Landsat Land Surface Temperature Product: Global Validation and Cloud Analysis

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LST Goals

- Develop an automated method to obtain per-pixel LST results for Landsat scenes
- Determine how accurate the method is for North American regions
- Determine how accurate the method is globally and for all Landsat sensors
- Develop a way to estimate expected LST errors in order to make a quality map

LST Methodology

The "Big Equation"

$$L_{obs}=[\varepsilon L_T+(1-\varepsilon)L_d]\tau+L_u$$

L_{obs} = radiance seen by satellite

L_T = radiance emitted from target

ε = emissivity of target

L_d = downwelled radiance

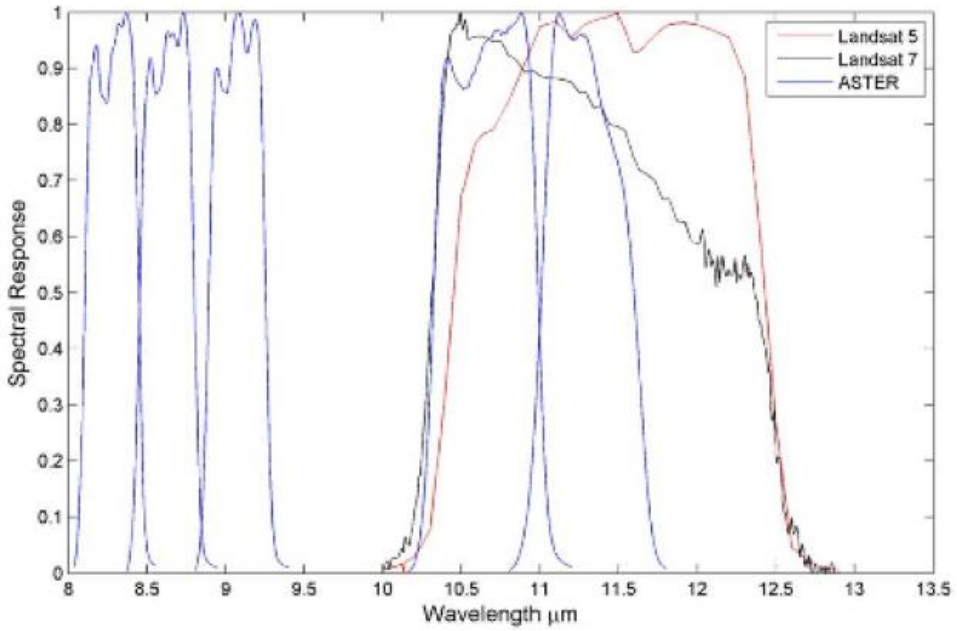
τ = transmission

L_u = upwelled radiance

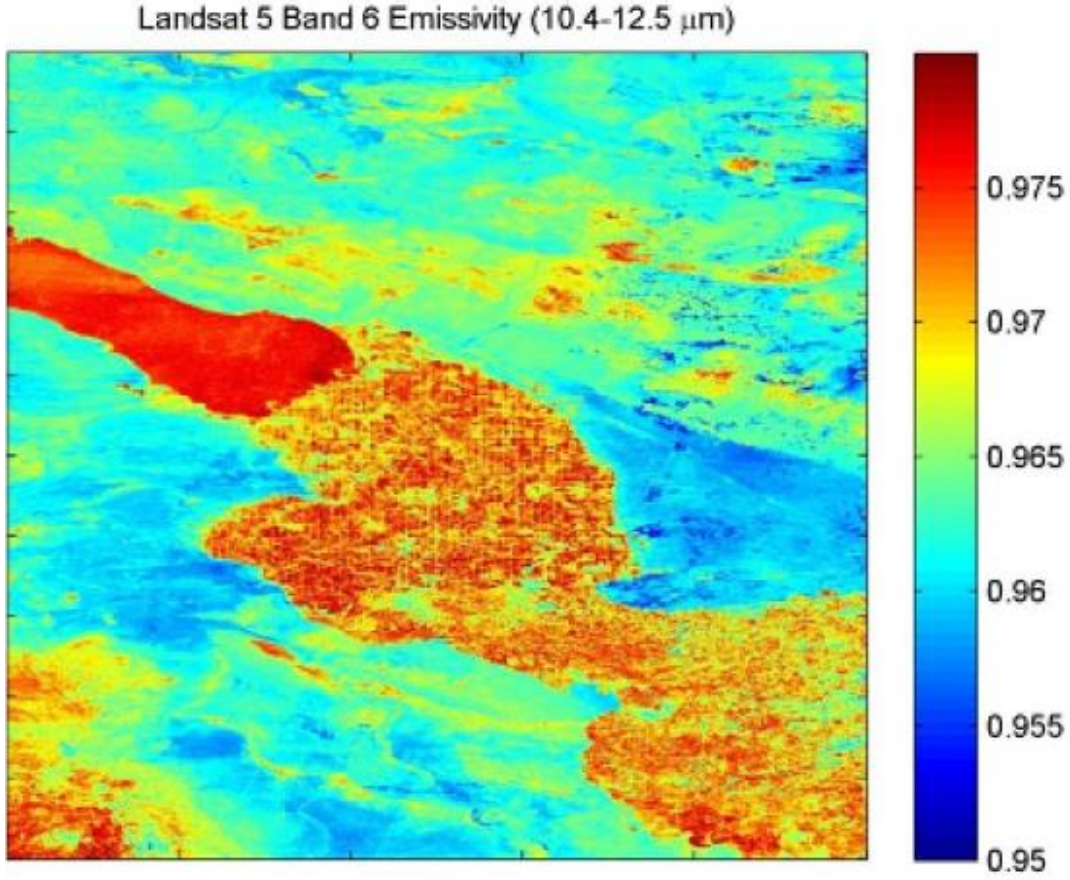
EMISSIVITY

- Extract Bare Earth Emissivity from the North American Aster Land Surface Emissivity Database (NAALSED)-Soon available globally!
  - Emissivities (ε_{13} , ε_{14}) and regression coefficients (JPL)

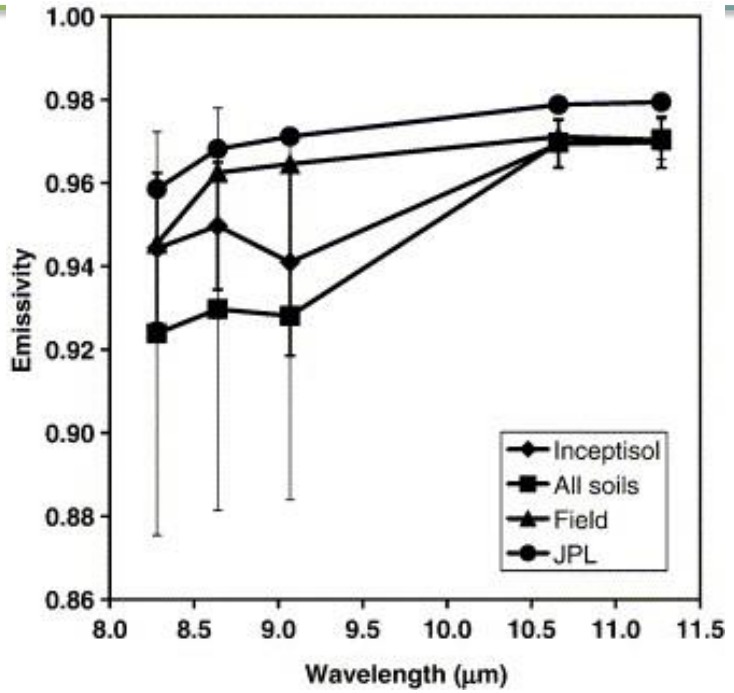
$$\varepsilon_{landsat} = C_{13}\,\varepsilon_{13} + C_{14}\,\varepsilon_{14} + C$$



LANDSAT 5 derived emissivity from NAALSED bands 13 & 14 over the Salton Sea and Imperial Valley, CA.(JPL)



Correct Emissivity for High NDVI conditions
Note: an error in emissivity of 0.01 corresponds to 0.7K error in temperature in these bands.



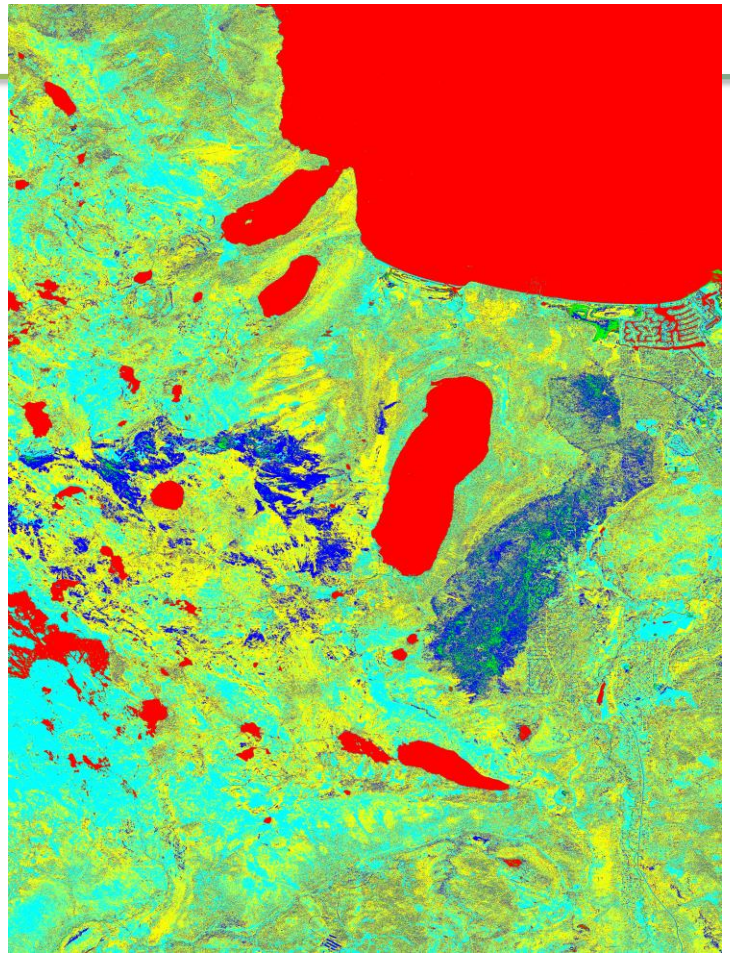
$$\varepsilon_{13} = 0.968 + 0.022\ P_V$$

$$\varepsilon_{14} = 0.970 + 0.020\ P_V$$

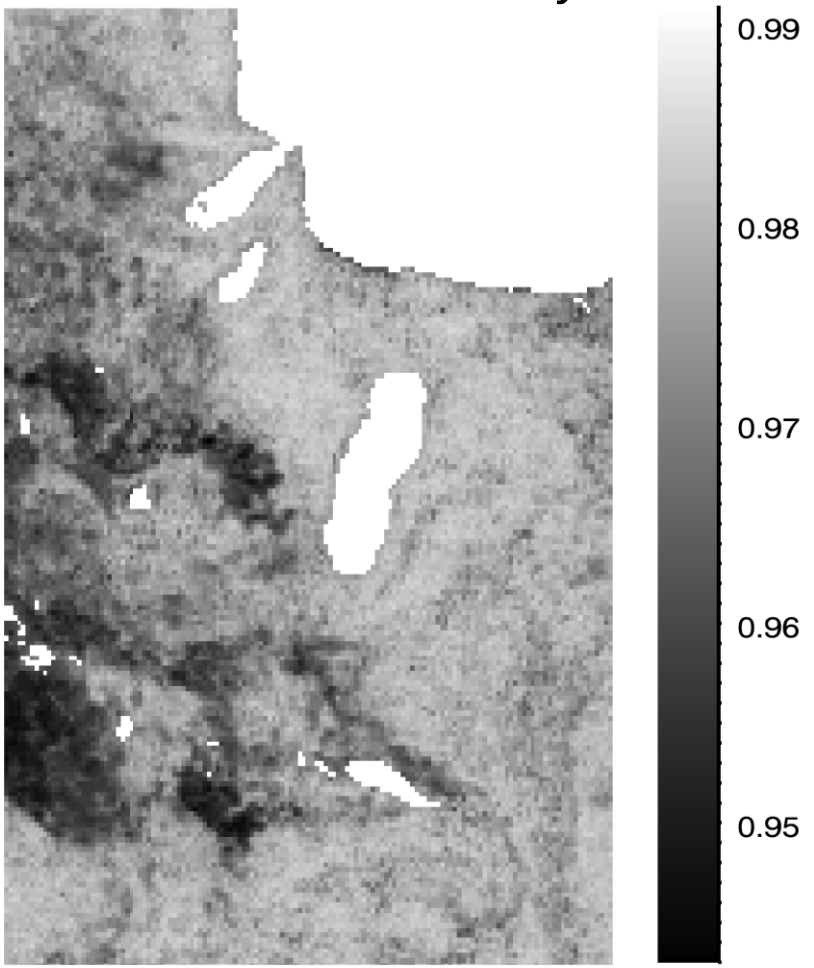
$$P_V = \left(\frac{\mathrm{NDVI}-\mathrm{NDVI_s}}{\mathrm{NDVI_v}-\mathrm{NDVI_s}}\right)^2$$

Fig. 3. Average emissivity spectra for different soil samples included in the ASTER spectral library (http://speclib.jpl.nasa.gov). 'Inceptisol' refers to the mean value for all the soil samples included in the ASTER library and classified as Inceptisol (7 samples). These values have been chosen a soil emissivities in the NDVI method. 'All soils' refers to the mean value for all the soil samples included in the ASTERlib (49 samples). Error bars refer to the standard deviation of the mean values. The emissivity spectrum obtained from field measurements (Field) and the one measured in the JPL are also given for comparison.[Munoz et al. (2006) RSofE V.103,#4, pp. 474-487].

Lake Tahoe
5 Class Classification Map



Aster Band 13
Lake Tahoe Emissivity Data



Class 1	Average Emissivity	0.988	SD	0.00736
Class 2	Average Emissivity	0.976	SD	0.00698
Class 3	Average Emissivity	0.975	SD	0.00748
Class 4	Average Emissivity	0.975	SD	0.00681
Class 5	Average Emissivity	0.972	SD	0.00890

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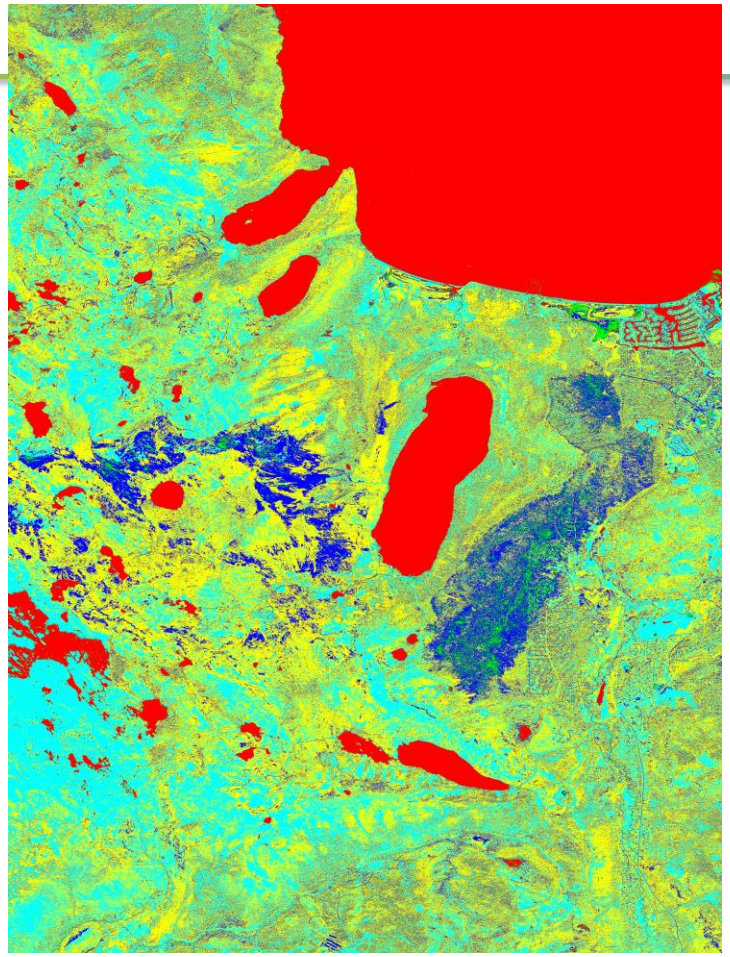
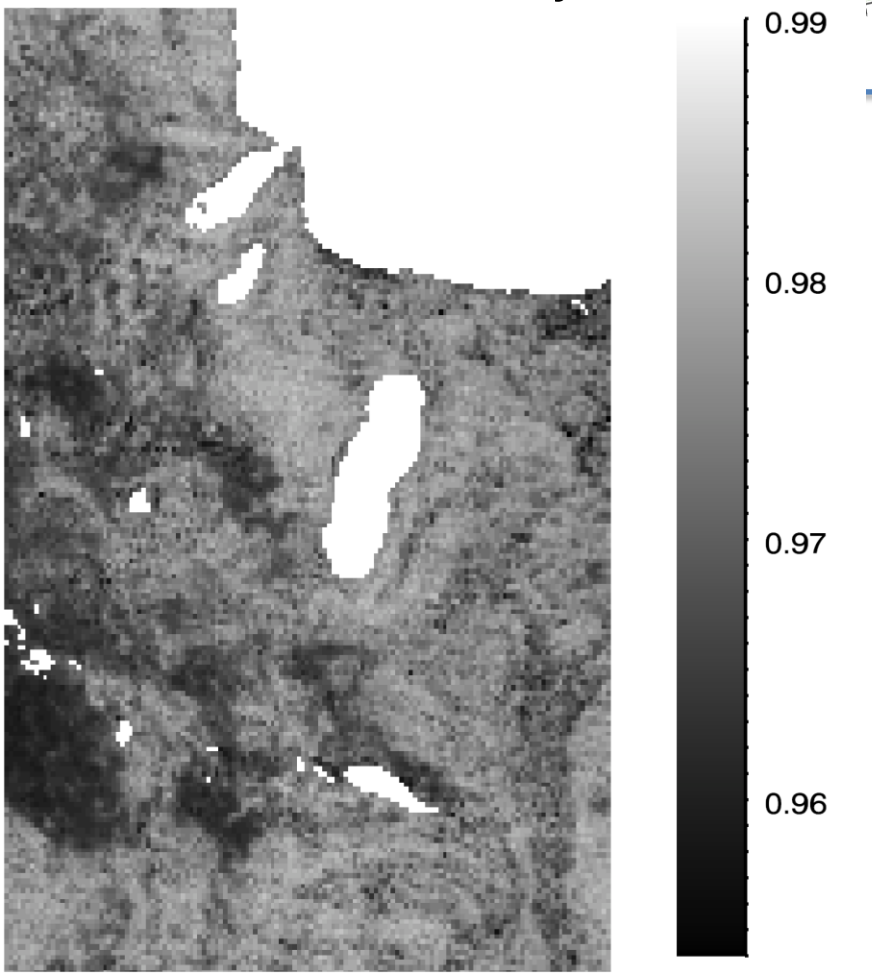
Lake Tahoe
5 Class Classification Map



Aster Band 14
Lake Tahoe Emissivity Data



Class 1	Average Emissivity	0.988	SD 0.00644
Class 2	Average Emissivity	0.974	SD 0.00476
Class 3	Average Emissivity	0.974	SD 0.00477
Class 4	Average Emissivity	0.974	SD 0.00472
Class 5	Average Emissivity	0.972	SD 0.00572

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A Land Surface Temperature Product

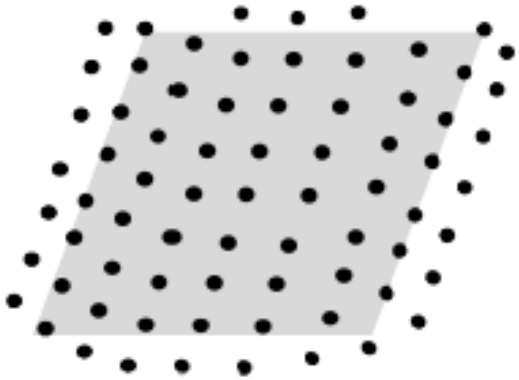
Validation of atmospheric component

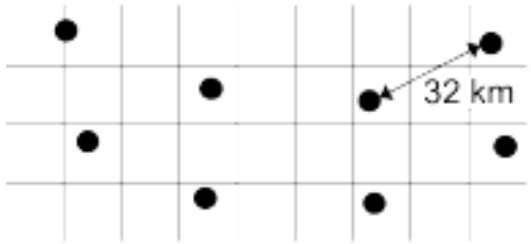
- Use calibration sites – Atm. Compensation
  - Salton Sea (below sea level and hot)
  - East & West Coast (sea level – wide range of atmosphere)
  - Great Lakes (≈ 0.2 km)
  - Lake Tahoe (≈ 1.4 km)
- Covers all dates, all instruments
- Only tests atmospheric compensation since all targets are water

NARR Reanalysis Data

- **N**orth **A**merican **R**egional **R**eanalysis
- Available every 3 hours
- 32 km spacing (0.3 x 0.3 degrees)
- 29 pressure levels (1000 – 100 hPa)
- Lambert Conformal coordinates

Need to interpolate in time, elevation and location

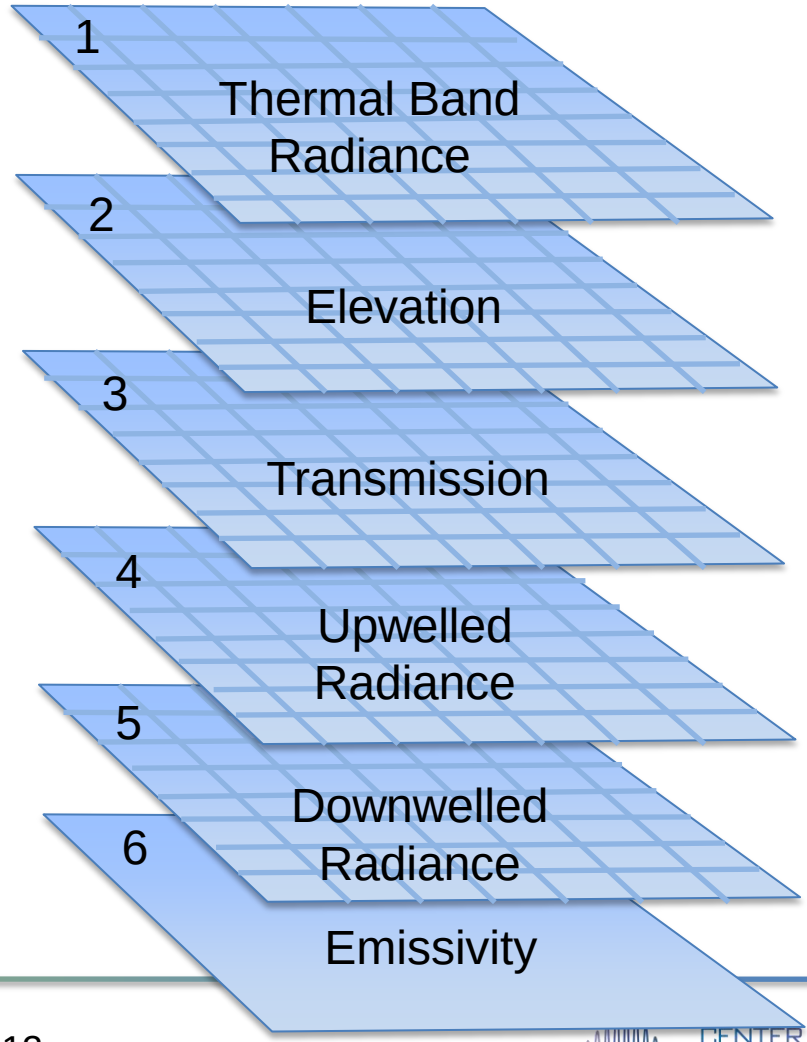




Final Output

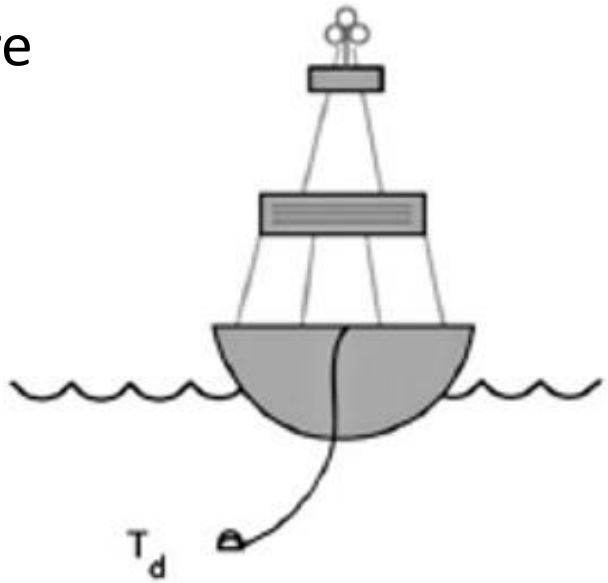
- Landsat sized array
- 5 parameters total
- Use parameters around buoy location to get estimated temperature

$$L_{obs}=[\varepsilon L_T+(1-\varepsilon)L_d]\tau+L_u$$



Validation

- Use Landsat scenes over valid buoys
- Correct buoy measurement to skin temperature
- Compare to Landsat predicted temperature

