SLW and Vapor Observations from a Seeding Aircraft Equipped with a Side Scanning G-Band Radiometer

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Icing Flight Testing & Validation Study

- Improve real-time cloud seeding opportunity recognition
- Improve icing risk detection and passive detection of SLW fields
- Aircraft multichannel 170-183 GHz & complementary Observations
- Cloud seeding aircraft provides a unique cloud liquid observatory
- Part of an ongoing winter seeding program

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Seeding Opportunity Recognition

- Scanning to improve SLW detection (spatial location and extent – area/volume vs ribbon)
- Reduce time to recognize opportunities
- Improved real-time guidance and assessment systems
- Radiometric methods offer advanced capability over aircraft mounted sensors
- Next gen G band radiometers have a smaller size and potentially lower unit cost
- Need for improved training for Pilots - seeding strategies

Cloud Seeding Aircraft/Cloud Liquid Observatory

Hot Wire Liquid Water, Temp Probes

CDP2 Droplet Probe

G Band Radiometer Low loss viewport

Nose and Wing Video Cameras


RESTRICTED
Mini MPL Pulsed Lidar
MP-183A on shock-mounted platform

Microwave Radiometer (G-Band)

- Multiple 170-183 GHz Channels
- Liquid Water Sensor
- 1 Degree Beamwidth
- 25 m to >50 km Clear Air Effective Range
- Current study uses side scanning to avoid ice accumulation on sensor (signal contamination-scattering)

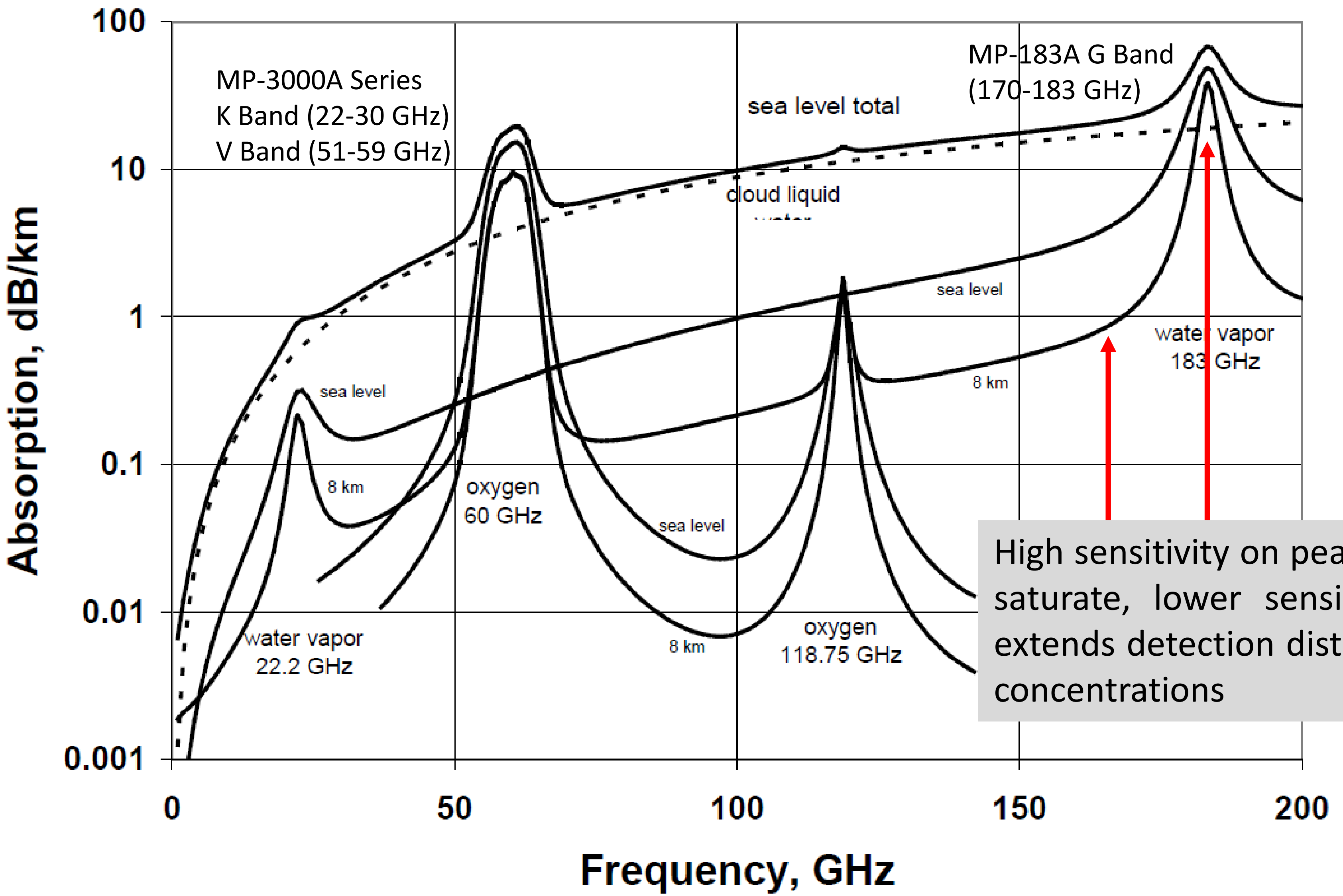
radiometrics
Ahead of the Weather®

Cross-Polarization Lidar

MiniMPL

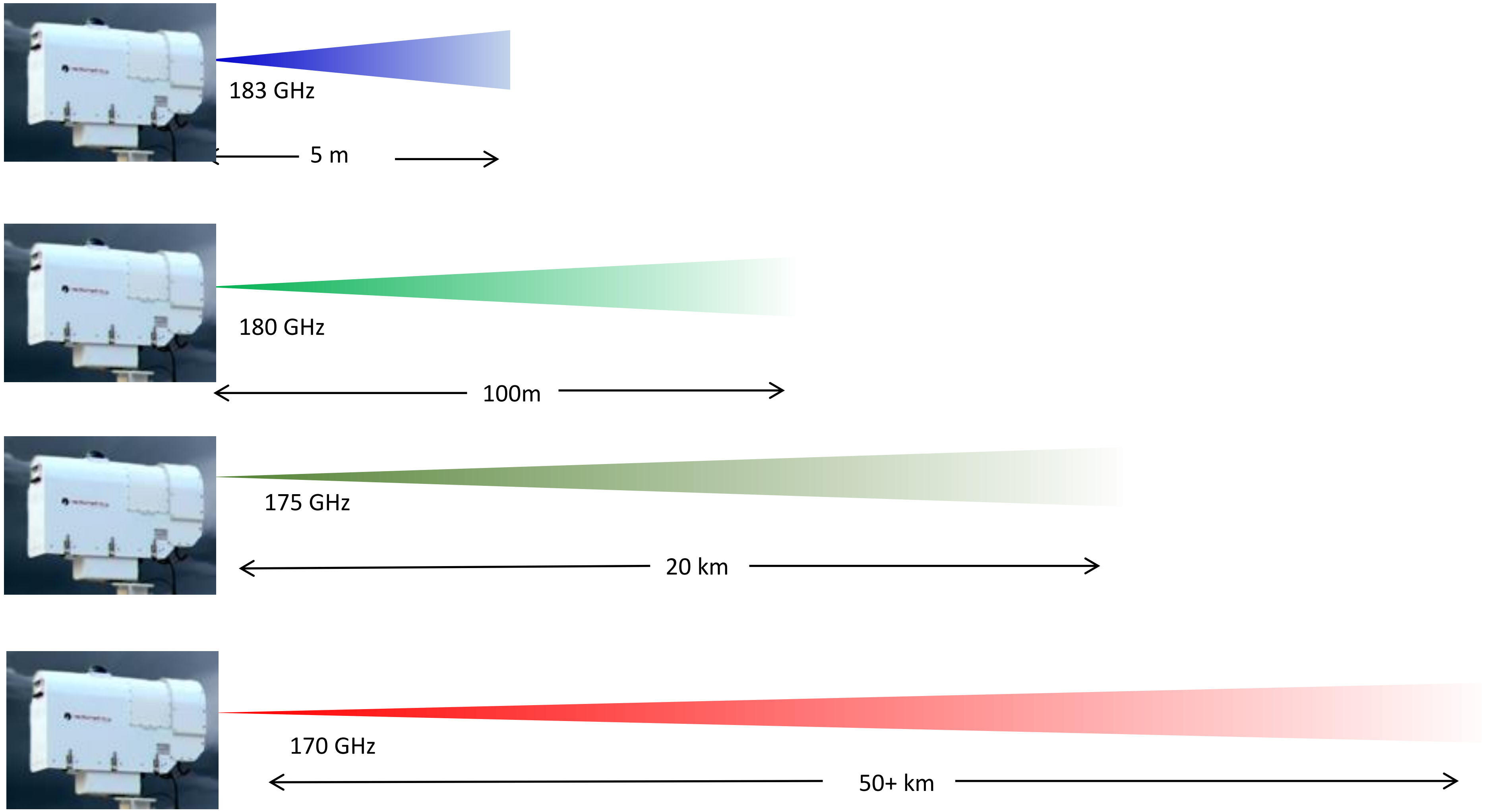
- Particle Range, Density & Type
- Range to cloud
- Ground or Aircraft Based
- Eye friendly laser

Liquid and Vapor Spectra < 200 GHz

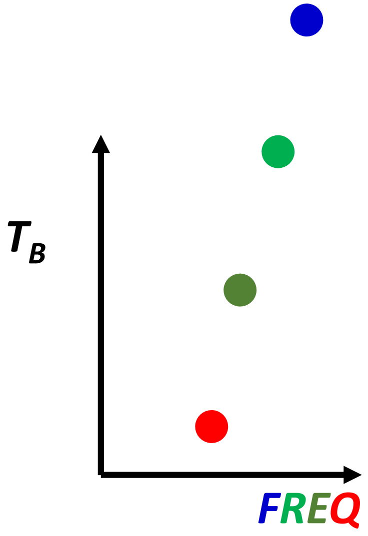


High sensitivity on peak centerline-easy to saturate, lower sensitivity on shoulder-extends detection distance and saturation concentrations

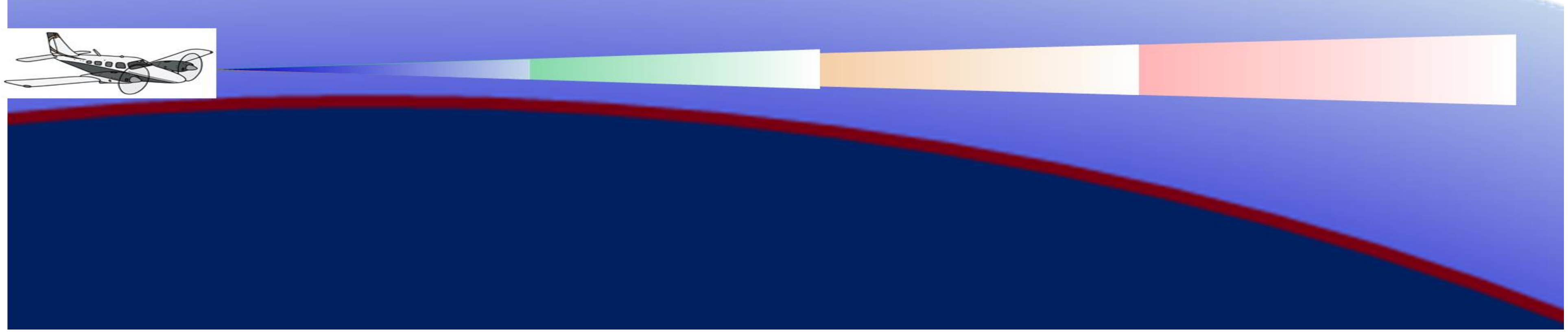
G-Band Clear-Air Operation



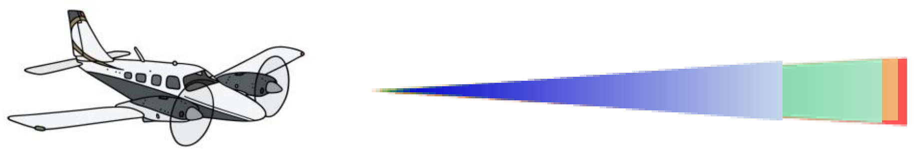
Measurement Scenario 1
Horizontal Measurement

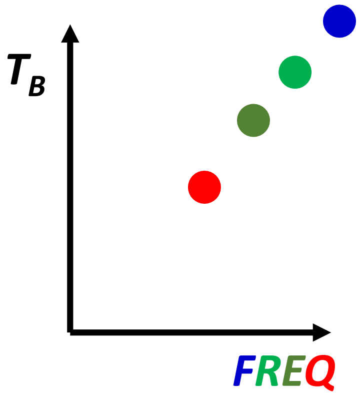


- Clear Air Propagation
- Logarithmic increase in range with frequency
- Decreasing temperature and moisture content with altitude
- Earth curvature leads to lower brightness temps (T_B) at lower frequency
- T_B "expands" with frequency
- Range heavily dependent on liquid and vapor content



