

UNIVERSITY  
of HAWAII®  
MĀNOA

# Cross-Sensor Continuity Science Algorithm

- NASA MEaSURES VI and Phenology ESDRs -

**Tomoaki Miura and Javzan Tsend-Ayush**

**Alex Dale (M.S. Graduate Student)**

**Joshua Turner (Federal Work Study Student)**

Department of Natural Resources and Environmental Management  
University of Hawaii at Manoa



# The Goal of the Algorithm

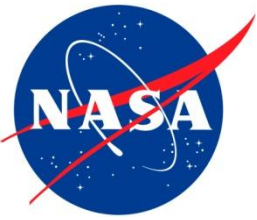


UNIVERSITY  
of HAWAI'I  
MĀNOA

- ▶ To translate NDVI and EVI2 to ensure their continuity across sensors (AVHRR – MODIS – VIIRS)
- ▶ Accounting for biases or discontinuity among sensors due to differences in:
  - ▶ Sensor characteristics
  - ▶ Product generation algorithms
- ▶ Estimating uncertainties

$$NDVI_{MOD} = f_{MOD \leftarrow AVH}^{NDVI} (NDVI_{AVH})$$

$u(NDVI_{MOD})$  and/or  $\pm 95\%$  Prediction Interval



# Factors Affecting Cross-Sensor Continuity & Considered in Science Algorithm



UNIVERSITY  
of HAWAII  
MĀNOA

1. Spectral bandpass
2. Spatial resolution
  - ▶ Point spread function
  - ▶ Scaling uncertainty
  - ▶ GAC vs. CMG
3. Algorithm
  - ▶ Atmospheric correction
  - ▶ Radiometric calibration
  - ▶ (Cloud mask)
4. Geometry
  - ▶ Mis-registration
  - ▶ Pixel deformation
  - ▶ Overpass time
  - ▶ (Sun-target-view geometry)

*\* To understand and model how these factors affect cross-sensor relationships*

(Swinnen and Veroustraete, 2008)



# Previous Studies



UNIVERSITY  
of HAWAI'I  
MĀNOA

## ▶ Empirical approaches

1. Weighted averages of two or more spectral bands (Gao, 1992; Gitelson and Kaufman, 1998;)

▶ Degrading MODIS by re-introducing water vapor absorptions

2. Polynomials

▶ 1st-order

- Hyperspectral data (Steven et al., 2003; van Leeuwen et al., 2006)
- Actual MODIS-AVHRR data (Gallo et al., 2005; Ji et al., 2008):
  - Land cover dependent

▶ 2nd-order

- Hyperspectral data (Trishchenko et al., 2002; Miura et al., 2006; Trishchenko, 2009):
  - "Spectral corrections" applied to actual data (e.g., Swinnen & Veroustraete, 2008)
- Actual MODIS-AVHRR data
  - Single, land cover independent

▶ Theoretical approach (Yoshioka et al., 2003; 2005; 2006; Miura et al., 2008)

▶ Pade approximation to polynomials



# Science Algorithm – Two Approaches



UNIVERSITY  
of HAWAII  
MĀNOA

- I. **Top-down, direct image comparison using overlapping period of observation**  
(Javzan Tsend-Ayush & Alex Dale)
  - ▶ Derivation of multi-sensor translation equations
  - ▶ Development of an evaluation methodology
  
- II. **Bottom-up, simulation analysis using hyperspectral imagery** (Tomoaki Miura & Joshua Turner)
  - ▶ Derivation of multi-sensor translation equations
  - ▶ Characterization of factorial effects, error budgets

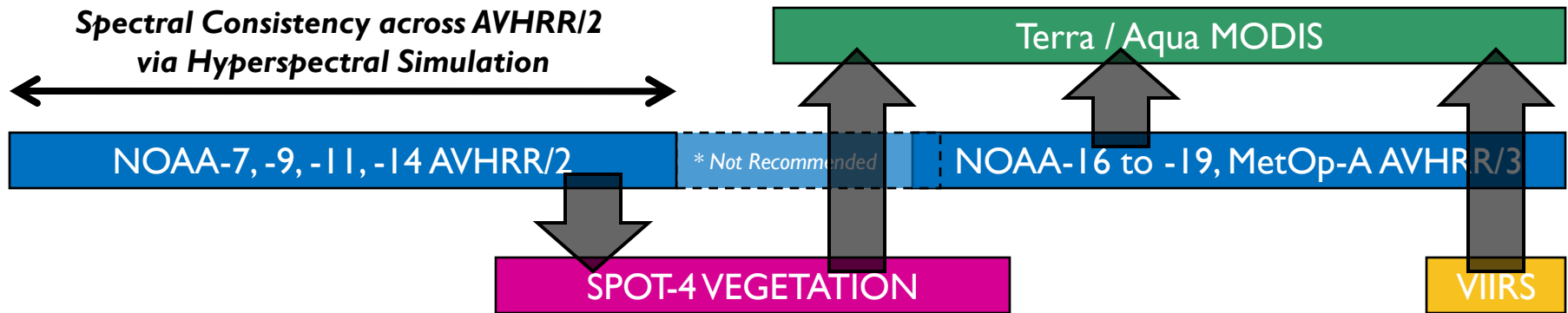


# Science Algorithm – Two Approaches

## I. Top-down, Direct Image Comparison



UNIVERSITY  
of HAWAII  
MĀNOA



- ▶ Actual observations of interest
- ▶ Global & full seasonal coverage
- ▶ Subtle details possibly neglected
- ▶ Overlapping period required
- ▶ Multiple-translations required

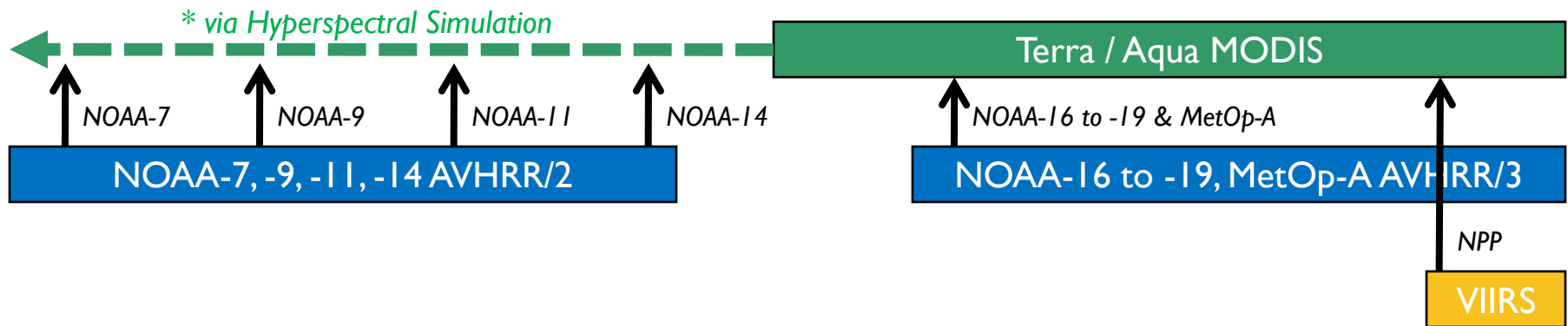


# Science Algorithm – Two Approaches

## II. Bottom-up, Hyperspectral Analysis



UNIVERSITY  
of HAWAII  
MĀNOA



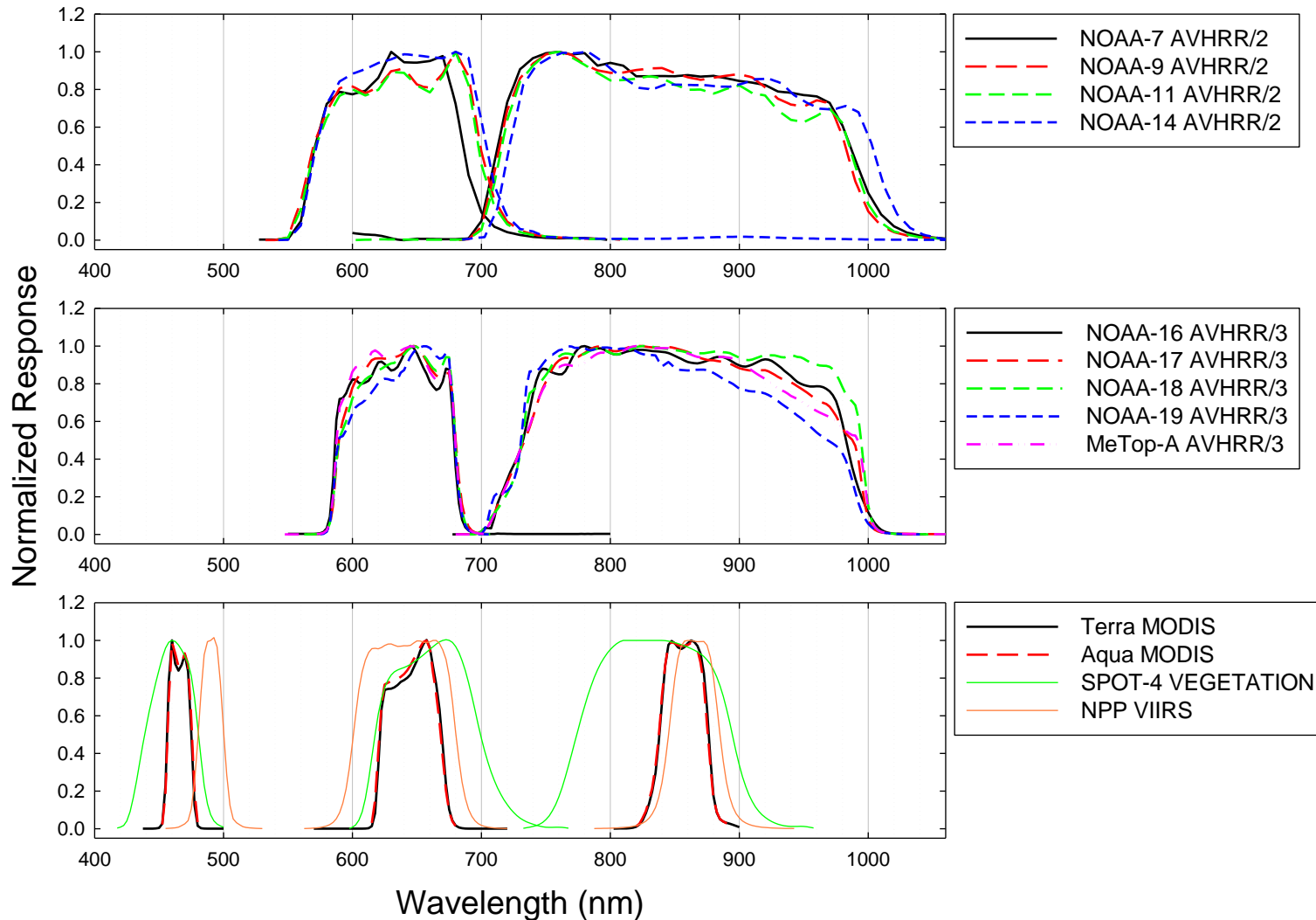
- ▶ Actual satellite observations
- ▶ Limited geographic and seasonal coverage
- ▶ Detail analyses possible for deepening understanding
- ▶ Overlapping period not required
- ▶ Only one translation required



# Normalized Spectral Responses



UNIVERSITY  
of HAWAII  
MĀNOA

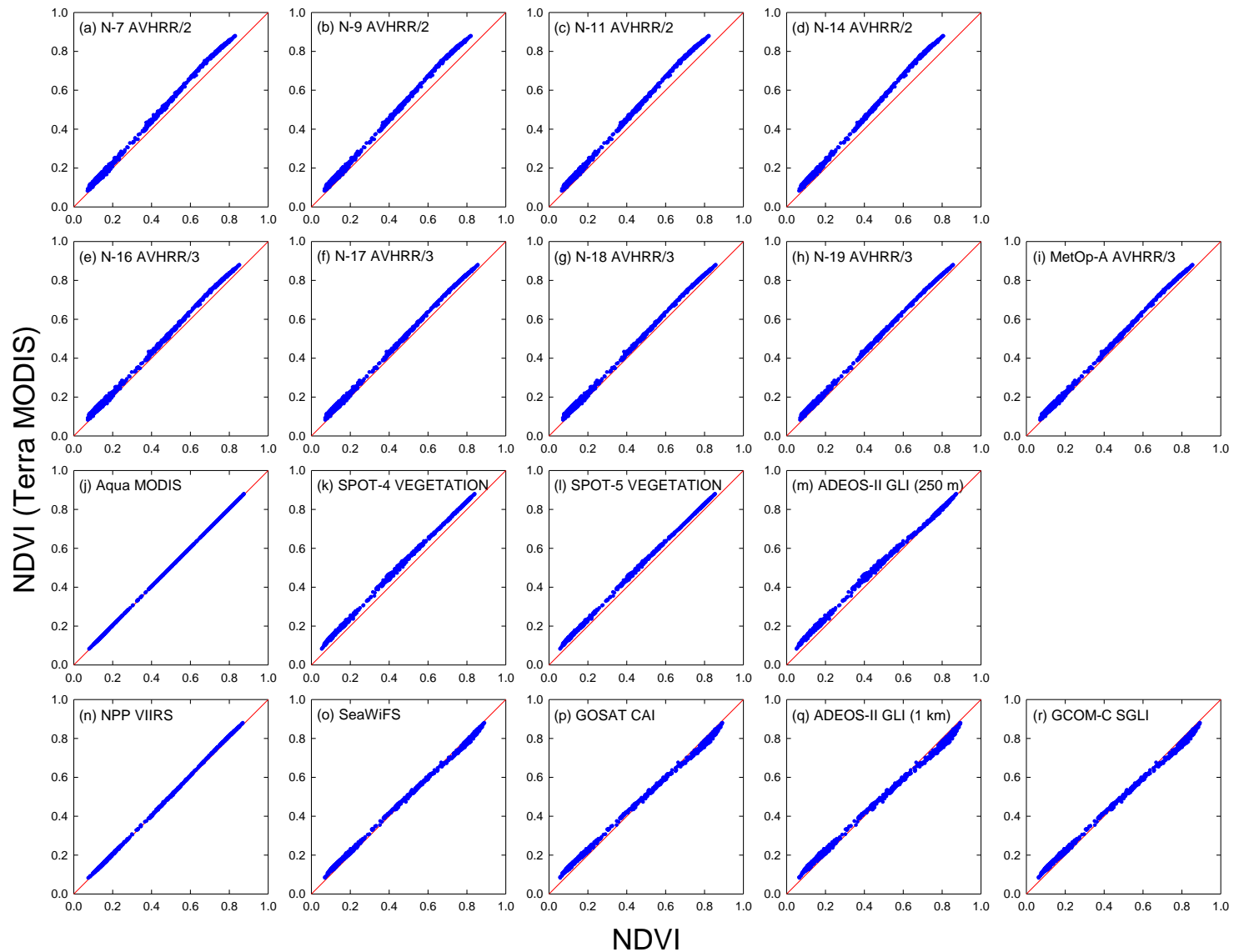


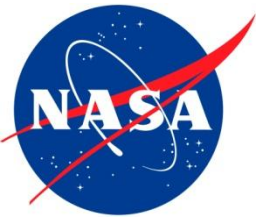


# Spectral Compatibility - NDVI

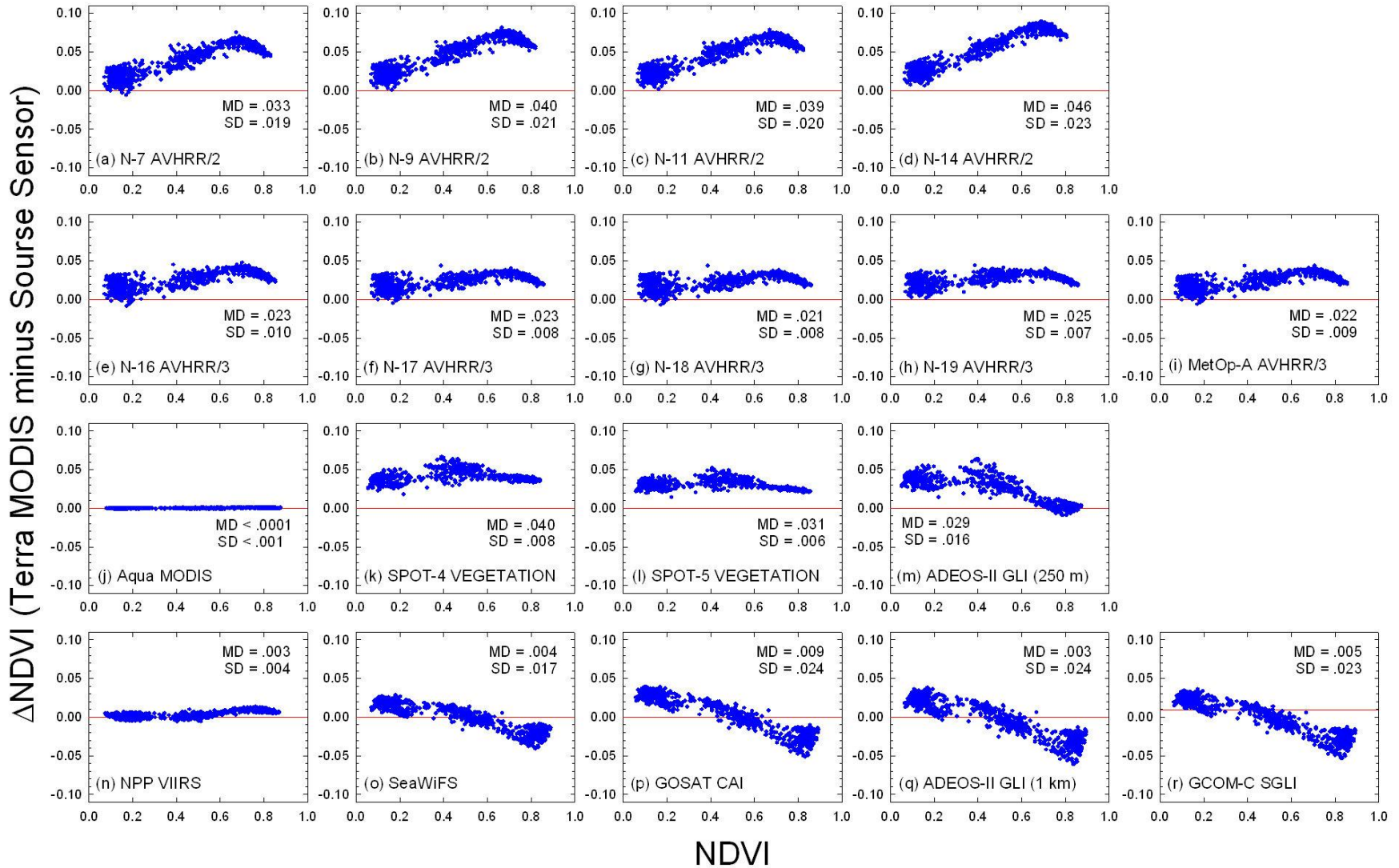


UNIVERSITY  
of HAWAII  
MĀNOA



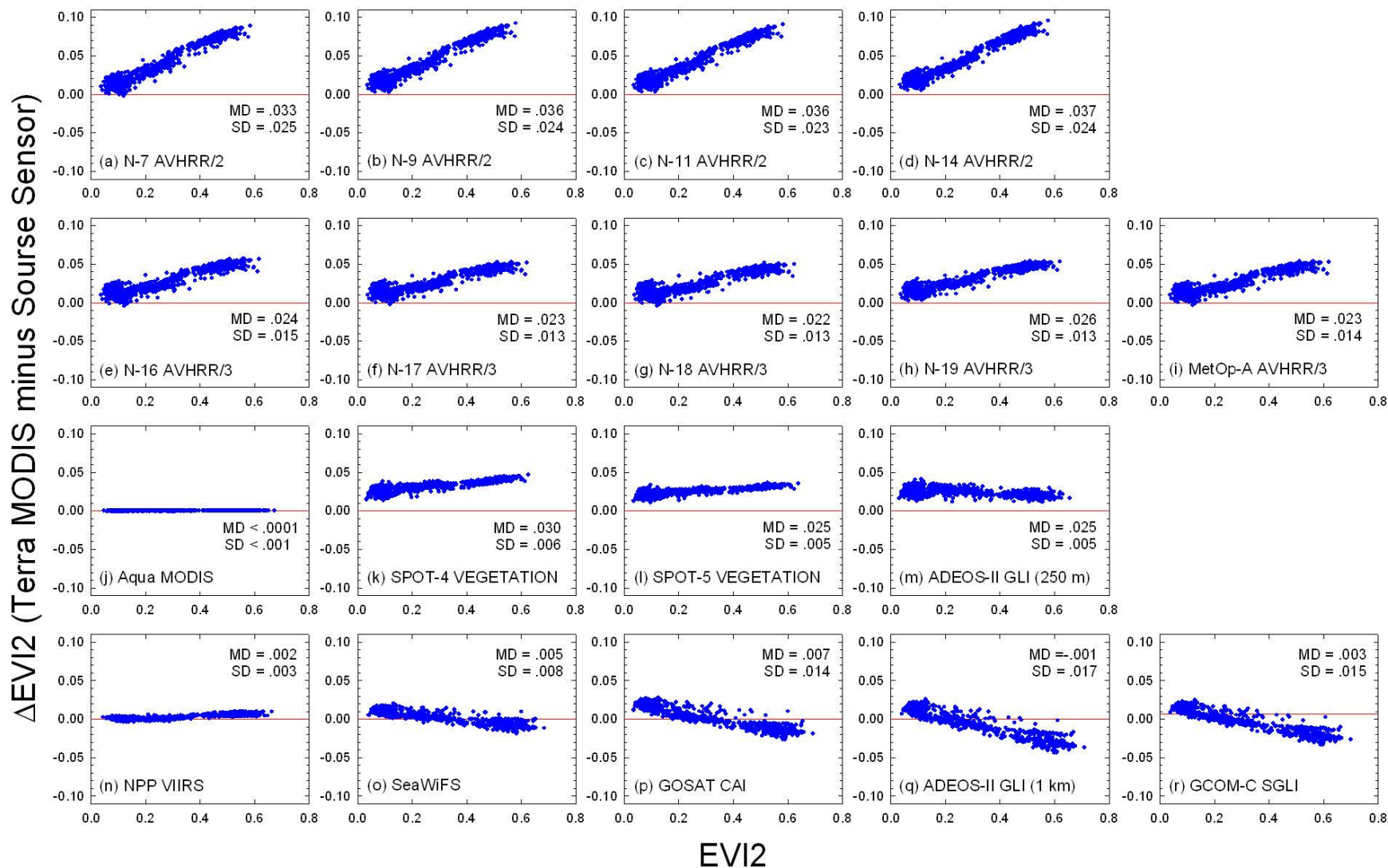


# Spectral Compatibility – NDVI





# Spectral Compatibility – EVI2



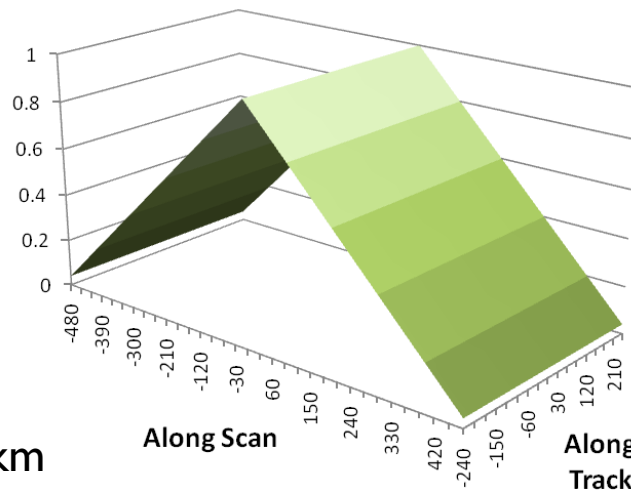


# Spatial Resolution & PSFs

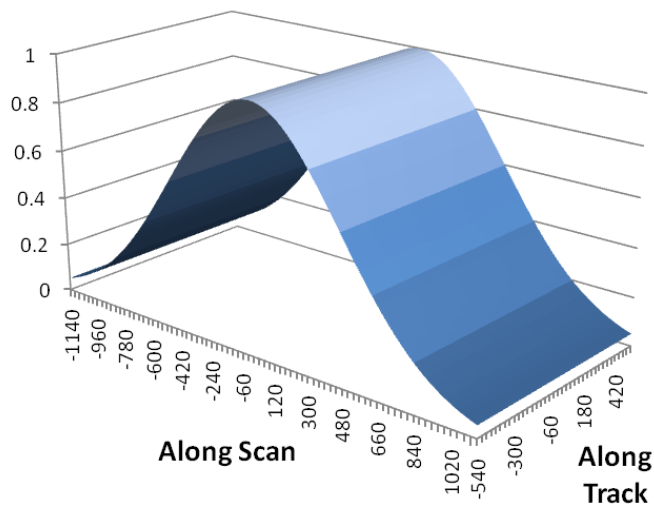


UNIVERSITY  
of HAWAII  
MĀNOA

**MODIS**  
250m, 500m

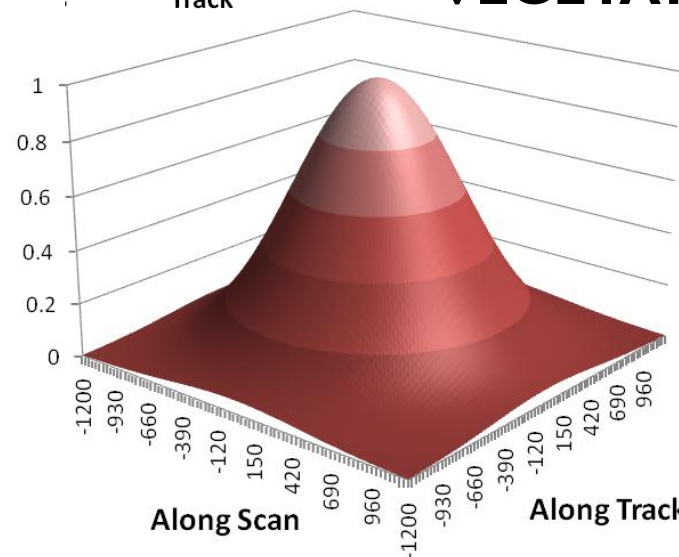


**AVHRR** 1.1 km



**VEGETATION**

1.15 km



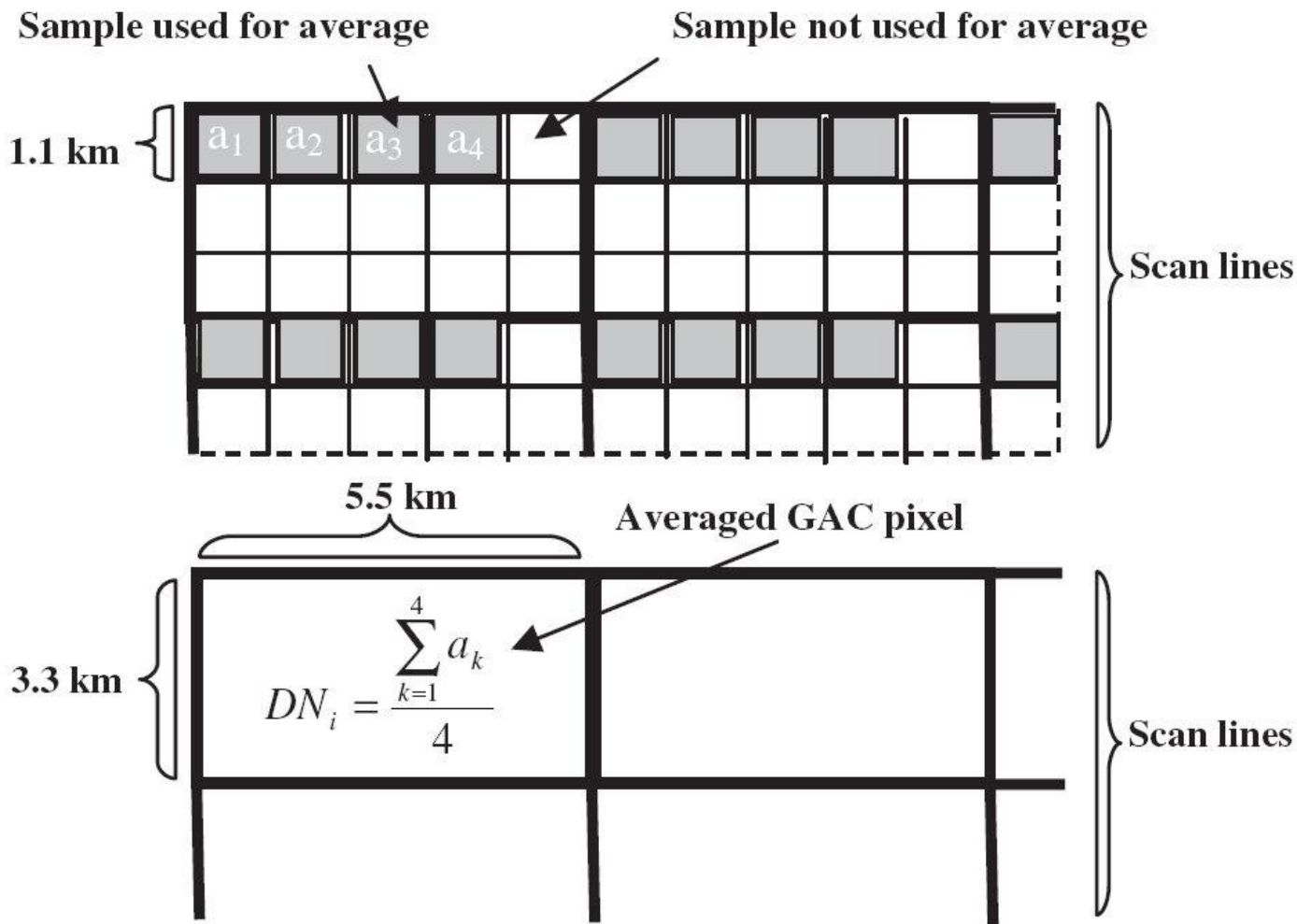
(Wolfe et al., 2002; Schowengerdt, 2006)



# Global Area Coverage Sampling



UNIVERSITY  
of HAWAII  
MĀNOA



(Pinheiro et al., 2006)



# Scaling Uncertainties between CMG and GAC Resolutions



UNIVERSITY  
of HAWAII  
MĀNOA

- ▶ MODIS CMG (5 km) vs. AVHRR GAC (4-by-1 km)
- ▶ Potentially different sensitivities to surface changes, i.e., whether a relationship for one resolution holds for another

MODIS CMG:

$$NDVI_{\text{coarse}} = \frac{\sum_{i=1}^n \rho_{\text{nir},i} - \sum_{i=1}^n \rho_{\text{red},i}}{\sum_{i=1}^n \rho_{\text{nir},i} + \sum_{i=1}^n \rho_{\text{red},i}} = \frac{\sum_{i=1}^n (\rho_{\text{nir},i} - \rho_{\text{red},i})}{\sum_{i=1}^n (\rho_{\text{nir},i} + \rho_{\text{red},i})}$$

AVHRR GAC (average of 5 GAC pixels):

$$NDVI_{\text{fine}} = \sum_{i=1}^n NDVI_i = \sum_{i=1}^n \left( \frac{\rho_{\text{nir},i} - \rho_{\text{red},i}}{\rho_{\text{nir},i} + \rho_{\text{red},i}} \right)$$

Scaling Error:

$$D \equiv NDVI_{\text{coarse}} - NDVI_{\text{fine}} \neq 0$$



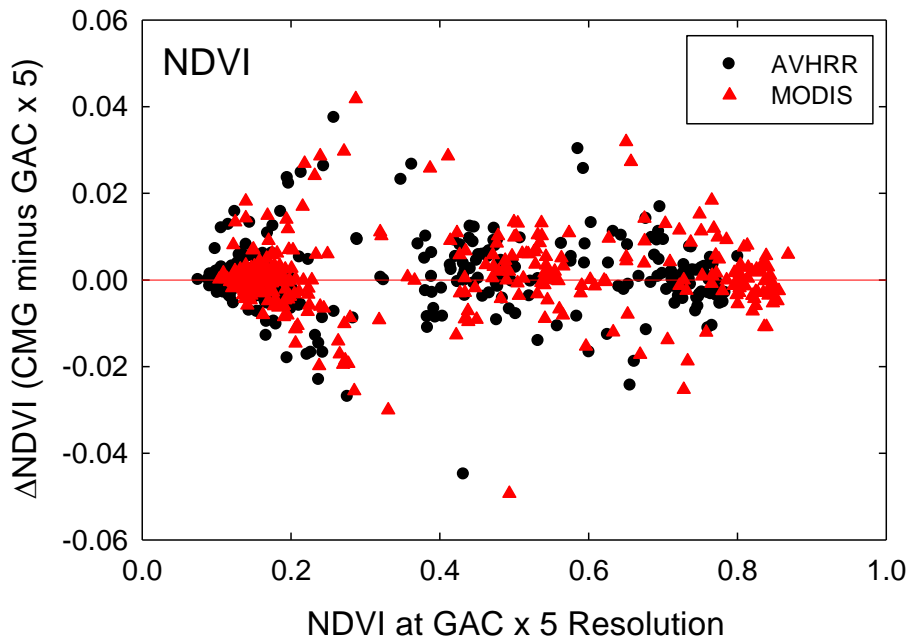


# Scaling Uncertainties between CMG and GAC Resolutions (cont.)



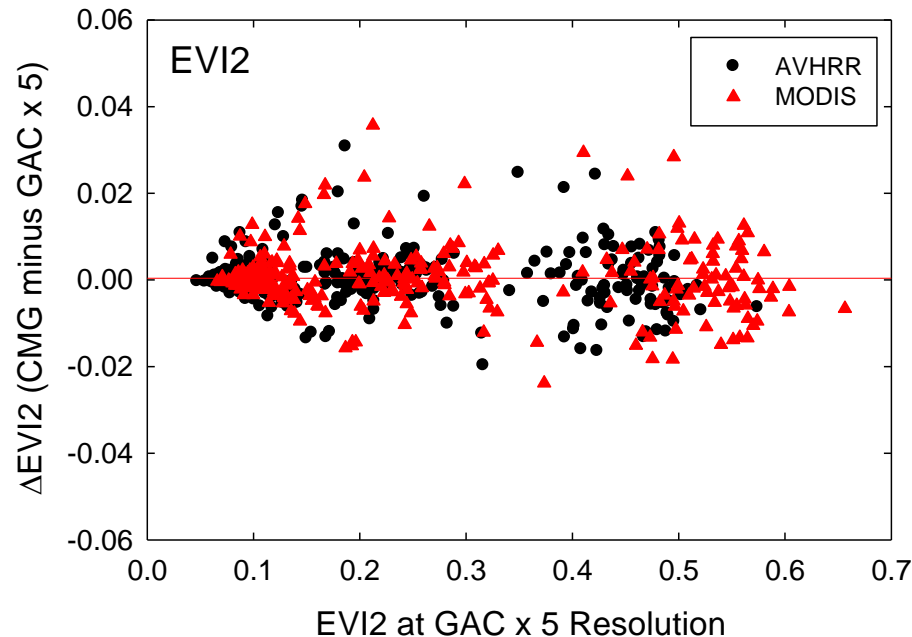
UNIVERSITY  
of HAWAII  
MĀNOA

NDVI



	AVHRR	MODIS
MD:	<.001	<.001
RMSE:	.008	.008
95% PI:	.015	.016

EVI2



	AVHRR	MODIS
MD:	<.001	<.001
RMSE:	.006	.007
95% PI:	.011	.013



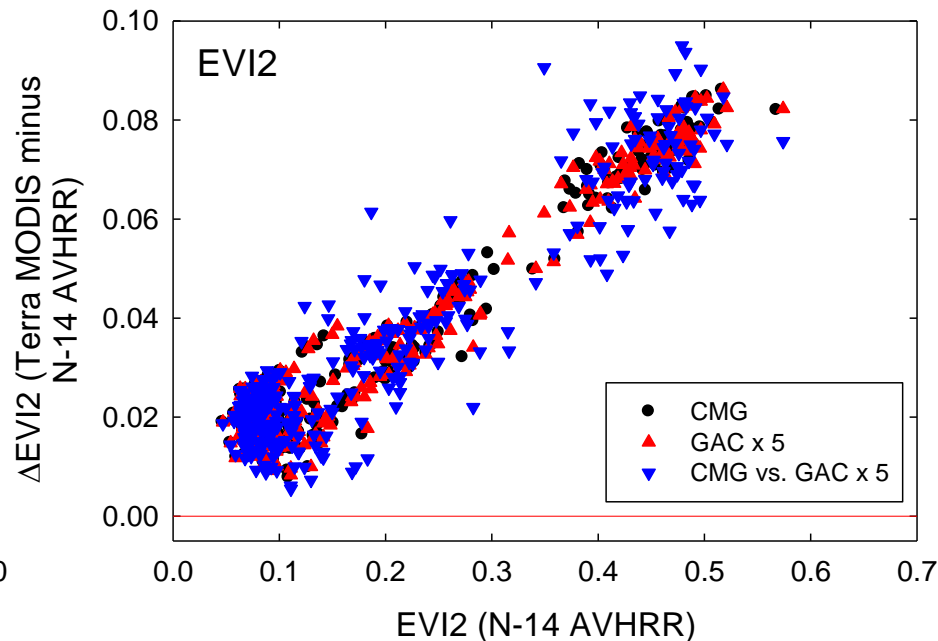
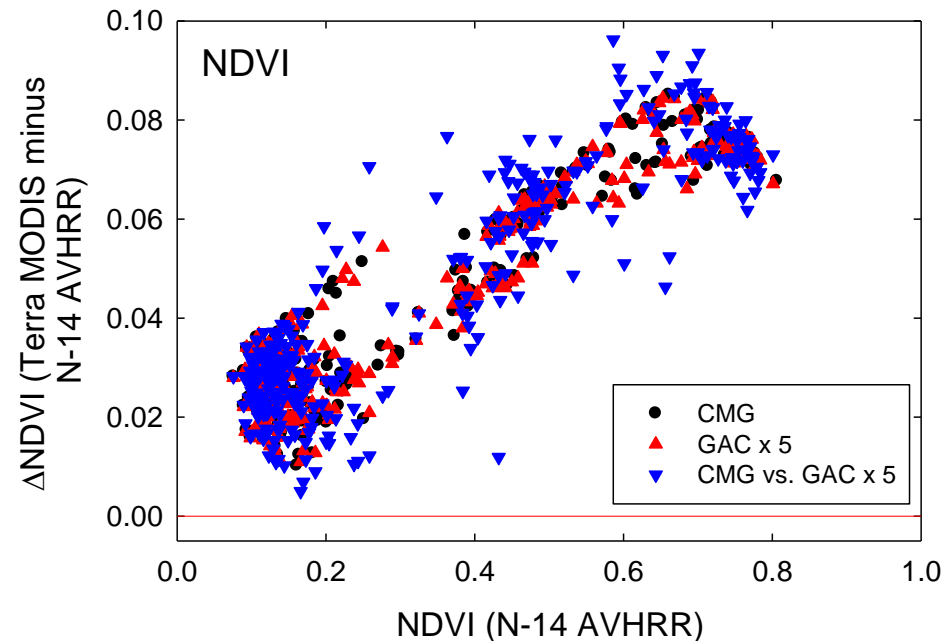
# Scaling Uncertainties between CMG and GAC Resolutions (cont.)



