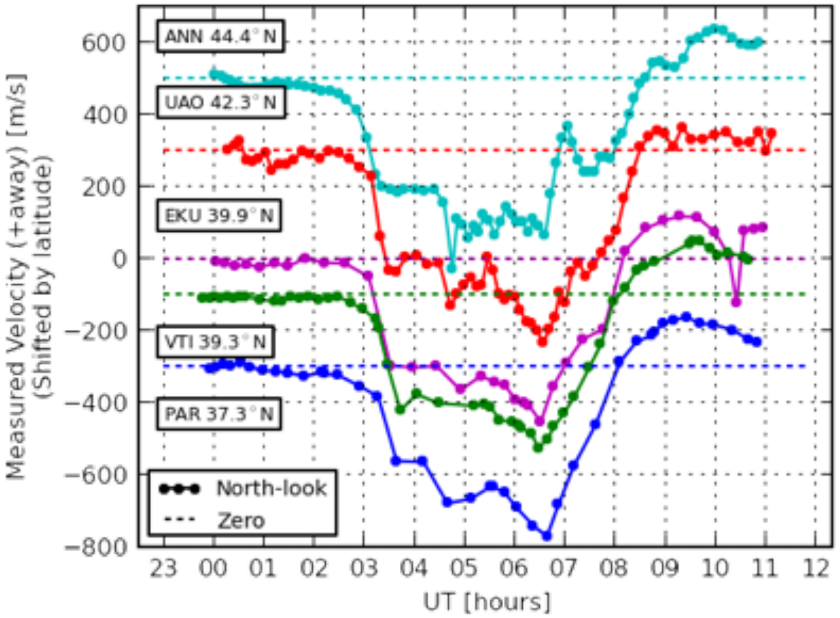
-232 m/s

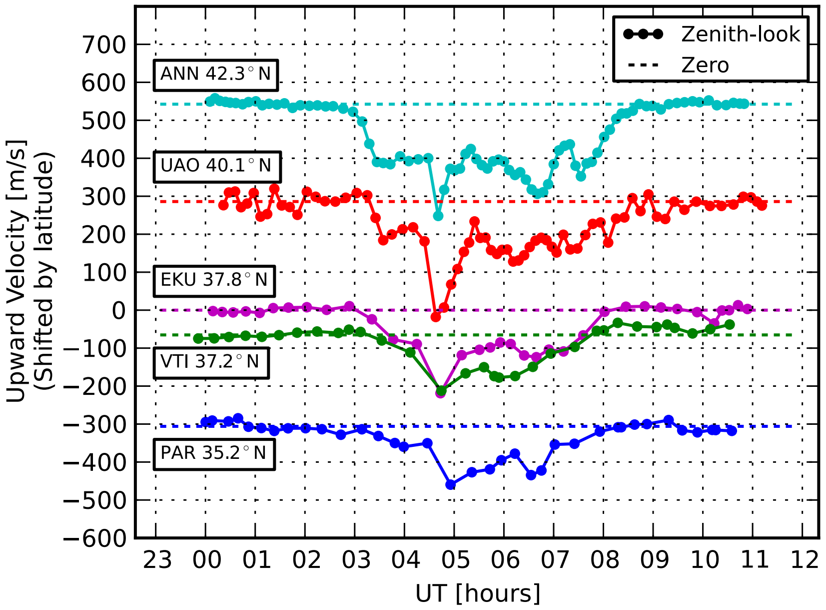


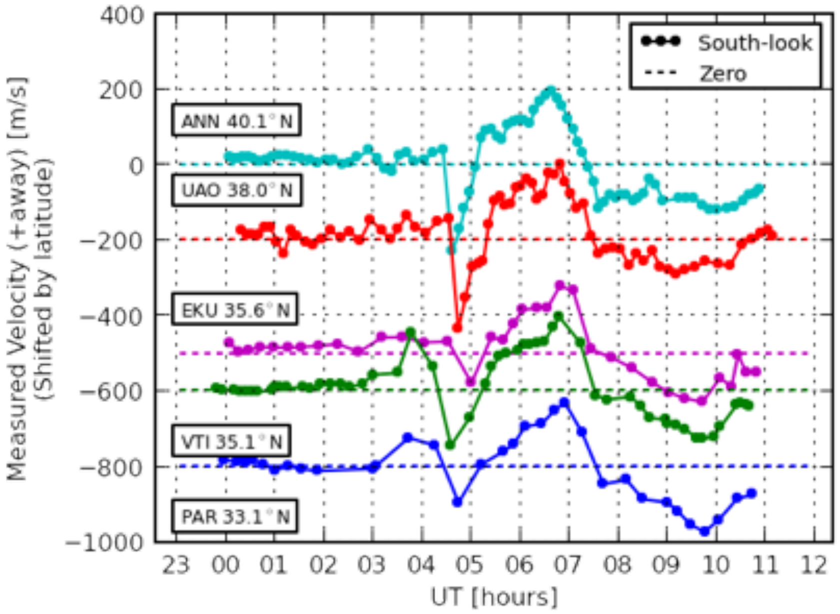
-156 m/s



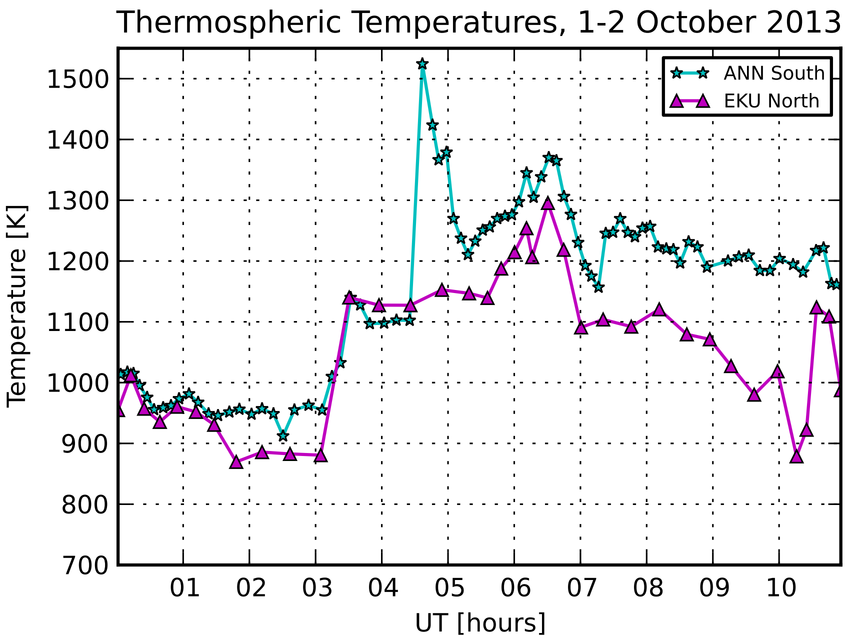
