Spatial structures of stratospheric gravity waves derived from COSMIC GPS occultation data

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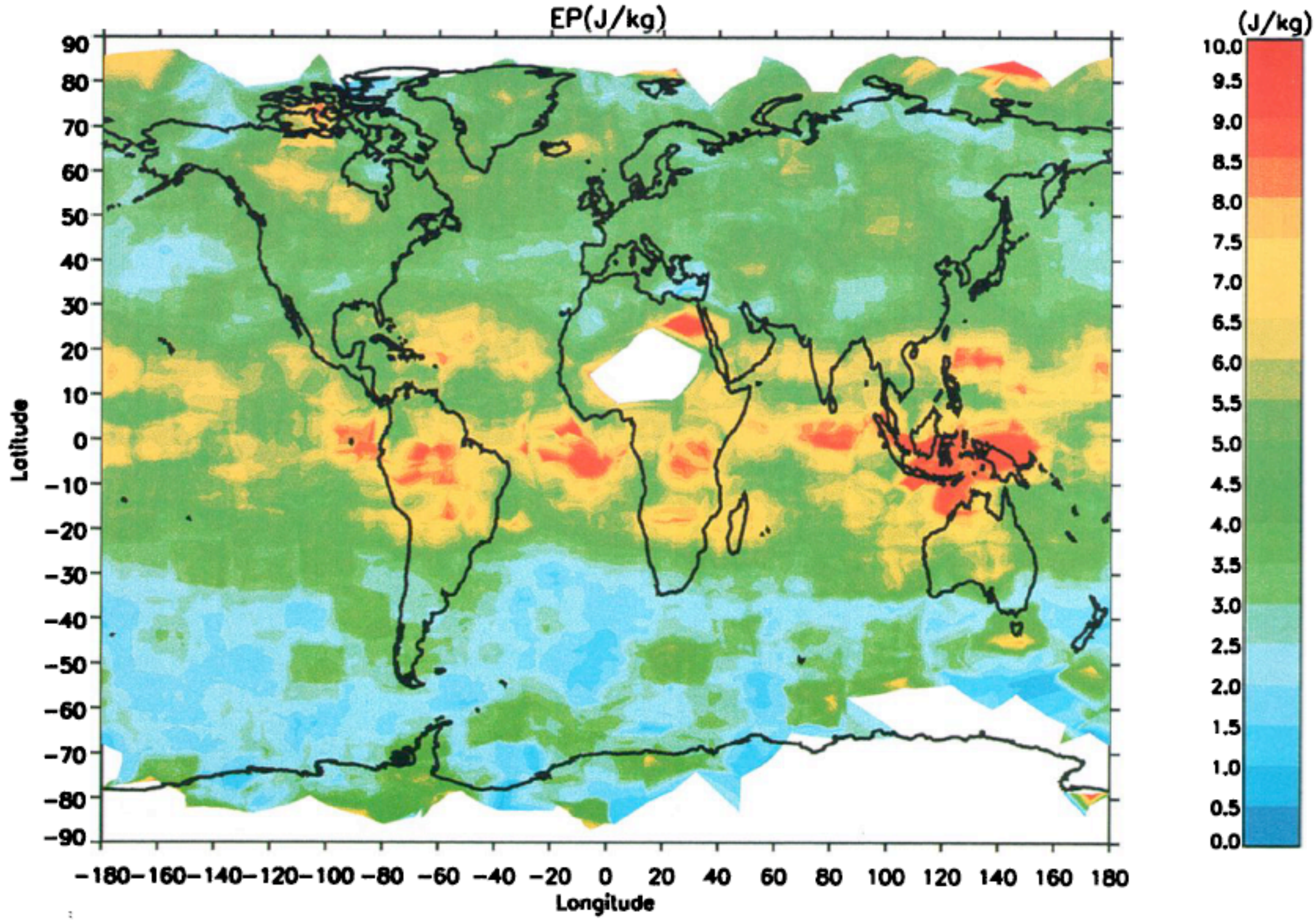
GPS Radio Occultation (RO)

- GPS signals are received by low-earth-orbiting satellites

→ refractivity profiles → Temperature (&humidity in lower-to-mid troposphere)

Tsuda et al (2000) with GPS/MET: 1st GPS RO mission



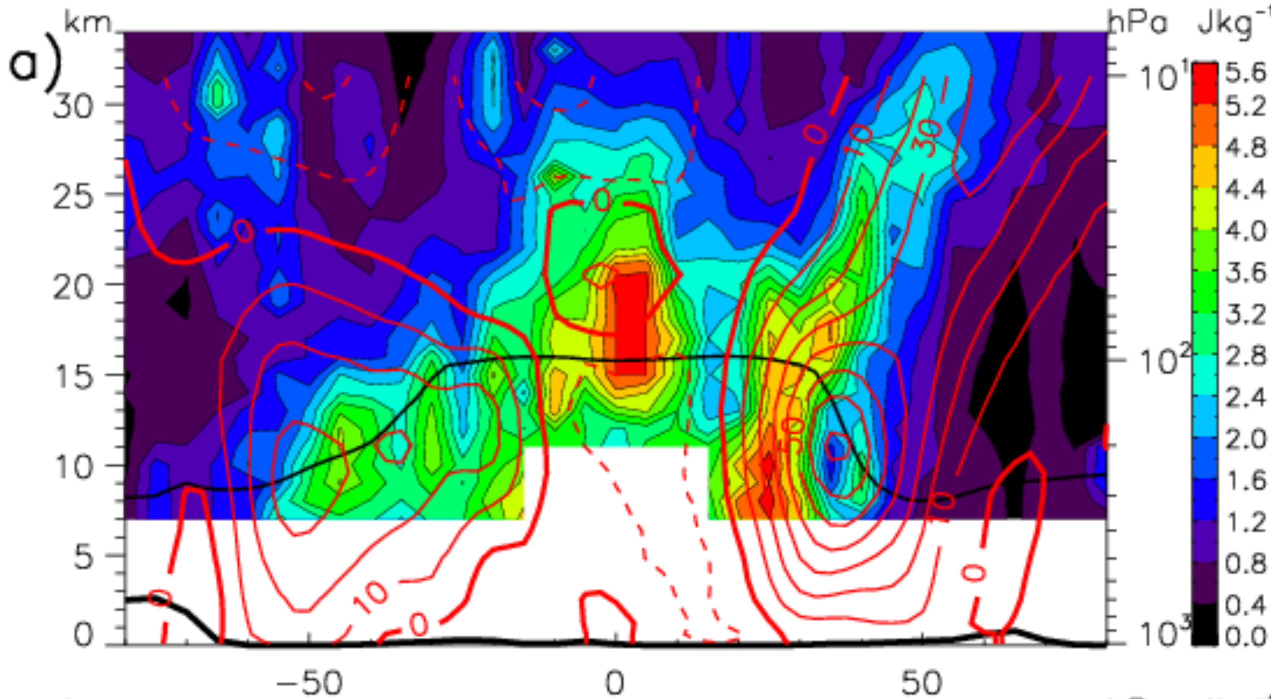
Global distribution of potential energy of stratospheric GWs

COSMIC / FORMOSAT-3

- by UCAR(US) & NSPO(Taiwan)
- Launch: Apr 2006
- 6 LEO satellites (recv 2 ways)

→ substantial increase of RO measurements (~2500 per day)

S. Alexander et al 2008



GW energy averaged between 130E-150E
23-28 Dec 2006 using COSMIC data

Purpose of this study

- To study spatial structures of gravity waves using multiple GPS RO profiles nearby
  - Earlier studies: profile-base

- Merit: Good vertical resolution (1km or better)
- Demerit: Horizontal resolution/sampling lower than conventional instruments (e.g. AIRS)

On the average, COSMIC sampling is still too sparse (1 per 500km*500km*1day) → Examine satellite orbits

- Launched by a single rocket (inclination 72°)
- Alt. raised 1 per ~2 months (500km → 800km)

Liou et al (2007)

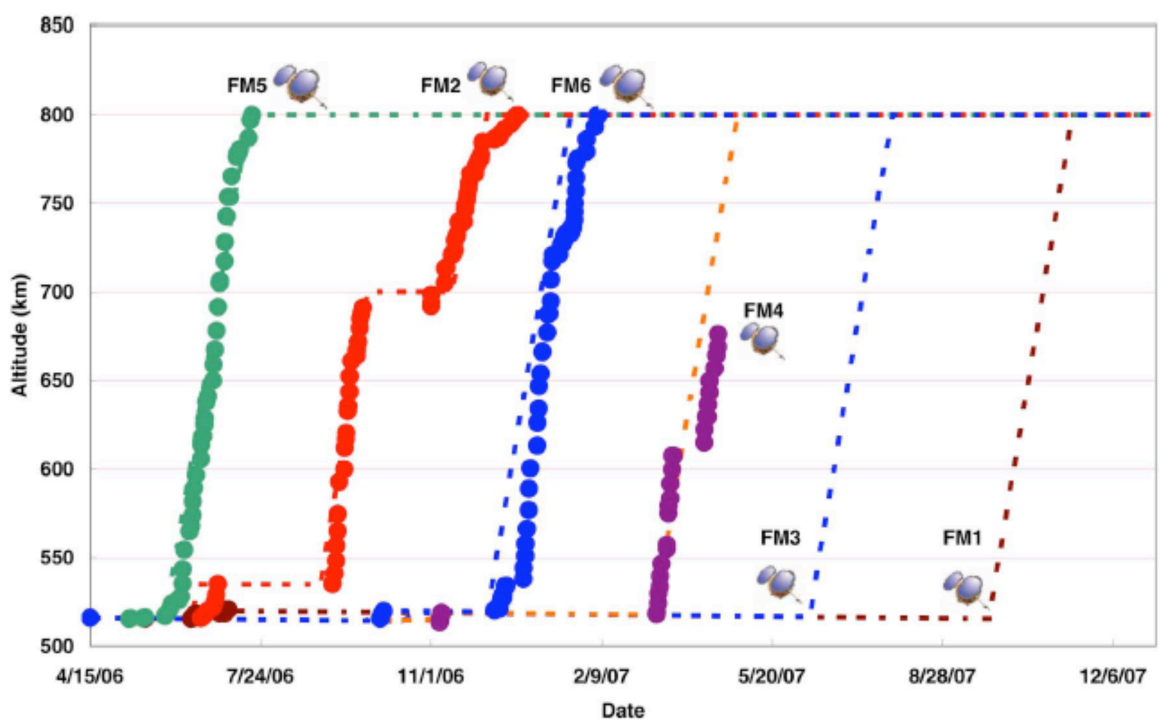
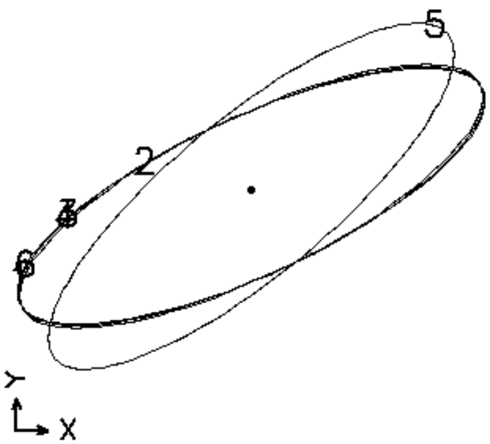
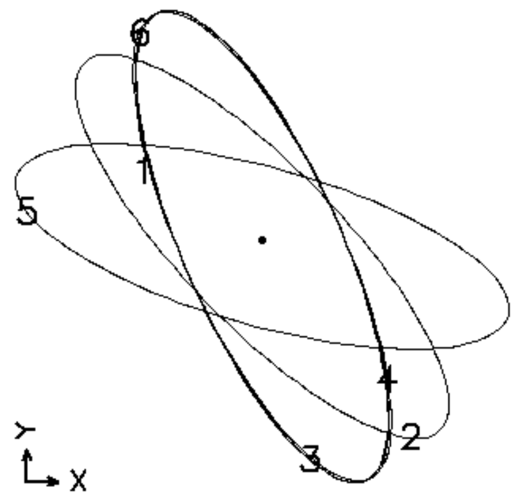


Fig. 4. FORMOSAT-3 constellation deployment profile versus time. The FORMOSAT-3 satellites flight model no. 2 (FM2), no. 5 (FM5), and no. 6 (FM6) have arrived to the 800-km orbit in early February 2007. The final mission constellation configuration will arrive to the 800-km orbit around November 30, 2007.

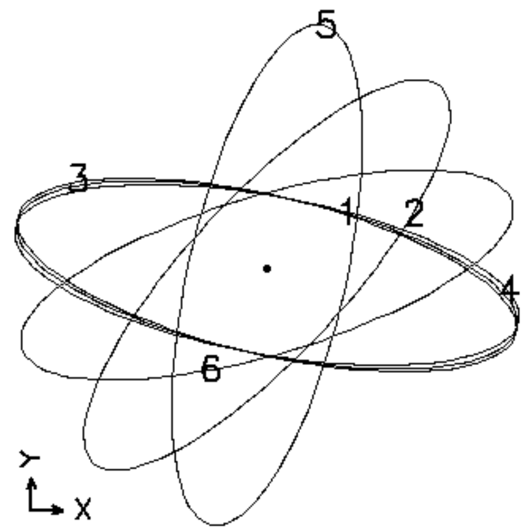
LEO orbits relative to the stars (ECI coordinate)



2006-08-12



2006-12-06

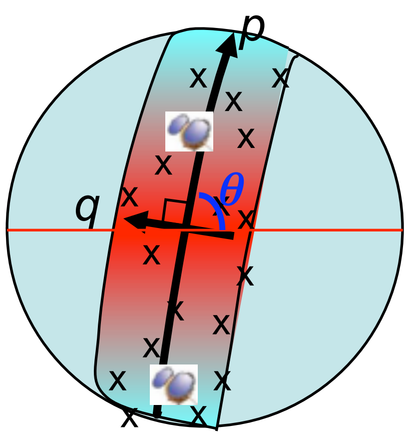


2007-04-16

3 LEOs still on one orbit after 1 year since launch

→ High data acquisition rate around the orbit

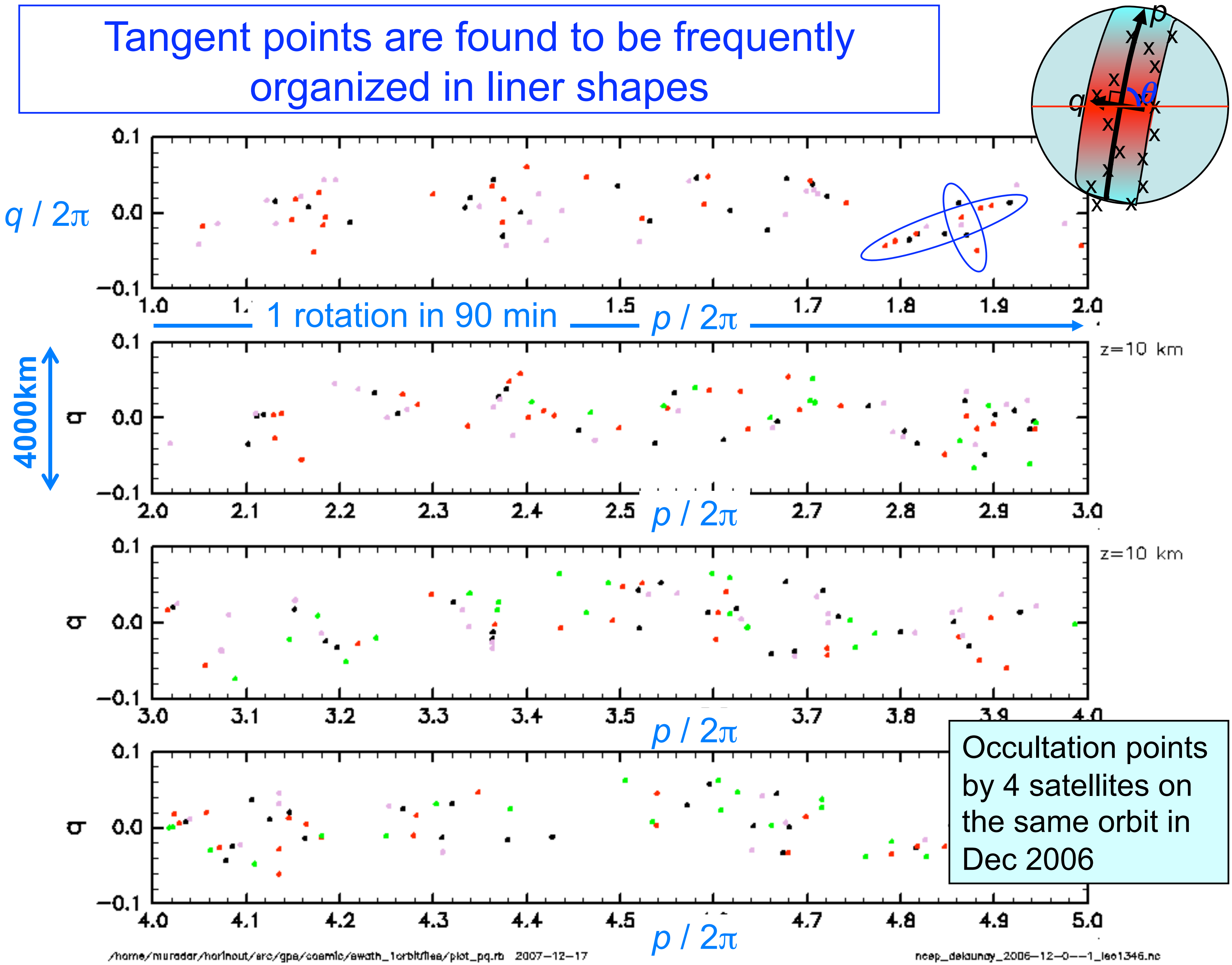
We focus on the neighborhood of the orbit having multiple satellites



Coordinate transformation

- *p*: along the satellite track
- *q*: perp to *p*

Tangent points are found to be frequently organized in liner shapes



Strategy

- Extract groups of data points organized linearly → Obtain vertical cross sections
  - Snapshots within ~ 1 hours → Good to analyze short-lived disturbances with high vertical resolution

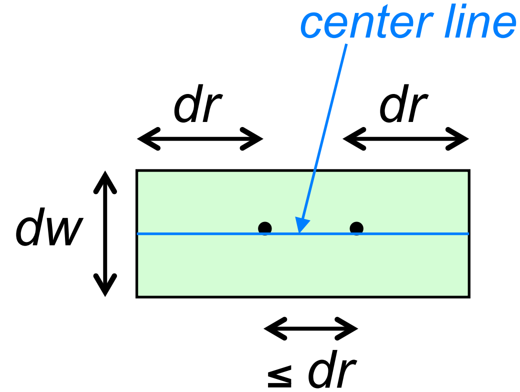
Dataset used

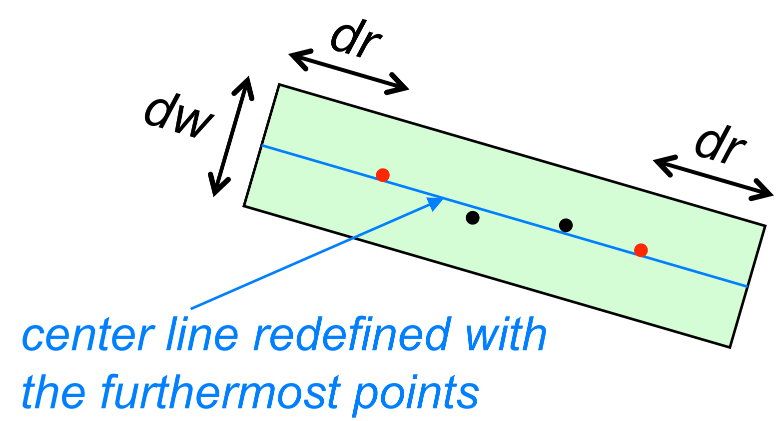
- COSMIC Level 2 by UCAR (dry temperature)
  - Used: Dec 2006 – Feb 2007