UNIVERSITY  
of HAWAII  
MĀNOA

NDVI

EVI2





# Algorithm Difference: Atmospheric Correction



UNIVERSITY  
of HAWAII  
MĀNOA

- ▶ One key algorithm difference that exists among products

Product Name	Atmospheric Correction Scheme
GIMMS AVHRR NDVI	TOA NDVI, but corrected for stratospheric aerosol effects
LTDR AVHRR Reflectance & NDVI	Partial correction for molecular scattering, ozone & water vapor absorptions, and stratospheric aerosol effects
MODIS NDVI & EVI	TOC NDVI & EVI
SPOT VEGETATION	TOC reflectance NDVI, but different atmospheric data sources and algorithms
NPP VIIRS Vegetation Indices	TOA NDVI & TOC EVI

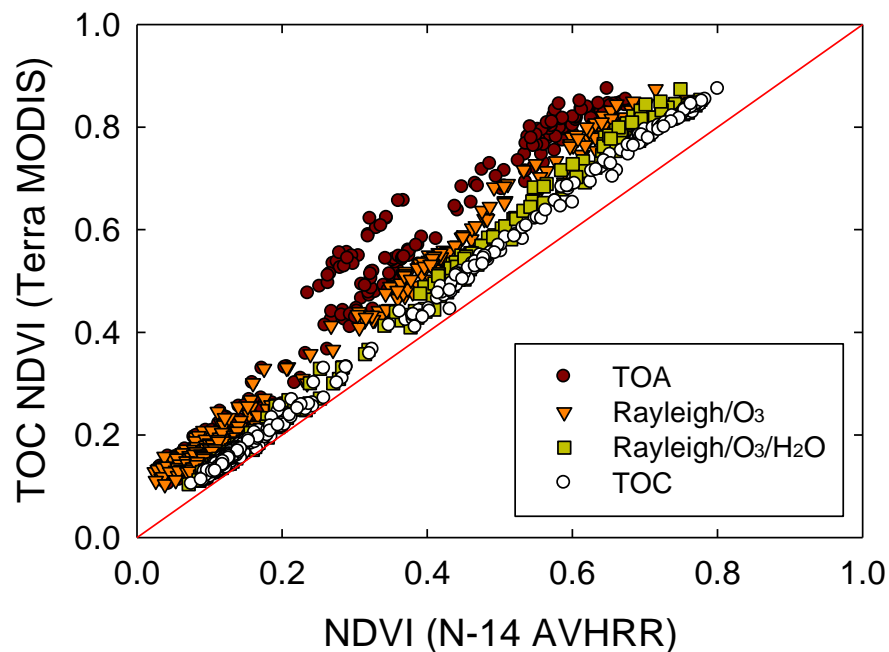


# NDVI Relationship under Various Atmospheric Correction Scenarios

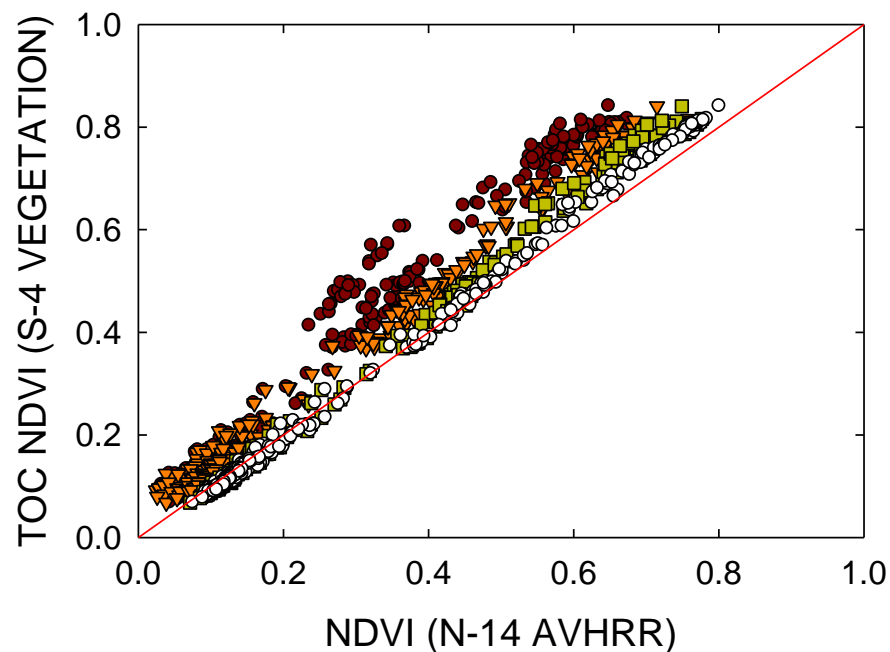


UNIVERSITY  
of HAWAII  
MĀNOA

## MODIS vs. AVHRR/2



## VEGETATION vs. AVHRR/2



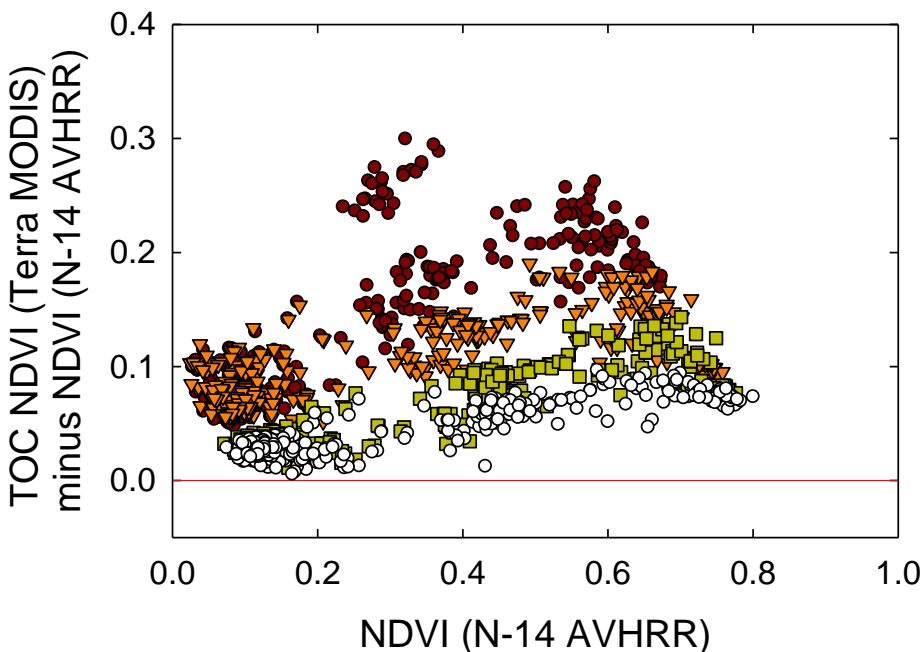


# NDVI Relationship under Various Atmospheric Correction Scenarios

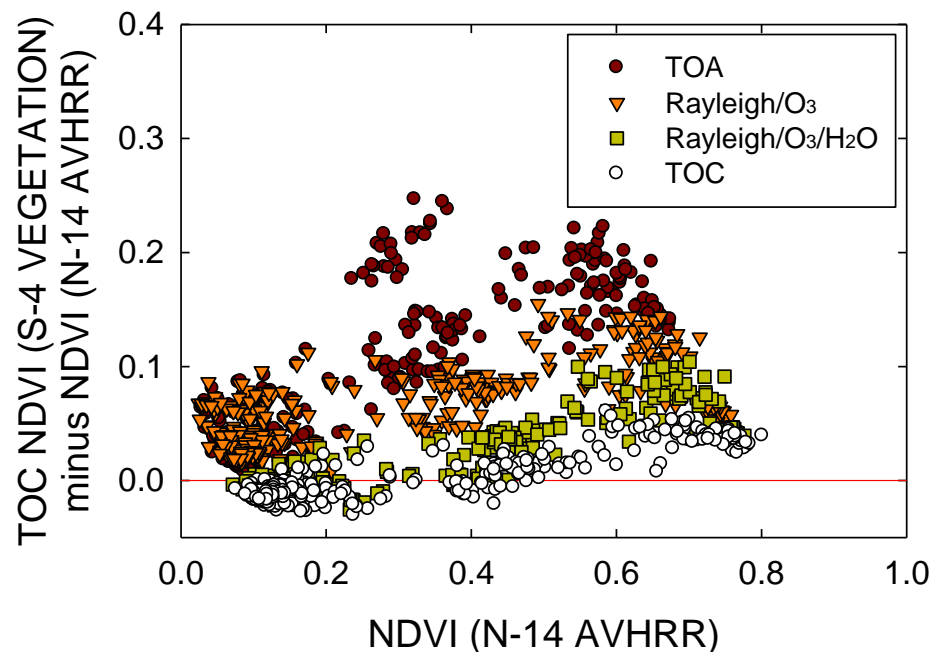


UNIVERSITY  
of HAWAII  
MĀNOA

## MODIS vs. AVHRR/2



## VEGETATION vs. AVHRR/2



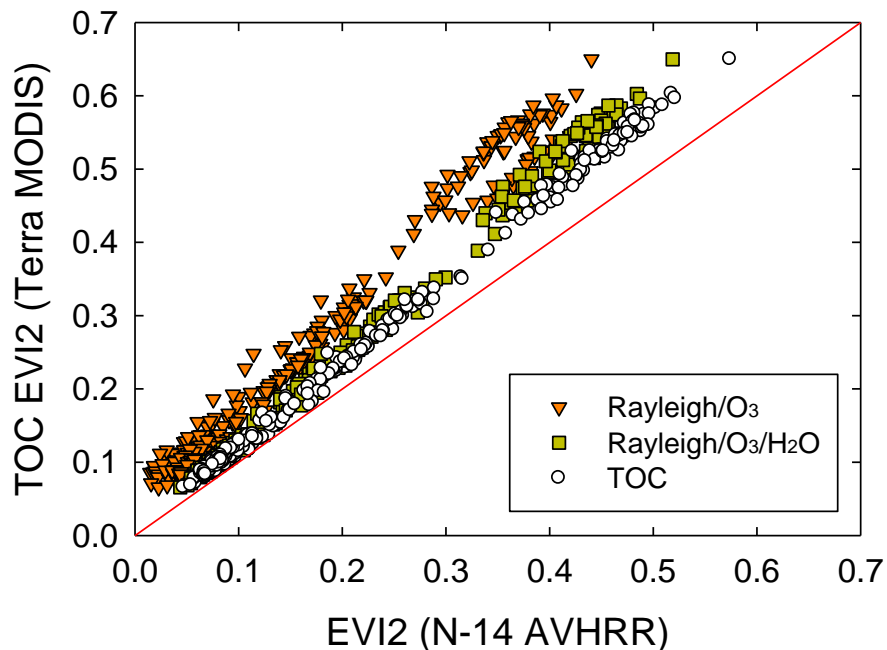


# EVI2 Relationship under Various Atmospheric Correction Scenarios

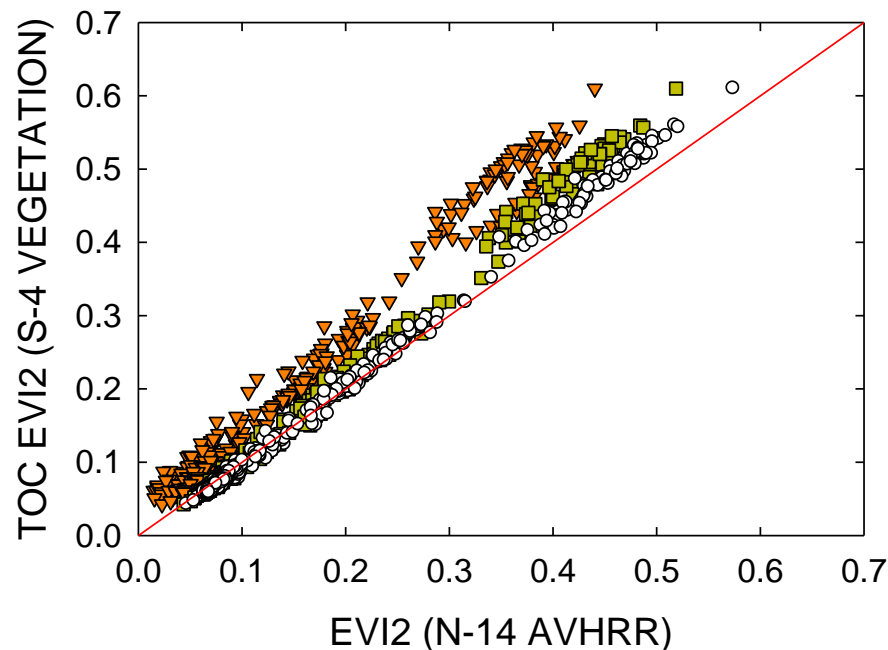


UNIVERSITY  
of HAWAII  
MĀNOA

## MODIS vs. AVHRR/2



## VEGETATION vs. AVHRR/2



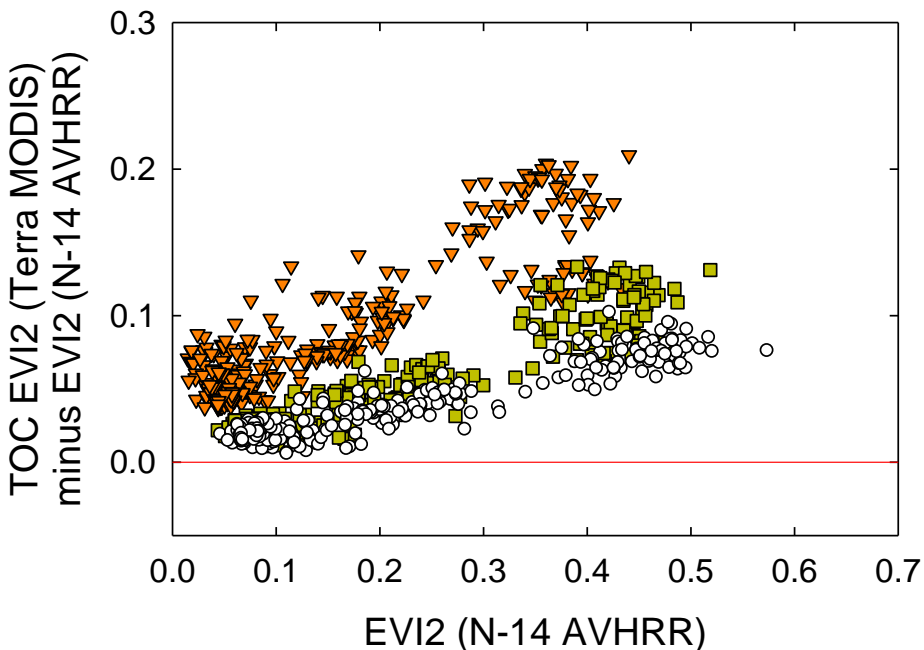


# EVI2 Relationship under Various Atmospheric Correction Scenarios

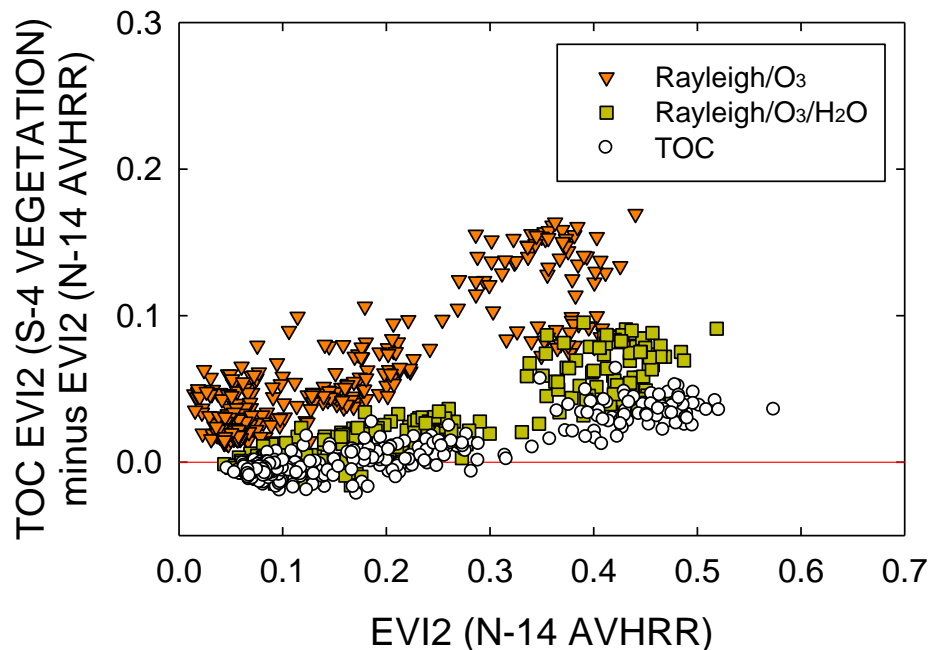


UNIVERSITY  
of HAWAII  
MĀNOA

## MODIS vs. AVHRR/2



## VEGETATION vs. AVHRR/2



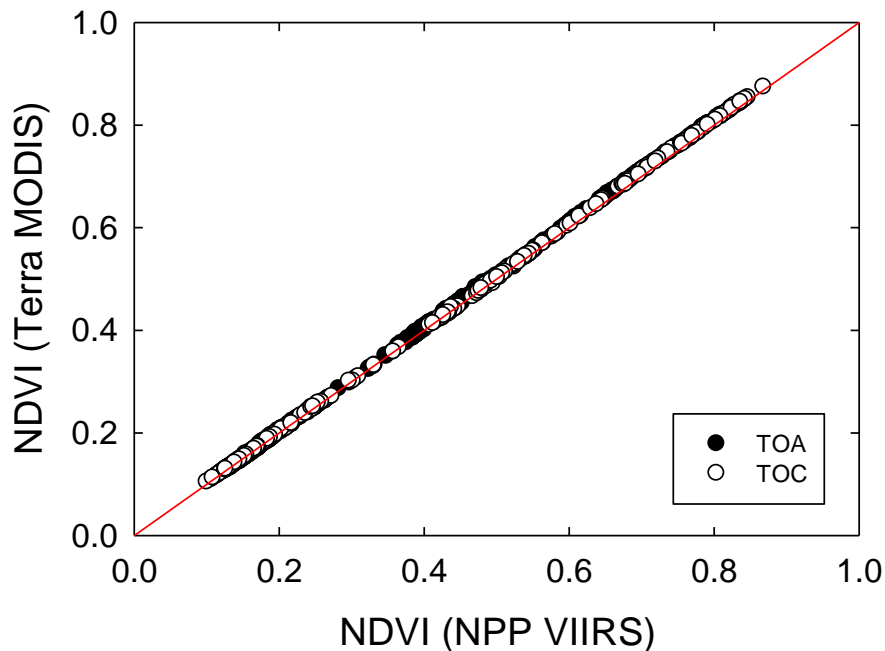


# MODIS-VIIRS NDVI Relationships under Two Atmospheric Correction Scenarios

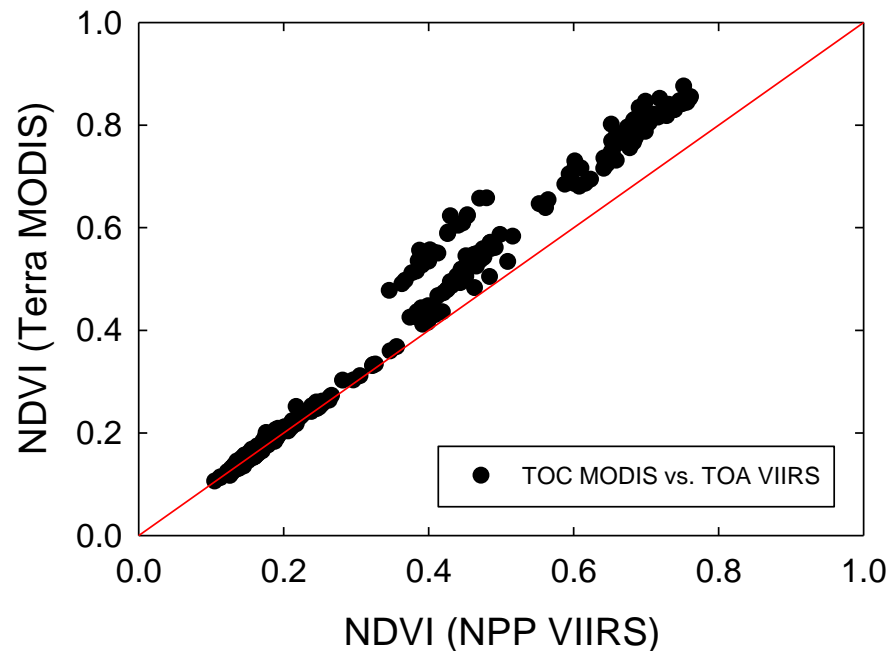


UNIVERSITY  
of HAWAII  
MĀNOA

### Same ACs



### Different ACs



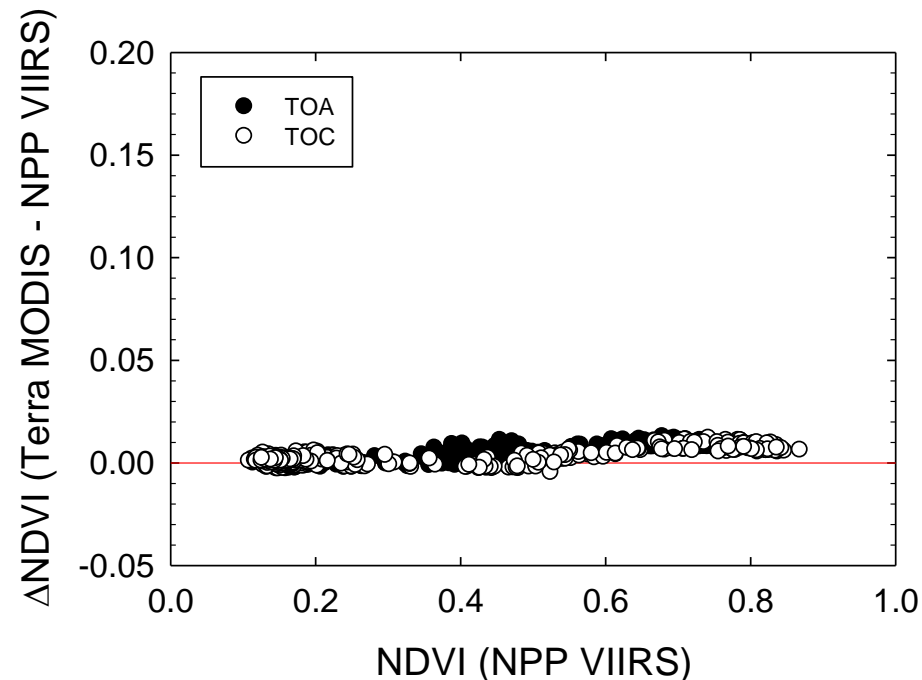


# MODIS-VIIRS NDVI Relationships under Two Atmospheric Correction Scenarios

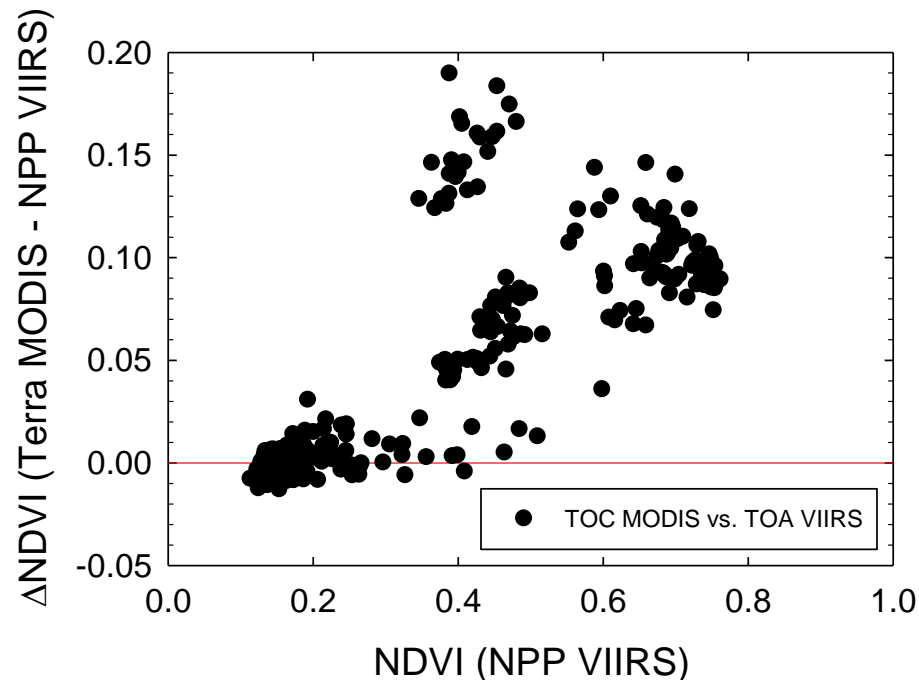


UNIVERSITY  
of HAWAII  
MĀNOA

### Same ACs



### Different ACs



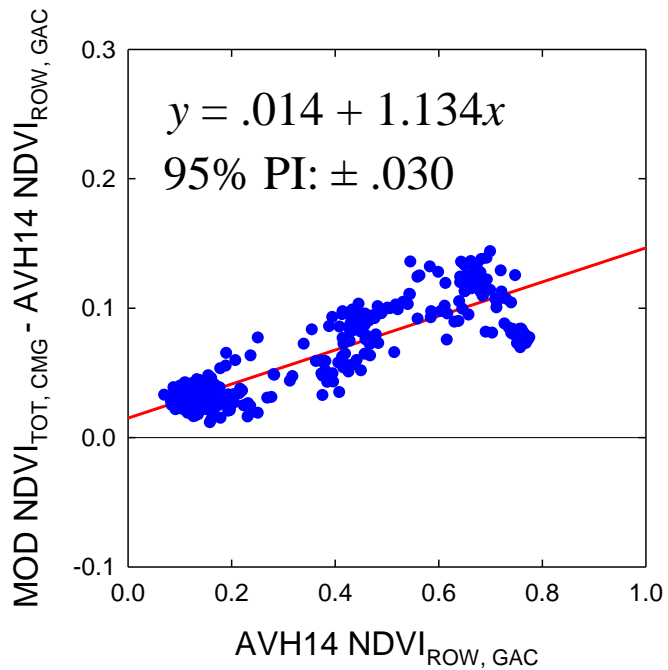


# Spectral Transformation Equations to MODIS-equivalents (TOC, CMG)

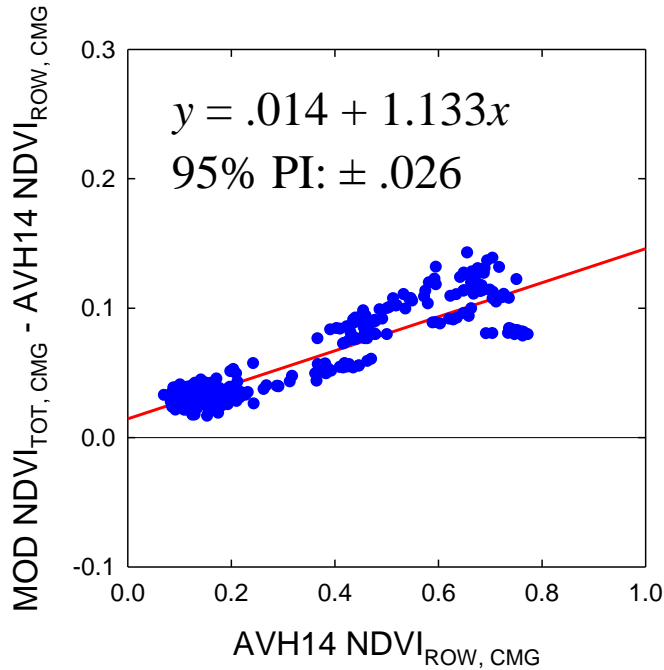


NDVI ( <i>x</i> variable)	Equation	Uncertainty (95% PI)
N-7 AVHRR, ROW, GAC	$y = 0.0105080 + 1.1144501x$	±0.033
N-9 AVHRR, ROW, GAC	$y = 0.0127476 + 1.1215841x$	±0.032
N-11 AVHRR, ROW, GAC	$y = 0.0143102 + 1.1167148x$	±0.032
N-14 AVHRR, ROW, GAC	$y = 0.0143951 + 1.1336442x$	±0.030
S-4 VEGETATION, TOC, CMGV	$y = 0.0381324 + 1.0064999x$	±0.013

EVI2 ( <i>x</i> variable)	Equation	Uncertainty (95% PI)
N-7 AVHRR, ROW, GAC	$y = -0.000084 + 1.2339542x$	±0.023
N-9 AVHRR, ROW, GAC	$y = 0.0023720 + 1.2298151x$	±0.022
N-11 AVHRR, ROW, GAC	$y = 0.0033594 + 1.2256970x$	±0.022
N-14 AVHRR, ROW, GAC	$y = 0.0044528 + 1.2244740x$	±0.022
S-4 VEGETATION, TOC, CMGV	$y = 0.0232545 + 1.0324644x$	±0.006



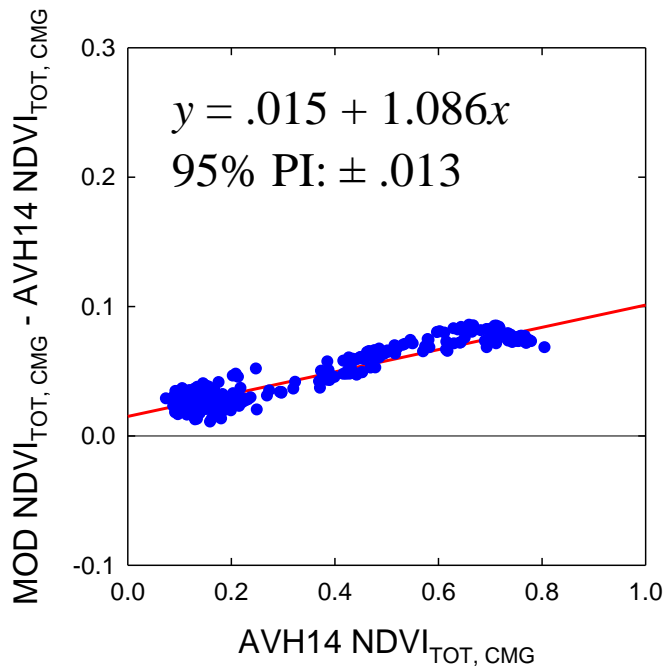
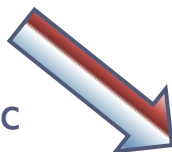
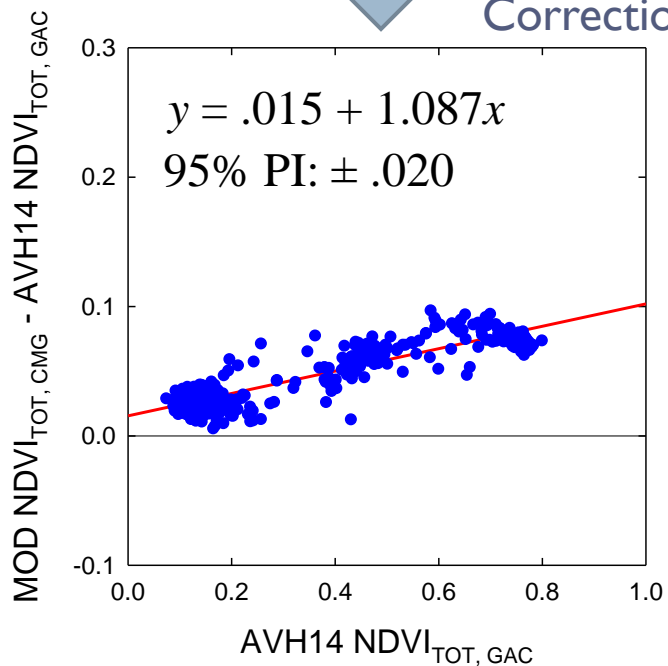
Spatial Resolution

