Trajectories of air parcel transport driven by thermospheric winds, as derived from ground-based Fabry-Perot observations

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Motivation: Understanding Transport in Earth's Thermosphere

- Neutral wind in Earth's thermosphere is a *three-component vector field that varies in four dimensions* (three spatial, one temporal.)
- This dimensionality potentially allows very complex flows to develop, that are well beyond the ability of existing observational techniques to resolve.
- This is unfortunate, because there are a number of thermospheric phenomena of societal relevance, such as *transport of composition perturbations*, that cannot be determined without complete knowledge of the winds.
- Here we describe a new technique to provide the most complete thermospheric wind reconstruction that we are aware of to date.
- The method reconstructs the four-dimensional vector wind field from line-of-sight wind components measured by ground-based Doppler remote sensing.

Technique

- An array of ground-based Scanning Doppler Imager (SDI) instruments is used to measure the radial component of the wind along several hundred lines of sight using 2-4 geographically separate observing sites.

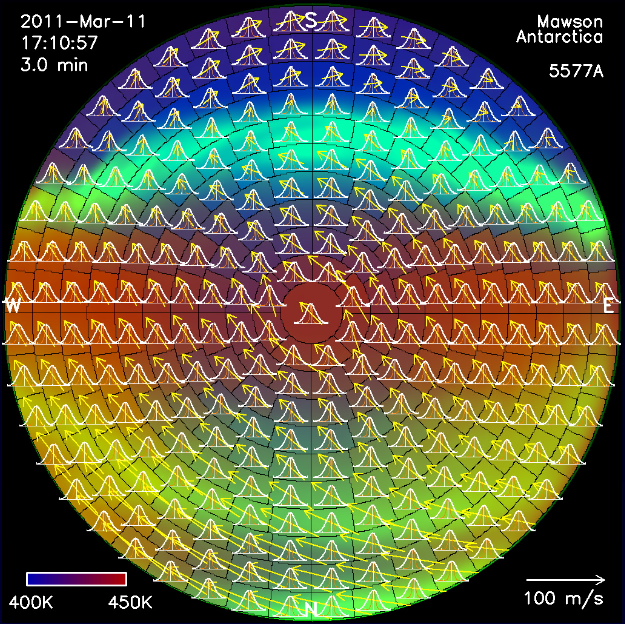
- Height resolution is obtained by observing at two wavelengths ($630\,\mathrm{nm}$ and $558\,\mathrm{nm}$) which originate from heights of $\sim 240\,\mathrm{km}$ and roughly $100\,\mathrm{km} - 150\,\mathrm{km}$ respectively.

- Furthermore, the $558\,\mathrm{nm}$ *spectra provide some additional altitude resolution*, because *changing auroral characteristic energy changes the emission height profile*.

- We use an "evolutionary" algorithm to infer the vector wind field that *best reproduces the observed line-of-sight wind components*, as a function of the four independent dimensions of longitude, latitude, altitude, and time.

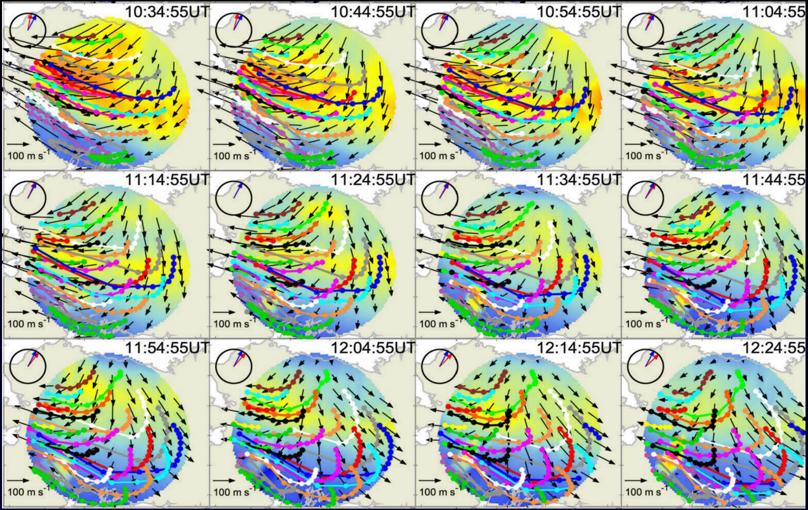
- Here we apply the results of this analysis to infer trajectories that would be followed by tracer particles moving through the fitted 4D vector fields.