Heuristic Line Clustering

- Algorithm

1. Initial pairs: nearest neighbors (distance ≤ *dr* , and ≥ a threshold)
2. Find points in a rectangle like this:
3. If found, add & extend the rectangle like this: (back to 2)

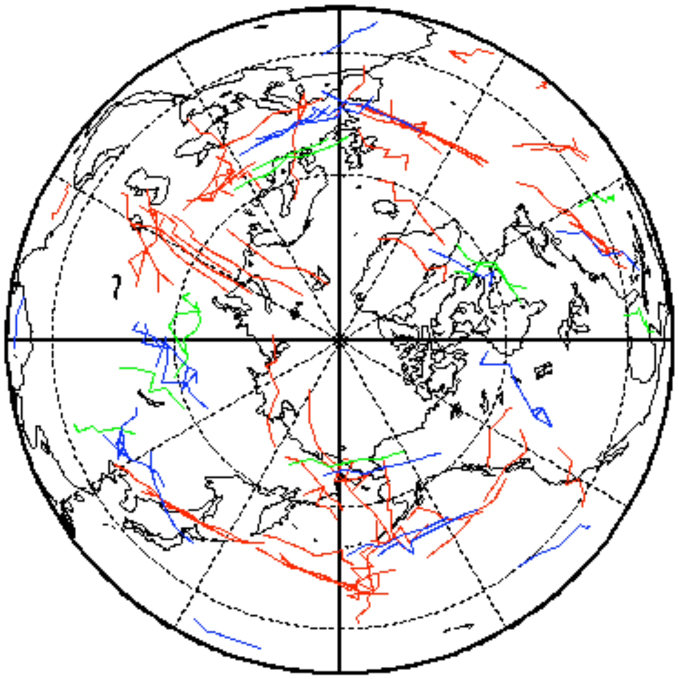




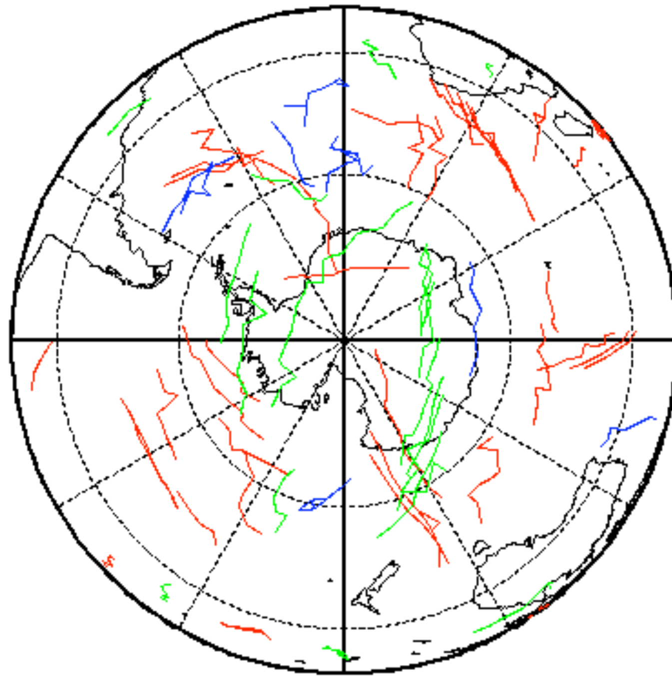
Extracted lines

dr = *dw* = 600 km

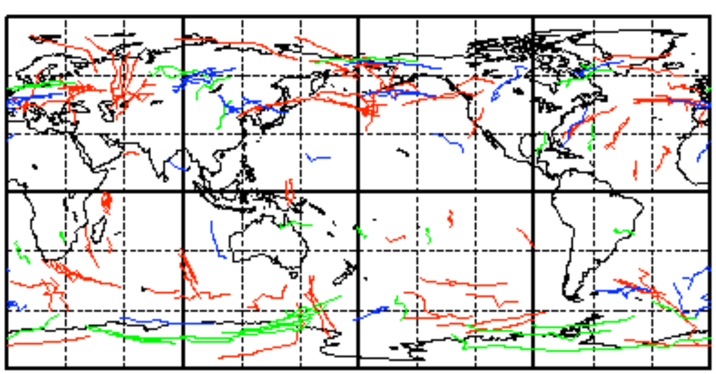
NH



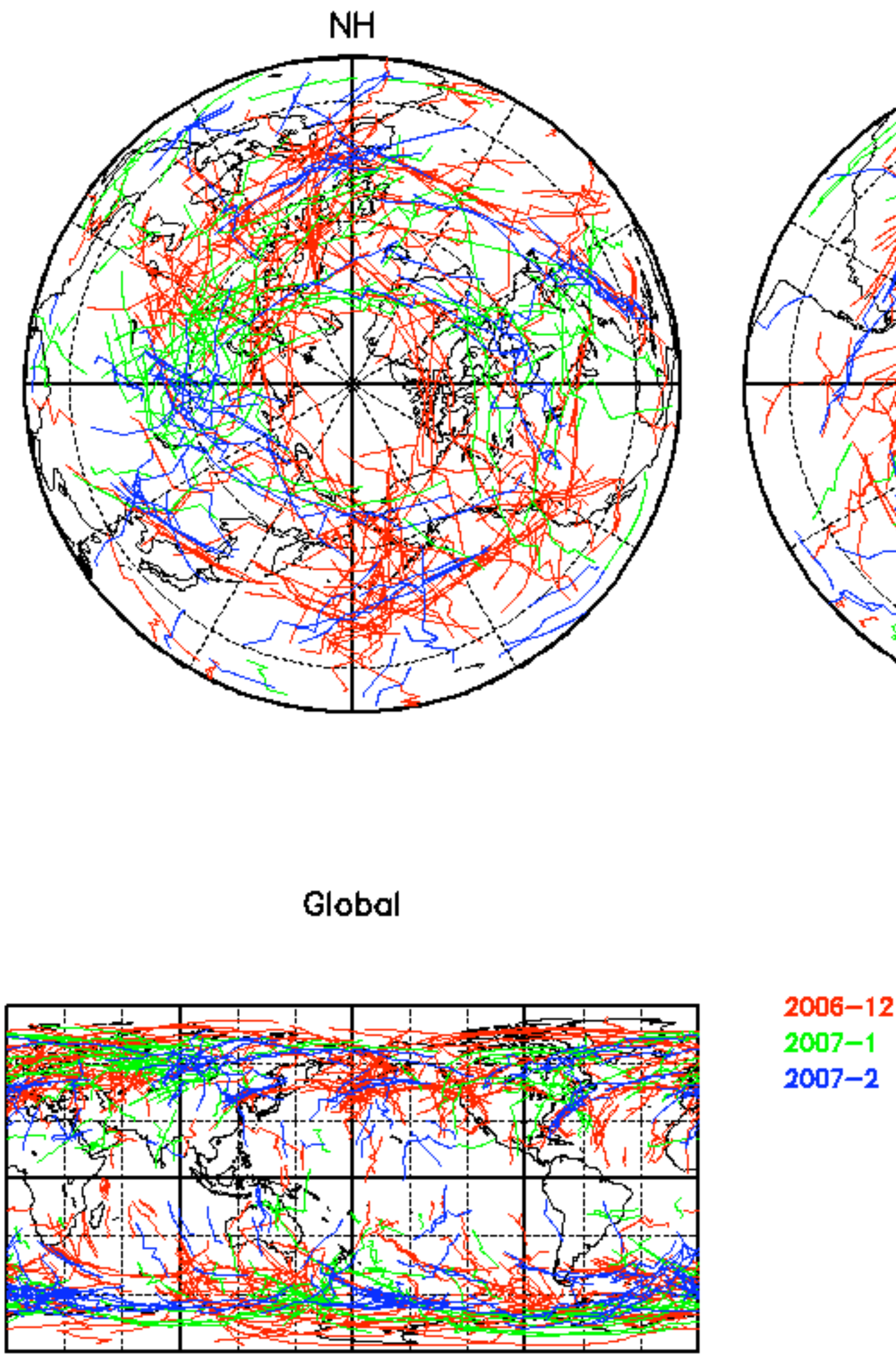
SH



Global



2006–12
2007–1
2007–2



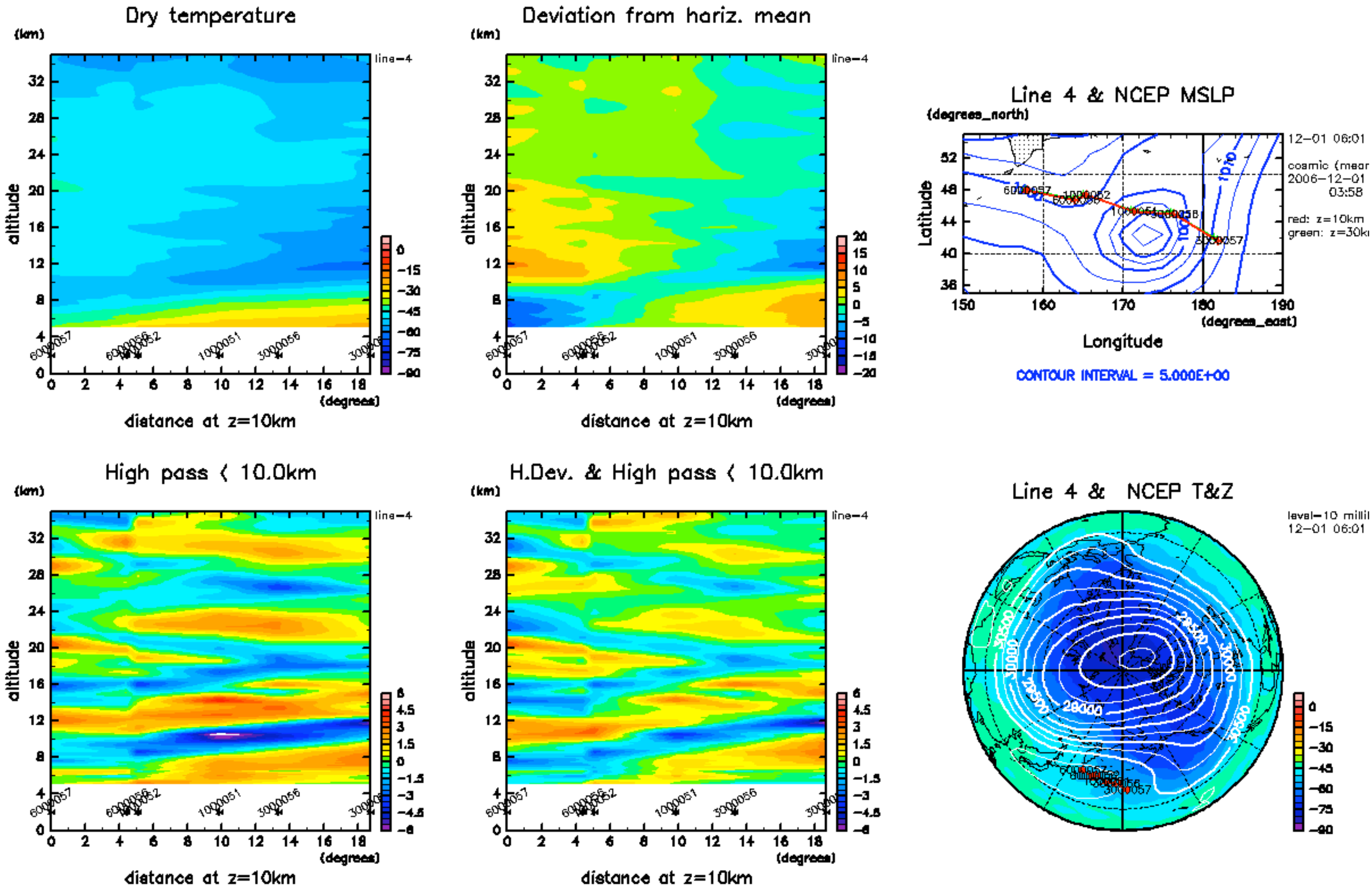
Extracted lines

dr = 1000 km

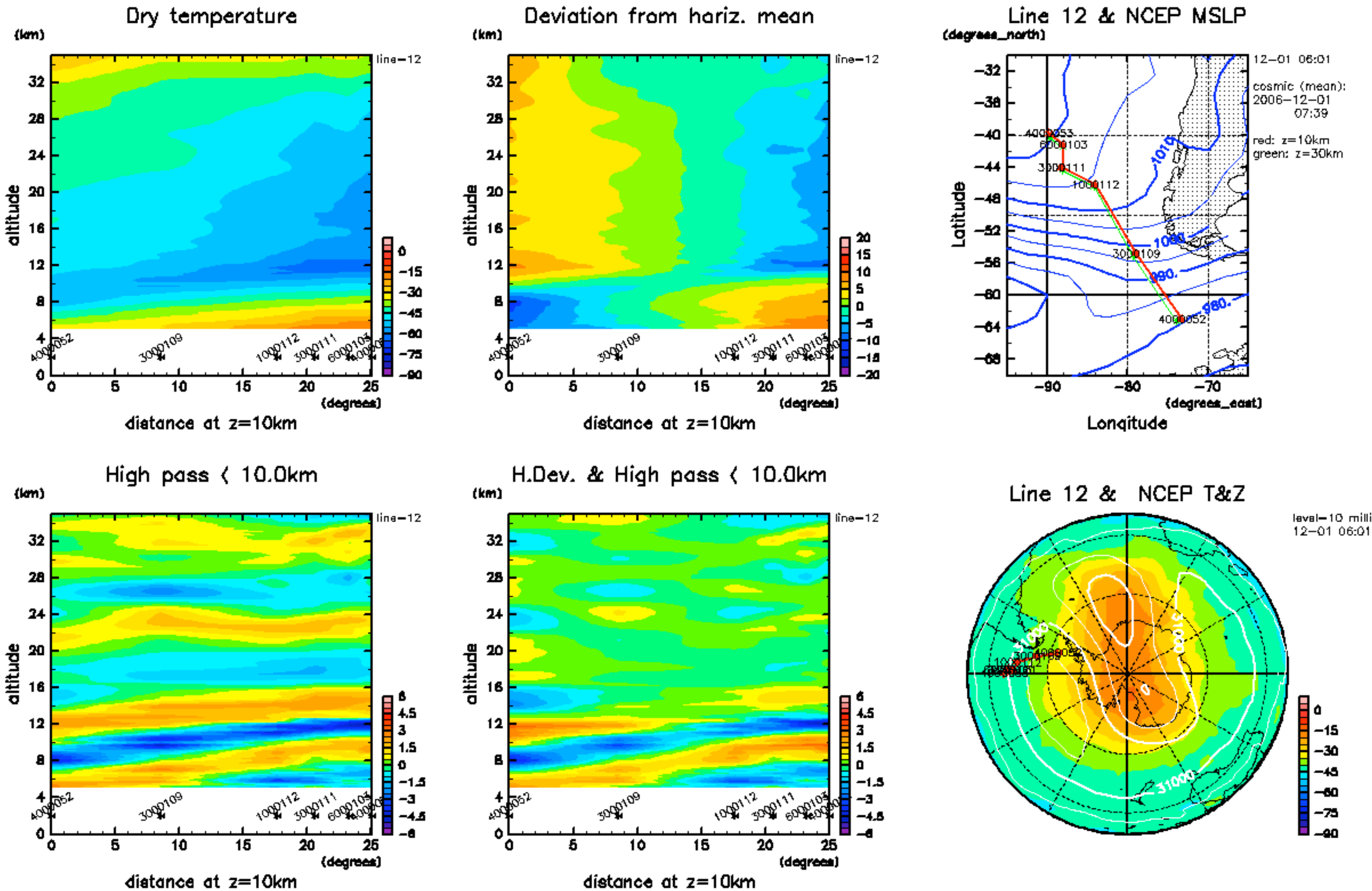
dw = 600 km

✓ Dense in mid to high latitudes
(Rarely crossing the equator)

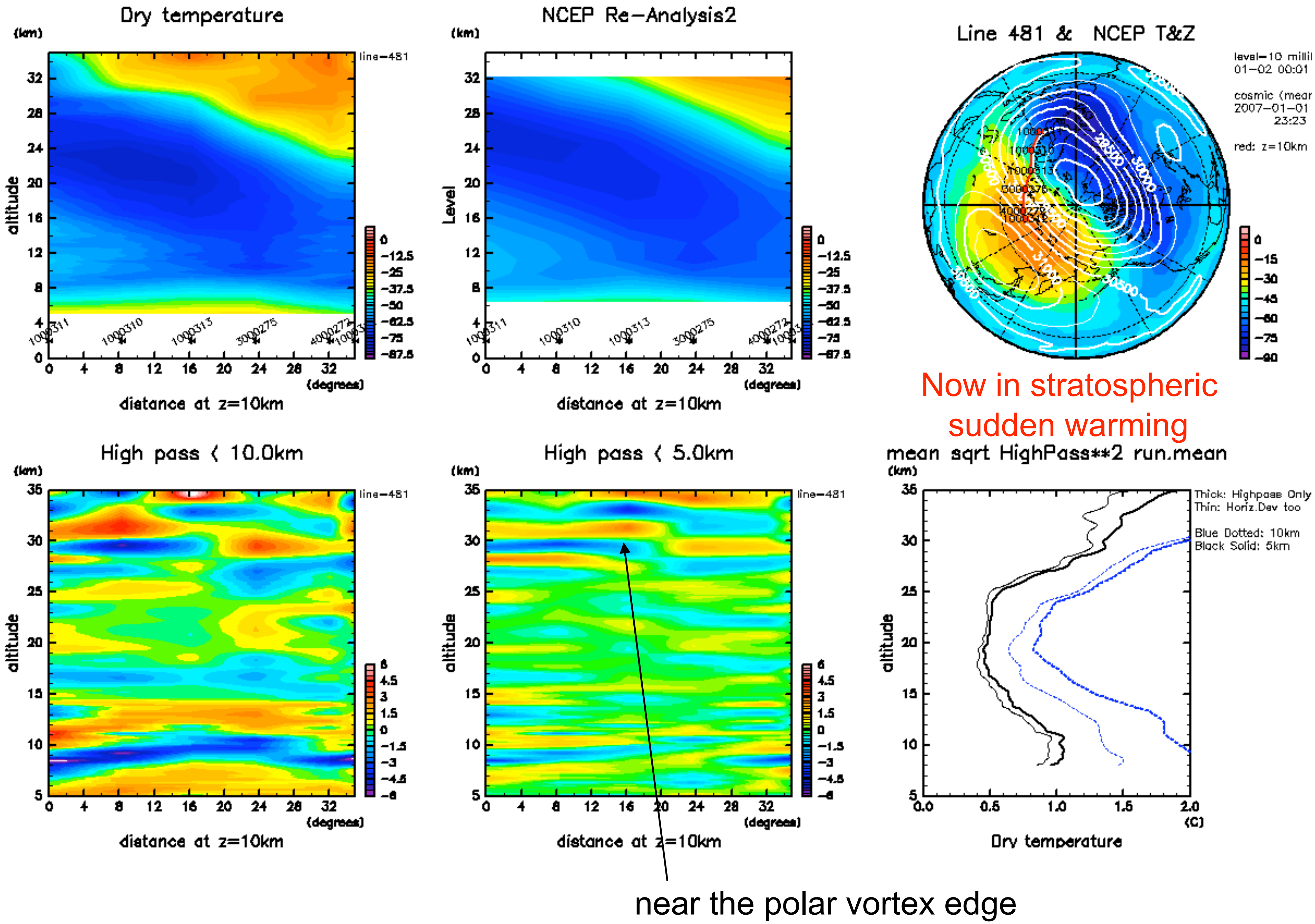
✓ Hemispheric, preferred longitudes moving eastward slowly, with wave number=2

