Wave Cloud Dynamics in MMS Data

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Meteorological Measurement System Data

Sub-systems:

Inertial Navigation Unit
(aircraft attitude, position, velocity, acceleration)
Air Motion Sensing System
(Pstatic, Ptotal, Ttotal, attack and yaw angles)
GPS Receiver
(latitude, longitude, geometric altitude)
Data Acquisition System
(continuous sampling @ 20 – 300 Hz)

Raw variables are desampled to 20Hz for calculations
Data products available @ 1Hz and 20Hz

	Accuracy	Resolution
Static Pressure:	± 0.3 mb	0.02 mb
Static Temperature:	± 0.3K	0.01 K
Wind Components		
Horizontal (U, V)	± 1 m/s	0.05 m/s
Vertical (W)	± 0.5 m/s	0.05 m/s

Turbulent Dissipation Rate (€)
(Assumes inertial subrange exists at 3.2-6.0 Hz)

Calibration of the MMS

- **Lab Cals of Pressure & Temperature**

  (Ps, Pt, Qlocal, Attack & Yaw angles – tolerance <0.05 mb)
  (Tslow & Tfast Bath Calibrations – tolerance < 0.05K, long term drift < 0.1K)

- **Inertial Navigation Systems are response-tested**

  (Time delays of EGI & CMIGIT attitude [pitch,roll,heading], velocity & acceleration determined to < 0.005 sec accuracy)

- **Maneuver calibrations (pitch & yaw, box turns)**

  Pitching – calibrates AOA gain & time delay, adjust Pstatic response & delay
  Yawing – calibrates YAW gain & time delay, adjust Pstatic response
  Boxes – calibrates AOA & YAW offsets, overall Pstatic error (Re, Mach, AOA)

- **Uncertainty of air data calibrations**

  Pstatic – 0.1 – 0.2 mb per maneuver, additional 0.1 mb due to statistical modeling
  Tstatic – 0.1K per maneuver, additional 0.05K due to modeling
  Air data errors are in addition to lab errors – overall 0.3 mb & 0.3K accuracy

- **Litton 100-G and C-MIGIT II inter-compared**

  C-MIGIT heading angle errors of 0.5-1 deg result in U,V errors of 0.5-1 m/s.
  C-MIGIT horizontal velocities differ from EGI xdot, ydot by < 0.5 m/s.
  C-MIGIT Vz similar to EGI Vz, W differences < 0.2 m/s at freqs > 1 Hz.

MidCiX: Problems to be Mitigated

- **MMS sensors operated normally on four flights: 040417, 040419, 040422, 040502**

- **Pstatic, Ptotal noise above 0.02 Hz (040503/040505)**

  Low Pass Filtering & Smoothing removed noise and (oops!) some signal
  Fuselage Q, Ptotal reconstructed from AOA probe Q & statistical relation

  Uncertainties contribute to U,V error (1 m/s) and temperature error (0.2K).
  Pstatic in error (< 3 mb) near beginning/end of ascent/descent (blackouts)

  Level flight and most ascent/descent data are OK

- **Partial Failure of Litton INU (040430/040506)**

  Affected ~ 15 minutes on 040430, but most of 040506 flight

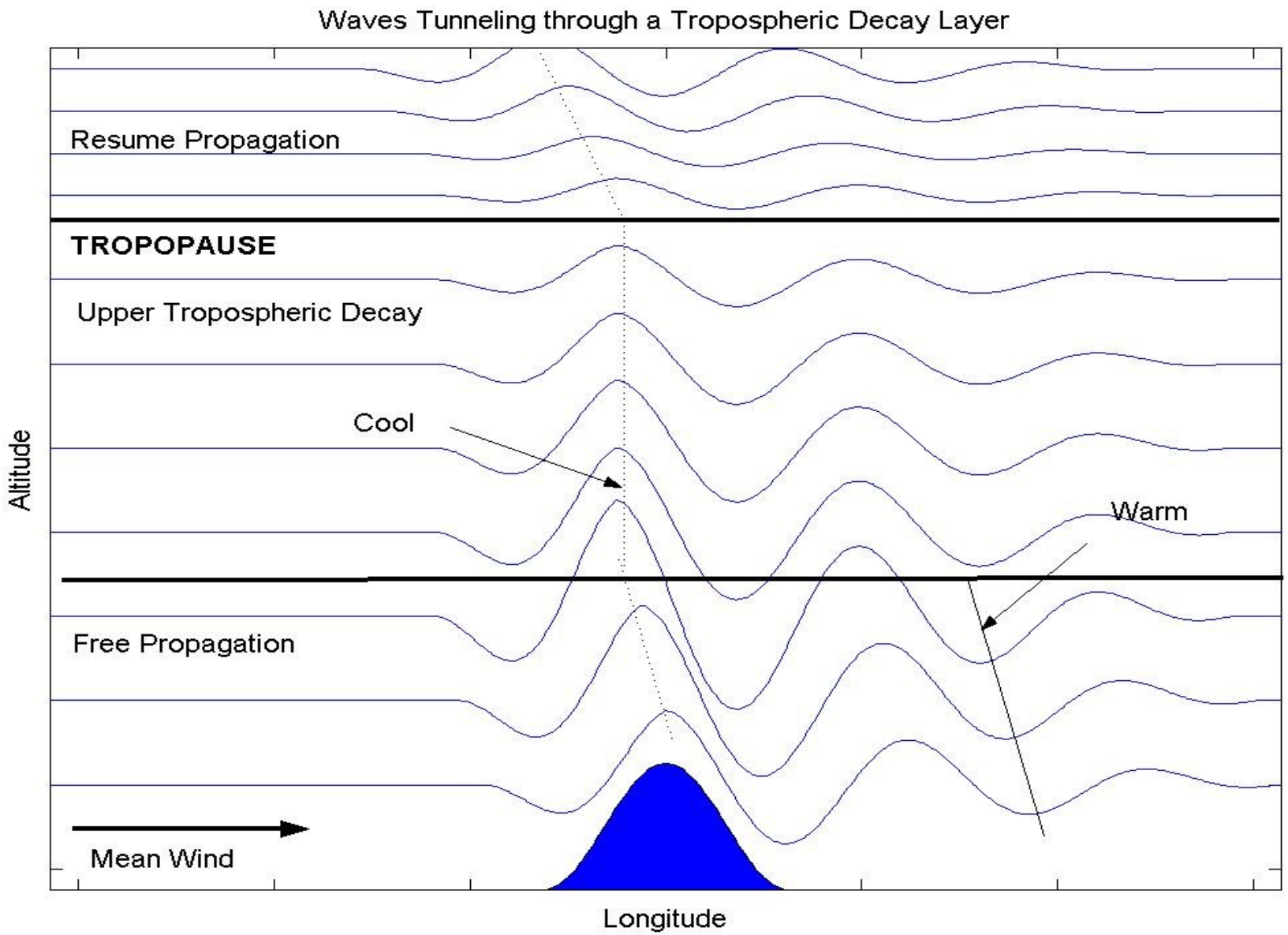
  EGI Pitch & Roll, Accelerometer were OK; Heading data was corrected with an offset
  Substituted C-MIGITS velocities, GPS RACAL position data

  U,V may have 0.5 m/s errors due to C-MIGIT velocity uncertainty

- **Total Failure of Litton INU (040505 @ 61500 utsec)**

  Used C-MIGIT Velocity and Attitude (pitch, roll, heading), GPS position

  U,V are uncertain by 1 – 1.5 m/s, W uncertain by 0.2 m/s


Waves Tunneling through a Tropospheric Decay Layer
Resume Propagation
TROPOPAUSE
Upper Tropospheric Decay
Cool
Warm
Free Propagation
Mean Wind
Altitude
Longitude

Phasing Between MMS Variables
<u>In Decaying Gravity Waves</u>

Equations derived from linear wave theory

1. **Vertical wind shear (of horizontal wind) is small**
2. **Gradual decay – waves are "tunneling" upwards**
3. **Intrinsic frequency >> Coriolis frequency**
4. **Anelastic assumption (no horizontal sound waves)**

Vertical wavelengths as deep as H are allowed

$$w = \frac{i\hat{\omega}\, g}{N^2 \overline{T}} T$$

(Thermodynamics)