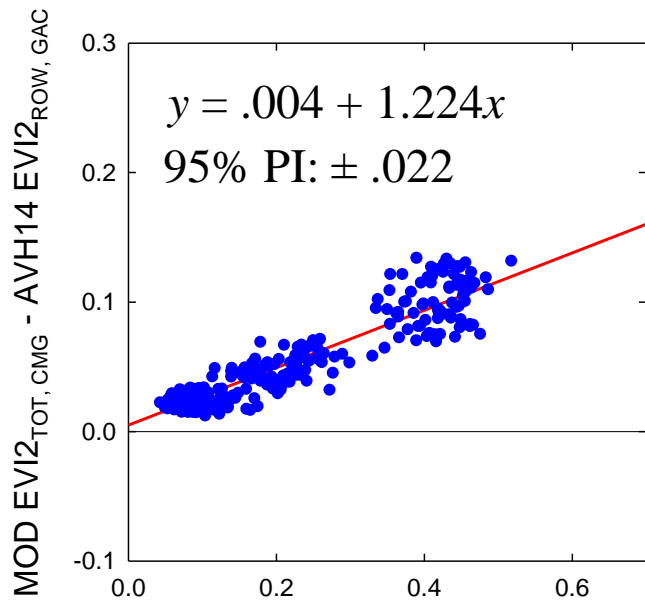


AVH14 NDVI<sub>ROW, GAC</sub>

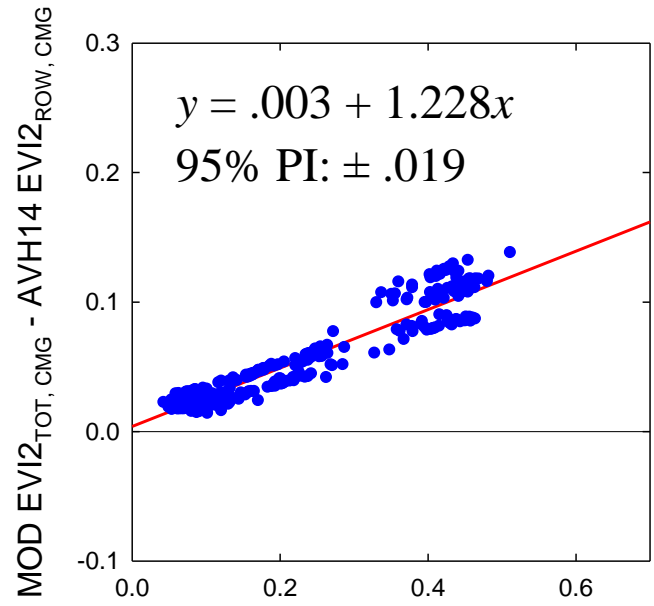


Atmospheric Correction

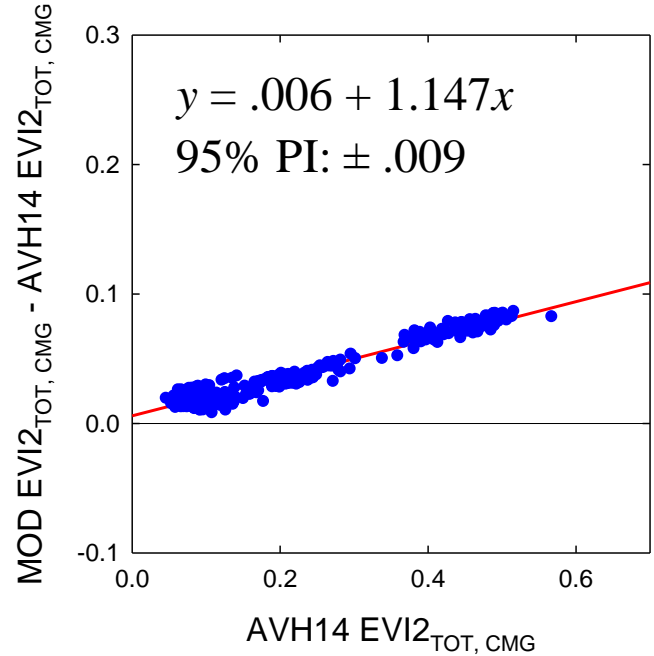
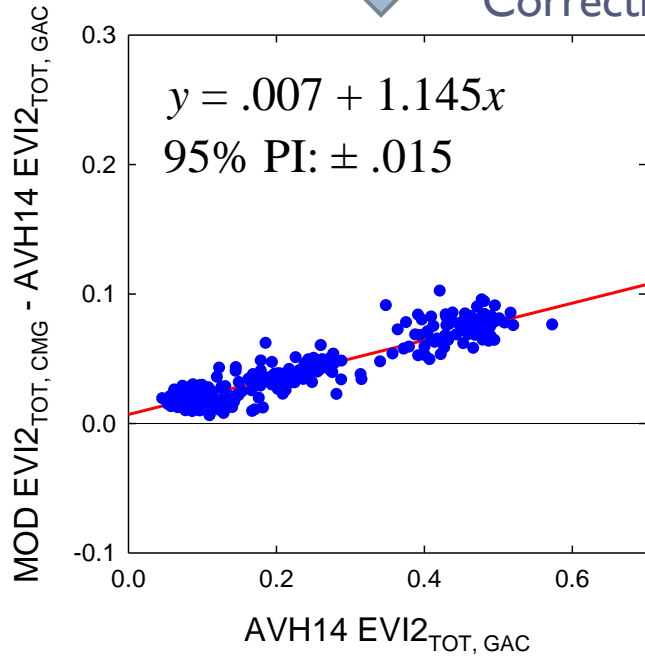




Spatial Resolution



Atmospheric Correction





# Uncertainty Estimates & Error Budgets



UNIVERSITY  
of HAWAII  
MĀNOA

<b>Factor</b>	<b><i>NDVI: AVHRR → MODIS</i></b>		<b><i>EVI2: AVHRR → MODIS</i></b>	
	<b>95% PI</b>	<b>% Contrib.</b>	<b>95% PI</b>	<b>% Contrib.</b>
Spectral	0.013	18%	0.009	20%
Spatial	0.016	25%	0.011	28%
Atmosphere	0.023	57%	0.015	52%
<b>Total</b>	<b>0.030</b>		<b>0.022</b>	



# Top-down, Direct Image Comparison: Global Reflectance Datasets Used



UNIVERSITY  
of HAWAII  
MĀNOA

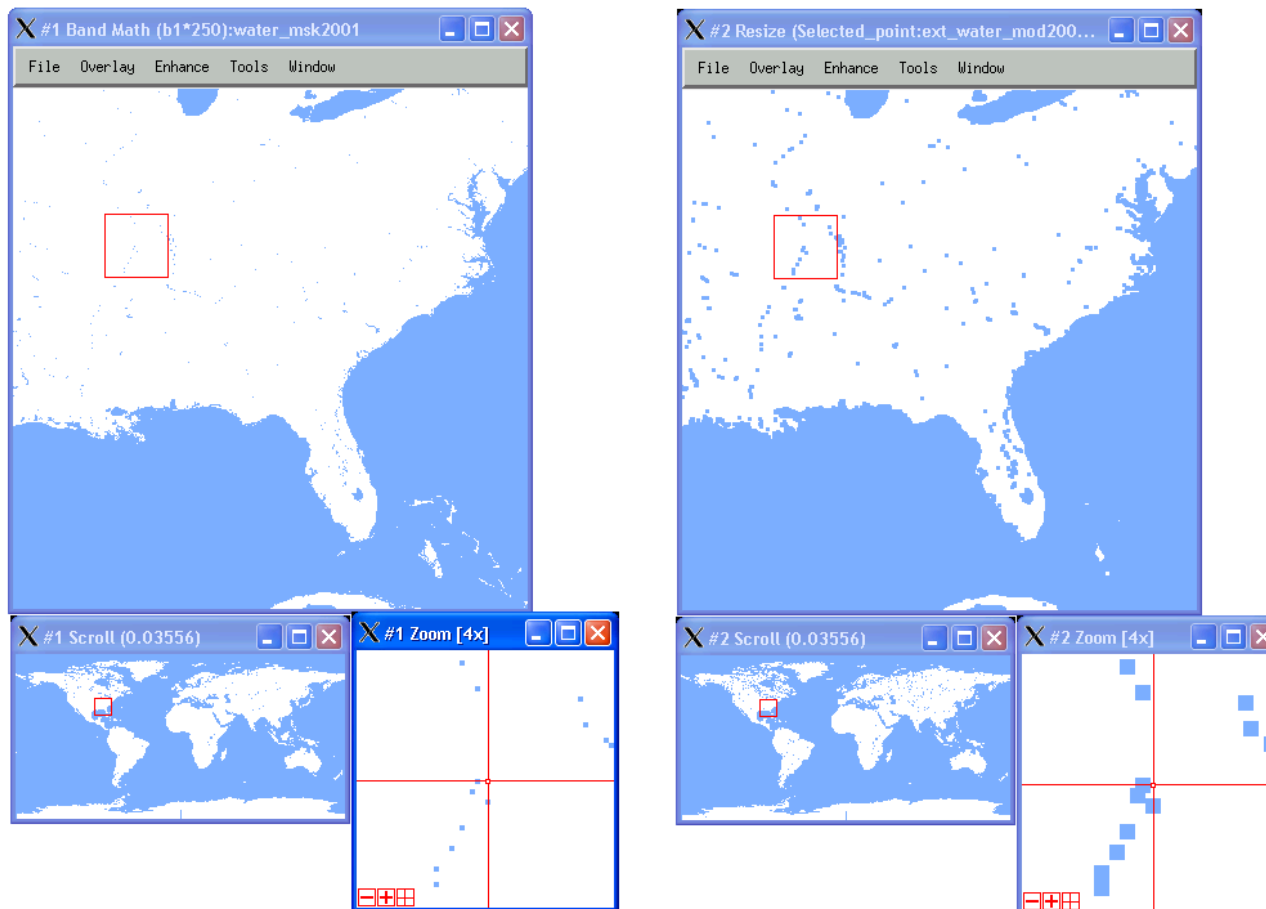
Product	Period	Data Screening
MOD09CMG Collection 5	2001 – 2002	UA Algorithm & QA – Cloud, Cloud Shadow, Fire, Snow/Ice, Aerosol Med-High, View Zenith Angle
LTDR AVHRR Ver. 2	1998 – 1999	UA Algorithm & QA – Cloudy, Partly Cloudy, Shadow, View Zenith Angle
LTDR AVHRR Ver. 3	1998 – 1999	UA Algorithm & QA – Cloudy, Partly Cloudy, Shadow, View Zenith Angle
VEGETATION S10*	1998 – 2002	UA Algorithm & SM – Cloud, Shadow, View Zenith Angle
VEGETATION S1*	1998 – 2002	UA Algorithm & SM – Cloud, Shadow, View Zenith Angle

\* Spatially-aggregated value for a CMG pixel was produced only when all of 1 km pixels inside the CMG pixel were available after the screening.



# Additional Data Screening

- ▶ The 2001 water mask expanded by one pixel

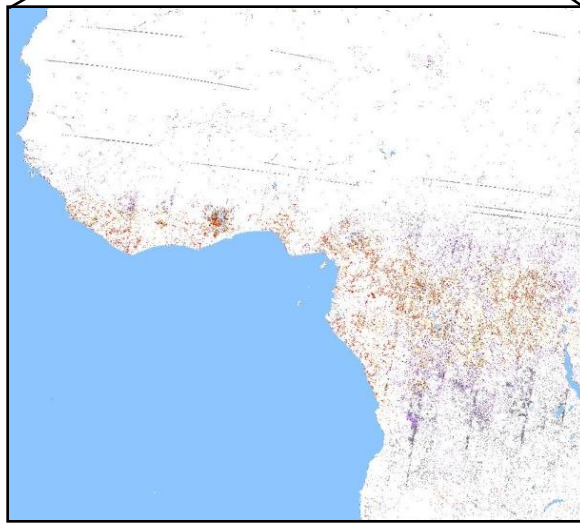
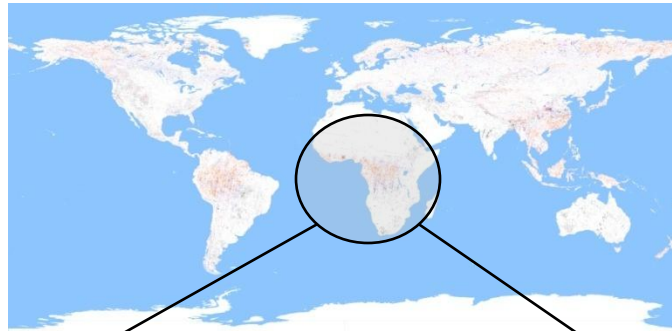


(Chen, 1999)

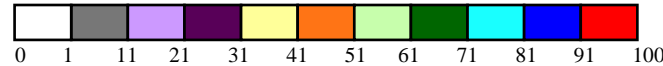
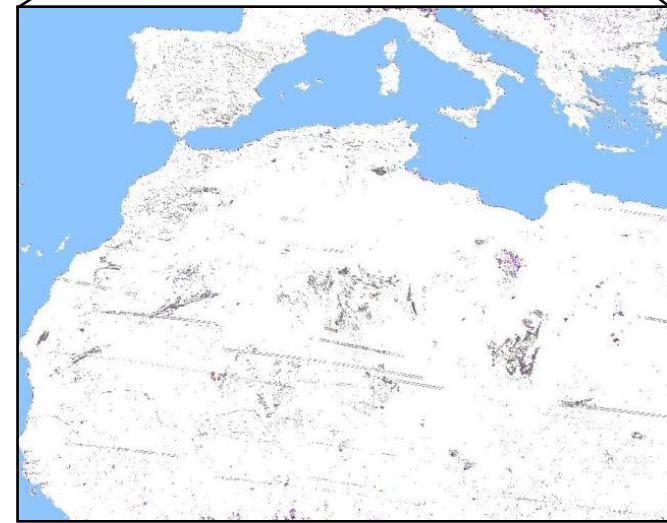
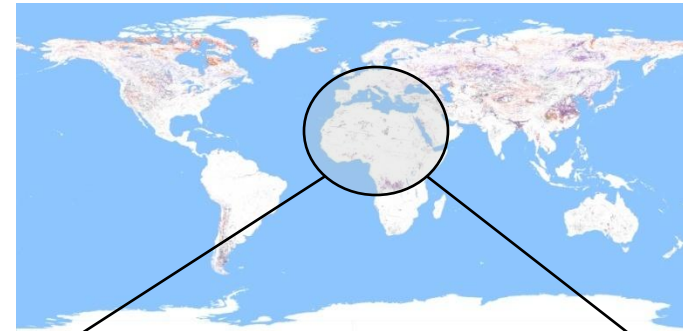


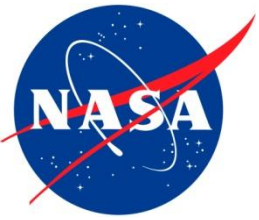
# Additional Data Screening (cont.)

Percent difference less than -45



Percent difference greater than 45

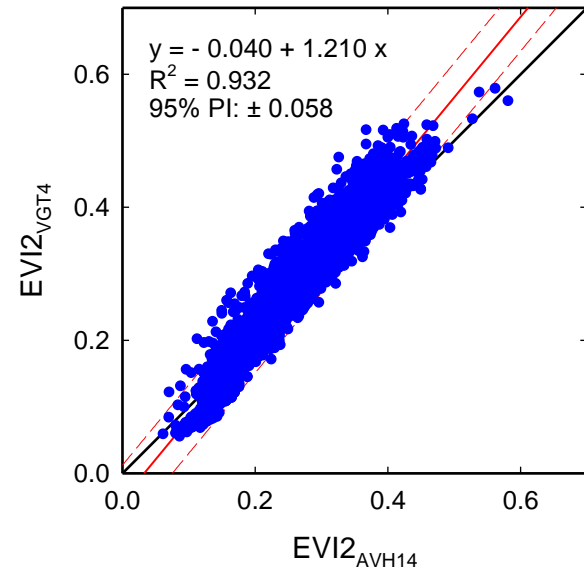
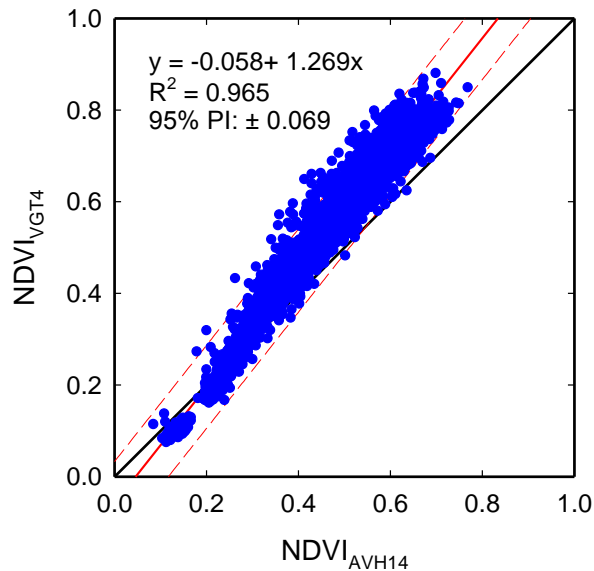
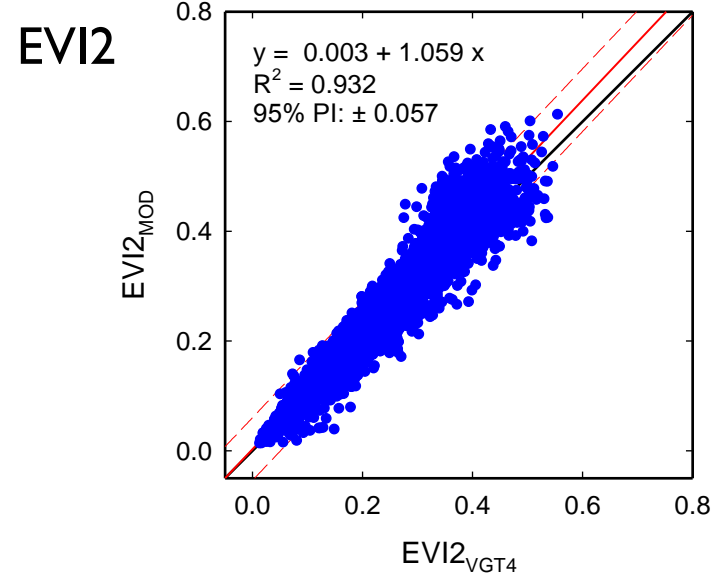
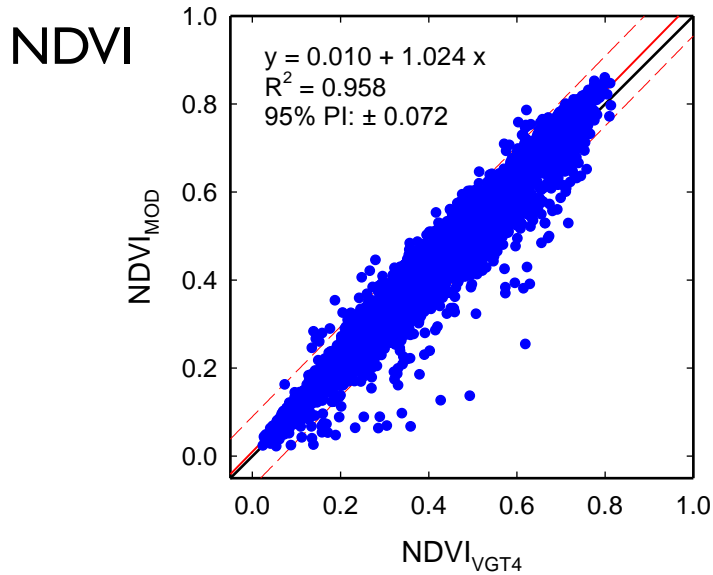




# Single, Global Translation Equations



UNIVERSITY  
of HAWAII  
MĀNOA





# Stratifications: Global vs. Land Cover Dependent Equations



- ▶ Various land stratifications were examined with the objective of minimizing multi-sensor VI translation errors:

- ▶ Single Equation: All samples with all land cover types

$$VI_{vgt/mod} = b + aVI_{avh/vgt}$$

- ▶ Stratification Method-1: IGBP land cover

$$VI_{vgt/mod}^k = b_k + a_k VI_{avh/vgt}^k \quad k = \overline{1, 15};$$

- ▶ Stratification Method-2: IGBP land cover & latitudinal zoning

$$VI_{vgt/mod}^{i_k} = b_{i_k} + a_{i_k} VI_{avh/vgt}^{i_k} \quad i = \overline{1, 6}; \quad k = \overline{1, 15};$$

- ▶ Stratification Method-3: Phenological regions (2956 classes)

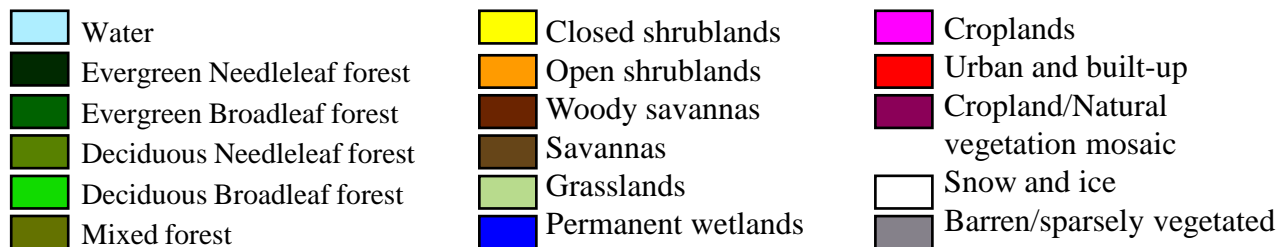
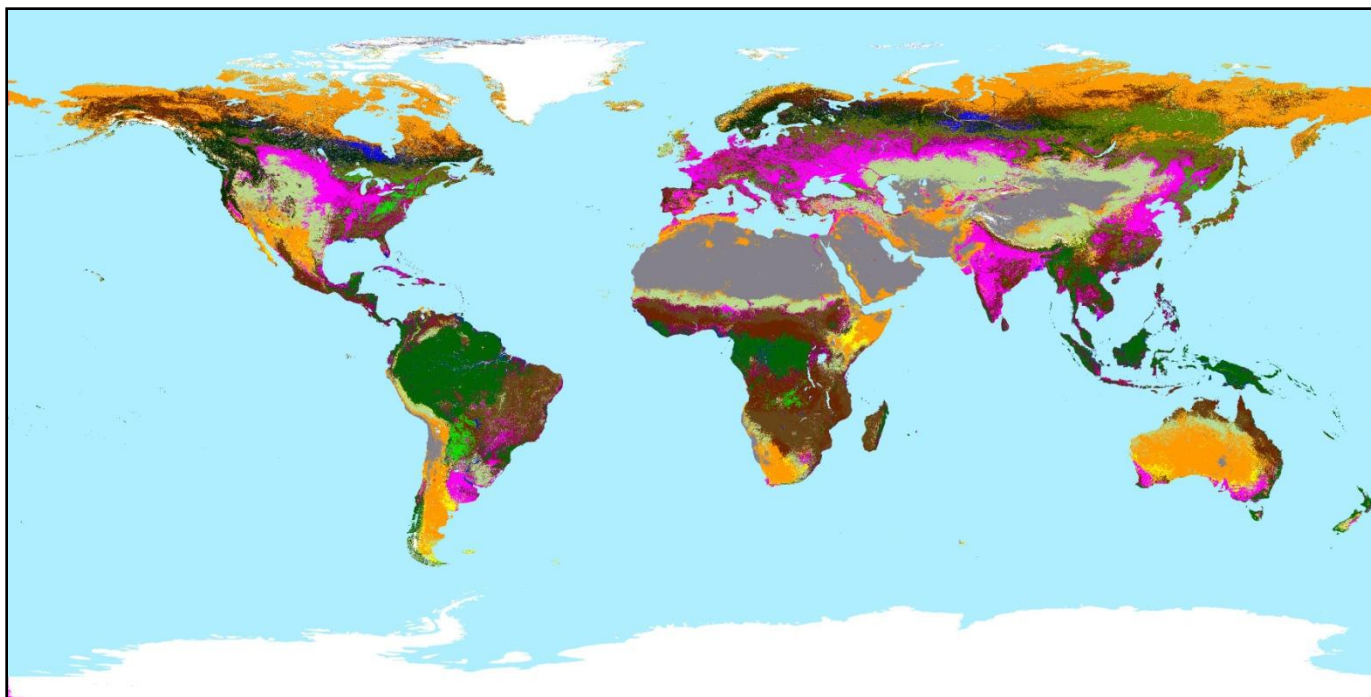
$$VI_{mod/vgt}^k = b_k + a_k VI_{avh/vgt}^k \quad k = \overline{1, 2956};$$



# Stratification Method 1: IGBP Land Cover 2001 (MCD12Q1)



UNIVERSITY  
of HAWAII  
MĀNOA

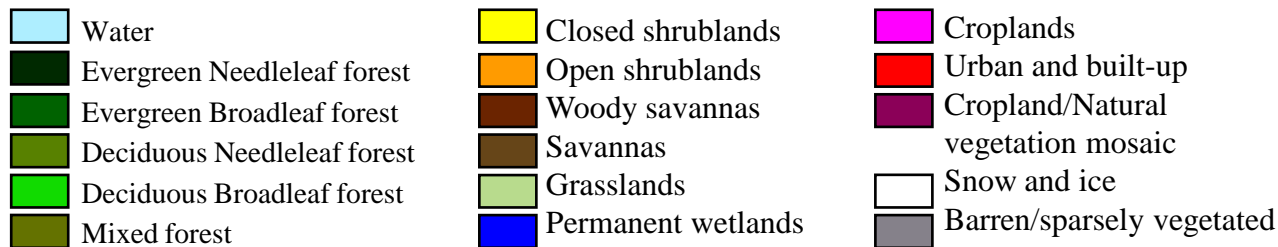
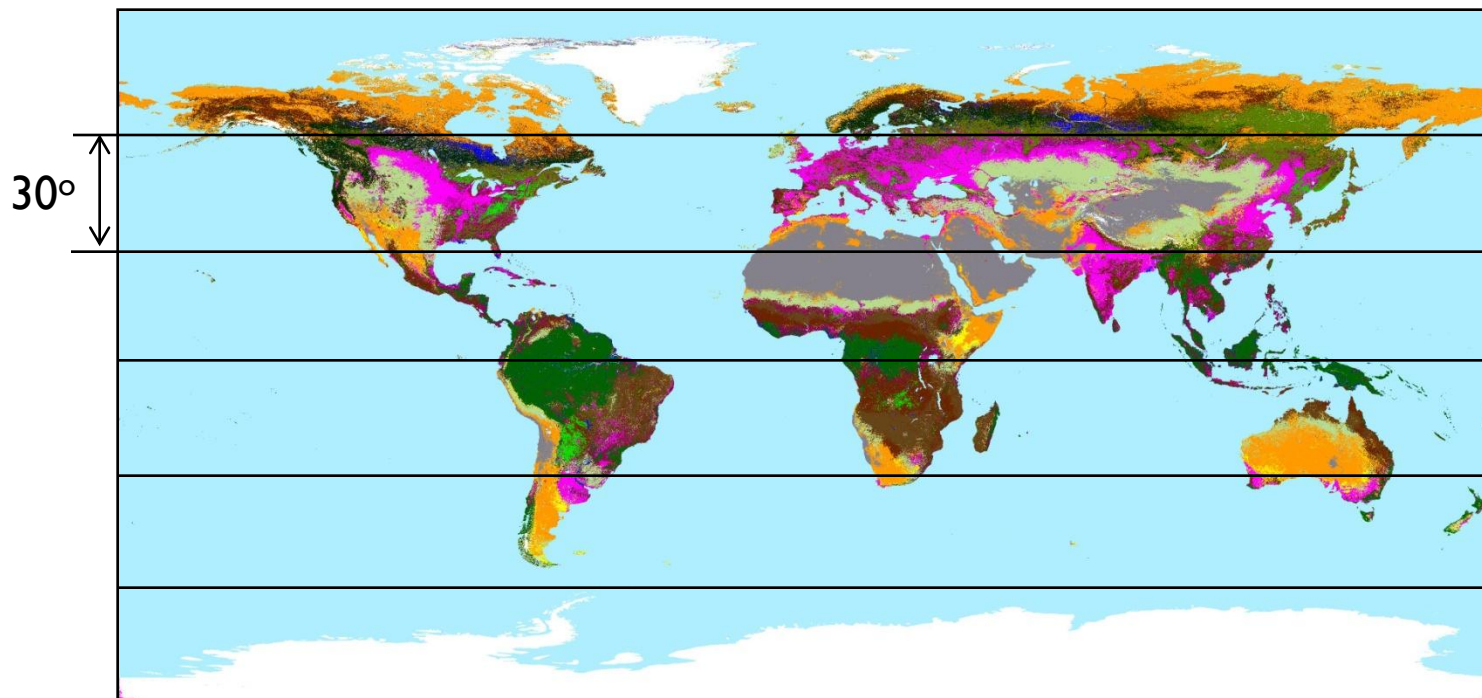