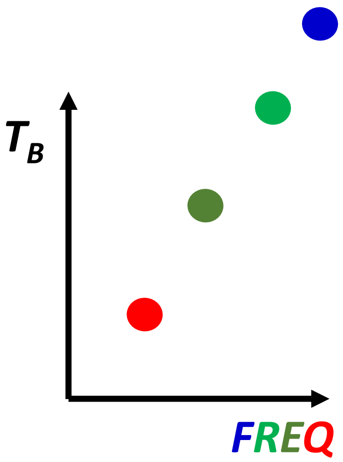
Measurement Scenario 2
Beam Looking Upwind of Seeding Track





- Beam heavily attenuated looking upwind into saturated cloud – reduces detection range
- T_B (water is warmer and brighter) looking upwind into approaching vapor and liquid water
- Signal more compressed because of higher vapor and/or water contents
- T_B *compresses* with frequency – accordion effect increases and shows more compression

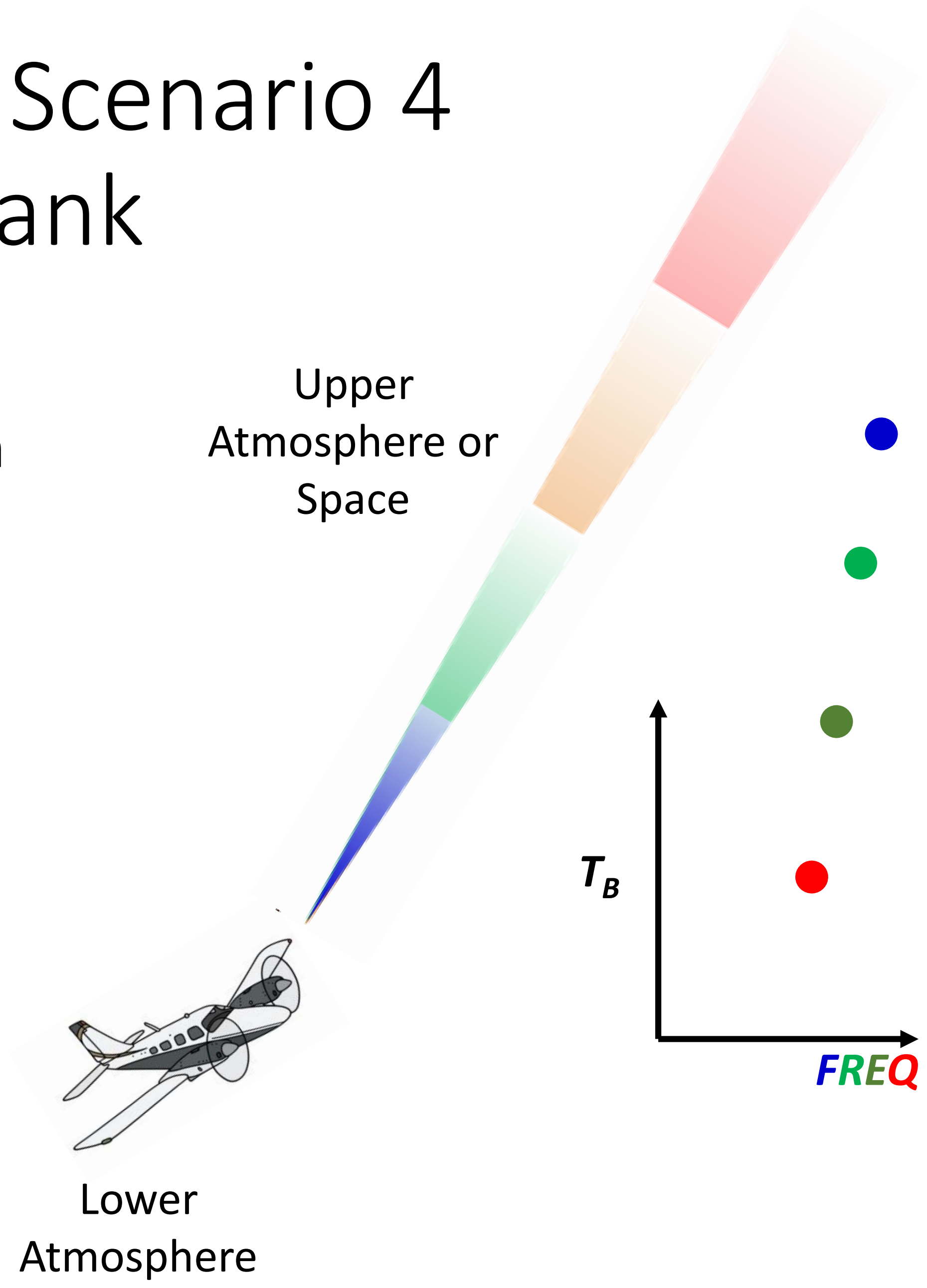
Measurement Scenario 3
Beam Looking Downwind of Seeding Track



- Beam less attenuated, looks farther Downwind - cloud vapor and water are converted to ice by seeding
- T_B cooler - water vapor and liquid cooler depleted downwind of seed track
- Signal shows lower compression - seeding lowers liquid water and vapor content reducing accordion effect
- T_B *decompresses* with frequency – slightly more open accordion

Measurement Scenario 4
Right Bank

- Beam Looking up
- Long range achieved as humidity drops with altitude
- Decreasing atmospheric temperature with altitude
- Significant reduction in observed T_B, especially at lower frequencies
- Degree of bank directly modulates degree of T_B separation with frequency
- Expanded Accordion

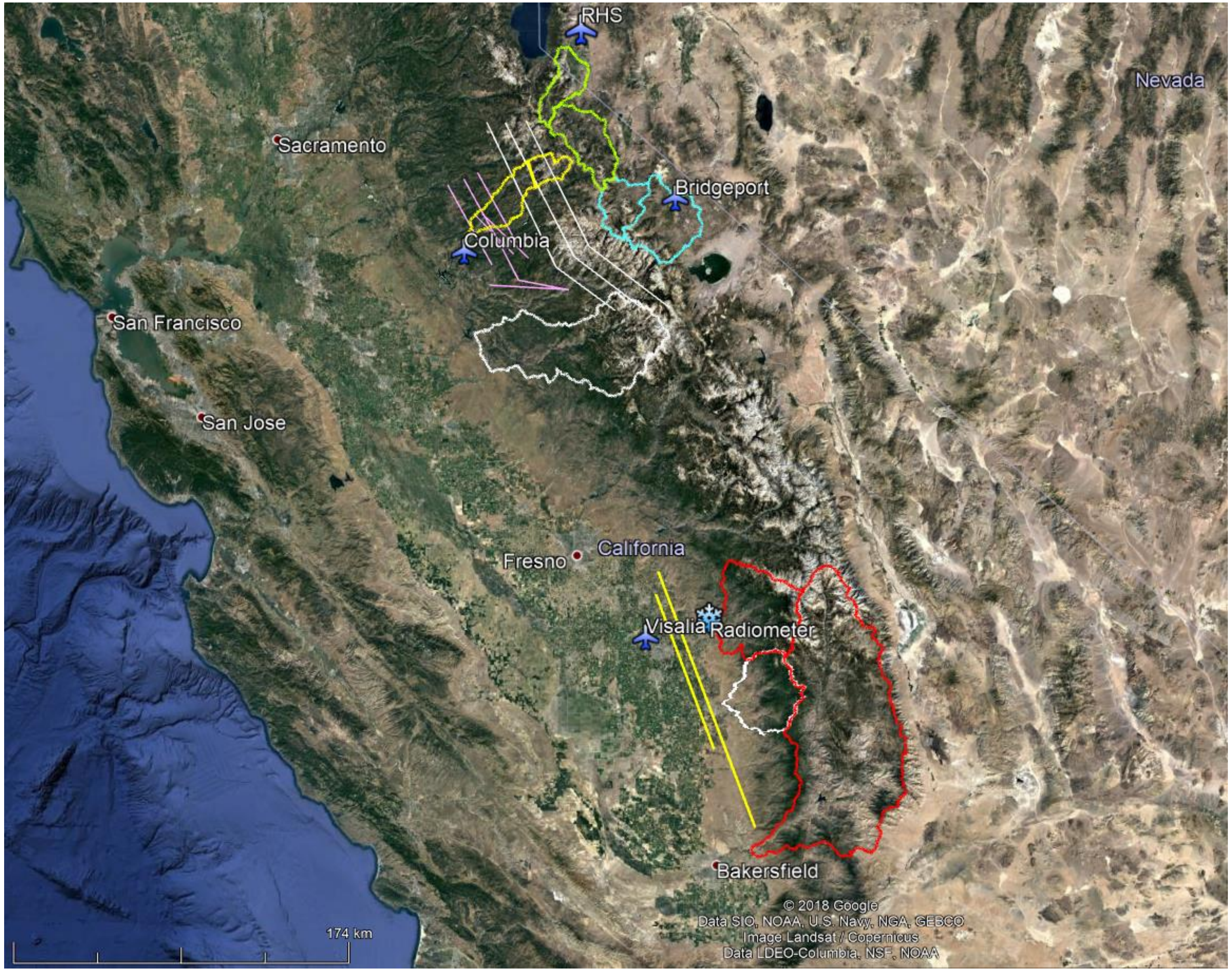


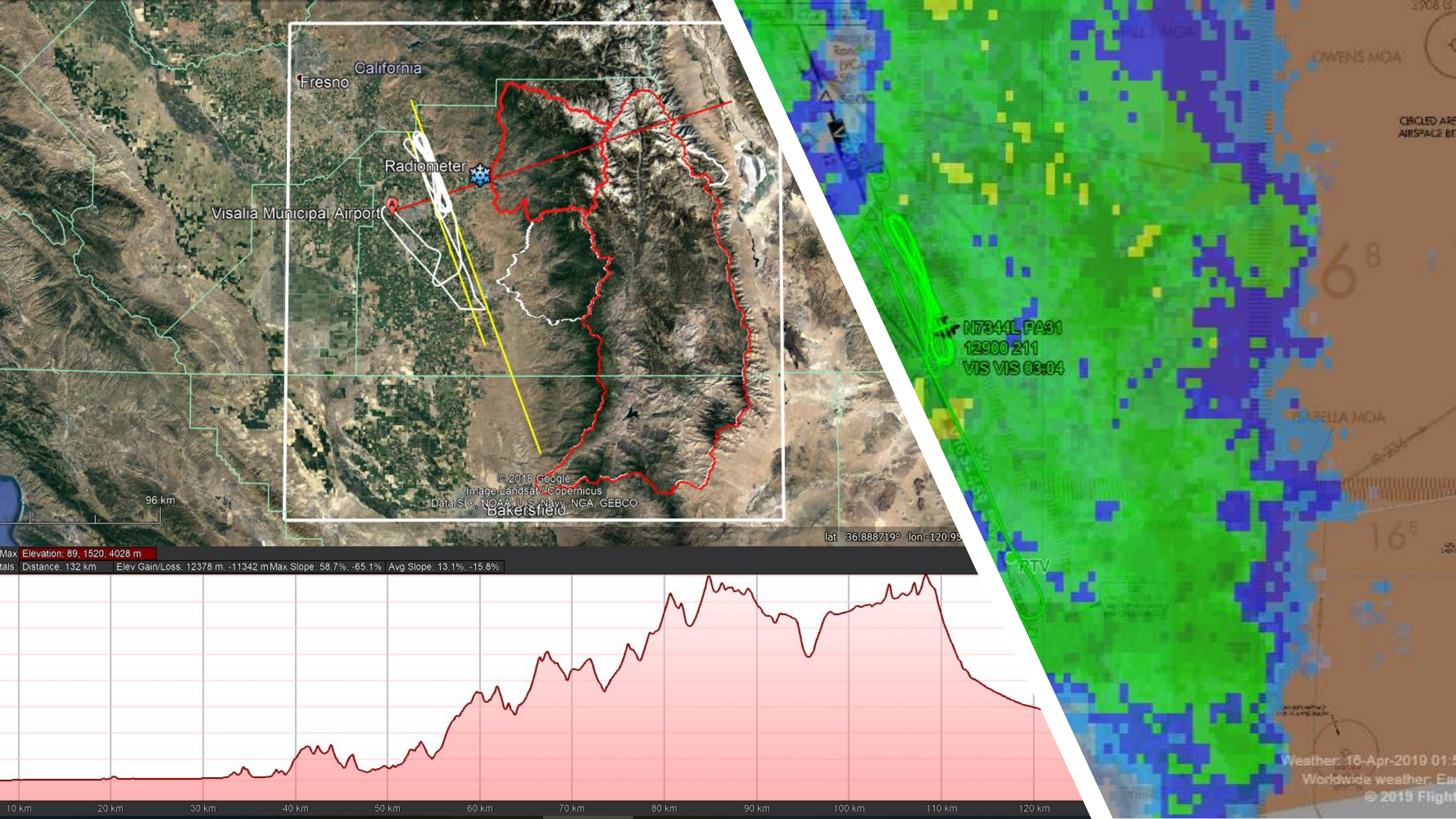
WY2019 RHS Target Areas and Sponsors

- Carson River Basins (Nevada State)
- Walker River Basins (Nevada State)
- North Fork Stanislaus (NCPA)
- Kaweah River (KDWCD)
- Kern River (NKWSD)