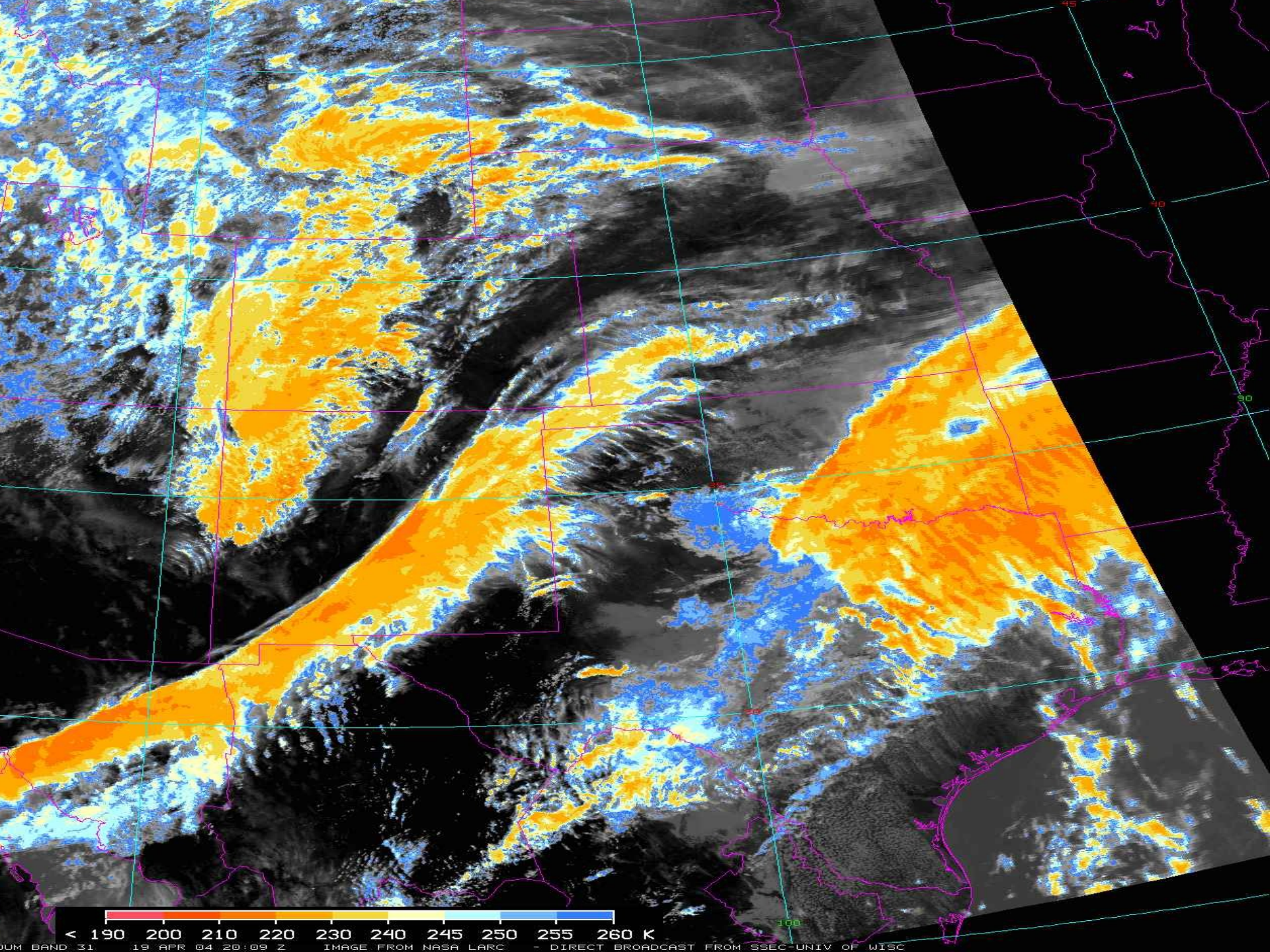
$$u = \frac{k}{l} v$$

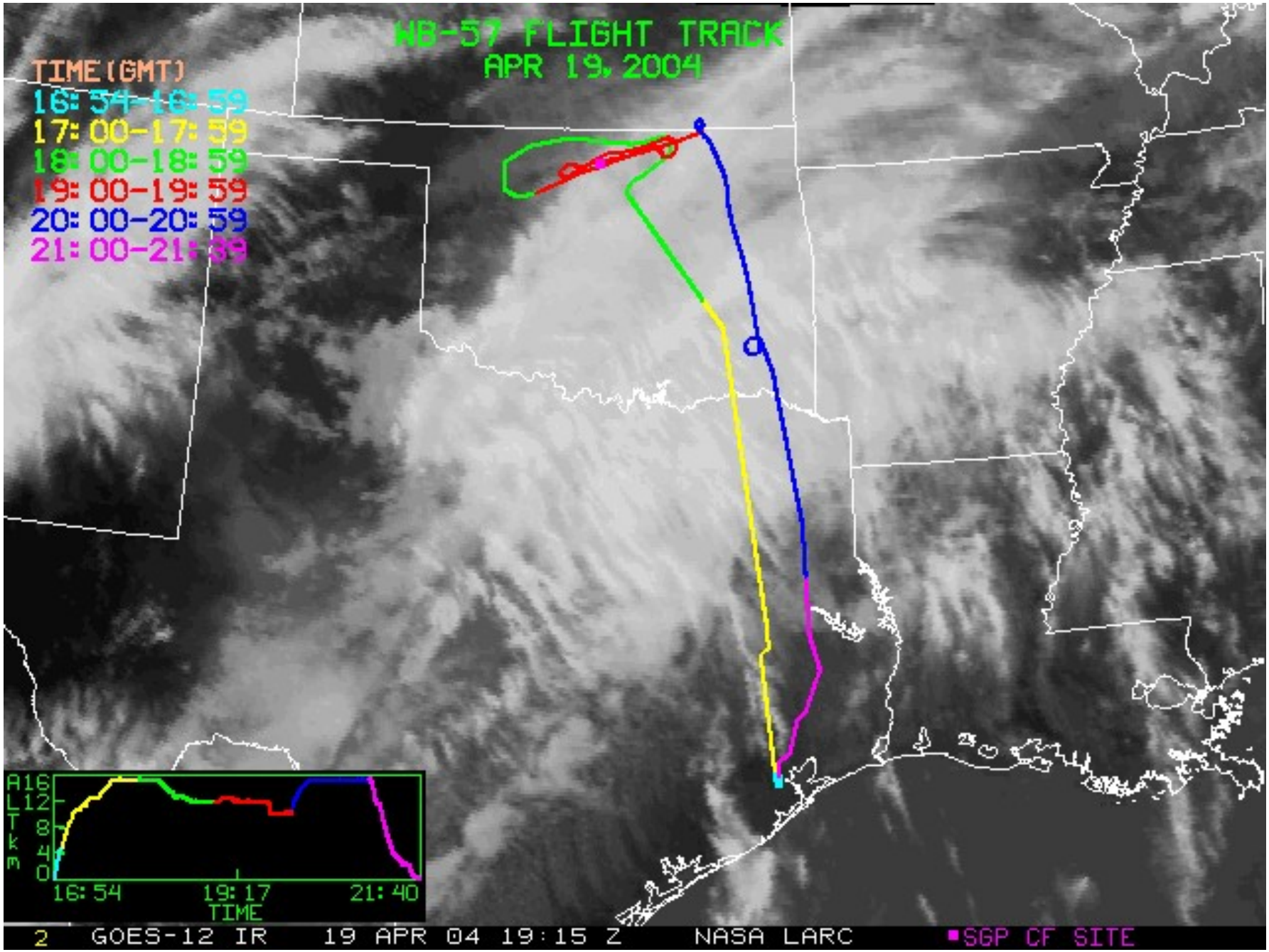
(Horizontal momentum)