# Stratification Method 2: IGBP Land Cover plus Lat. Zoning



UNIVERSITY  
of HAWAII  
MĀNOA

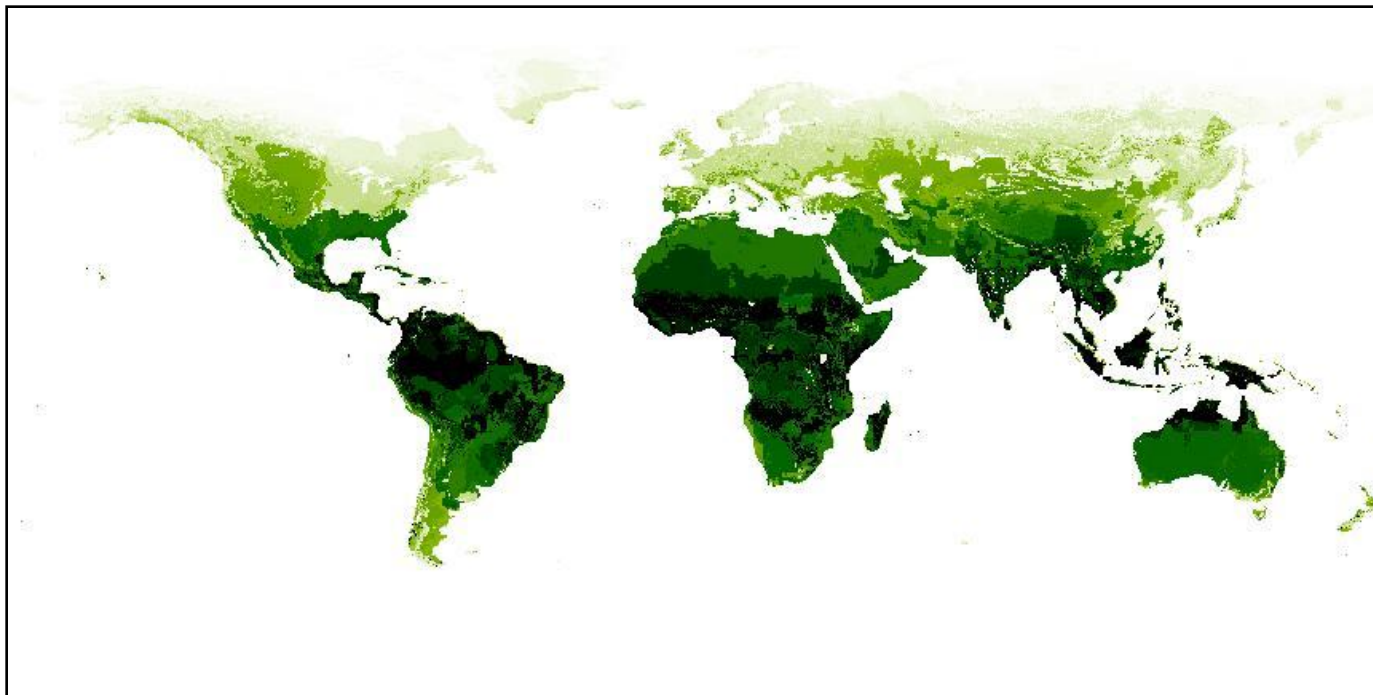




# Stratification Method 3: Phenological Regions (UA Algorithm)



UNIVERSITY  
of HAWAII®  
MĀNOA



- ▶ 2956 classes derived from MODIS



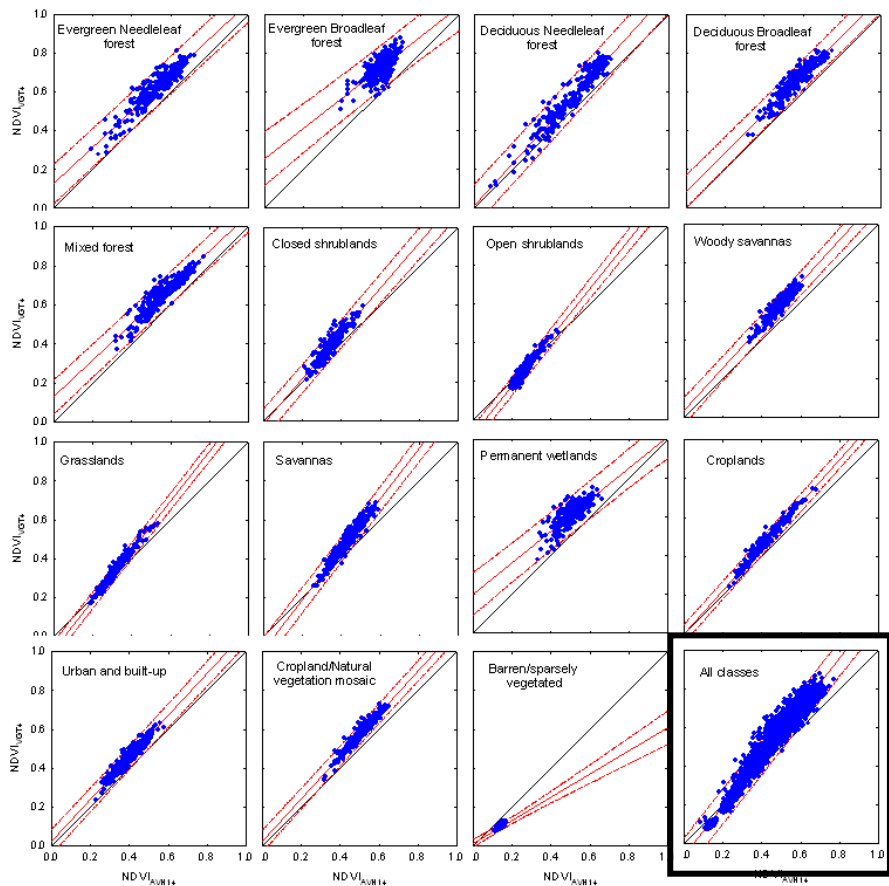


# Stratification Method 1: VEGETATION vs. AVHRR/2 (v. 2)

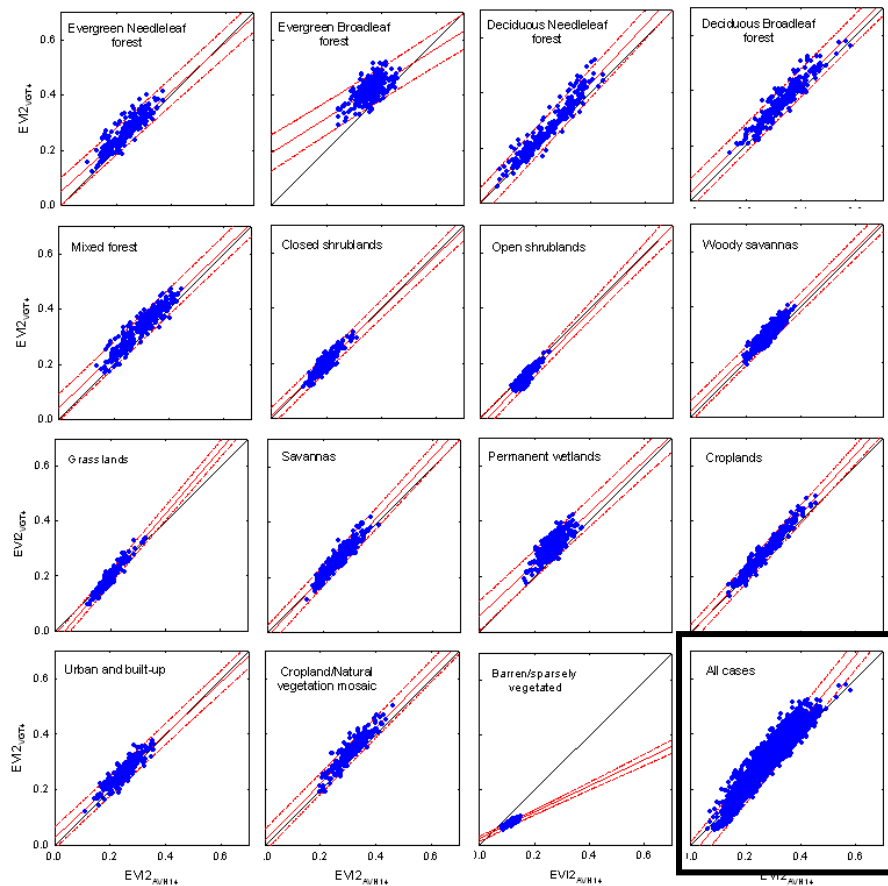


UNIVERSITY  
of HAWAII  
MĀNOA

## NDVI



## EVI2





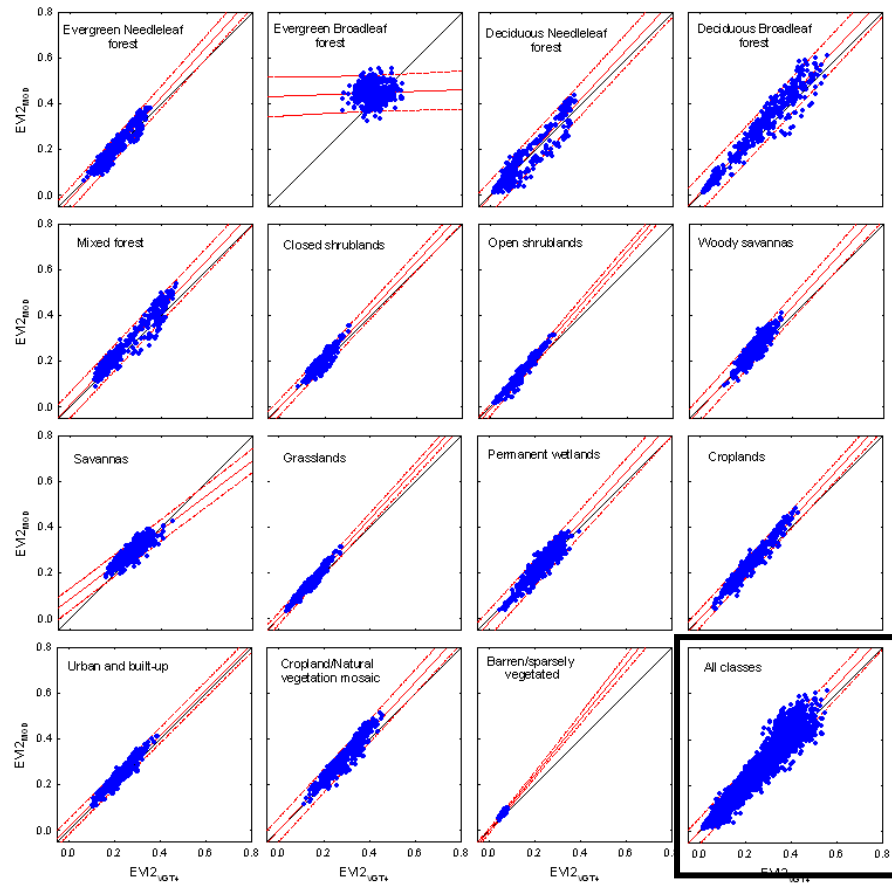
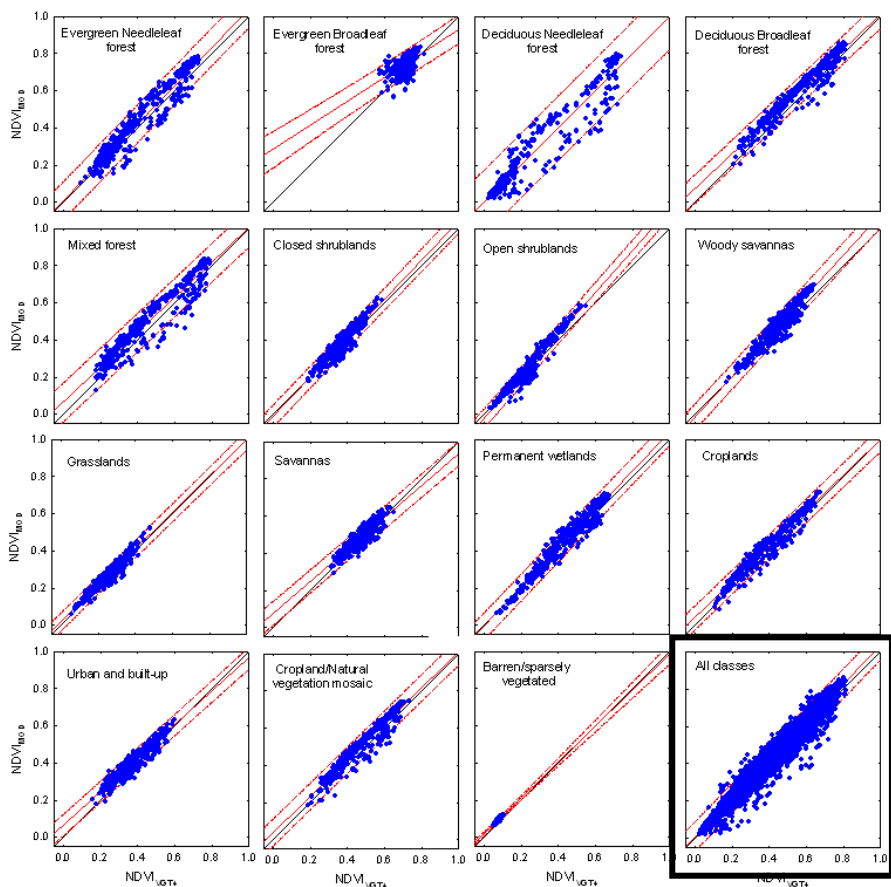
# Stratification Method 1: MODIS vs. VEGETATION



UNIVERSITY  
of HAWAII  
MĀNOA

## NDVI

## EVI2





# Stratification Method 2: VEGETATION vs. AVHRR/2

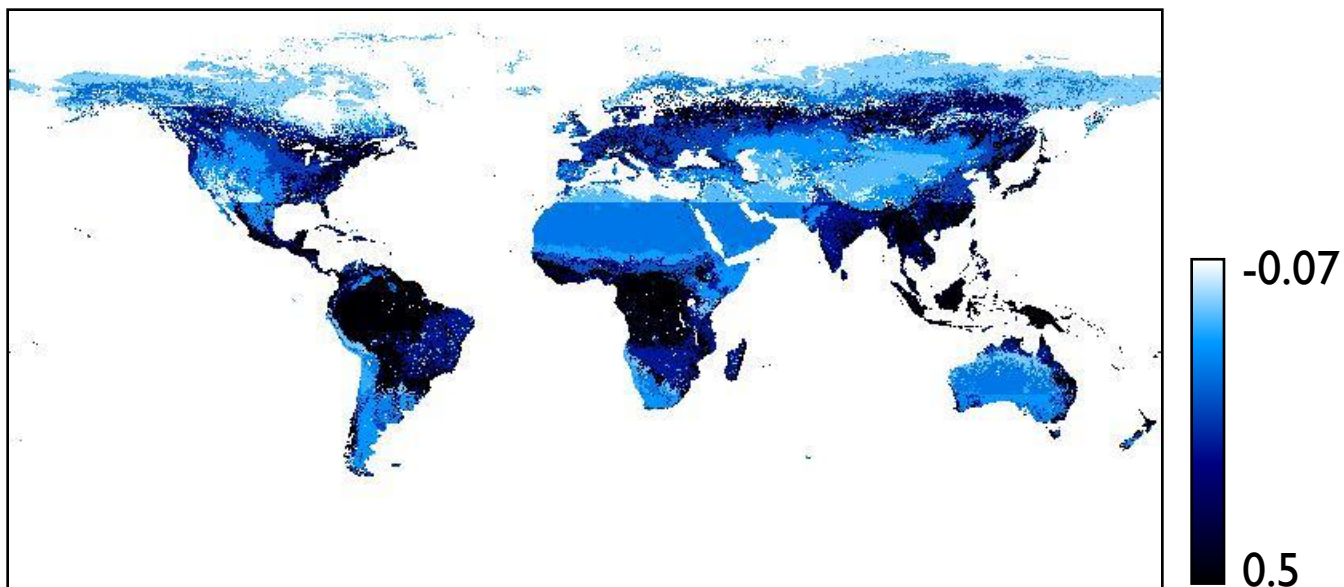


UNIVERSITY OF  
HAWAII  
MĀNOA

$a$  – slope



$b$  – intercept

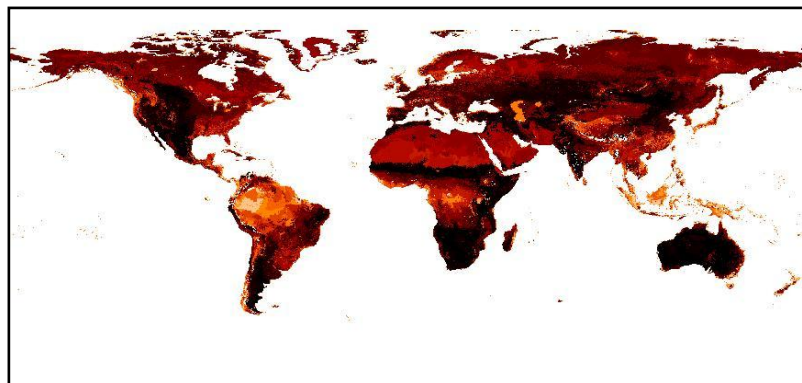




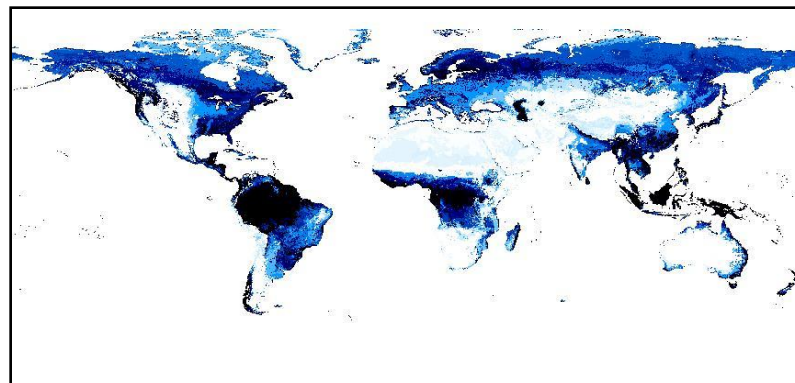
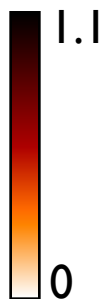
# Stratification Method 3: VEGETATION vs. AVHRR/2



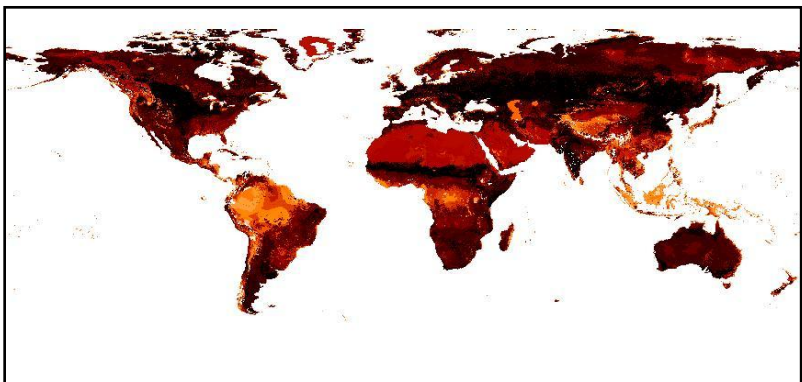
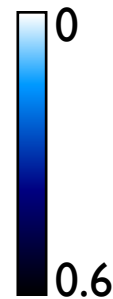
UNIVERSITY  
of HAWAII  
MĀNOA



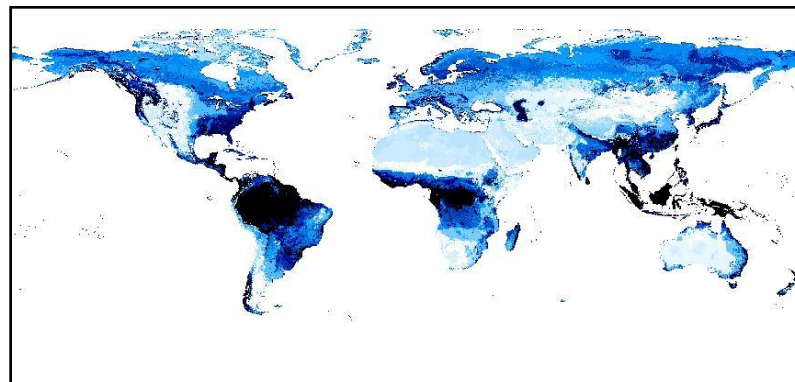
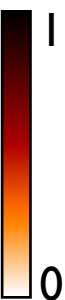
NDVI:  $a$  – slope



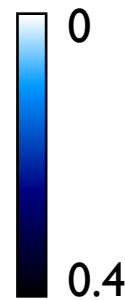
$b$  – intercept



EVI2:  $a$  – slope



$b$  – intercept

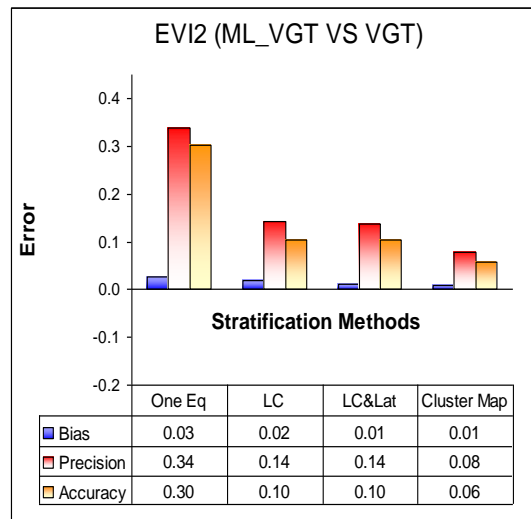
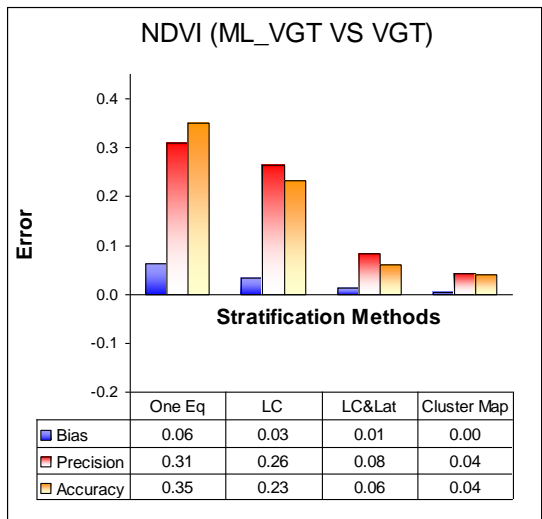
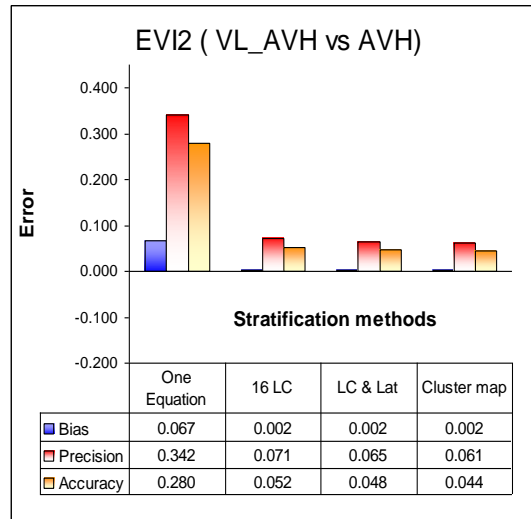
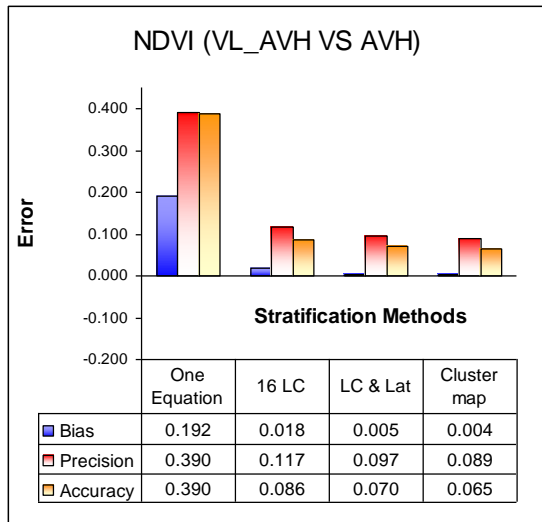




# Error Comparisons among Stratification Methods



UNIVERSITY  
of HAWAII  
MĀNOA

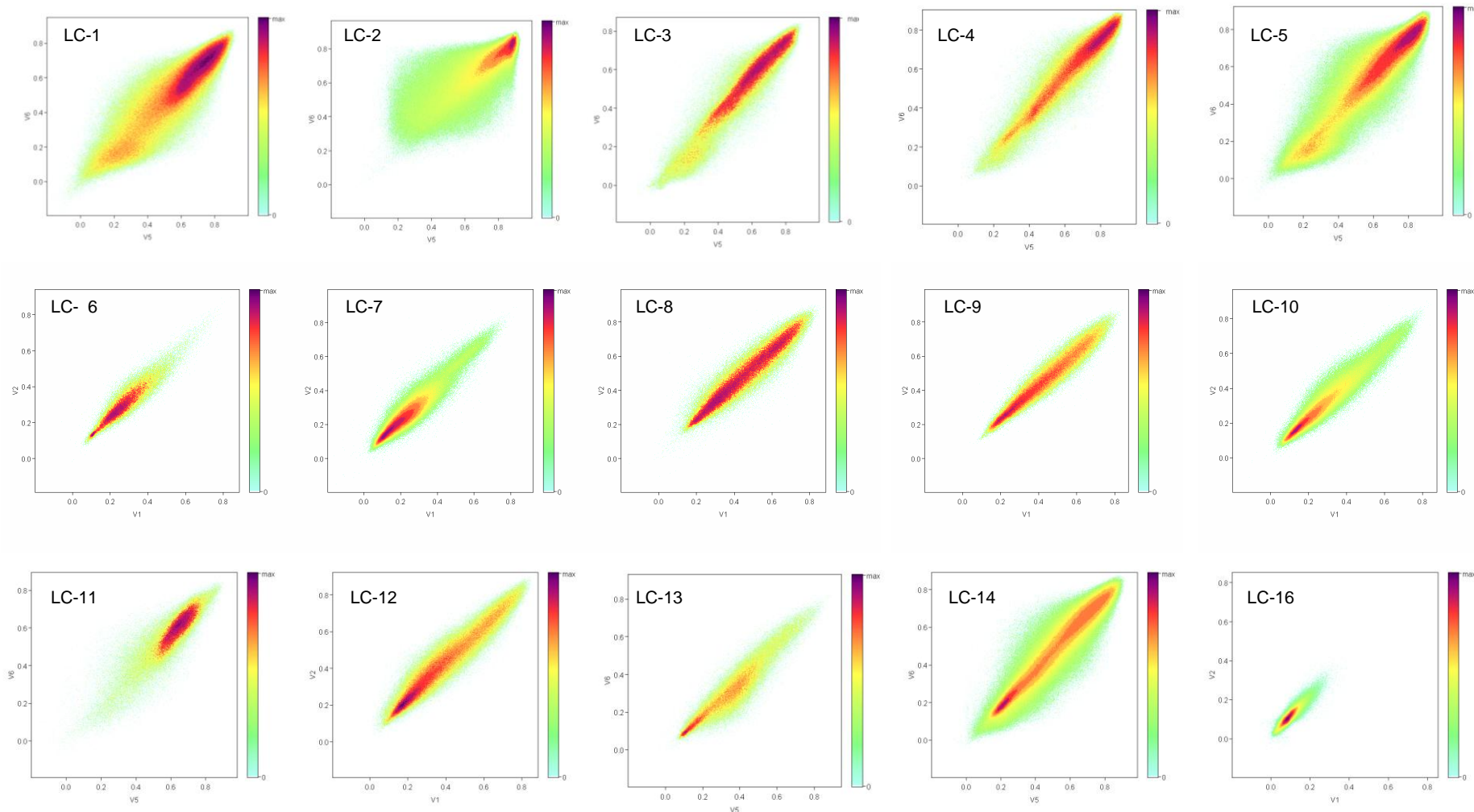




# MODIS vs. VEGETATION NDVI: Day-to-day Matched without View Angle Constraint



UNIVERSITY  
of HAWAII  
MĀNOA





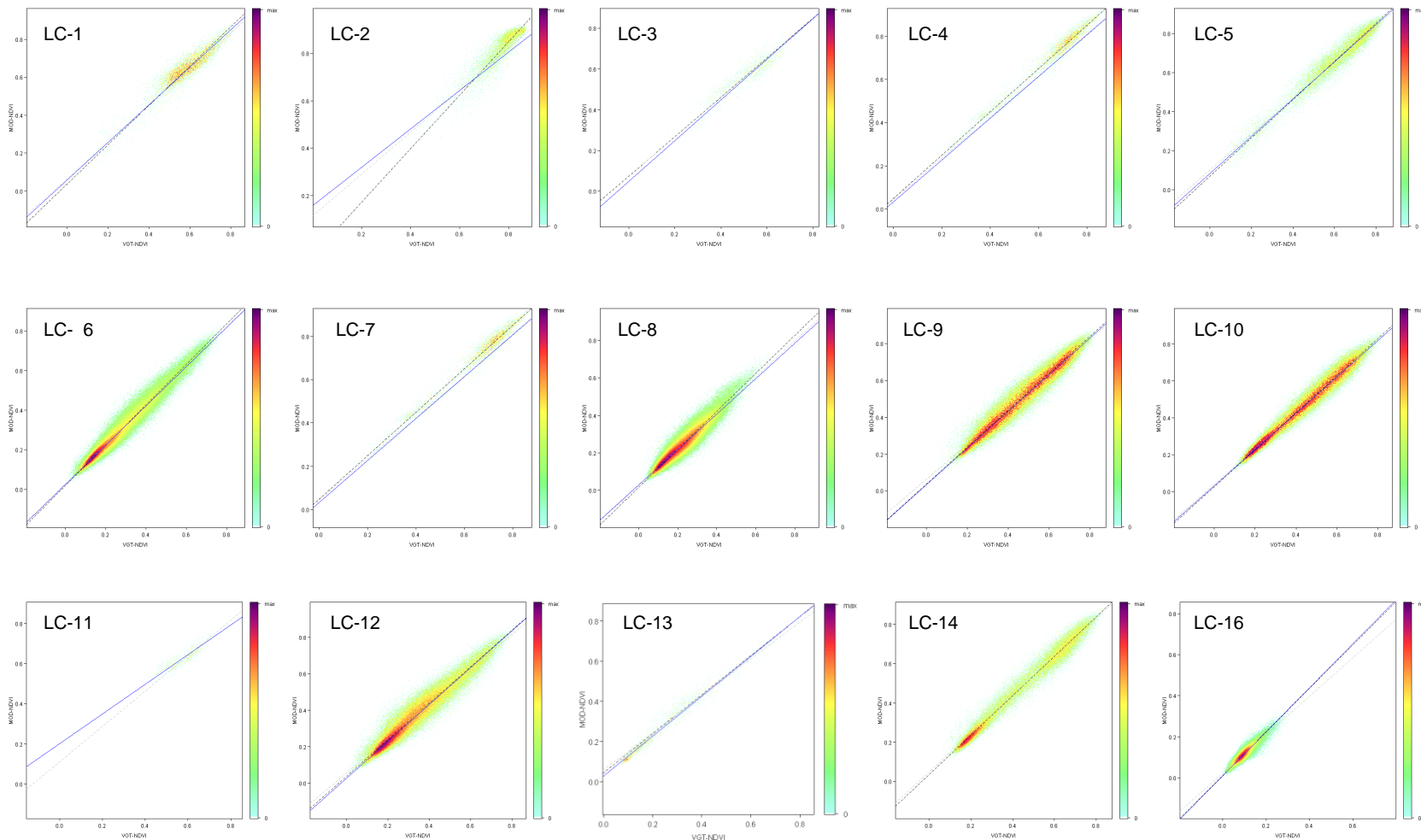
# MODIS vs. VEGETATION NDVI:

View zenith angle differences less than 10 degrees



UNIVERSITY  
of HAWAII®

MĀNOA





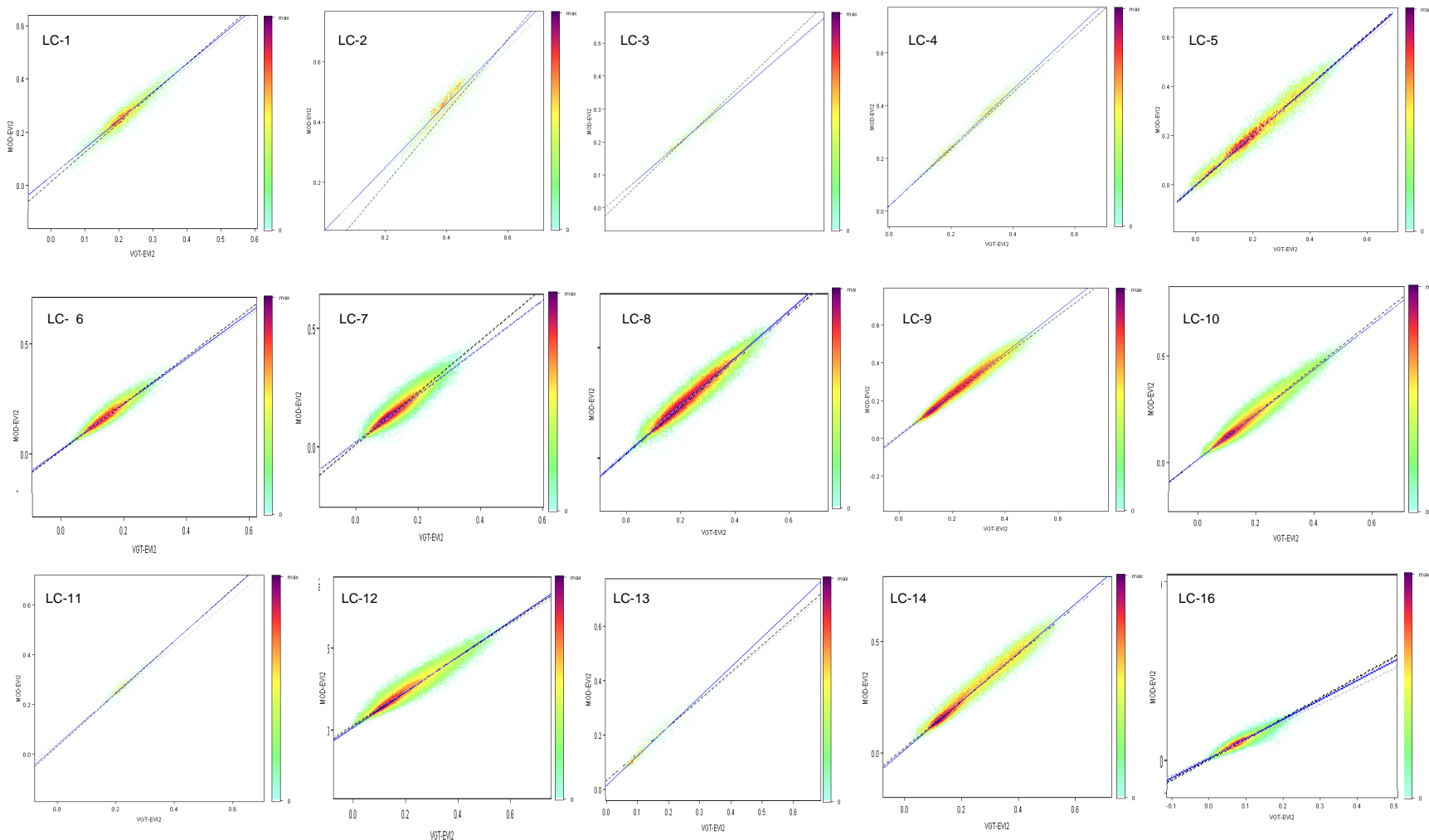
# MODIS vs. VEGETATION EVI2:

View zenith angle differences less than 10 degrees



UNIVERSITY  
of HAWAII

MĀNOA

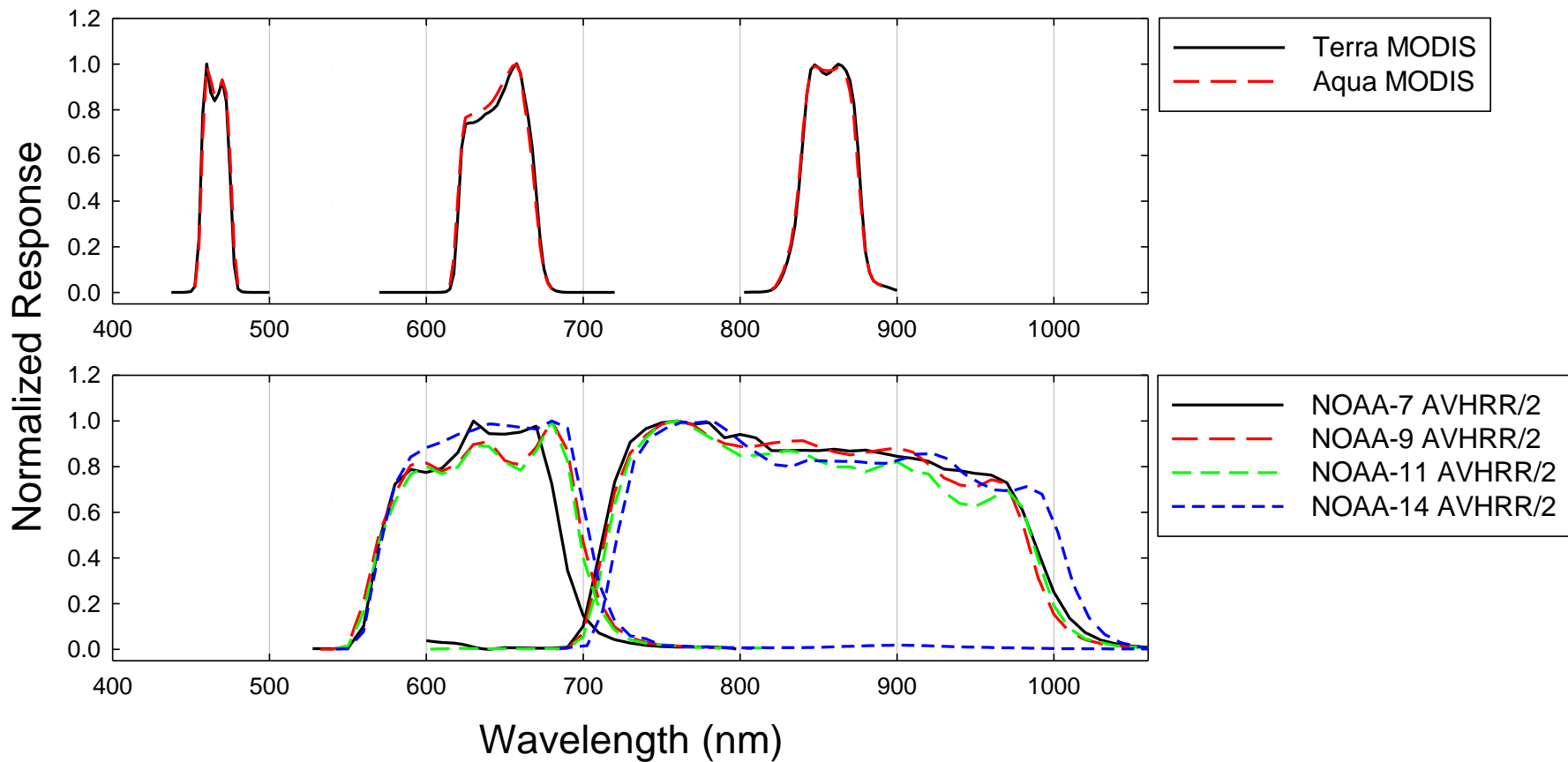




# Spectral Response Curves across Sensor Series



UNIVERSITY  
of HAWAII  
MĀNOA

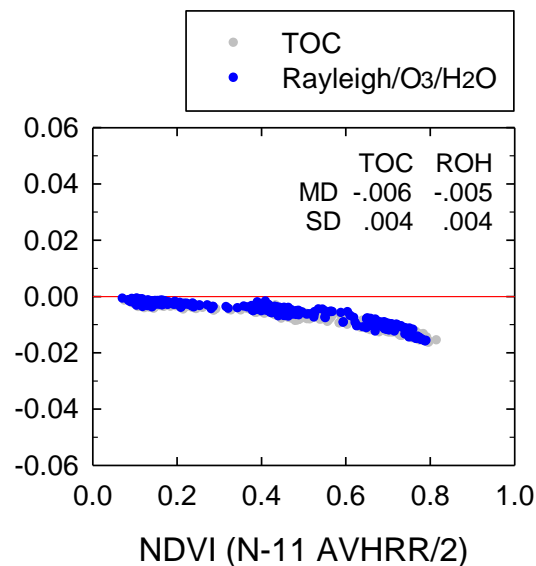
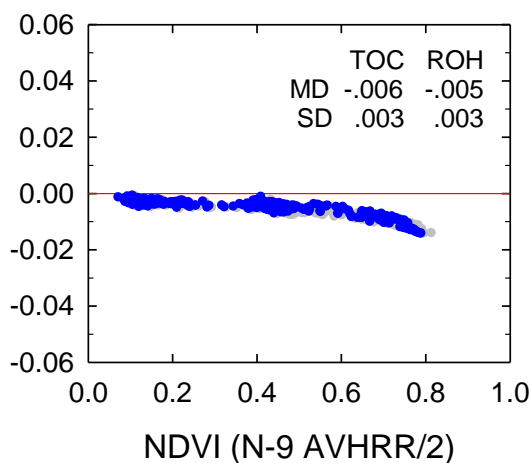
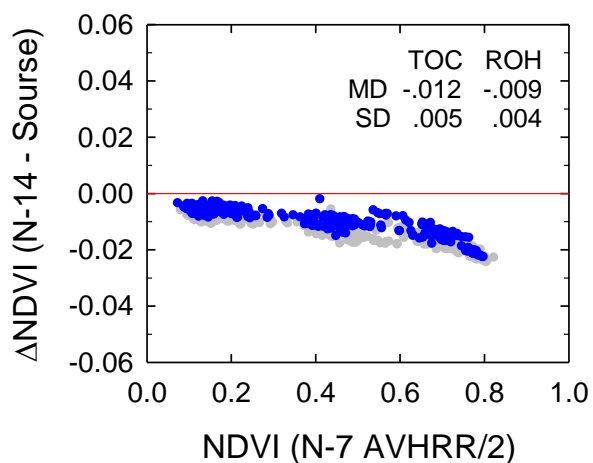
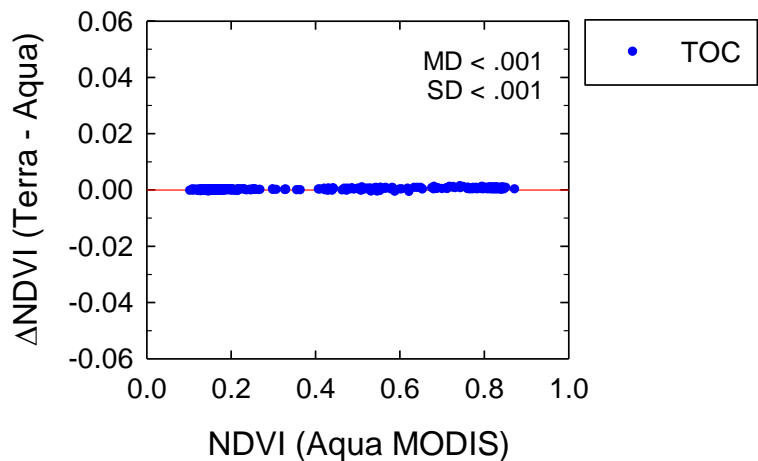




# Spectral Response Curves across Sensor Series (Cont.)



UNIVERSITY  
of HAWAII  
MĀNOA

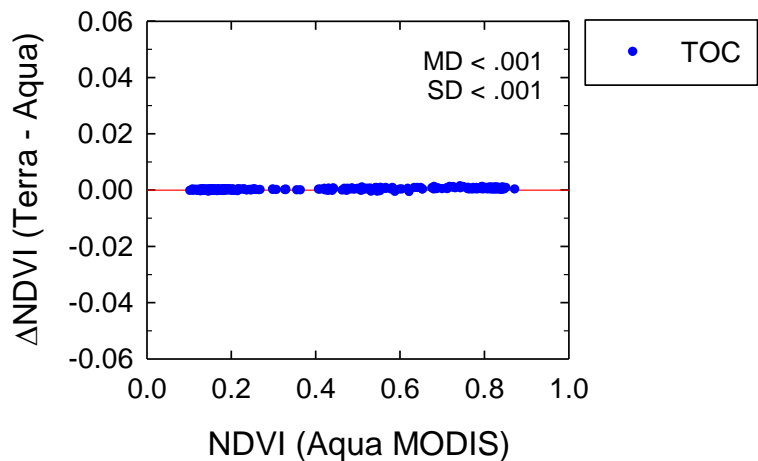




# Spectral Response Curves across Sensor Series (Cont.)



UNIVERSITY  
of HAWAII  
MĀNOA



## Spectral Correction

(Trishchenko et al., 2002; Cohen et al., 2003)

N-7 AVHRR/2:

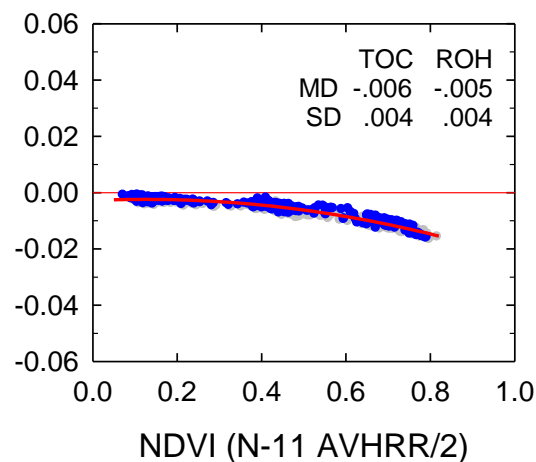
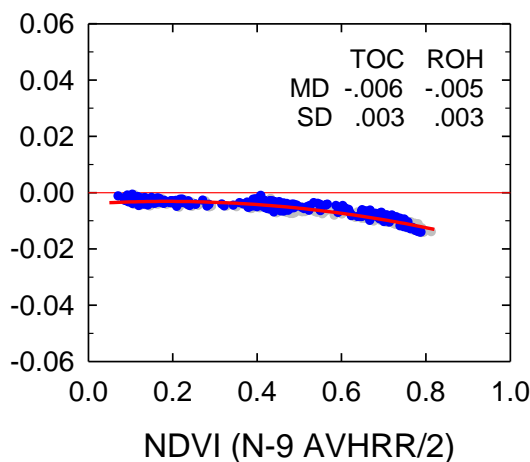
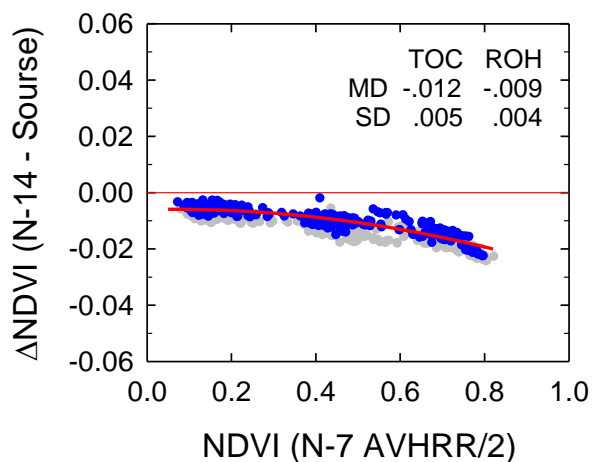
$$y = -.0060 + 1.0030 x - .0246 x^2 \quad (\pm.004, 95\% \text{PI})$$

N-9 AVHRR/2:

$$y = -.0040 + 1.0093 x - .0248 x^2 \quad (\pm.002, 95\% \text{PI})$$

N-11 AVHRR/2:

$$y = -.0028 + 1.0068 x - .0271 x^2 \quad (\pm.002, 95\% \text{PI})$$

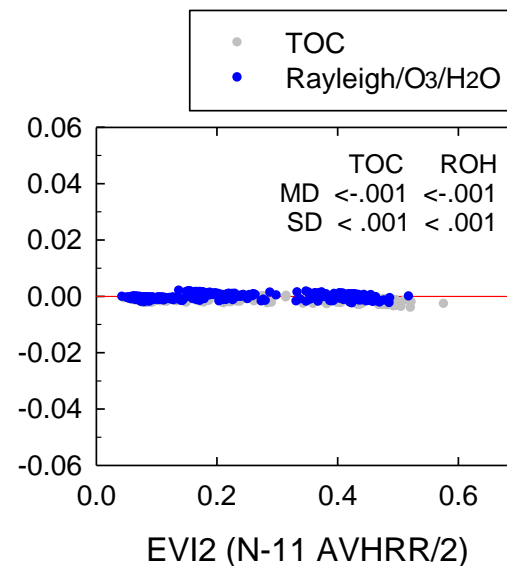
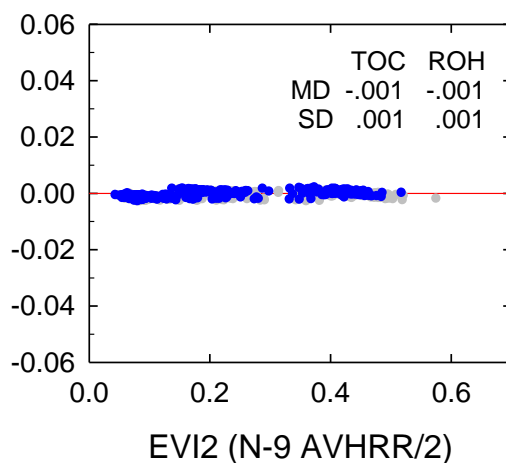
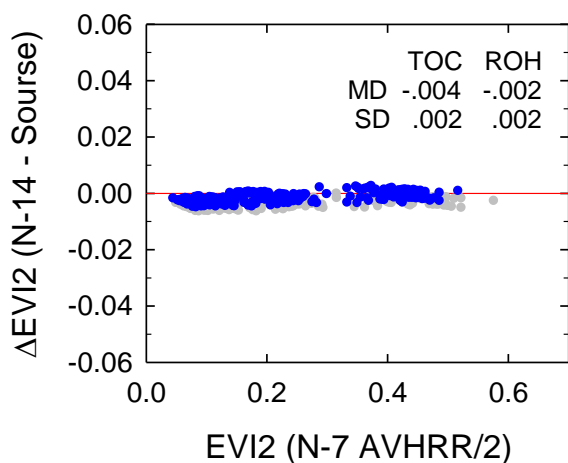
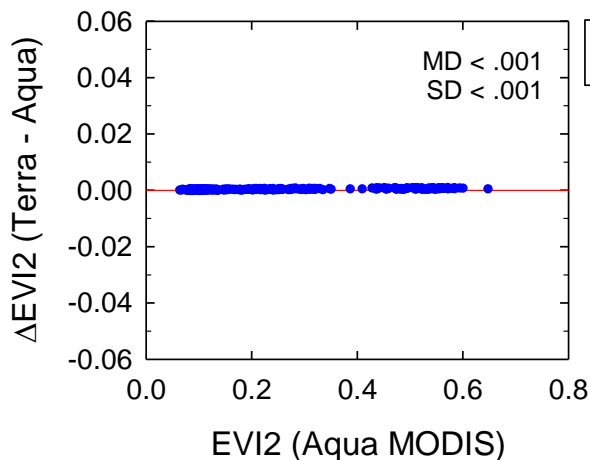




# Spectral Response Curves across Sensor Series (Cont.)



UNIVERSITY  
of HAWAII  
MĀNOA





# Spectral Transformation Equations to MODIS-equivalents (TOC, CMG)



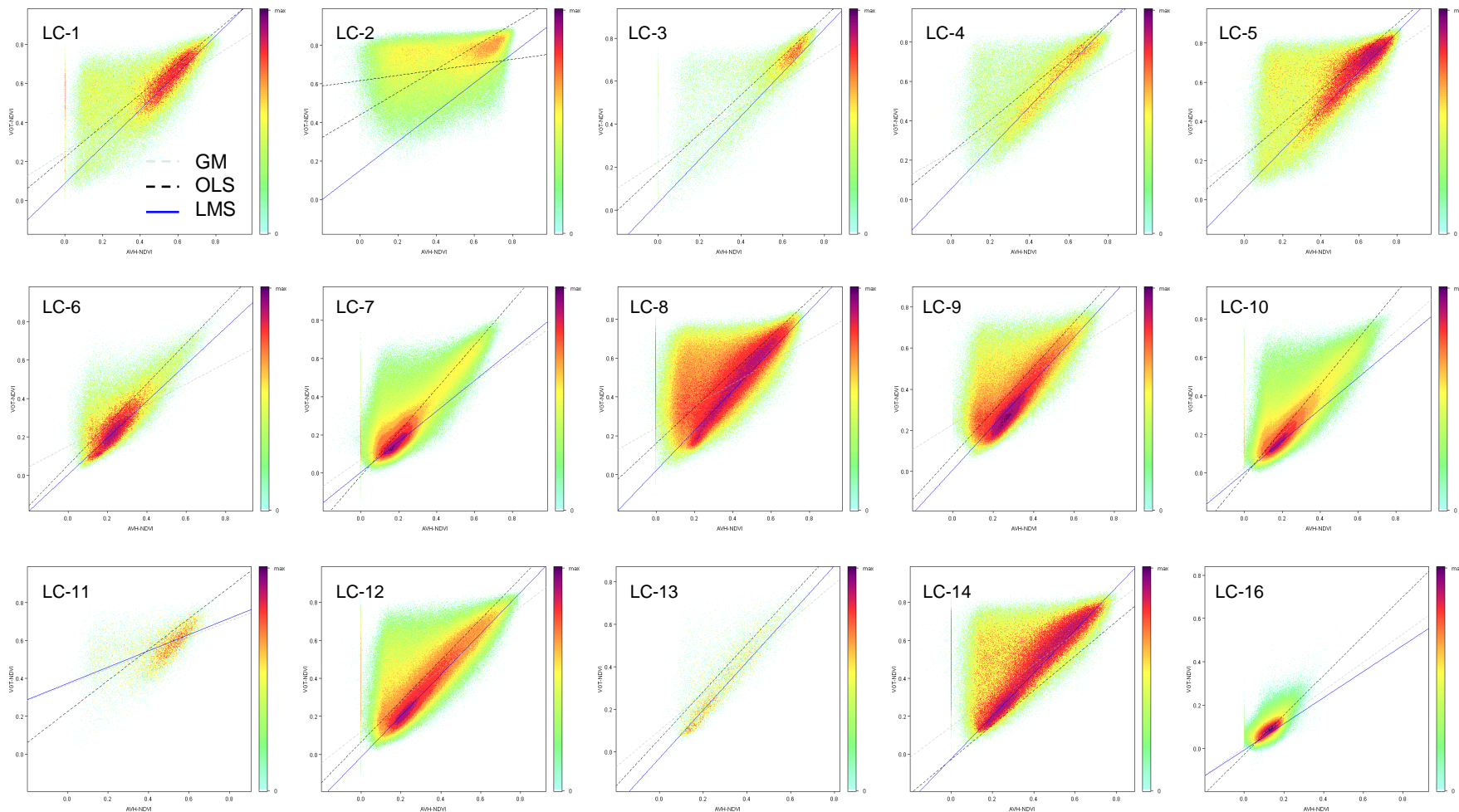
NDVI ( <i>x</i> variable)	Equation	Uncertainty (95% PI)
N-7 AVHRR, ROW, GAC	$y = -0.0646111 + 1.2409713x - 0.0304219x^2$	±0.0138
N-9 AVHRR, ROW, GAC	$y = -0.0621082 + 1.2487272x - 0.0307315x^2$	±0.0138
N-11 AVHRR, ROW, GAC	$y = -0.0606805 + 1.2456808x - 0.0335204x^2$	±0.0138
N-14 AVHRR, ROW, GAC	$y = -0.0571829 + 1.2372178x$	±0.0138
S-4 VEGETATION, TOC, CMGV	$y = 0.0156834 + 1.0610148x$	±0.061
EVI2 ( <i>x</i> variable)	Equation	Uncertainty (95% PI)
N-7 AVHRR, ROW, GAC	$y = -0.0403338 + 1.2400319x$	±0.088
N-9 AVHRR, ROW, GAC	$y = -0.0403338 + 1.2400319x$	±0.088
N-11 AVHRR, ROW, GAC	$y = -0.0403338 + 1.2400319x$	±0.088
N-14 AVHRR, ROW, GAC	$y = -0.0403338 + 1.2400319x$	±0.088
S-4 VEGETATION, TOC, CMGV	$y = 0.0085842 + 1.1557716x$	±0.037



# VEGETATION vs. AVHRR (v. 3) NDVI: Day-to-day Matched without View Angle Constraint



UNIVERSITY  
of HAWAII  
MĀNOA



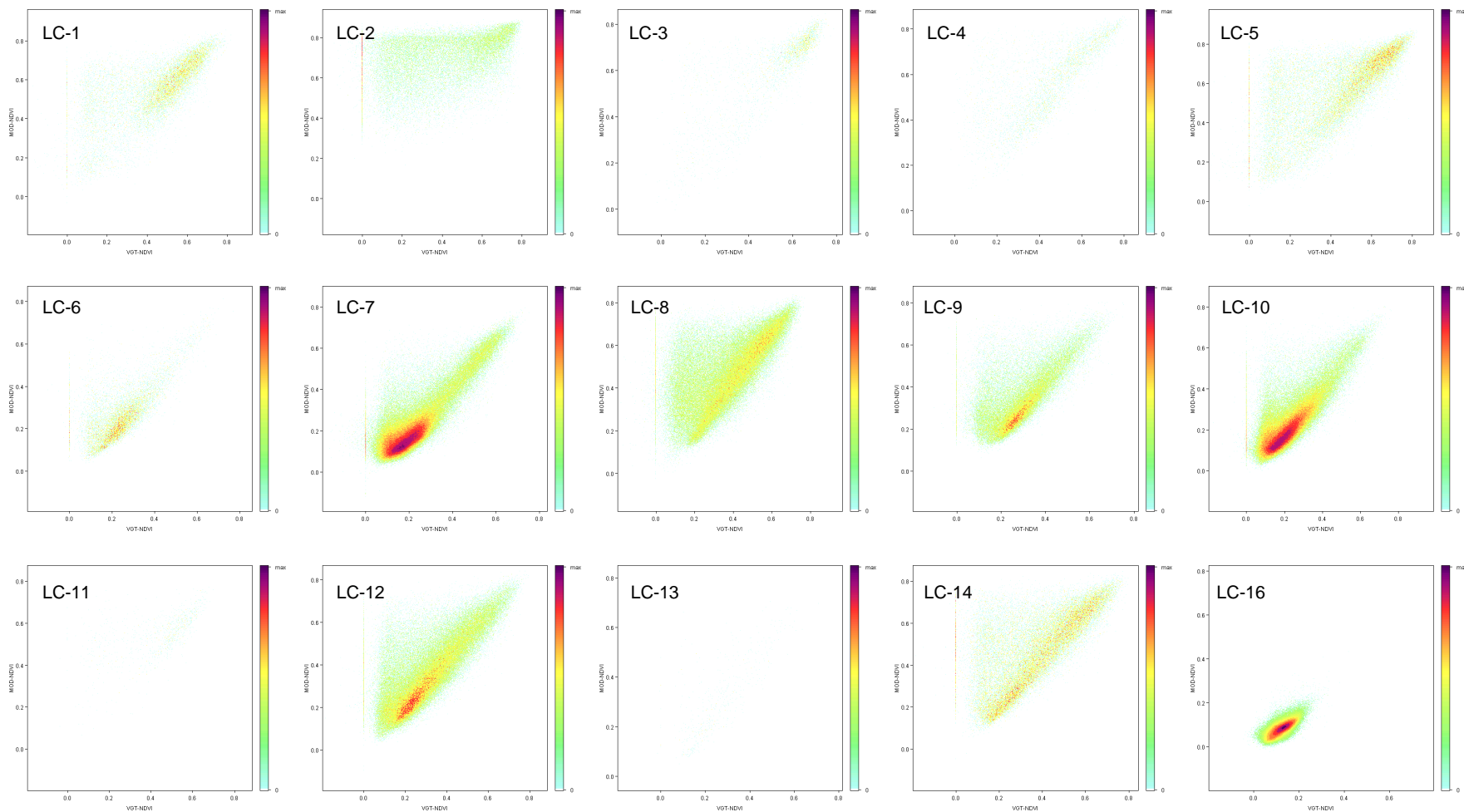


# VEGETATION vs. AVHRR (v. 3) NDVI:

## View zenith angle differences less than 10 degrees



UNIVERSITY  
of HAWAII  
MĀNOA





# Agreement Analysis & Coefficient

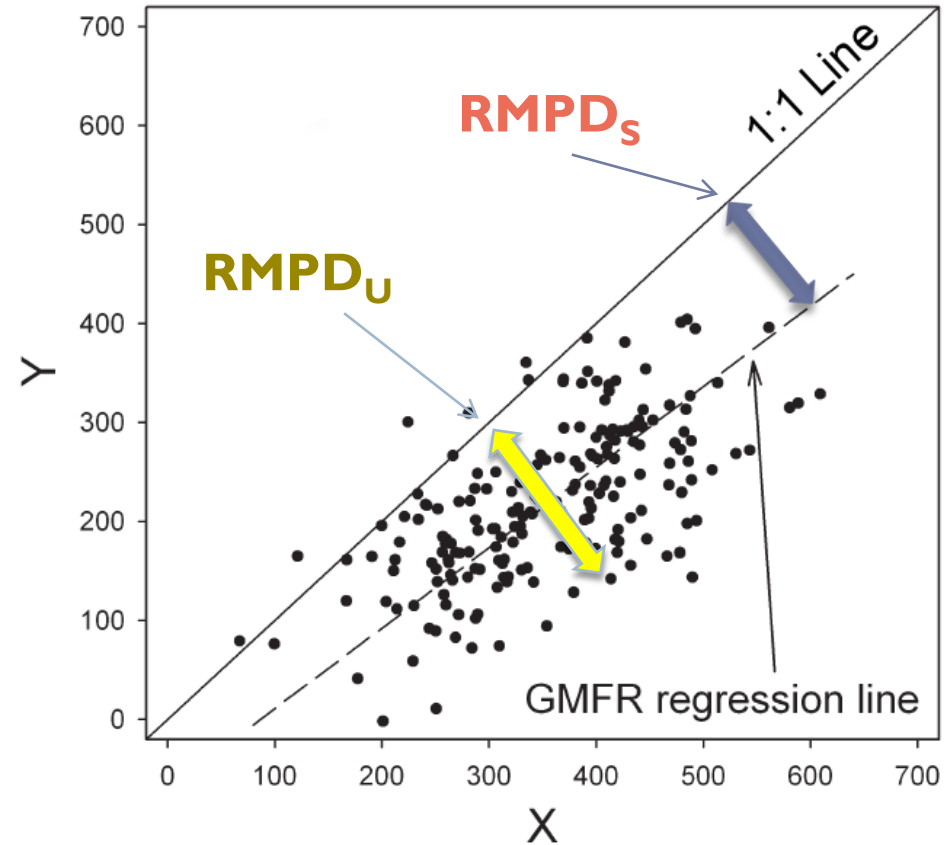
(Ji & Gallo, 2006)



UNIVERSITY  
of HAWAII  
MĀNOA

- ▶ The agreement coefficient (AC) considers that both x- and y-variables are subject to random errors.
- ▶ The AC measures the *systematic* ( $RMPD_S$ ) and *unsystematic* ( $RMPD_U$ ) components of the root mean square difference (RMSD):

$$RMSD = \sqrt{(RMPD_S)^2 + (RMPD_U)^2}$$



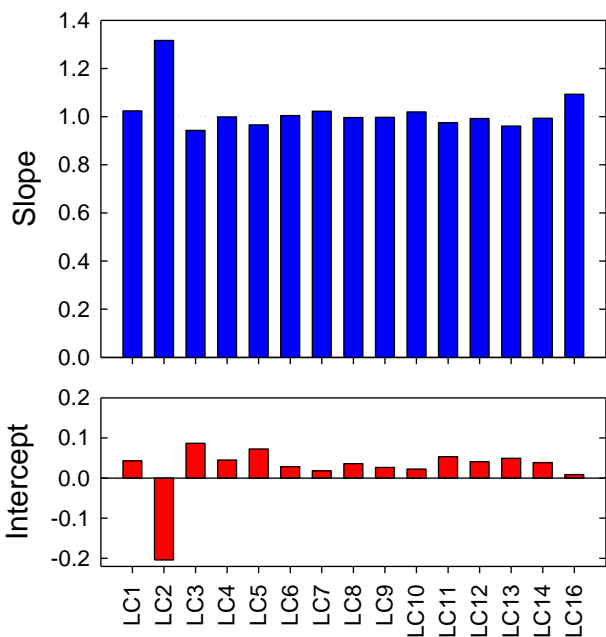


# Evaluation & Error Analysis: MODIS vs. VEGETATION NDVI

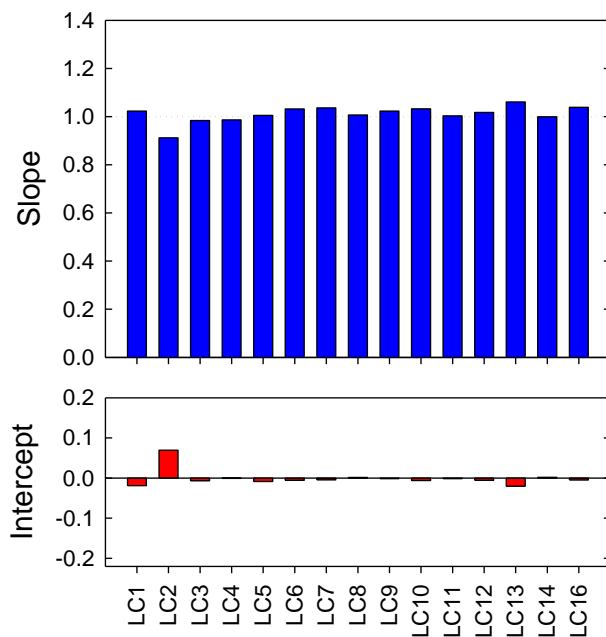


UNIVERSITY  
of HAWAII  
MĀNOA

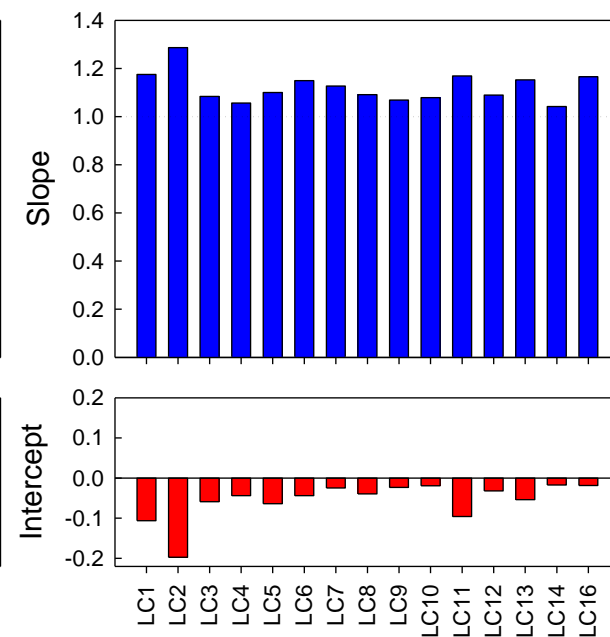
Original



Translated (GMFR)



Translated (OLS)

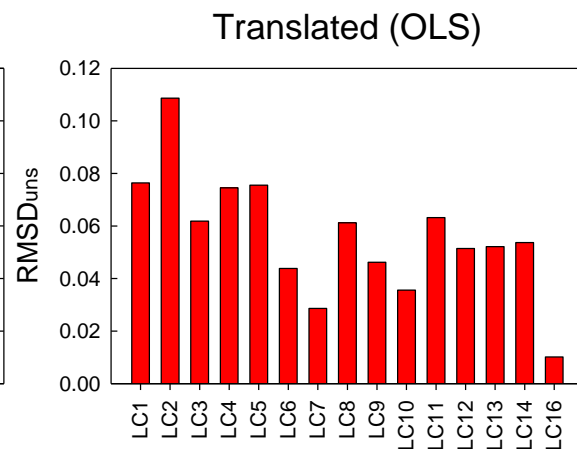
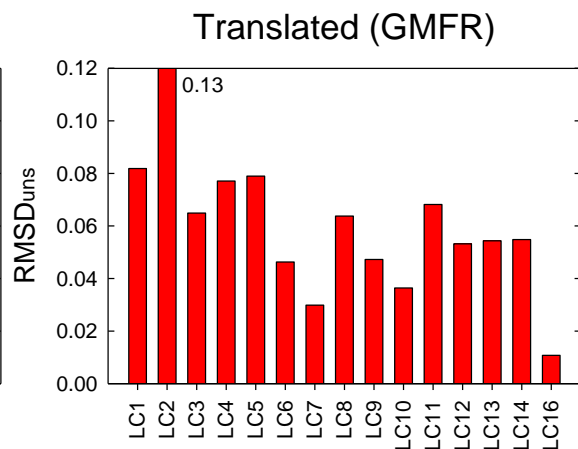
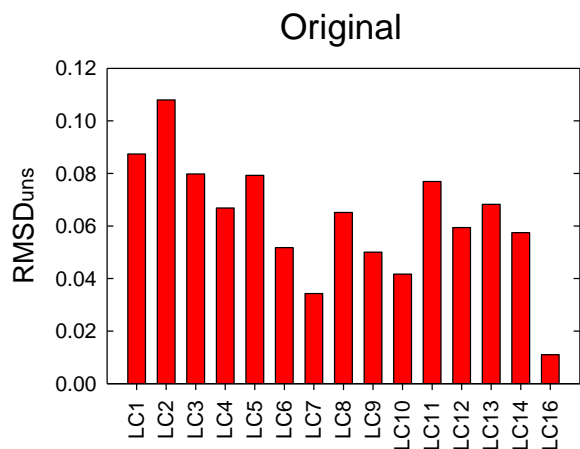
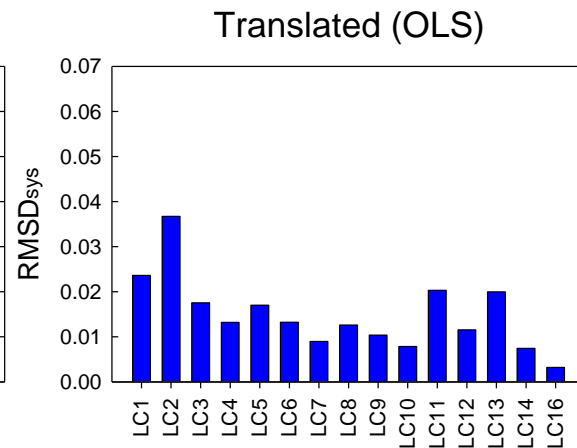
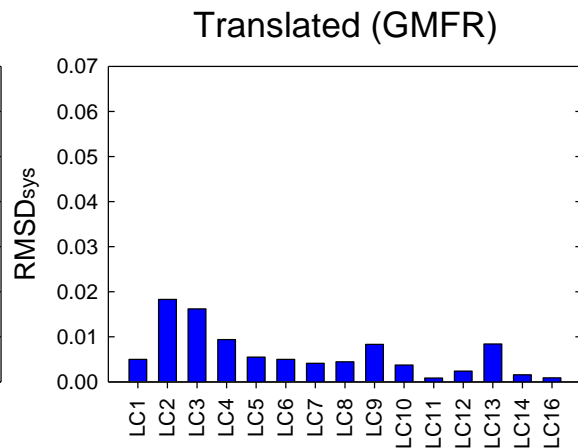
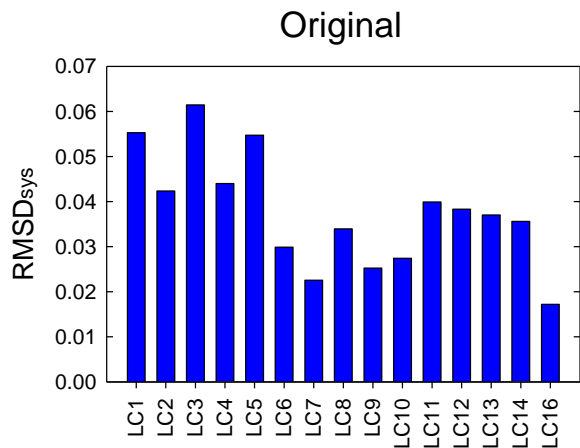