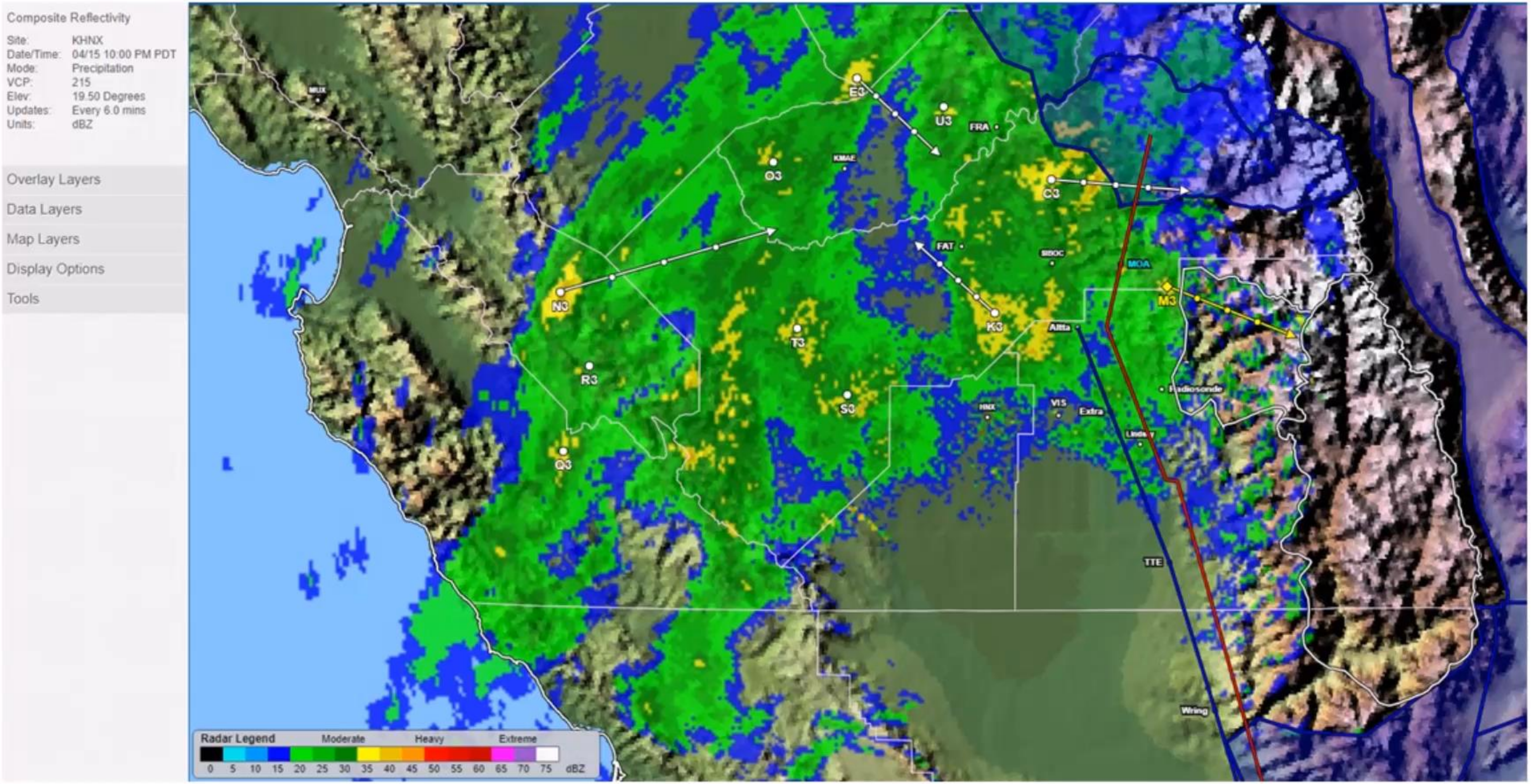
Control Areas

- Tule River Basin
- Cottonwood Creek
- Merced River Basin
- San Joaquin River Basin