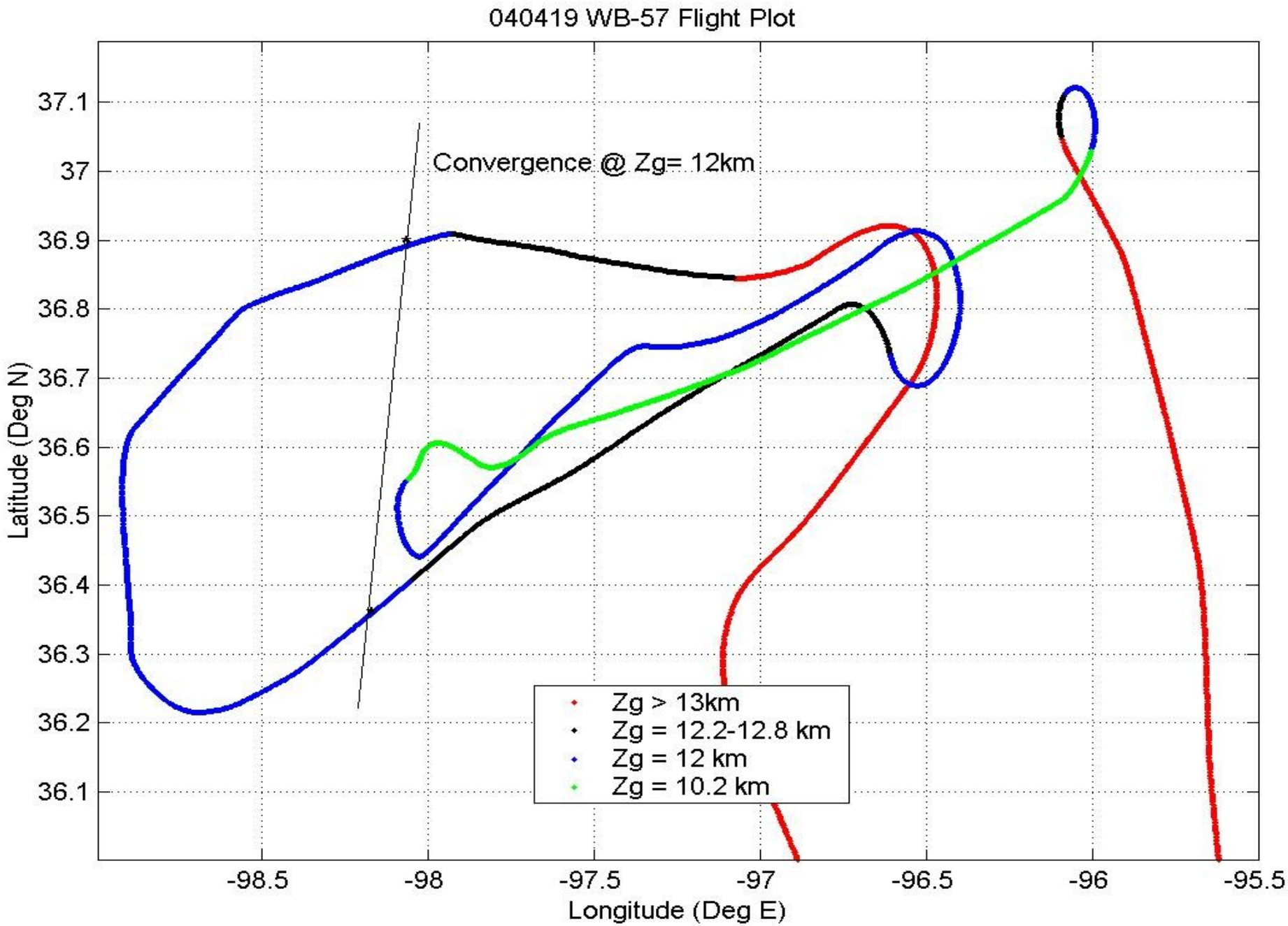
$$u = \left(\frac{k}{k^2 + l^2} \right) \left(\frac{\hat{\omega}\, g}{\gamma\, HN^2 \overline{T}} \right) T$$

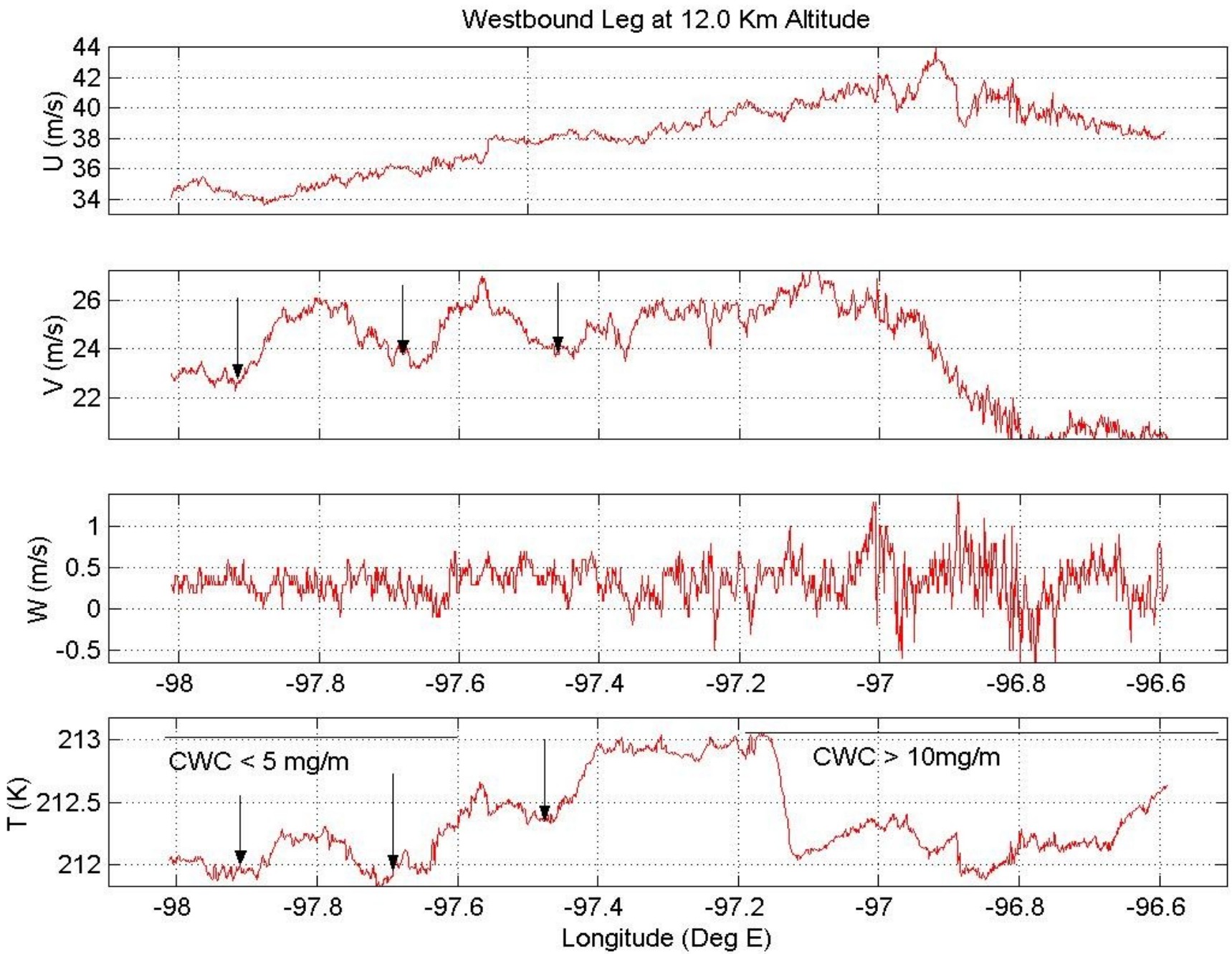
(Continuity + Momentum)

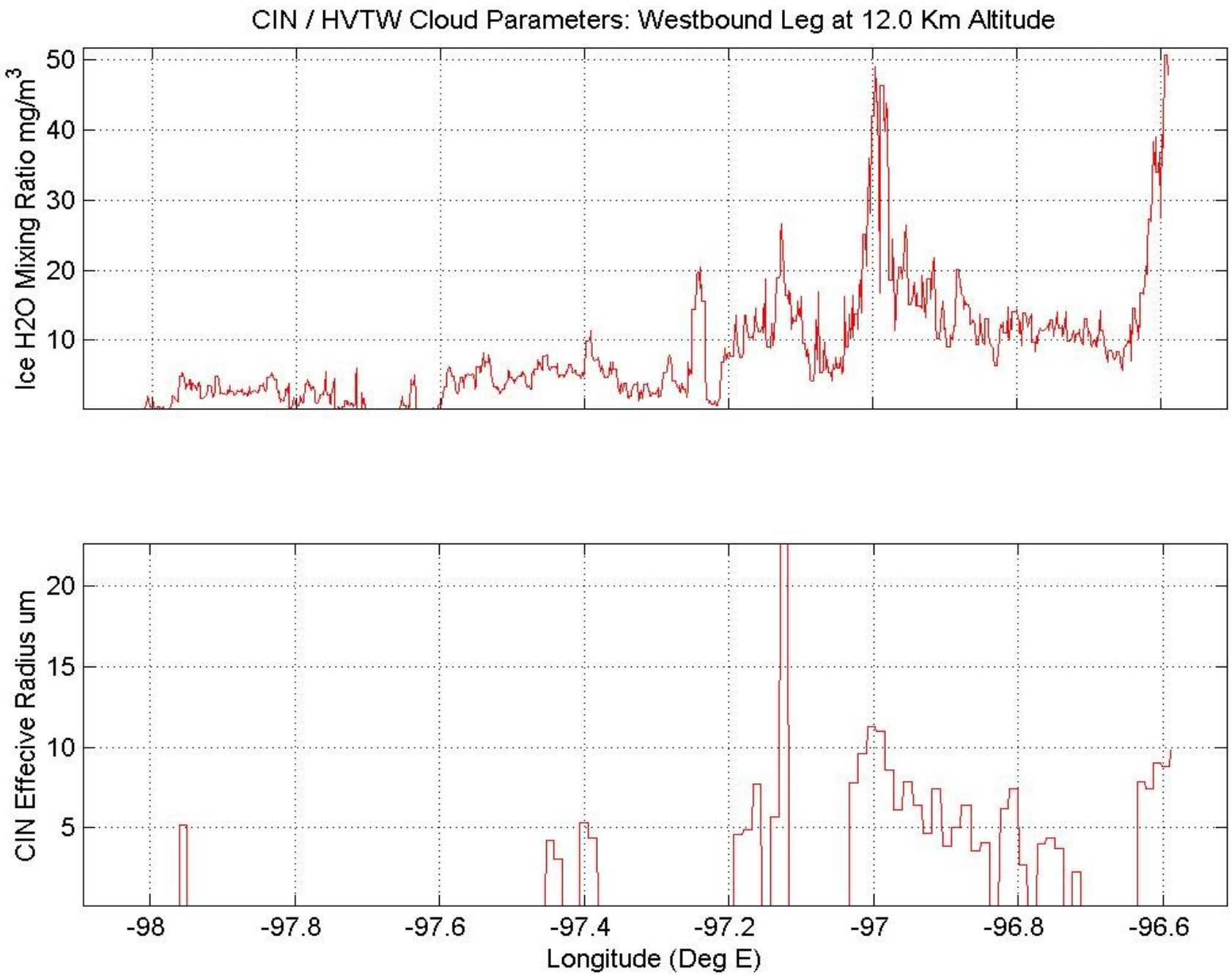
$$v = \left(\frac{l}{k^2 + l^2} \right) \left(\frac{\hat{\omega}\, g}{\gamma\, HN^2 \overline{T}} \right) T$$