5 m/s

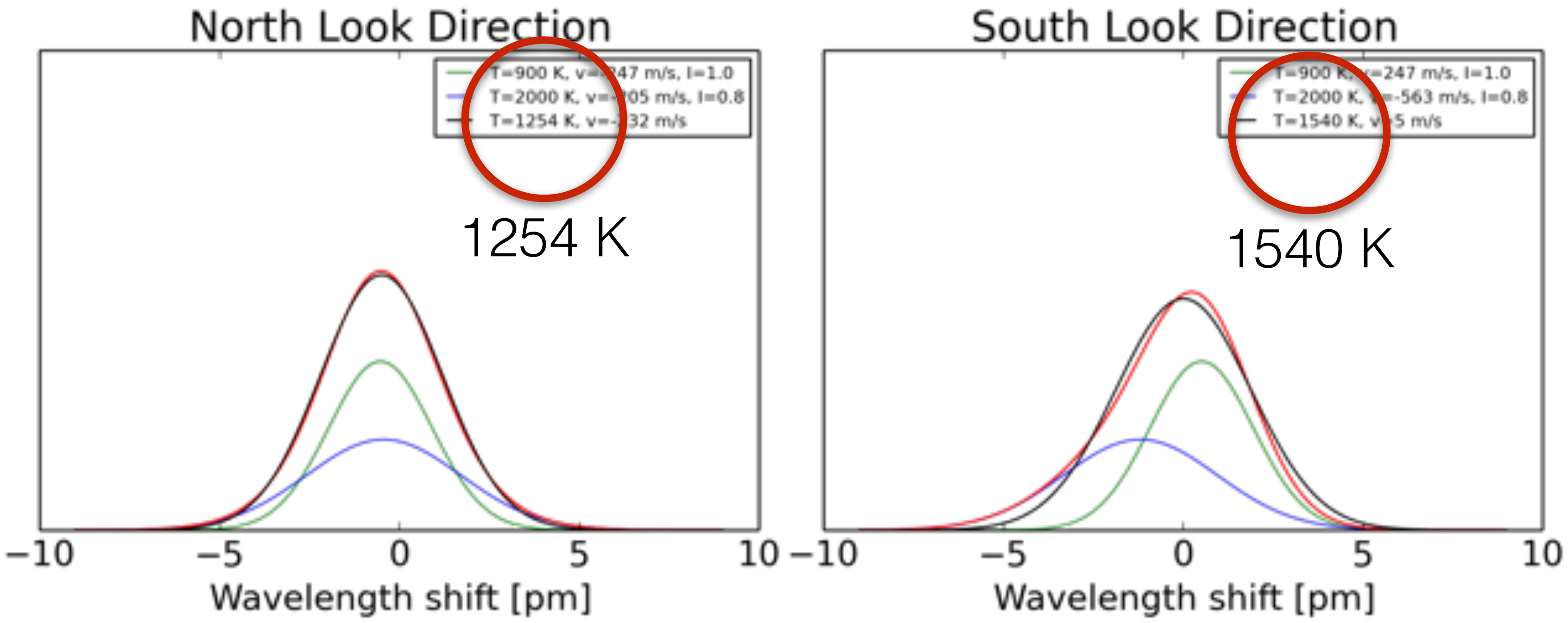






Effects of a second non-(or partially)-thermalized population





1254 K

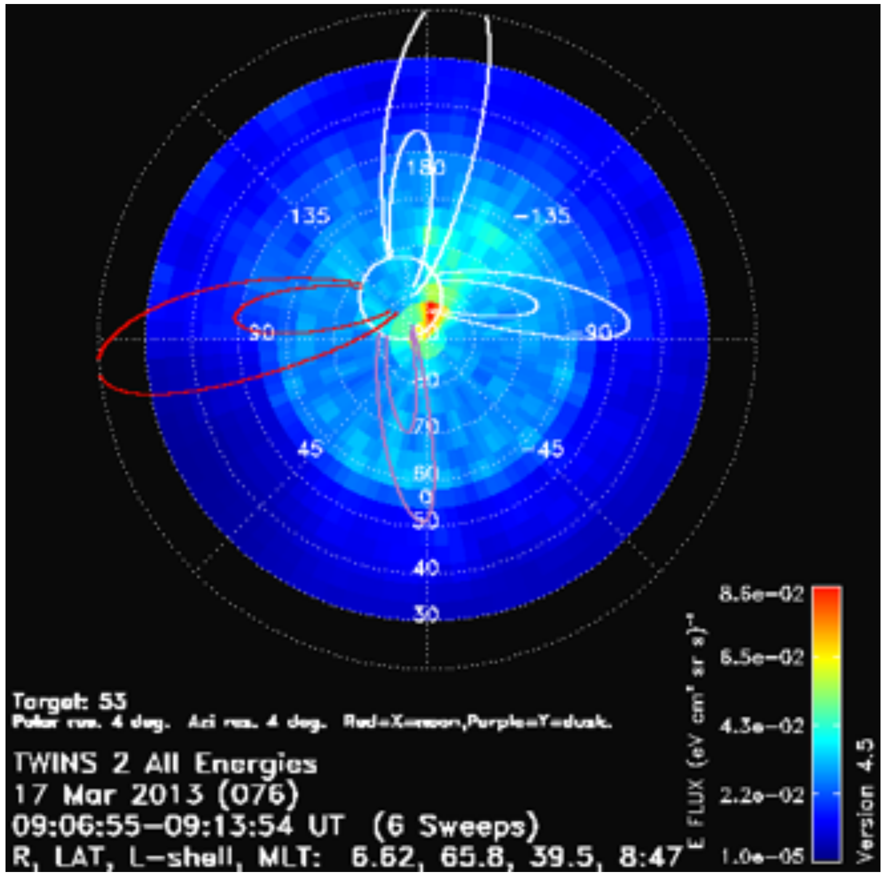