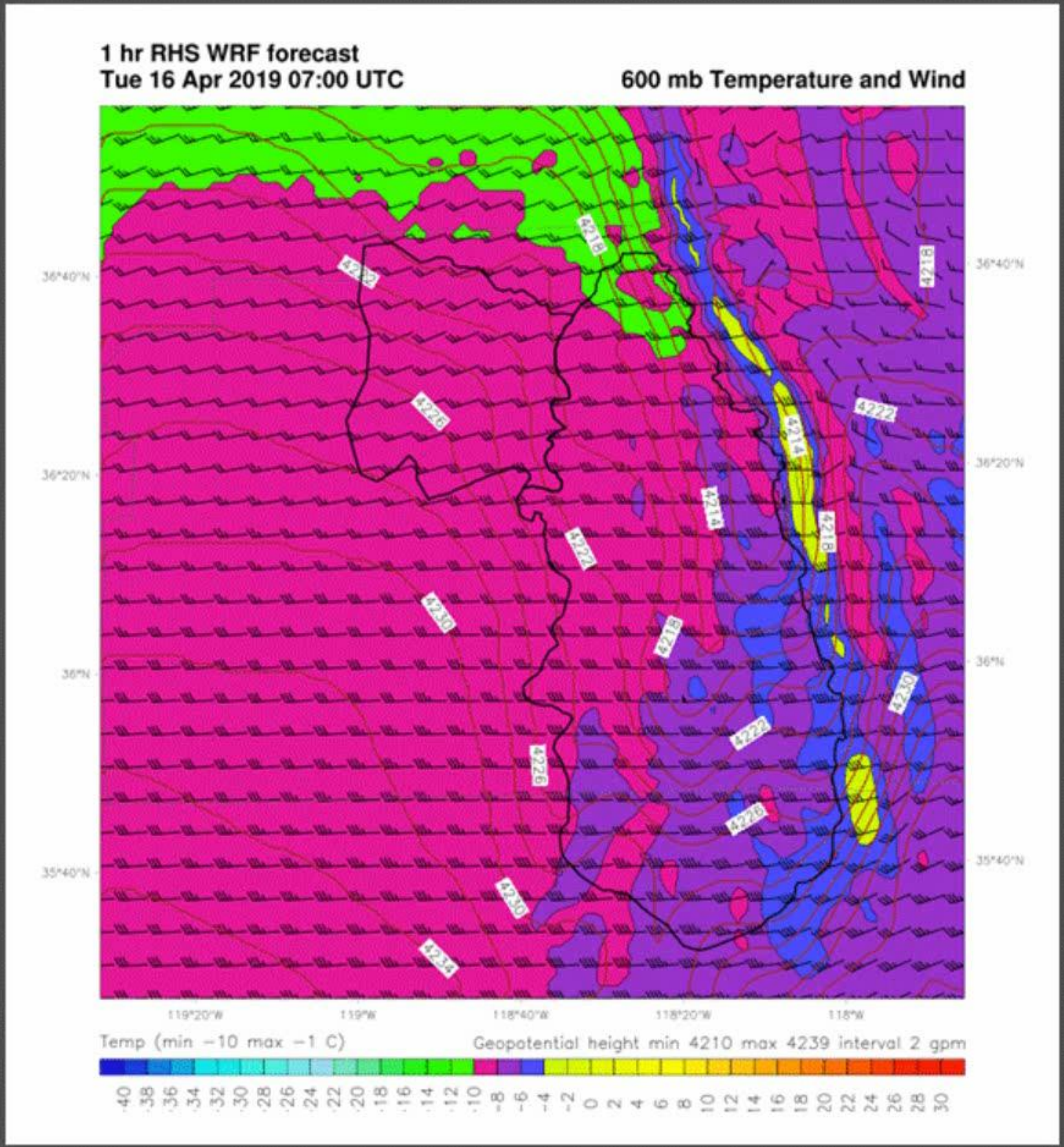


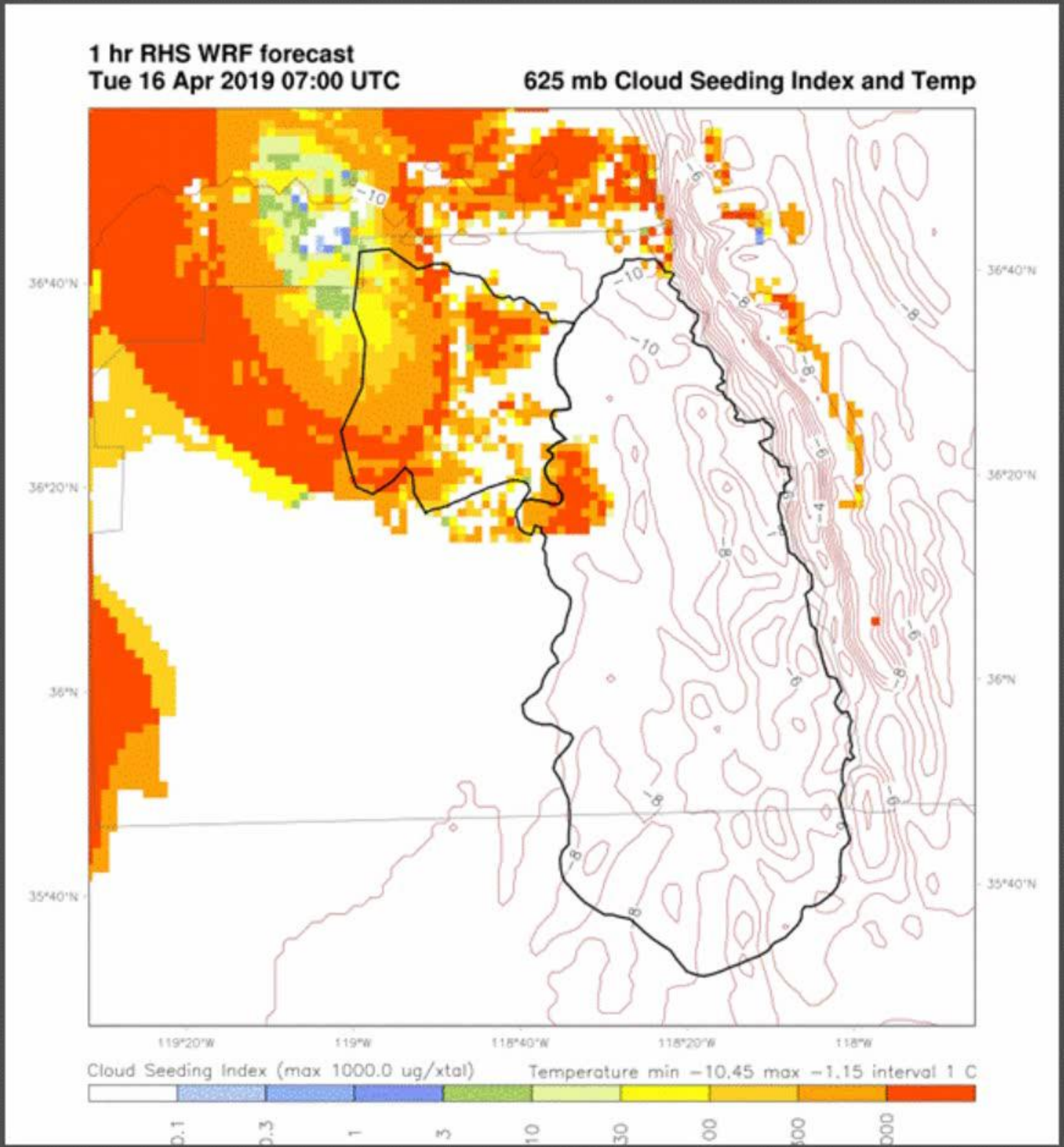


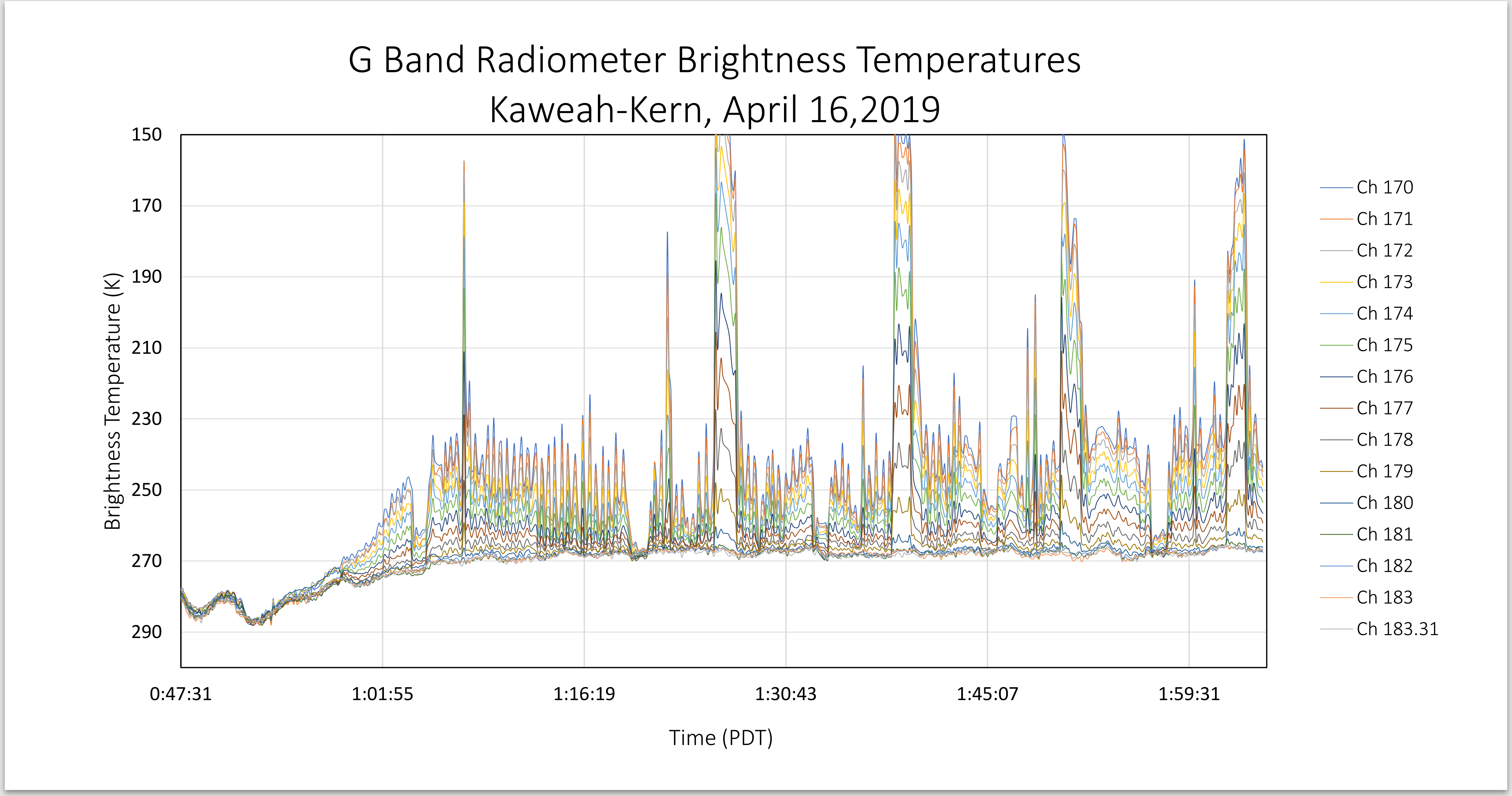
California
Fresno
Radiometer
Visalia Municipal Airport
Bakersfield
96 km
© 2018 Google
Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
lat 36.888719° lon -120.95
Elevation: 89, 1520, 4028 m
Distance: 132 km
Elev Gain/Loss: 12378 m, -11342 m
Max Slope: 58.7%, -65.1%
Avg Slope: 13.1%, -15.8%
10 km
20 km
30 km
40 km
50 km
60 km
70 km
80 km
90 km
100 km
110 km
120 km
OWENS MOA
ISABELLA MOA
N7344L PA31
12900 211
VIS VIS 03:04
RTV

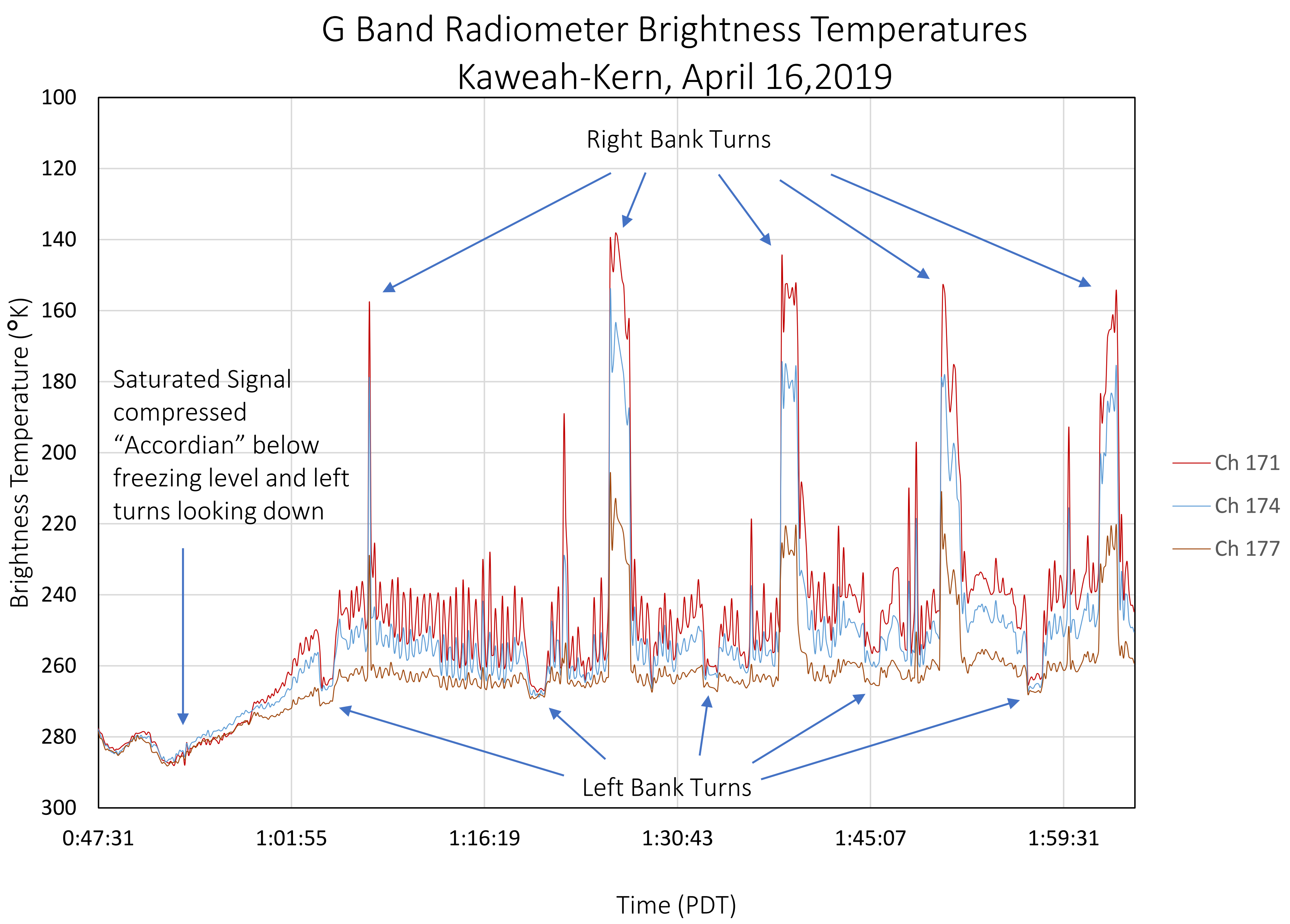


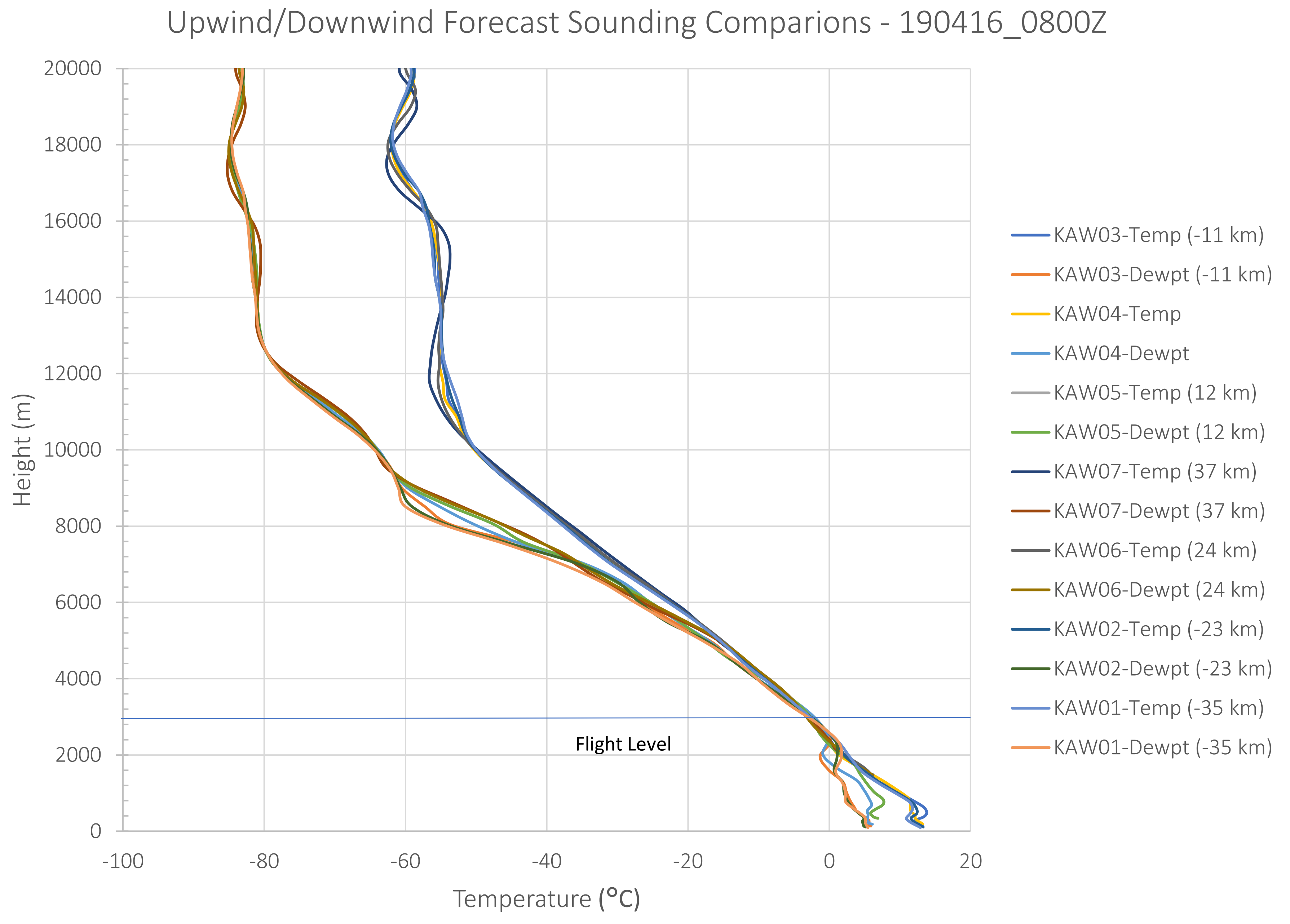
Composite Reflectivity
Site: KHNX
Date/Time: 04/15 10:00 PM PDT
Mode: Precipitation
VCP: 215
Elev: 19.50 Degrees
Updates: Every 6.0 mins
Units: dBZ
Overlay Layers
Data Layers
Map Layers
Display Options
Tools
E3
U3
FRA
O3
KMAE
C3
FAT
N3
M3
K3
T3
R3
S3
Q3
HNX
VIS
Extra
Radiosonde
TTE
MOA
Radar Legend
Moderate
Heavy
Extreme
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 dBZ

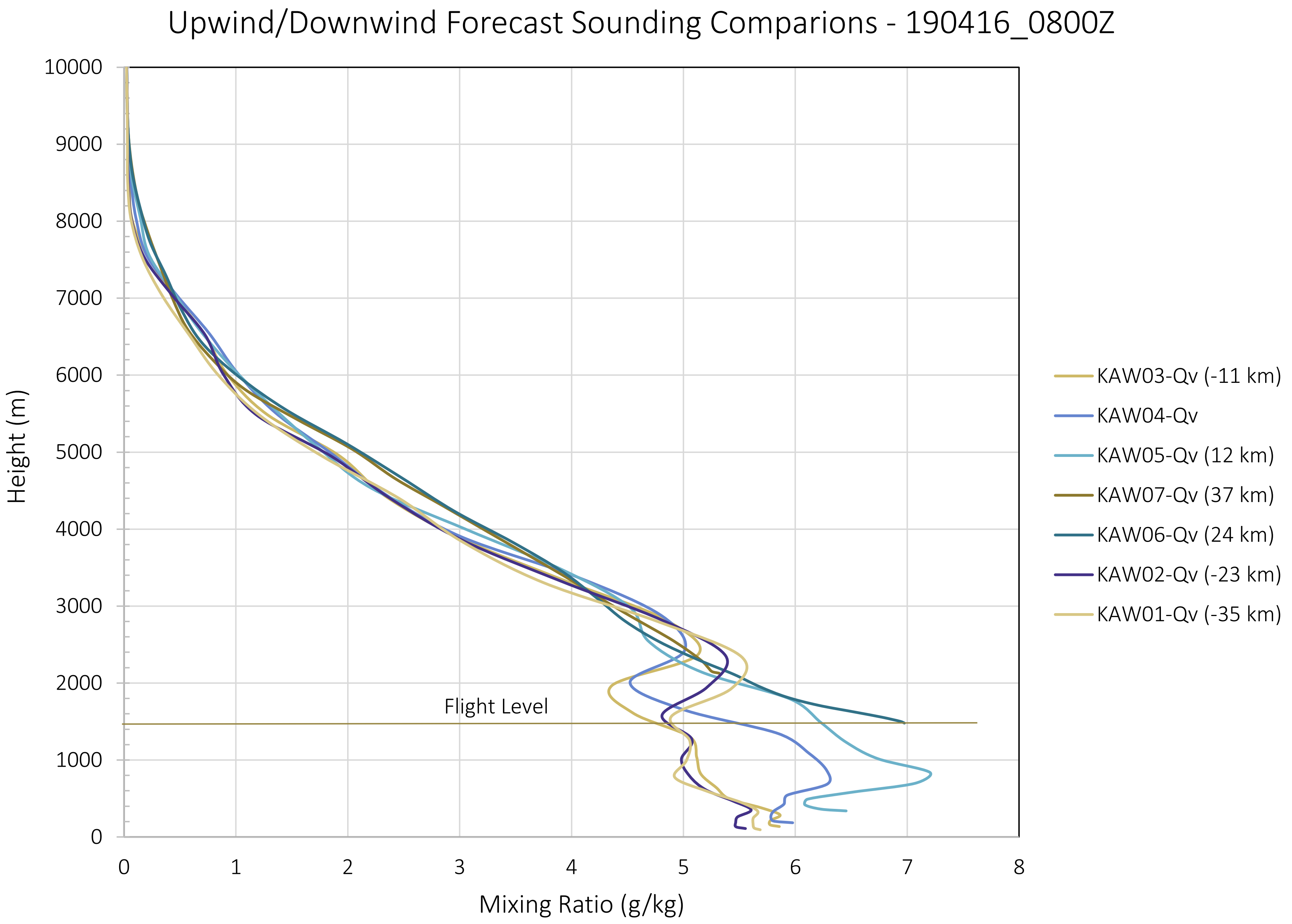

1 hr RHS WRF forecast
Tue 16 Apr 2019 07:00 UTC
600 mb Temperature and Wind
36°40'N
36°20'N
36°N
35°40'N
119°20'W
119°W
118°40'W
118°20'W
118°W
Temp (min −10 max −1 C)
Geopotential height min 4210 max 4239 interval 2 gpm
-40 -38 -36 -34 -32 -30 -28 -26 -24 -22 -20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30