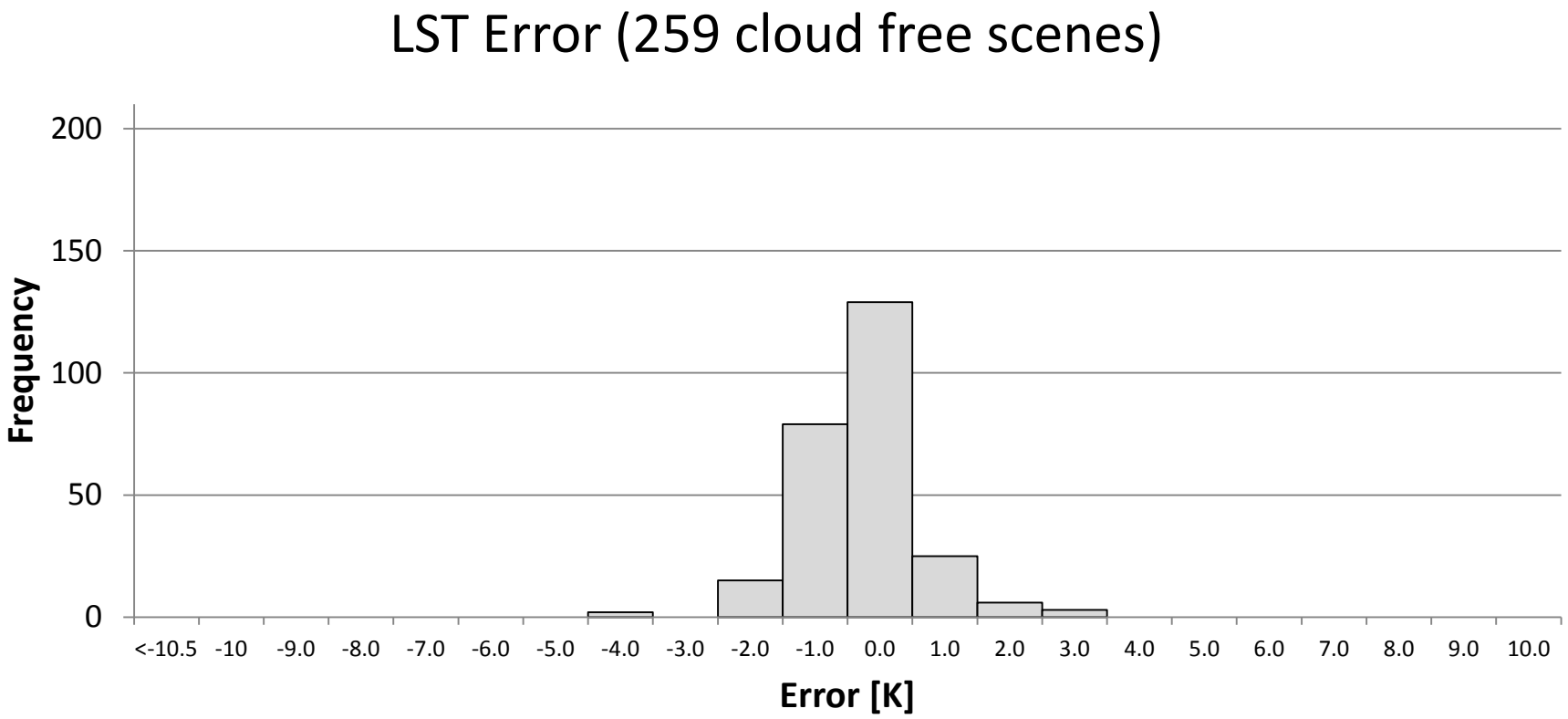


Landsat 5, North America

- 259, cloud free scenes

Location	Path_Row	Mean Error [K]	Standard Deviation [K]	RMSE [K]	No. of Scenes
Salton Sea	39_37	-0.12	0.558	0.545	11
Lake Tahoe	43_33	-0.213	0.713	0.740	89
Lake Ontario	16_30 17_30	-0.068	0.639	0.626	89
Delaware Bay	13_33 14_33	-0.447	1.179	1.245	34
Georgia (coast)	16_38	0.041	1.267	1.239	23
Santa Maria (coast)	43_36	-0.219	0.789	0.799	19
Santa Monica (coast)	41_37	-0.574	1.089	1.208	21
Lake Huron	20_29	-0.695	0.820	1.059	19
Lake Superior	24_27	-0.167	0.676	0.682	23
Total	—	**-0.267**	**0.900**	**0.905**	**259**

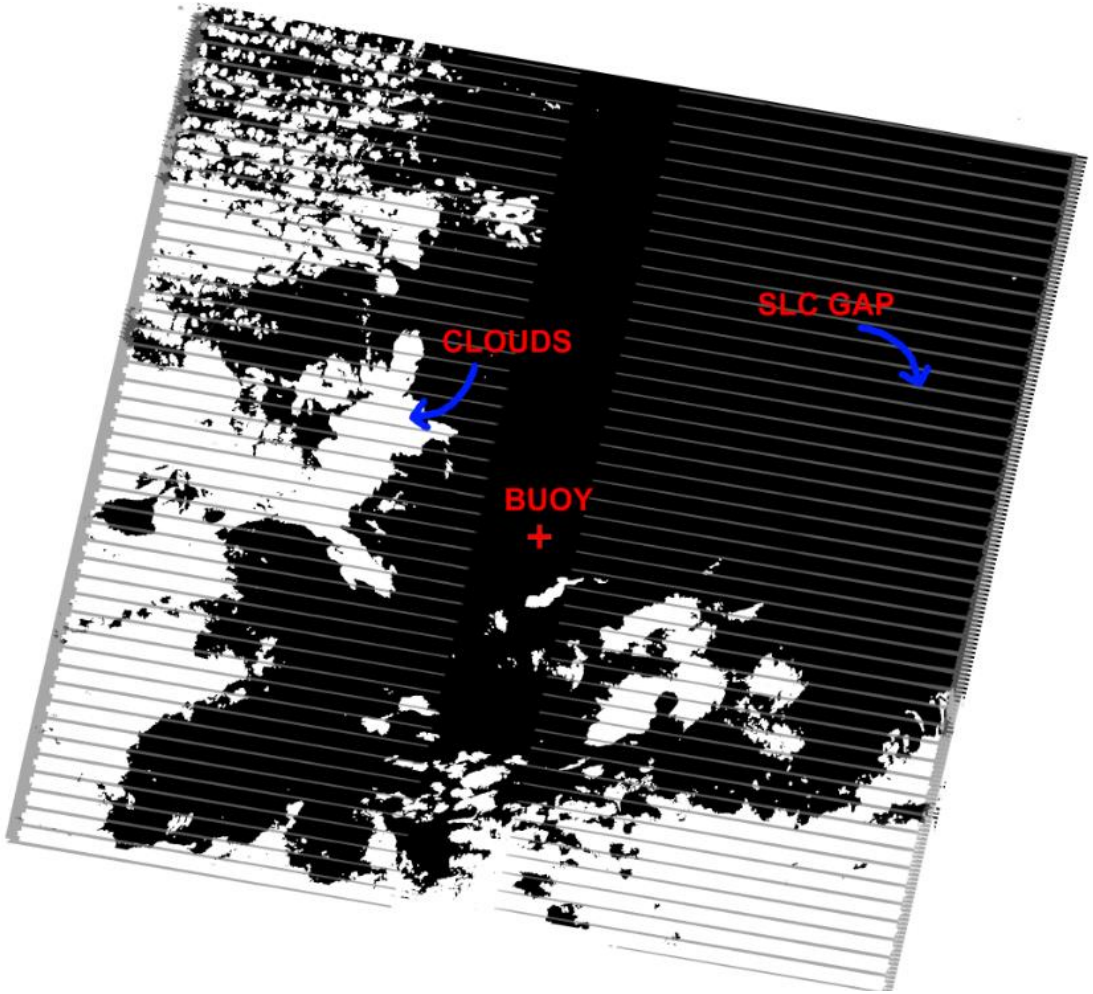
Landsat 5, North America



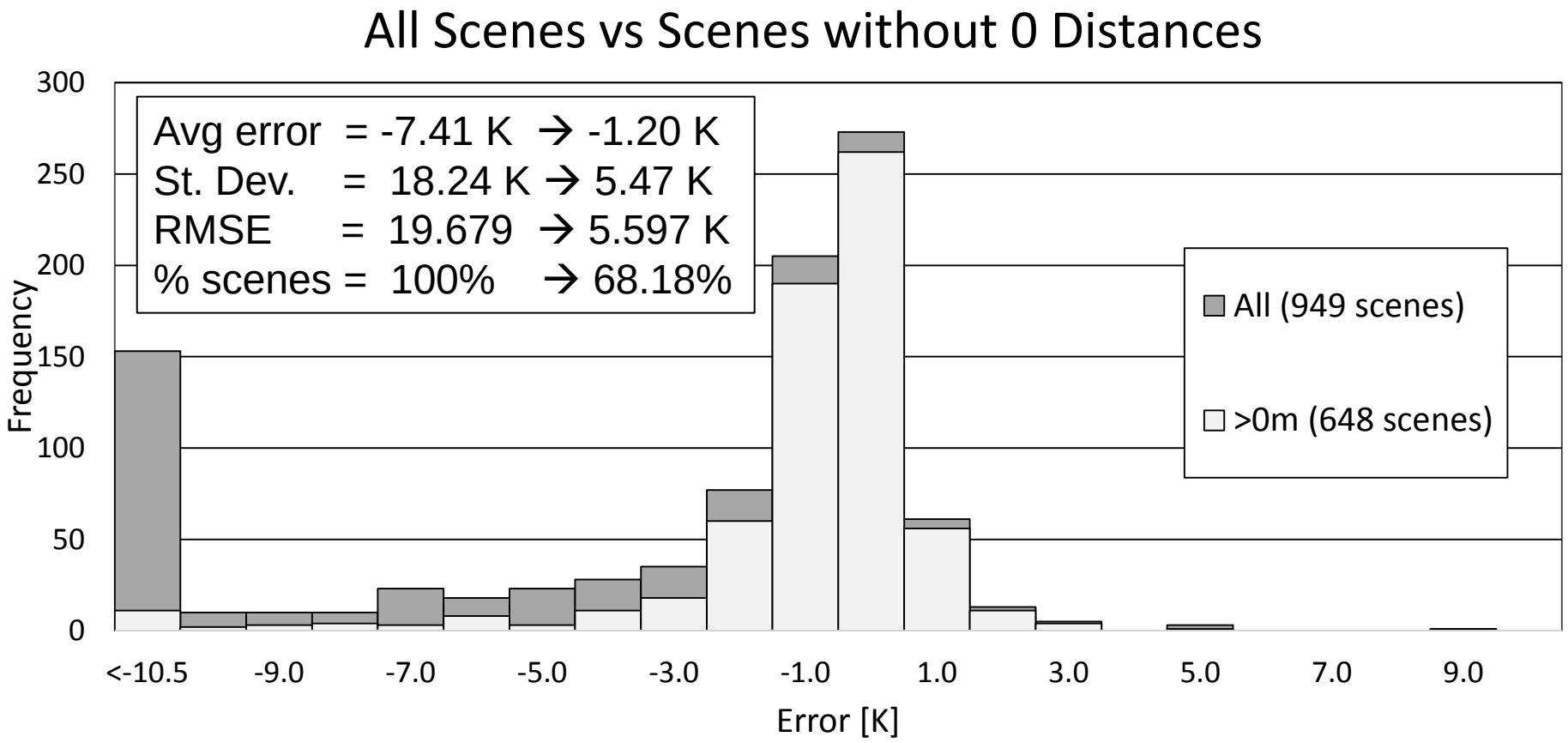
Don’t want to restrict product to cloud free scenes: Development of Quality Metric for cloud in scene

- Use reflectance product to get cloud mask for Landsat scene
- Calculate distance from buoy to nearest cloud pixel
- See how cloud proximity relates to LST error

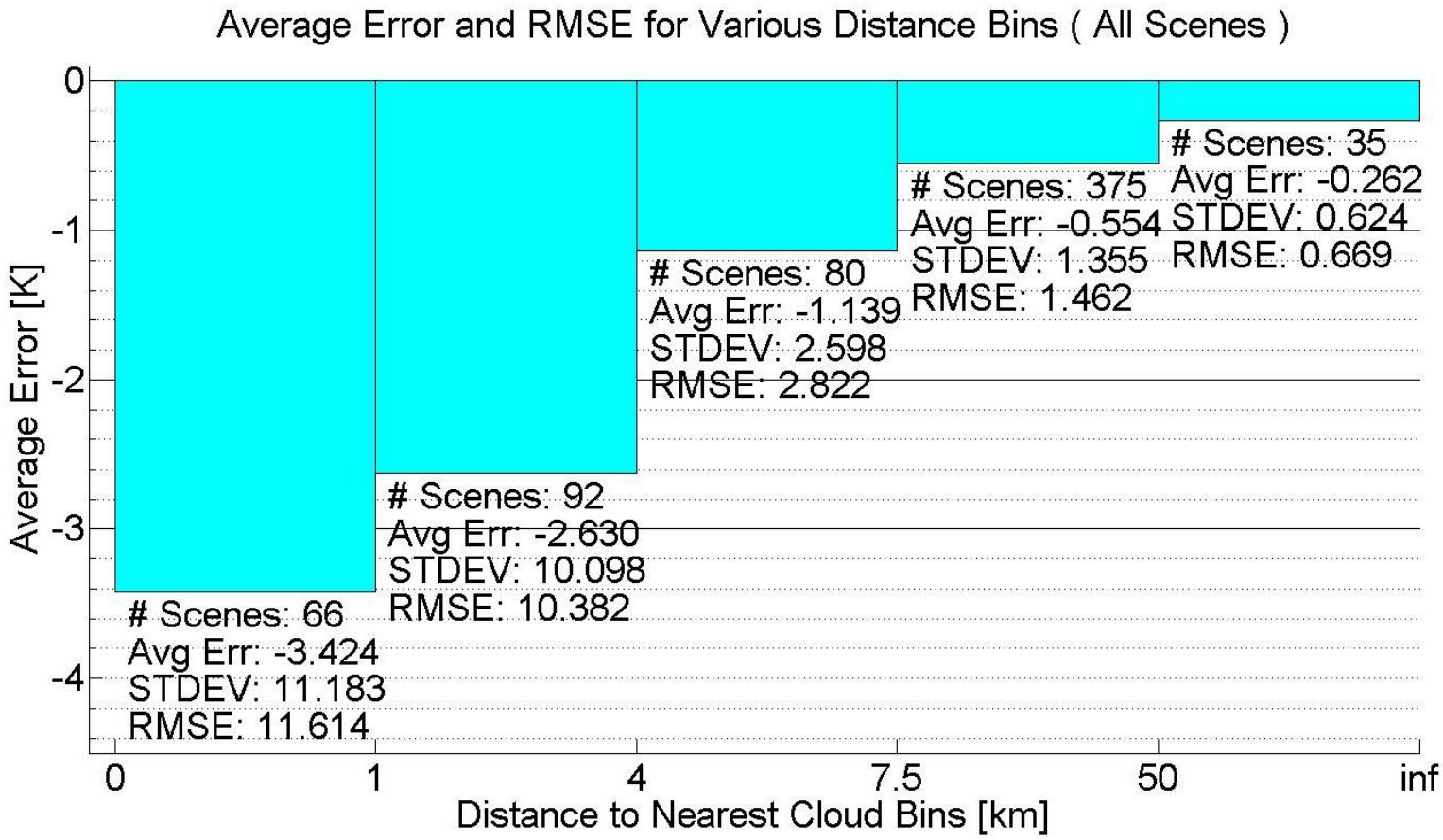
Cloud Mask Example



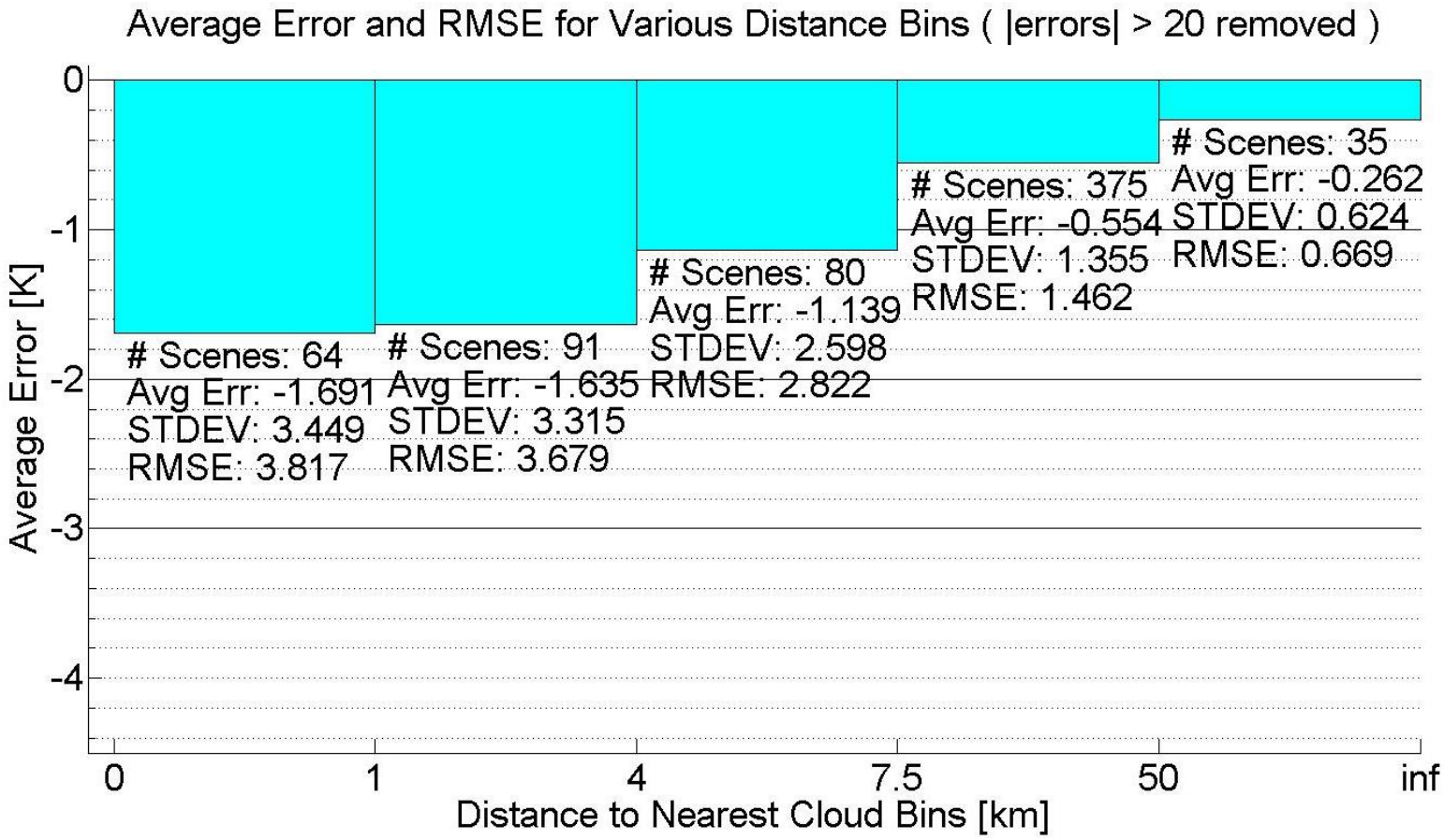
Removing “0” Distances



Average Error for Distance Bins



Removing Bad Scenes



Global Validation Problems

- Problems
  - NARR is only available for North America
  - Buoys unavailable on a global scale

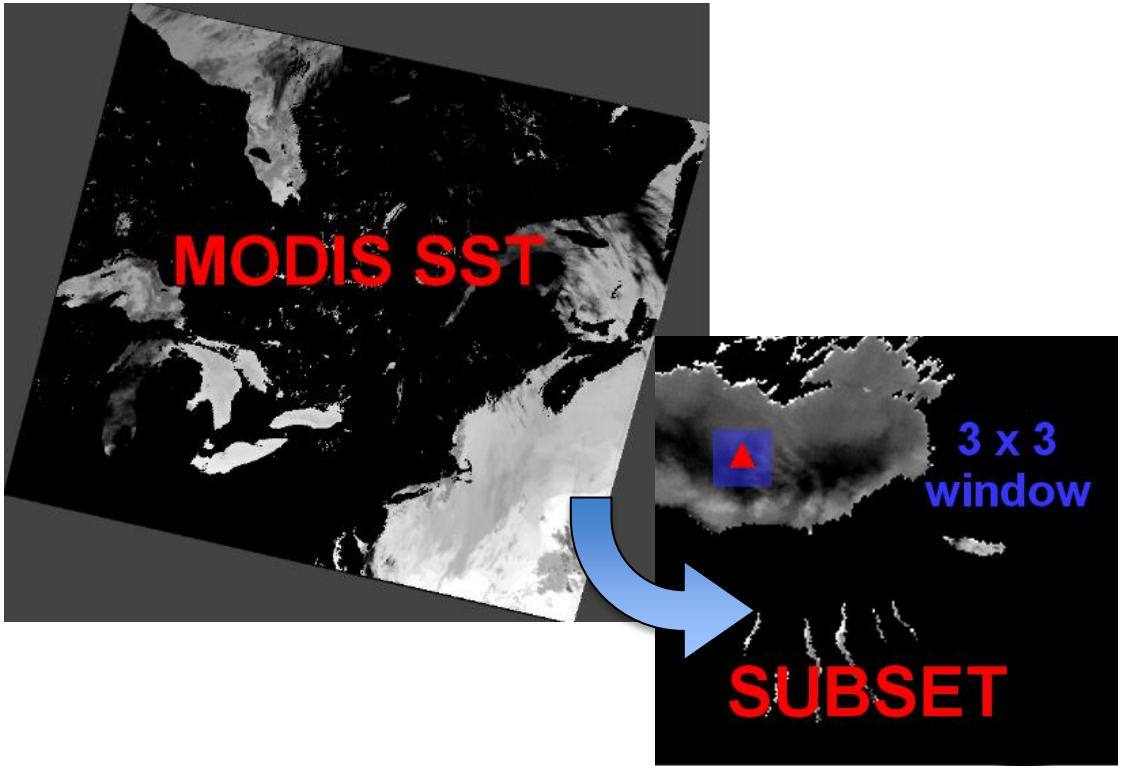
- Solutions
  - Compare LST NARR results to LST results using global reanalysis products
  - For truth, use MODIS (**MOD**erate resolution **I**maging **S**pectroradiometer)

Choosing a New Reanalysis Product

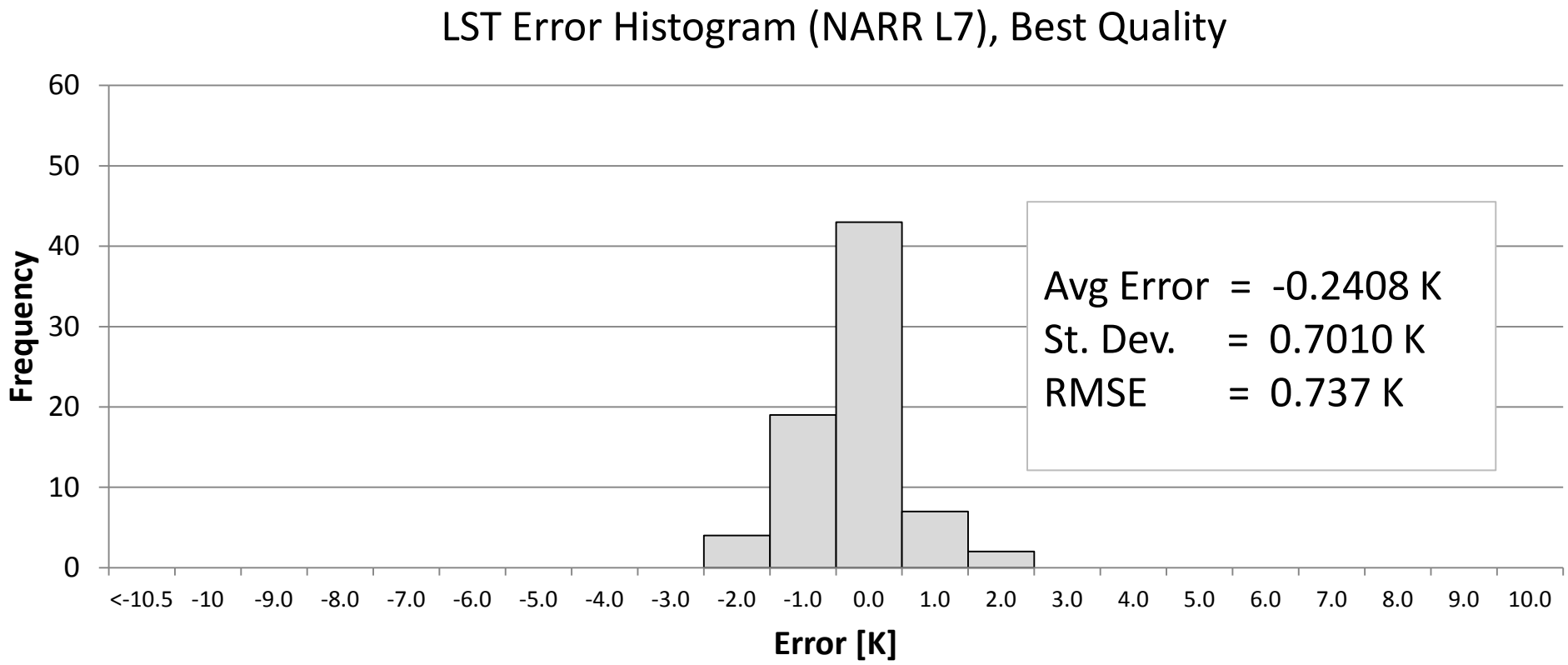
	NARR (NOAA)	MERRA (NASA)	CFSR (NOAA)
Coverage	North America	Global	Global
Spatial	32 km spacing (0.3° at equator) 349x277	1.25° x 1.25° (140 km at equator) 288x144	~38 km spacing (0.5° x 0.5°) 720x361
Temporal	8x daily 3-hr intervals	8x daily 3-hr intervals	4x daily 6-hr intervals
Pressure Levels	29 levels 1000 - 100 hPa	42 levels 1000 - 0.1 hPa	37 levels 1000 - 1 hPa