1540 K

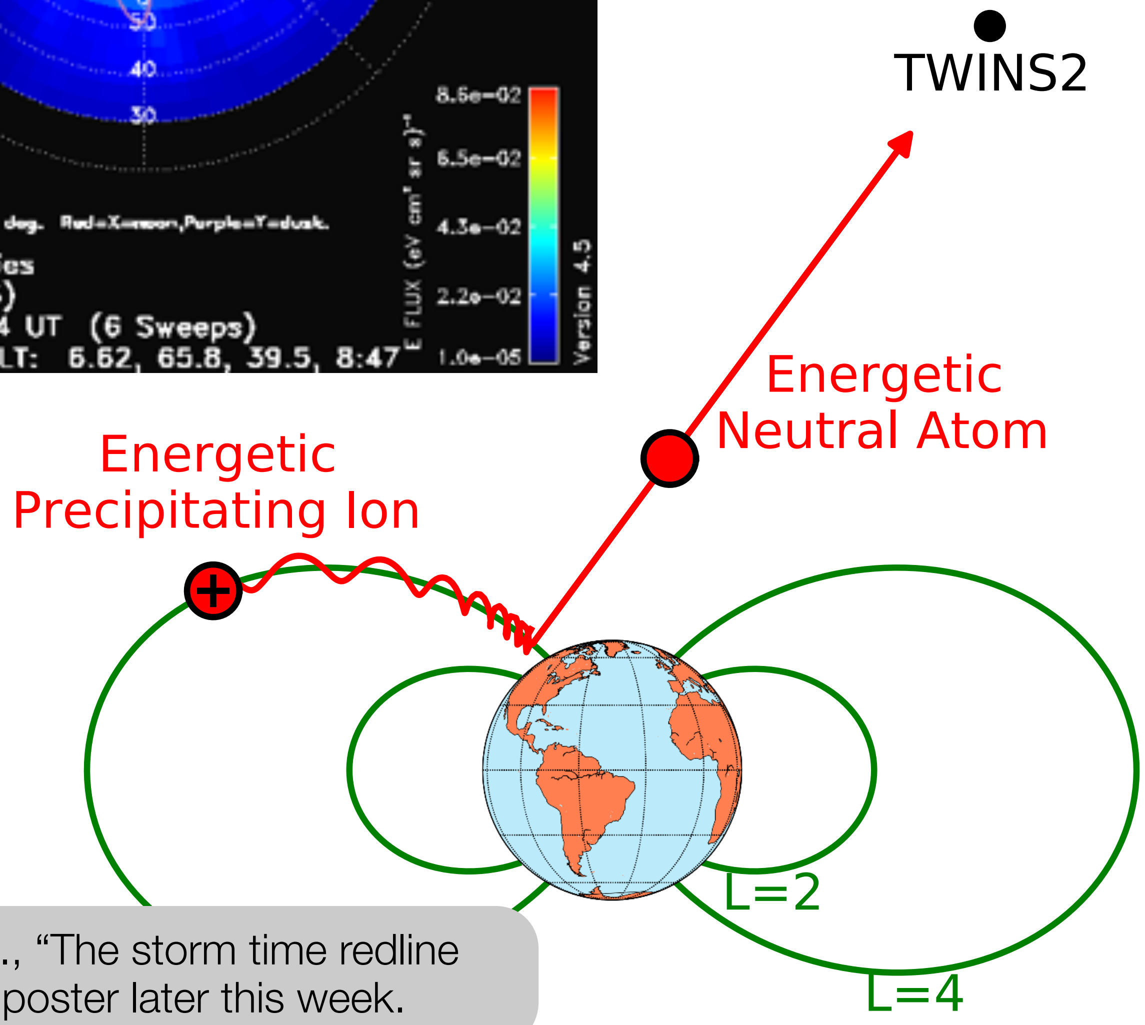
- It is possible to explain both the apparent wind gradients, temperature anisotropies, and apparent vertical winds by considering a contaminating population of "non-thermalized" redline photons
  - This effect would affect previous single-FPI observations during storms