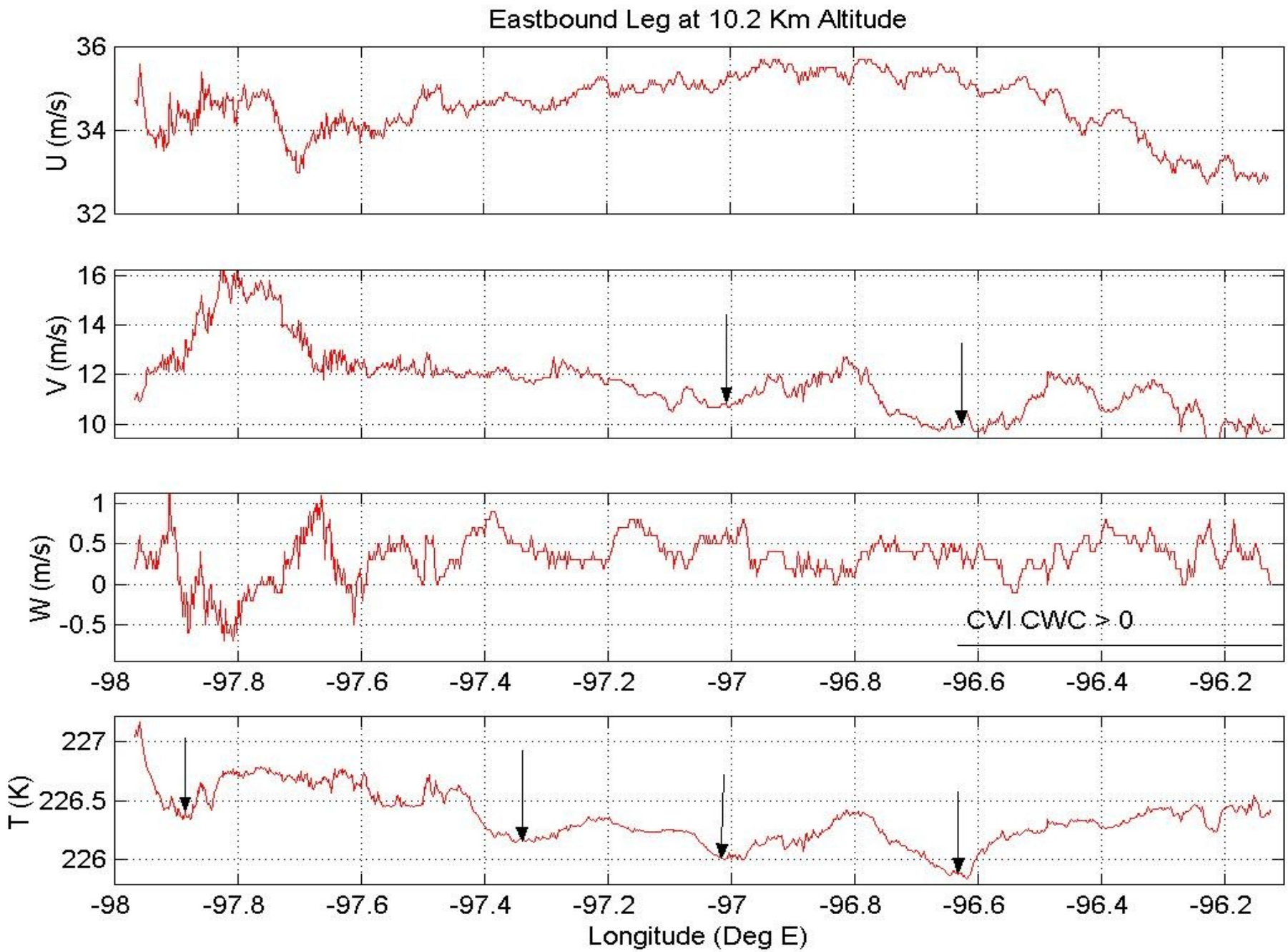

< 190 200 210 220 230 240 245 250 255 260 K
DUM BAND 31 19 APR 04 20:09 Z IMAGE FROM NASA LARC - DIRECT BROADCAST FROM SSEC-UNIV OF WISC