Finding Acceptable Truth Data

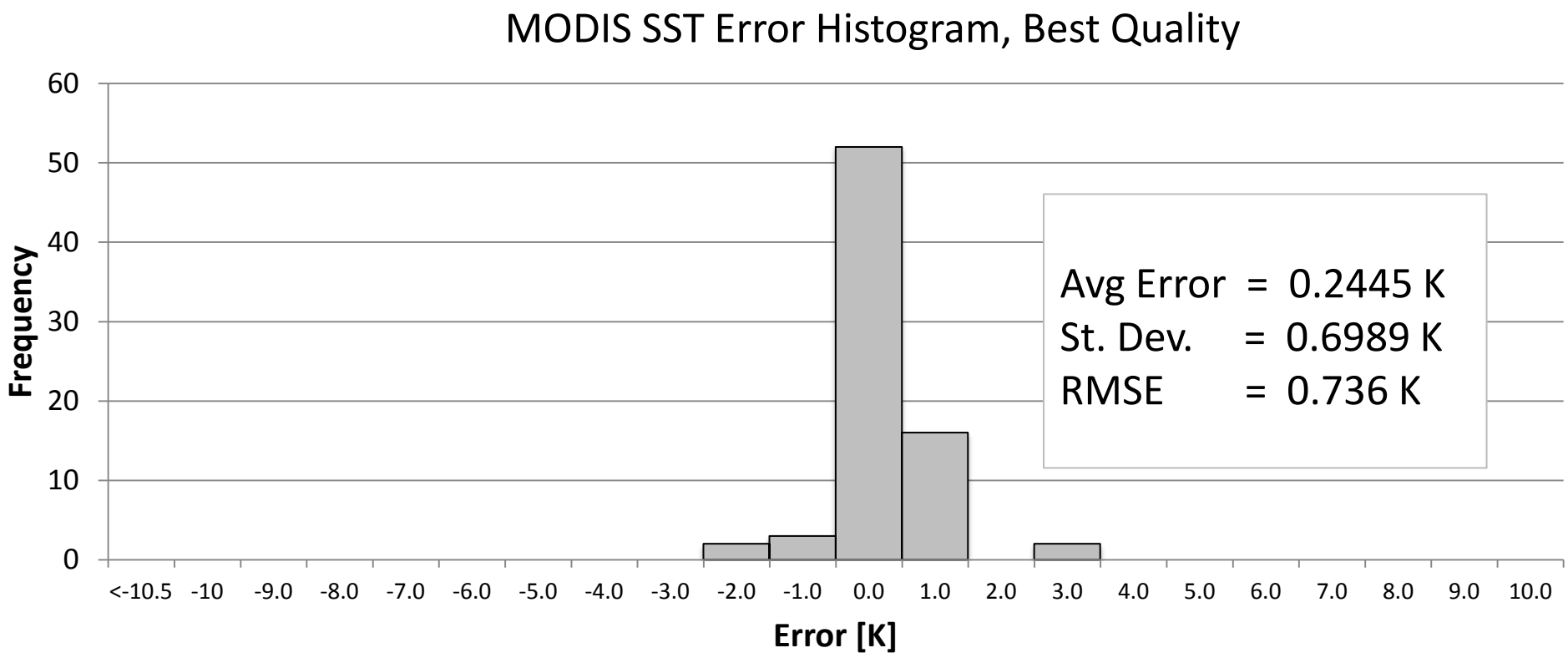
- MODIS Sea Surface Temperature
  - MODIS TERRA has an orbit track similar to Landsat 7 (~20 min behind)
  - Quality band gives each pixel a 0-4 rating, 0 being the best quality



Comparing LST vs. Buoys



Comparing MODIS vs. Buoys



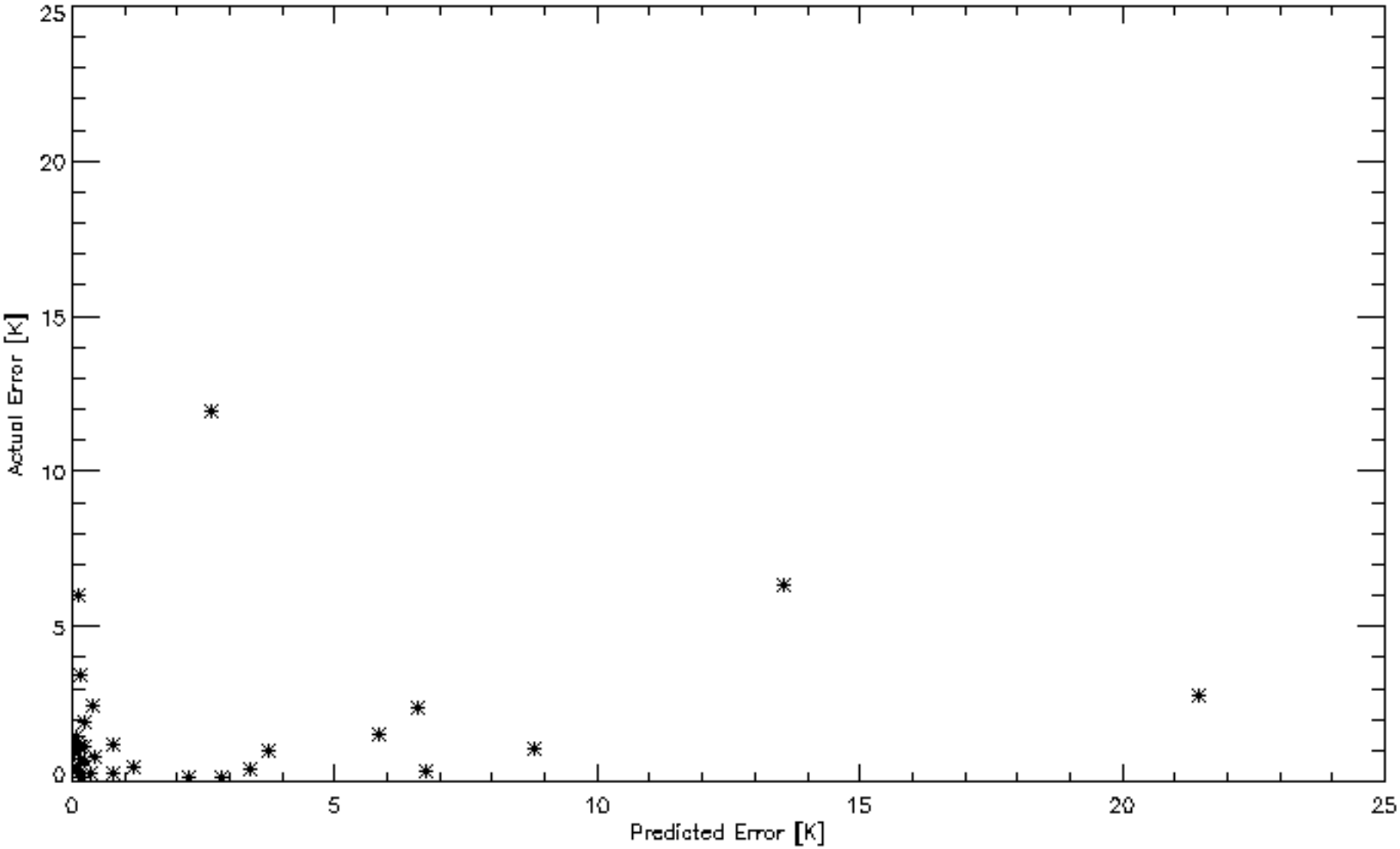
Preliminary Global Validation of Landsat 7

- Compared MODIS SST product to LST results using MERRA
  - 63 scenes globally, 11 sites
  - Errors range from -0.68 to 1.06 K

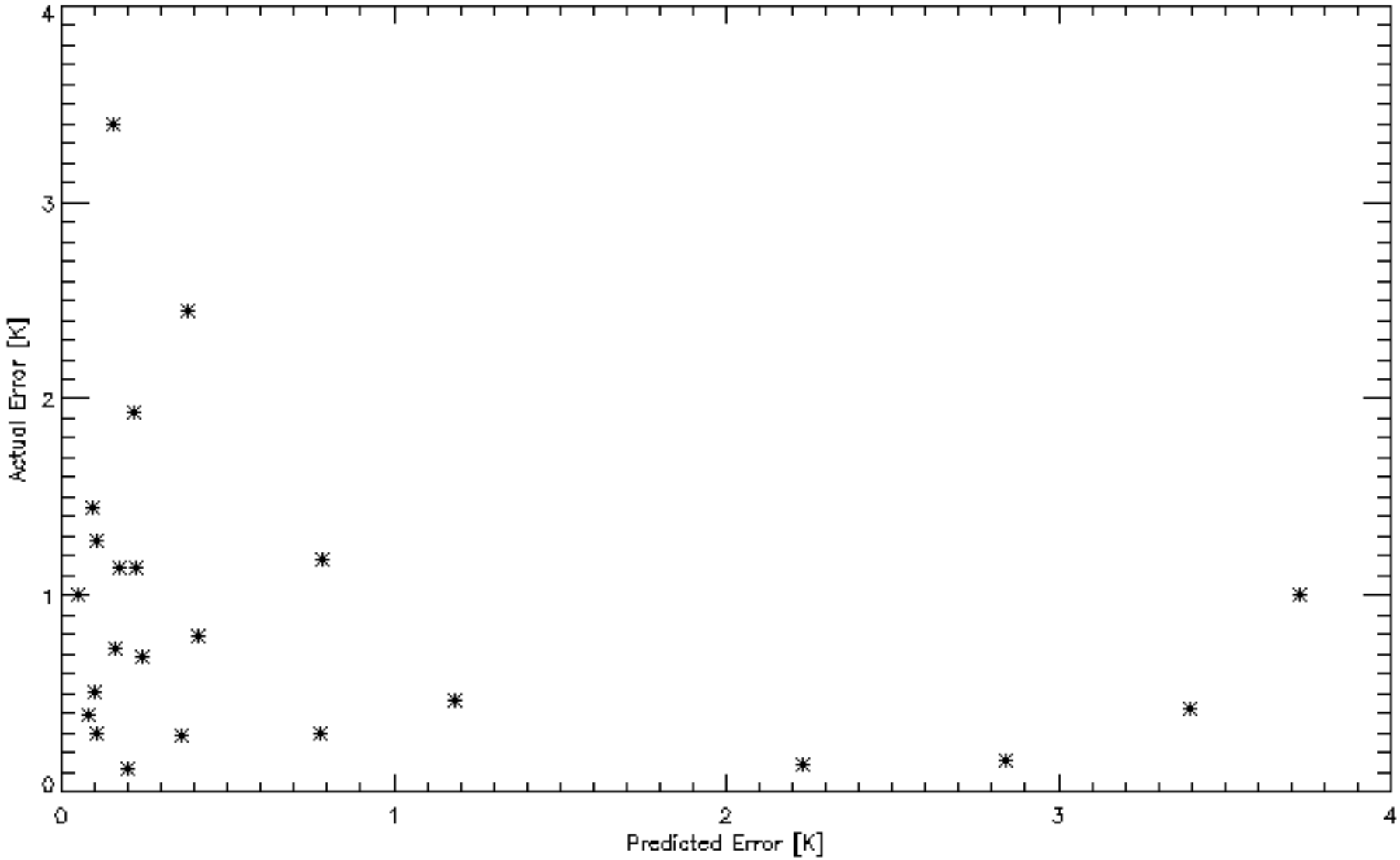
Steps Forward

- Run LST process for hundreds of global scenes for Landsat 7
  - Use MERRA as reanalysis product
  - Use MODIS SST as truth
- Perform Landsat 4 and Landsat 8 validation: Using Buoys
- Continue to utilize the “distance to nearest cloud” metric
- Merge emissivity error, atmospheric error propagation error estimate and cloud proximity errors into confidence metric??????????

Error Propagation



Error Propagation



Multilevel Confidence Estimation

Calculated without clouds (398 scenes total, 332 without clouds)

Best: $\tau > 0.9$

Good: $0.8 < \tau < 0.9$

Bad: $\tau < 0.8$

Category	Mean	SD	# scenes	% of cloud free data
Best	0.868 K	1.083 K	95	28.6%
Good	1.500 K	2.828 K	93	28.0%
Bad	2.318 K	2.867 K	144	43.4%

Estimating LST Error

- $S_a =$ Error due to atmosphere (τ, L_u, L_d)
  - Determine using error propagation for cloud free scenes
- $S_c =$ Error due to presence of clouds
  - Develop relationship between cloud proximity and LST error
- $S_e =$ Error due to emissivity
  - Obtained from JPL

- $S_{TOTAL} = \sqrt{S_a^2 + S_c^2 + S_e^2}$
  - For cloud free cases, S_a will dominate
  - As clouds get closer, S_c will dominate

INPUT?

Extra Slides

Further Explanation

Radiance Paths

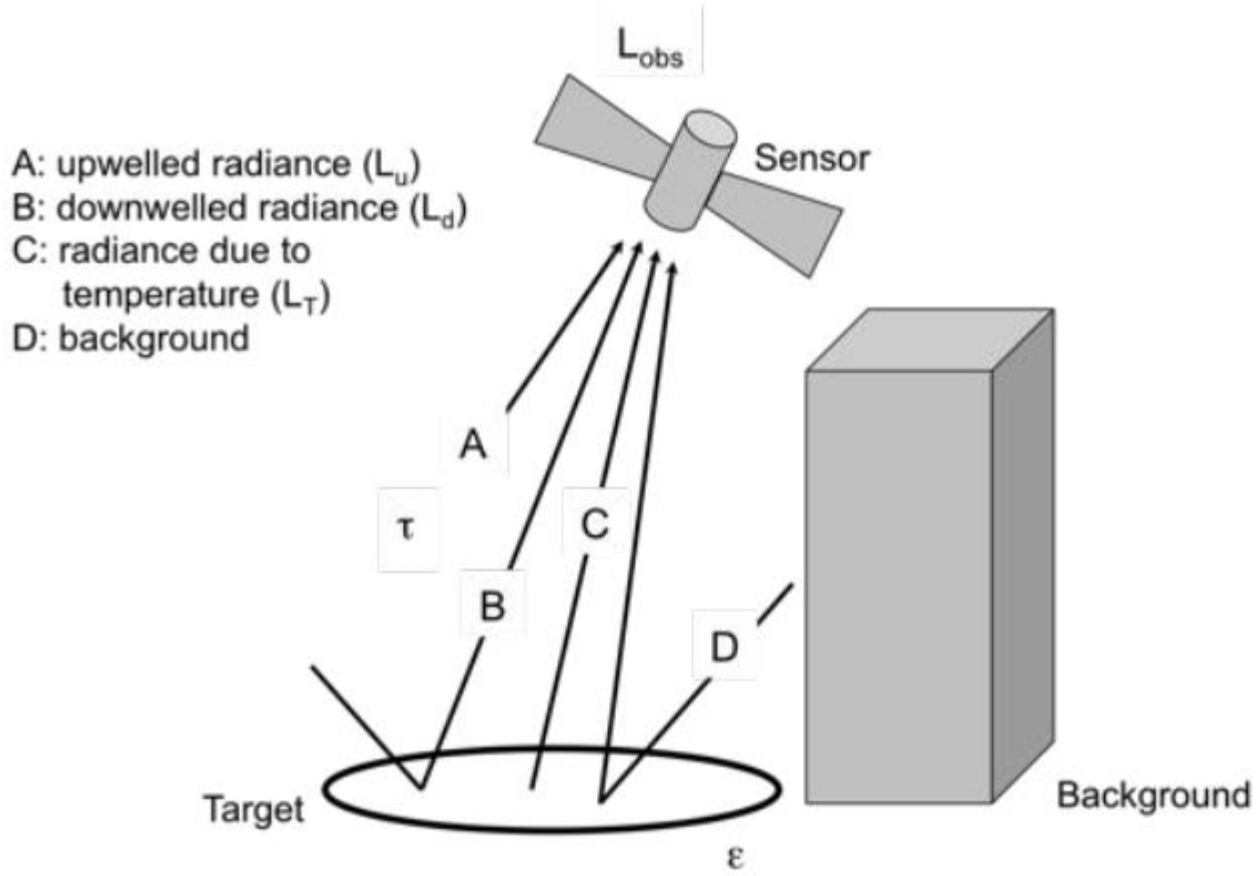


Figure 3.1: Thermal energy paths contributing to the sensor reaching radiance.

Skin Correction

$z =$ sensor depth
$Tz =$ 24 hr avg at z
$T_s =$ 24 hr avg at skin
$a =$ thermal gradiant
$d =$ cool skin effect = 0.17 K
$\mu_m =$ 24 hr avg wind speed
$c =$ phase constant
$b =$ damping constant

$$\langle T_s \rangle = \langle T_z \rangle - az - d$$

$$\mathrm{a} = 0.05 - \frac{0.6}{\mu_m} + 0.03\ln(\mu_m)$$

$$f(t - cz) = \frac{T(z,t) - \langle T_z \rangle}{\mathrm{e}^{-bz}}$$

$$c = 1.32 - 0.64\ln(\mu_m)$$

$$b = 0.35 + 0.018e^{0.4\mu_m}$$

$$T_s = T(0,t) = \langle T_s \rangle + f(t)$$

Shepard's method

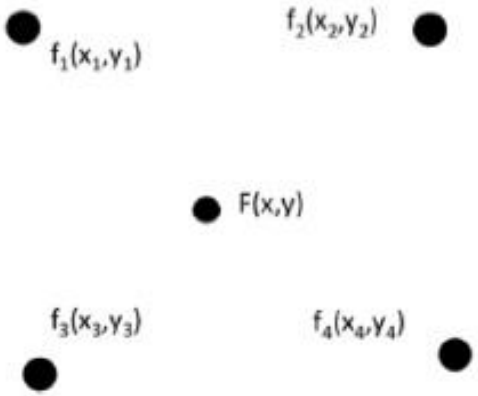


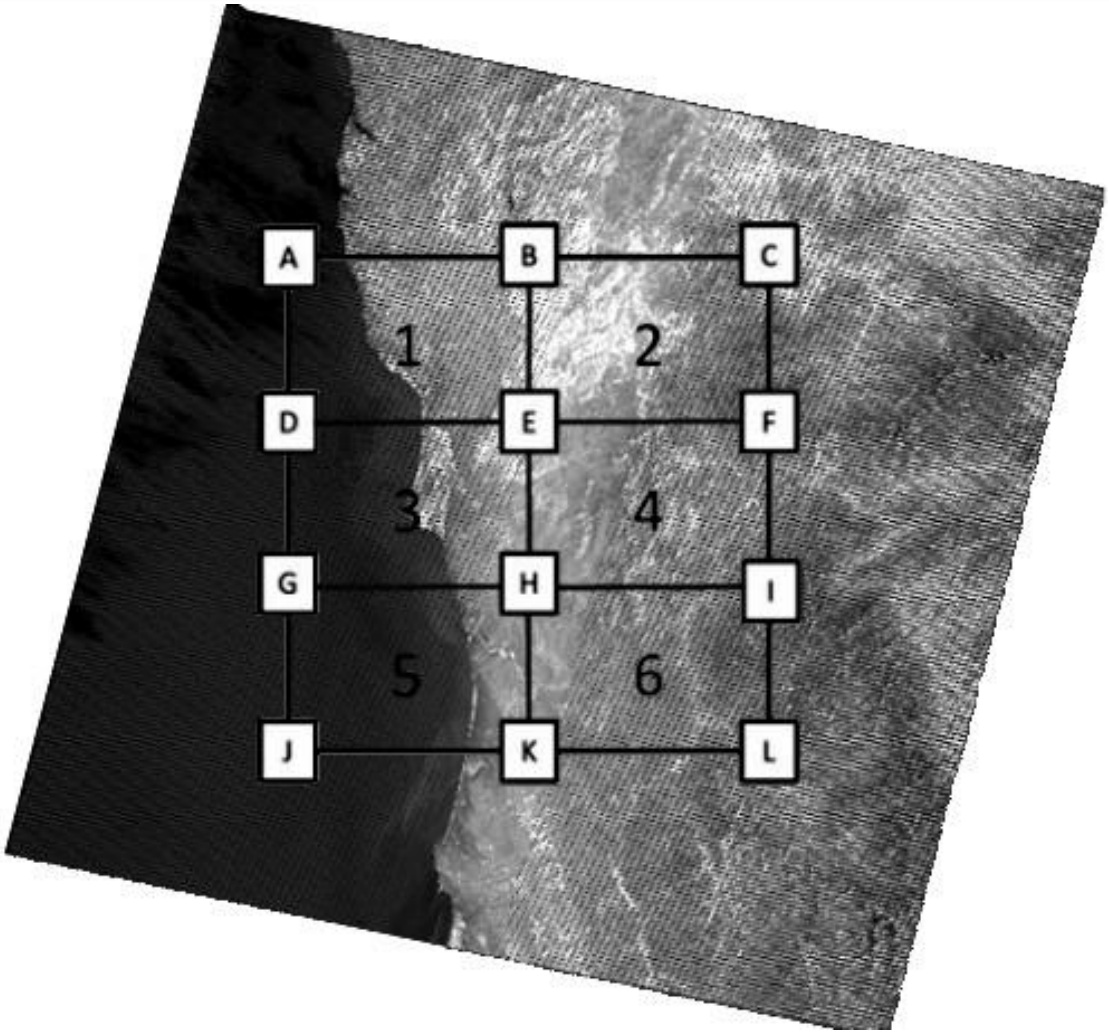
Figure 4.19: caption

$$d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$$

$$w_i = \frac{d_i^{-p}}{\sum_{j=1}^{n} d_j^{-p}}$$

$$F(x, y) = \sum_{i=1}^{n} w_i f_i$$

Spatial Interpolation



CFSR (Climate Forecast System Reanalysis)

- Global, high resolution, coupled atmosphere-ocean-land surface-sea ice system
- Initialized 4x daily (0000, 0600, 1200, 1800 UTC)
- Time series products available at 0.3, 0.5, 1.0, and 2.5° horizontal resolutions
- Available from January 1979 to December 2010
- CFSRv2 is available form January 2011-present
- Data format- WMO GRIB2 (NARR was WMO GRIB1)

Description of Global Sites

Table 6.4: Descriptions of locations and radiosonde densities for each point selected for global MODIS and Landsat LST comparisons. Note that the radiosonde description refers to the description of the density of input observations to the MERRA product provided in Figure 6.10.