# Evaluation & Error Analysis: MODIS vs. VEGETATION NDVI



UNIVERSITY  
of HAWAII  
MĀNOA



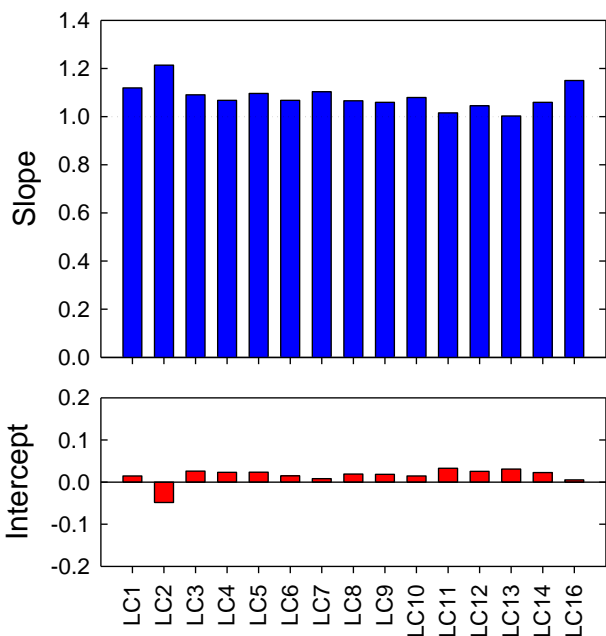


# Evaluation & Error Analysis: MODIS vs. VEGETATION EVI2

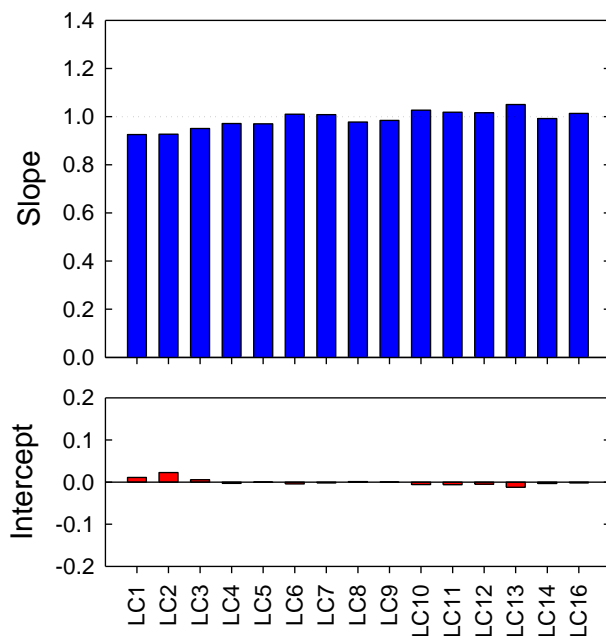


UNIVERSITY  
of HAWAII  
MĀNOA

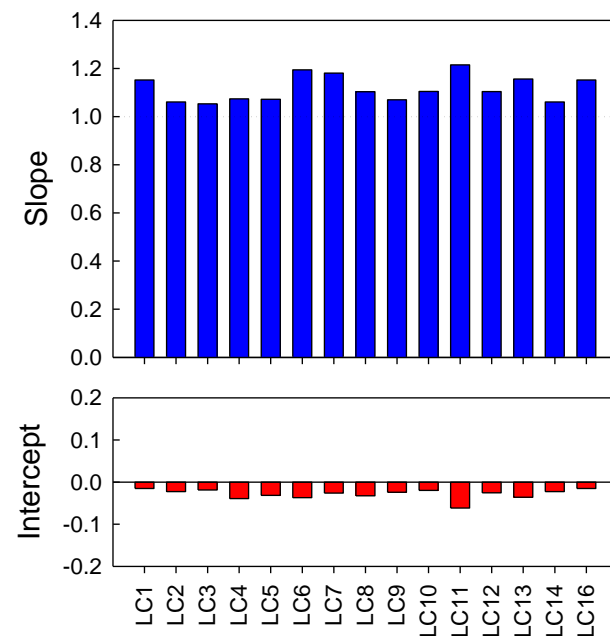
Original



Translated (GMFR)



Translated (OLS)

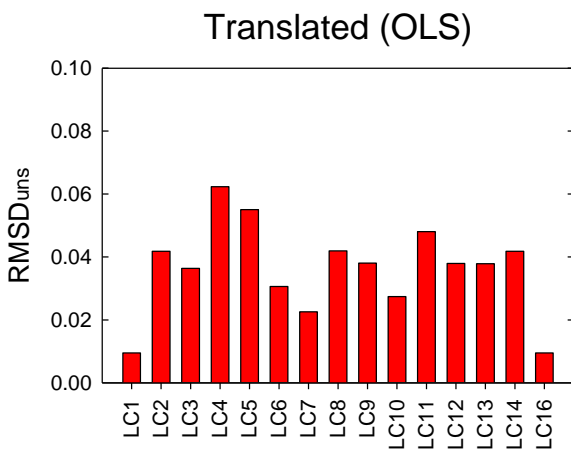
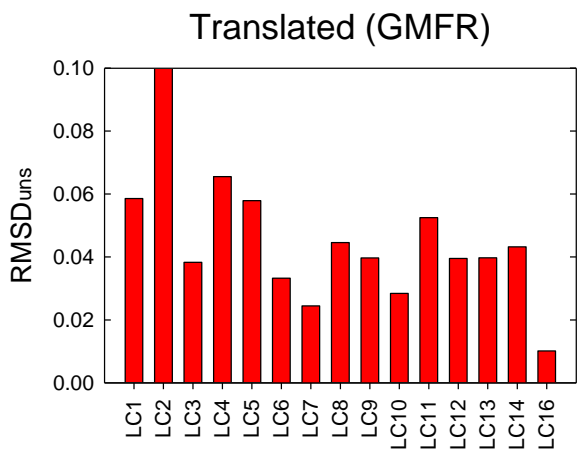
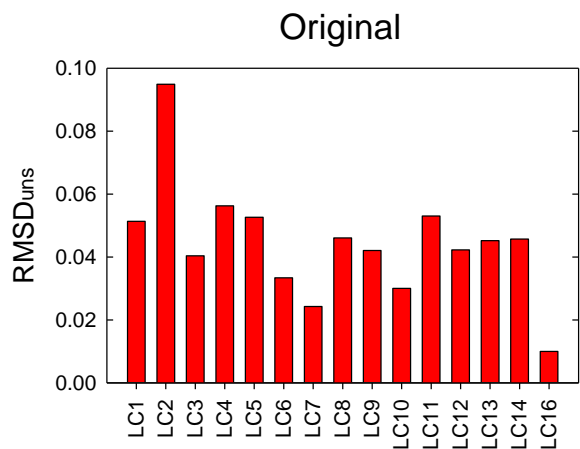
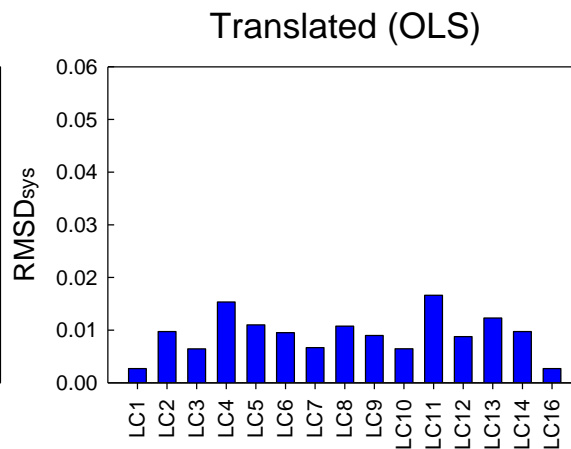
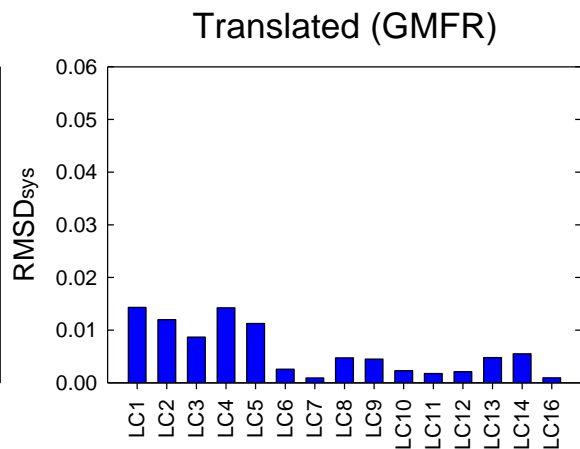
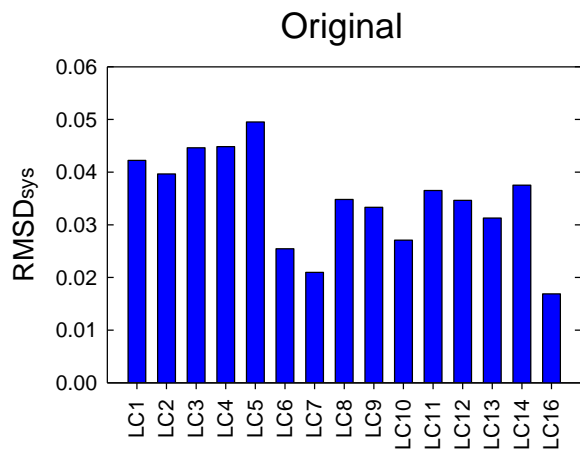




# Evaluation & Error Analysis: MODIS vs. VEGETATION EVI2



UNIVERSITY  
of HAWAII  
MĀNOA



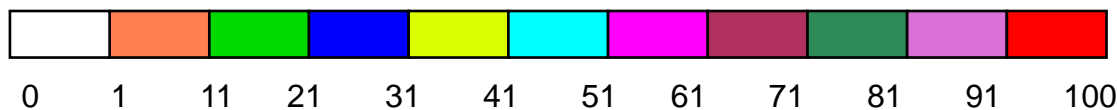
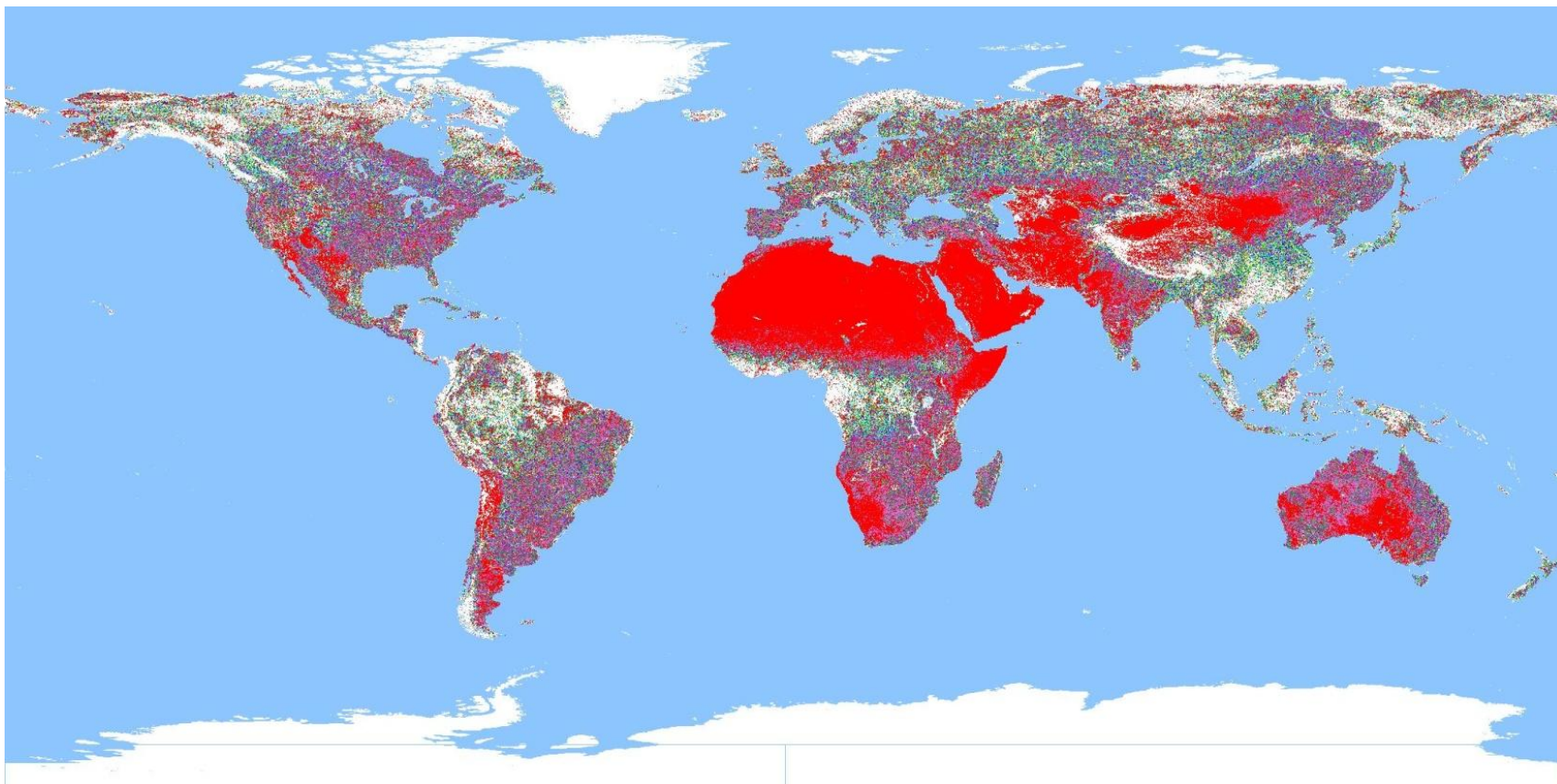


# Evaluation & Error Analysis: MODIS vs. VEGETATION NDVI



UNIVERSITY  
of HAWAII  
MĀNOA

Number of Pixels (%) with  $NDVI_{MOD} - NDVI_{MOD-like\ VGT4} < \pm 0.05$



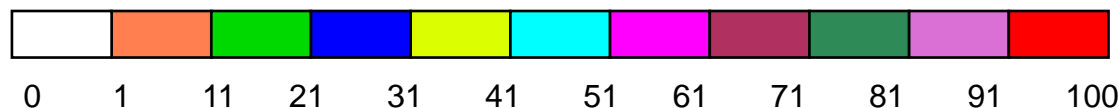
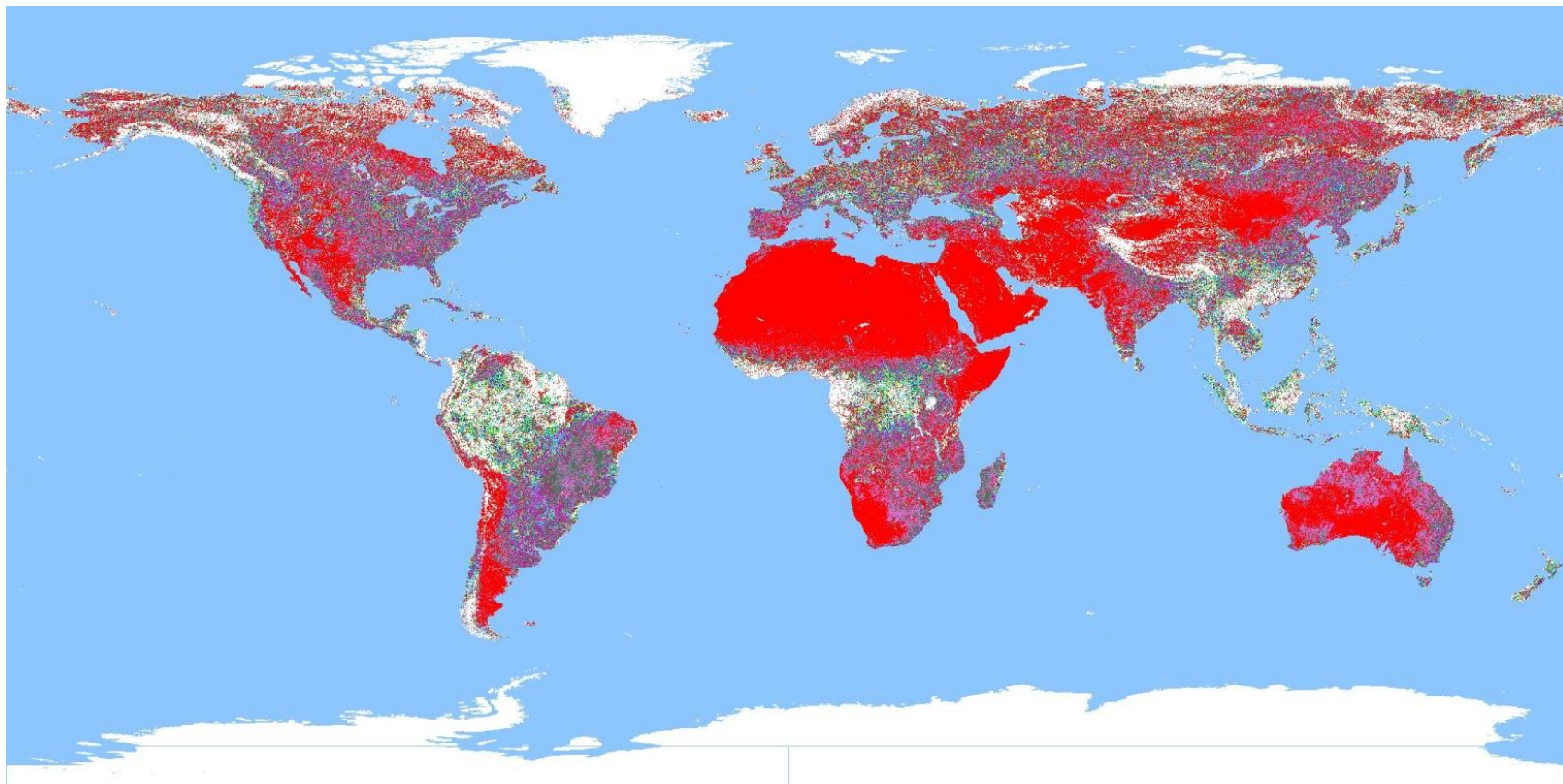


# Evaluation & Error Analysis: MODIS vs. VEGETATION EVI2



UNIVERSITY  
of HAWAII  
MĀNOA

Number of Pixels (%) with  $EVI2_{MOD} - EVI2_{MOD-like\ VGT4} < \pm 0.05$





# Issues & Future Work

---



UNIVERSITY  
of HAWAII®  
MĀNOA

- ▶ Validation: Landsat-5 TM time series
- ▶ LTDR improvements: ver. 2 vs. ver. 3
- ▶ Expansion of global & temporal coverage of Hyperion
- ▶ Incorporation of AOT into translation equations
- ▶ Evaluation of the integrity of GAC data with respect to MODIS CMG & mis-registration
- ▶ Terra vs. Aqua comparisons for establishing error bounds
- ▶ Observation geometries
  - ▶ Solar zenith angle: (1) overpass time, (2) drift
  - ▶ View zenith angle: BRDF



# Issues & Future Work

---



UNIVERSITY  
of HAWAII®  
MĀNOA

- ▶ Validation: Landsat-5 TM time series
- ▶ LTDR AVHRR algorithm improvements
  - ▶ BRDF-adjustment
  - ▶ Aerosol correction
- ▶ Terra vs. Aqua comparisons [to establish error bounds]
- ▶ Expansion of geographic & temporal coverage
- ▶ Use “differences” as dependent variable  $\leq$  then, test statistics become very severe & tough
- ▶ View zenith angle: It's not the absolute angle, but relative view zenith angle differences that would change the relationships.  $\leq$  this requires a further investigation.

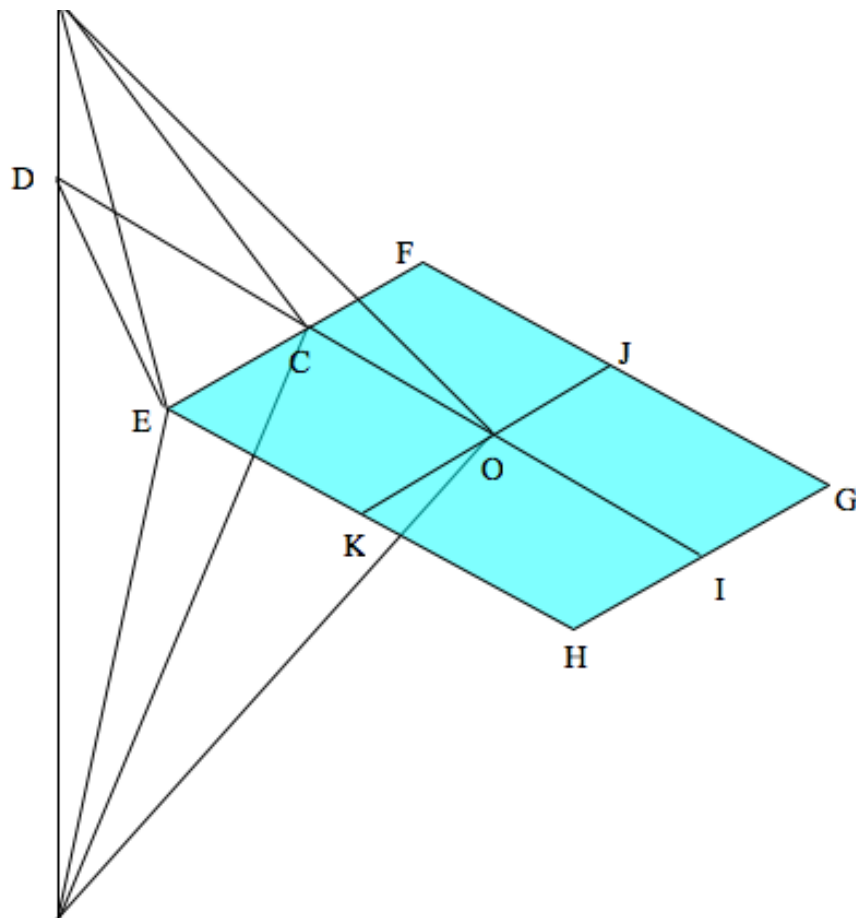


# Footprint Simulation



UNIVERSITY  
of HAWAII  
MĀNOA

Satellite



Center of the Earth

- ▶ Changes in footprint size and PSF modeled using a satellite orbital model (Tan et al., 2006)
- ▶ Daily basis over a 16-day period in June 2002
  - ▶ Terra MODIS
    - ▶ 250m/500m at nadir
  - ▶ NOAA-16 AVHRR
    - ▶ 1.1 km at nadir
  - ▶ SPOT-4 VEGETATION
    - ▶ 1.1 km at nadir



# Statement of Problem



- ▶ Different sensor/platform characteristics  
(orbit, scanning, point spread function, and geolocation error)

	Terra MODIS	Aqua MODIS	NOAA-14 AVHRR/2	NOAA-17 AVHRR/3	SPOT-4 VEGETATION
<b>Repeat cycle</b>	16 days		9 days		26 days
<b>Swath width</b>	110° ( $\pm 55^\circ$ ), 2,330 km (wiskbroom)		110° ( $\pm 55^\circ$ ), 2,800 km (wiskbroom)		101°, 2,250 km (pushbroom)
<b>Spatial resolution</b>	<u>Band 1 and 2</u> 250 m at nadir 0.4-by-0.7 km at $\theta_v = 55^\circ$ 0.5-by-1.2 km at edge ( $\theta_v = 65.4^\circ$ ) <u>Band 3 - 7</u> 500 m at nadir 0.8-by-1.4 km at $\theta_v = 55^\circ$ 1-by-2.4 km at edge ( $\theta_v = 65.4^\circ$ )		1.1 km at nadir 1.7-by-3 km at $\theta_v = 55^\circ$ 2-by-6 km at edge ( $\theta_v = 68^\circ$ )		1.15 km at nadir 1.15-by-2.2 km at $\theta_v = 55^\circ$ 1.15-by-2.5 km at edge ( $\theta_v = 60^\circ$ )

- ▶ Pairs of observations to be cross-compared having different coverage of surface areas

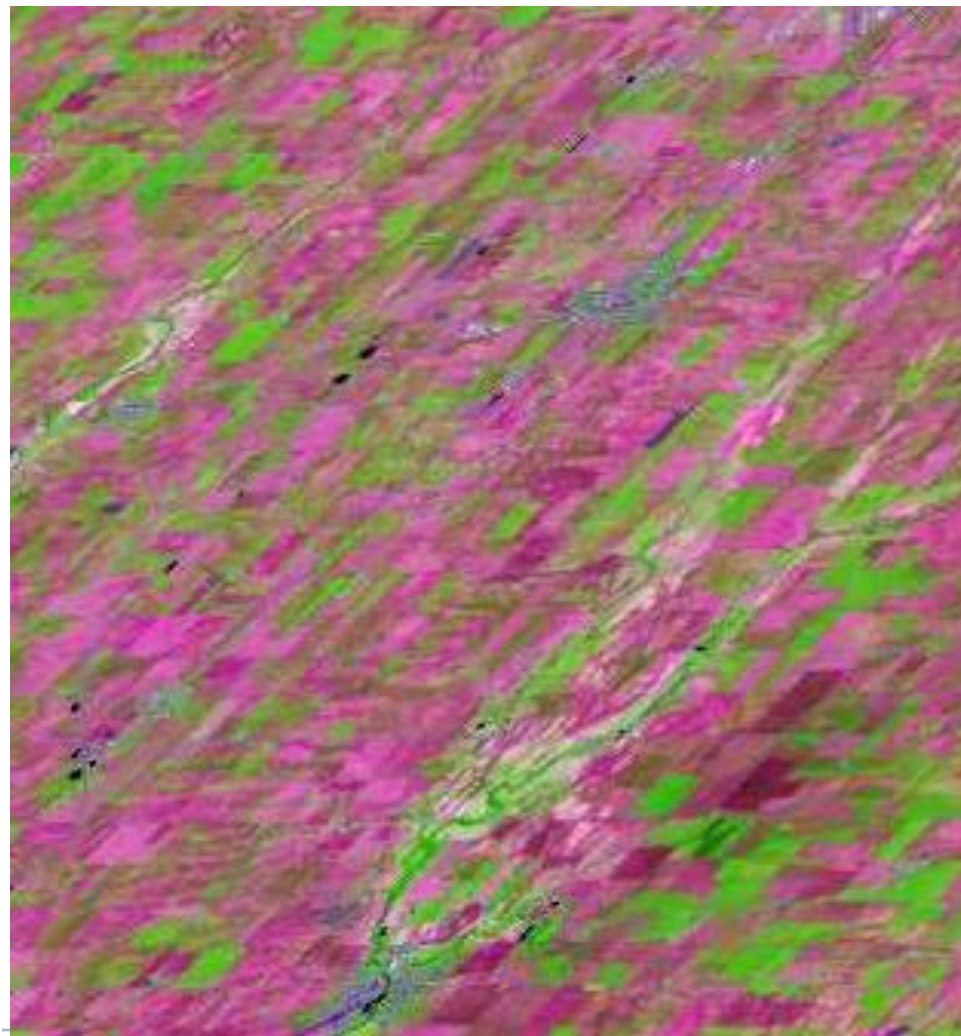


# Materials & Methods



UNIVERSITY  
of HAWAII  
MĀNOA

- ▶ Pixel deformation & mis-registration simulated on Landsat ETM+ imagery
- ▶ Landsat ETM+
  - ▶ June 2001, Bondville, Illinois, USA
  - ▶ Atmospherically-corrected with 6S



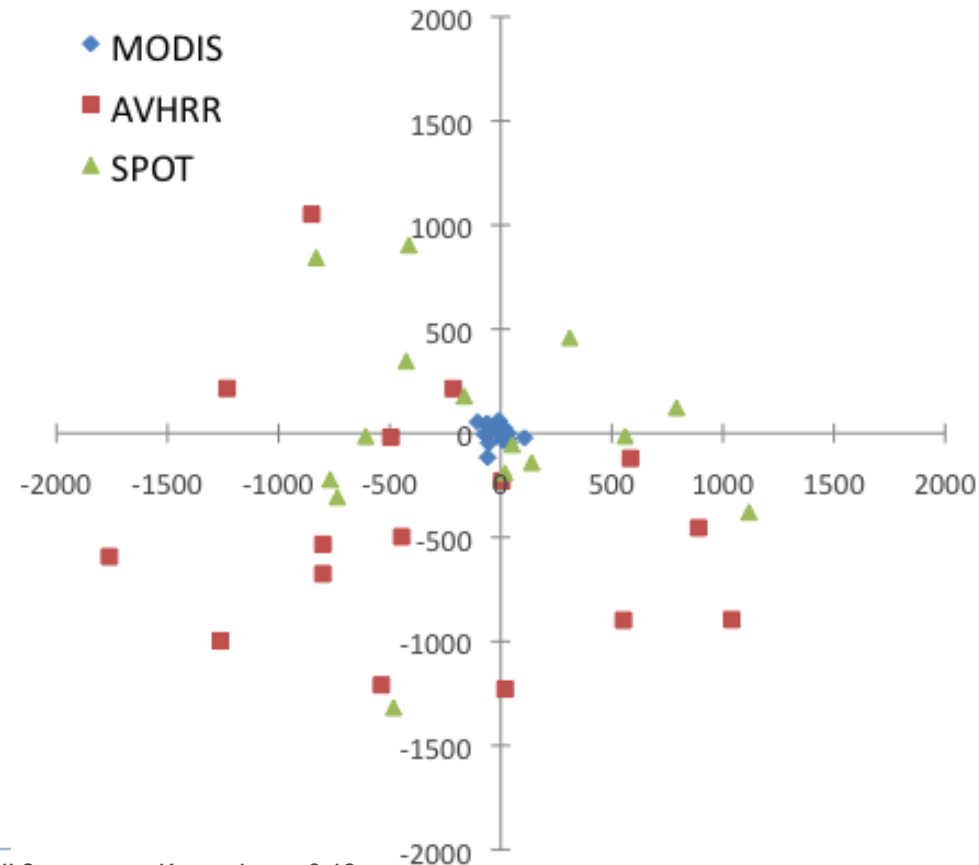


# Geolocation Error Simulation



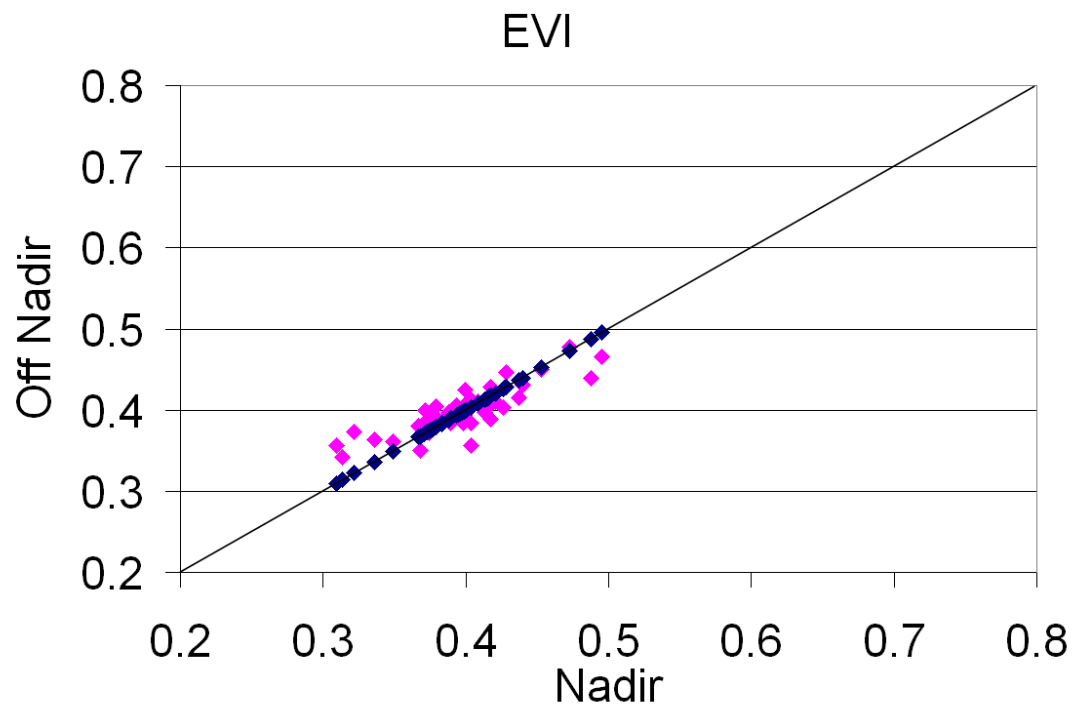
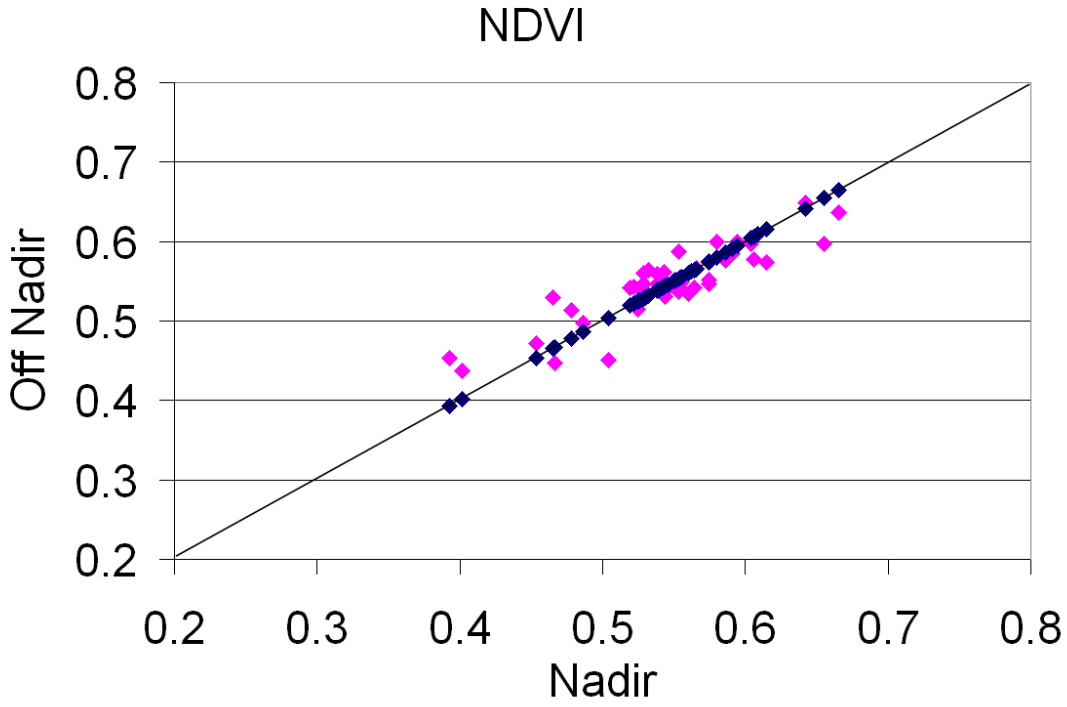
UNIVERSITY  
of HAWAII  
MĀNOA

- ▶ Extraction locations of aggregated pixels shifted (as a multiple of 30m)
- ▶ Directions and magnitudes of the shifts determined randomly
  - ▶ MODIS:  $\pm 40\text{m}$  (1 s.d.)
  - ▶ AVHRR:  $\pm 1,000\text{m}$
  - ▶ VEGETATION:  $\pm 800\text{m}$
- ▶ Two MODIS VIs
  - ▶ NDVI
  - ▶ EVI (Enhanced Vegetation Index)