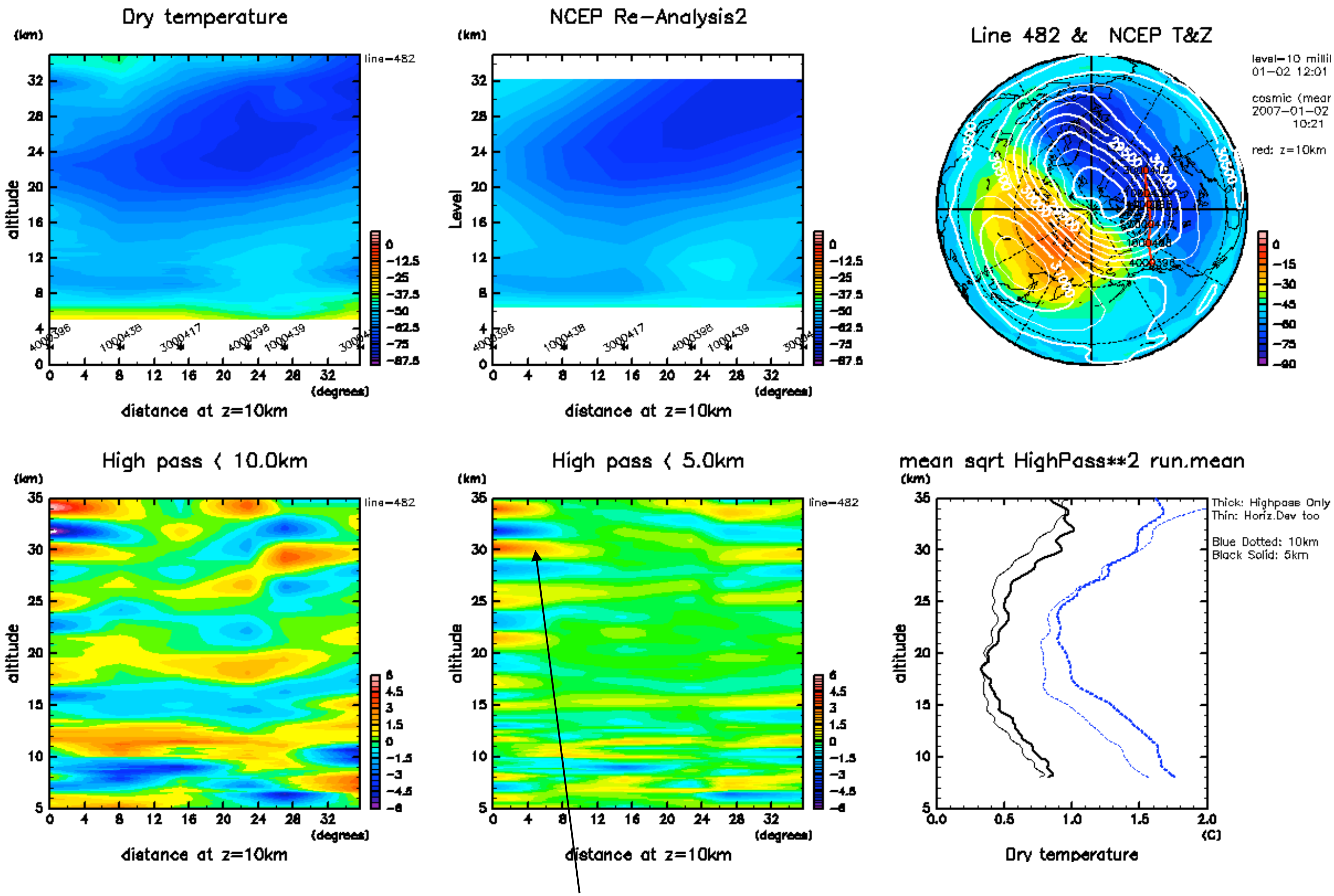


Dry temperature
Deviation from hariz. mean
Line 4 & NCEP MSLP
High pass < 10.0km
H.Dev. & High pass < 10.0km
Line 4 & NCEP T&Z
altitude
(km)
line-4
distance at z=10km
(degrees)
Latitude
(degrees_north)
Longitude
(degrees_east)
12-01 06:01
cosmic (mear
2006-12-01
03:58
red: z=10km
green: z=30k
CONTOUR INTERVAL = 5.000E+00
level=10 milli
12-01 06:01

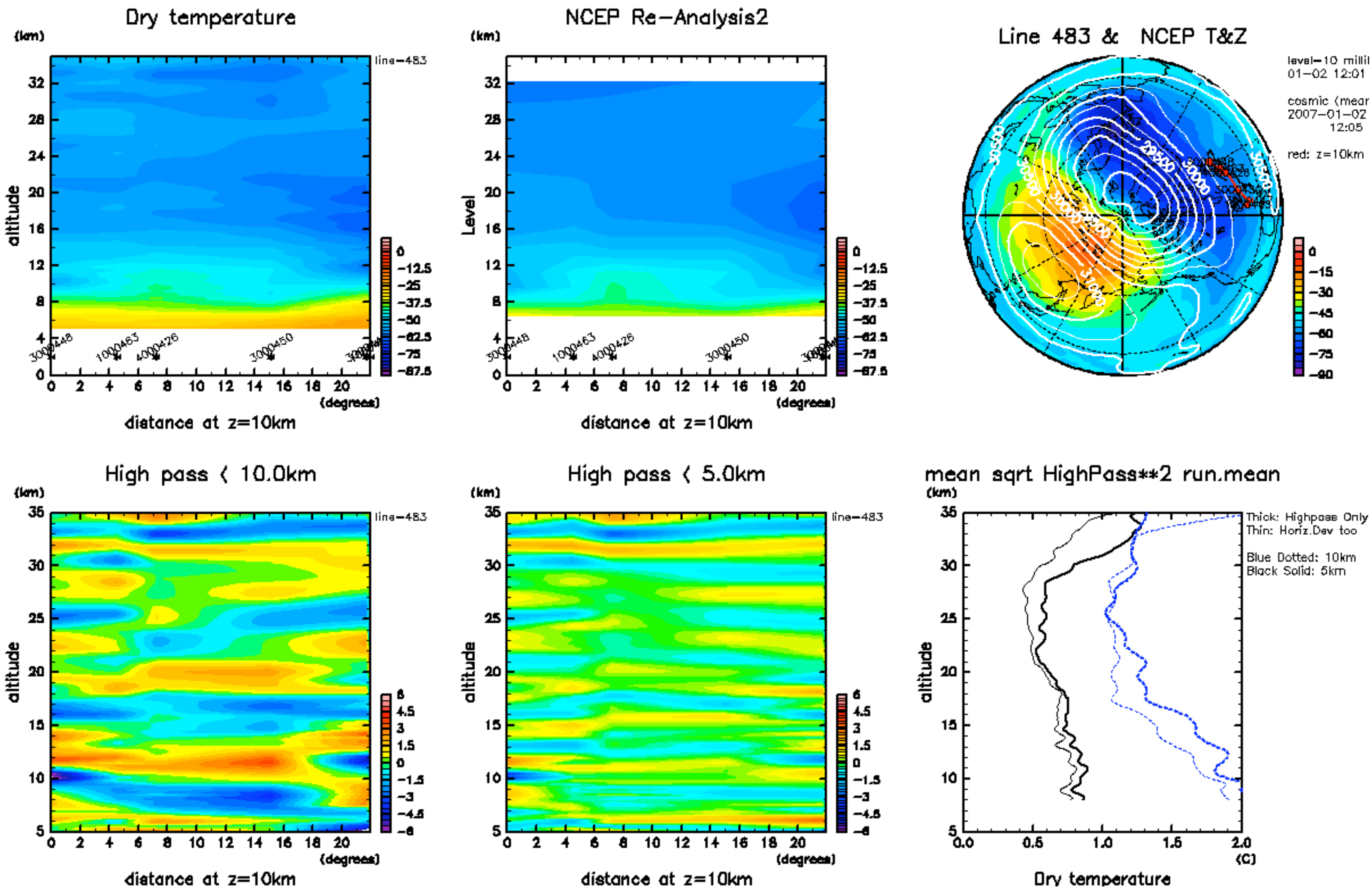


Dry temperature
Deviation from horiz. mean
Line 12 & NCEP MSLP
High pass < 10.0km
H.Dev. & High pass < 10.0km
Line 12 & NCEP T&Z
(km)
altitude
distance at z=10km
(degrees)
line-12
(degrees_north)
Latitude
Longitude
(degrees_east)
12-01 06:01
cosmic (mean):
2006-12-01
07:39
red: z=10km
green: z=30km
level=10 millil
12-01 06:01
4000052
3000109
1000112
3000111
6000103
4000053

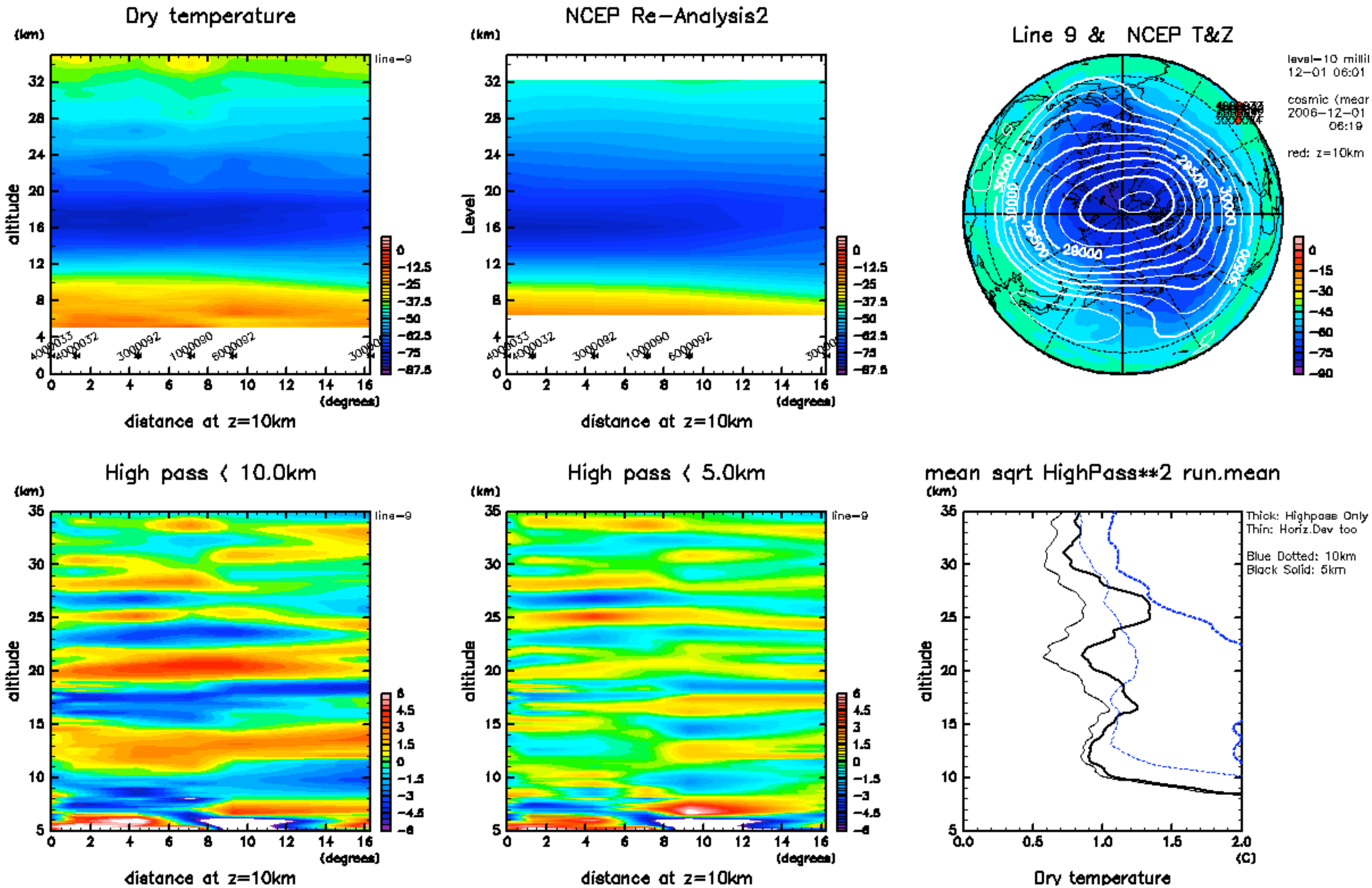

Dry temperature
line-481
altitude (km)
distance at z=10km (degrees)
NCEP Re-Analysis2
Level (km)
Line 481 & NCEP T&Z
level=10 milli
01-02 00:01
cosmic (mear
2007-01-01
23:23
red: z=10km
Now in stratospheric sudden warming
High pass < 10.0km
High pass < 5.0km
mean sqrt HighPass**2 run.mean
Thick: Highpass Only
Thin: Horiz.Dev too
Blue Dotted: 10km
Black Solid: 5km
Dry temperature (C)
near the polar vortex edge



near the polar vortex edge

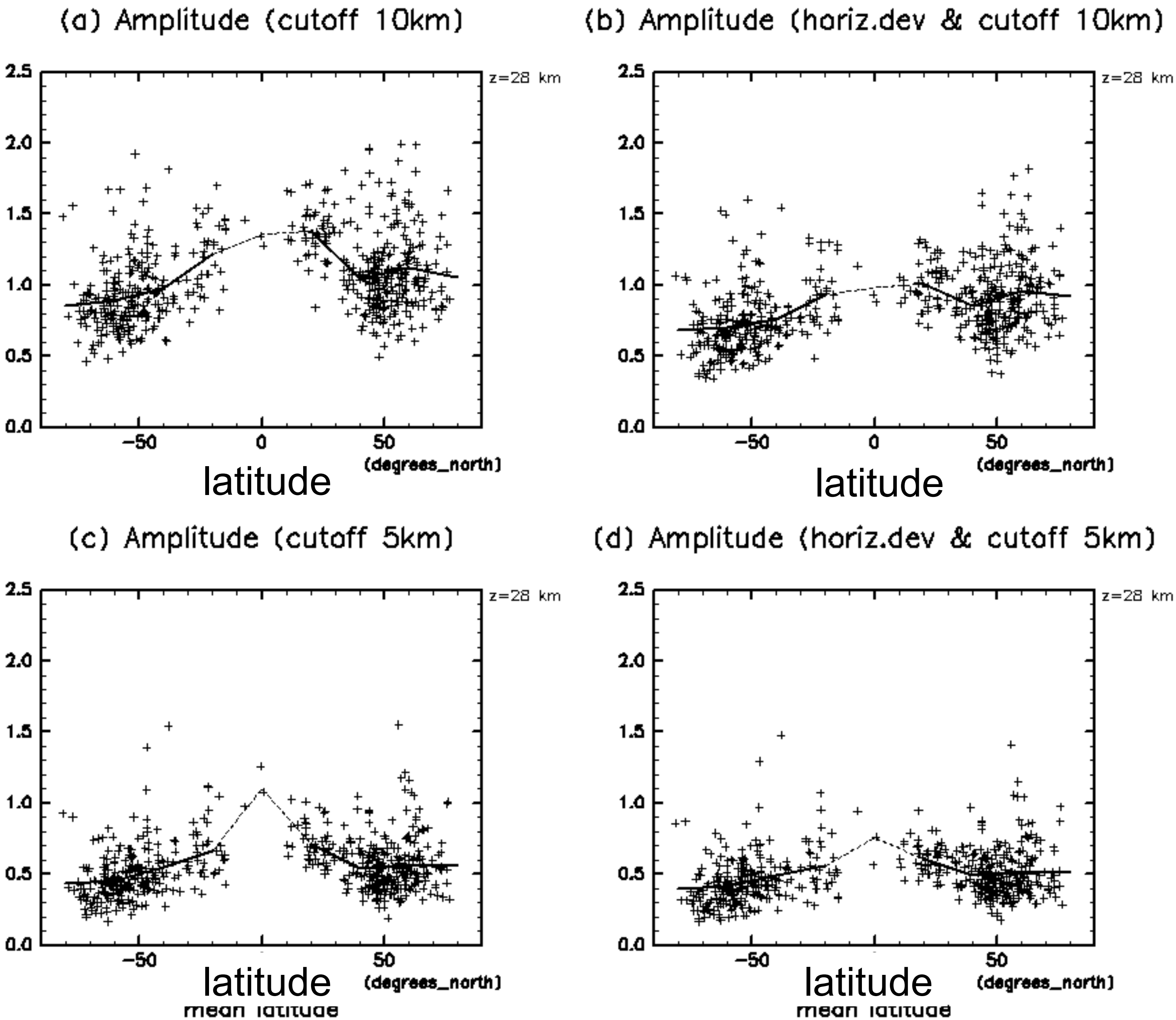


Dry temperature
NCEP Re-Analysis2
Line 483 & NCEP T&Z
level=10 millil
01-02 12:01
cosmic (mear
2007-01-02
12:05
red: z=10km
line-483
altitude
Level
(km)
distance at z=10km
(degrees)
High pass < 10.0km
High pass < 5.0km
mean sqrt HighPass**2 run.mean
Thick: Highpass Only
Thin: Horiz.Dev too
Blue Dotted: 10km
Black Solid: 5km
Dry temperature
(C)



Dry temperature
NCEP Re-Analysis2
Line 9 & NCEP T&Z
level=10 millil
12-01 06:01
cosmic (mear
2006-12-01
06:19
red: z=10km
line-9
altitude
Level
(km)
distance at z=10km
(degrees)
High pass < 10.0km
High pass < 5.0km
mean sqrt HighPass**2 run.mean
Thick: Highpass Only
Thin: Horiz.Dev too
Blue Dotted: 10km
Black Solid: 5km
Dry temperature
(C)

Amplitudes at 28km using lines with lengths 1500 ~ 3000 km



Preusse 2006

- Mean horizontal wavelength estimated for Aug 1997 & Aug 2003 from CRISTA data (infrared limb sounder) using adjacent profile pairs