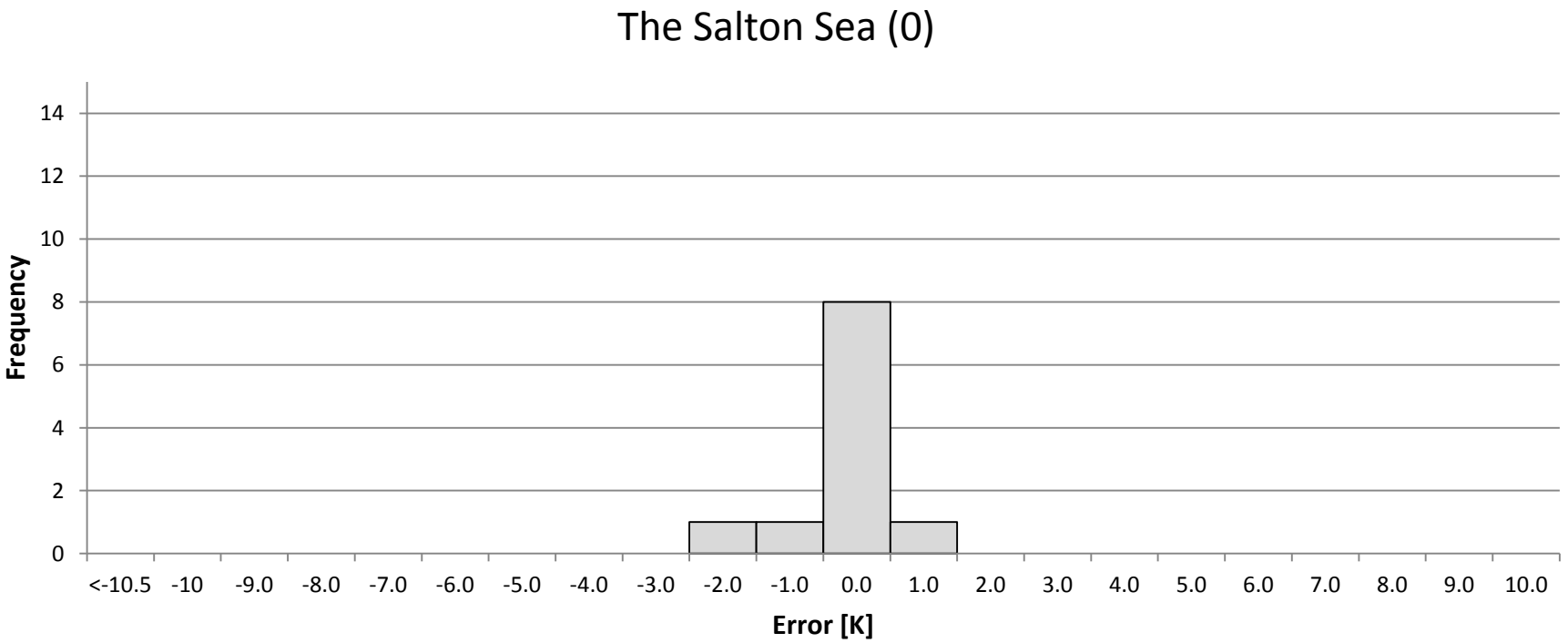
Location	WRS-2 path_row	[lat, lon]	Radiosonde	Description
South America	216_63	[-4.26, -37.7]	1	Tropical
Mediterranean	196_30	[43.3, 4.8]	2	Mid Lat - Northern
Black Sea	174_30	[43.47, 38.91]	2	Mid Lat - Nothern
India	144_54	[9.0, 76.34]	0	Tropical
Hong Kong	121_44	[22.46, 114.9]	2	Low Lat - Northern
Russia	107_19	[58.85, 149.43]	1	High Lat - Northern
Australia	113_82	[-31.9, 114.95]	2	Mid Lat - Southern
Africa	180_75	[-22.0, 14.0]	0	Low Lat - Southern
Greenland	232_17	[61.5, -41.75]	1	High Lat - Nothern
South America	218_77	[-24.045, -45.18]	2	Low Lat - Southern
South America	233_93	[-47.88, -75.45]	1	Mid Lat - Southern

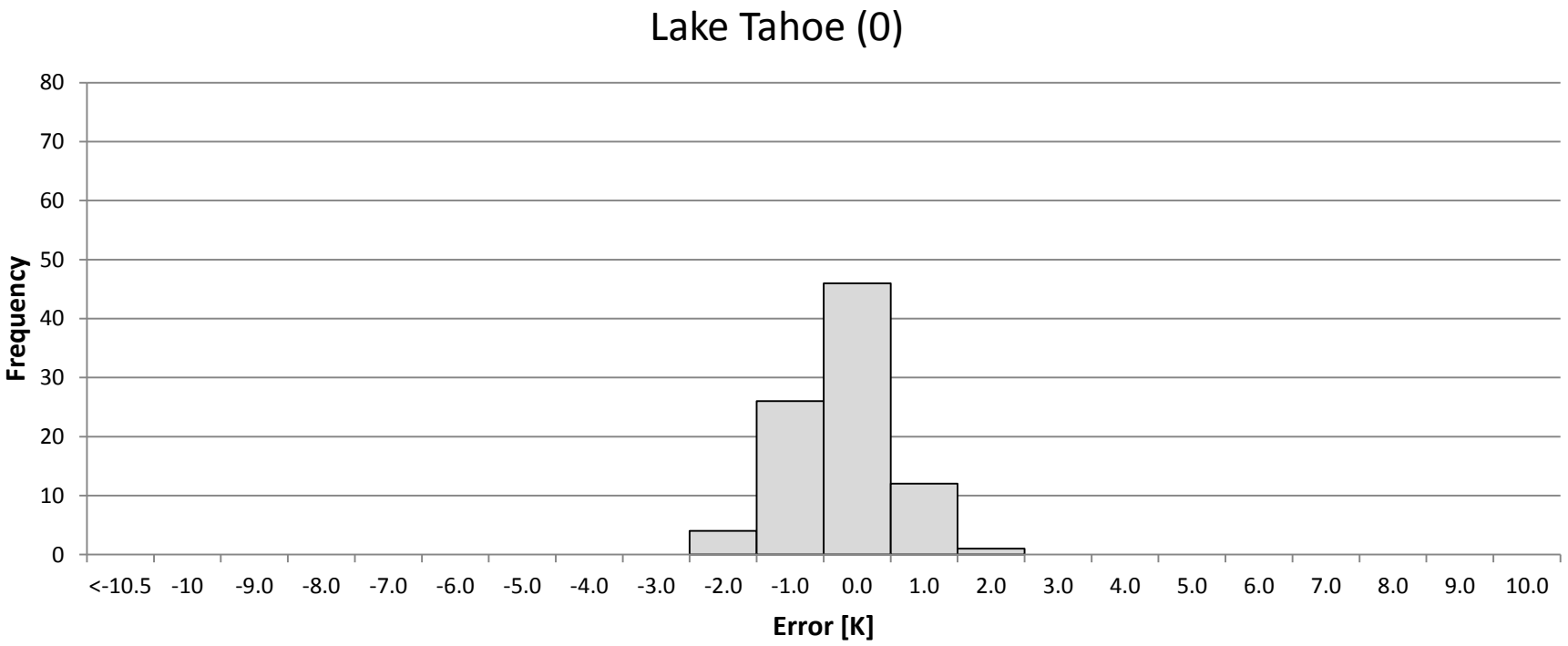
MERRA vs MODIS SST

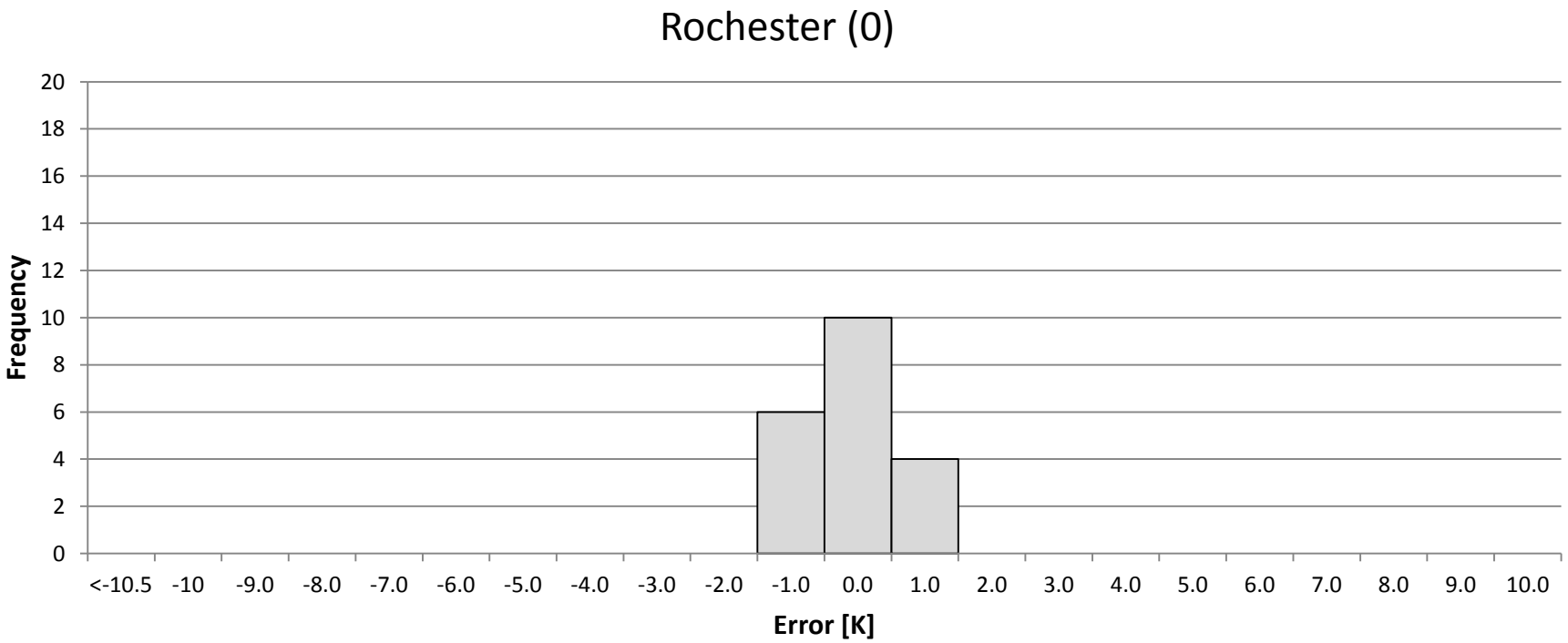
Table 6.5: Statistics of errors for each individual location for MODIS SST and Landsat comparisons. The error is calculated using Equation 6.2, n is the number of scenes analyzed for each location after removing scenes with less than the best quality, and SD is the standard deviation.

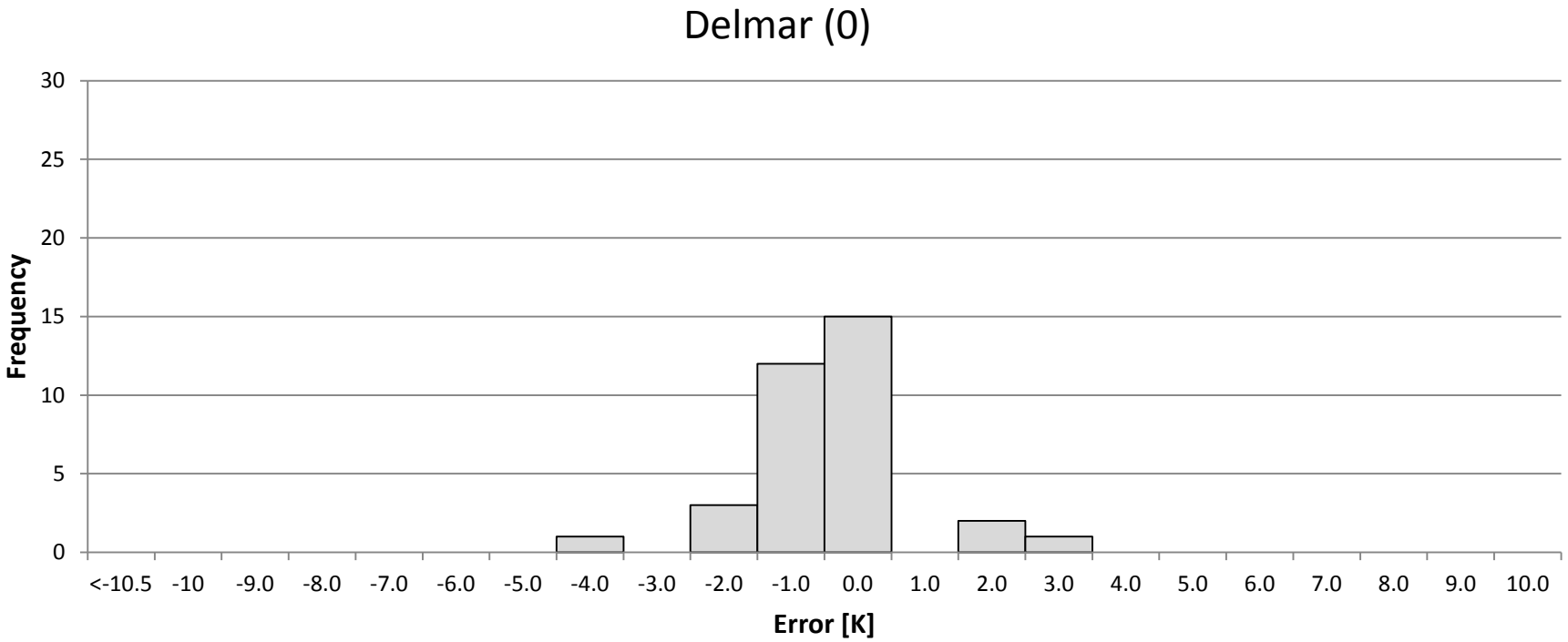
Location	Radiosonde	Description	n	Mean [K]	SD [K]
South America	1	Tropical	4	1.06	0.79
Mediterranean	2	Mid Lat - Northern	4	-0.27	0.28
Black Sea	2	Mid Lat - Northern	6	-0.41	0.45
India	0	Tropical	6	0.82	0.43
Hong Kong	2	Low Lat - Northern	4	0.09	1.31
Russia	1	High Lat - Northern	3	-0.60	0.32
Australia	2	Mid Lat - Southern	8	-0.32	0.43
Africa	0	Low Lat - Southern	4	-0.47	0.27
Greenland	1	High Lat - Nothern	1	-0.24	–
South America	2	Low Lat - Southern	3	0.58	0.29
South America	1	Mid Lat - Southern	5	-0.68	0.25

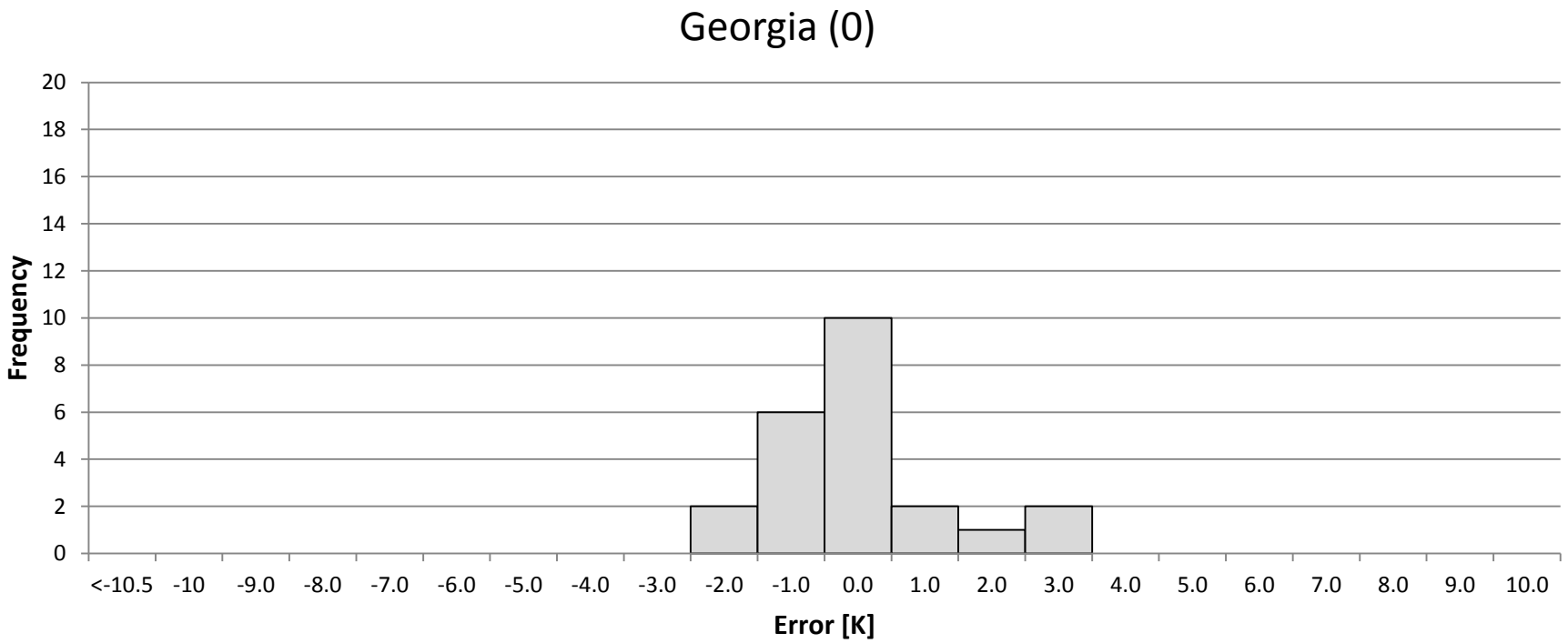
Monica's Cloud Free Histograms

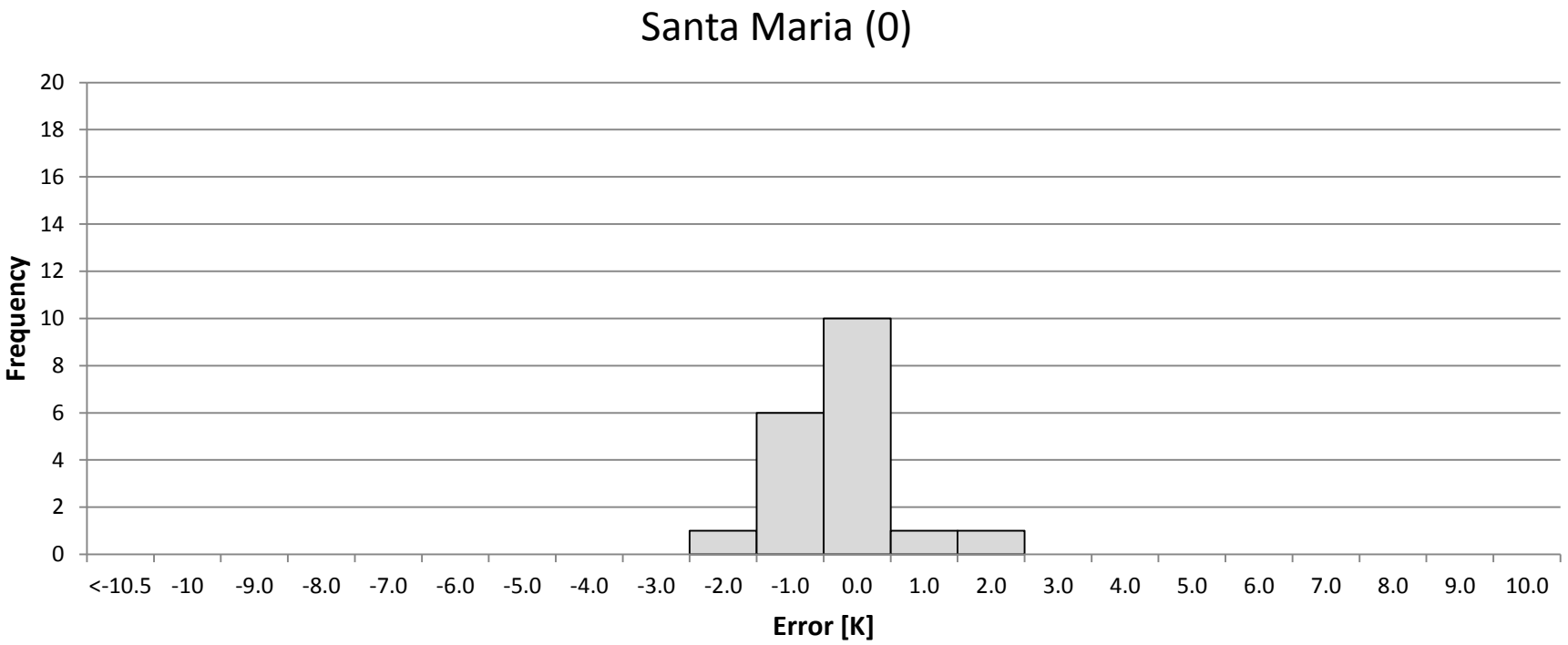

The Salton Sea (0)
Frequency
14
12
10
8
6
4
2
0
<-10.5
-10
-9.0
-8.0
-7.0
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Error [K]

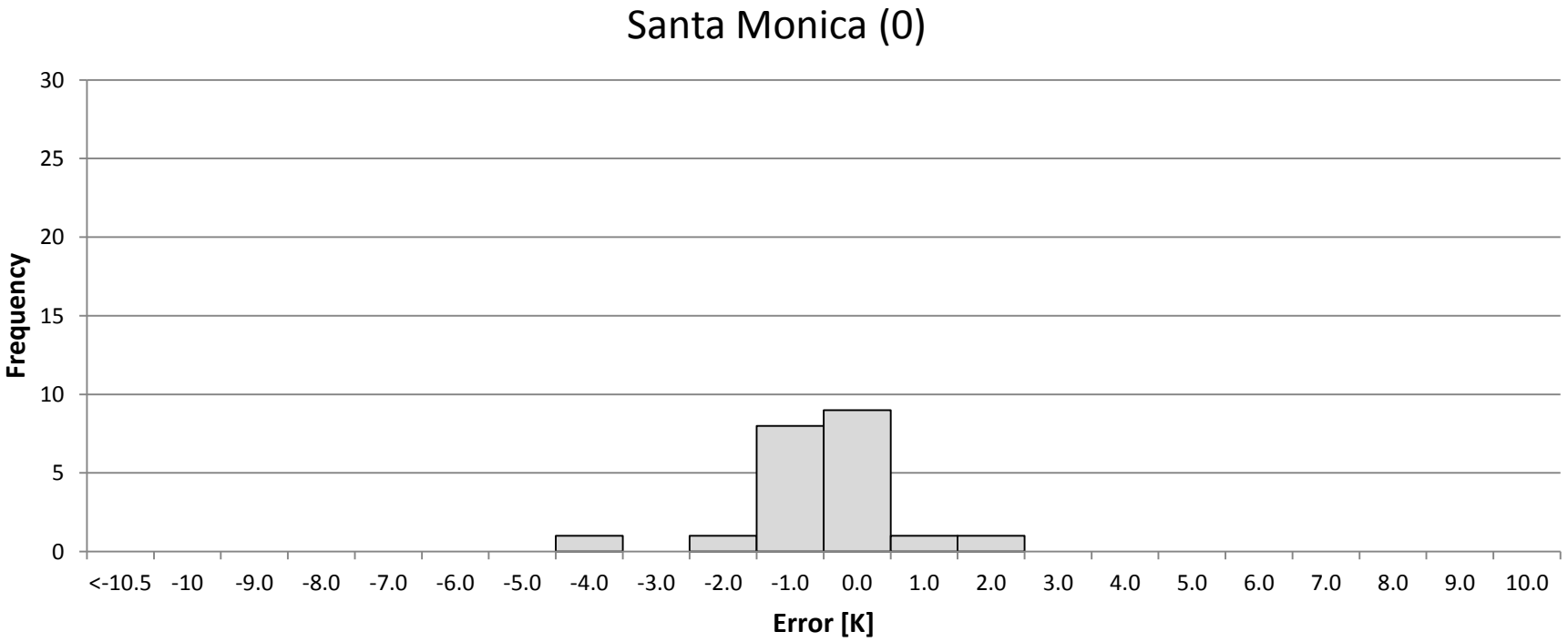

Lake Tahoe (0)
Frequency
80
70
60
50
40
30
20
10
0
<-10.5
-10
-9.0
-8.0
-7.0
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Error [K]

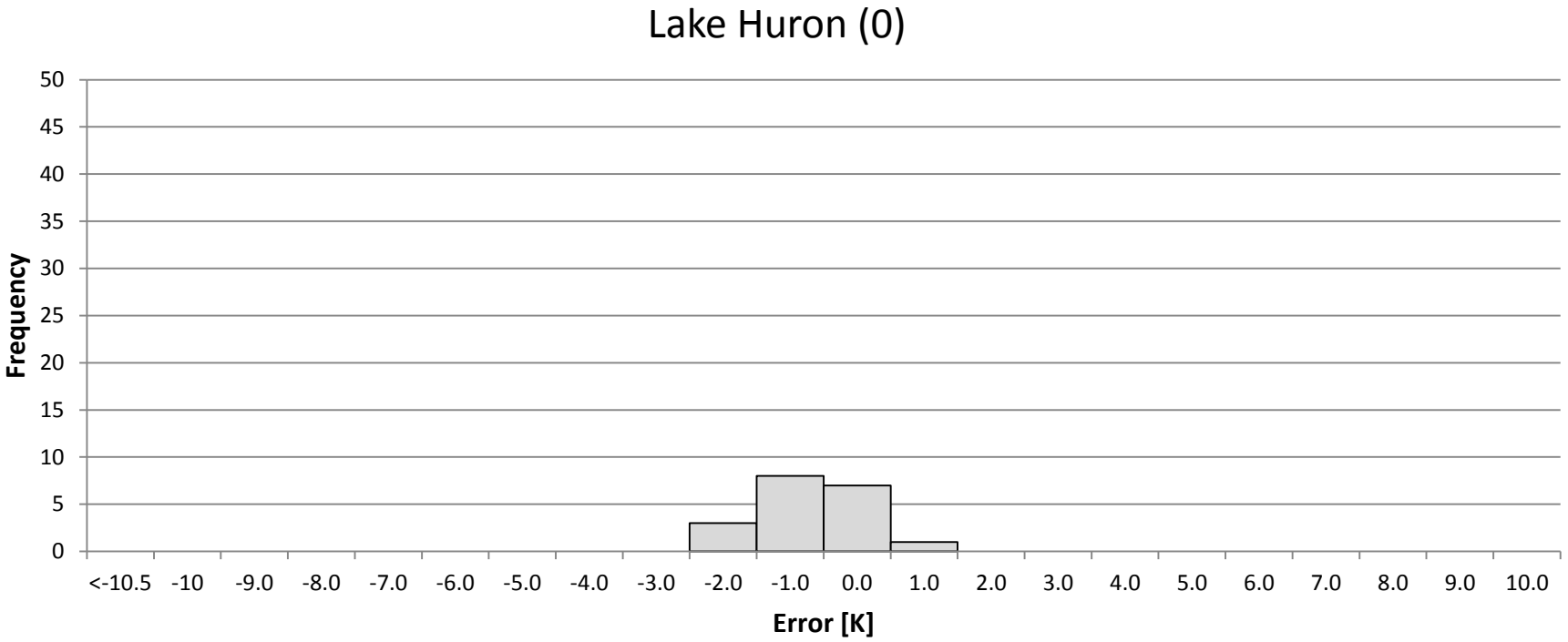

Rochester (0)
Frequency
20
18
16
14
12
10
8
6
4
2
0
<-10.5
-10
-9.0
-8.0
-7.0
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Error [K]