1: View Zenith Angle Effects

# AVHRR Off Nadir vs Nadir

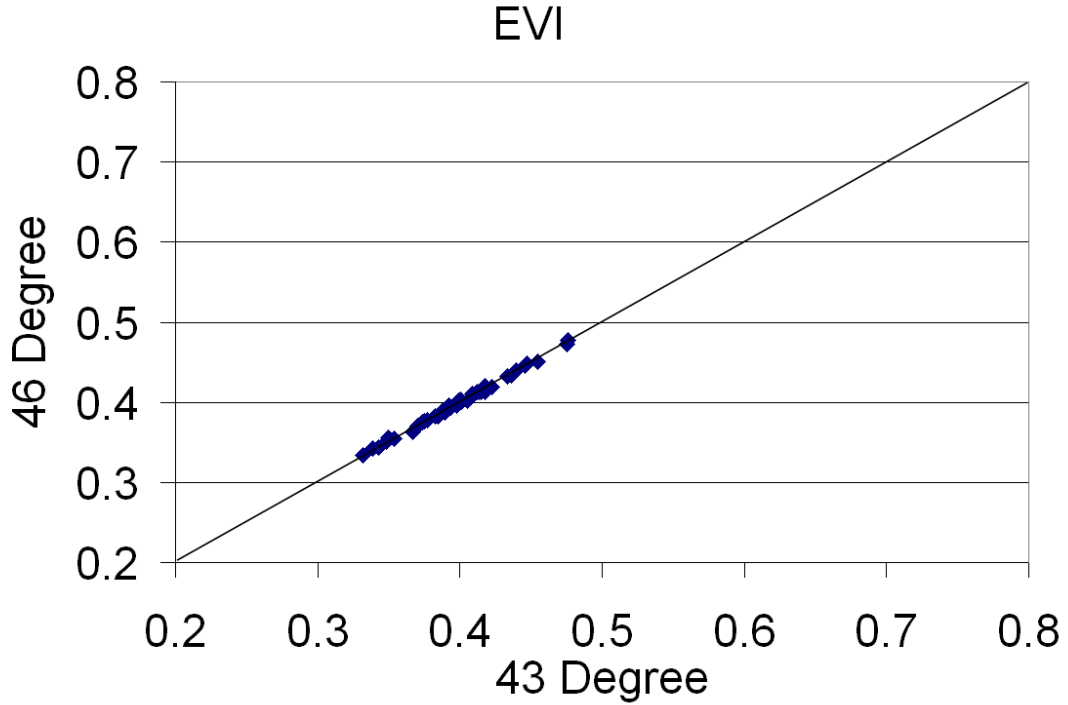
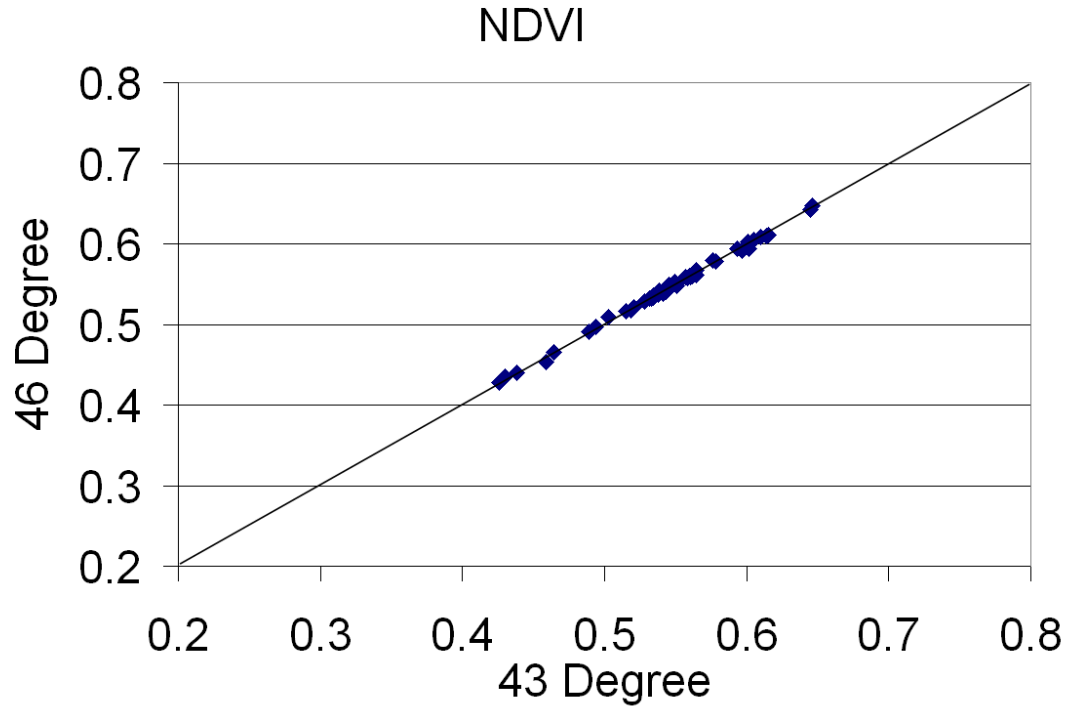


◆ ViewZenith=55  
◆ ViewZenith=5

1: View Zenith Angle Effects

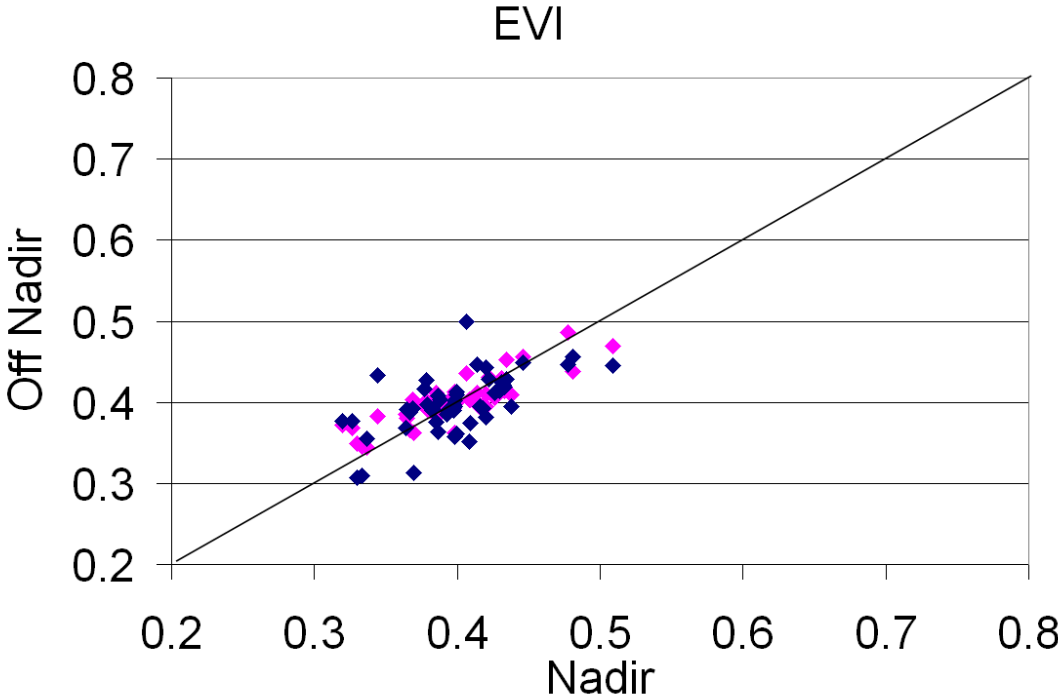
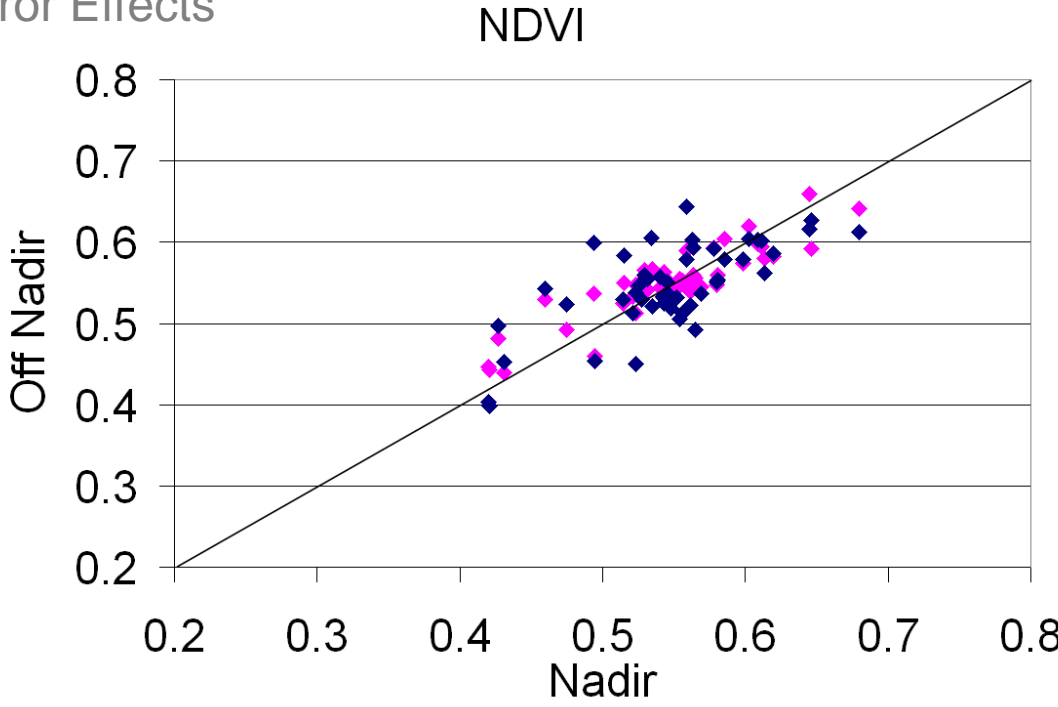
# AVHRR

## Off Nadir vs Off Nadir



## 2: View Zenith Angle & Geolocation Error Effects

# AVHRR Off Nadir vs Nadir

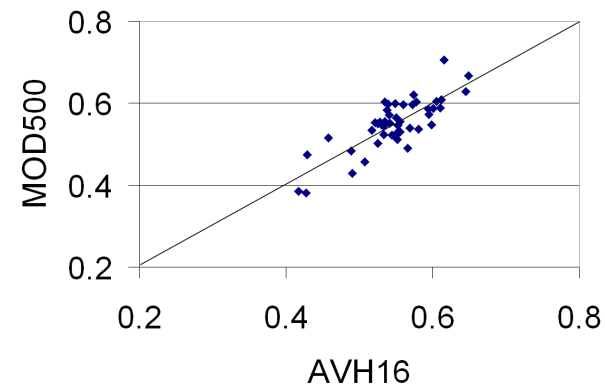
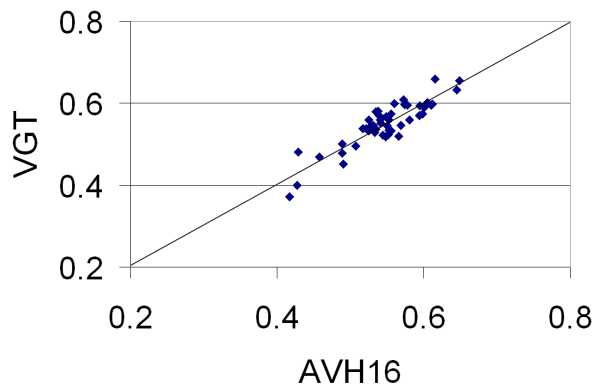
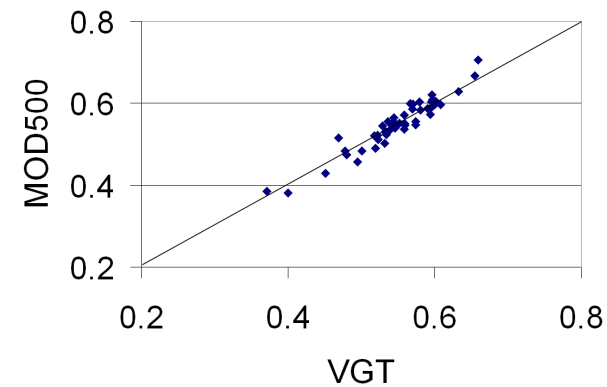


◆ ViewZenith=55  
◆ ViewZenith=5

Geolocation Error (m)  
X=-480, Y=30 (Angle=55)  
X=540, Y=-900 (Angle=5)

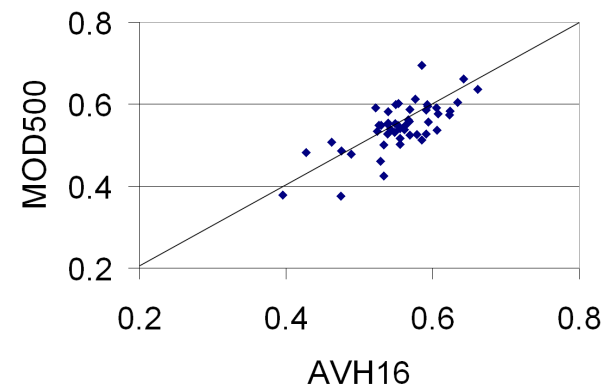
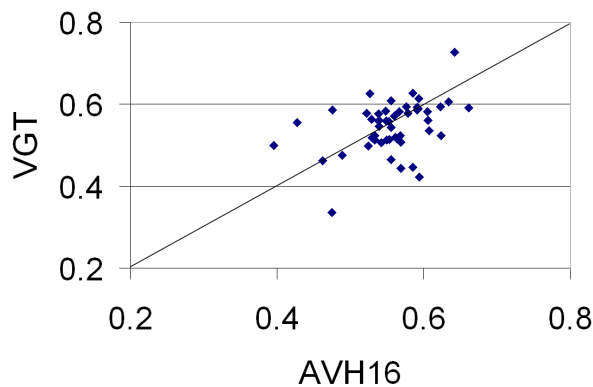
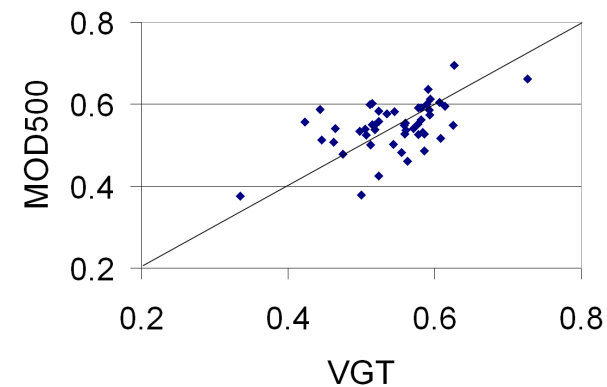
# Sensor Comparison ~ NDVI

DOY=175



MOD500 = 26° (X=-2, Y=0), AVH16 = 43° (X=0, Y=-8), VGT = 50° (X=1, Y=-6)

DOY=181



MOD500 = 37° (X=1, Y=-1), AVH16 = 45° (X=-27, Y=-18), VGT = 36° (X=68, Y=-15)

(Miura et al., 2010, in prep.)

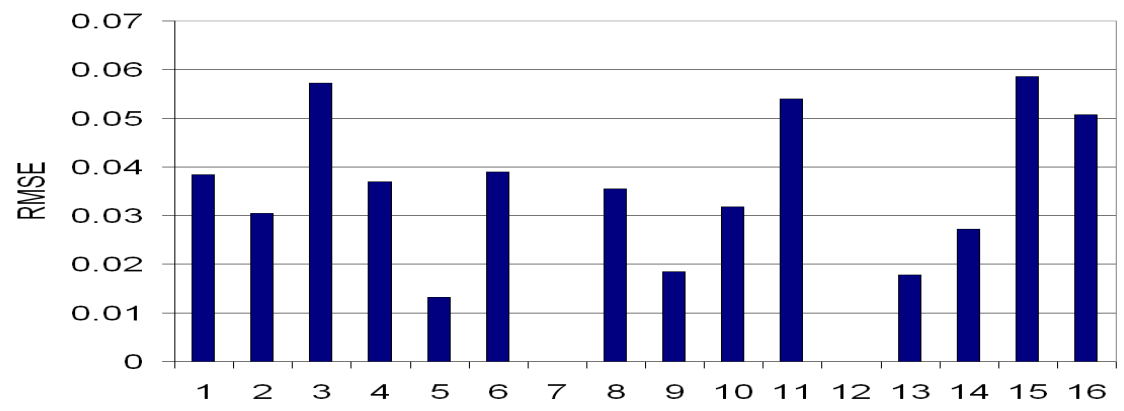


# Daily RMSE ~NDVI

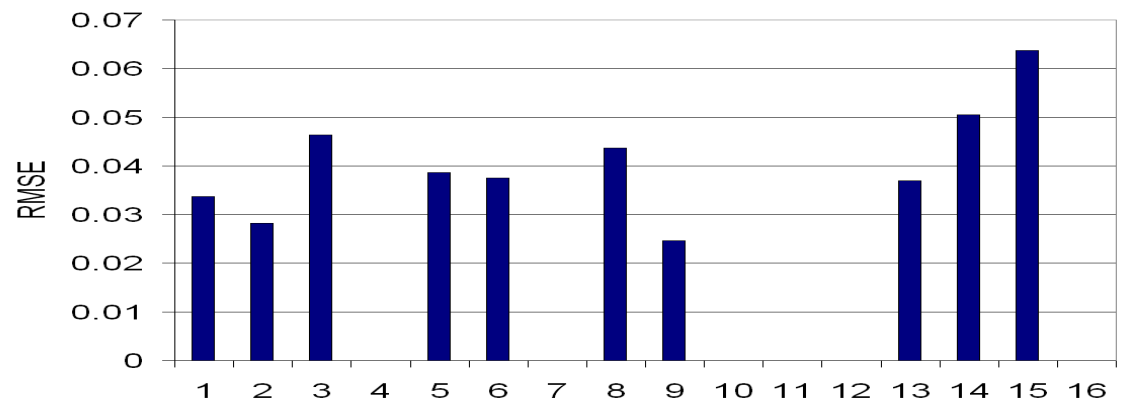


UNIVERSITY  
HAWAII  
DA

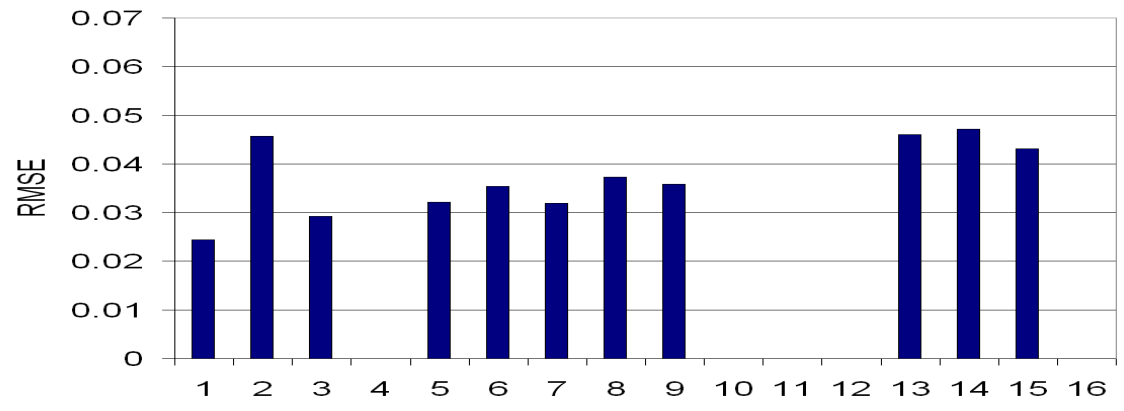
MOD500 vs VGT



VGT vs AVHI16



MOD500 vs AVHI16

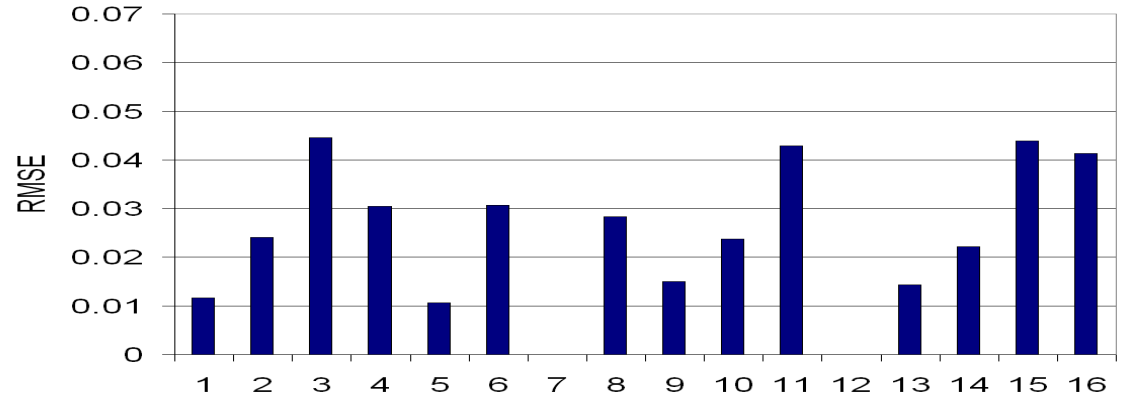




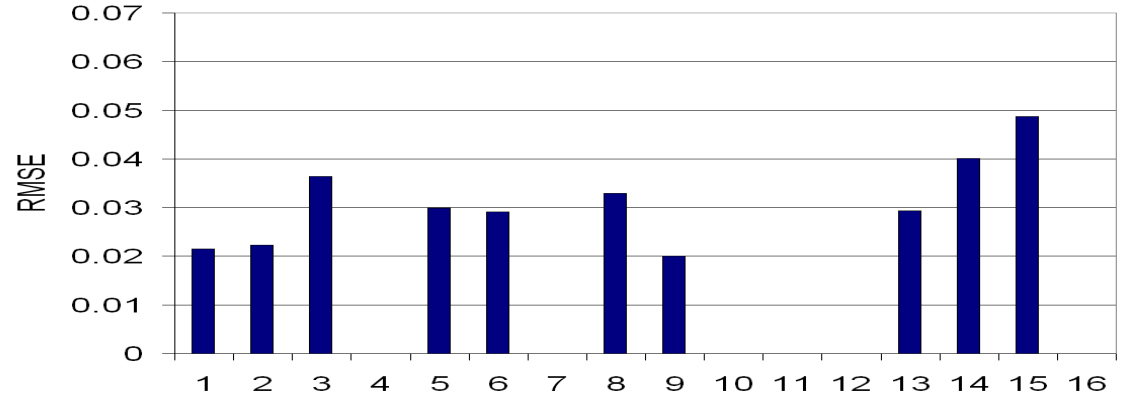
# Daily RMSE ~EVI



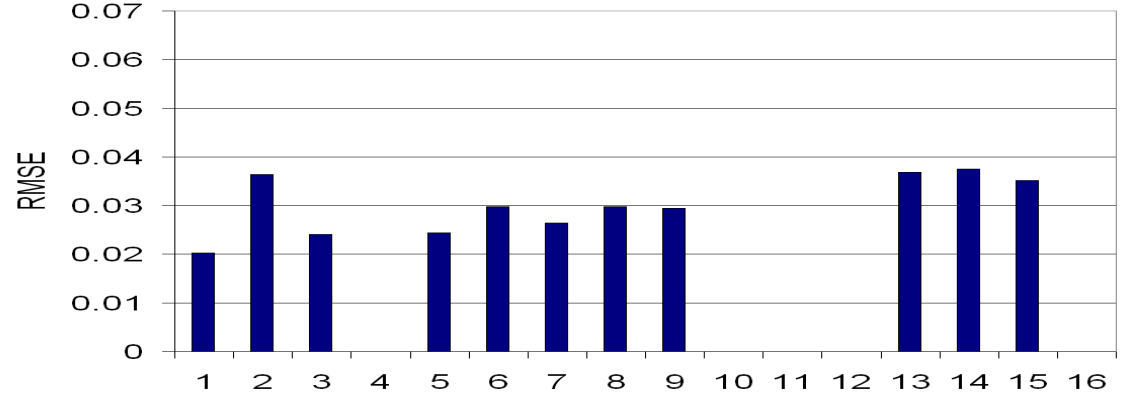
MOD500 vs VGT



VGT vs AVHI6



MOD500 vs AVHI6

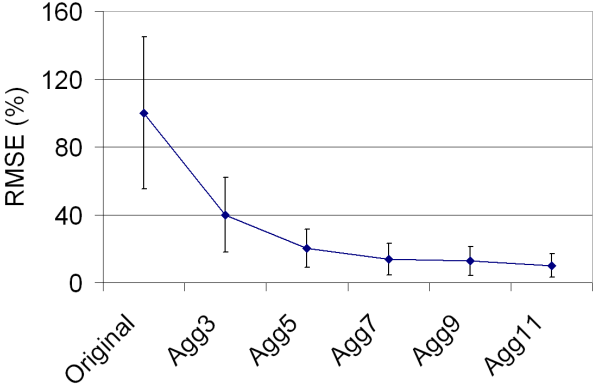
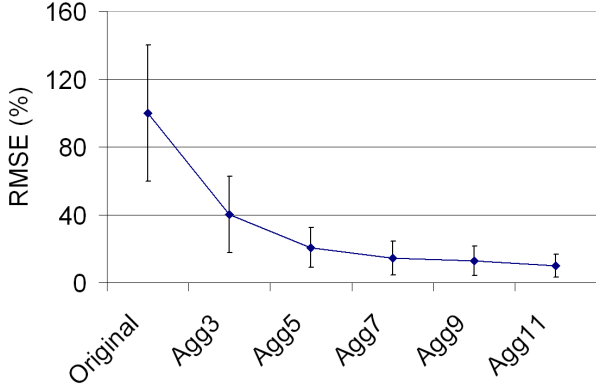


### 3: Pixel Averaging

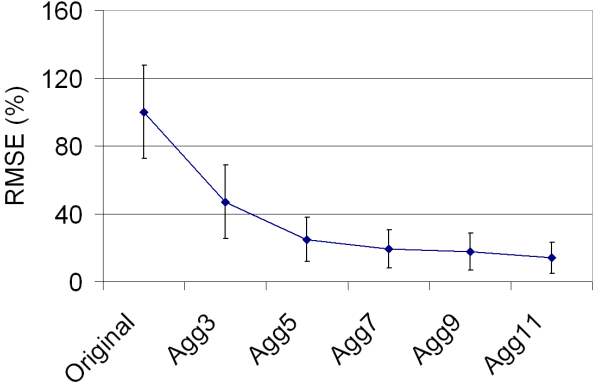
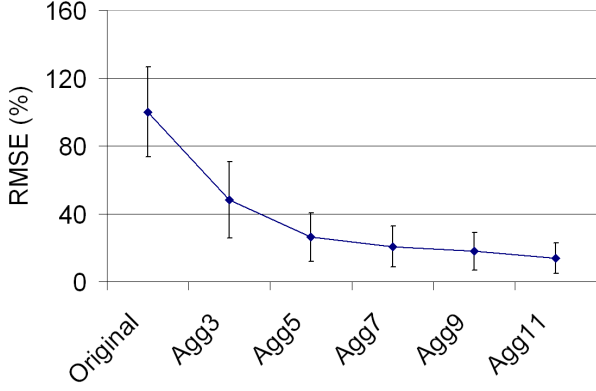
## NDVI

## EVI

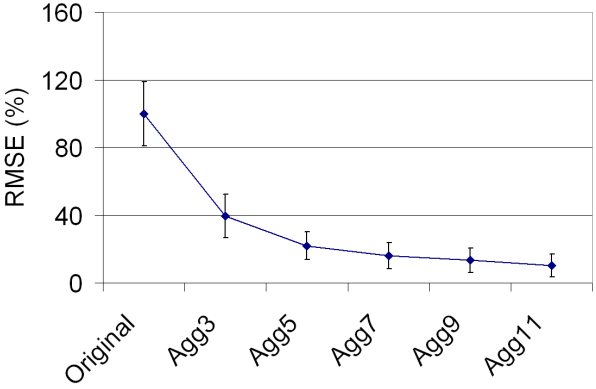
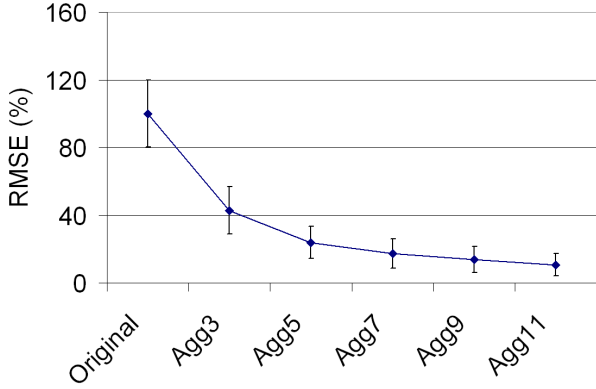
MOD500 vs VGT



VGT vs AVHRR



MOD500 vs AVHRR



# Backup Slides



# Scaling Uncertainties



UNIVERSITY  
of HAWAII  
MĀNOA

- ▶ MODIS CMG (5 km) vs. AVHRR GAC (4-by-1 km)
  - ▶ Potentially different sensitivities to surface changes

$$NDVI_{\text{coarse}} = \frac{\sum_{i=1}^n \rho_{\text{MOD},i}(\text{NIR}) - \sum_{i=1}^n \rho_{\text{MOD},i}(\text{red})}{\sum_{i=1}^n \rho_{\text{MOD},i}(\text{NIR}) + \sum_{i=1}^n \rho_{\text{MOD},i}(\text{red})} = \frac{\sum_{i=1}^n (\rho_{\text{MOD},i}(\text{NIR}) - \rho_{\text{MOD},i}(\text{red}))}{\sum_{i=1}^n (\rho_{\text{MOD},i}(\text{NIR}) + \rho_{\text{MOD},i}(\text{red}))}$$

$$NDVI_{\text{fine}} = \sum_{i=1}^n NDVI_{\text{GAC},i} = \sum_{i=1}^n \left( \frac{\rho_{\text{GAC},i}(\text{NIR}) - \rho_{\text{GAC},i}(\text{red})}{\rho_{\text{GAC},i}(\text{NIR}) + \rho_{\text{GAC},i}(\text{red})} \right)$$

$$D \equiv NDVI_{\text{coarse}} - NDVI_{\text{fine}} \neq 0$$



# Scaling Uncertainties



UNIVERSITY  
of HAWAII  
MĀNOA

- ▶ MODIS CMG (5 km) vs. AVHRR GAC (4-by-1 km)
- ▶ Potentially different sensitivities to surface changes

$$NDVI_{\text{fine}} = \sum_{i=1}^n f_i \cdot NDVI_i = \sum_{i=1}^n f_i \cdot \left( \frac{\rho_{\text{nir},i} - \rho_{\text{red},i}}{\rho_{\text{nir},i} + \rho_{\text{red},i}} \right)$$

$$NDVI_{\text{coarse}} = \frac{\sum_{i=1}^n f_i \cdot \rho_{\text{nir},i} - \sum_{i=1}^n f_i \cdot \rho_{\text{red},i}}{\sum_{i=1}^n f_i \cdot \rho_{\text{nir},i} + \sum_{i=1}^n f_i \cdot \rho_{\text{red},i}} = \frac{\sum_{i=1}^n f_i \cdot (\rho_{\text{nir},i} - \rho_{\text{red},i})}{\sum_{i=1}^n f_i \cdot (\rho_{\text{nir},i} + \rho_{\text{red},i})}$$

$$D \equiv NDVI_{\text{fine}} - NDVI_{\text{coarse}} \neq 0$$





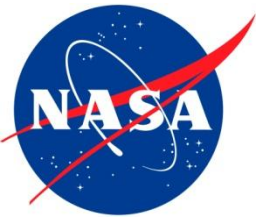
# Data processing

---



UNIVERSITY  
of HAWAII®  
MĀNOA

- ▶ Data screening (from Univ.Arizona)
- ▶ Extended water mask
- ▶ Additional cloud mask (band and NDVI thresholds)
- ▶ Sampling data
  - ▶ 5% or 40% of paired observations were selected randomly for each land cover class without any overlap for all time series data records.