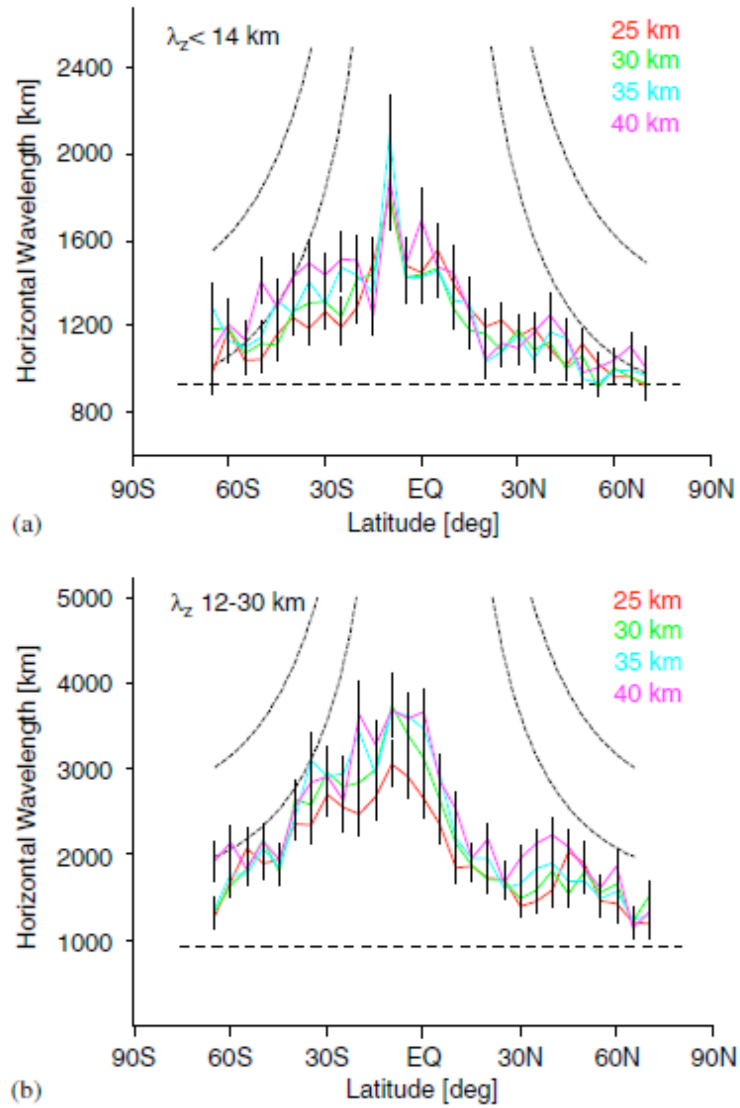
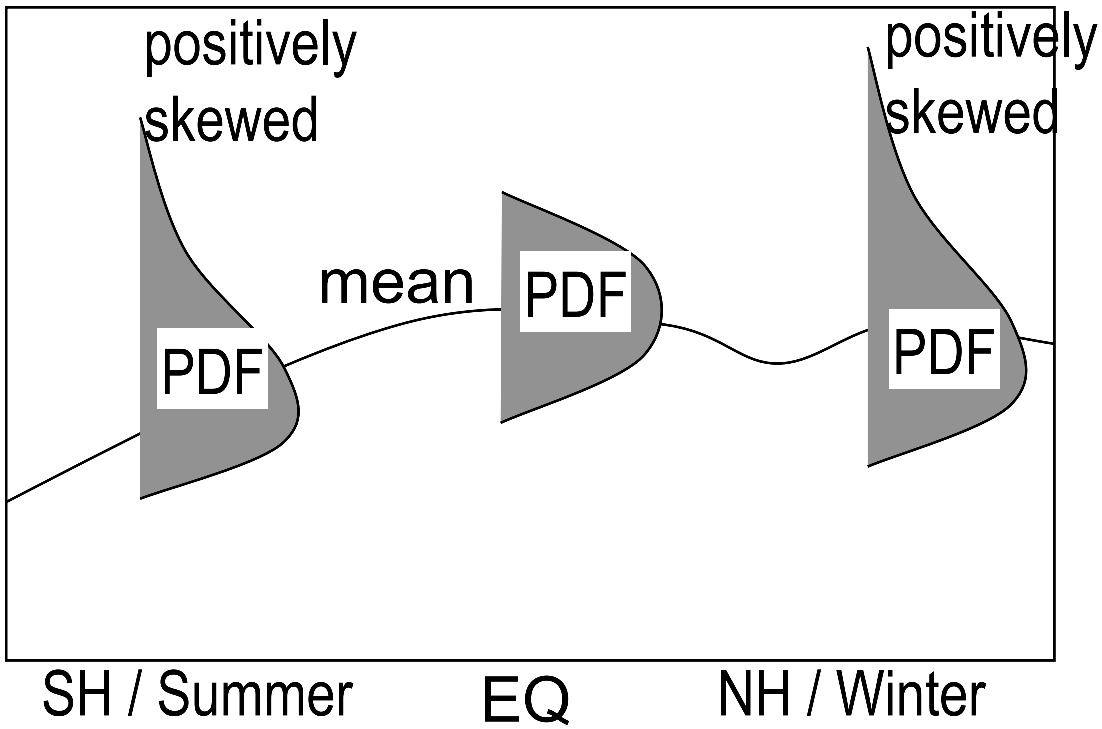


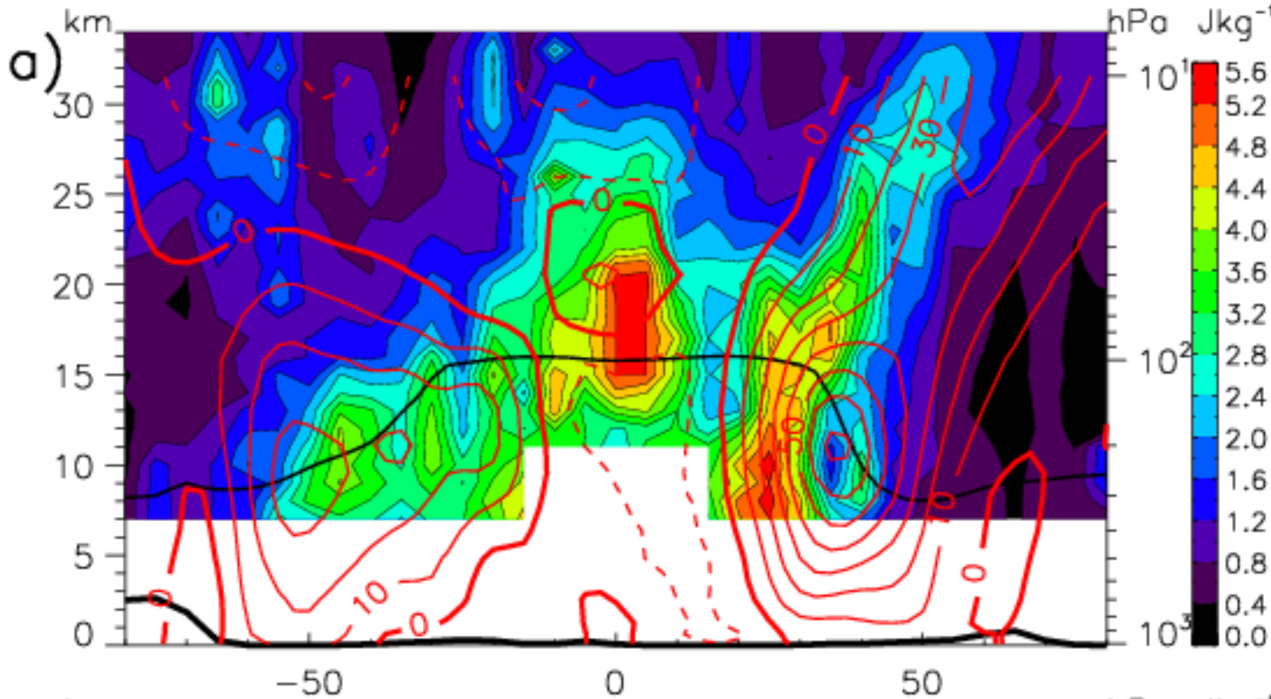
Fig. 3. Zonal mean horizontal wavelength $\bar{\lambda}_h = 2\pi/\bar{k}$ measured by CRISTA-2 (color code gives altitude), horizontal wavelength ensemble average lower limit (horizontal line), and upper limit for two values of constant ω/f (black dashed). The upper panel shows short vertical wavelengths, the lower panel shows long vertical wavelengths. For details see text.

Features of GW amplitudes in *T*

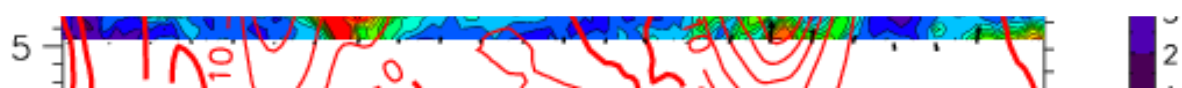
(cutoff: 10 km)



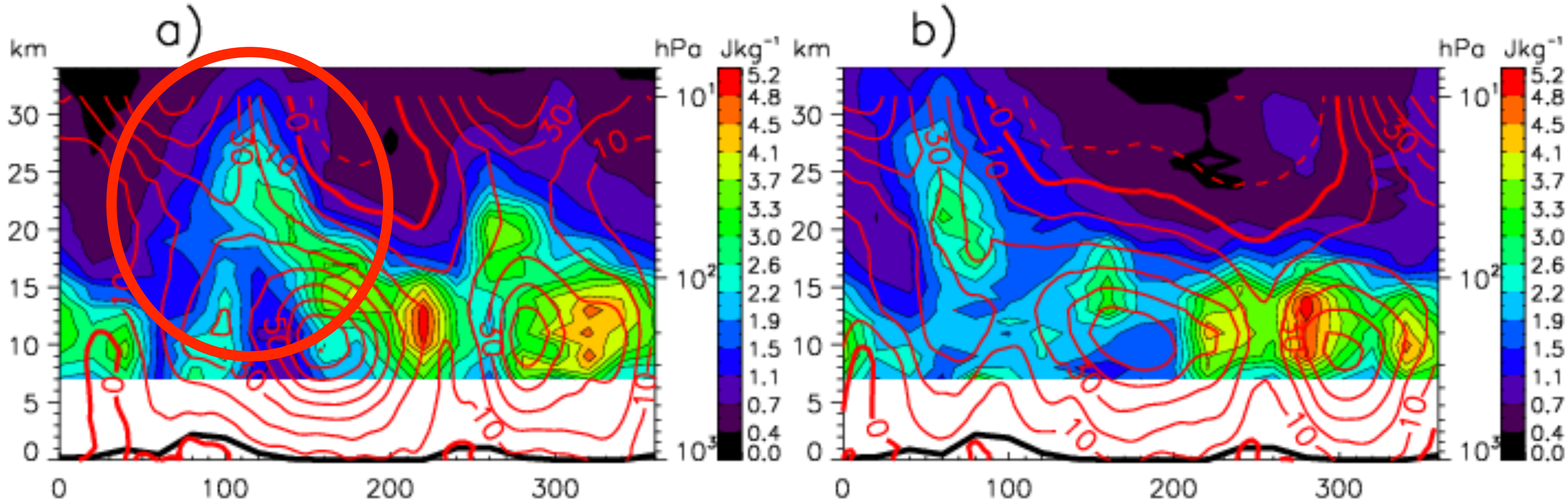
S. Alexander et al 2008 (again)



GW energy averaged between 130E-150E
23-28 Dec 2006 using COSMIC data

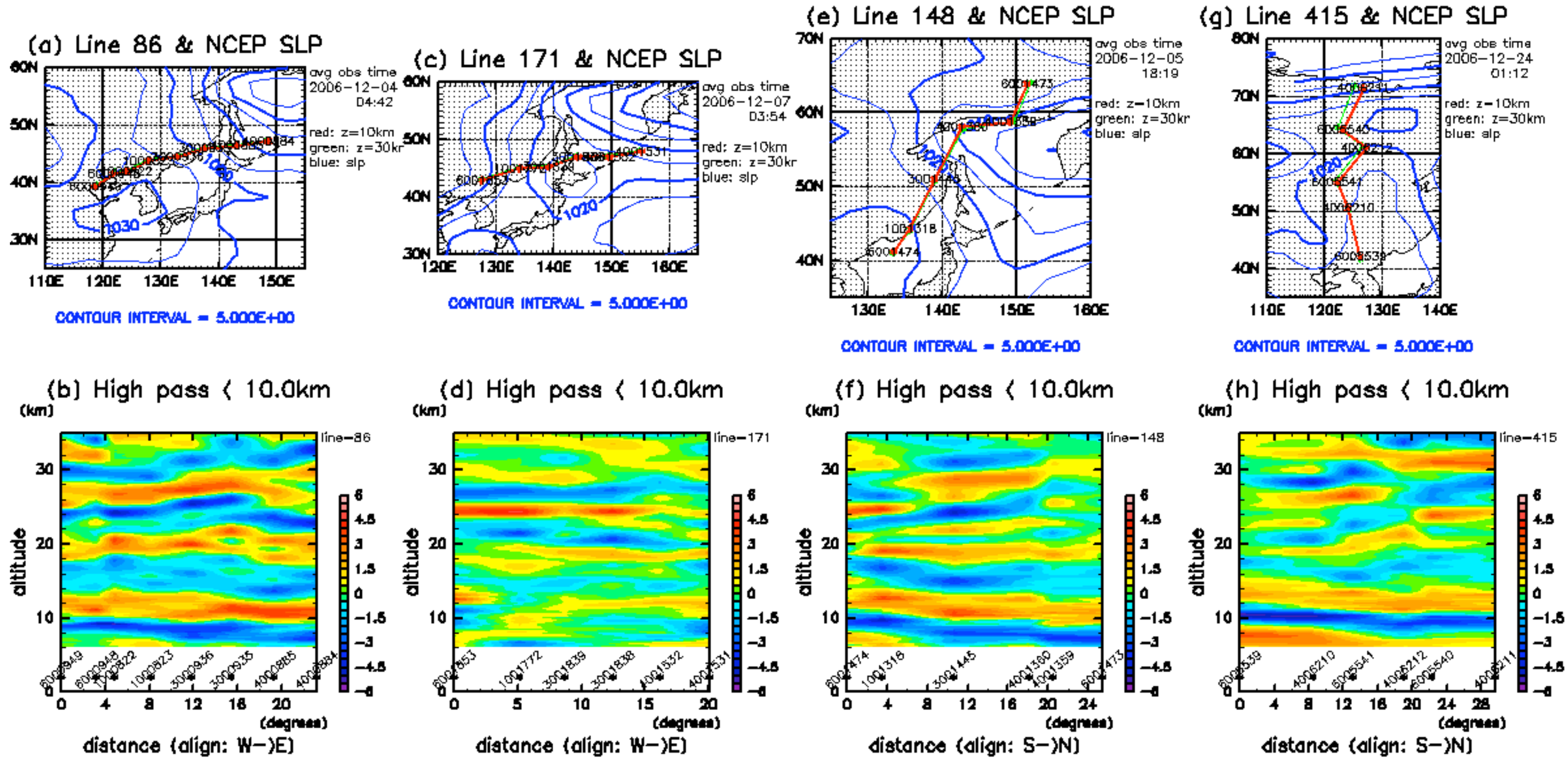


Alexander et al 2008

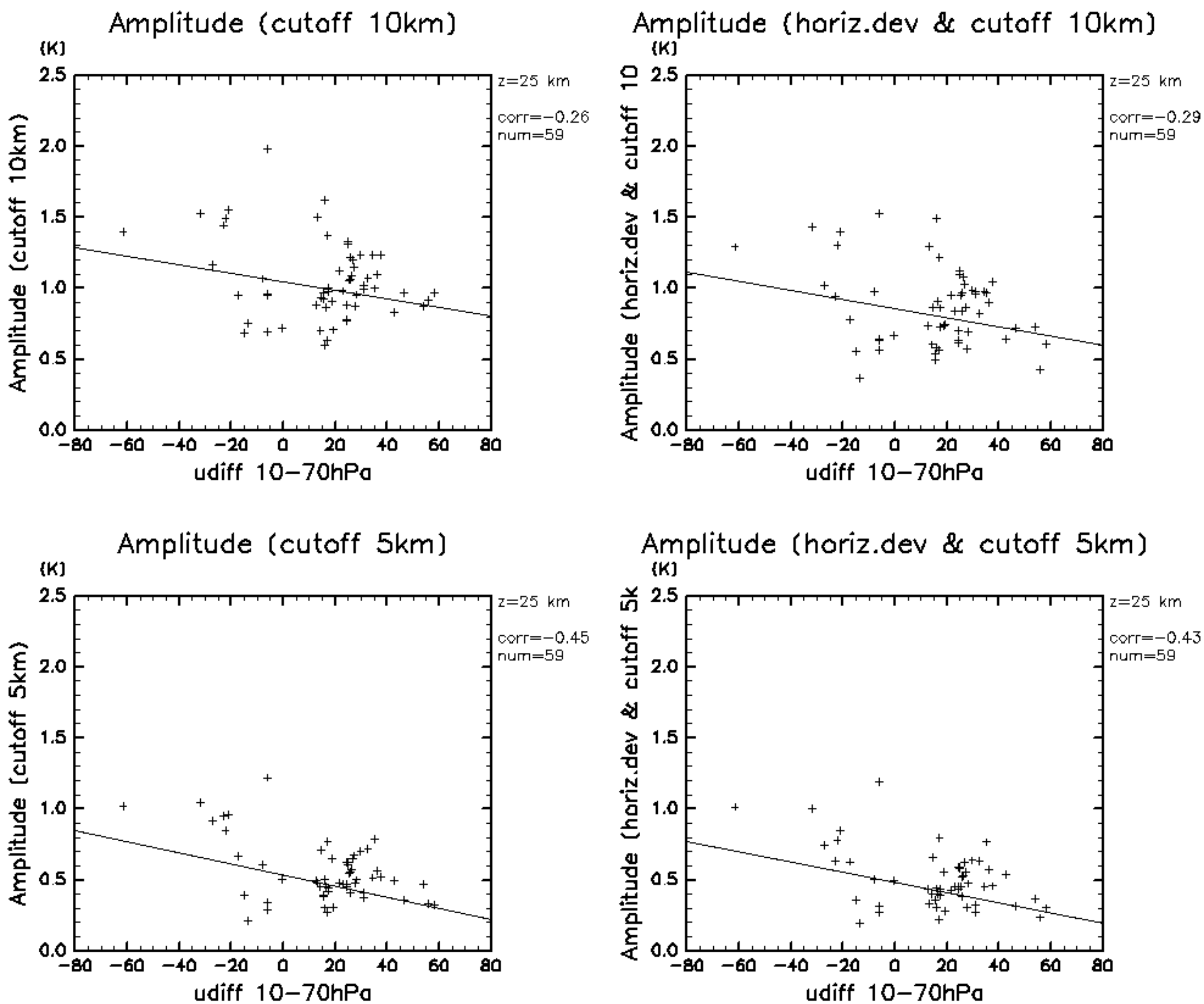


GW energy averaged at 40N using COSMIC data
(a) 29 Nov-5 Dec 2006 (b) 24-30 Dec 2006