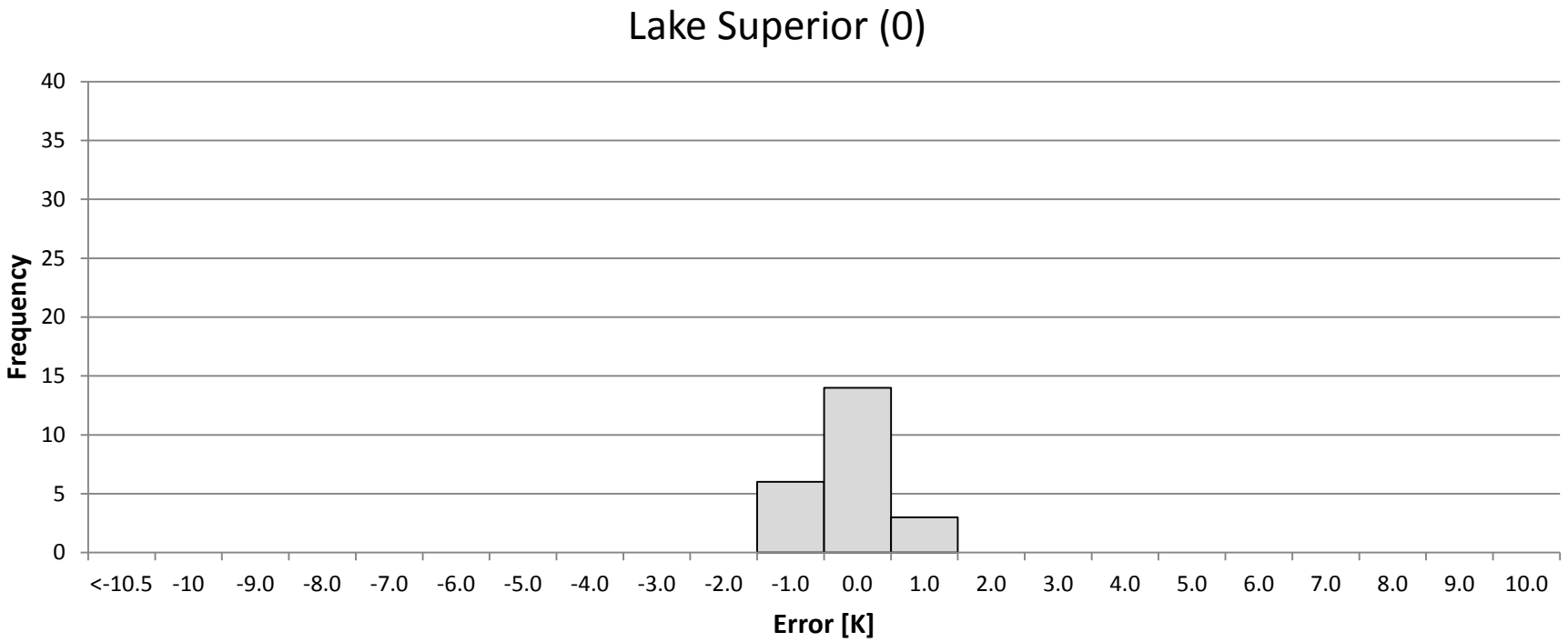

Delmar (0)
Frequency
30
25
20
15
10
5
0
<-10.5
-10
-9.0
-8.0
-7.0
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Error [K]


Georgia (0)
Frequency
20
18
16
14
12
10
8
6
4
2
0
<-10.5
-10
-9.0
-8.0
-7.0
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Error [K]

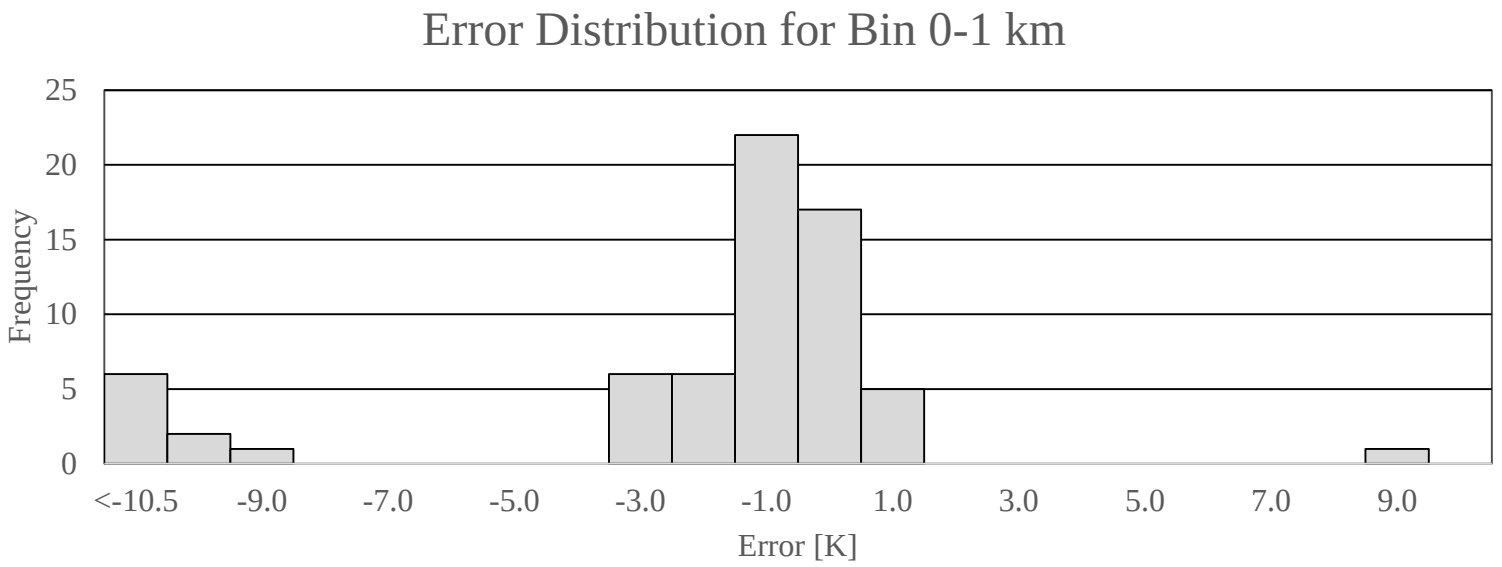

Santa Maria (0)
Frequency
20
18
16
14
12
10
8
6
4
2
0
<-10.5
-10
-9.0
-8.0
-7.0
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Error [K]

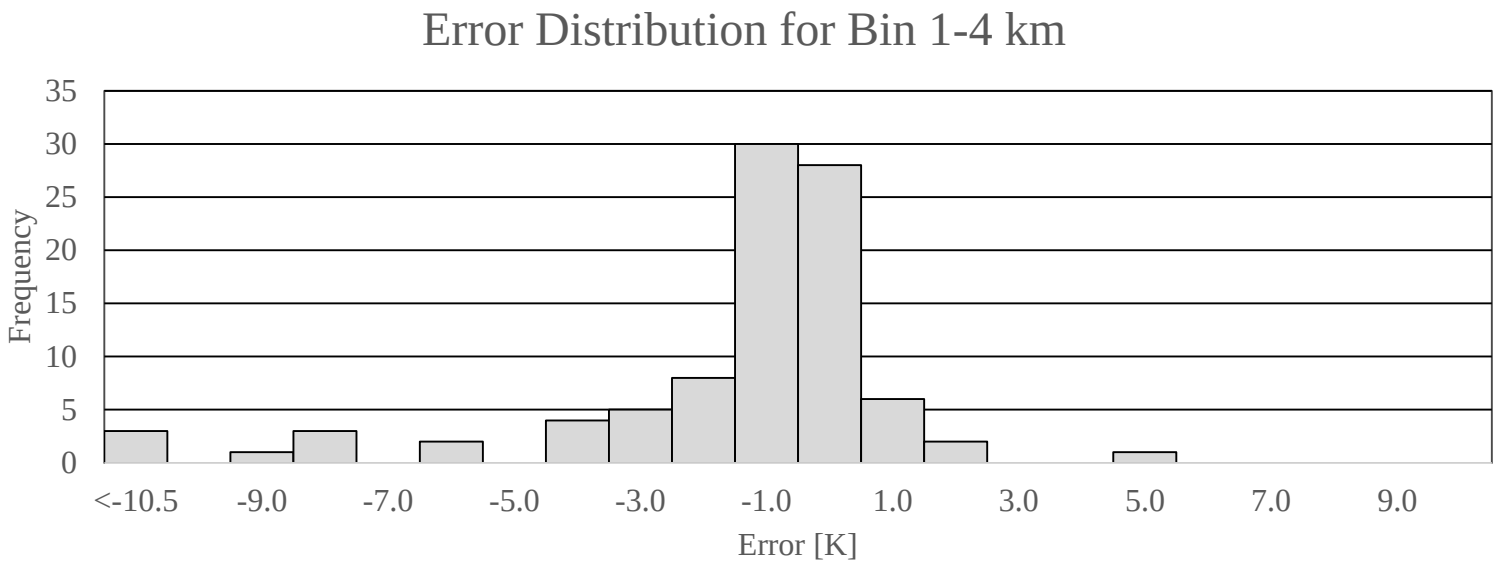

Santa Monica (0)
Frequency
30
25
20
15
10
5
0
<-10.5
-10
-9.0
-8.0
-7.0
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Error [K]

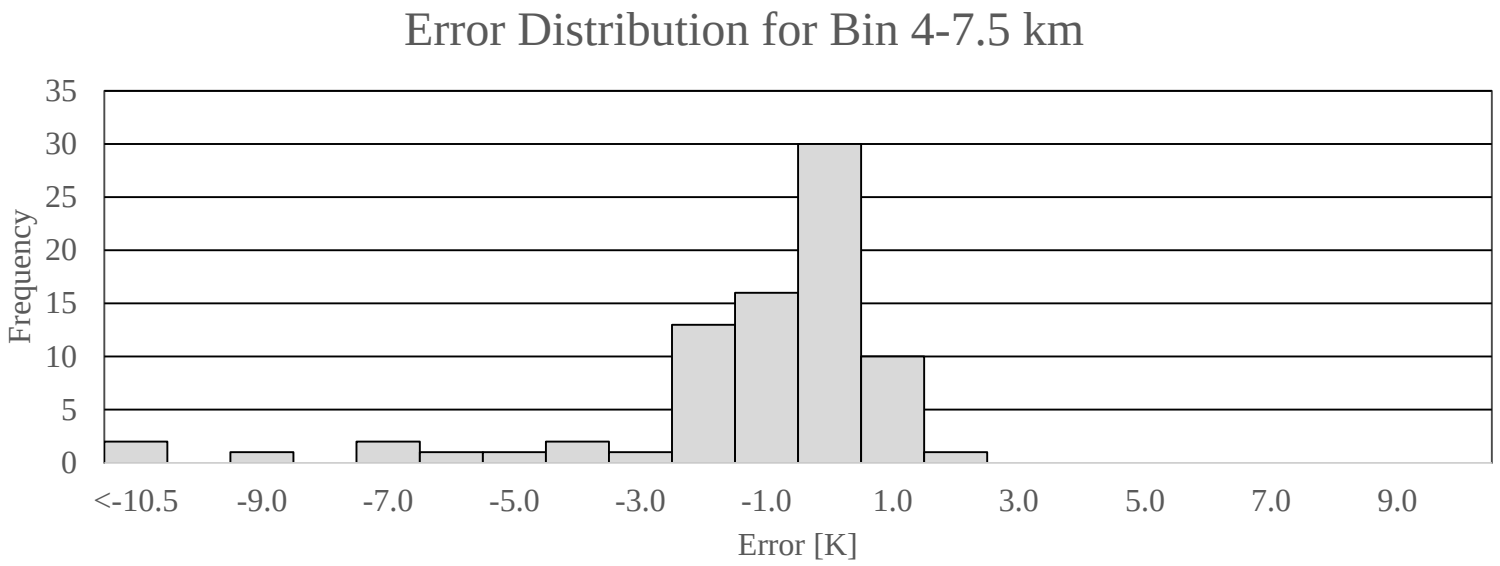

Lake Huron (0)
Frequency
50
45
40
35
30
25
20
15
10
5
0
<-10.5
-10
-9.0
-8.0
-7.0
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Error [K]

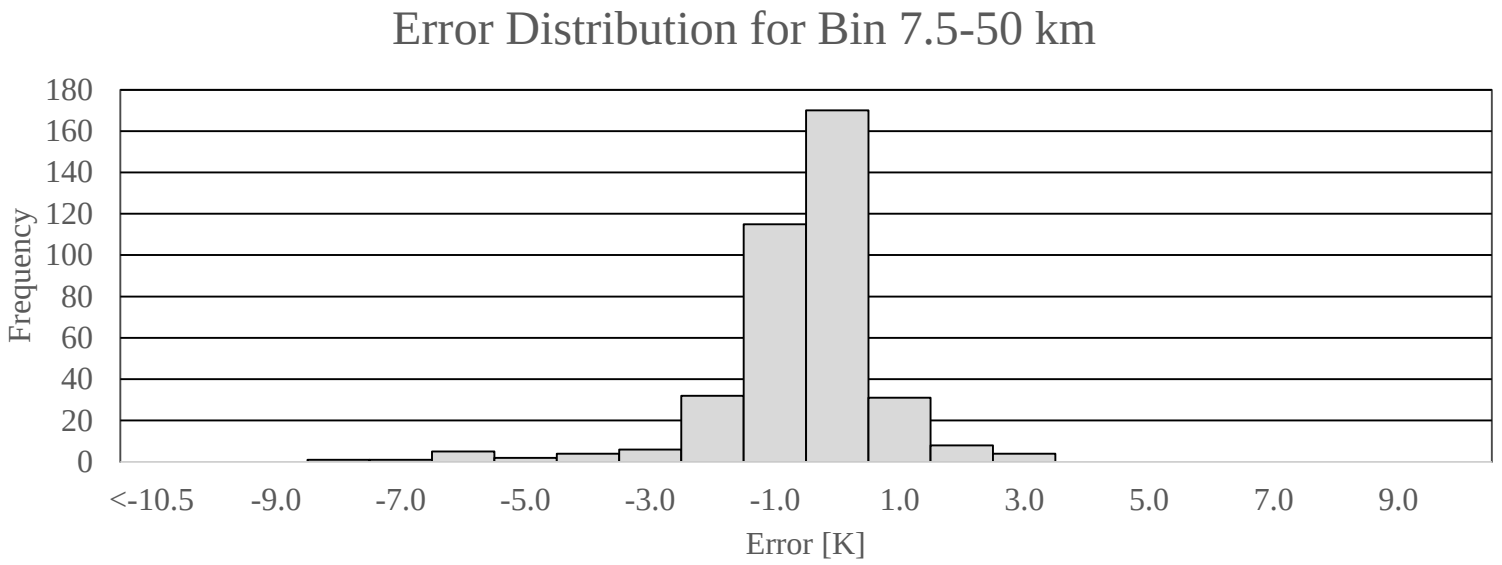

Lake Superior (0)
Frequency
40
35
30
25
20
15
10
5
0
<-10.5
-10
-9.0
-8.0
-7.0
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Error [K]

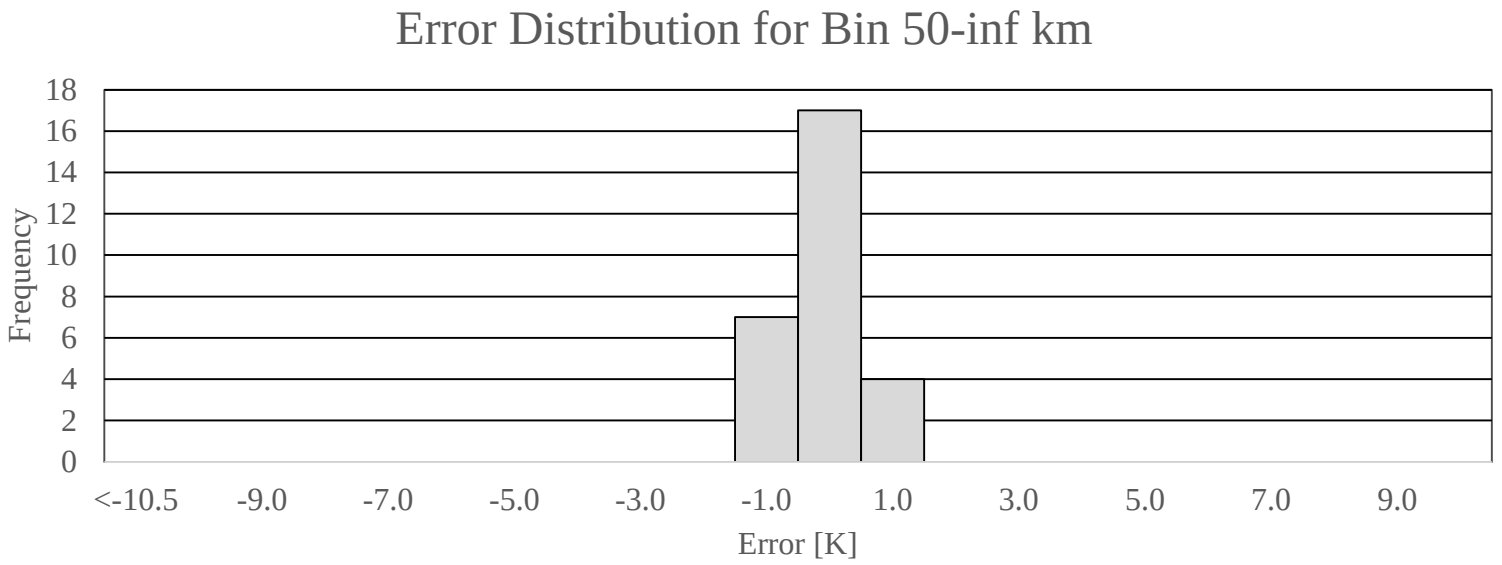
Distance Bin Histograms

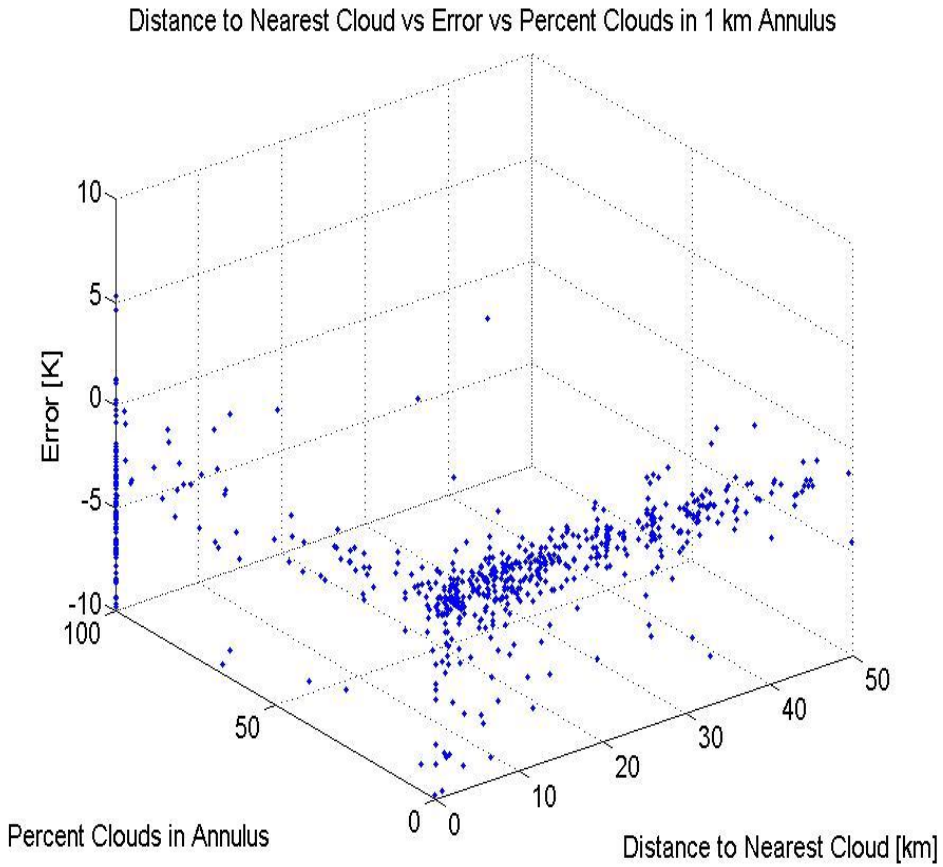

Error Distribution for Bin 0-1 km
Frequency
25
20
15
10
5
0
<-10.5
-9.0
-7.0
-5.0
-3.0
-1.0
1.0
3.0
5.0
7.0
9.0
Error [K]

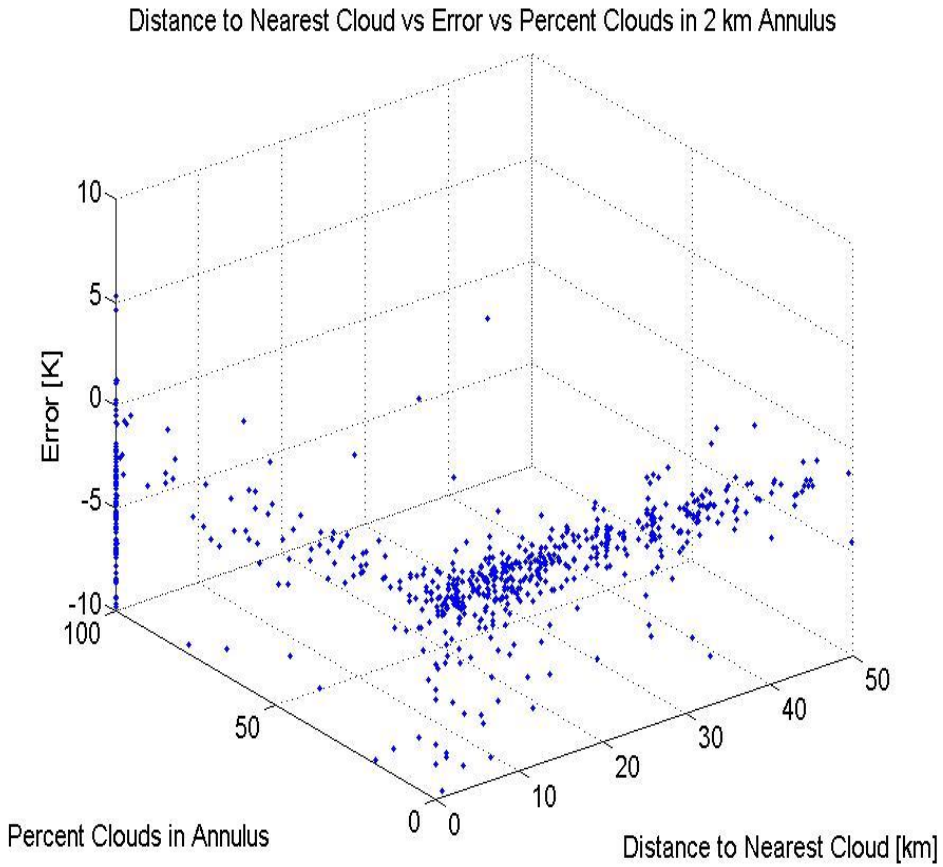

Error Distribution for Bin 1-4 km
Frequency
35
30
25
20
15
10
5
0
<-10.5
-9.0
-7.0
-5.0
-3.0
-1.0
1.0
3.0
5.0
7.0
9.0
Error [K]