All-Sky Line-of-Sight Doppler Wind Measurements



- A single SDI measures optical Doppler spectra of airglow/aurora from multiple "zones" across the sky.
- Derived Level-1 data are emission brightness, plus the temperature and line-of-sight wind component prevailing within the emission volume.
- Horizontal vector wind fields can be inferred from a single site, but only by *enforcing major assumptions*.

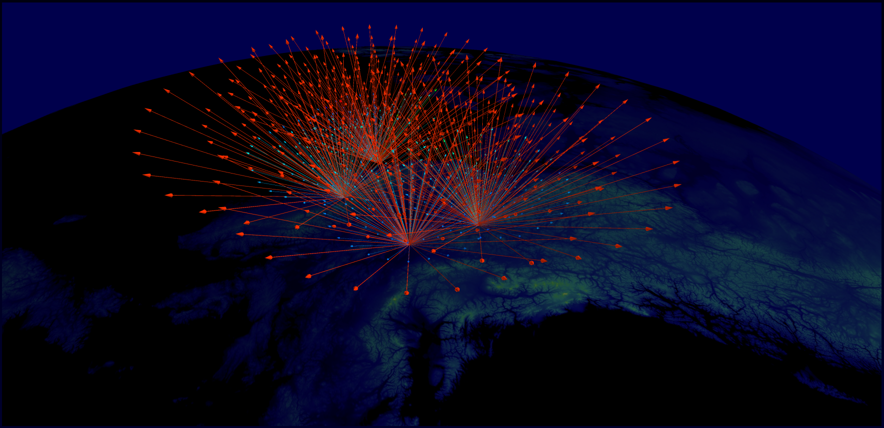
Air Parcel Trajectories



- Dhadly & Conde [*JGR 122, 6635–6651, 2017*] presented transport trajectories derived from single station "monostatic" wind fields.
- But these results are only as good as the assumptions involved in monostatic wind reconstruction. Also, they had *no vertical component*, and *no height resolution*.

Multistatic Wind Observations Using an Array of SDI Instruments

- LOS winds seen from one site cannot uniquely constrain all 3 wind components.
- Improved wind reconstructions require wind components measured along multiple independent lines of sight – which we now do, using an array of Scanning Doppler Imagers located across Alaska,[1] with overlapping fields of view.



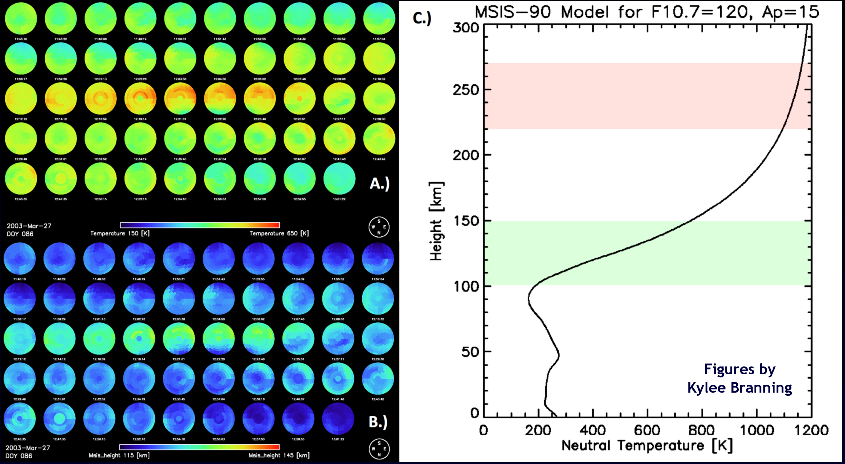
[Figures in This Style Were Provided by John Elliott]

[1] At Poker Flat, Eagle, Toolik Lake, and Kaktovik.