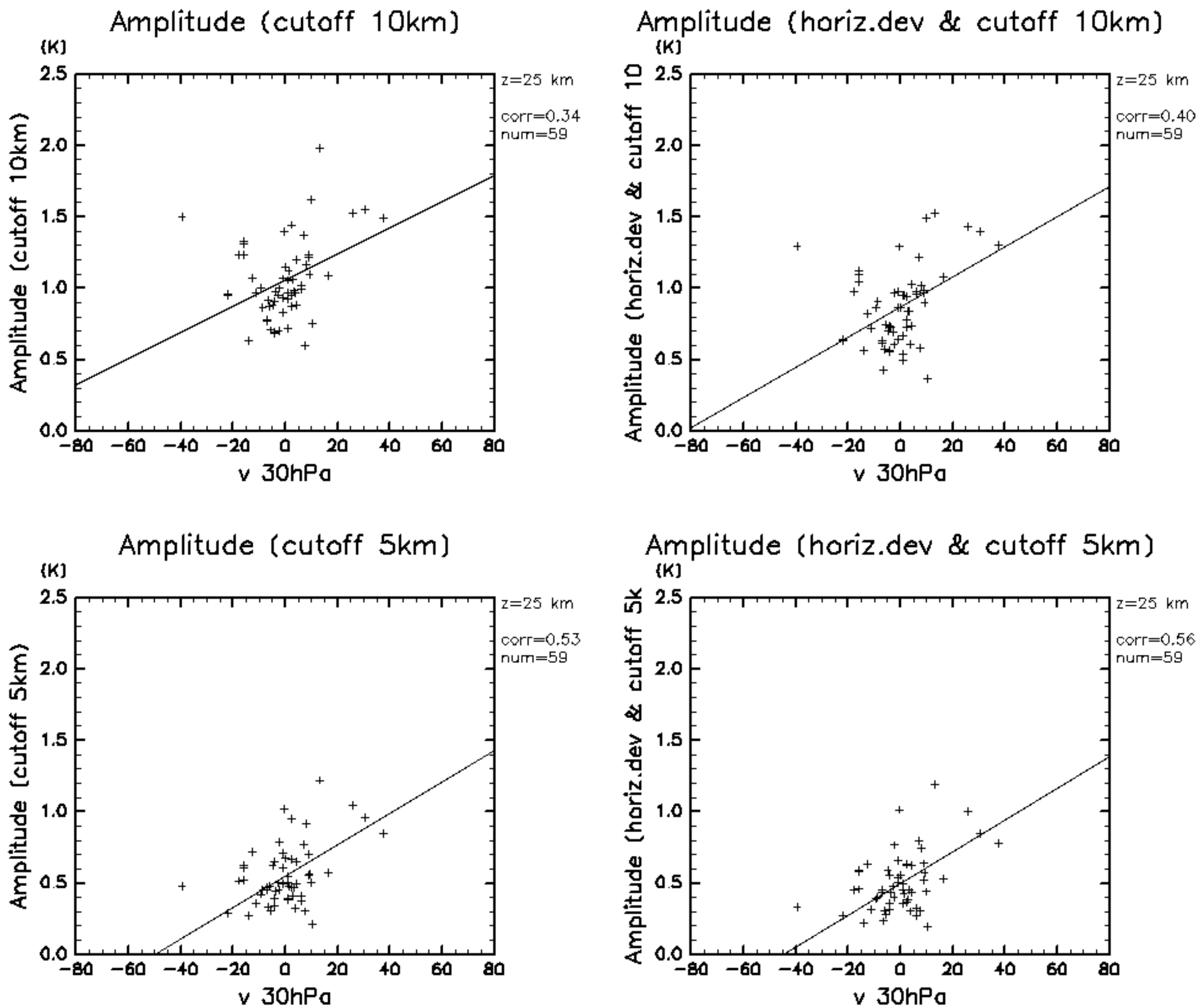
Winter NH cases



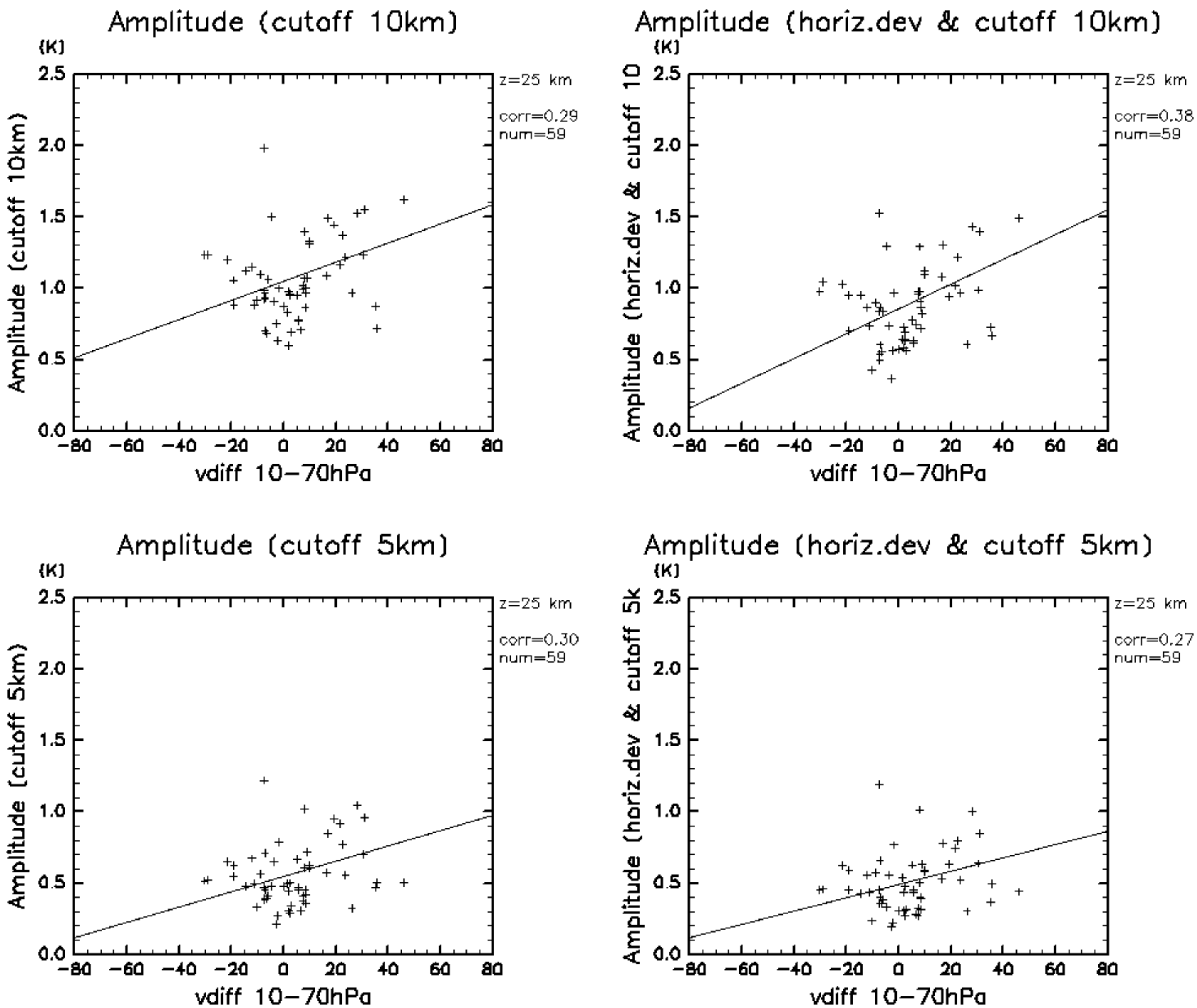
T amp (25km) vs *U* shear (10 – 70hPa) 40-65N



T amp (25km) vs *V* (30hPa)   40-65N

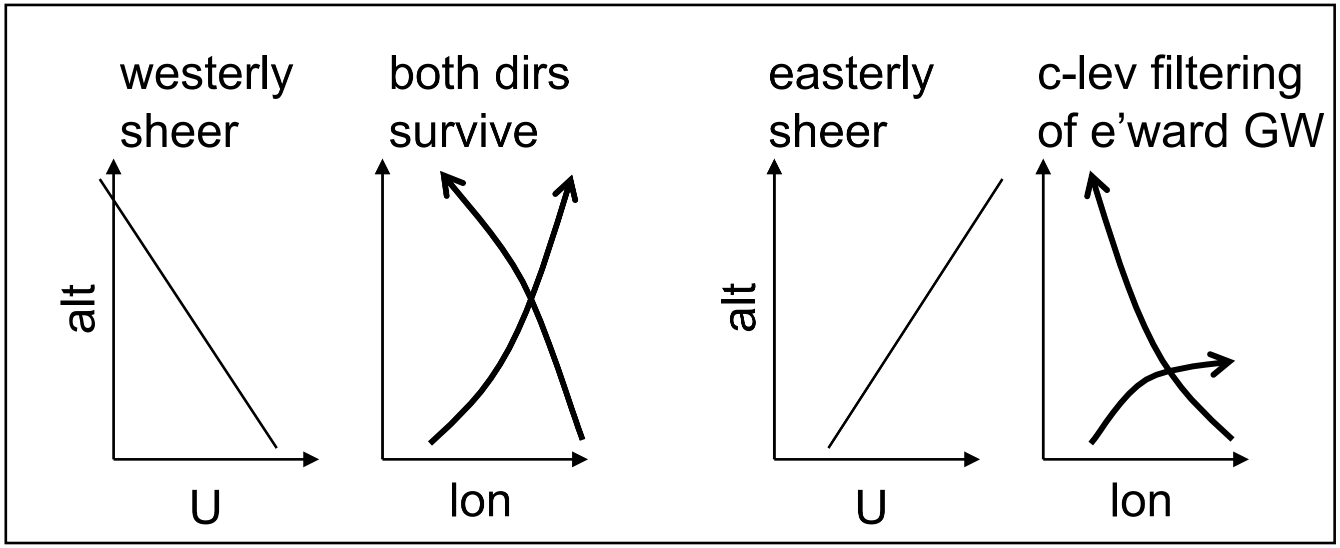


T amp (25km) vs *V* shear (10 – 70hPa)   40-65N

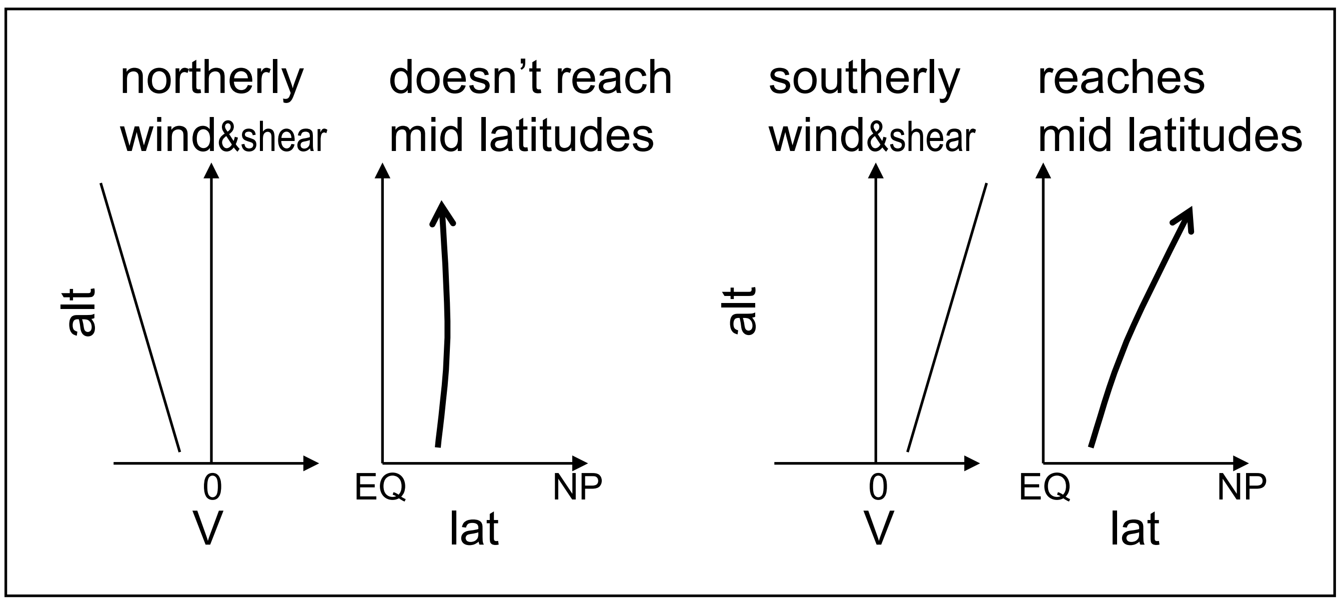


GW propag directions and mean winds

Zonal propagation



Meridional propagation



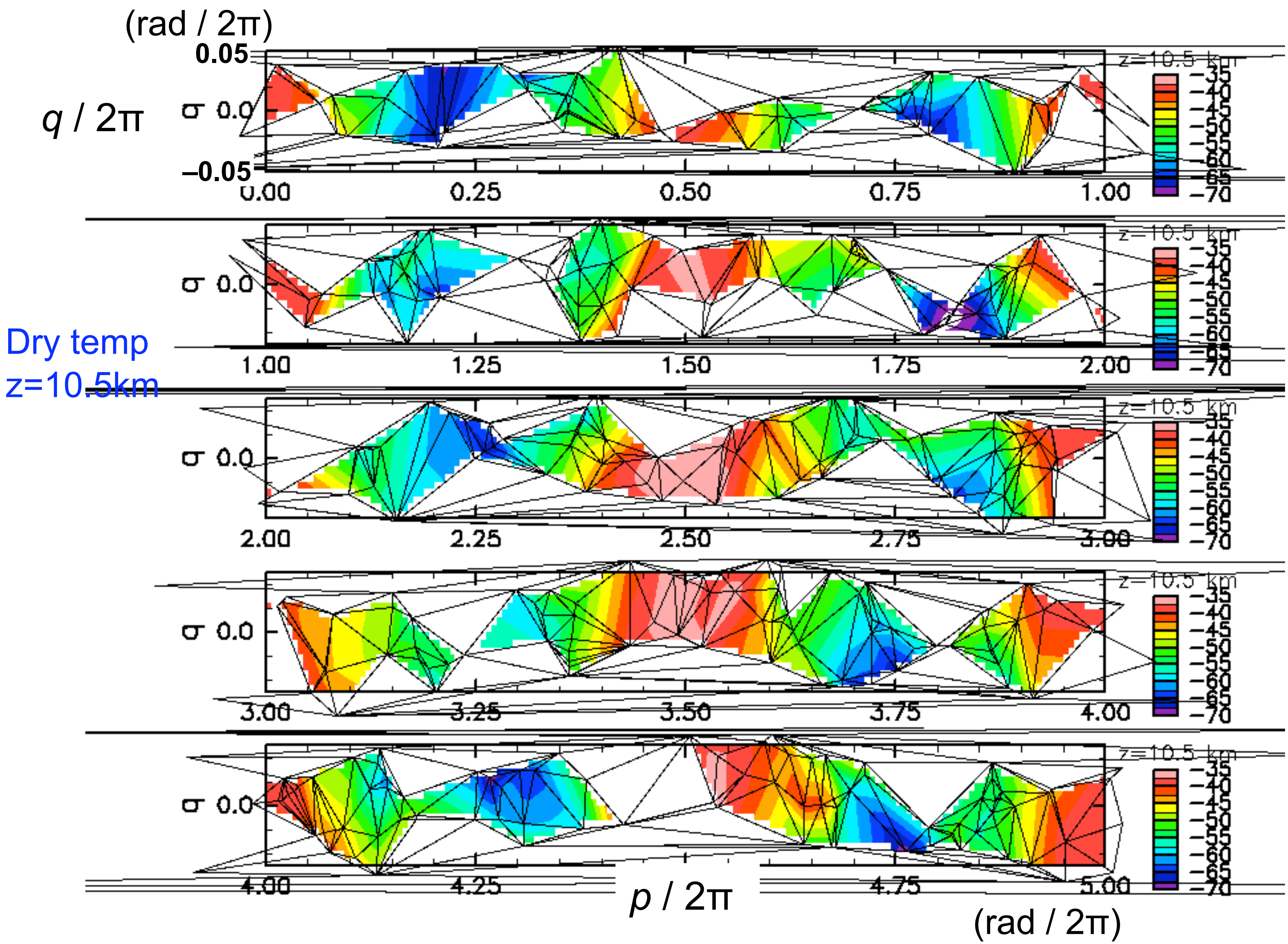
submitted to *JGR*

Summary

- Snapshot “lines” were extracted from COSMIC RO data
  - Found: GPS RO events are frequently form lines (esp. mid-high latitudes)
  - Longitudinally concentrated, which moves eastward
- Vertical cross sections → Spatial structures of GWs
  - In many cases, horizontal structures indicating GWs are identified over multiple RO events
  - Statistics → GWs of $5 < \lambda_z < 10$ km tend to have relatively large λ_H in the equatorial region & SH.
  - GW in NH (winter) mid-to-high lat
    - Propagation: zonally both Eward&Wward, meridionally northward
    - Source: mainly in subtropics
    - GW amp correlated negatively with U shear and positively with V wind; Critical-level filtering for zonal amp fluctuation

Gridding by triangulation (2006/12/01 4LEOs $\Delta p_{max}=\Delta q_{max}$= 0.1 rad / 2π)

Work done by Y. Azuma, Horinouchi, and Tsuda

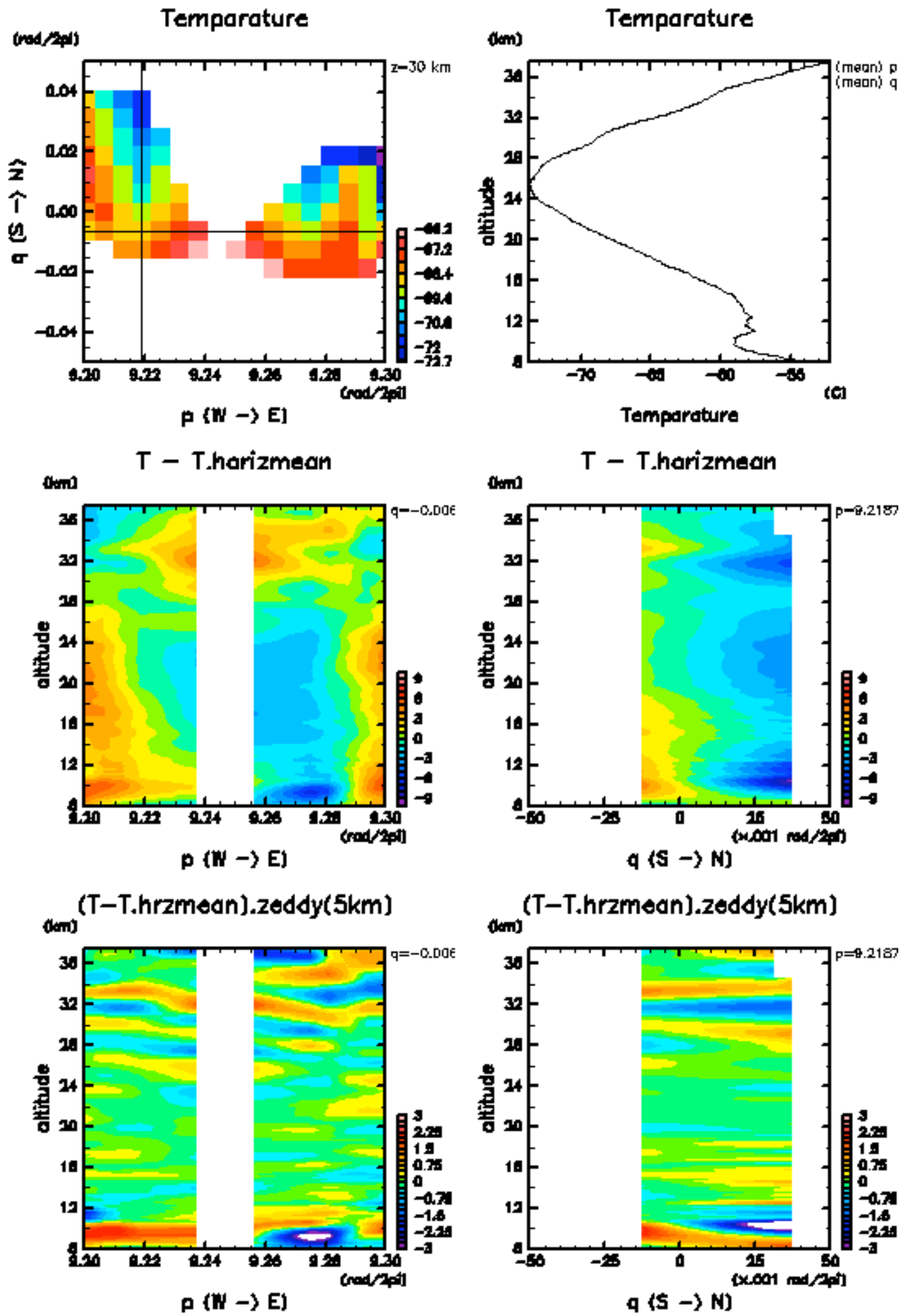


Polar case

Horizonal x-sec
z=30km
(2000 km x
2000 km)

x-z sec
(dev. from horiz.
mean)

z high pass
(< 5km)