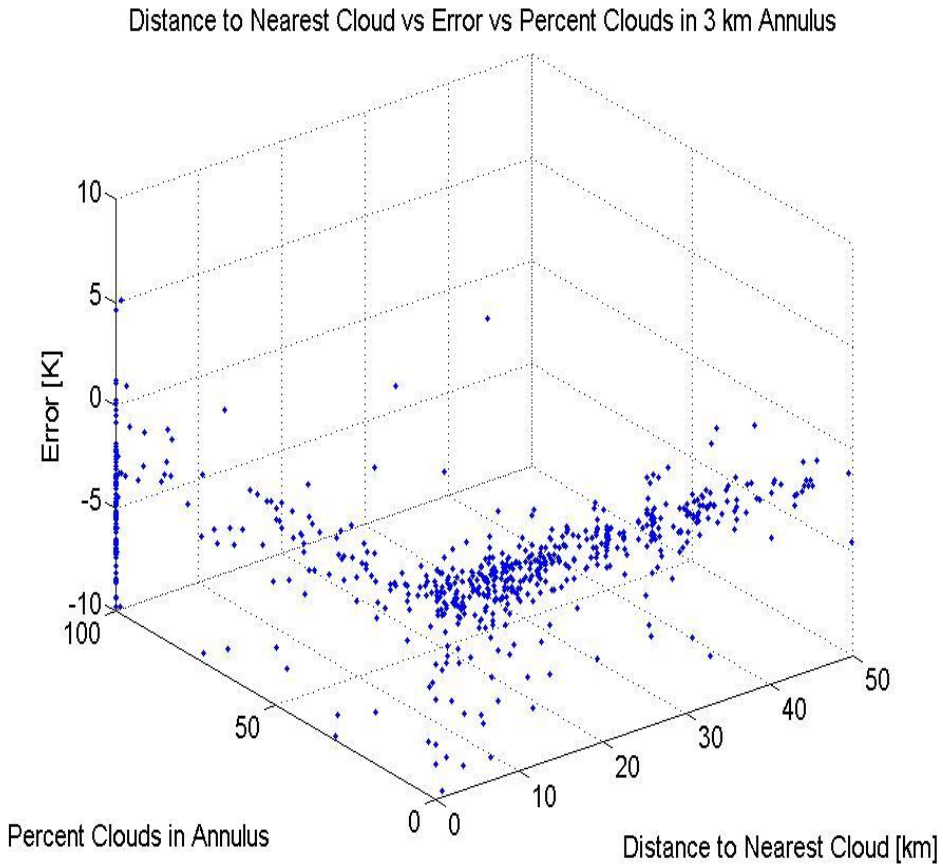

Error Distribution for Bin 4-7.5 km
Frequency
35
30
25
20
15
10
5
0
<-10.5
-9.0
-7.0
-5.0
-3.0
-1.0
1.0
3.0
5.0
7.0
9.0
Error [K]

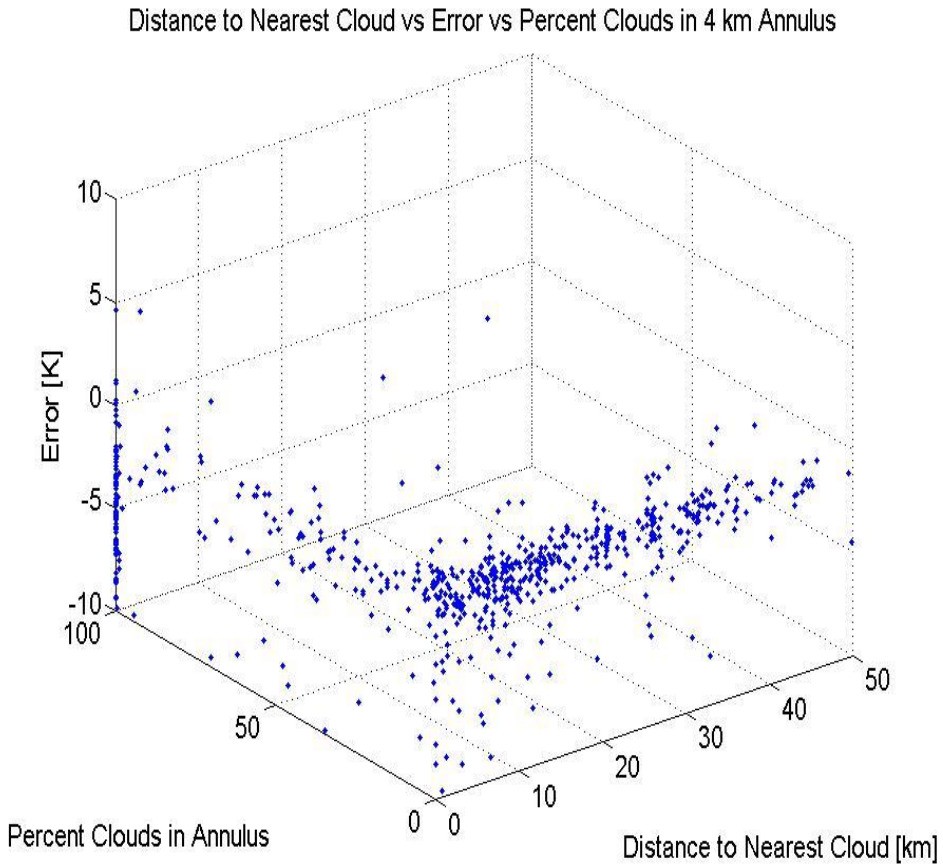

Error Distribution for Bin 7.5-50 km
Frequency
180
160
140
120
100
80
60
40
20
0
<-10.5
-9.0
-7.0
-5.0
-3.0
-1.0
1.0
3.0
5.0
7.0
9.0
Error [K]

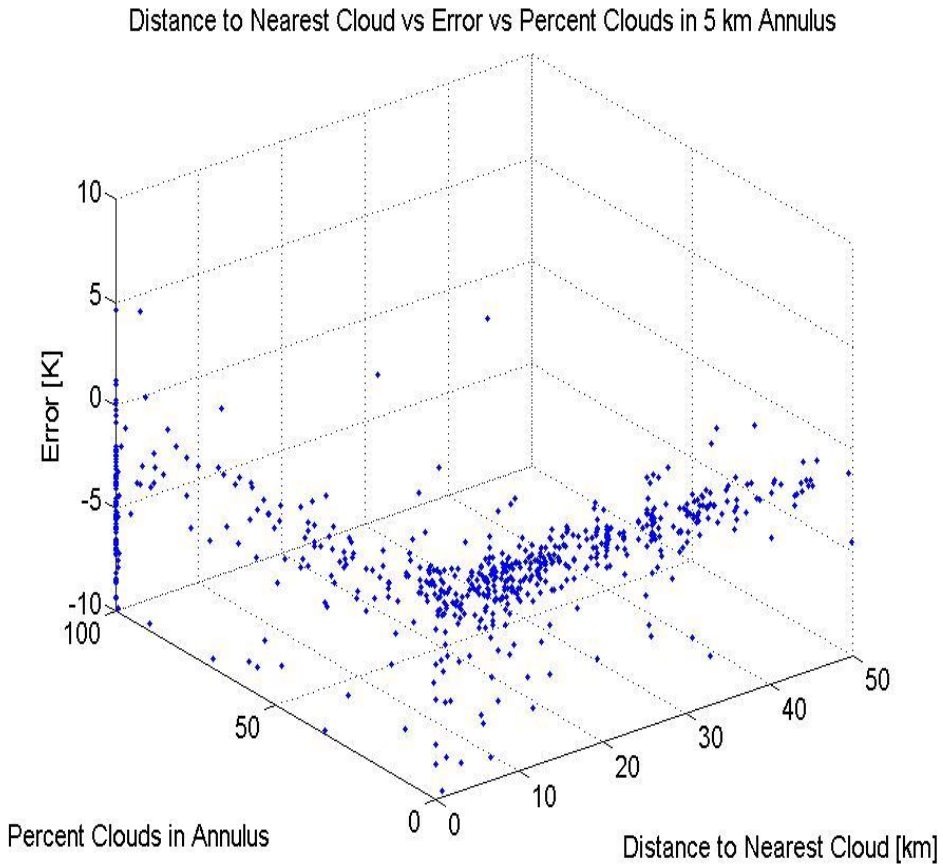

Error Distribution for Bin 50-inf km
Frequency
18
16
14
12
10
8
6
4
2
0
<-10.5
-9.0
-7.0
-5.0
-3.0
-1.0
1.0
3.0
5.0
7.0
9.0
Error [K]

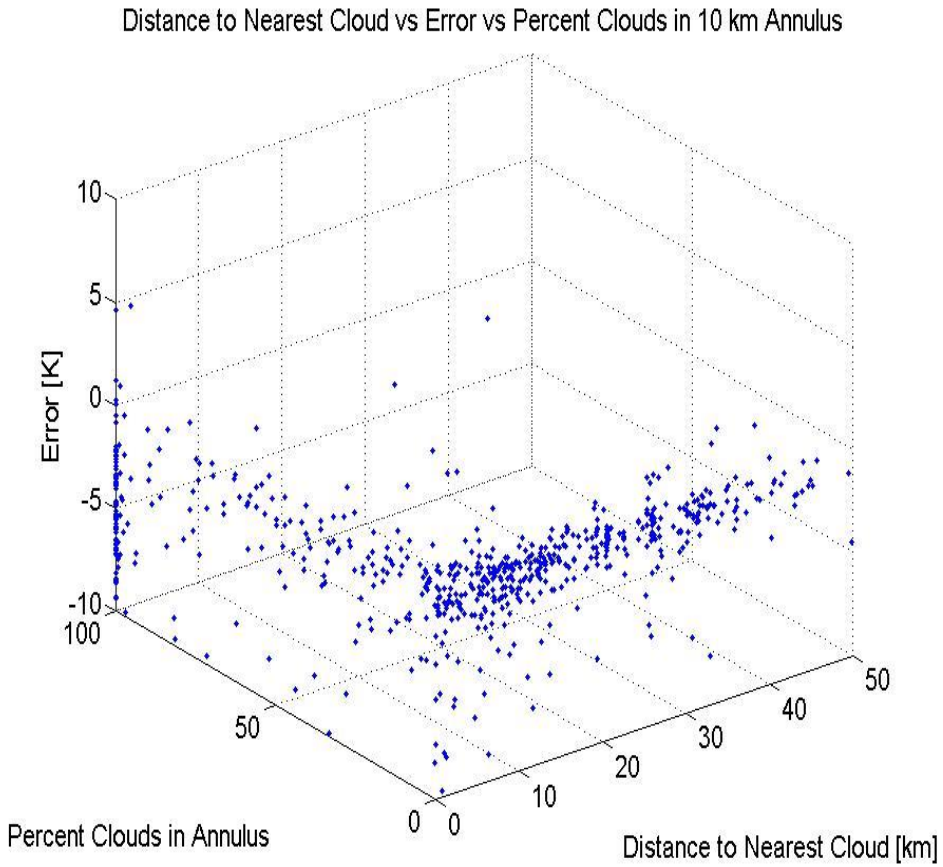

Distance to Nearest Cloud vs Error vs Percent Clouds in 1 km Annulus
Error [K]
10
5
0
-5
-10
100
50
0
Percent Clouds in Annulus
0
10
20
30
40
50
Distance to Nearest Cloud [km]


Distance to Nearest Cloud vs Error vs Percent Clouds in 2 km Annulus
Error [K]
10
5
0
-5
-10
100
50
0
Percent Clouds in Annulus
0
10
20
30
40
50
Distance to Nearest Cloud [km]


Distance to Nearest Cloud vs Error vs Percent Clouds in 3 km Annulus
Error [K]
10
5
0
-5
-10
100
50
0
Percent Clouds in Annulus
0
10
20
30
40
50
Distance to Nearest Cloud [km]


Distance to Nearest Cloud vs Error vs Percent Clouds in 4 km Annulus
Error [K]
10
5
0
-5
-10
100
50
0
Percent Clouds in Annulus
0
10
20
30
40
50
Distance to Nearest Cloud [km]


Distance to Nearest Cloud vs Error vs Percent Clouds in 5 km Annulus
Error [K]
10
5
0
-5
-10
100
50
0
Percent Clouds in Annulus
0
10
20
30
40
50
Distance to Nearest Cloud [km]


Distance to Nearest Cloud vs Error vs Percent Clouds in 10 km Annulus
Error [K]
10
5
0
-5
-10
100
50
0
Percent Clouds in Annulus
0
10
20
30
40
50
Distance to Nearest Cloud [km]

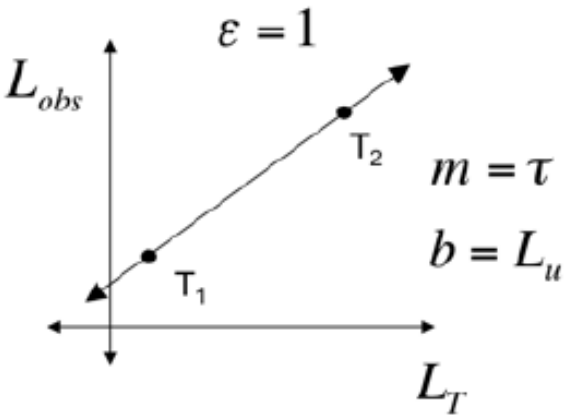
The Basics

- Land Surface Temperature (LST) methodology
- Review of Monica's work
- Development of a quality metric
- Approaches to global validation

Solving for Atmospheric Parameters

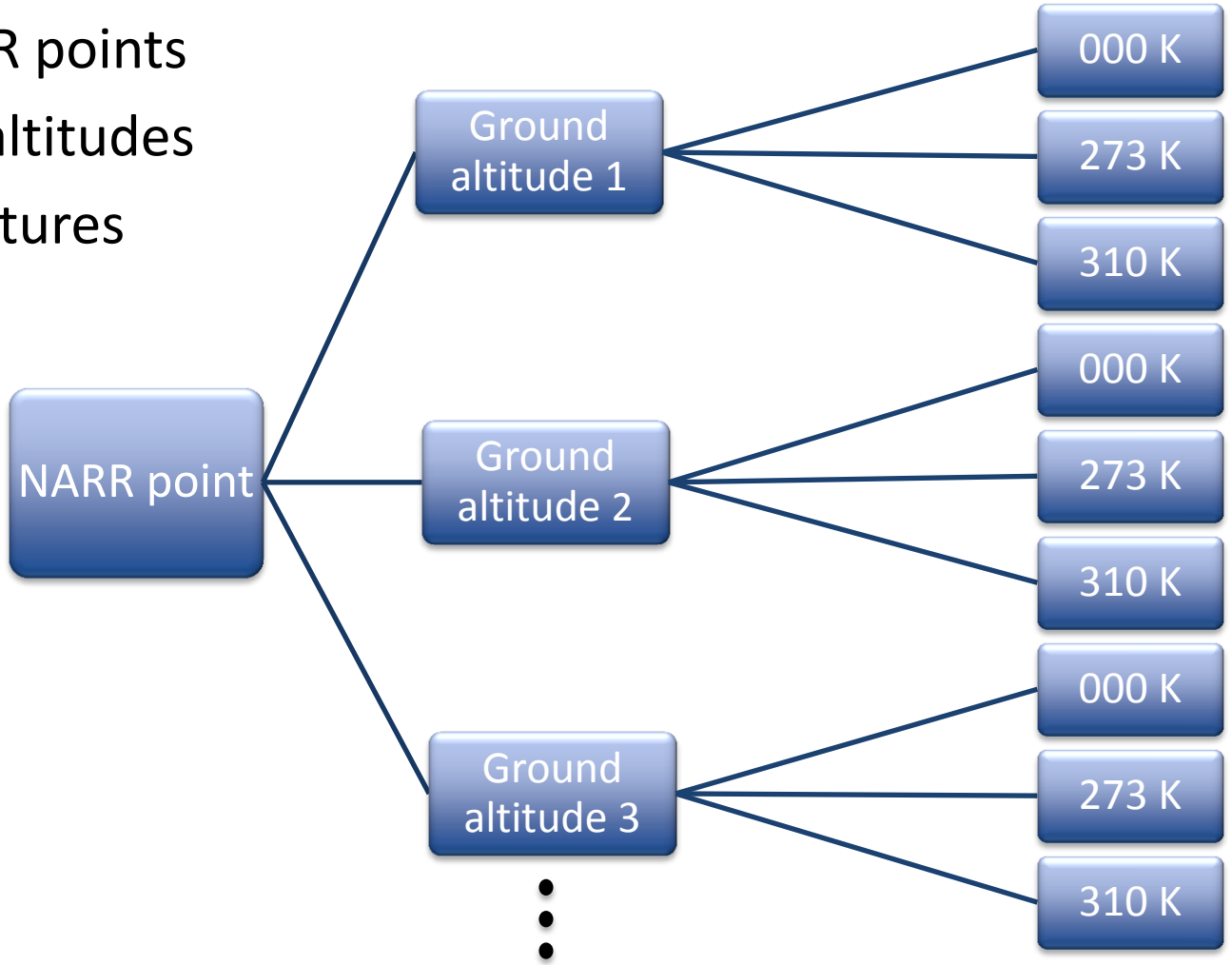
- Finding transmission and upwelled
  - If emissivity ≅ 1, then $L_{obs} = L_T \epsilon \tau + L_u$
  - Slope is transmission and intercept is upwelled

- Finding downwelled
  - If emissivity < 1, then $L_d = \frac{\frac{L_{obs} - L_u}{\tau} - L_T \epsilon}{1 - \epsilon}$
  - Simply solve for L_d



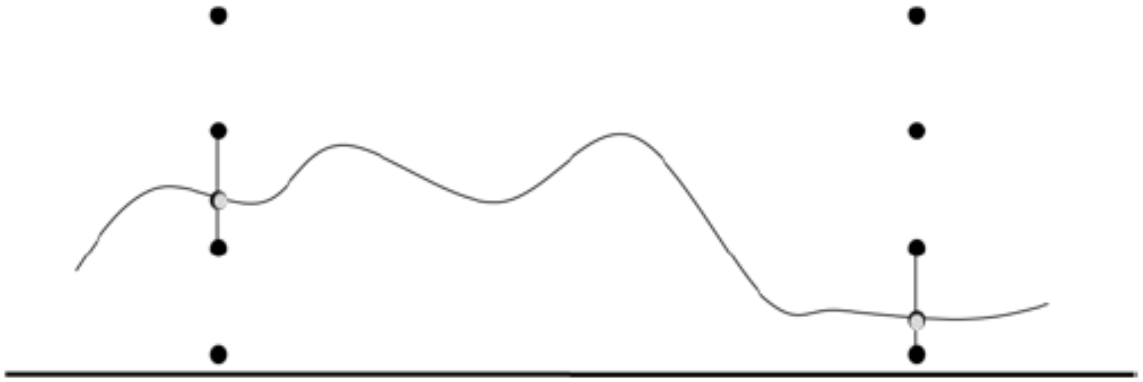
MODTRAN Runs

- ~100 NARR points
- 9 ground altitudes
- 3 temperatures



Interpolation

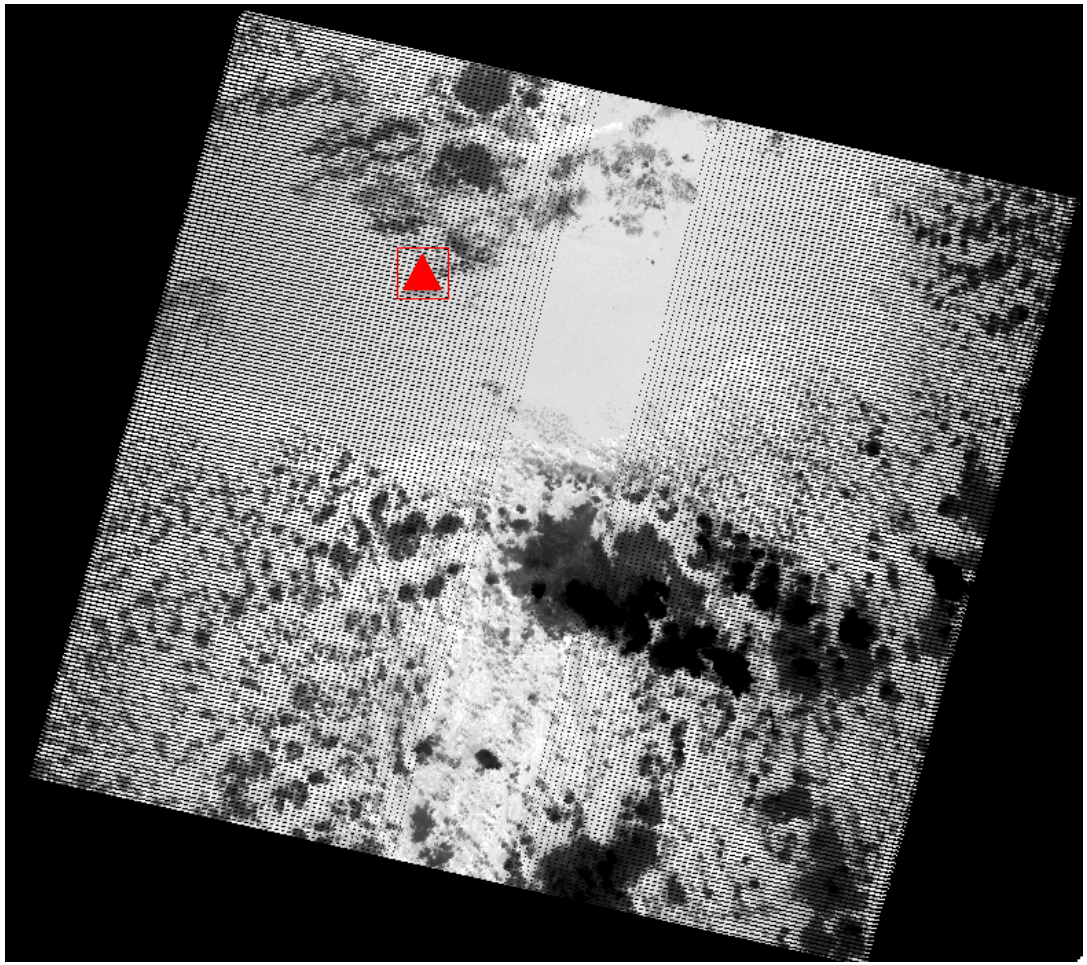
- Temporal (to get NARR data at proper time)
- Height (to get parameters at appropriate pixel height)
- Spatial (to get parameters at a per-pixel level)



Cook's Validation Results

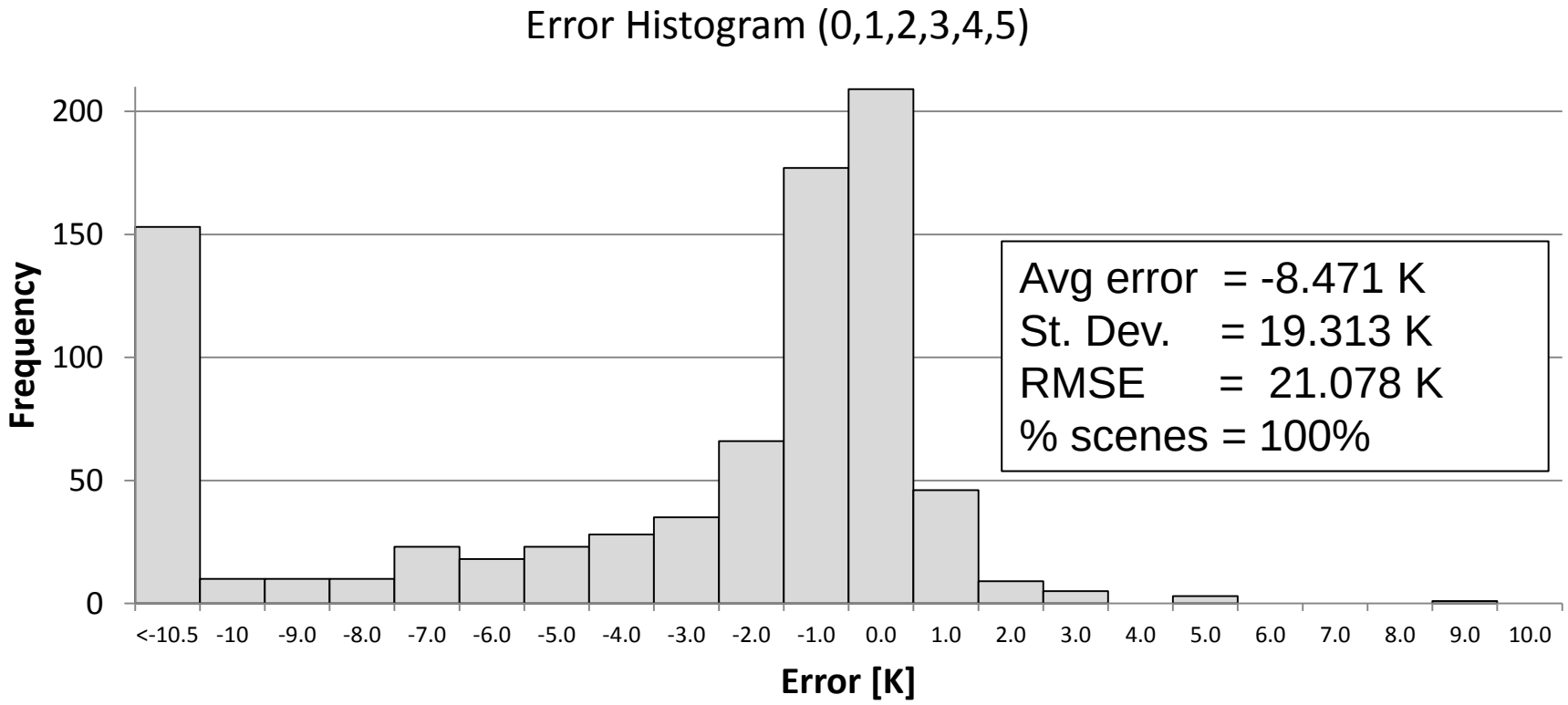
- Landsat 5, North American Scenes
  - 9 sites, 259 cloud free scenes
  - 9 sites, 827 scenes with varying types/amounts of clouds