Adding Height Resolution Gives True 4D Vector Wind Fields

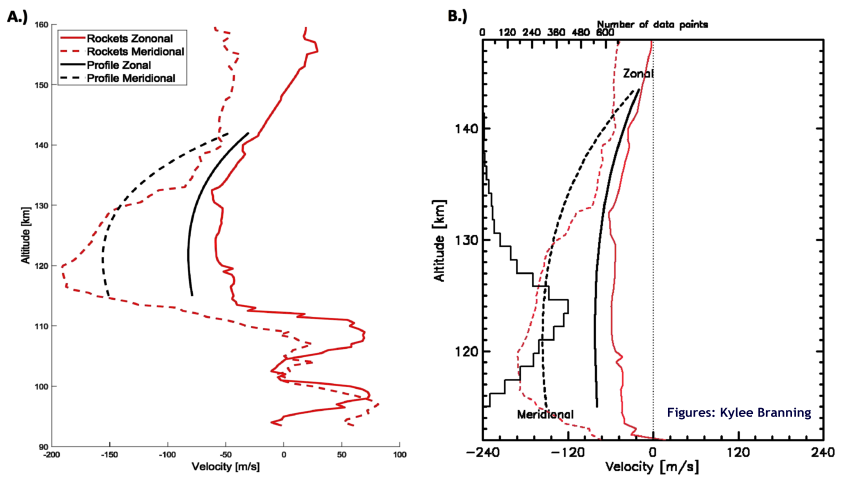
- Prior work on the SDI data has focused on "red line" observations at 630 nm wavelength, for which it is reasonable (if imperfect) to assume a constant emission height of around 240 km for all observations.
- The new evolutionary algorithm ingests data derived from spectra recorded at two wavelengths: 630 nm and 558 nm. (Dual wavelength data are obtained by alternating observations through two different narrow passband interference filters.)
- By contrast to the red line, aurorally excited 558 nm emission heights vary roughly in the range 100 km to 150 km depending on the characteristic energy of precipitating auroral electrons.
- Furthermore, *it is possible to infer the centroid height of observed 558 nm optical emissions*, using the temperature obtained from a numerical fit to its Doppler spectrum [e.g. *Holmes et al.*, 2005; *Kaeppler et al.*, 2015.]
- Here we use this approach to obtain some continuous height resolution in the lower thermosphere, as the changing shapes and characteristic energy of the auroral arcs "paint in" different heights over space and time within our observing volume.

Height Resolution from 558 nm Temperatures & MSIS



- 558 nm green-line observations give height resolution between ∼ 100 km – 150 km – where *strong vertical shear is common*.
- 630 nm red-line gives winds at ∼ 240 km. Previous *rocket flights usually show relatively smooth height profiles for winds at altitudes above 150 km*, meaning it is reasonable for the model to interpolate winds between red & green heights.

1D Height-Resolved SDI Winds Validated by Chemical Releases



- 1D height profiles of winds derived using 558 nm temperatures match absolute winds from rocket-borne chemical releases, *provided the field is reasonably uniform in the other three dimensions* – i.e. in longitude, latitude, and time.
- A more sophisticated approach is needed for the (frequent) scenarios where the wind field is not so uniform.

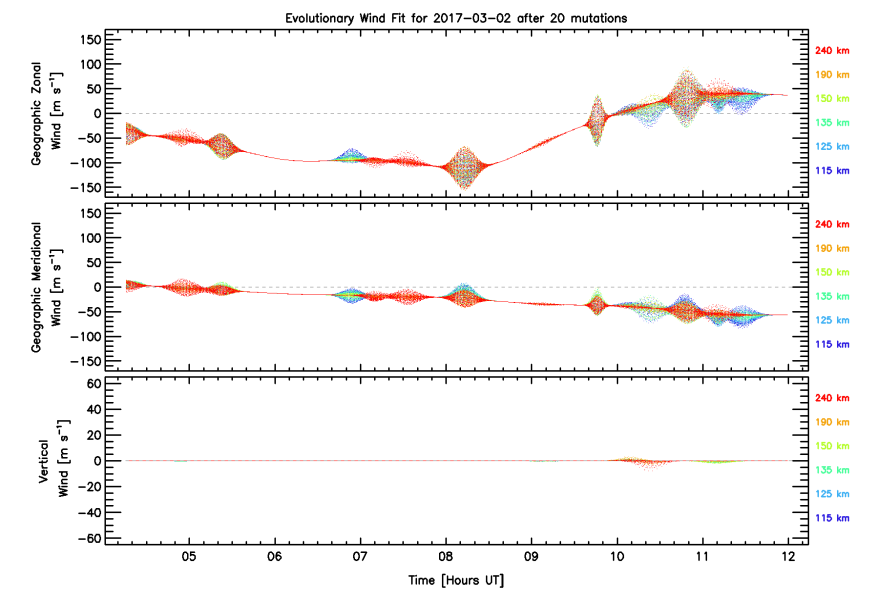
4D Evolutionary Wind Fitting

- The evolutionary method adopted here starts with an initial four-dimensional (longitude, latitude, altitude, time) three-component vector wind field model that is easily derived from the data but is too crude to be realistic or useful.
- The algorithm then applies numerous random "mutations" sequentially to the model, scaling each to best improve the model's goodness of fit to the data.