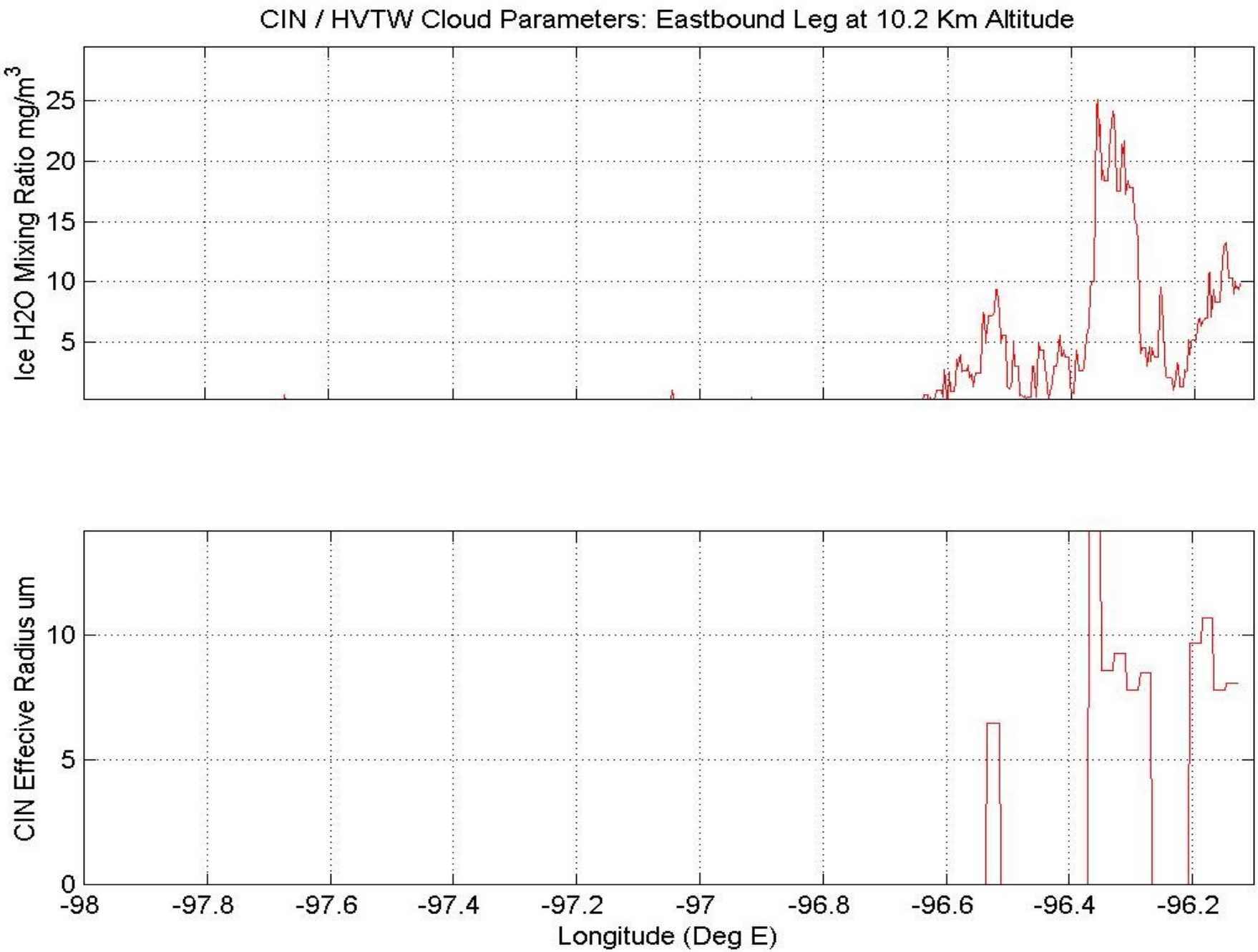

WB-57 FLIGHT TRACK
APR 19, 2004
TIME (GMT)
16: 54-16: 59
17: 00-17: 59
18: 00-18: 59
19: 00-19: 59
20: 00-20: 59
21: 00-21: 39
ALTITUDE (km)
16
12
8
4
0
16: 54
19: 17
21: 40
TIME
2 GOES-12 IR 19 APR 04 19:15 Z NASA LARC
SGP CF SITE

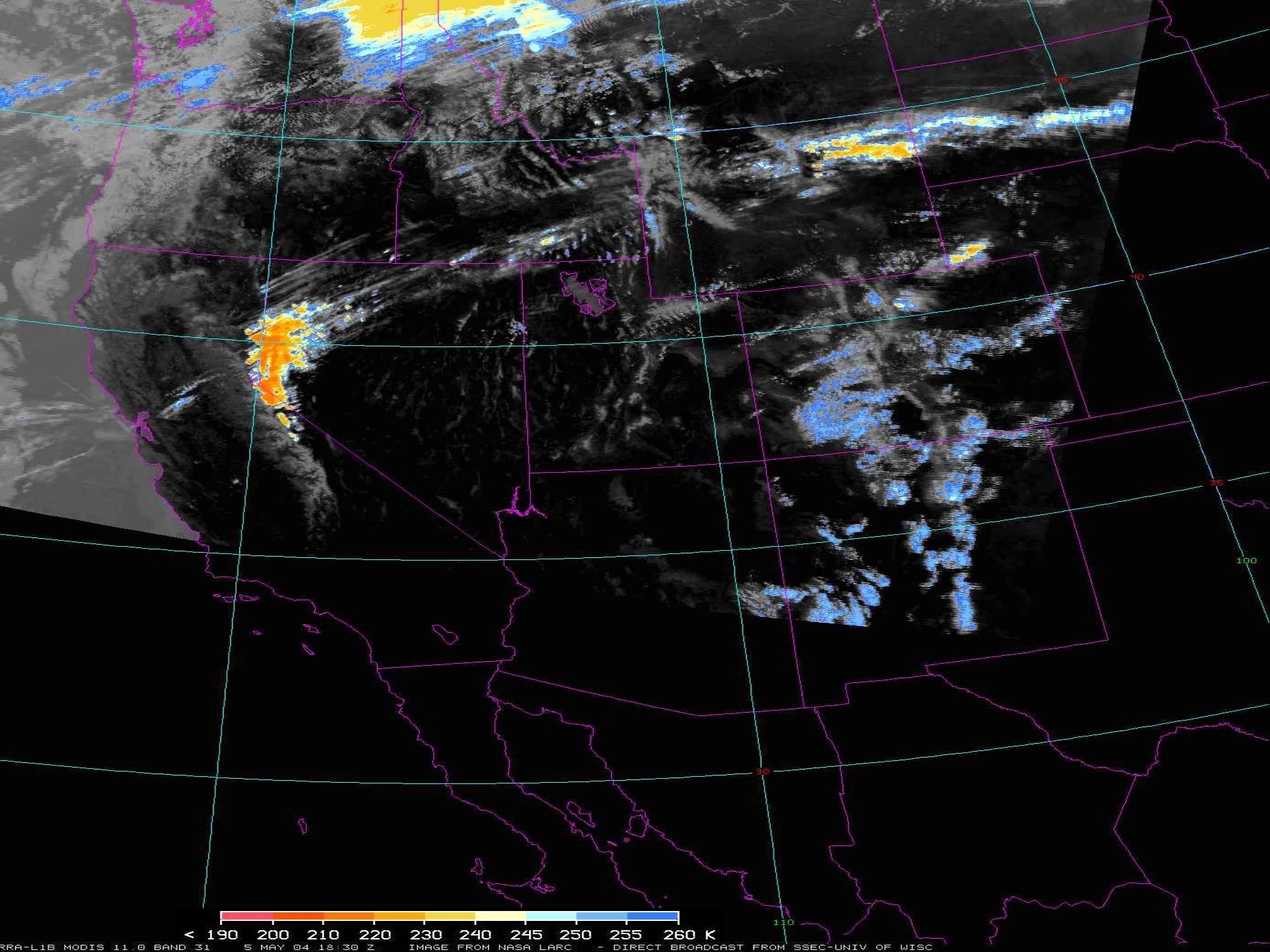

040419 WB-57 Flight Plot
Convergence @ Zg= 12km
Zg > 13km
Zg = 12.2-12.8 km
Zg = 12 km
Zg = 10.2 km
Latitude (Deg N)
Longitude (Deg E)
37.1
37
36.9
36.8
36.7
36.6
36.5
36.4
36.3
36.2
36.1
-98.5
-98
-97.5
-97
-96.5
-96
-95.5

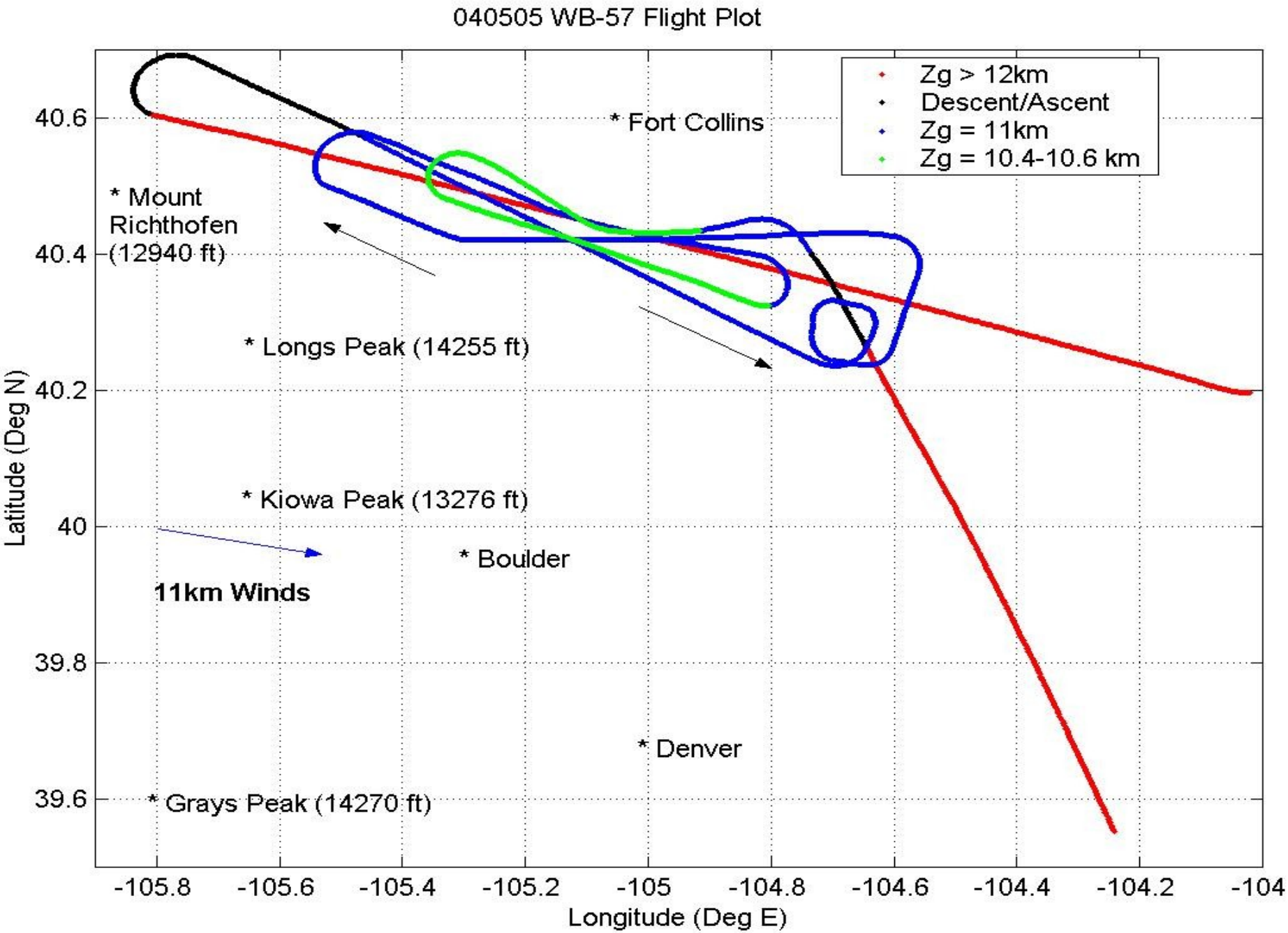

Westbound Leg at 12.0 Km Altitude
U (m/s)
44
42
40
38
36
34
V (m/s)
26
24
22
W (m/s)
1
0.5
0
-0.5
-98
-97.8
-97.6
-97.4
-97.2
-97
-96.8
-96.6
T (K)
213
212.5
212
CWC < 5 mg/m
CWC > 10mg/m
Longitude (Deg E)