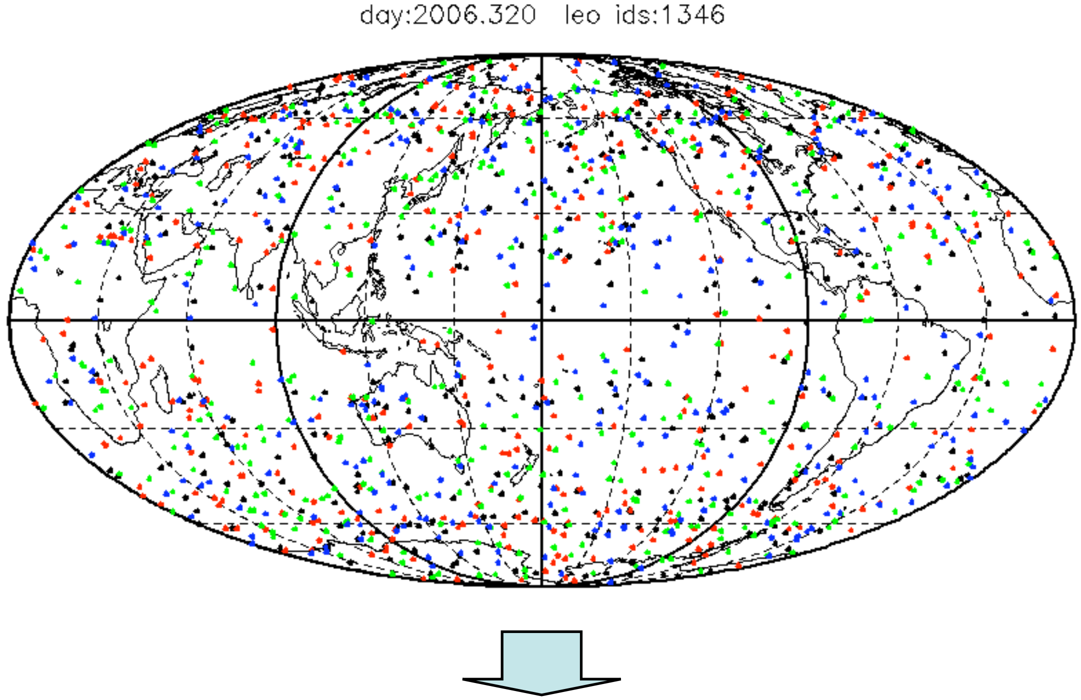


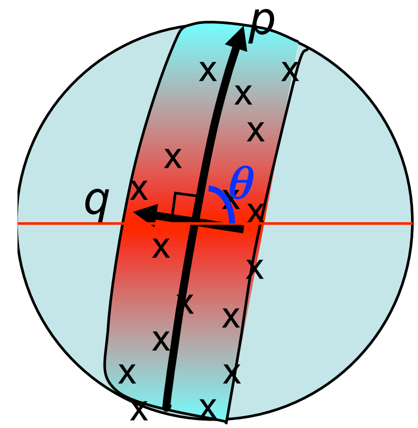
Horizontal mean

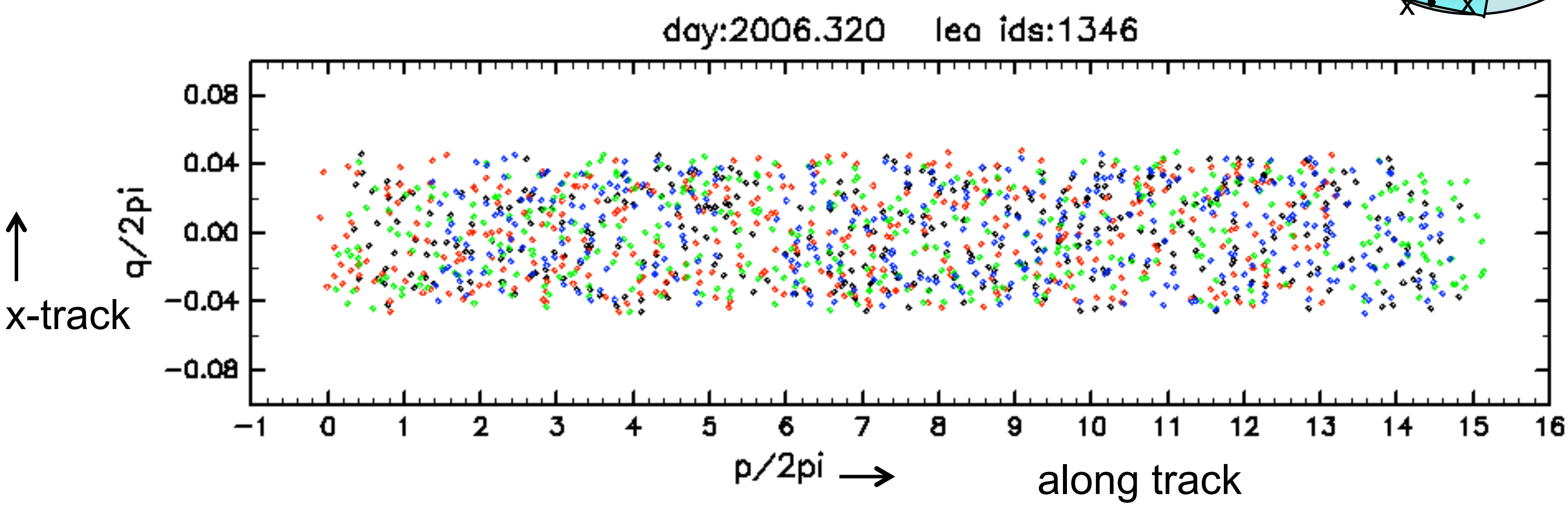
y-z sec
(dev. from horiz.
mean)

z high pass
(< 5km)

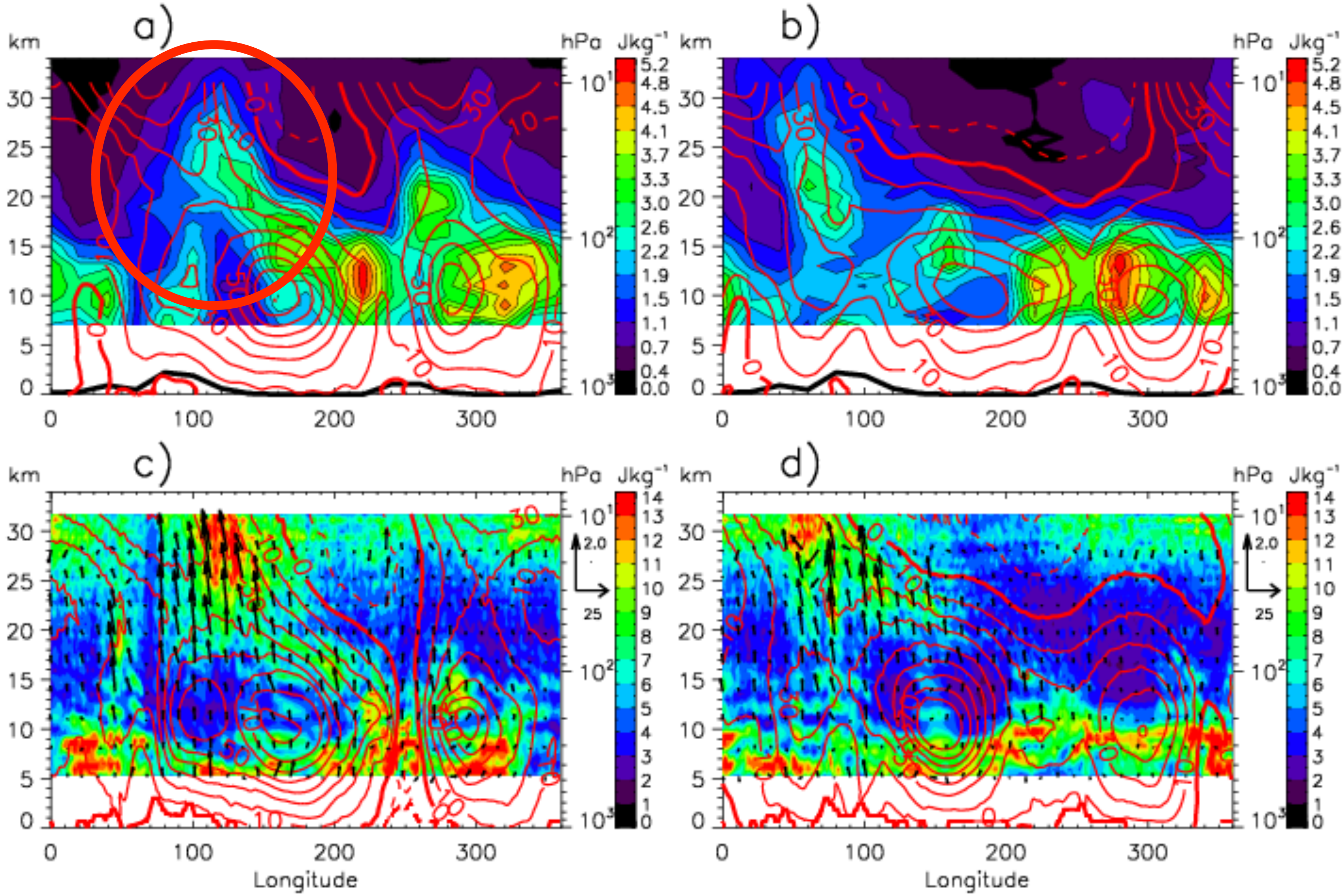
Sample transformation results（Nov 16, 2006 leo:1,3,4,6）