Characteristics of the Evolutionary Wind Model

- The initial wind field is derived using a distance-weighted average of the monostatic red-line winds from each observing site. It contains no height variation, and the vertical wind component is zero at all vertices.
- Mutations are based on non-divergent Gaussian radial basis functions, localized around a point in longitude, latitude, altitude, & time that is independently and randomly chosen at each iteration.
- The wind component (zonal, meridional, or vertical) to be used for the "primary" mutation is also randomly chosen at each iteration.
- The other two components are calculated such that the overall divergence of the mutation field is almost (but not exactly) zero everywhere.
- "Survival of the fittest" corresponds to finding the amplitude of each mutation that best optimizes the overall goodness-of-fit between the observed LOS winds and the corresponding components of the 4D vector model.

Appearance of the Mutations



Survival of the Fittest

- Goodness-of-fit (or just "fitness", in evolutionary parlance) is determined primarily by a simple χ^2 parameter. This is just a *sum of squares of the differences* between observed line-of-sight wind components and the corresponding line-of-sight components of the vector wind model , *evaluated on the observational grid.*

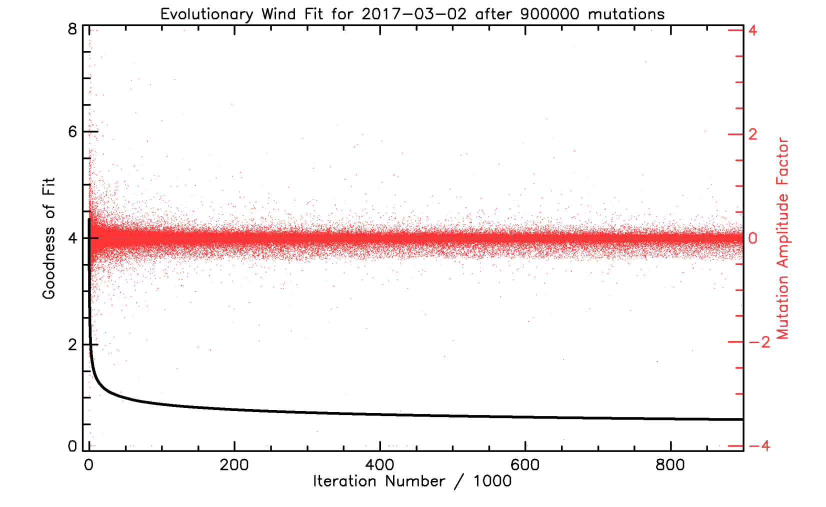
- Additional terms are added to the goodness-of-fit calculation to penalize large wind speeds ($> 250\,\mathrm{m\,s^{-1}}$ for horizontal components, and $> 100\,\mathrm{m\,s^{-1}}$ in the vertical.) There is also a term that penalizes high spatial frequencies.

- Survival of the fittest is not implemented as a simple "keep or reject" decision.

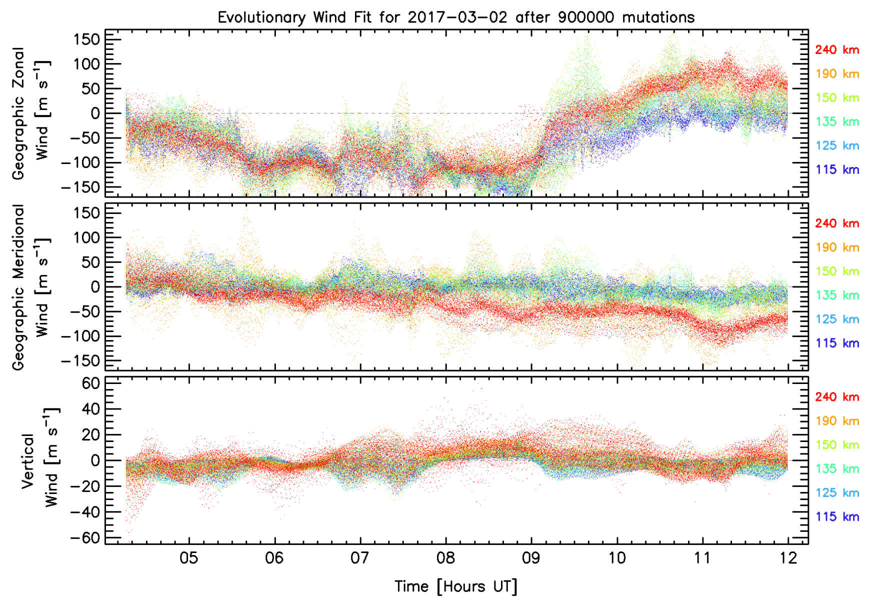
- Rather, *the algorithm examines how goodness-of-fit behaves as a function of three trial amplitudes for the mutation*, and uses a constrained quadratic fit to this behavior to predict the optimum amplitude for each mutation.