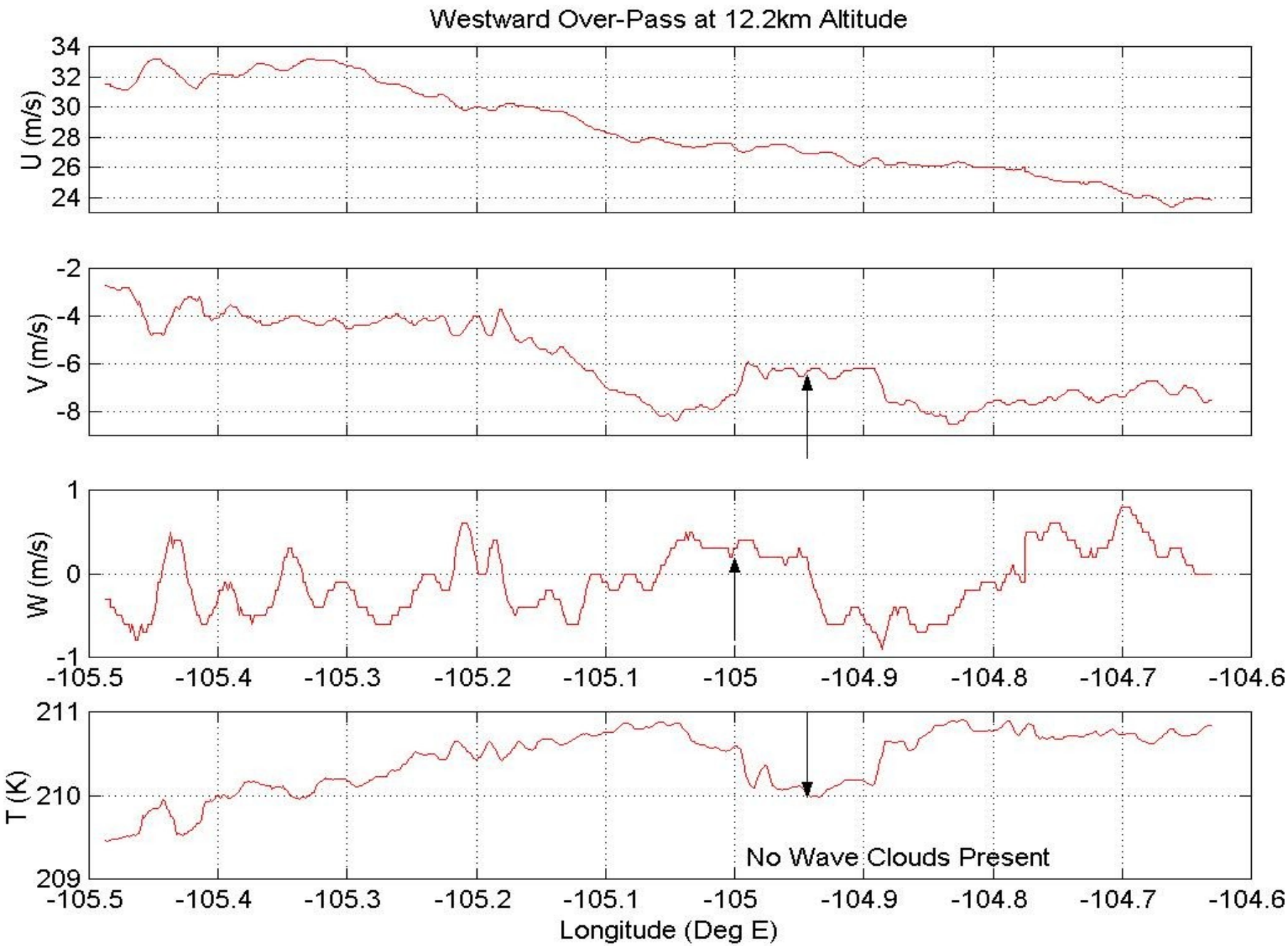

CIN / HVTW Cloud Parameters: Westbound Leg at 12.0 Km Altitude
Ice H2O Mixing Ratio mg/m3
50
40
30
20
10
CIN Effecive Radius um
20
15
10
5
-98
-97.8
-97.6
-97.4
-97.2
-97
-96.8
-96.6
Longitude (Deg E)

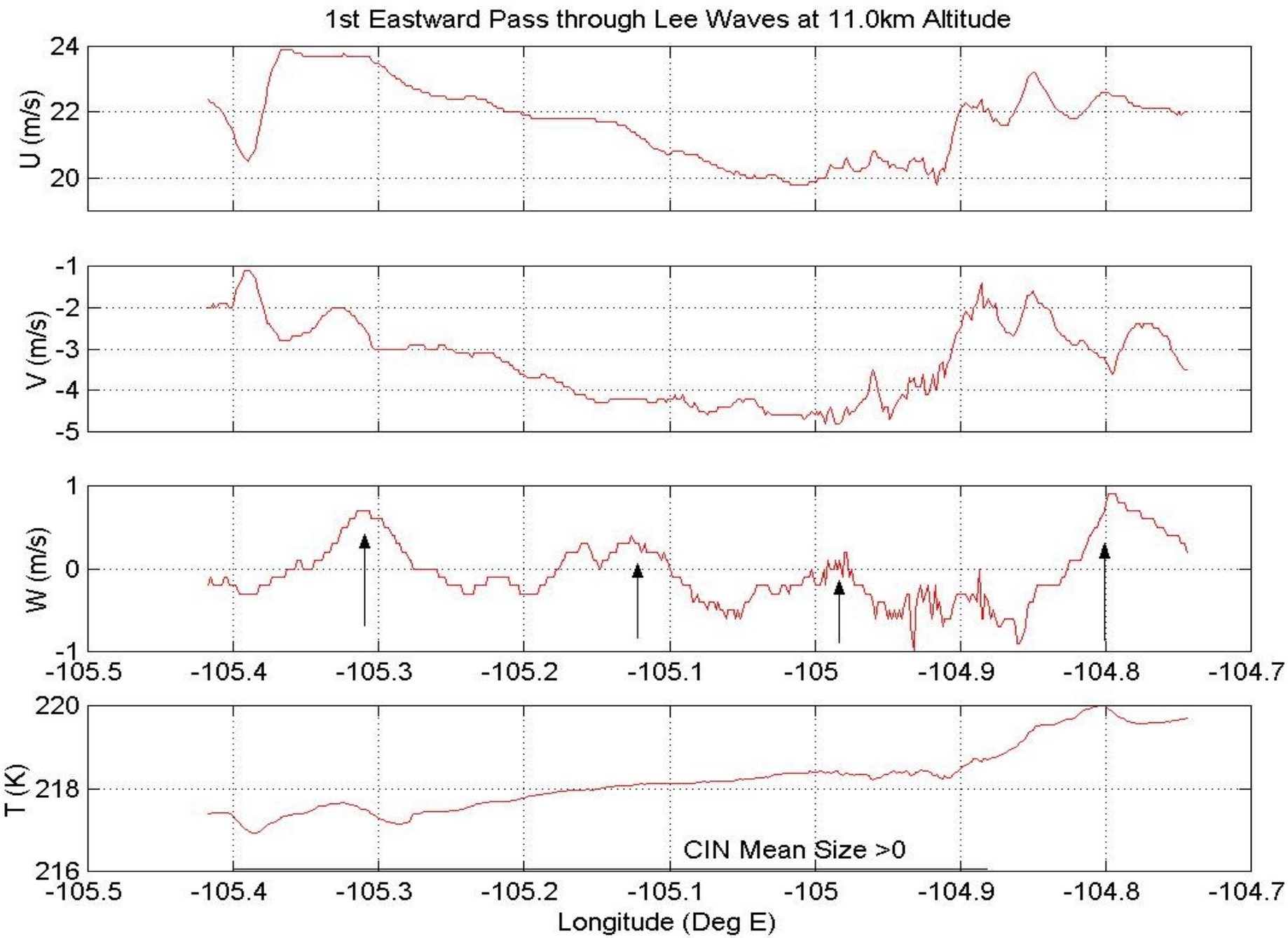

Eastbound Leg at 10.2 Km Altitude
U (m/s)
36
34
32
V (m/s)
16
14
12
10
W (m/s)
1
0.5
0
-0.5
CVI CWC > 0
T (K)
227
226.5
226
-98
-97.8
-97.6
-97.4
-97.2
-97
-96.8
-96.6
-96.4
-96.2
Longitude (Deg E)