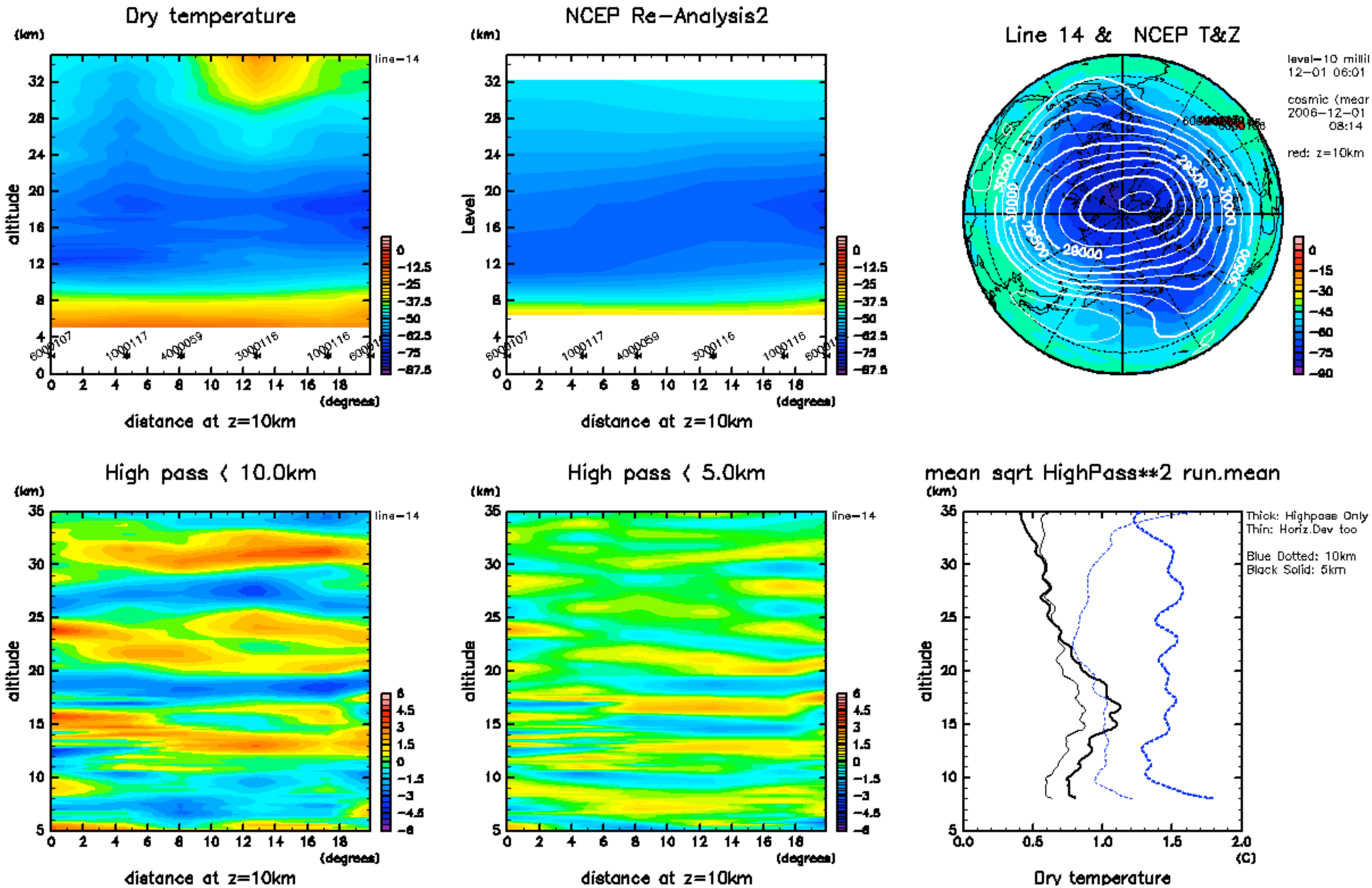




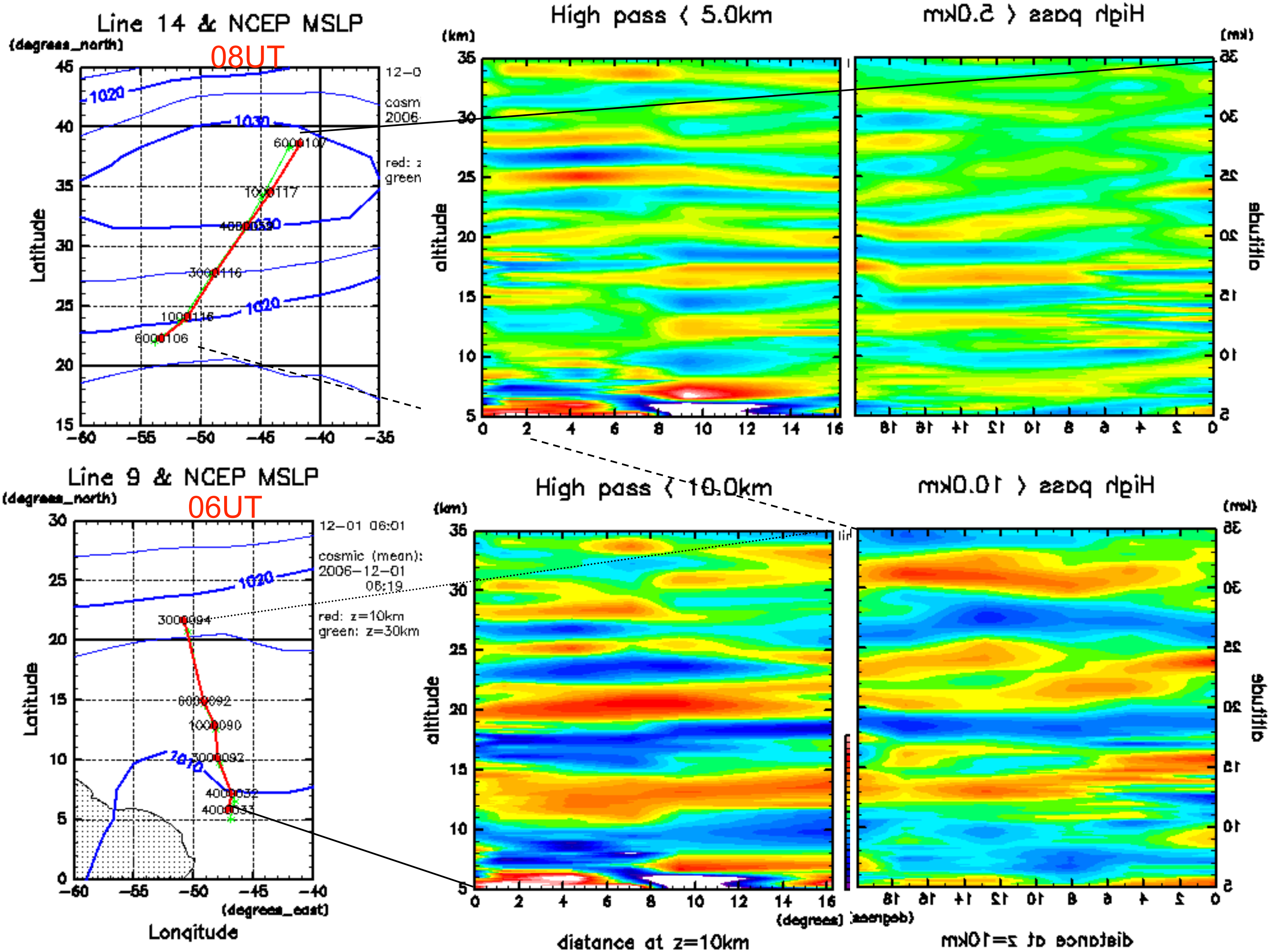


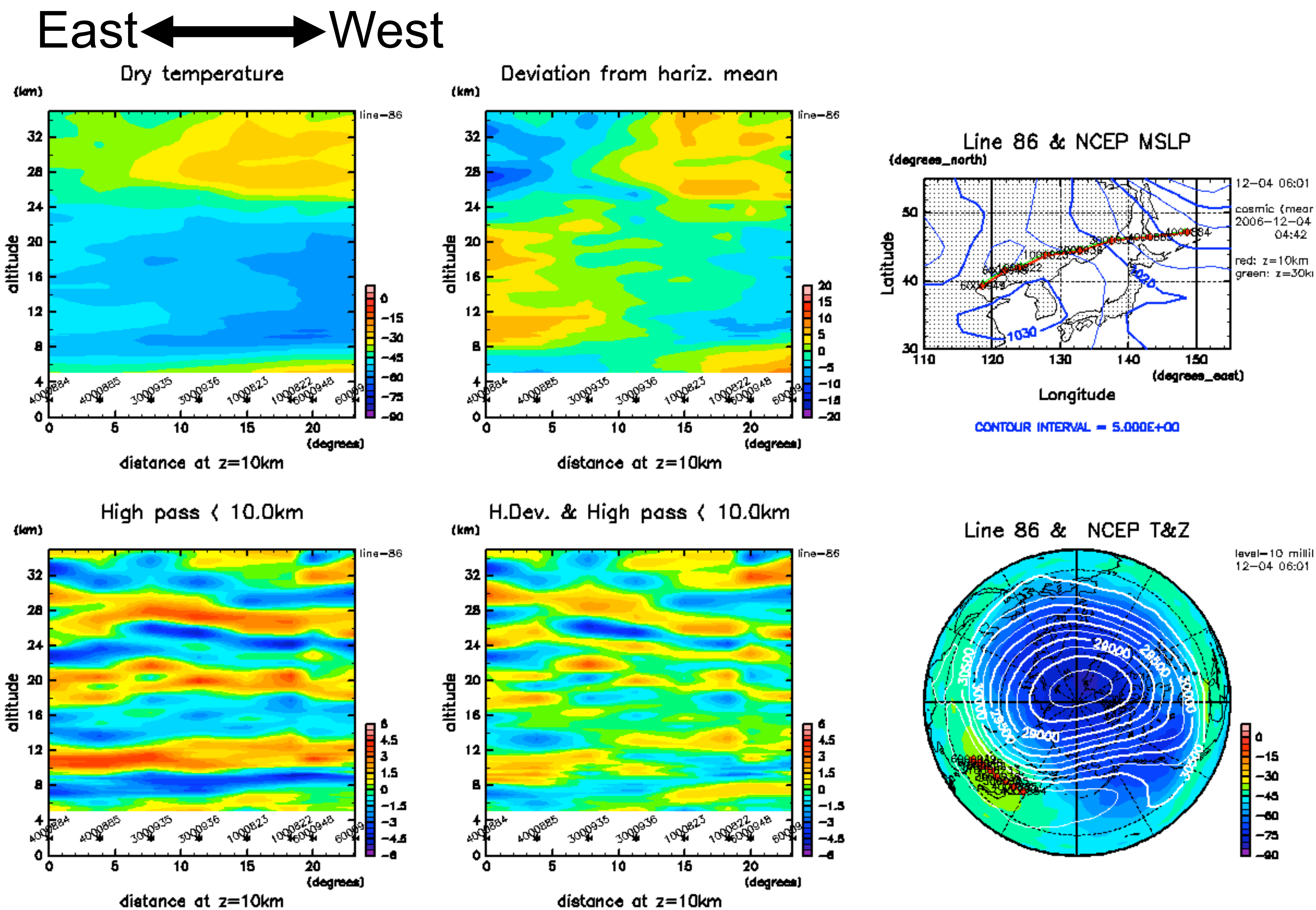
Alexander et al 2008





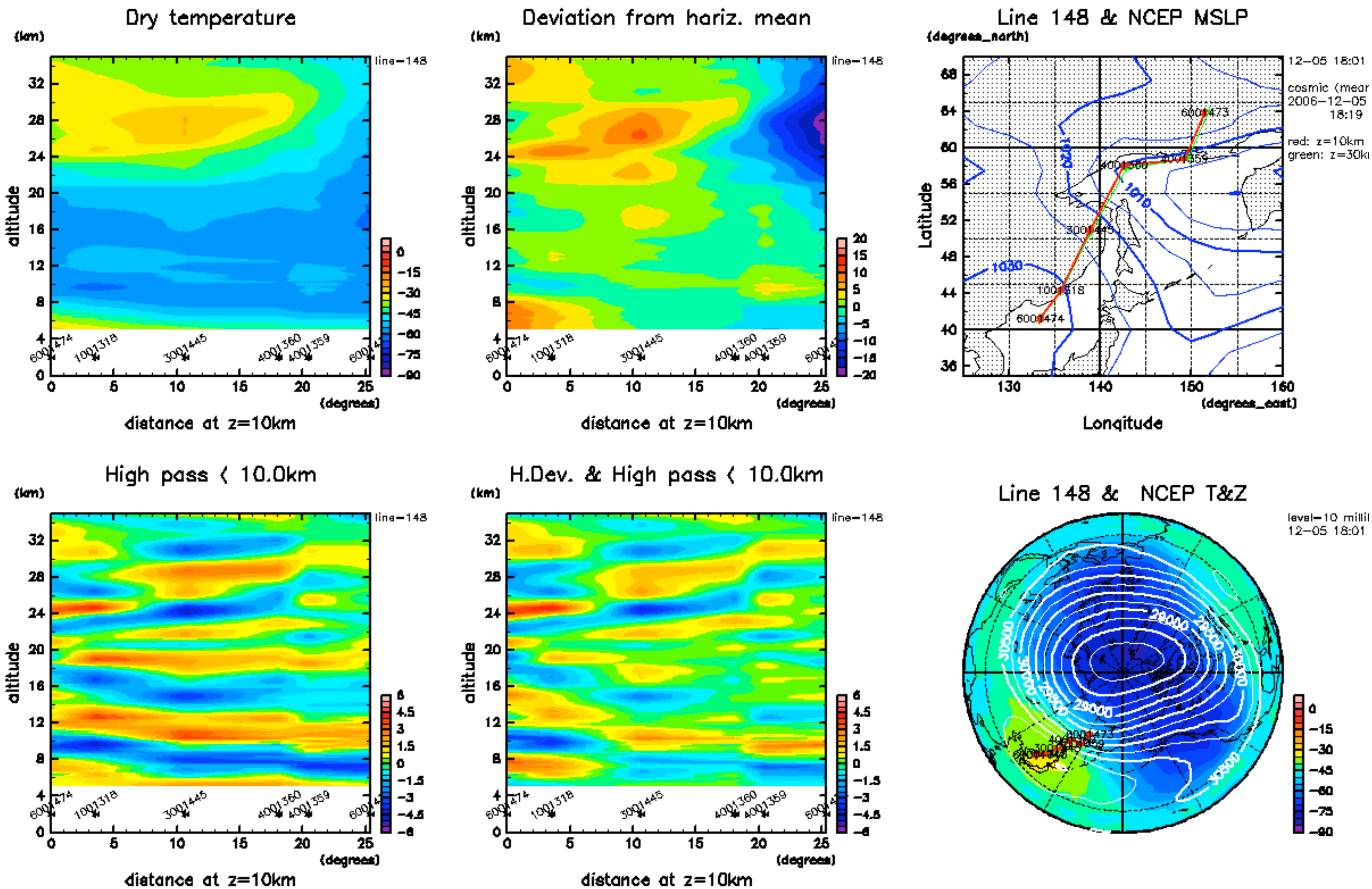
Dry temperature
NCEP Re-Analysis2
Line 14 & NCEP T&Z
level=10 milli
12-01 06:01
cosmic (mear
2006-12-01
08:14
red: z=10km
line-14
(km)
altitude
Level
distance at z=10km
(degrees)
High pass < 10.0km
High pass < 5.0km
mean sqrt HighPass**2 run.mean
Thick: Highpass Only
Thin: Horiz.Dev too
Blue Dotted: 10km
Black Solid: 5km
Dry temperature
(C)

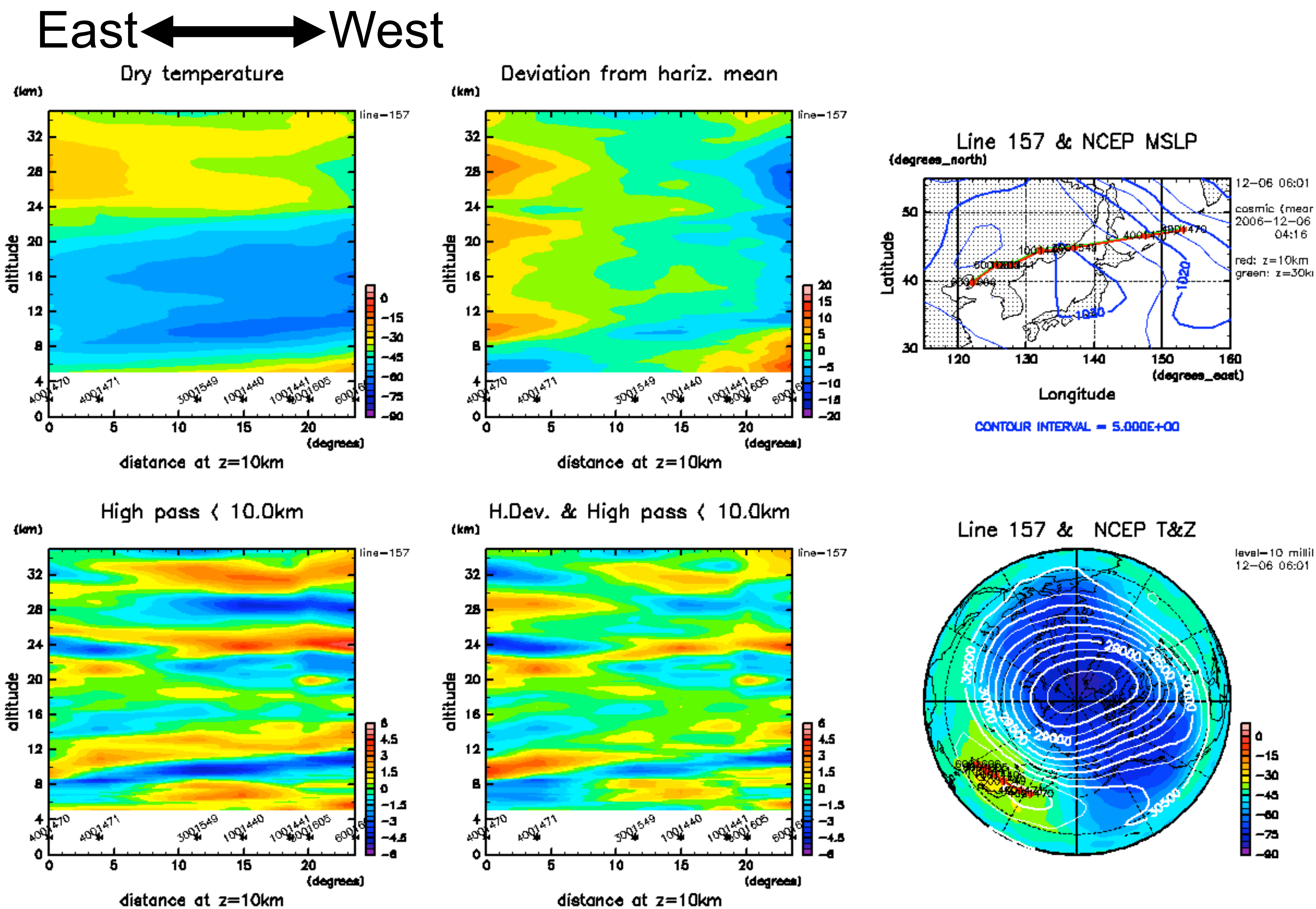

Line 14 & NCEP MSLP
(degrees_north)
08UT
Latitude
1020
1030
6000107
1000117
4000032
3000116
1000116
6000106
red: z
green
cosm
2006
High pass < 5.0km
(km)
altitude
Line 9 & NCEP MSLP
(degrees_north)
06UT
12-01 06:01
cosmic (mean):
2006-12-01
06:19
red: z=10km
green: z=30km
3000094
6000092
1000090
3000092
4000032
4000033
1020
1010
Latitude
(degrees_east)
Longitude
High pass < 10.0km
(degrees)
distance at z=10km



East
West
Dry temperature
Deviation from horiz. mean
High pass < 10.0km
H.Dev. & High pass < 10.0km
(km)
altitude
line-86
distance at z=10km
(degrees)
Line 86 & NCEP MSLP
(degrees_north)
Latitude
Longitude
(degrees_east)
12-04 06:01
cosmic (mear
2006-12-04
04:42
red: z=10km
green: z=30k
1030
CONTOUR INTERVAL = 5.000E+00
Line 86 & NCEP T&Z
level=10 milli
12-04 06:01

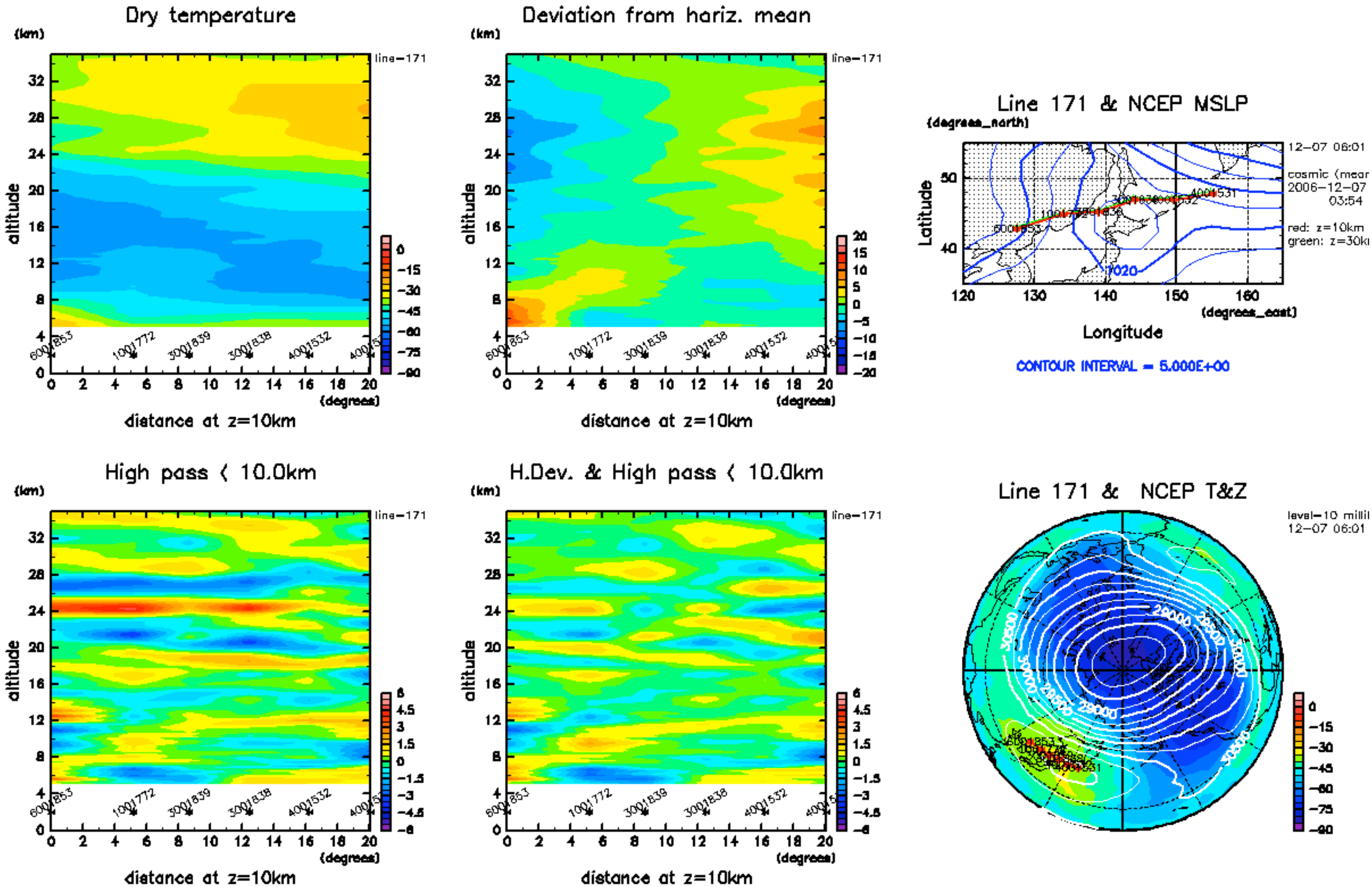
SSW ⟷ NNE


Dry temperature
Deviation from horiz. mean
Line 148 & NCEP MSLP
High pass < 10.0km
H.Dev. & High pass < 10.0km
Line 148 & NCEP T&Z
(km)
altitude
distance at z=10km
(degrees)
line-148
(degrees_north)
Latitude
Longitude
(degrees_east)
12-05 18:01
cosmic (mear
2006-12-05
18:19
red: z=10km
green: z=30k
level=10 milli
12-05 18:01
6001474
1001318
3001445
4001360
4001359
6001473

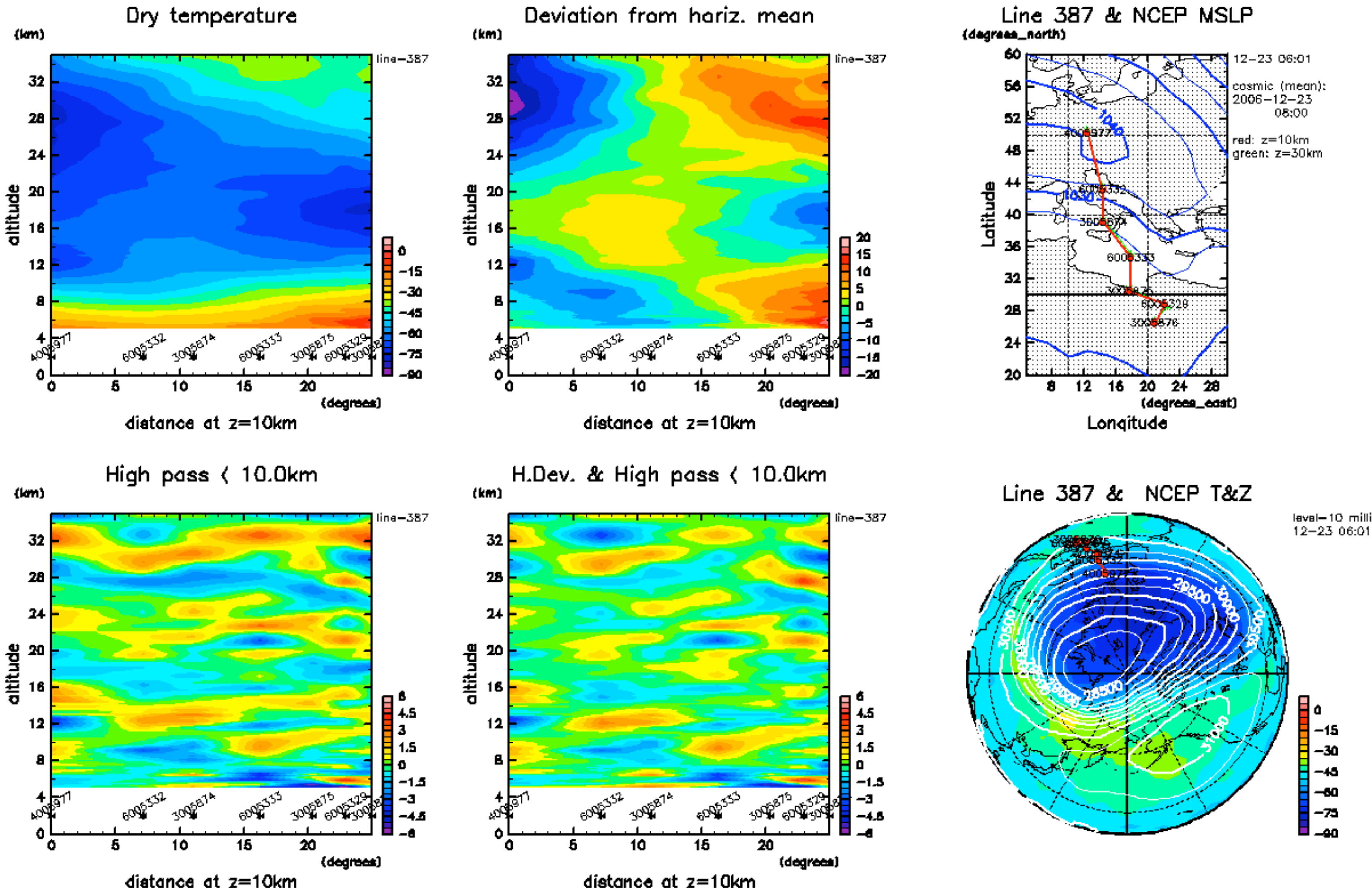


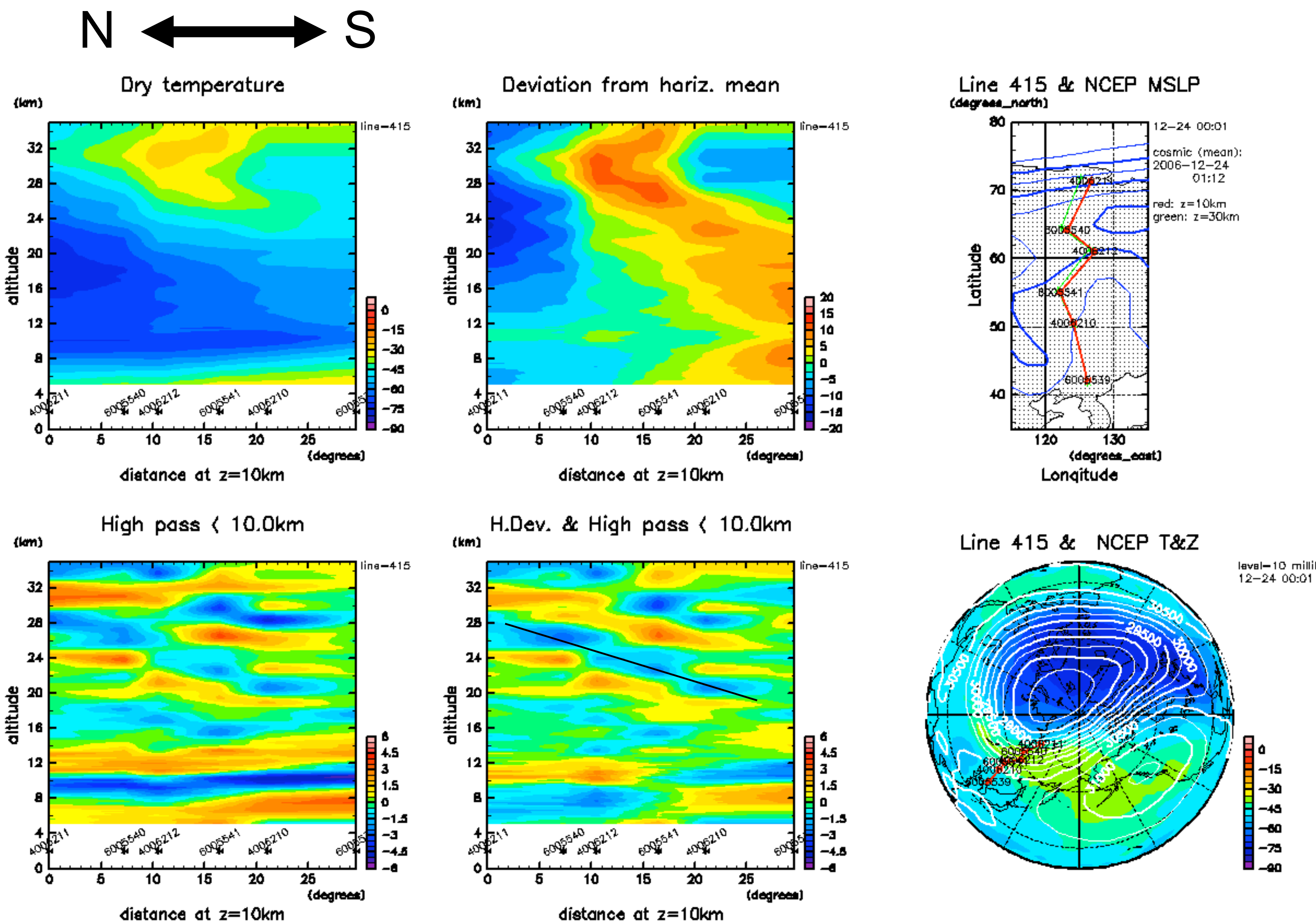
East ↔ West
Dry temperature
Deviation from hariz. mean
Line 157 & NCEP MSLP
High pass < 10.0km
H.Dev. & High pass < 10.0km
Line 157 & NCEP T&Z
altitude
(km)
distance at z=10km
(degrees)
line-157
Latitude
Longitude
(degrees_north)
(degrees_east)
12-06 06:01
cosmic (mean
2006-12-06
04:16
red: z=10km
green: z=30km
CONTOUR INTERVAL = 5.000E+00
level=10 millib