1 hr RHS WRF forecast
Tue 16 Apr 2019 07:00 UTC
625 mb Cloud Seeding Index and Temp
36°40'N
36°20'N
36°N
35°40'N
119°20'W
119°W
118°40'W
118°20'W
118°W
Cloud Seeding Index (max 1000.0 ug/xtal)
Temperature min −10.45 max −1.15 interval 1 C


G Band Radiometer Brightness Temperatures
Kaweah-Kern, April 16,2019
Brightness Temperature (K)
150
170
190
210
230
250
270
290
0:47:31
1:01:55
1:16:19
1:30:43
1:45:07
1:59:31
Time (PDT)
Ch 170
Ch 171
Ch 172
Ch 173
Ch 174
Ch 175
Ch 176
Ch 177
Ch 178
Ch 179
Ch 180
Ch 181
Ch 182
Ch 183
Ch 183.31


G Band Radiometer Brightness Temperatures
Kaweah-Kern, April 16,2019
Right Bank Turns
Saturated Signal
compressed
“Accordian” below
freezing level and left
turns looking down
Left Bank Turns
Brightness Temperature (°K)
100
120
140
160
180
200
220
240
260
280
300
0:47:31
1:01:55
1:16:19
1:30:43
1:45:07
1:59:31
Time (PDT)
Ch 171
Ch 174
Ch 177


Upwind/Downwind Forecast Sounding Comparions - 190416_0800Z
Height (m)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Flight Level
-100
-80
-60
-40
-20
0
20
Temperature (°C)
KAW03-Temp (-11 km)
KAW03-Dewpt (-11 km)
KAW04-Temp
KAW04-Dewpt
KAW05-Temp (12 km)
KAW05-Dewpt (12 km)
KAW07-Temp (37 km)
KAW07-Dewpt (37 km)
KAW06-Temp (24 km)
KAW06-Dewpt (24 km)
KAW02-Temp (-23 km)
KAW02-Dewpt (-23 km)
KAW01-Temp (-35 km)
KAW01-Dewpt (-35 km)


Upwind/Downwind Forecast Sounding Comparions - 190416_0800Z
Height (m)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Flight Level
0
1
2
3
4
5
6
7
8
Mixing Ratio (g/kg)
KAW03-Qv (-11 km)
KAW04-Qv
KAW05-Qv (12 km)
KAW07-Qv (37 km)
KAW06-Qv (24 km)
KAW02-Qv (-23 km)
KAW01-Qv (-35 km)

Conceptual Model

- Upwind of the seed track average T_b's are higher (brighter) because they contain more liquid water and vapor relative to seeded air downwind of the track
- Downwind average T_b's are lowered as ice forms downwind of the seeding track depleting LWC's and vapor
- Upwind T_b's decrease as the back edge of a band approaches the seed track because shorter liquid and vapor paths result as colder drier air approaches the track (lowering upstream T_b's)

Conceptual Model

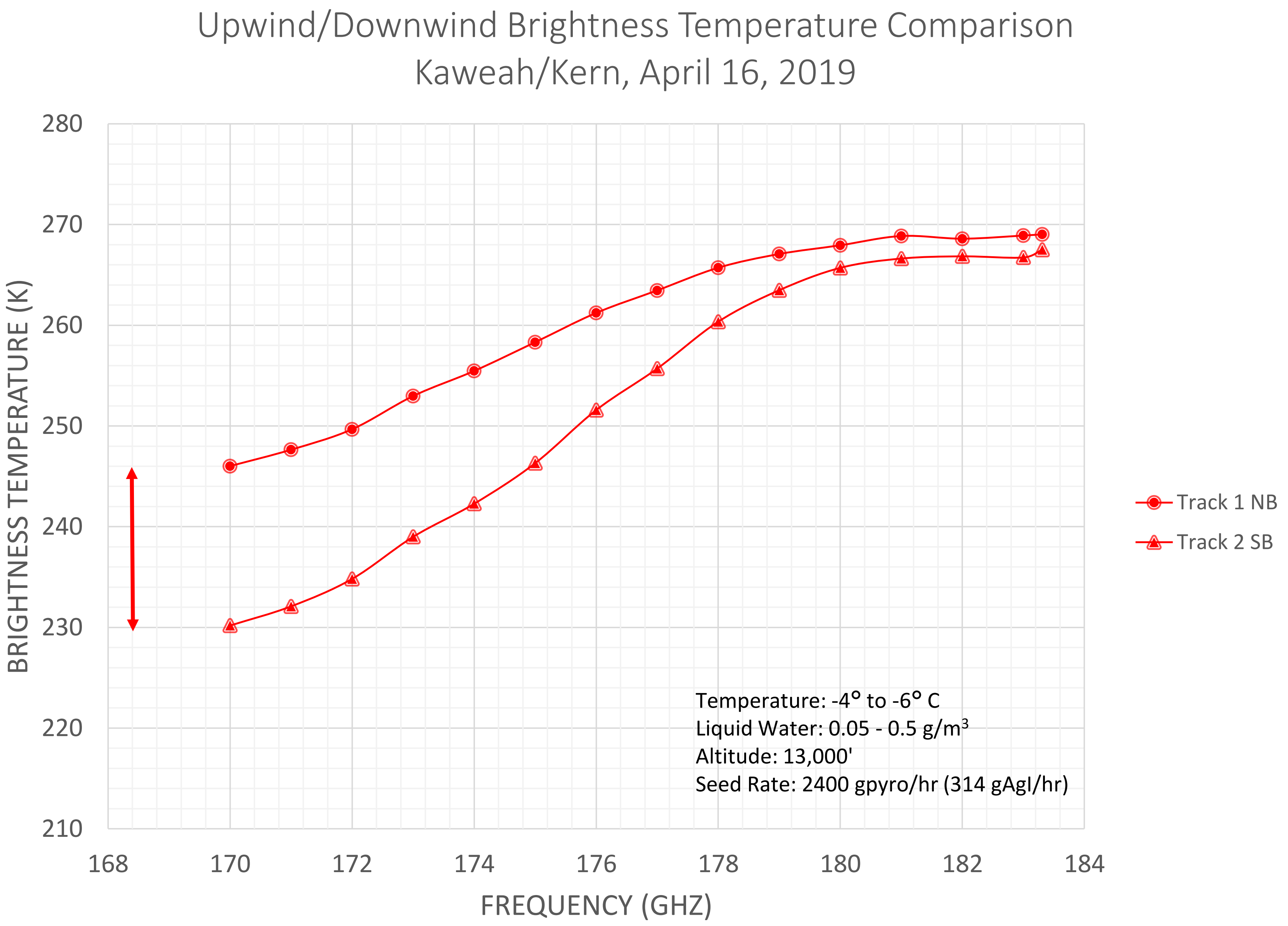
- T_b's decrease with time as more cloud passes across the track and seeding material fills the volume nucleating new ice crystals that deplete the cloud water and vapor in the seeded volume
- Higher LWC's reduce the upwind/downwind ΔT_b because of saturation at G band frequencies.
- Seeding effects are easier to detect in colder temperatures and lower LWC's because of lower saturation vapor pressures

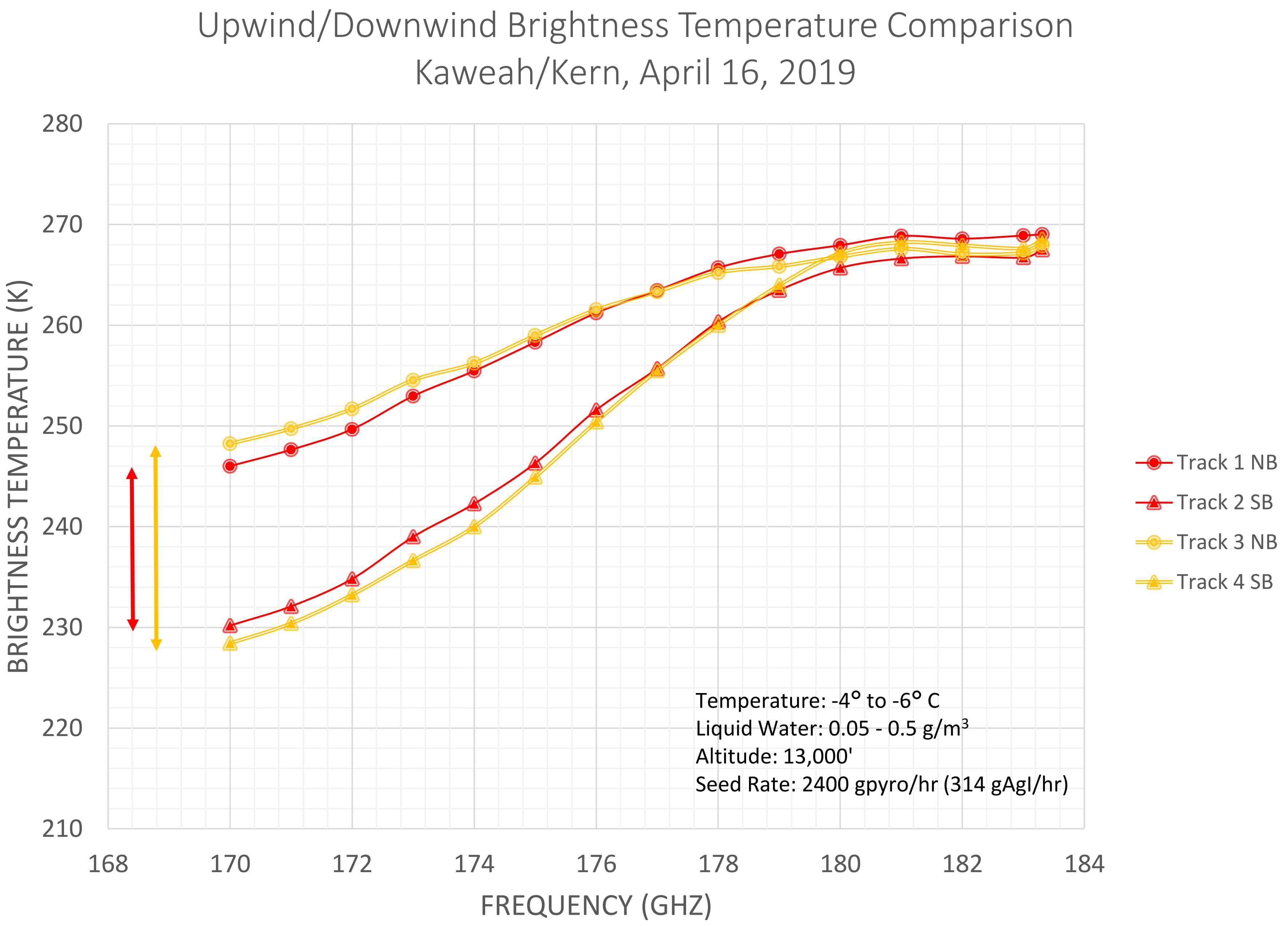
Interpretation Sierra Projects

- Upwind T_b's (northbound) give average liq/vap brightness temperature of incoming air mass
- Downwind T_b's (southbound) give average liq/vap brightness temperature of departing air mass
- Seeding creates new ice crystals that deplete liq/vap downwind of the seed track lowering T_b's