- Convergent behavior of both this amplitude factor and the overall goodness-of-fit is illustrated on the next slide.

Convergence

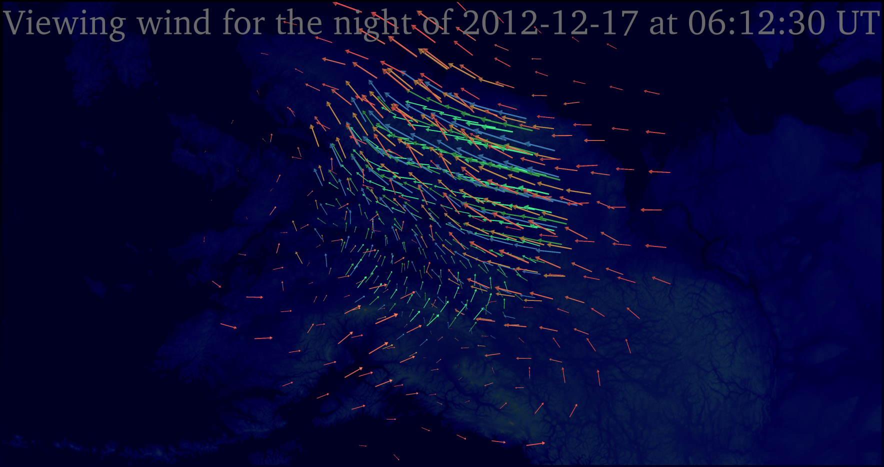


Model Appearance After Many Mutations



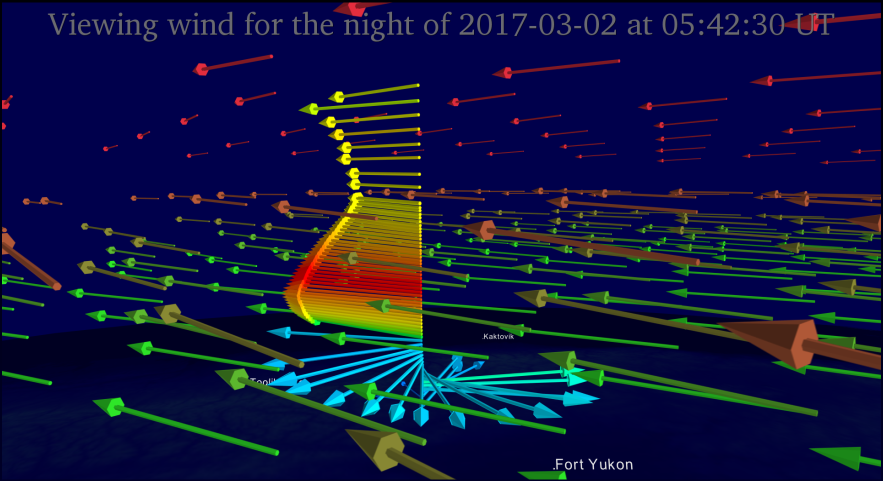
Fitted Winds After Six Million Mutations

Another Example



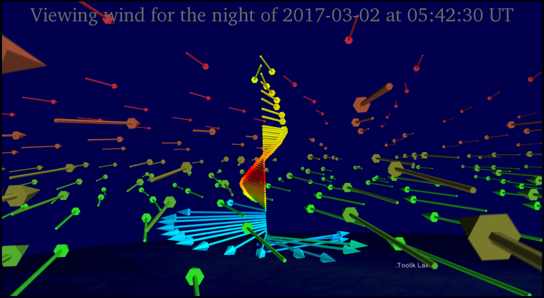
This is a plan view of the evolutionary wind fit for December 17, 2012 at 06:13:30 UT. Colors depict heights in the range 115 to 240 km, with warmer colors corresponding to greater altitudes. The longest arrows here correspond to wind speeds of around $150\,\mathrm{m\,s^{-1}}$.

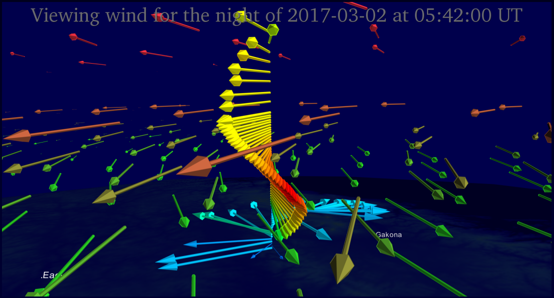
Absolute Wind Validation: The 02-March-2017 JETS Mission



- Comparison of evolutionary wind fields (after 100 million mutations) with *TMA chemical release winds* obtained during the JETS rocket mission.
- The view is looking from the south. Blue TMA arrows represent lower heights than the SDIs can observe.