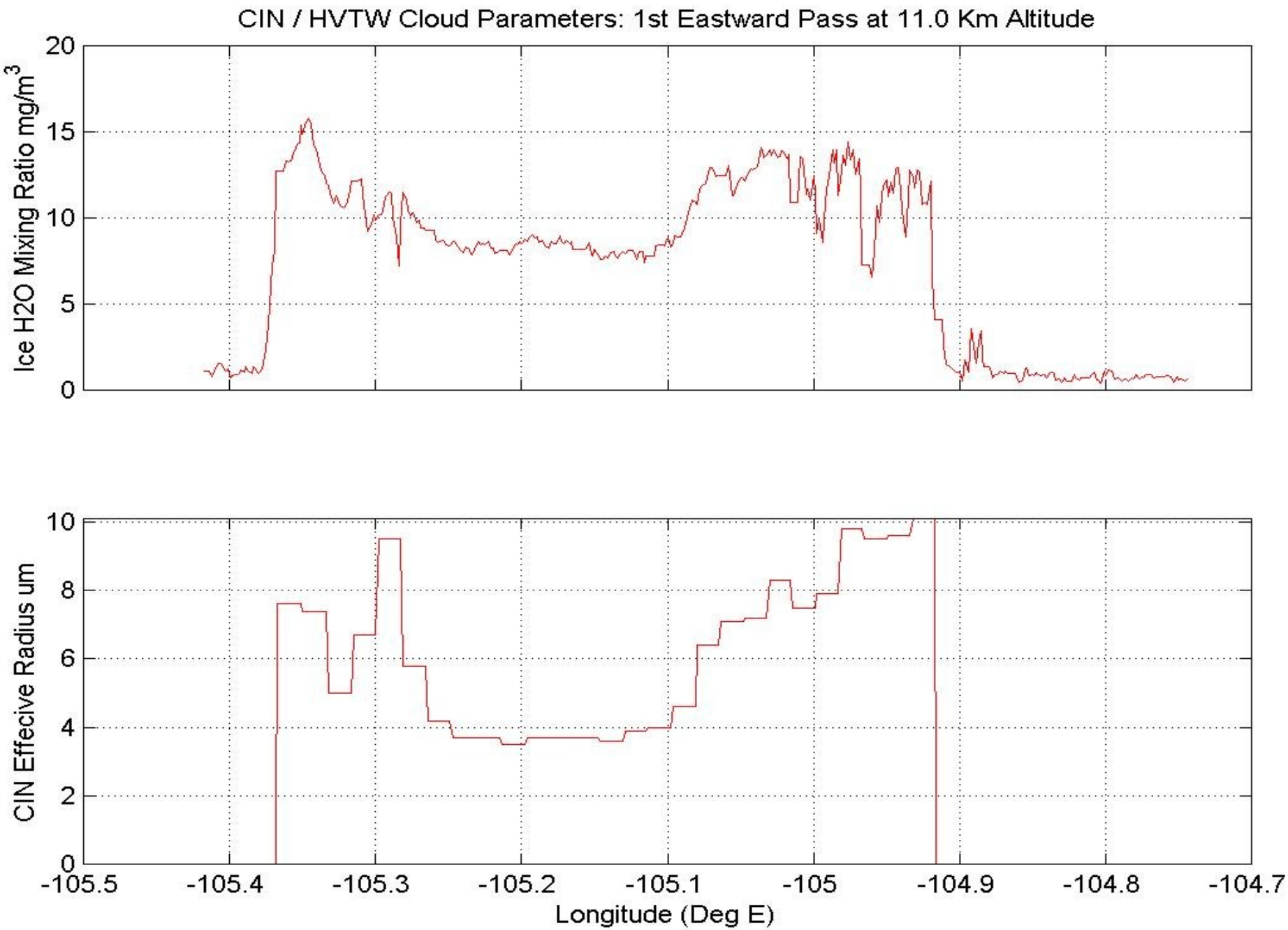

CIN / HVTW Cloud Parameters: Eastbound Leg at 10.2 Km Altitude
Ice H2O Mixing Ratio mg/m3
25
20
15
10
5
CIN Effecive Radius um
10
5
0
-98
-97.8
-97.6
-97.4
-97.2
-97
-96.8
-96.6
-96.4
-96.2
Longitude (Deg E)

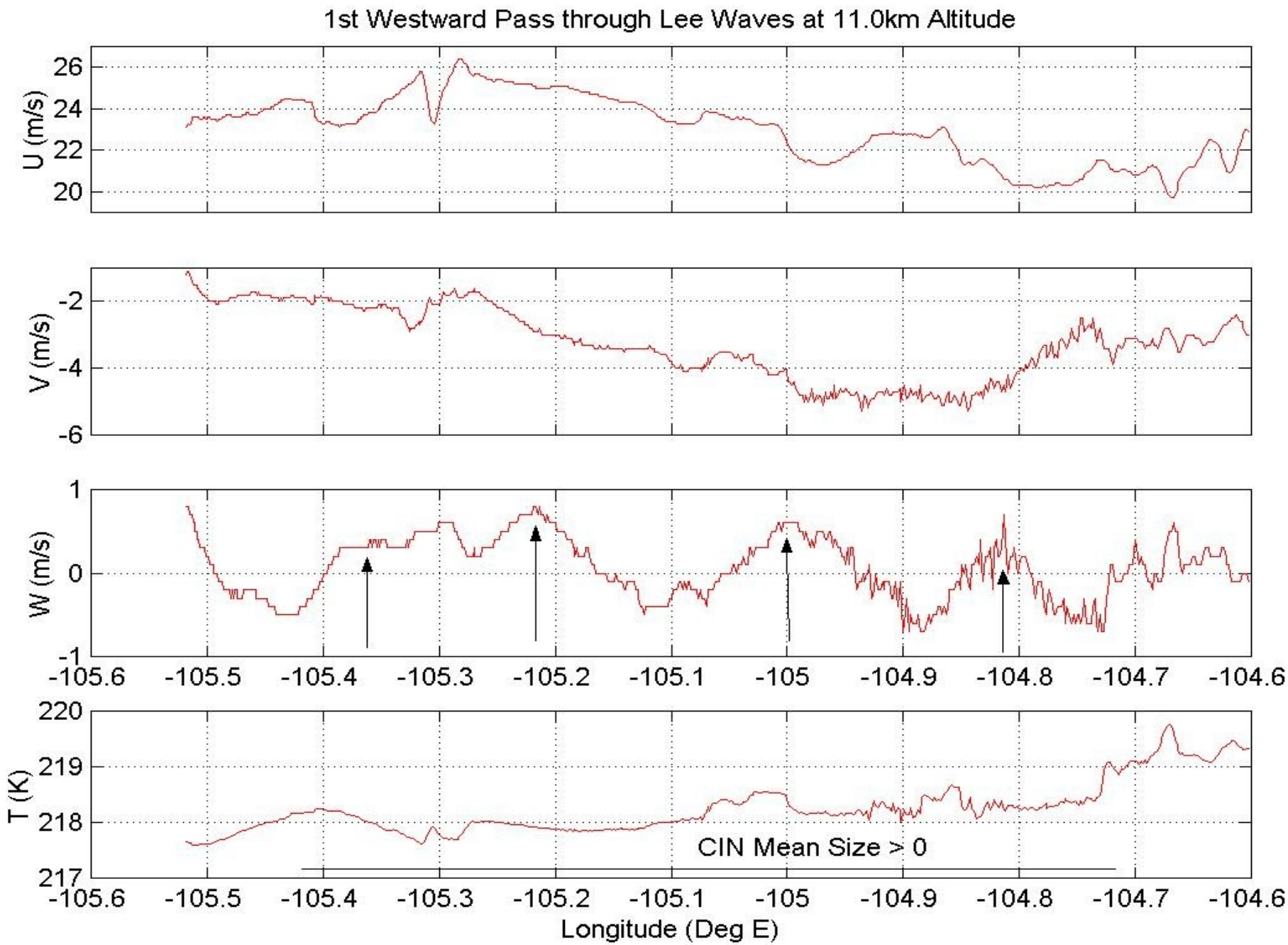

45
40
35
30
100
110
< 190 200 210 220 230 240 245 250 255 260 K
RRA-L1B MODIS 11.0 BAND 31 5 MAY 04 18:30 Z IMAGE FROM NASA LARC - DIRECT BROADCAST FROM SSEC-UNIV OF WISC