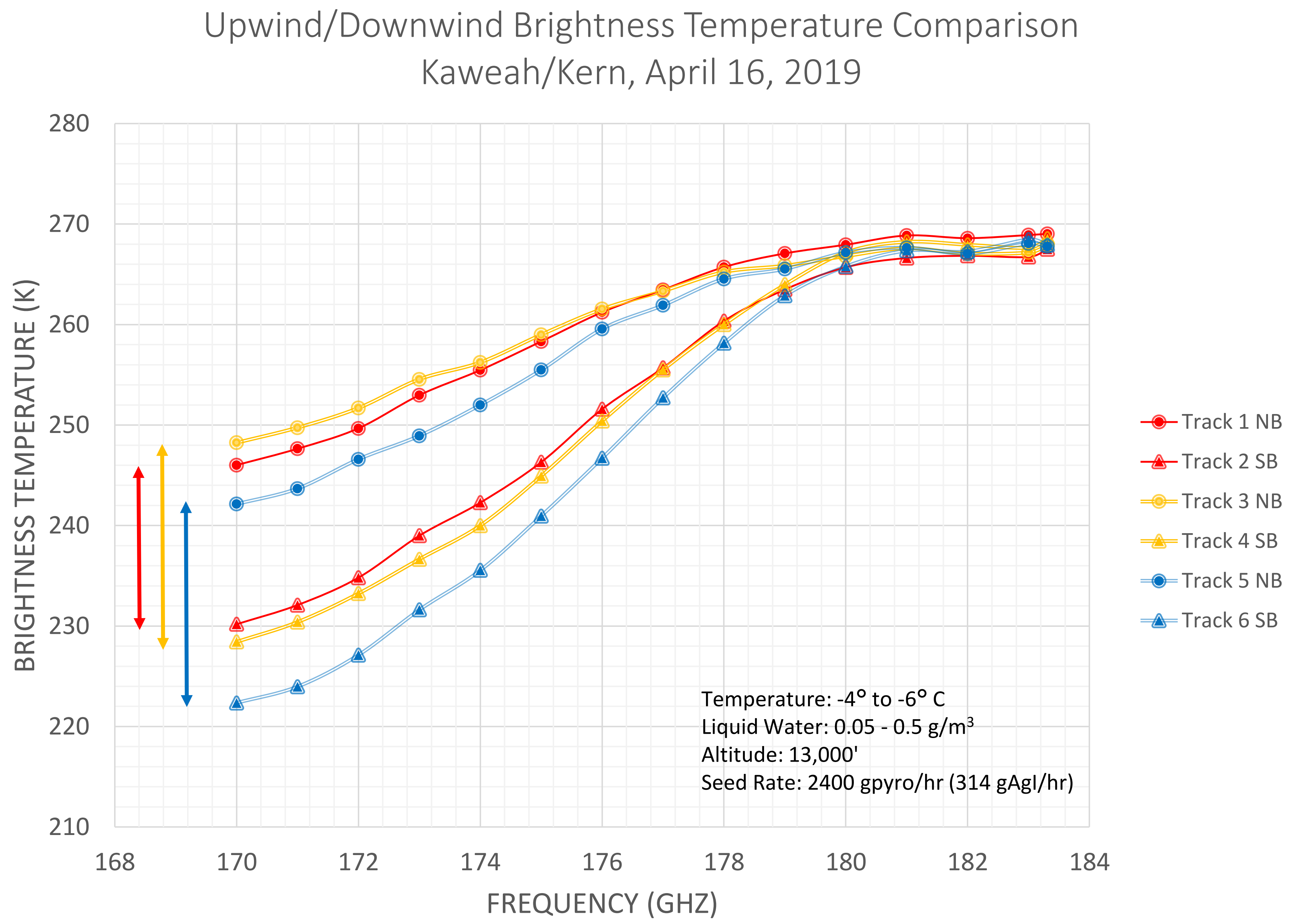
Interpretation Sierra Projects

- Colder temperatures increase activity of seeding materials. They also increase the chances that natural ice forms downwind of the track as it begins to ascend over the barrier
- G band frequencies saturate at higher LWC's limiting detection distances and lowers detectable volumes. This lowers ΔT_b's between upwind and downwind tracks
- As seeding material drifts downwind and fills the volume farther downwind expect larger ΔT_b up and downwind of seed track

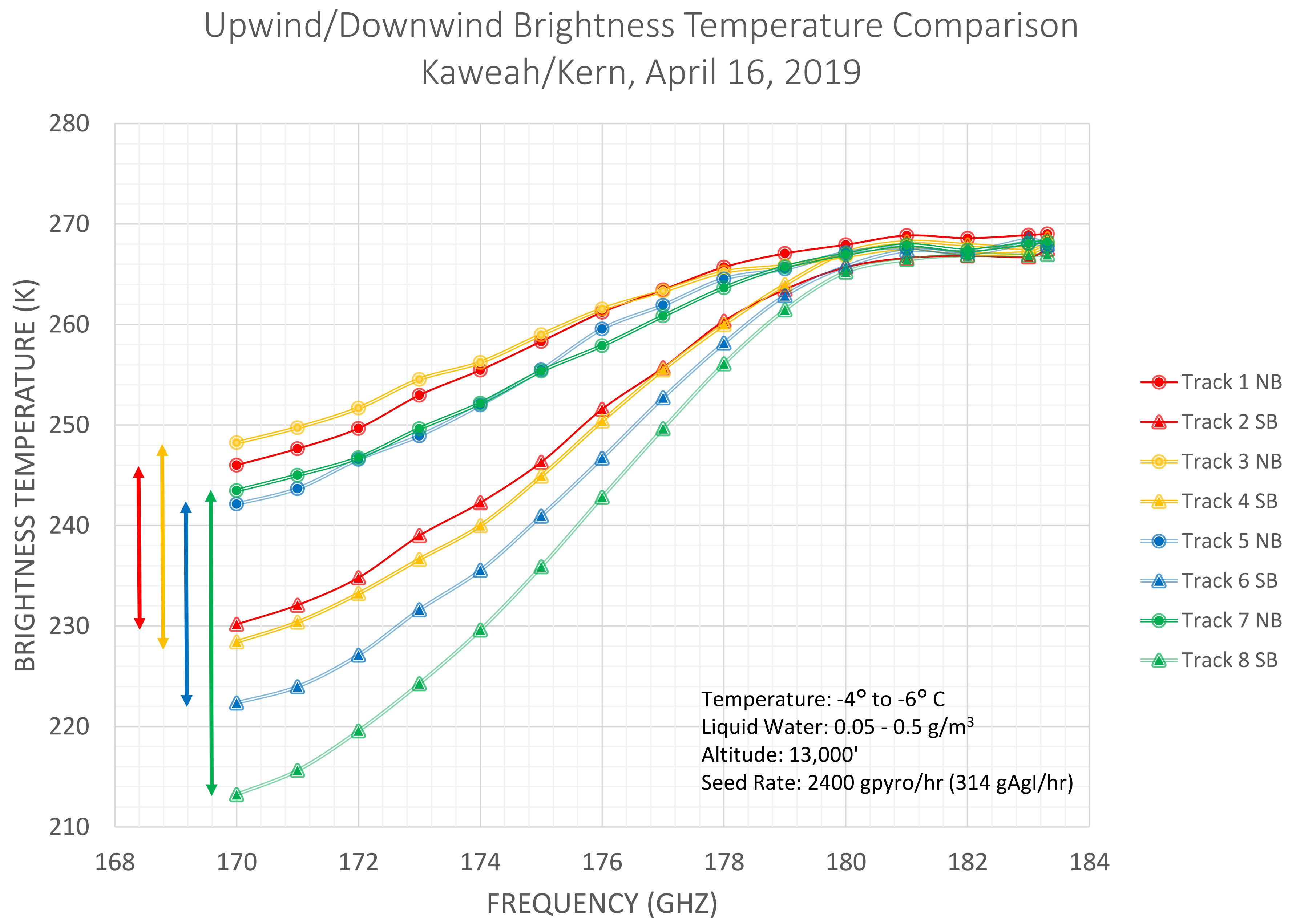

Upwind/Downwind Brightness Temperature Comparison
Kaweah/Kern, April 16, 2019
BRIGHTNESS TEMPERATURE (K)
280
270
260
250
240
230
220
210
168
170
172
174
176
178
180
182
184
FREQUENCY (GHZ)
Track 1 NB
Track 2 SB
Temperature: -4° to -6° C
Liquid Water: 0.05 - 0.5 g/m³
Altitude: 13,000'
Seed Rate: 2400 gpyro/hr (314 gAgI/hr)



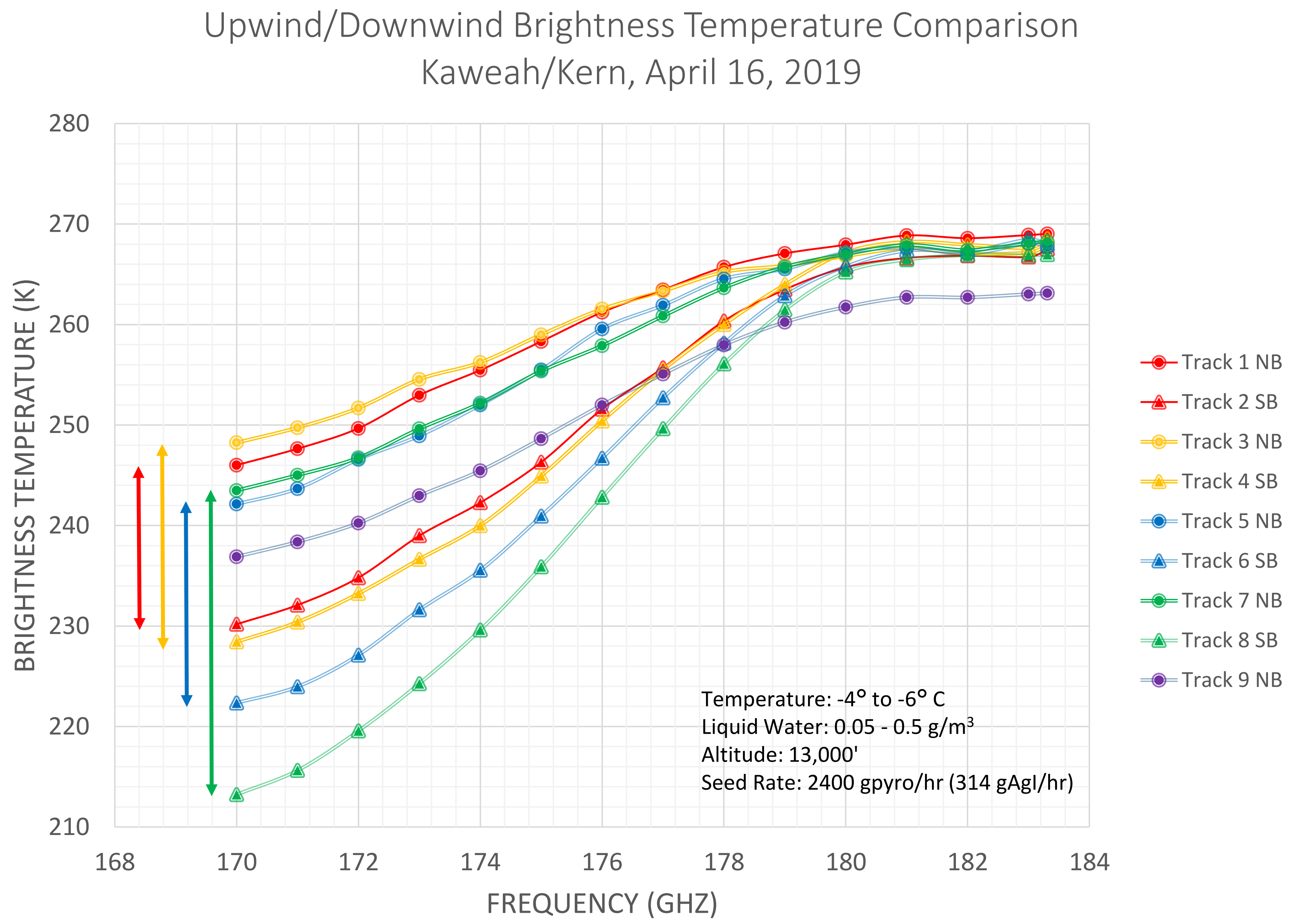
Upwind/Downwind Brightness Temperature Comparison
Kaweah/Kern, April 16, 2019
BRIGHTNESS TEMPERATURE (K)
280
270
260
250
240
230
220
210
168
170
172
174
176
178
180
182
184
FREQUENCY (GHZ)
Track 1 NB
Track 2 SB
Track 3 NB
Track 4 SB
Temperature: -4° to -6° C
Liquid Water: 0.05 - 0.5 g/m³
Altitude: 13,000'
Seed Rate: 2400 gpyro/hr (314 gAgI/hr)