Additional Views of the Comparison with JETS TMA Winds





- These are additional views of the evolutionary/TMA wind comparisons, in this case looking from the east (top) and west (bottom).
- The evolutionary wind speeds match quite well with those obtained from the drift of the TMA tracer clouds.
- The evolutionary fit also saw the same rotation of the wind vector with altitude (above $z = 115\,\text{km}$) as was seen in the TMA winds.

Tracing Air Parcel Trajectories

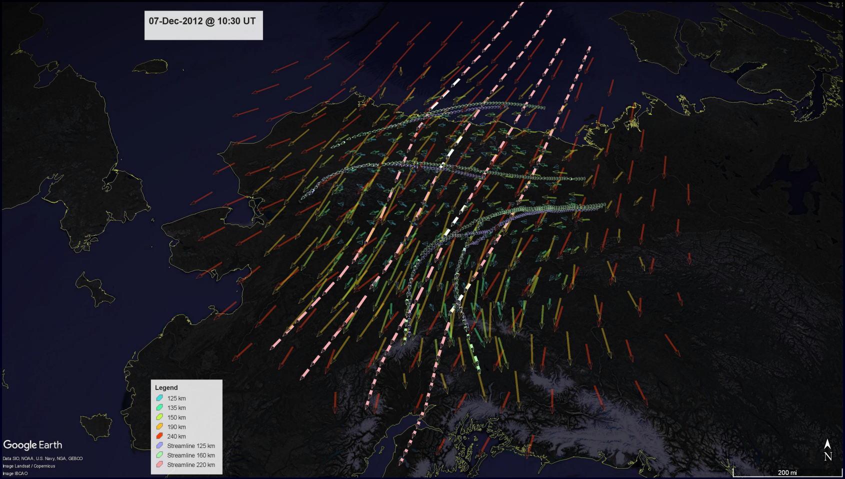
- Once we have an estimate of the full three-component vector field resolved over all four dimensions, it is computationally simple to follow the trajectories of any number of hypothetical "tracer particles" carried by the flow.

For a given time and spatial location, there two questions that can be asked:

- Where did the air parcels passing here now *come from*?
- Where will these air parcels *go in the future?*

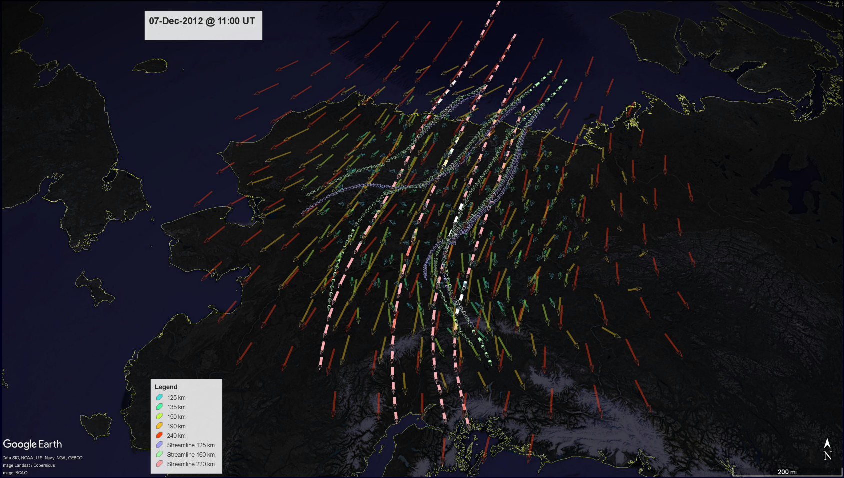
- Pathline arrows in the following figures address both questions.
- White pathline arrows are *the only ones that correspond to the time of the background wind field.*
- Arrows upstream of those in white show where these air parcels came from, whereas downstream arrows show where they will go subsequently. Each pathline arrow corresponds to 5 minutes of wind transport.