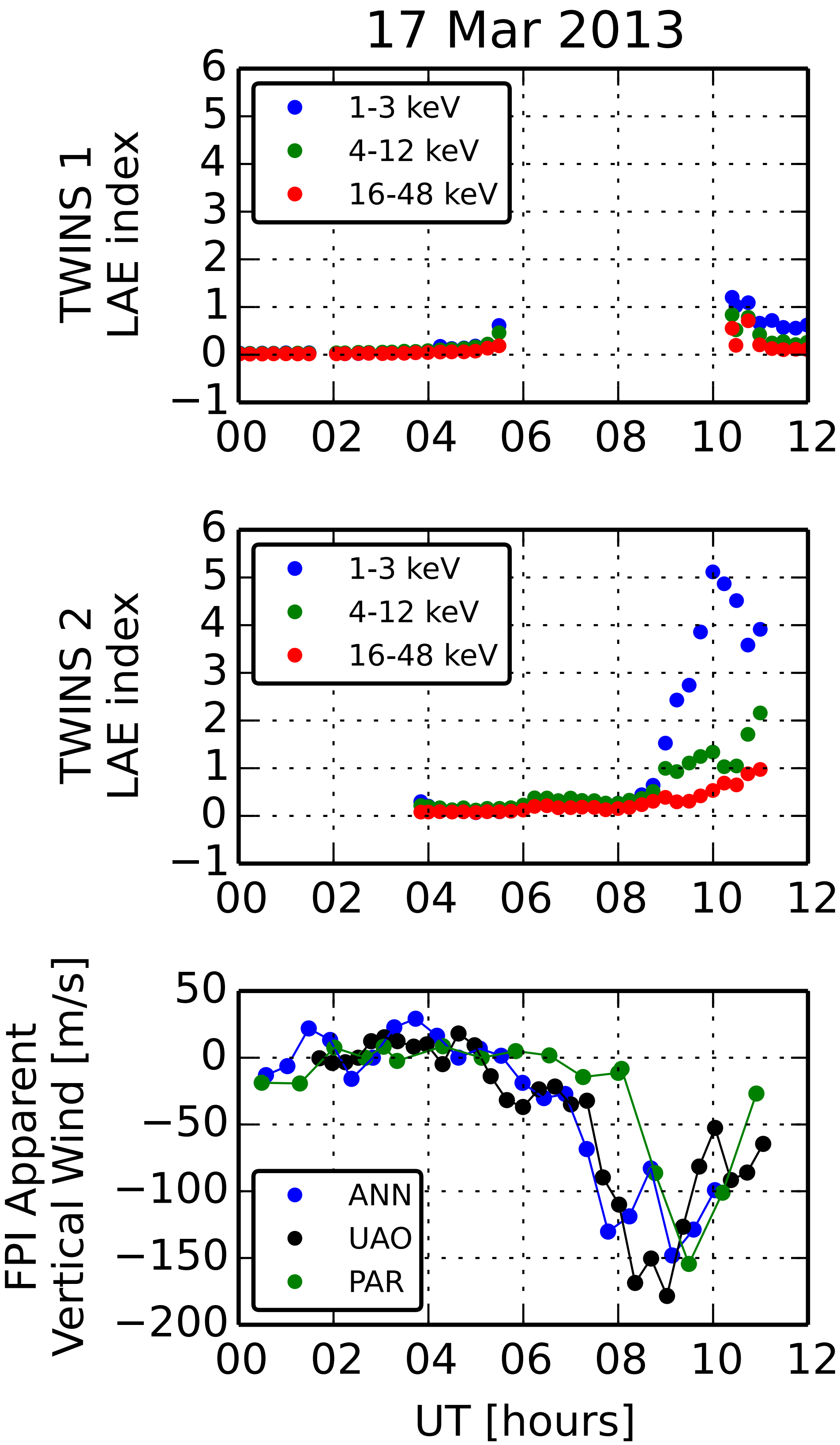
What now?

- Over the past decade, the number of FPIs worldwide has dramatically increased
  - Driven by a need to quantify neutral dynamics better than afforded by climatologies
  - Improved sensing technologies and signal processing have led to improved measurement qualities
- However, at least at mid-latitudes, during storms, there appears to be a non-thermalized contamination that makes interpretation challenging
  - 17% time above Kp 3 in my lifetime; 12% this century
- Combined with space-based instruments, perhaps this “contamination” can be used to understand spatial distributions of precipitation and elucidate magnetosphere-ionosphere coupling