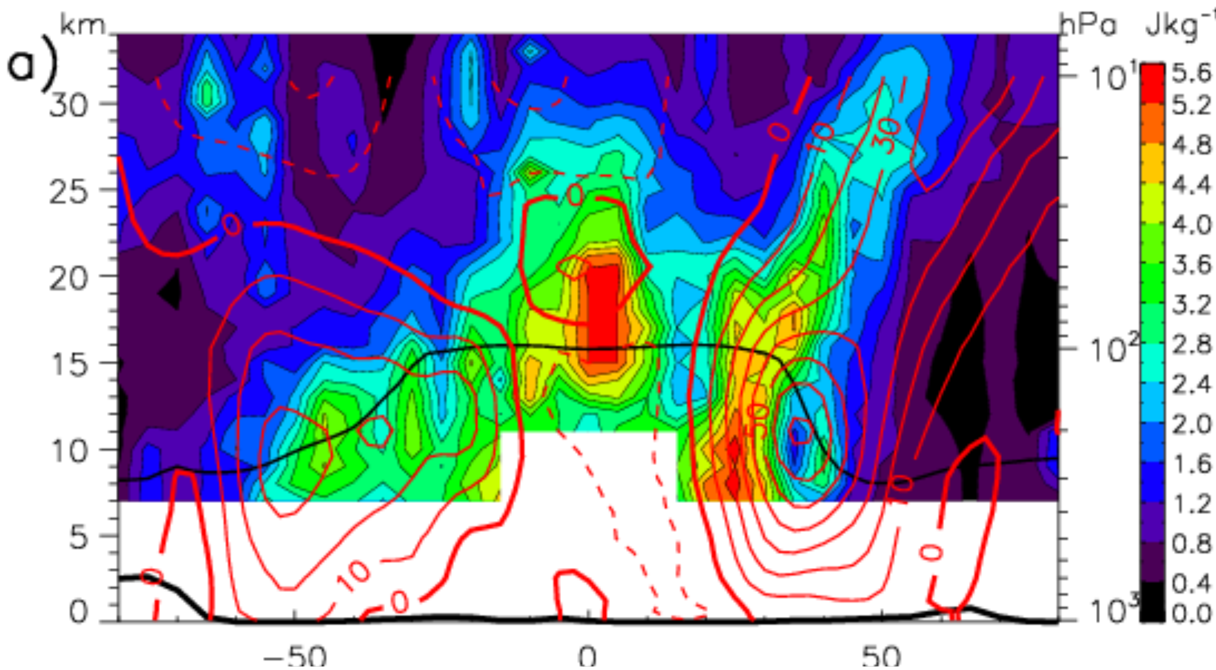
West ↔ East


Dry temperature
Deviation from horiz. mean
Line 171 & NCEP MSLP
High pass < 10.0km
H.Dev. & High pass < 10.0km
Line 171 & NCEP T&Z
altitude
(km)
line-171
distance at z=10km
(degrees)
Latitude
(degrees_north)
Longitude
(degrees_east)
12-07 06:01
cosmic (mear
2006-12-07
03:54
red: z=10km
green: z=30ki
CONTOUR INTERVAL = 5.000E+00
level=10 millil
12-07 06:01

NNW ⟷ SSE


Dry temperature
Deviation from hariz. mean
Line 387 & NCEP MSLP
(km)
line-387
altitude
distance at z=10km
(degrees)
(degrees_north)
Latitude
Longitude
(degrees_east)
12-23 06:01
cosmic (mean):
2006-12-23
08:00
red: z=10km
green: z=30km
High pass < 10.0km
H.Dev. & High pass < 10.0km
Line 387 & NCEP T&Z
level=10 millil
12-23 06:01


N S
Dry temperature
Deviation from hariz. mean
Line 415 & NCEP MSLP
(km)
altitude
line-415
distance at z=10km
(degrees)
(degrees_north)
Latitude
Longitude
(degrees_east)
12-24 00:01
cosmic (mean):
2006-12-24
01:12
red: z=10km
green: z=30km
4006211
6005540
4006212
6005541
4006210
6005539
High pass < 10.0km
H.Dev. & High pass < 10.0km
Line 415 & NCEP T&Z
level=10 millil
12-24 00:01



by Alexander and Tsuda

COSMIC PE 140E, 12 – 18 Dec 2006 (as before)

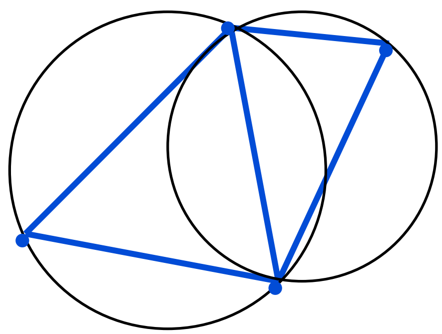
- Strong winter time sub-tropical jet
- Large PE from mid-troposphere up to PNJ

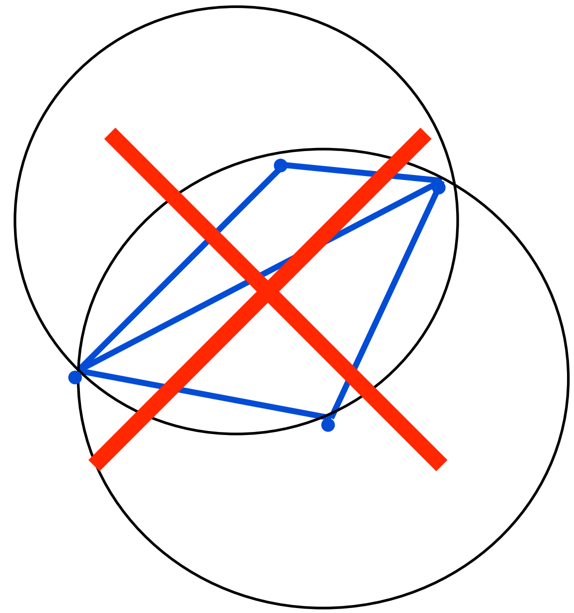
AGCM PE 140E, 1 – 7 Jan (similar wind conditions to COSMIC)

- PE from waves with periods 6hr – 1 month, $\lambda_z < 7$km, 380 $< \lambda_x <$ 40,000km
- Note different colour scale
- Vectors show meridional and vertical energy fluxes due to $\lambda_z < 7$km
- Most mid-lat stratospheric PE due to the jet (upward vectors)

予備スライド

Delaunay triangulation

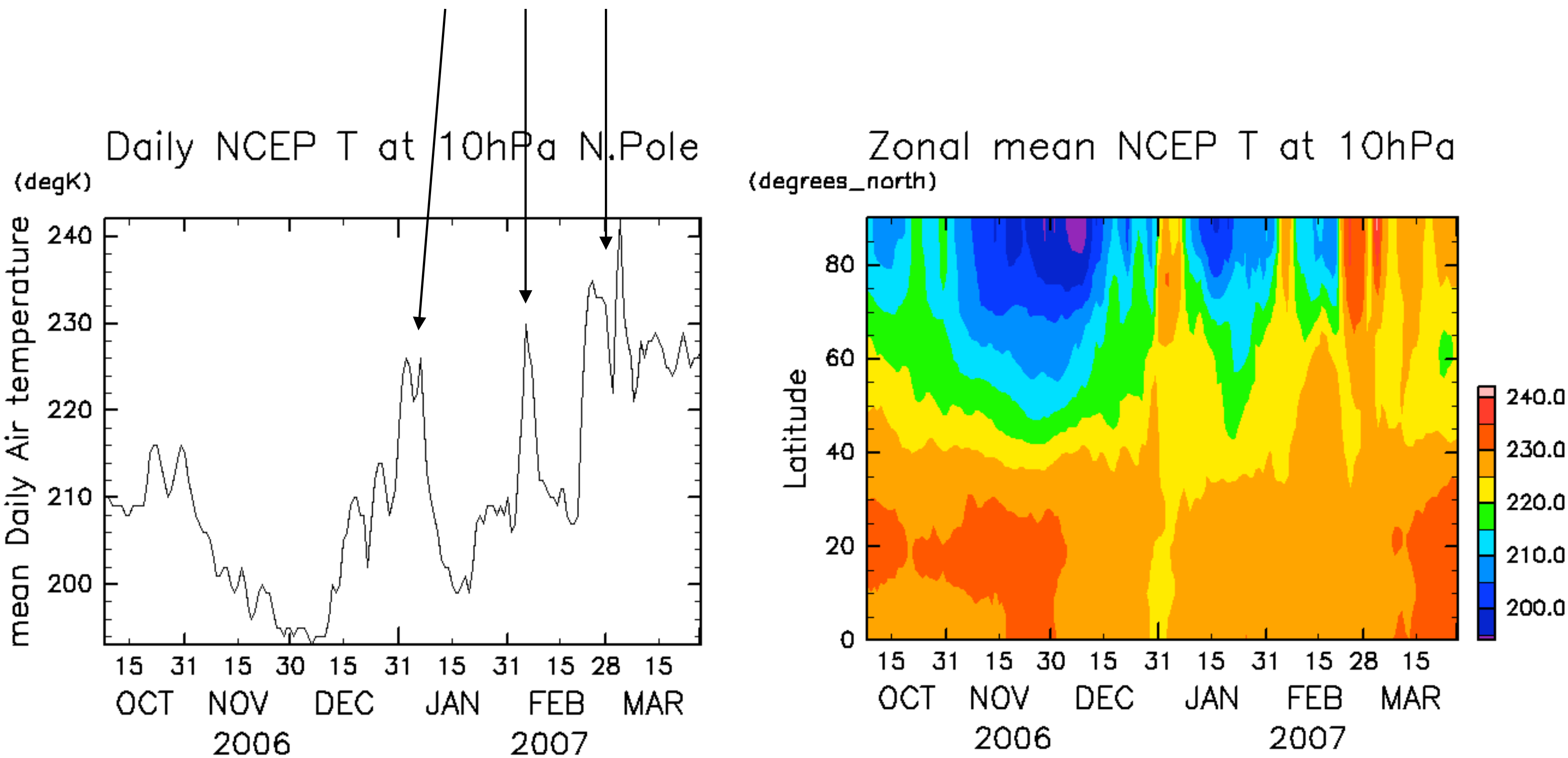


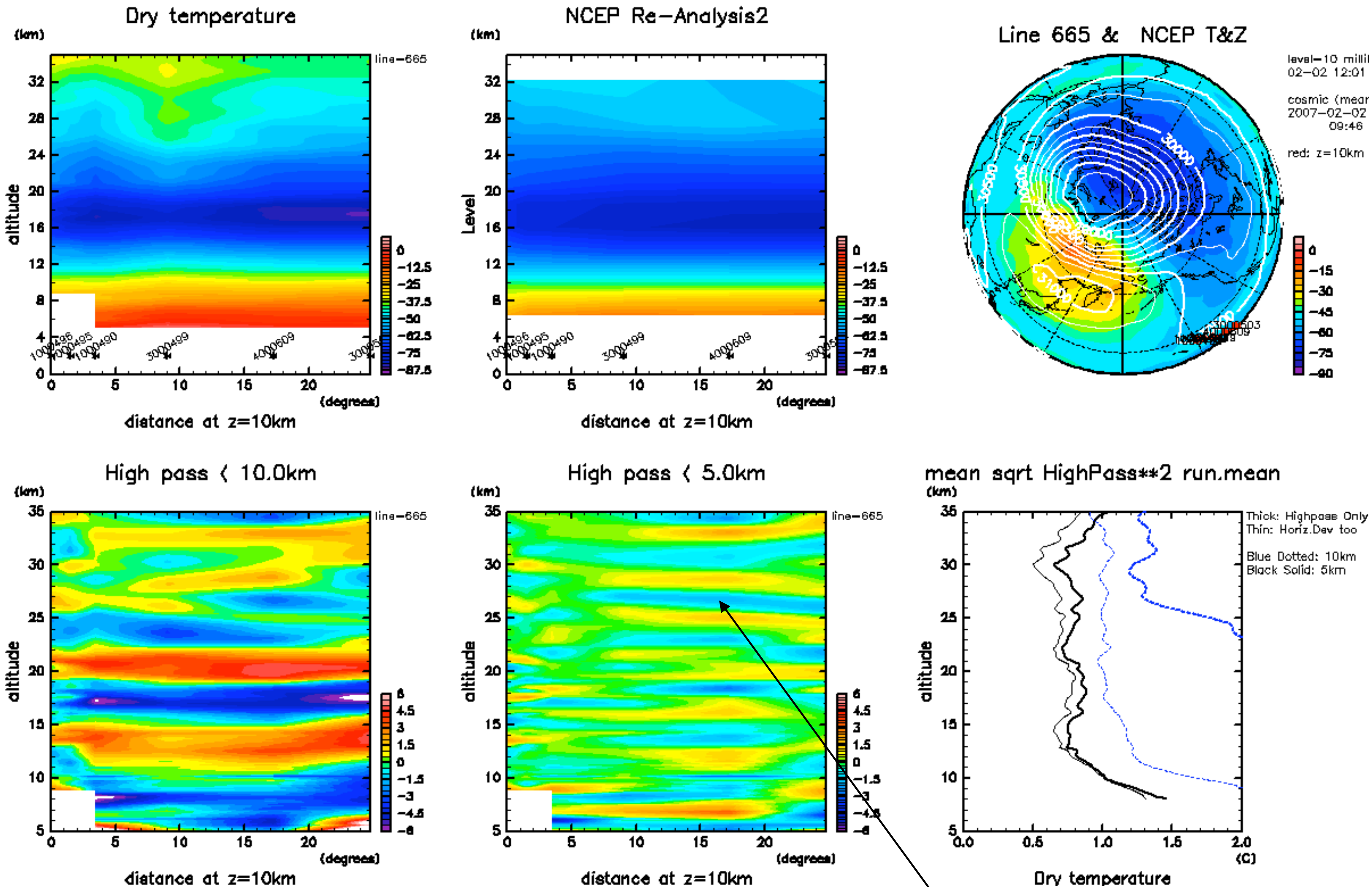


Allow no other point in the outer circles of all triangles

N.H. Stratosphere of the period

- 3 major sudden warmings



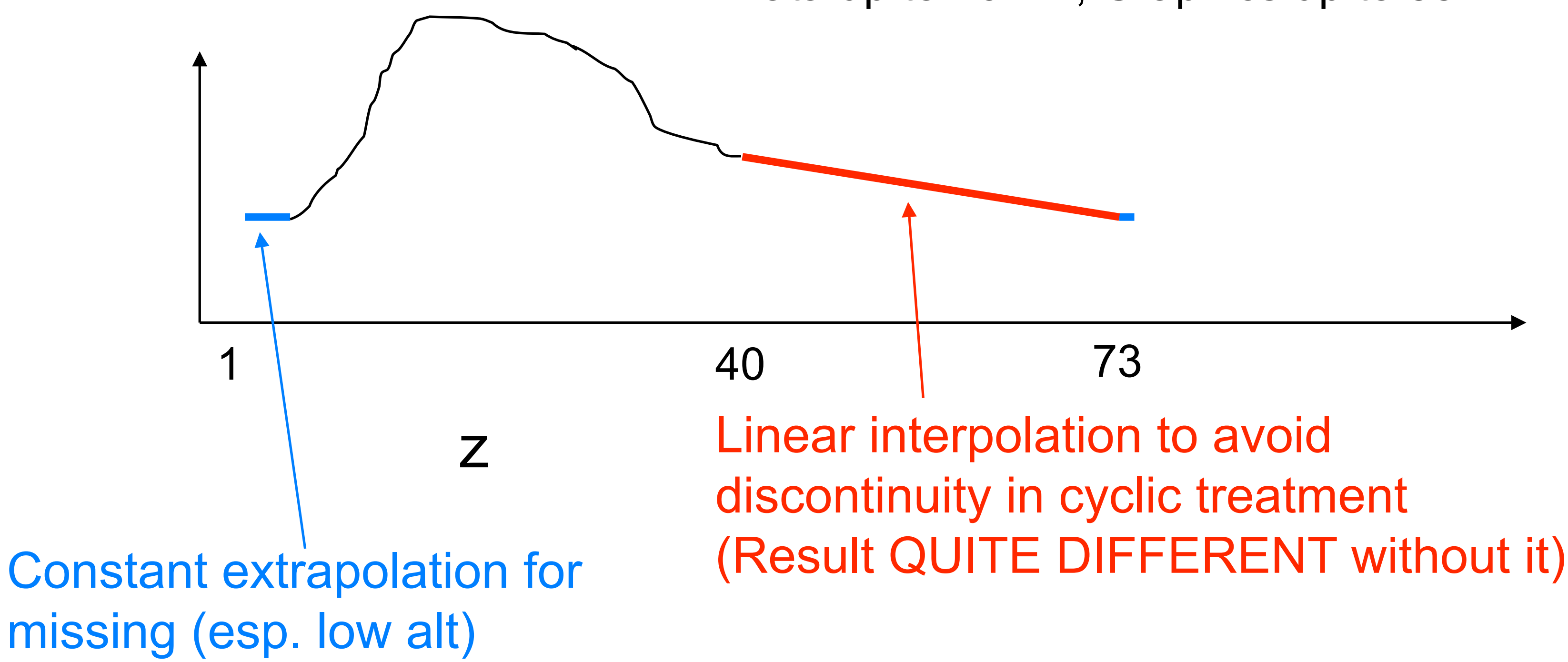


20N 5N Short λ_z wave

Vertical high-pass filtering

- Based on FFT
- Padding & Extending to avoid leak from cyclic discontinuity

Data up to 40 km; Graphics up to 35 km



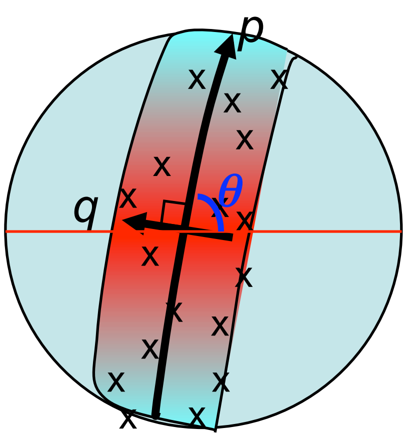
座標変換

- 衛星進行方向(pとする)とそれに直交する方向(q)に軸を取る。
  - 通常のswathデータ同様
  - ただし、軌道情報がなくても、掩蔽点の位置だけから求まるよう工夫(∵衛星が複数なので、軌道パラメタも一意でない。利点:解析的。軌道データがない場合でも適用できる)。

$$\sin q = \sin\phi\cos\theta - \sin\lambda'\cos\phi\sin\theta$$

$$\cos p = \frac{\sin\lambda'\cos\phi}{\sqrt{1-\sin 2q}}$$

$$\sin p = \frac{\sin\lambda'\cos\phi\cos\theta + \sin\phi\sin\theta}{\sqrt{1-\sin 2q}}$$



ここで $\lambda' = \lambda - \lambda_0 - \alpha\omega^{-1}p$ (衛星軌道面と共に回転する座標系での経度)

p について再帰的なので、反復法。

λ_0も $\overline{p\cos q}$ をゼロに近づける反復より求める。