A Simple Example of Transport Trajectories



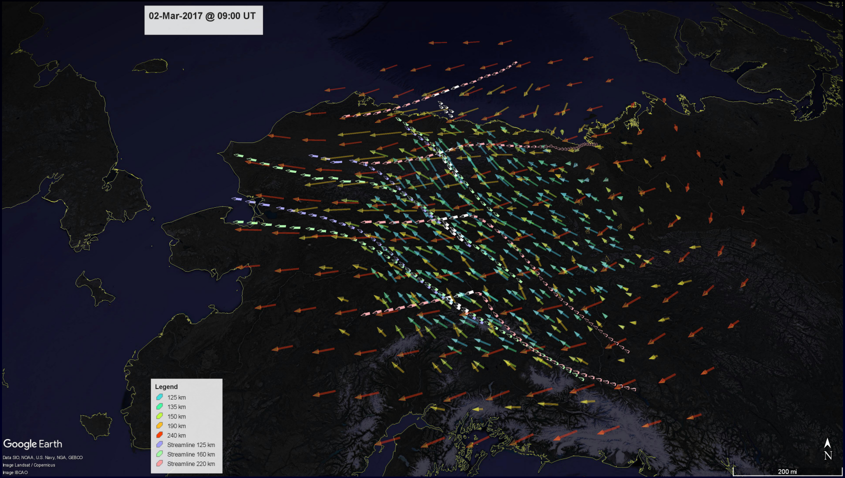
- F-region trajectories (pink) indicate uniform transport toward the south-west.
- E-region transport (olive & cyan) was more complex. All E-region air parcels passing the white reference locations originated from the east.
- Downstream transport remained westward over northern Alaska. But over southern Alaska, the downstream transport turned strongly southward.

30 Minutes Later



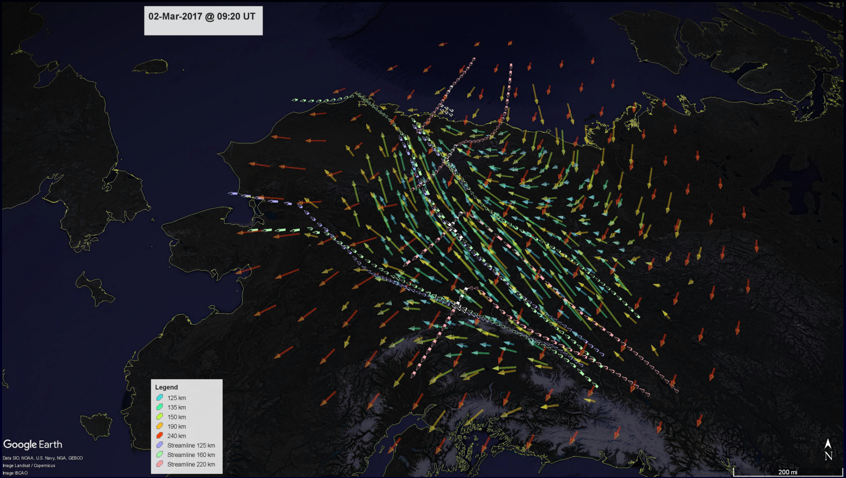
- 30 minutes later the F-region trajectories remained similar. But E-region trajectories rotated southwestward, similar to the F-region.
- The trajectories shown here represent several hours of transport. Changes this substantial over 30 minutes are the result of time varying vertical shear, which *can only be resolved from knowledge of the full 4D wind field.*

Another Example – From Later in the JETS Night



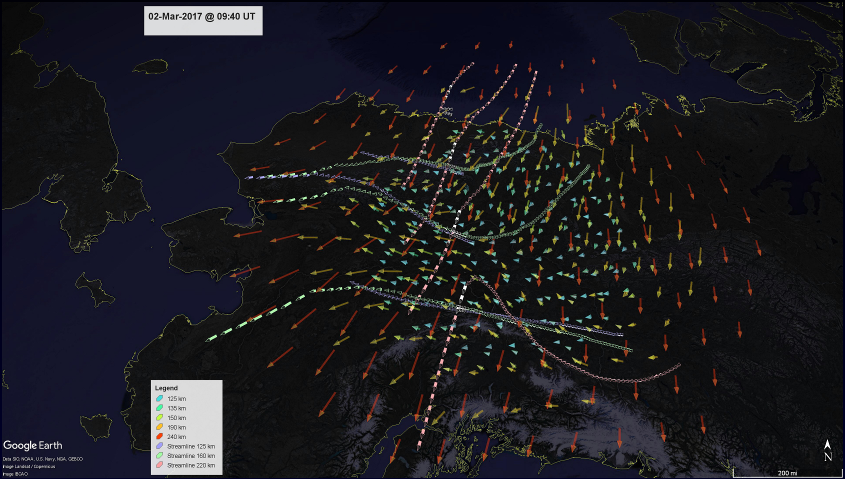
- Flows at both E- and F-region heights were generally westward at 09:00 UT on the JETS night.
- Prematurely truncated pathlines indicate the tracer moved outside the reconstruction domain – most likely in altitude, as a result of vertical transport .