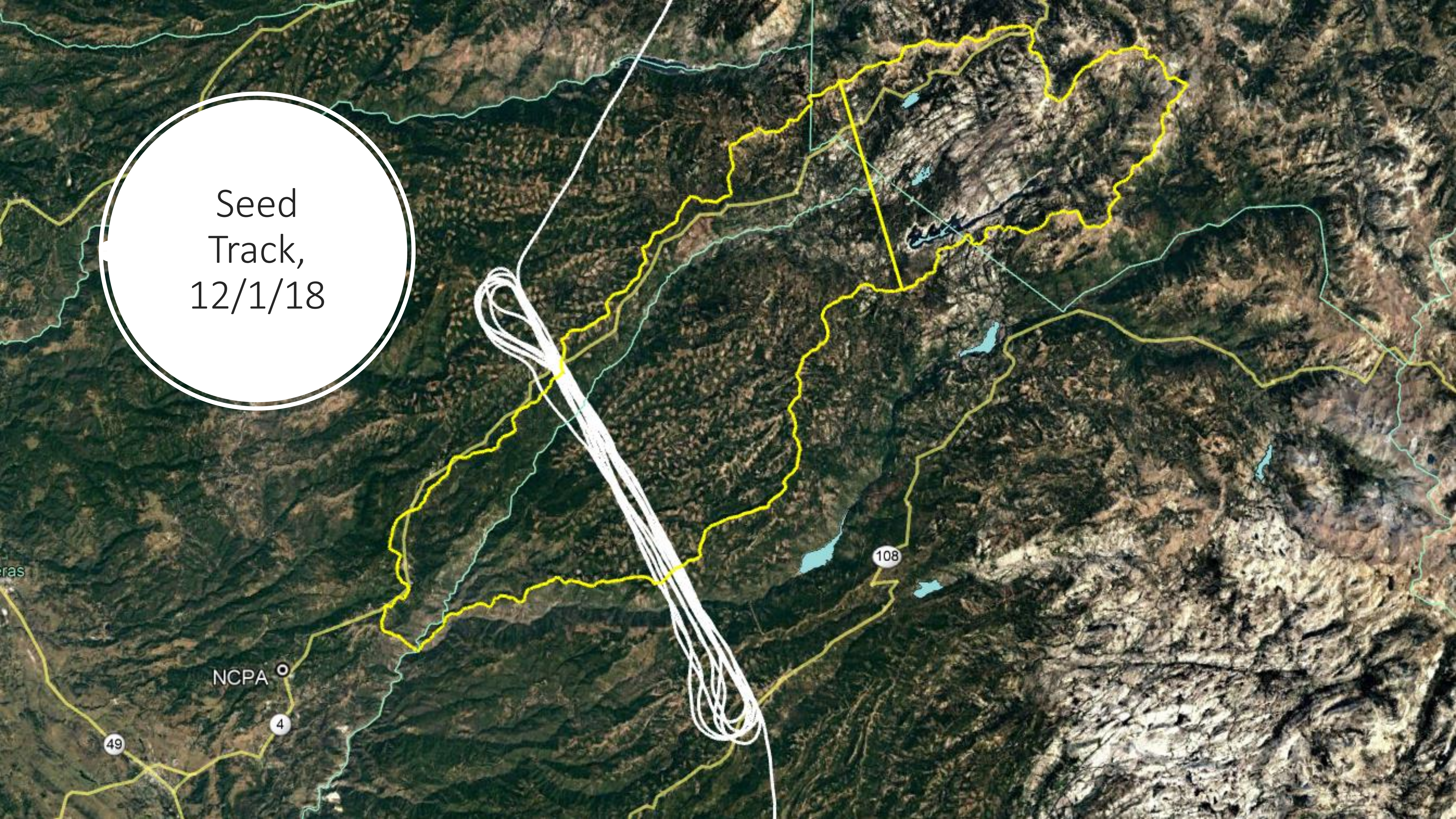
Upwind/Downwind Brightness Temperature Comparison
Kaweah/Kern, April 16, 2019
BRIGHTNESS TEMPERATURE (K)
280
270
260
250
240
230
220
210
168
170
172
174
176
178
180
182
184
FREQUENCY (GHZ)
Track 1 NB
Track 2 SB
Track 3 NB
Track 4 SB
Track 5 NB
Track 6 SB
Temperature: -4° to -6° C
Liquid Water: 0.05 - 0.5 g/m³
Altitude: 13,000'
Seed Rate: 2400 gpyro/hr (314 gAgI/hr)

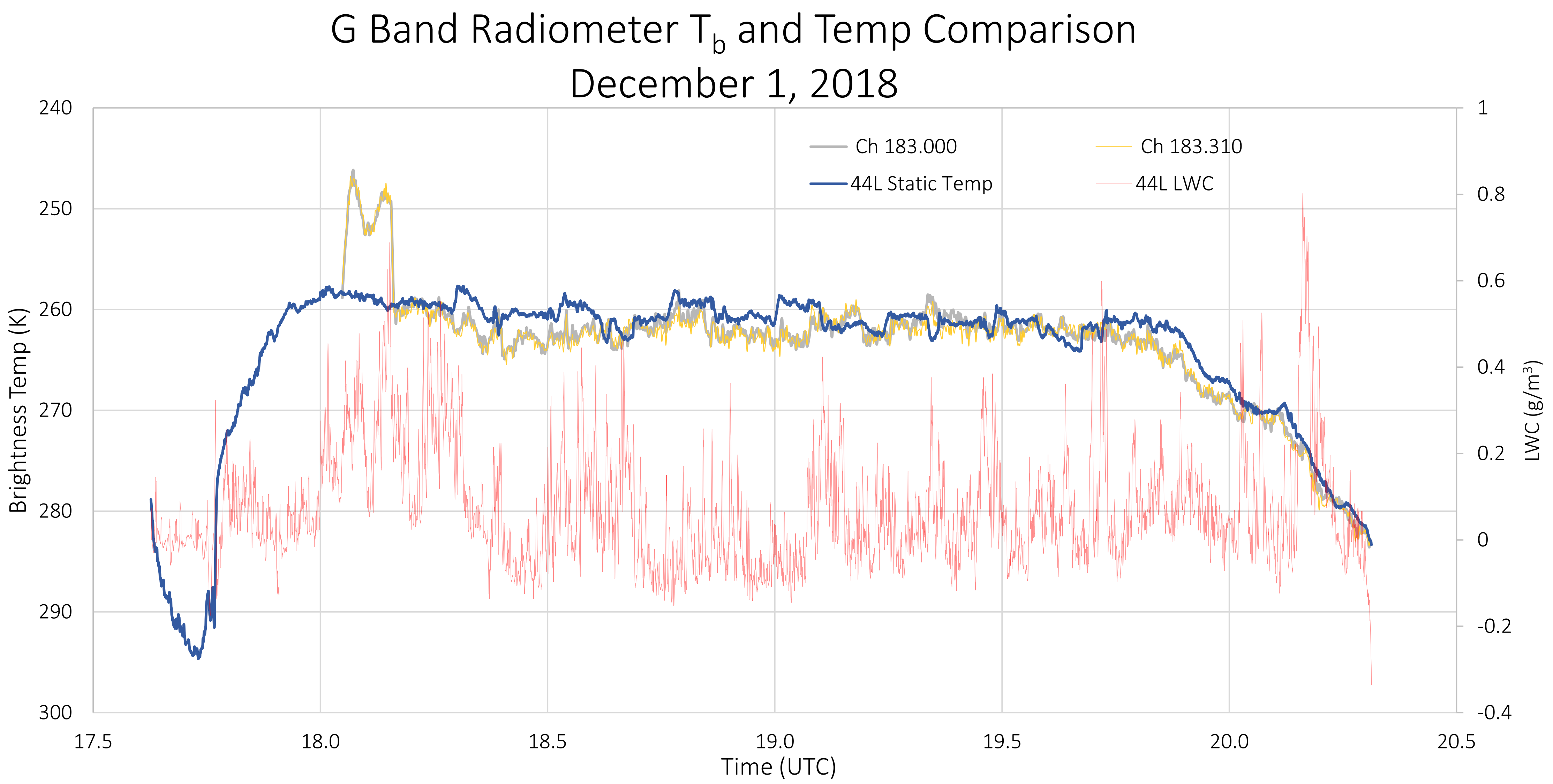


Upwind/Downwind Brightness Temperature Comparison
Kaweah/Kern, April 16, 2019
BRIGHTNESS TEMPERATURE (K)
280
270
260
250
240
230
220
210
168
170
172
174
176
178
180
182
184
FREQUENCY (GHZ)
Track 1 NB
Track 2 SB
Track 3 NB
Track 4 SB
Track 5 NB
Track 6 SB
Track 7 NB
Track 8 SB
Temperature: -4° to -6° C
Liquid Water: 0.05 - 0.5 g/m³
Altitude: 13,000'
Seed Rate: 2400 gpyro/hr (314 gAgI/hr)

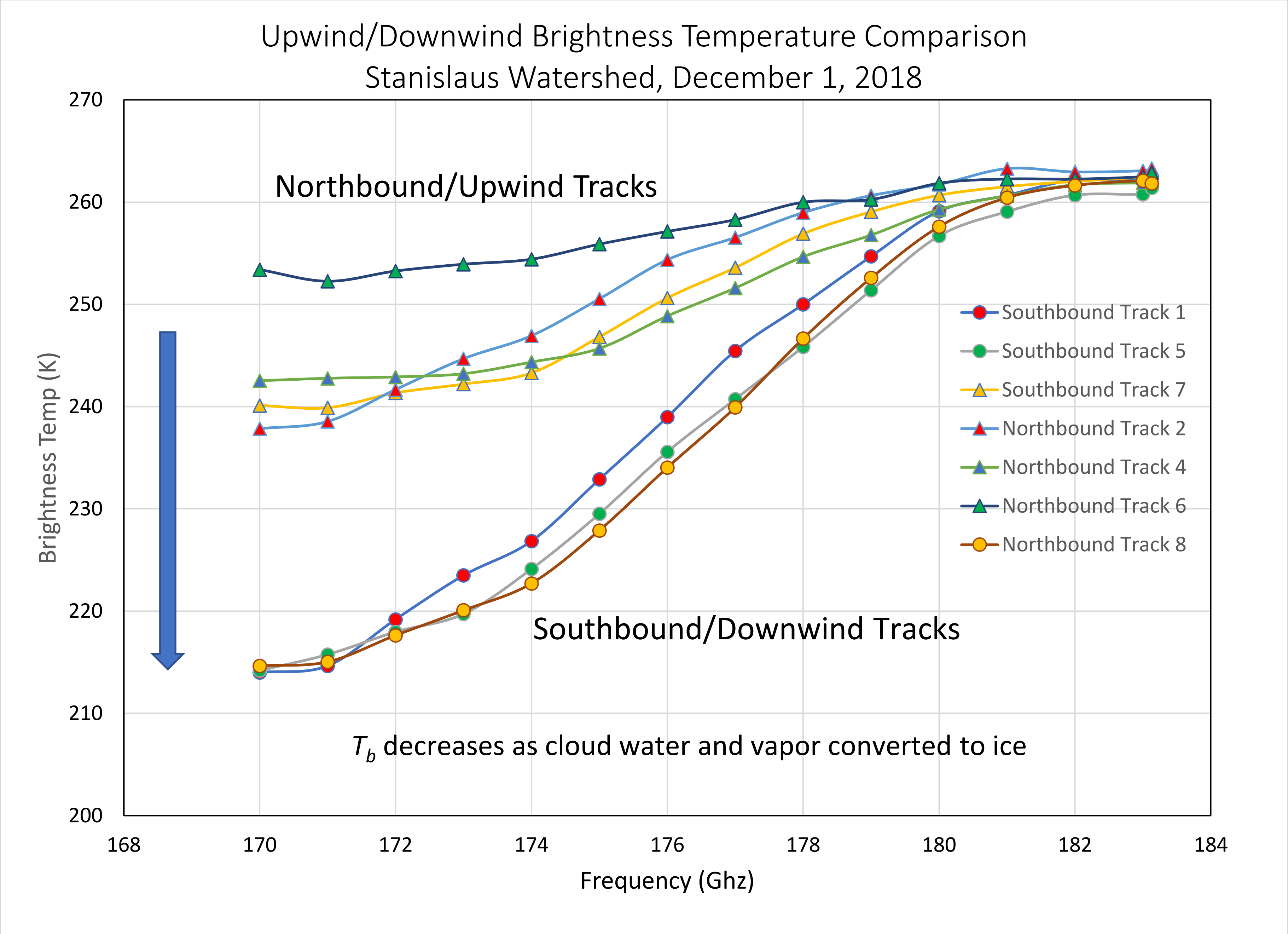

Upwind/Downwind Brightness Temperature Comparison
Kaweah/Kern, April 16, 2019
BRIGHTNESS TEMPERATURE (K)
280
270
260
250
240
230
220
210
168
170
172
174
176
178
180
182
184
FREQUENCY (GHZ)
Temperature: -4° to -6° C
Liquid Water: 0.05 - 0.5 g/m³
Altitude: 13,000'
Seed Rate: 2400 gpyro/hr (314 gAgI/hr)
Track 1 NB
Track 2 SB
Track 3 NB
Track 4 SB
Track 5 NB
Track 6 SB
Track 7 NB
Track 8 SB
Track 9 NB