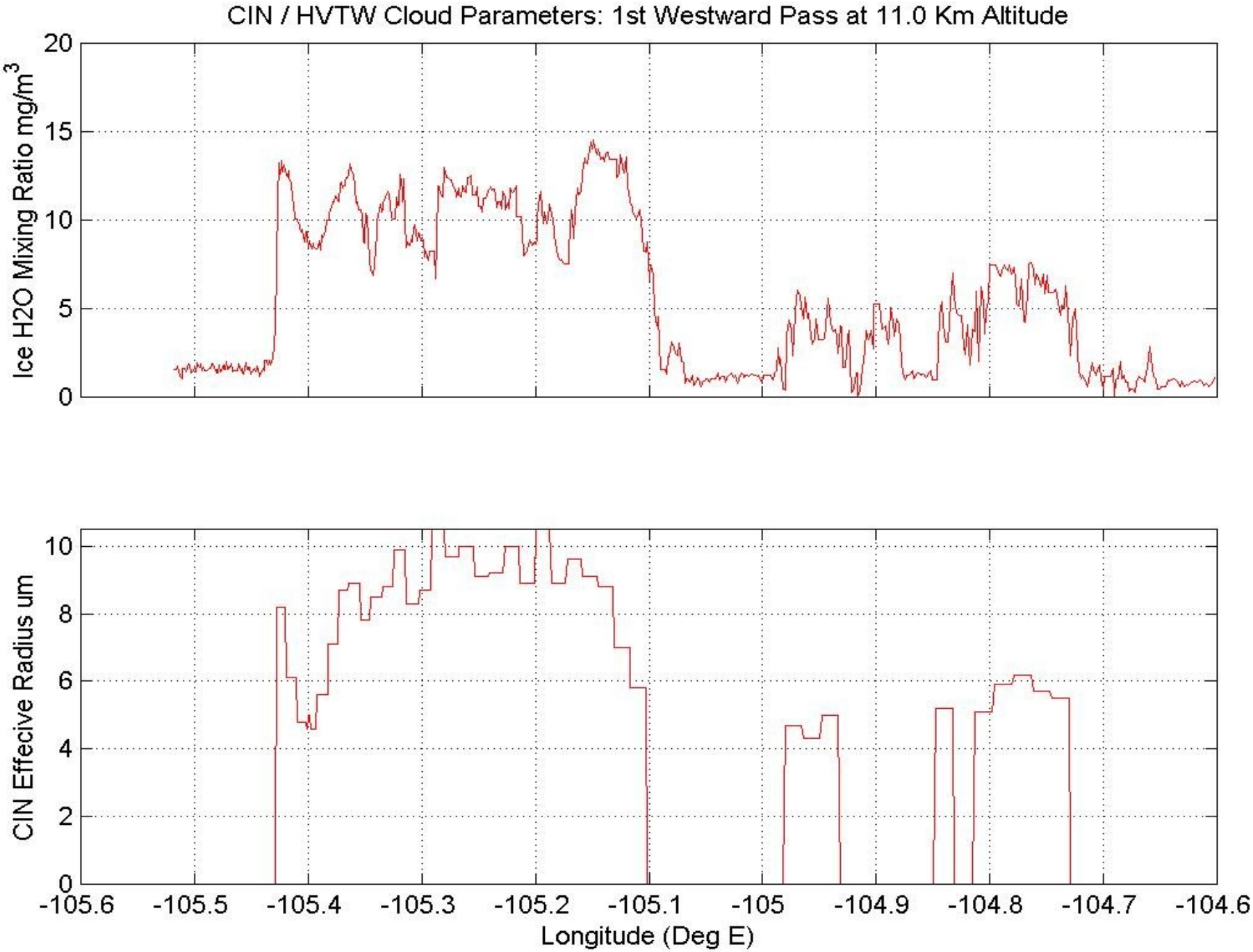

040505 WB-57 Flight Plot
Zg > 12km
Descent/Ascent
Zg = 11km
Zg = 10.4-10.6 km
* Fort Collins
* Mount Richthofen (12940 ft)
* Longs Peak (14255 ft)
* Kiowa Peak (13276 ft)
* Boulder
11km Winds
* Denver
* Grays Peak (14270 ft)
40.6
40.4
40.2
40
39.8
39.6
Latitude (Deg N)
-105.8
-105.6
-105.4
-105.2
-105
-104.8
-104.6
-104.4
-104.2
-104
Longitude (Deg E)


Westward Over-Pass at 12.2km Altitude
U (m/s)
34
32
30
28
26
24
V (m/s)
-2
-4
-6
-8
W (m/s)
1
0
-1
-105.5
-105.4
-105.3
-105.2
-105.1
-105
-104.9
-104.8
-104.7
-104.6
T (K)
211
210
209
No Wave Clouds Present
Longitude (Deg E)


1st Eastward Pass through Lee Waves at 11.0km Altitude
U (m/s)
24
22
20
V (m/s)
-1
-2
-3
-4
-5
W (m/s)
1
0
-1
-105.5
-105.4
-105.3
-105.2
-105.1
-105
-104.9
-104.8
-104.7
T (K)
220
218
216
CIN Mean Size >0
Longitude (Deg E)


CIN / HVTW Cloud Parameters: 1st Eastward Pass at 11.0 Km Altitude
Ice H2O Mixing Ratio mg/m3
20
15
10
5
0
CIN Effecive Radius um
10
8
6
4
2
0
-105.5
-105.4
-105.3
-105.2
-105.1
-105
-104.9
-104.8
-104.7
Longitude (Deg E)


1st Westward Pass through Lee Waves at 11.0km Altitude
U (m/s)
26
24
22
20
V (m/s)
-2
-4
-6
W (m/s)
1
0
-1
-105.6
-105.5
-105.4
-105.3
-105.2
-105.1
-105
-104.9
-104.8
-104.7
-104.6
T (K)
220
219
218
217
CIN Mean Size > 0
Longitude (Deg E)


CIN / HVTW Cloud Parameters: 1st Westward Pass at 11.0 Km Altitude
Ice H2O Mixing Ratio mg/m3
20
15
10
5
0
CIN Effecive Radius um
10
8
6
4
2
0
-105.6
-105.5
-105.4
-105.3
-105.2
-105.1
-105
-104.9
-104.8
-104.7
-104.6
Longitude (Deg E)

Wave Calculations

1. Waves are stationary

$$\omega = 0$$

$$c_x = 0$$

2. Horizontal wavelength = 15km

Assume wave vector parallel to wind vector @ Zg = 11km
Wave vector orientation = 97 degrees from north
Mean flow through waves = 22.7 m/s

3. Waves gradually decay w/altitude

$$\Gamma = 7.22K / Km$$

$$N = 8.78x10^{-3} s^{-1}$$

$$\left|\hat{\omega}\right| = \left|\kappa \bullet \overline{U}\right| = 9.50x10^{-3} s^{-1}$$

4. Vertical displacement = 230m

$$\Delta Zg = \frac{\Delta T}{\left(\Gamma_D - \Gamma\right)} = \frac{0.6K}{2.58K / Km}$$

5. Lee wave displacement = 138m

$$\Delta Zg = \frac{\overline{w}\lambda_H}{2\overline{U}} = \frac{0.42m / s \bullet 15000m}{2 \bullet 22.7m / s}$$

Decaying gravity waves observed in the upper troposphere (10-12km altitude) in the vicinity of a subtropical jet, and to the lee of the Rockies.

040419 (Subtropical Jet):

- Small (< 5 μm) ice crystals and ice water concentrations (< 5 mg/m^3) observed in some waves upwind or beneath the jet

- Synoptic scale motions lift air 400-500m to create cloud layers with 25 μm ice crystals having IWC's of 10-40 mg/m^3

- Observed gravity wave displacements were small (< 100m), but may augment cooling provided by larger scales to initiate cloud formation.

- Multiple constant-altitude flight tracks needed to fully characterize the gravity wave field (speed, direction).

040505 (Mountain waves):

- Small scale (~ 15km wavelength) standing lee waves were analyzed along WB-57 flight track, contributing small crystals (5 μm) & light IWC's (<8 mg/m^3).

- Larger scale lee waves contribute cooling, but were not analyzed -- limited sampling over the mountains.