20 Minutes Later



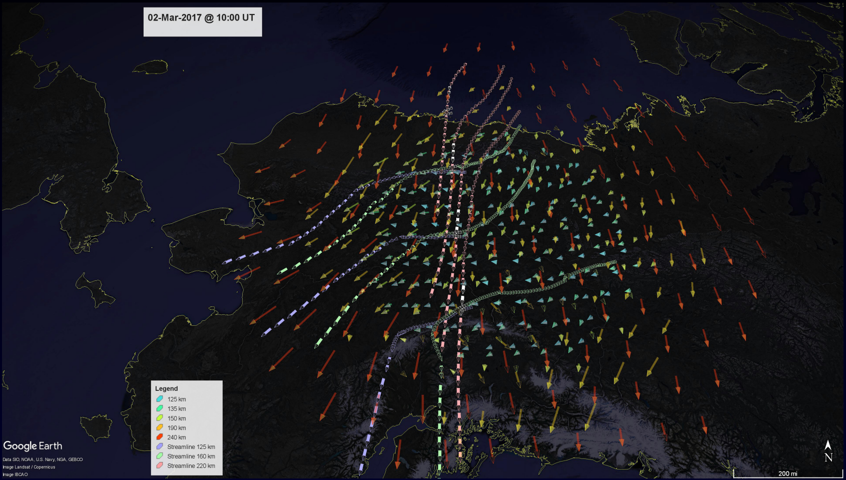
- Just 20 minutes later, a southward turning was apparent in the F-regions winds.

The Shear Reaches the E-Region



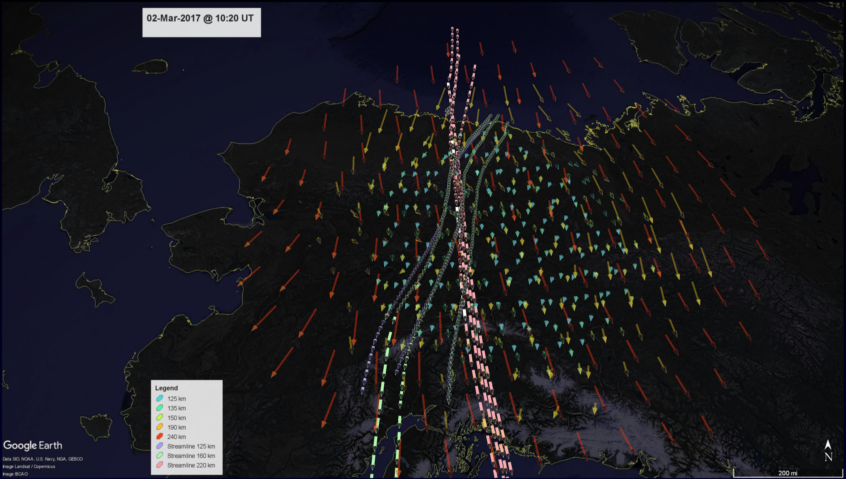
- By 09:40 UT, the southward turning had begun affecting the E-region, at least above northern Alaska.

The Southward Flow Increases



- By 10:00 UT the F-Region Flow was strongly southward, as were the downstream E-region trajectories.

Southward Flow Everywhere



- By 10:20 UT even the E-region had fully succumbed to the southward rotation of the flow.

Conclusions

- All-sky Doppler spectral observations of the $\lambda 630\,\mathrm{nm}$ and $\lambda 558\,\mathrm{nm}$ auroral emissions from several ground-based sites can allow *true 4D reconstructions of the full 3-component thermospheric wind field* over an extended geographic region.
- The winds reconstructed here used evolutionary fitting, based on non-divergent Gaussian radial basis function mutations.
- Comparison of the resulting winds with absolute wind measurements by the TMA chemical release technique show good agreement.
- With the full 4D wind field, it is straightforward to compute both the upstream and downstream trajectories of tracer particles transported by these winds.
- Results show that both upstream and downstream *trajectories passing through a given location can vary dramatically on short time scales* (5-10 minutes.)
- *This behavior can only be derived from the full 4D wind field* – yet it has important consequences for operational understanding of space weather.
- Results to date only span a limited geographic area. Truly understanding transport by thermospheric neutral winds would require a *far more extensive array of SDI instruments.*