Seed Track, 12/1/18

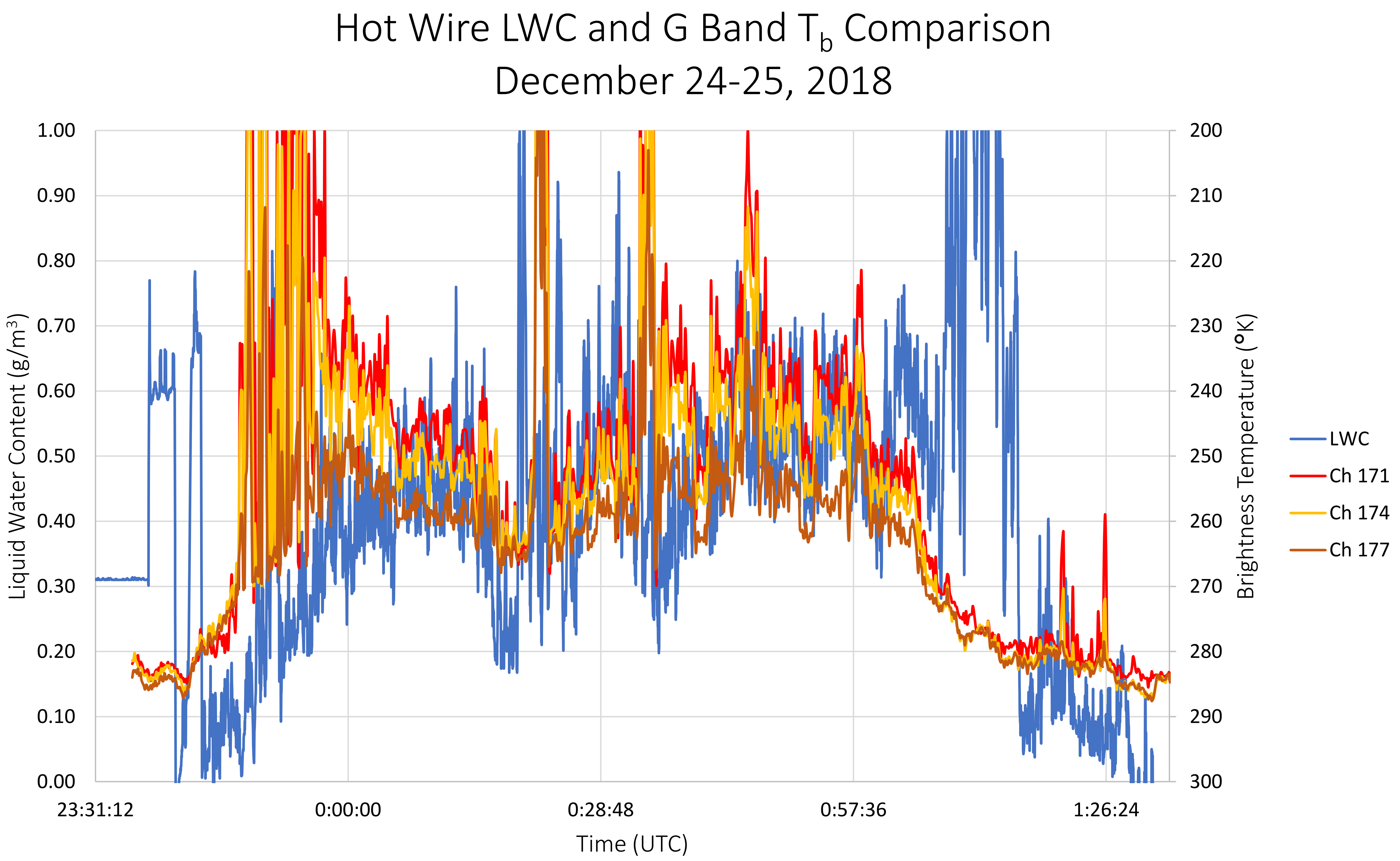




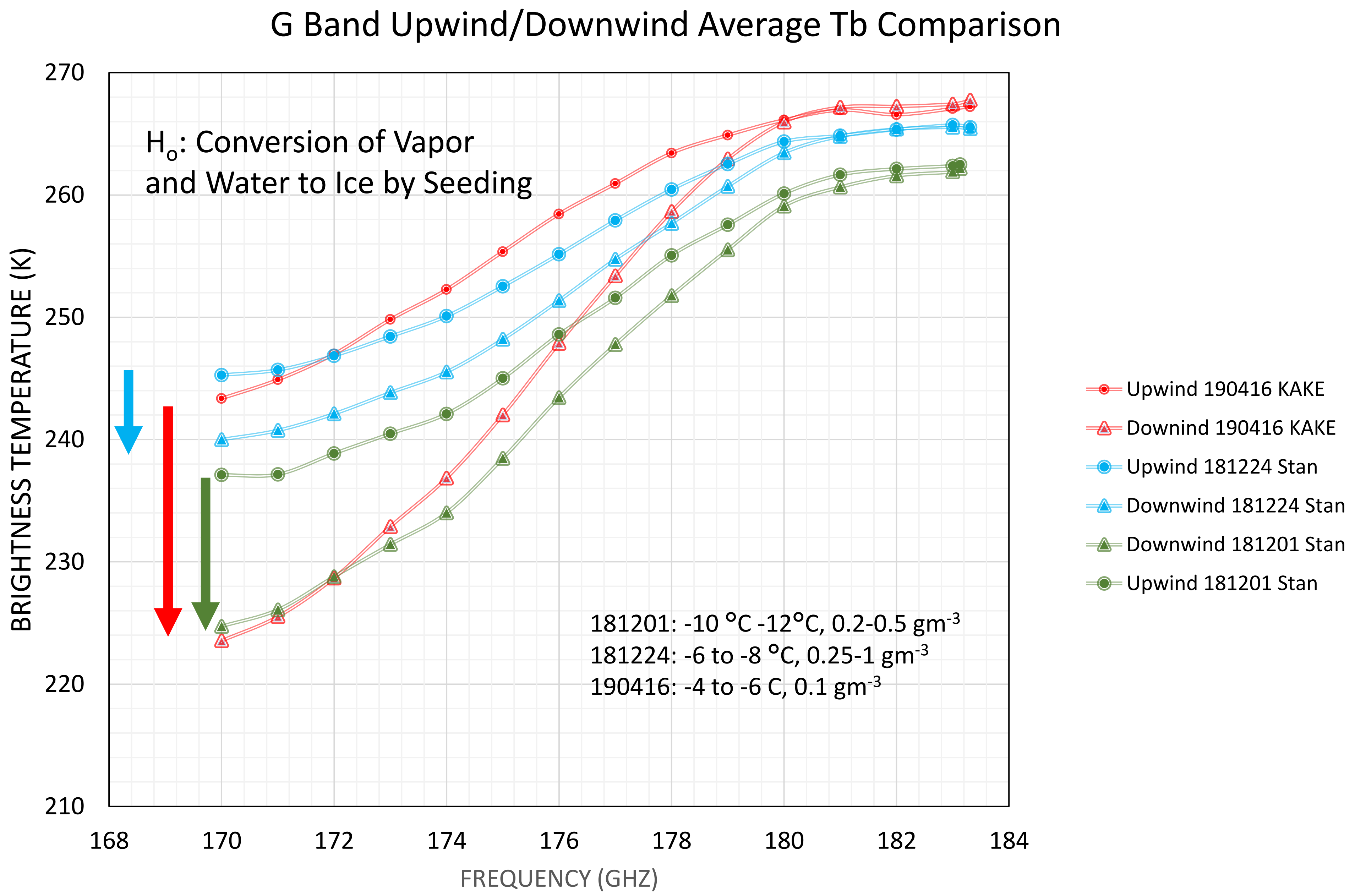
G Band Radiometer T_b and Temp Comparison
December 1, 2018
Ch 183.000
Ch 183.310
44L Static Temp
44L LWC
Brightness Temp (K)
240
250
260
270
280
290
300
LWC (g/m3)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
17.5
18.0
18.5
19.0
19.5
20.0
20.5
Time (UTC)



Upwind/Downwind Brightness Temperature Comparison
Stanislaus Watershed, December 1, 2018
Northbound/Upwind Tracks
Southbound/Downwind Tracks
T_b decreases as cloud water and vapor converted to ice
Brightness Temp (K)
Frequency (Ghz)
270
260
250
240
230
220
210
200
168
170
172
174
176
178
180
182
184
Southbound Track 1
Southbound Track 5
Southbound Track 7
Northbound Track 2
Northbound Track 4
Northbound Track 6
Northbound Track 8



Hot Wire LWC and G Band T$_b$ Comparison
December 24-25, 2018
Liquid Water Content (g/m^3)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
200
210
220
230
240
250
260
270
280
290
300
Brightness Temperature (°K)
23:31:12
0:00:00
0:28:48
0:57:36
1:26:24
Time (UTC)
LWC
Ch 171
Ch 174
Ch 177


G Band Upwind/Downwind Average Tb Comparison
H$_o$: Conversion of Vapor
and Water to Ice by Seeding
BRIGHTNESS TEMPERATURE (K)
270
260
250
240
230
220
210
168
170
172
174
176
178
180
182
184
FREQUENCY (GHZ)
181201: -10 °C -12°C, 0.2-0.5 gm^{-3}
181224: -6 to -8 °C, 0.25-1 gm^{-3}
190416: -4 to -6 C, 0.1 gm^{-3}
Upwind 190416 KAKE
Downind 190416 KAKE
Upwind 181224 Stan
Downwind 181224 Stan
Downwind 181201 Stan
Upwind 181201 Stan

Measurements required for Calibration

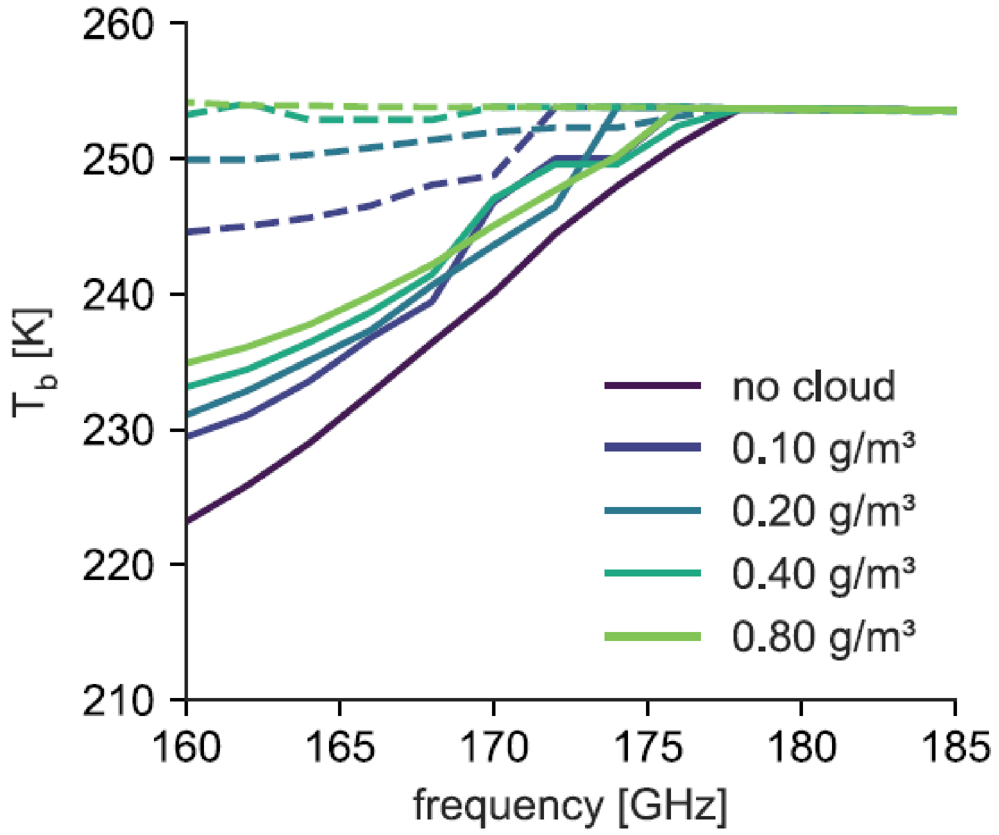
- Brightness temperatures by frequency
- Liquid water content
- Distance
- Cloud and Ice particle size distributions
- Provides a set of equations that can be solved for w as a function of distance

$$n(r) = 0\frac{3\times 10^{18} w}{4\pi\rho\beta^4\Gamma(\gamma+3)}\left(\frac{r}{\beta}\right)^{\gamma-1} e^{-\frac{r}{\beta}}$$

- r- particle radius (um)
- w- liquid water content
- P-density of liquid/ice content
- Γ-shape factor
- B = r_e /ϒ+2

G Band Modeling – Adams and Bobak (2018)

- Modeling results combined with measurements are needed to develop practical channel set and refine algorithms
- Scattering not considered – needed for mixed phase cloud and low liquid water contents
- Principal component analysis suggests it be desirable to include Ka band depending on SWAP considerations
- Forward looking radiometer feasible



Conclusions

- IT WORKS!
- Colder the better- G Band Radiometers Band can readily detect changes in T_b up and downwind of a seed track in mixed phase conditions in 30-40 dbz composite reflectivity's.
- T_b changes are consistent with seeding materials forming new ice crystals drifting downwind that deplete SLW and vapor
- Calibration needed to quantify cloud water converted to cloud ice with distance and frequency.

Conclusions

- Complimentary measurement of cloud droplet and ice crystal size distributions are needed for calibration and algorithm development to account for attenuation by ice scattering
- Data suggest 5-6 channels (eg., 165,168, 171, 174, 177, 180 GHz) can provide SLW detection up to 30 km in mixed phase winter clouds
- Provides new tool – a big step toward real time assessment of seeding effects