Comparison to TWINS



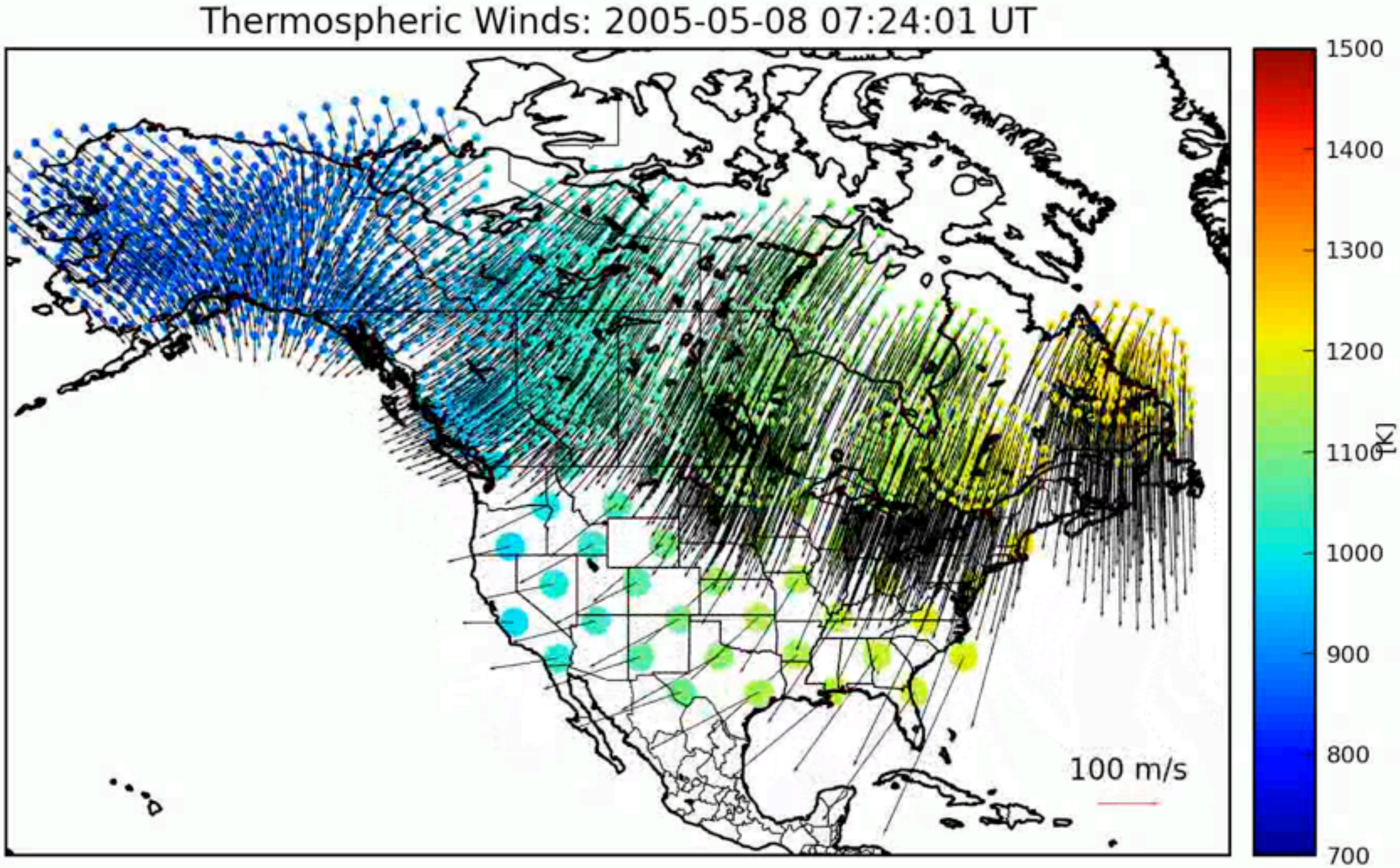




See Harding et al., “The storm time redline and fast oxygen” poster later this week.

What now?

- As models continue to improve, we will need increasingly better data to validate them
  - What density of measurements are needed? (what spatial scales in the neutral atmosphere are important?)
- Data quality and instrument robustness are such that thermospheric neutral wind and temperature measurements are a prime candidate for assimilation into next-generation models
  - Would be a major step forward in gaining an understanding of the four-dimensional state of the upper atmosphere
- A continental-scale network (or larger) is technologically (if not financially?) possible today
  - How can we bring down the cost of the instruments?


Thermospheric Winds: 2005-05-08 07:24:01 UT
100 m/s
1500
1400
1300
1200
1100
1000
900
800
700
[K]

Thank You!