Cloud Analysis

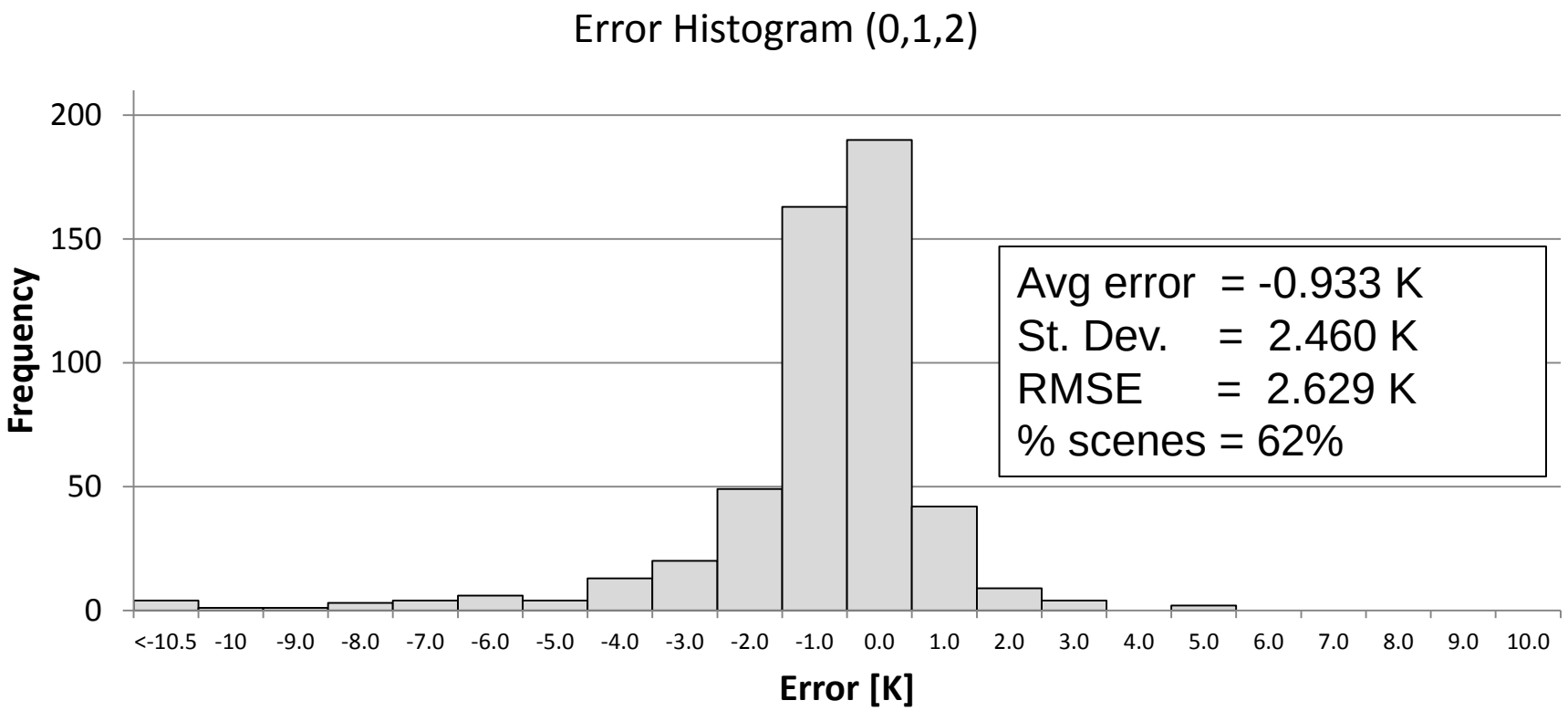


Category	Meaning
0	Cloud free around buoy
1	Cumulus in vicinity
2	Cirrus in vicinity
3	Cumulus over buoy
4	Cirrus over buoy
5	Cloud-covered scene

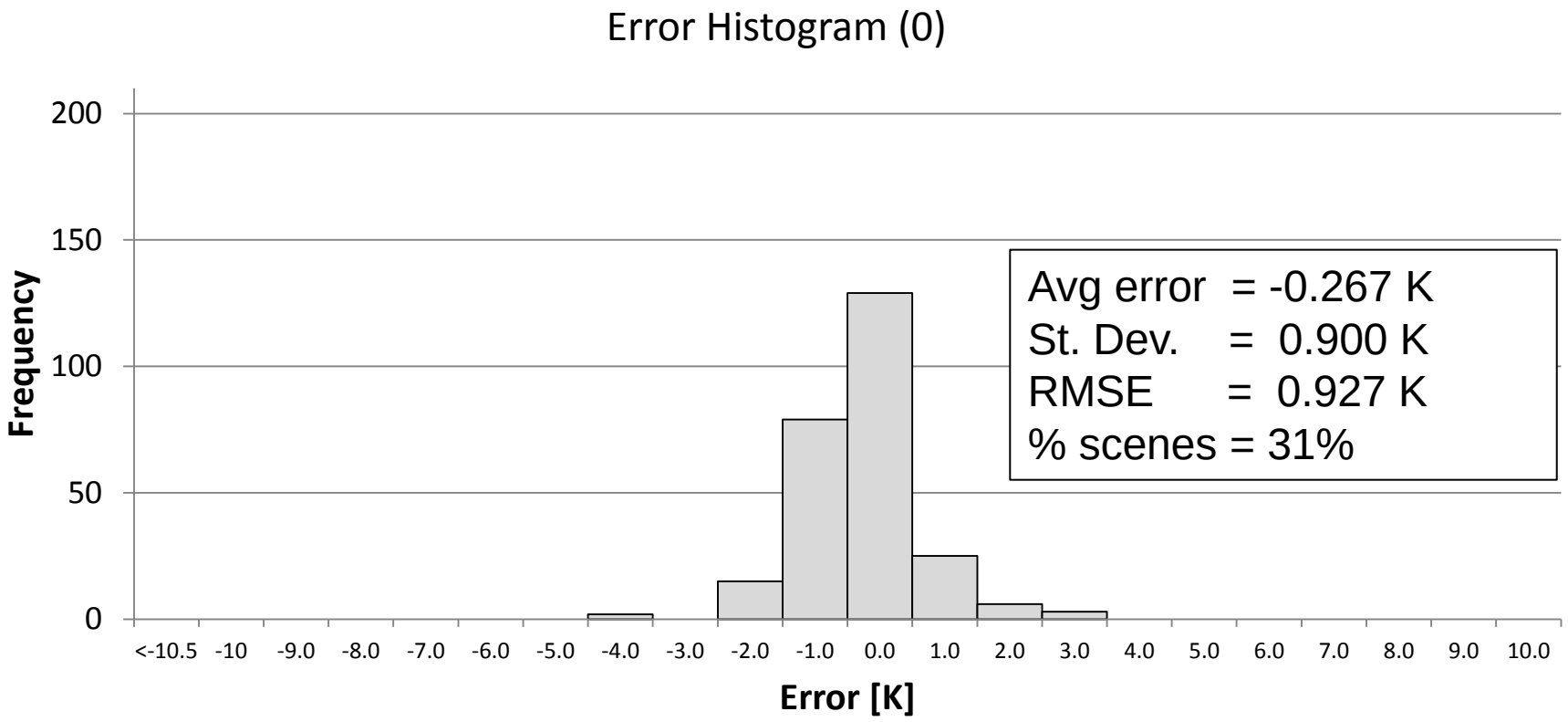
All Cloud Types (826 scenes)



"Clear and Near" Cloud Types (515 scenes)

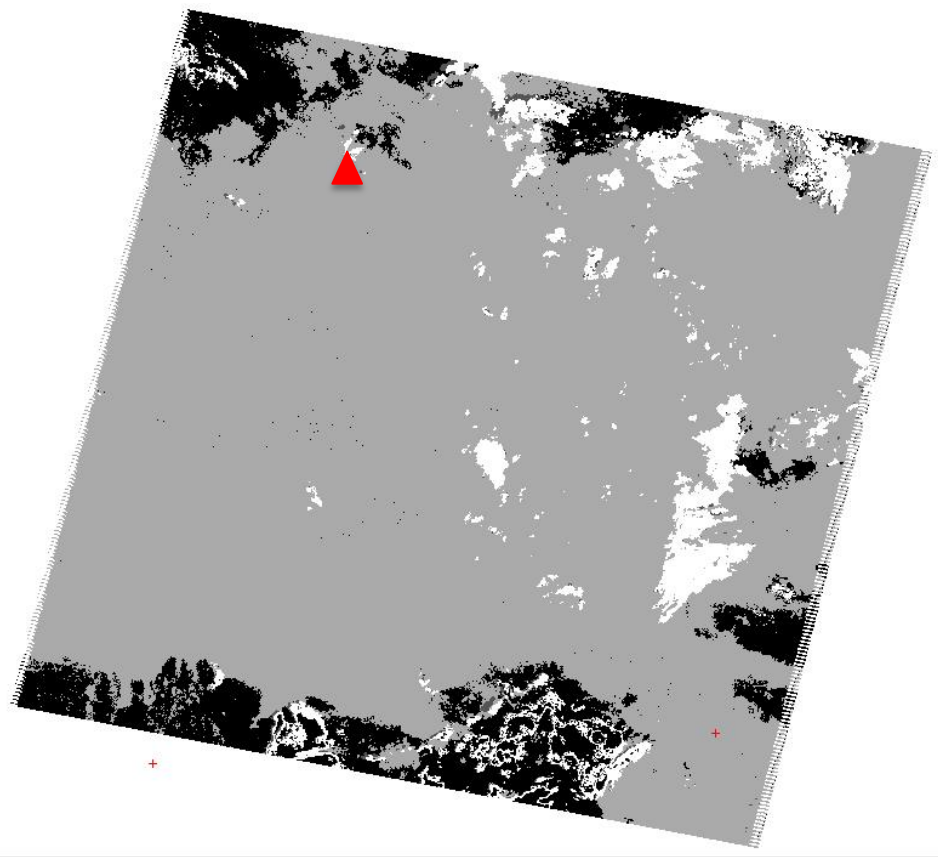


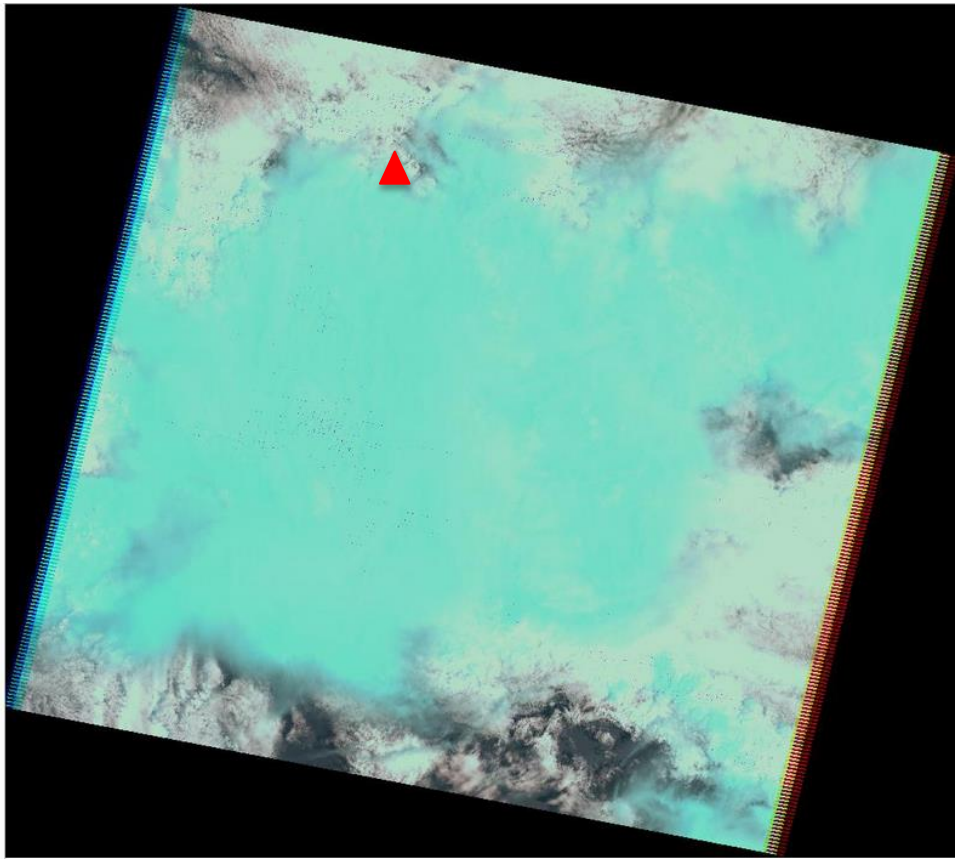
Cloud Free Scenes (259 scenes)



Cloud Mask Failure

Distance to cloud = 2.84 km
Error = -93.1886 K

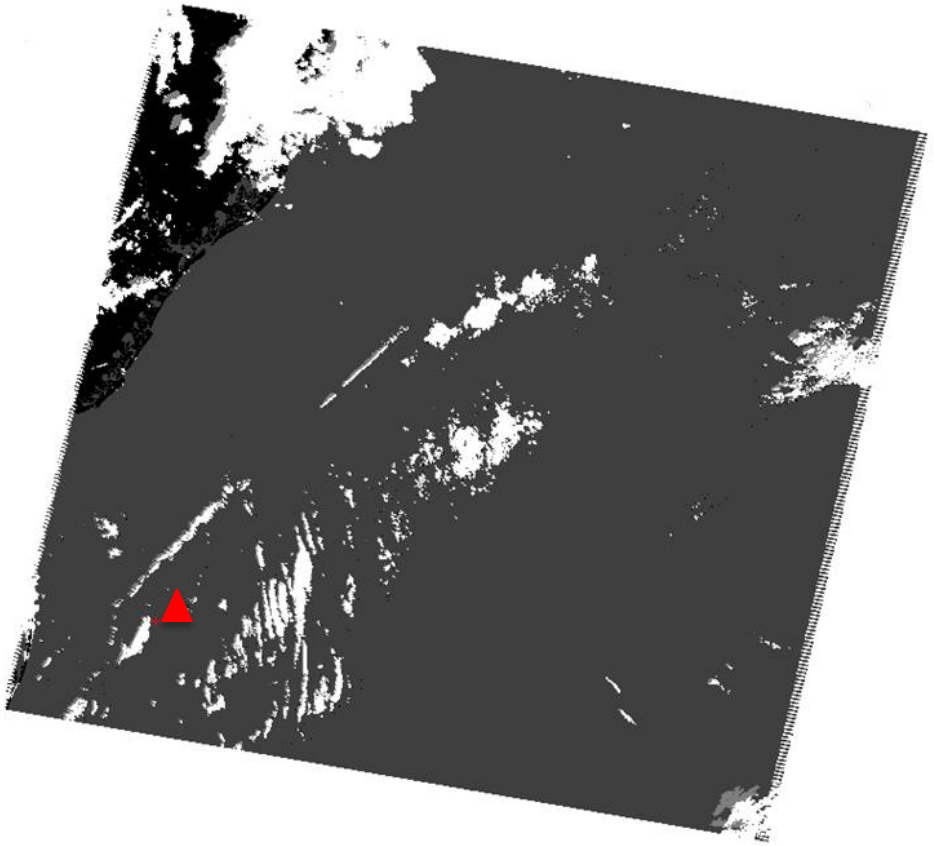




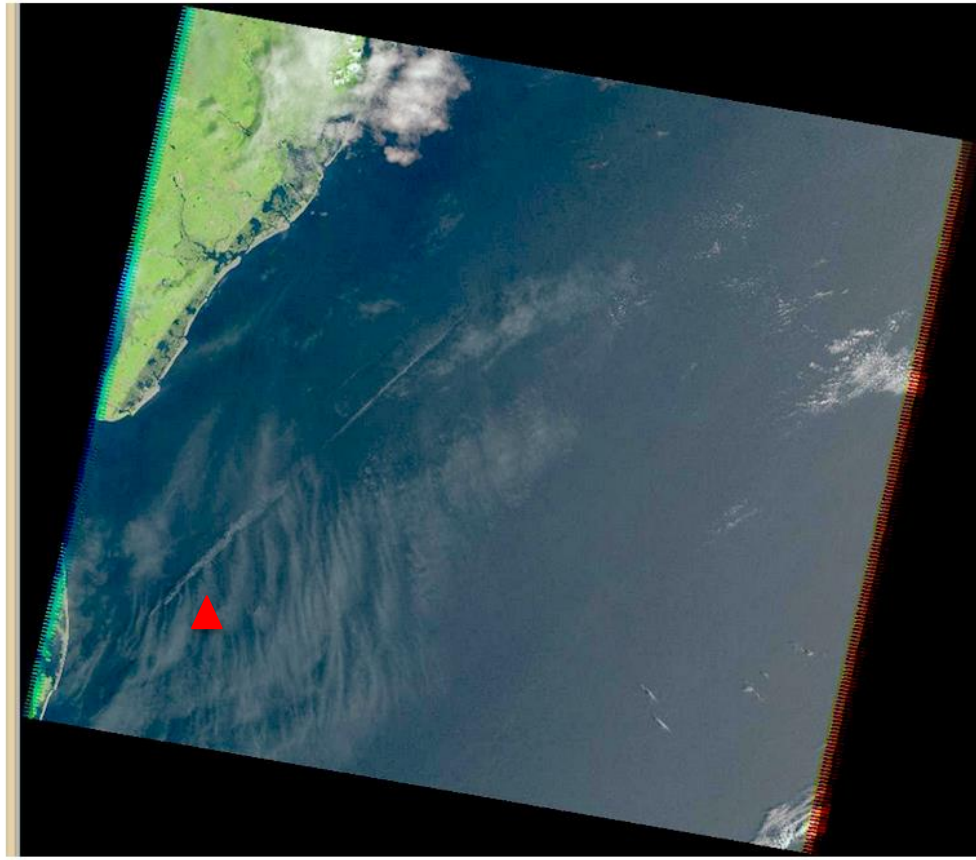
Cirrus Clouds Causing Trouble

Distance to cloud = 1.02 km
Error = -16.34297 K

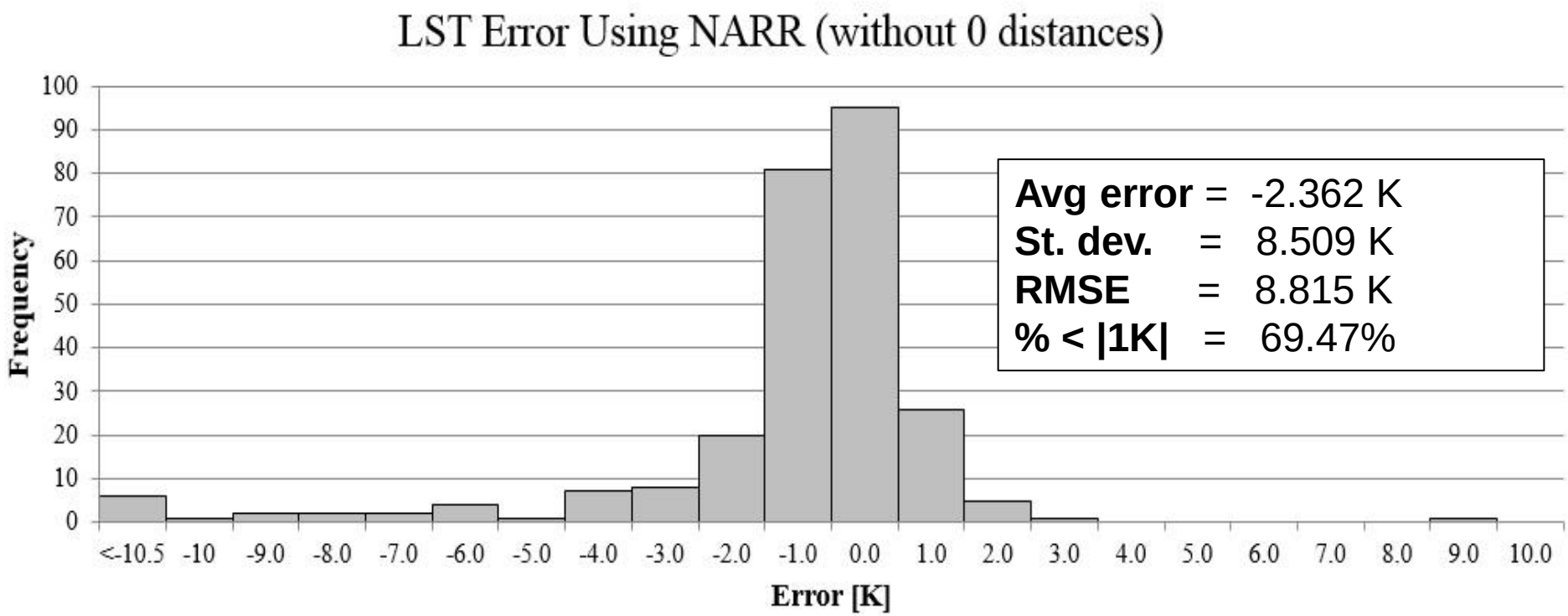
Cloud mask (clouds are white)



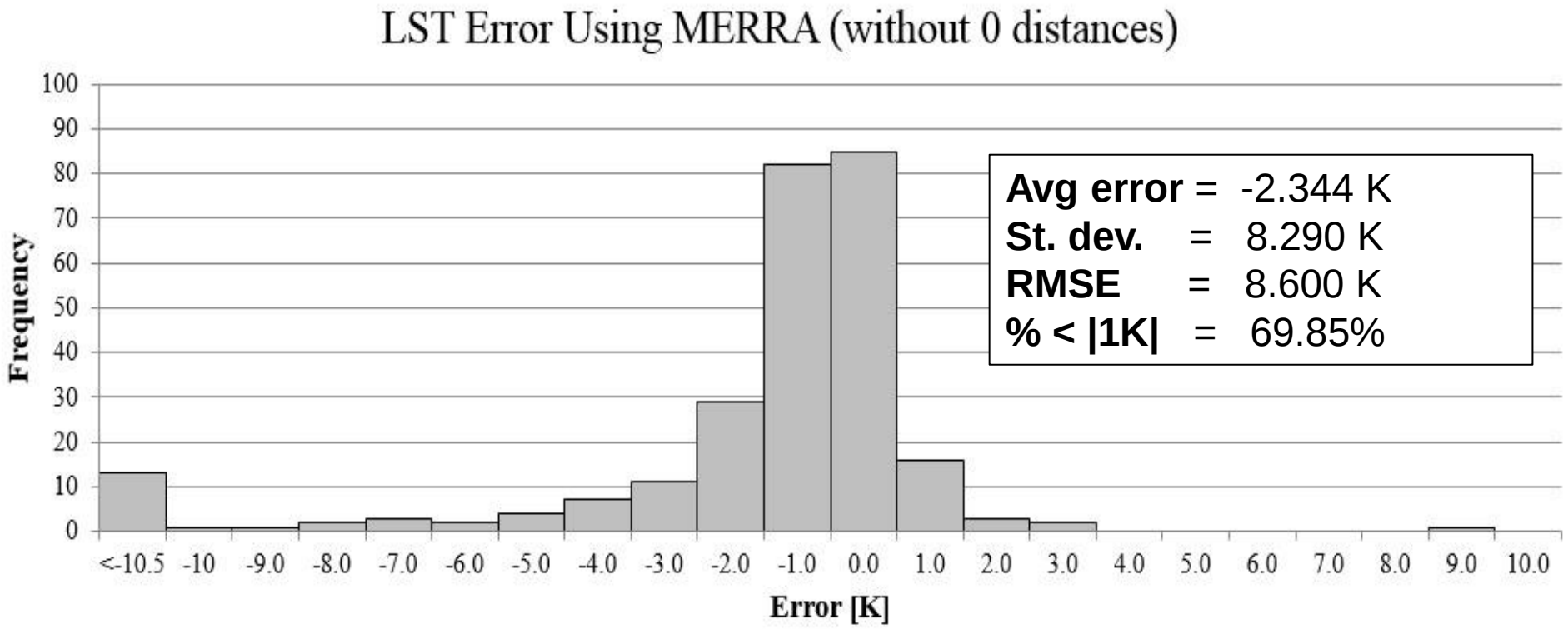
True color image (wispy cirrus)



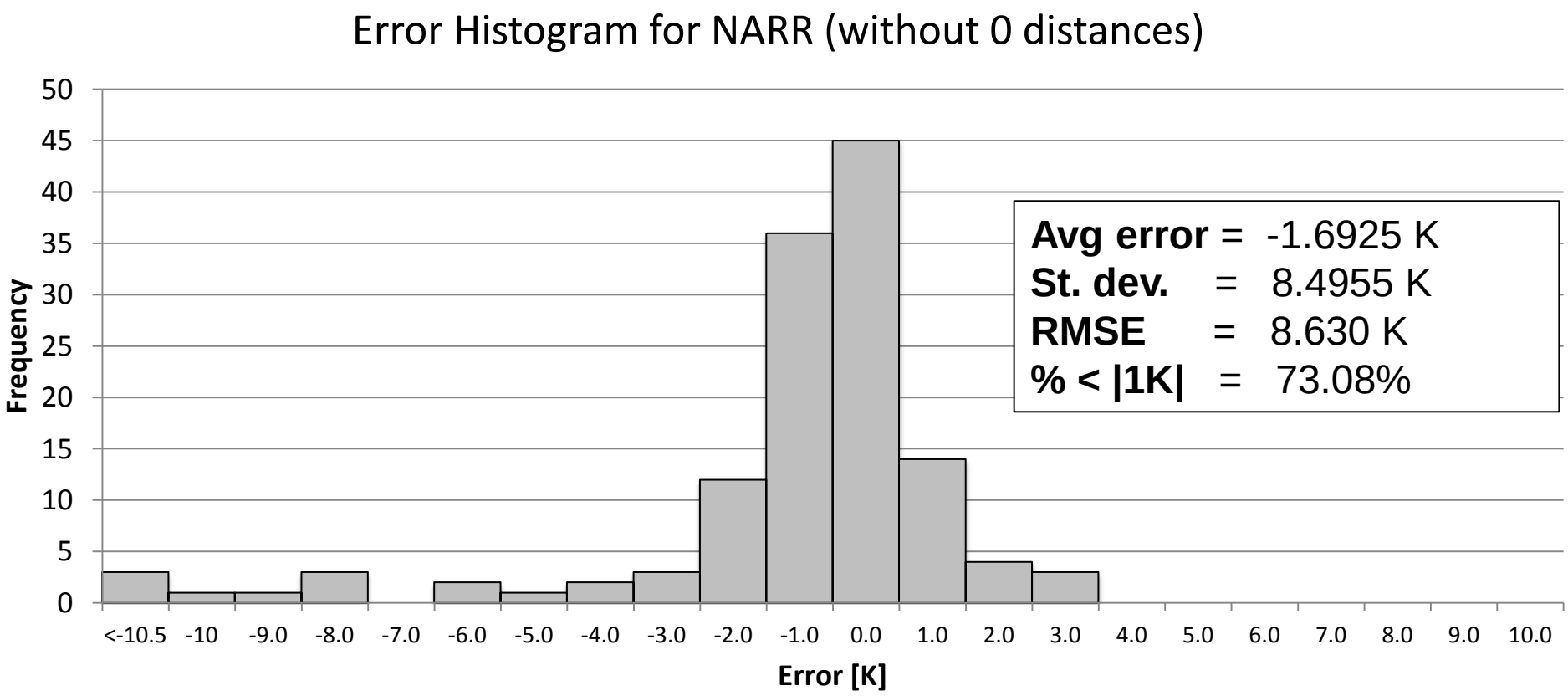
MERRA vs NARR (397 scenes)



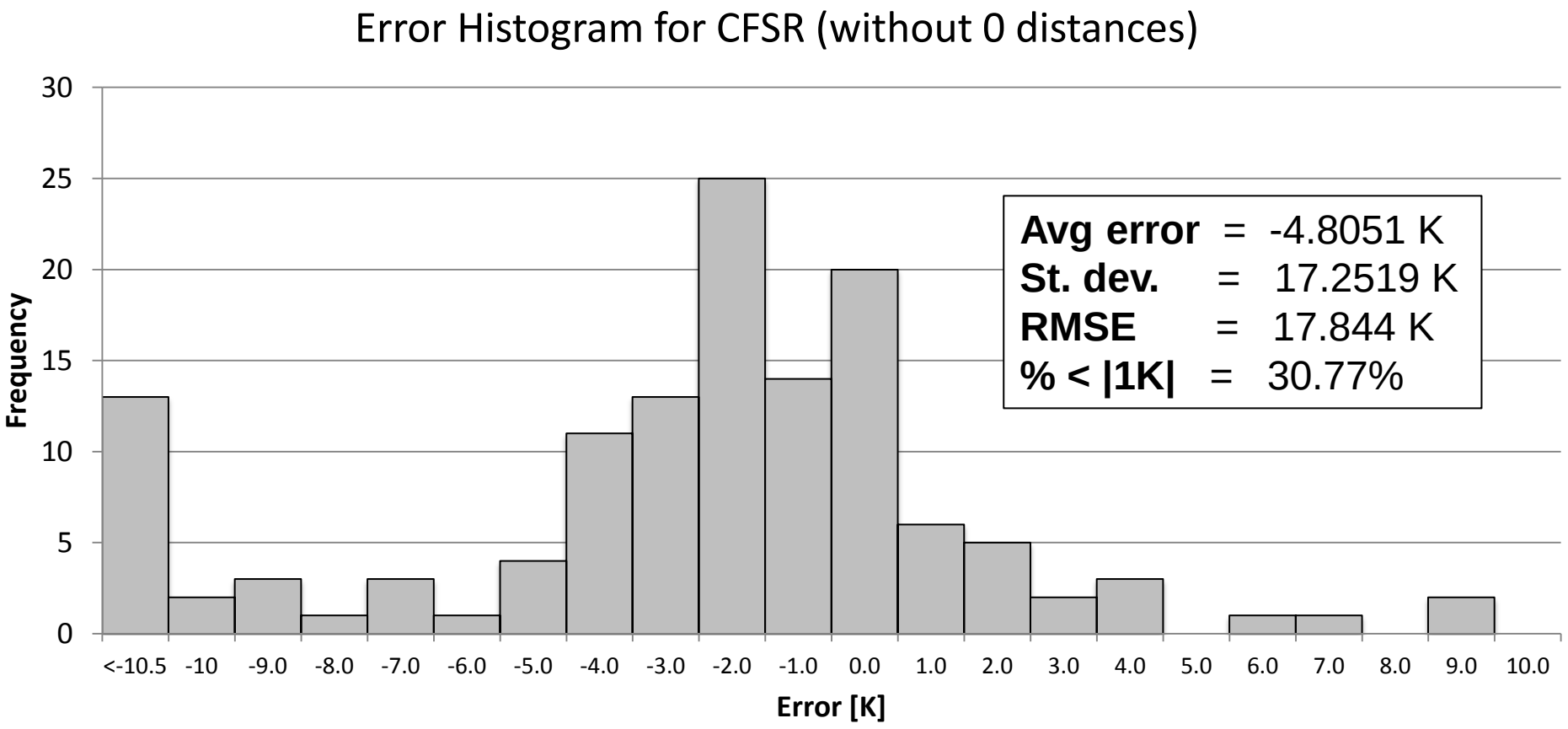
MERRA vs NARR (397 scenes)



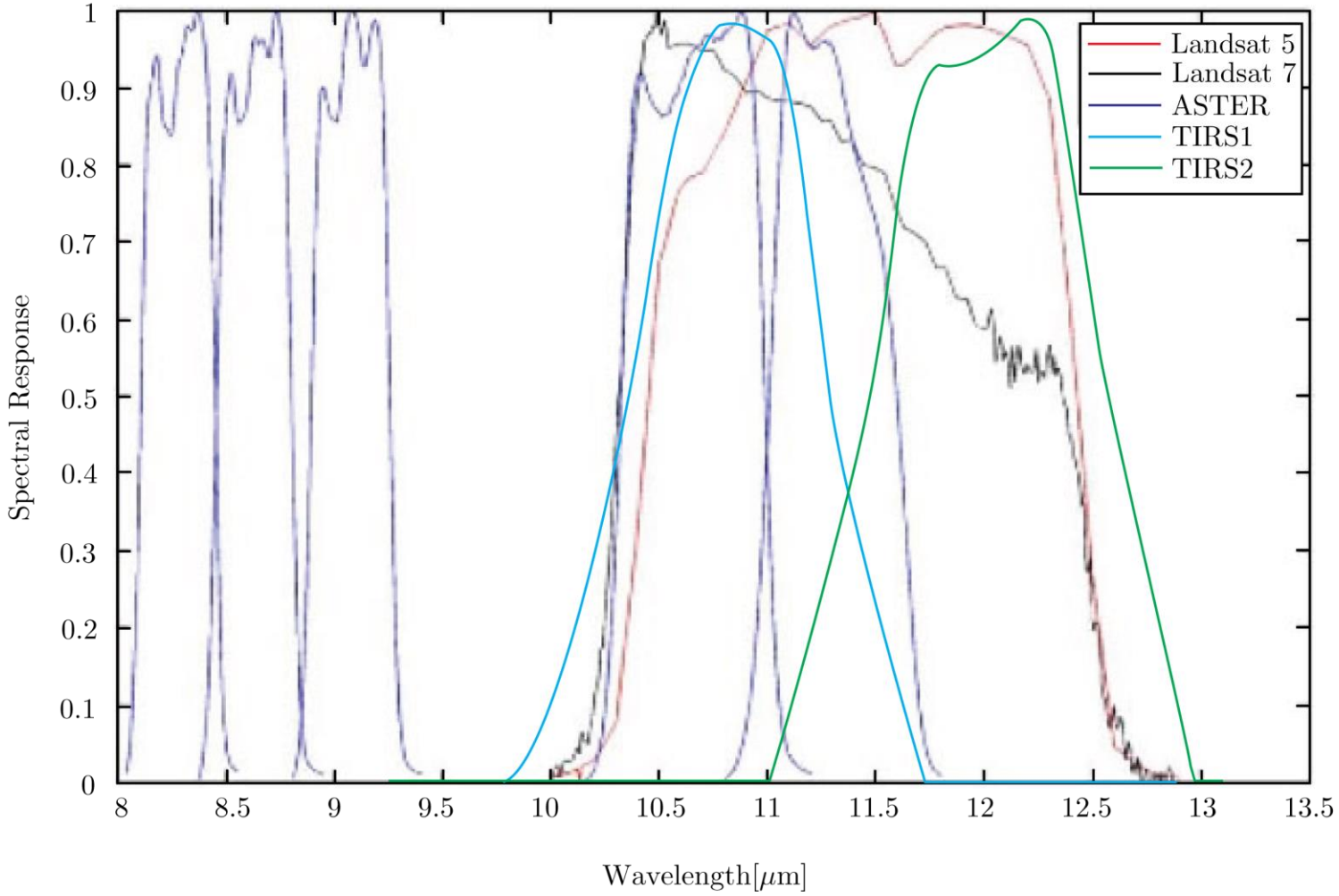
CFSR vs NARR (130 scenes)



CFSR vs NARR (130 scenes)

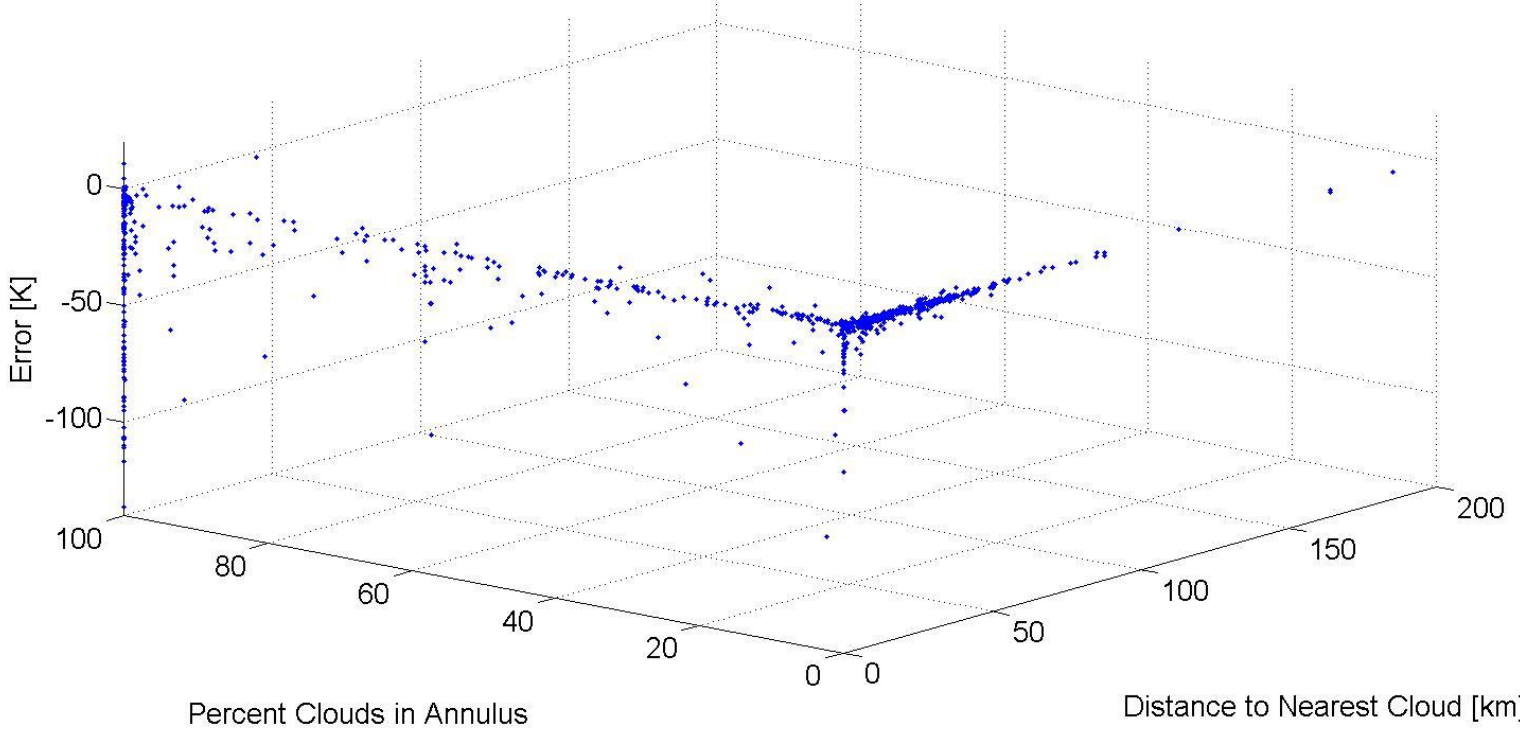


Spectral Response Functions TIRS and the Future



Initial Results

Distance to nearest cloud
vs
Percent clouds within 5 km annulus
vs
LST error

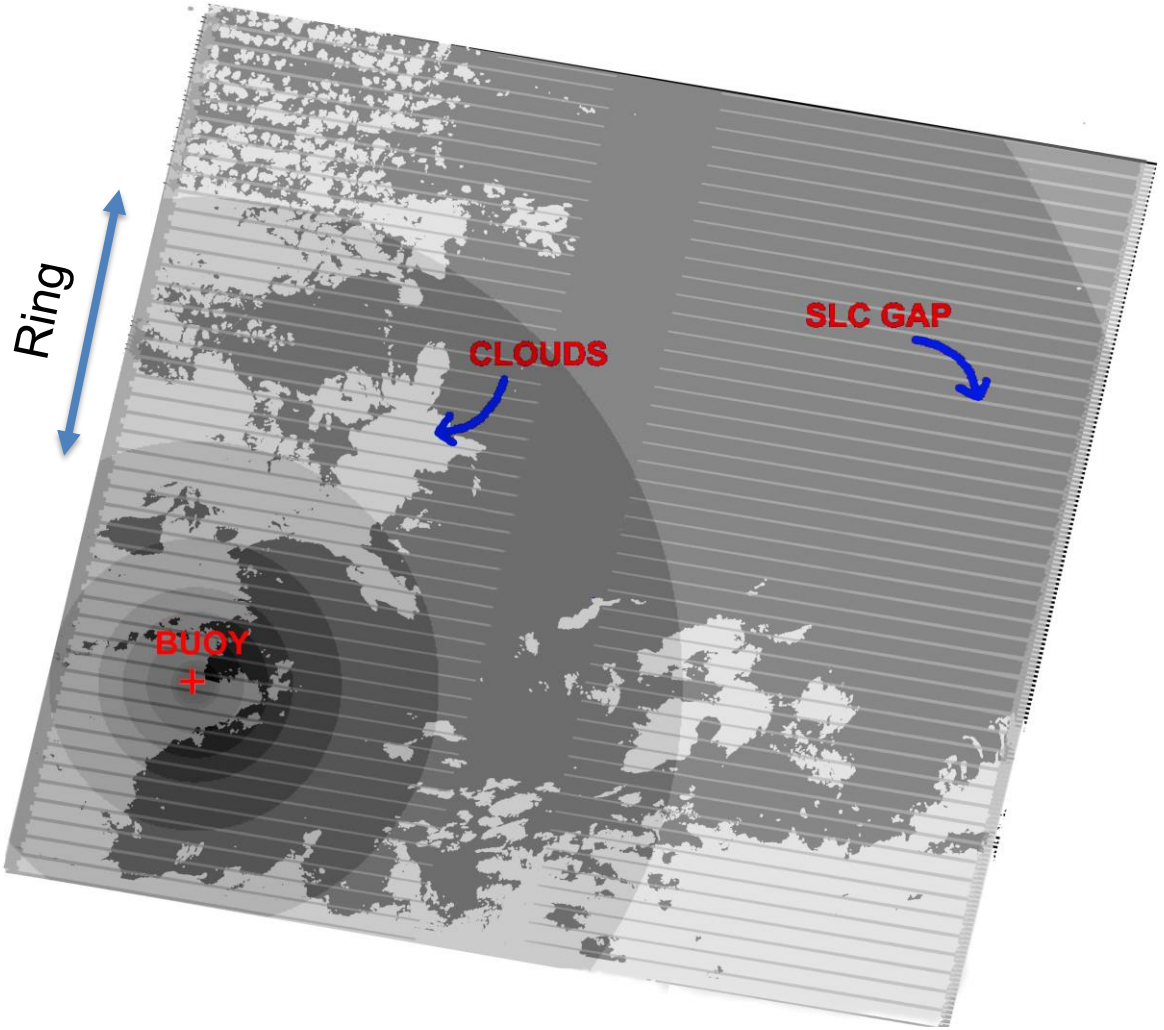


Cloud Summary & Steps Forward

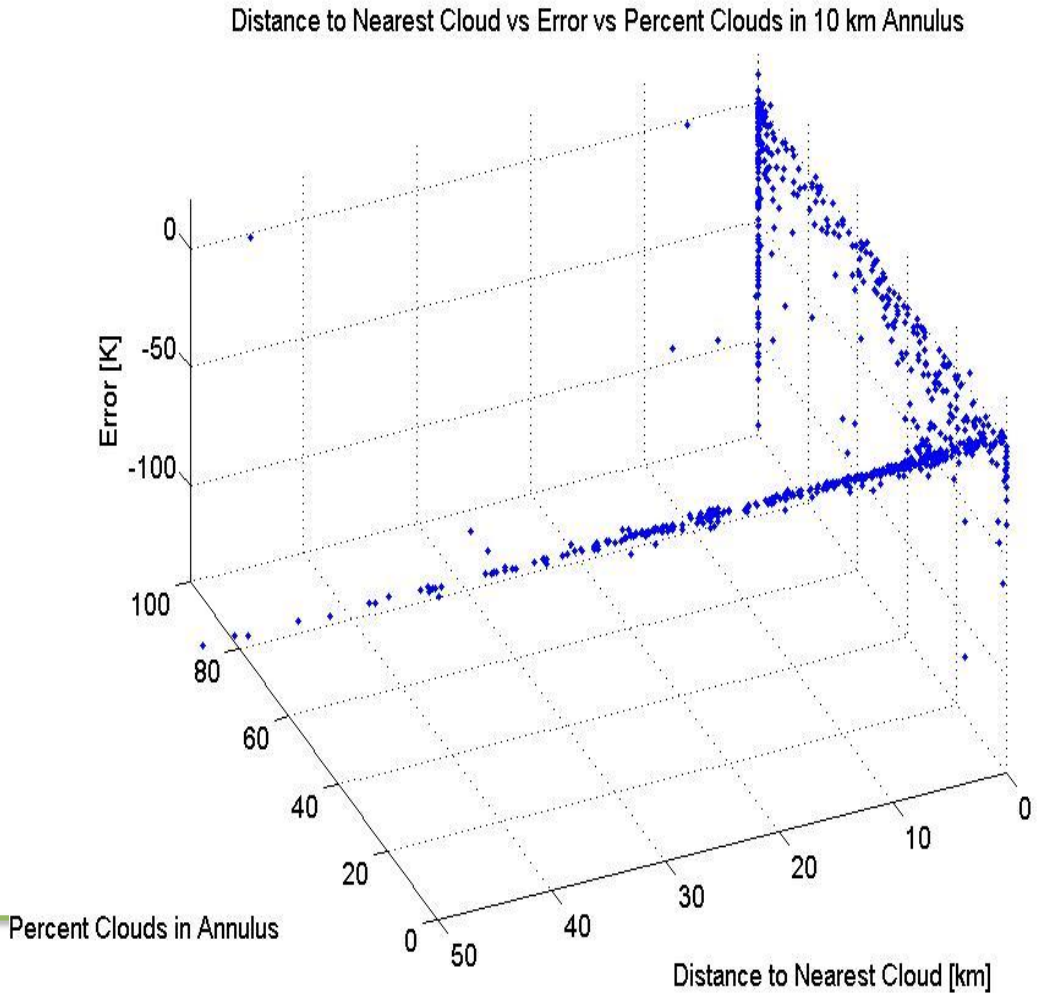
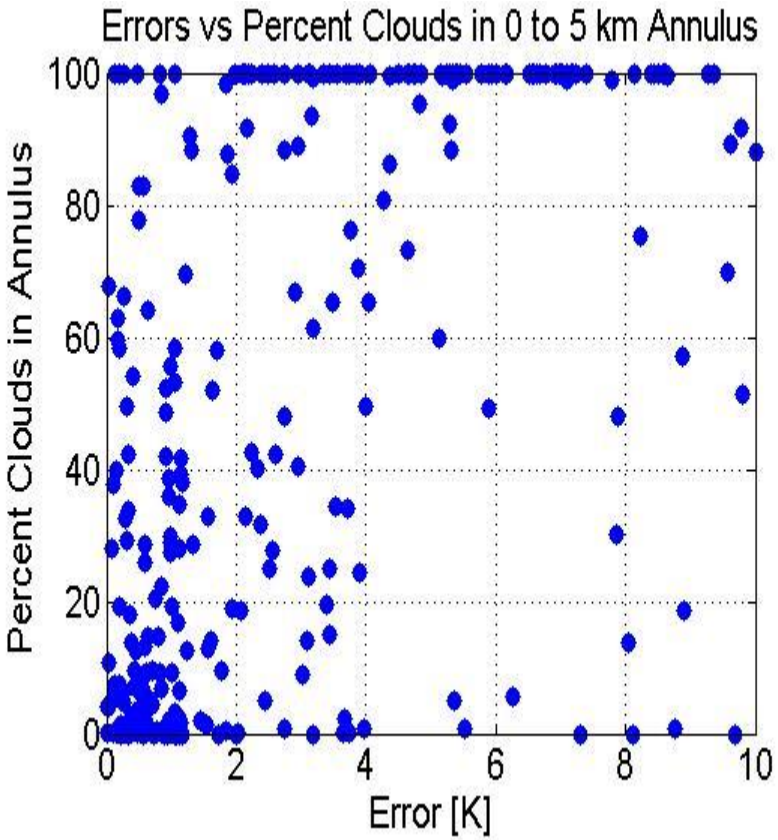
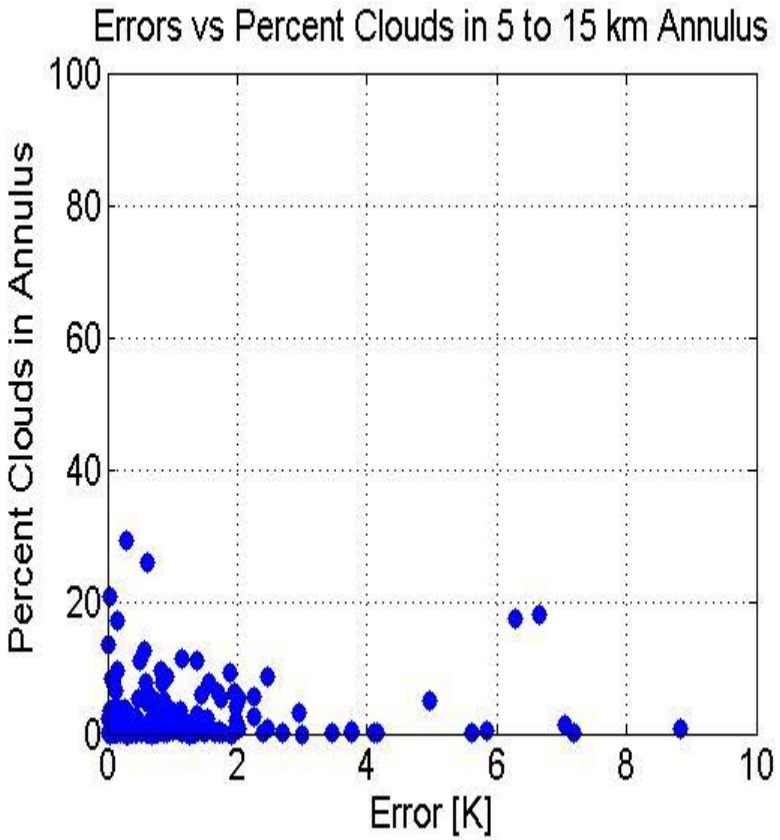
- Distance to nearest cloud method showed a general trend between cloud proximity and LST error
- This may not be the best method (doesn't consider the amount of clouds nearby)
- One option is to look at the fraction of clouds in "ring" areas around the buoy (see next slide)

“Clouds in Rings” Method

- Each scene has an error associated with it (at the buoy location)
- For each ring of a defined size, calculate the percent of pixels that are clouds
- Observe relationship between rings, cloud coverage, and error.



All data, reversed x-axis



Errors vs percent clouds in different rings