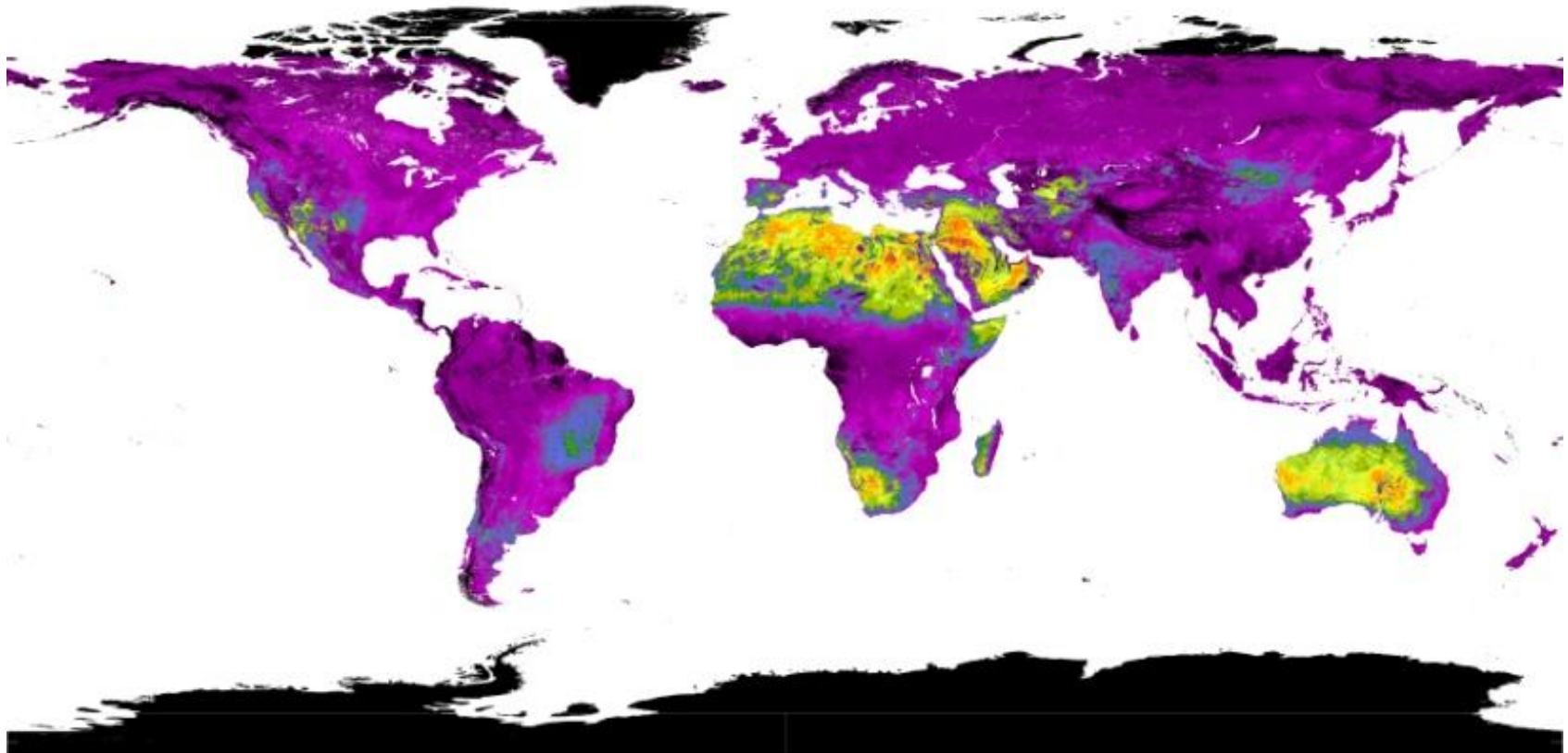


# Additional Data Screening (cont.)



UNIVERSITY  
of HAWAII  
MĀNOA

MODIS vs. VEGETATION





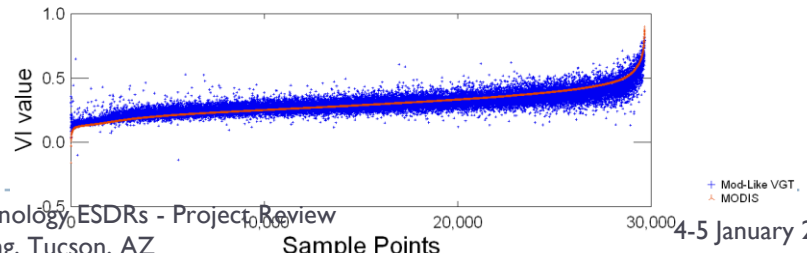
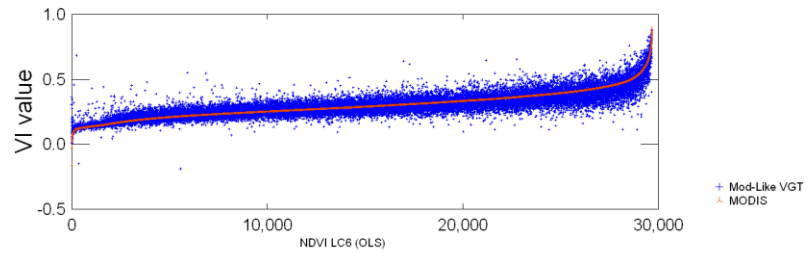
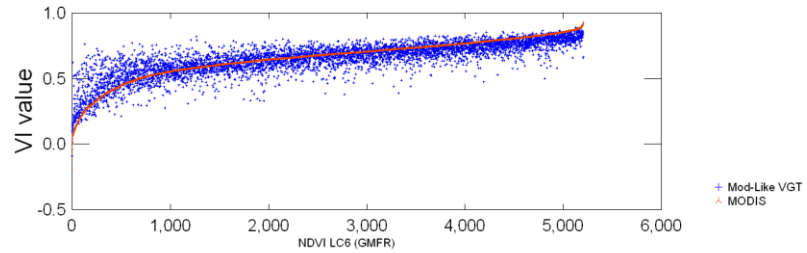
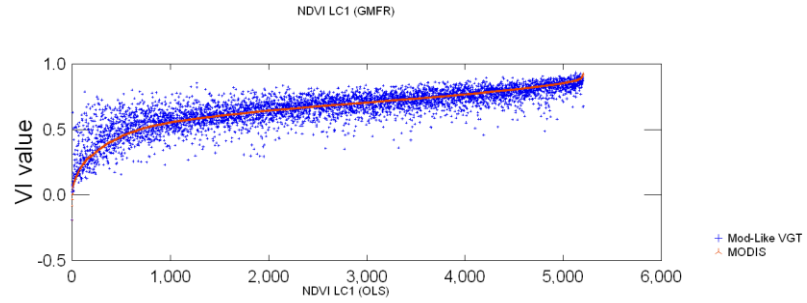
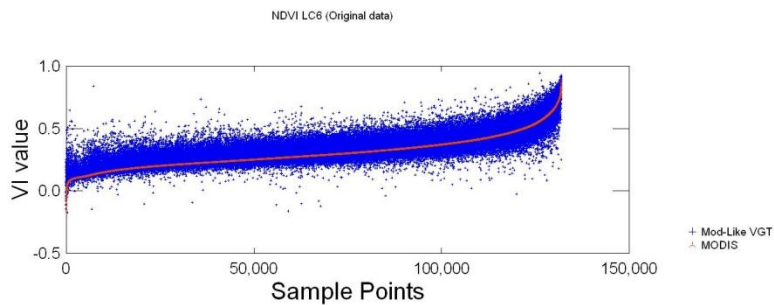
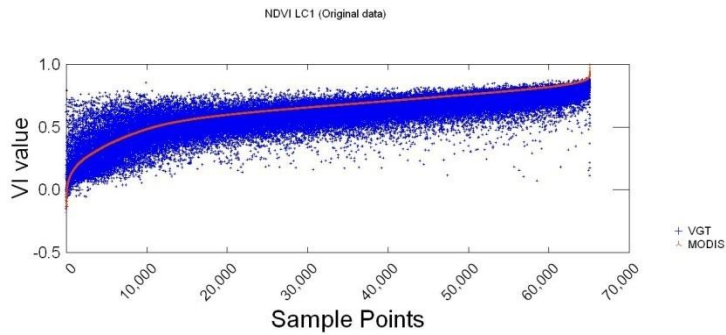
## 4. Regression Analysis

---

- ▶ **Regression Analysis**
  - ▶ Ordinary Least Squares
  - ▶ Geometric Mean Functional Relationship
  - ▶ Least Median
- ▶ **Agreement Analysis**
  - ▶ Mean product-difference
  - ▶ RMSD of systematic and unsystematic
  - ▶ Agreement coefficient
- ▶ **Error Analysis**
  - ▶ Classified percentage error and visual interpretation



# 4. Regression Analysis



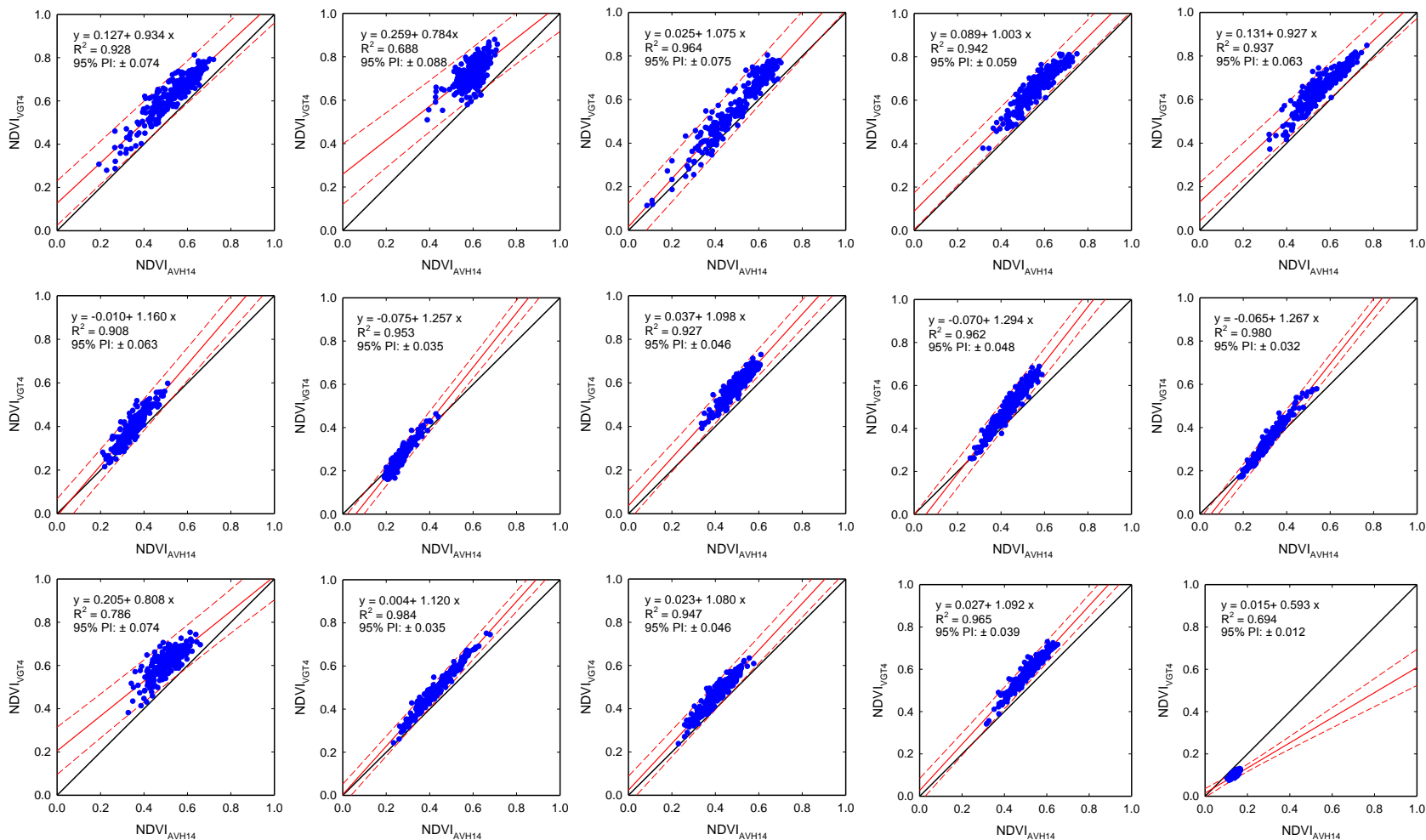


# Stratification Method 1: Plots with Equations & 95% PI



UNIVERSITY  
of HAWAII  
MĀNOA

## VGT4-NDVI vs. AVH14-NDVI



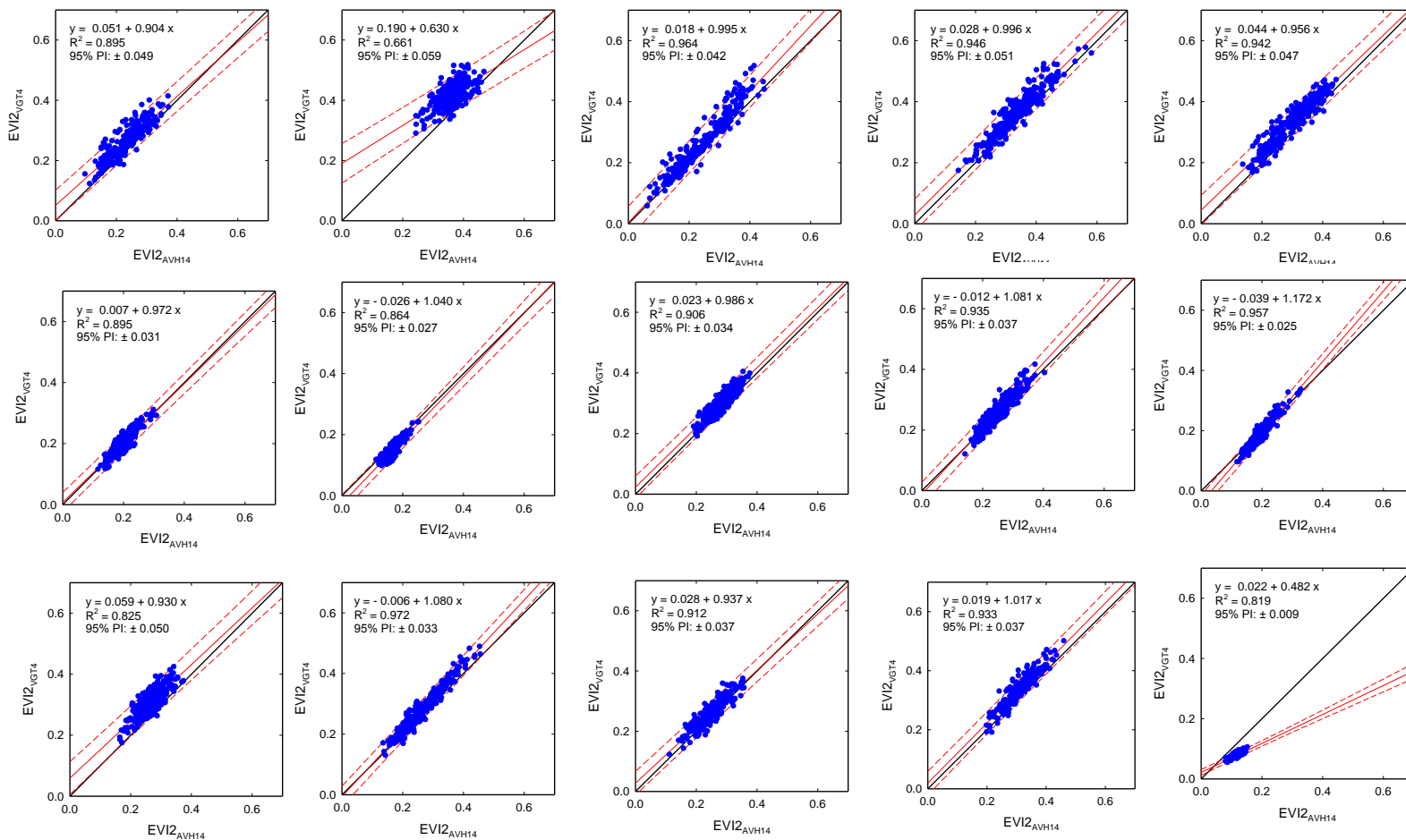


# Stratification Method 1: Plots with Equations & 95% PI



UNIVERSITY  
of HAWAII  
MĀNOA

Result: Regression analysis (AVH-EVI2 vs.VGT-EVI2)





# Evaluation Methods



UNIVERSITY  
of HAWAII  
MĀNOA

- ▶ The derived VI translation equations applied to translate
  - ▶ AVHRR VIs to “VEGETATION-like” VIs
  - ▶ VEGETATION VIs to “MODIS-like” VIs
- ▶ The remaining 20 % of the paired observations used
- ▶ The following statistics used to compare among stratification methods

$$\text{Bias}[\hat{\mathcal{G}}] = E[\hat{\mathcal{G}} - \mathcal{G}]$$

$$\text{Precision}[\mathcal{G}] = \sqrt{E(\mathcal{G} - E(\mathcal{G}))^2}$$

$$\text{RMSE}[\hat{\mathcal{G}}] = \sqrt{E((\hat{\mathcal{G}} - \mathcal{G})^2)}$$

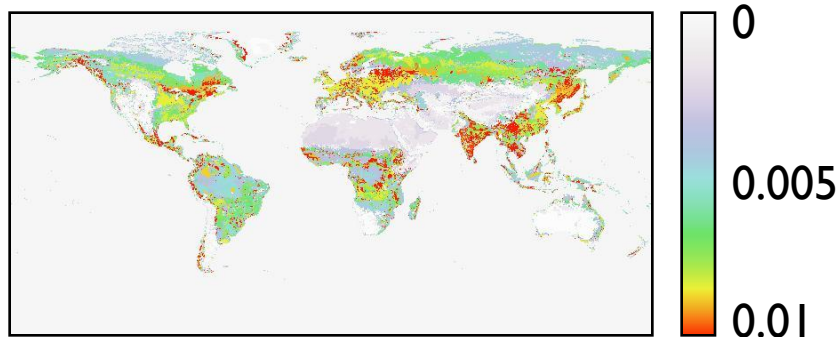




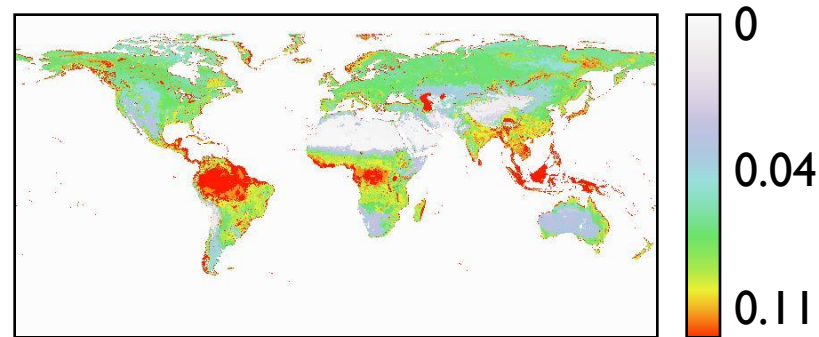
# Validation VI (Translated-AVH vs SPOT-4)



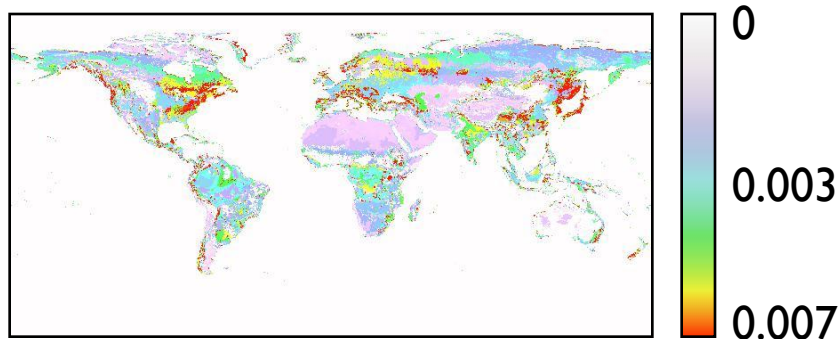
UNIVERSITY  
of HAWAII  
MĀNOA



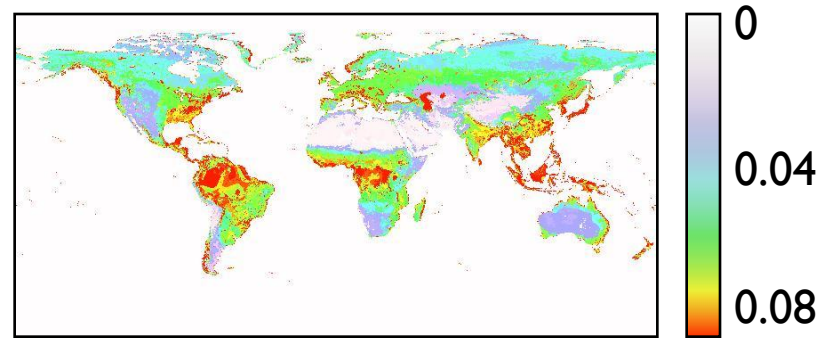
NDVI: Bias (ME)



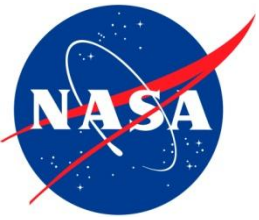
Accuracy (RMSE)



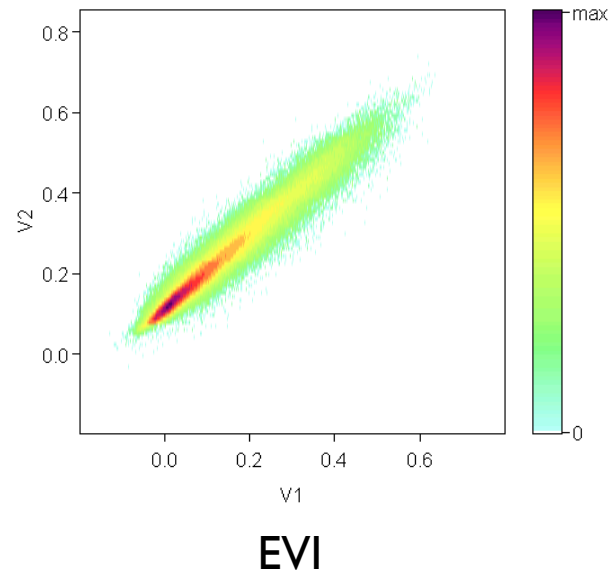
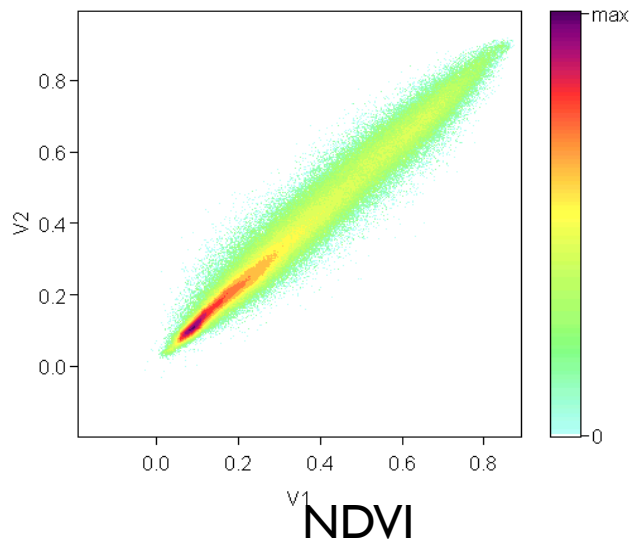
EVI2: Bias (ME)



Accuracy (RMSE)



UNIVERSITY  
of HAWAII®  
MĀNOA

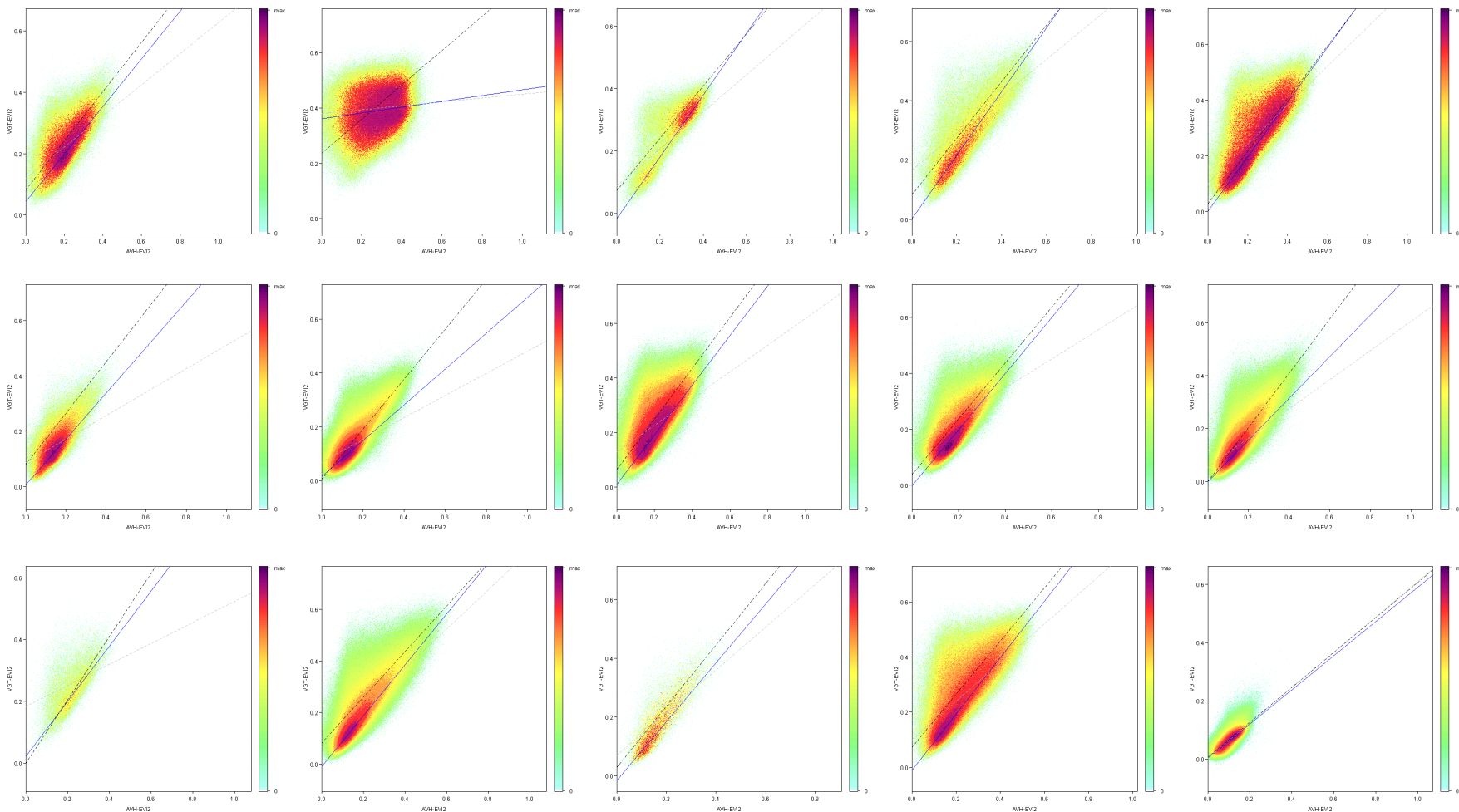




# VEGETATION vs. AVHRR (ver. 3) EVI2: Day-to-day Matched without View Angle Constraint



UNIVERSITY  
of HAWAII  
MĀNOA

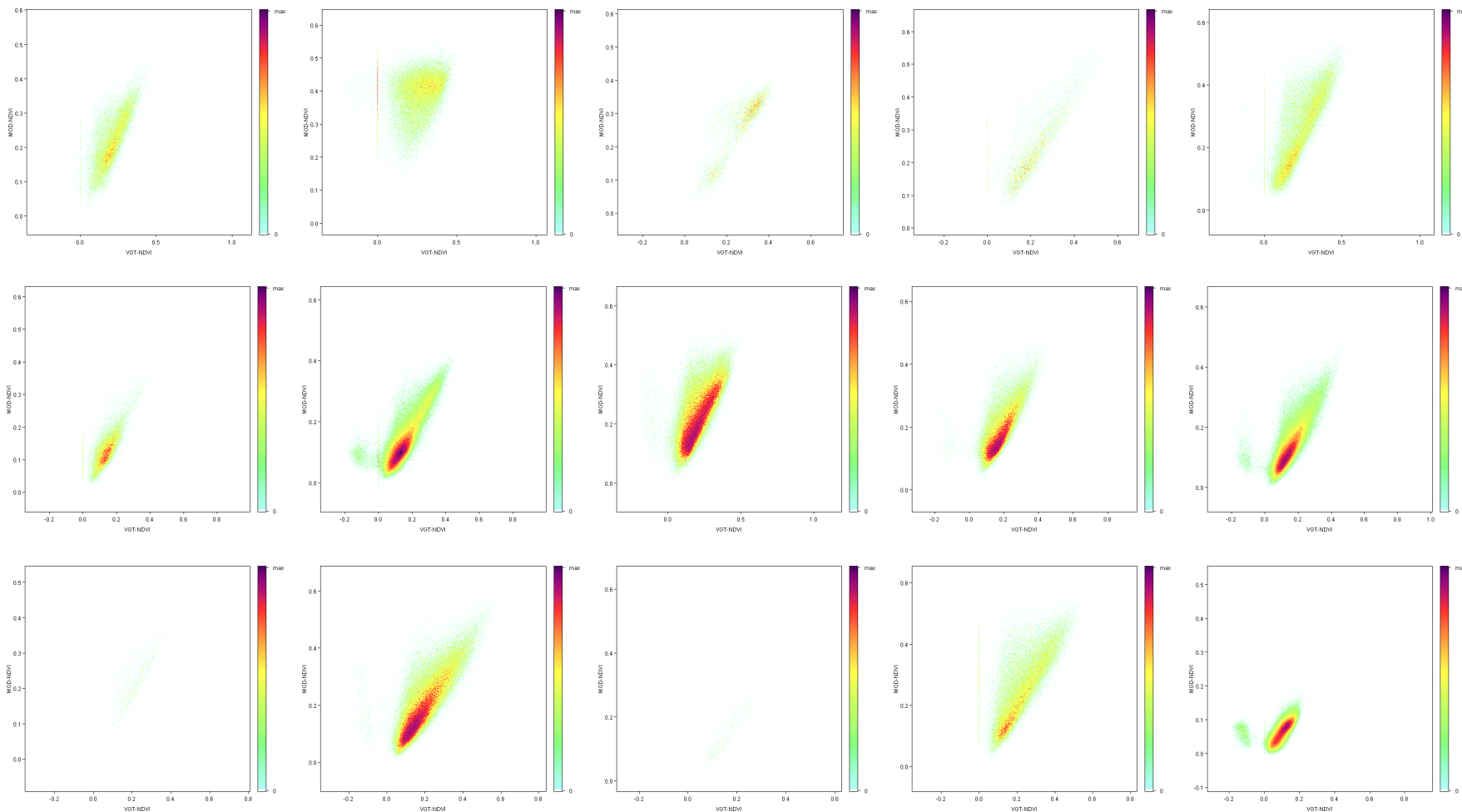




# VEGETATION vs. AVHRR (ver. 3) EVI2: View zenith angle differences less than 10 degrees



UNIVERSITY  
of HAWAII  
MĀNOA





# Translation Equations Derived from the Top-down Analyses

AVH VGT	Slope		Intercept		R2		Prediction interval	
	NDVI	EVI2	NDVI	EVI2	NDVI	EVI2	NDVI	EVI2
LC1	0.934	0.904	0.127	0.051	0.928	0.895	0.074	0.049
LC2	0.784	0.630	0.259	0.190	0.688	0.661	0.088	0.059
LC3	1.075	0.995	0.025	0.018	0.964	0.964	0.075	0.042
LC4	1.003	0.996	0.089	0.028	0.942	0.946	0.059	0.051
LC5	0.927	0.956	0.131	0.044	0.937	0.942	0.063	0.047
LC6	1.160	0.972	-0.010	0.007	0.908	0.895	0.063	0.031
LC7	1.257	1.040	-0.075	-0.026	0.953	0.864	0.035	0.027
LC8	1.098	0.986	0.037	0.023	0.927	0.906	0.046	0.034
LC9	1.294	1.081	-0.070	-0.012	0.962	0.935	0.048	0.037
LC10	1.267	1.172	-0.065	-0.039	0.980	0.957	0.032	0.025
LC11	0.808	0.930	0.205	0.059	0.786	0.825	0.074	0.050
LC12	1.120	1.080	0.004	-0.006	0.984	0.972	0.035	0.033
LC13	1.080	0.937	0.023	-0.028	0.947	0.912	0.046	0.037
LC14	1.092	1.017	0.027	0.019	0.965	0.933	0.039	0.037
LC15	0.593	0.482	0.015	0.022	0.694	0.819	0.012	0.009
Combined	1.269	1.134	-0.058	-0.057	0.982	0.954	0.069	0.058



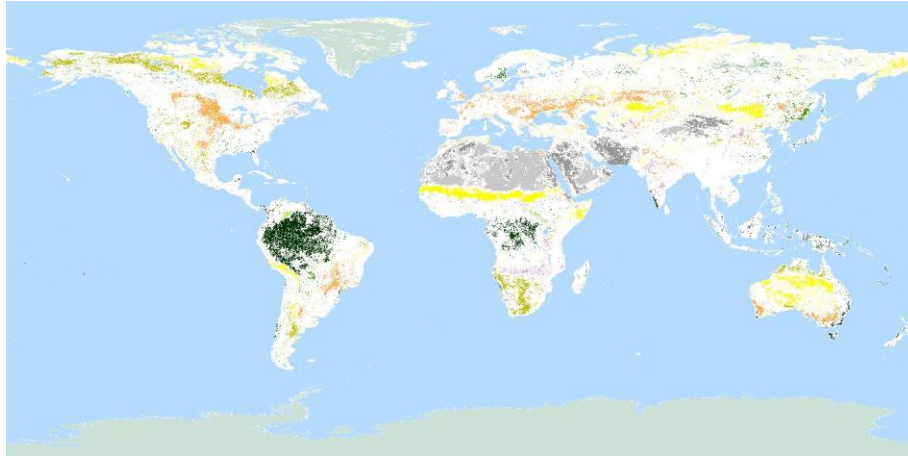
# Translation Equations Derived from the Top-down Analyses (cont.)

VGT MOD	Slope		Intercept		R2		Prediction interval	
	NDVI	EVI2	NDVI	EVI2	NDVI	EVI2	NDVI	EVI2
LC1	1.034	1.112	0.009	-0.014	0.964	0.949	0.102	0.048
LC2	0.647	0.431	0.283	0.035	0.562	0.043	0.073	0.097
LC3	1.031	1.079	-0.007	-0.007	0.959	0.958	0.160	0.071
LC4	0.939	1.067	0.072	0.007	0.964	0.956	0.076	0.078
LC5	0.939	1.055	0.065	0.009	0.960	0.967	0.104	0.056
LC6	1.047	1.062	-0.009	-0.001	0.928	0.905	0.058	0.033
LC7	1.133	1.153	-0.022	-0.012	0.975	0.977	0.052	0.025
LC8	1.088	1.102	-0.013	-0.004	0.947	0.885	0.068	0.050
LC9	0.859	0.760	0.077	0.085	0.880	0.850	0.061	0.046
LC10	0.978	1.088	0.018	0.00	0.956	0.963	0.048	0.025
LC11	1.045	1.102	-0.005	-0.019	0.962	0.924	0.072	0.057
LC12	0.961	1.080	0.040	0.002	0.969	0.976	0.064	0.040
LC13	0.897	0.999	0.067	0.017	0.951	0.962	0.057	0.034
LC14	0.973	1.085	0.039	0.002	0.957	0.953	0.071	0.051
LC15	0.966	1.224	0.020	-0.001	0.851	0.889	0.009	0.009
Combined	1.021	1.059	0.013	0.003	0.983	0.965	0.072	0.057

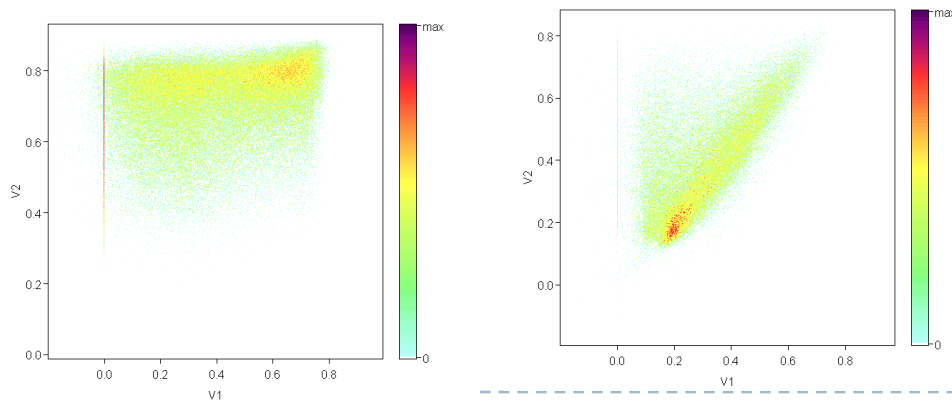


# Translation Equations Derived from the Top-down Analyses (cont)

AVH MOD	Slope		Intercept	
	NDVI	EVI2	NDVI	EVI2
LC1	0.966	1.005	0.140	0.043
LC2	0.507	0.272	0.451	0.117
LC3	1.108	1.074	0.019	0.012
LC4	0.942	1.063	0.156	0.037
LC5	0.870	1.009	0.188	0.055
LC6	1.215	1.032	-0.019	0.006
LC7	1.424	1.199	-0.107	-0.042
LC8	1.195	1.087	0.027	0.021
LC9	1.112	0.822	0.017	0.076
LC10	1.239	1.275	-0.046	-0.042
LC11	0.844	1.025	0.209	0.046
LC12	1.076	1.166	0.044	-0.004
LC13	0.969	0.936	0.088	-0.011
LC14	1.063	1.103	0.065	0.023
LC15	0.573	0.590	0.034	0.026
Combined	1.296	1.201	-0.046	-0.057



Homogeneous class type within 0.05degree (Global Land Cover Map –MODIS2003)





# Global Coarse Resolution (0.05°) Daily Products: Terra MODIS vs. SPOT-4 VEGETATION



UNIVERSITY  
of HAWAII  
MĀNOA

## NDVI

Sensor (Y vs. X)	RMPD <sub>S</sub> (RMPD <sub>U</sub> )	GMFR	R <sup>2</sup>
<b>Original (5%)</b>			
MOD vs. VGT4	.025 (± .045)	Y = .016 +1.034 X	.95
<b>Translated (5%)</b>			
MOD vs. ML-VGT4	<.001 (± .043)	Y = -.001 +1.004 X	.95

**Update numbers**

## EVI2

Sensor (Y vs. X)	RMPD <sub>S</sub> (RMPD <sub>U</sub> )	GMFR	R <sup>2</sup>
<b>Original (5%)</b>			
MOD vs. VGT4	.027 (± .032)	Y = .010 +1.102 X	.91
<b>Translated (5%)</b>			
MOD vs. ML-VGT4	.001 (± .032)	Y = -.002 +1.010 X	.91

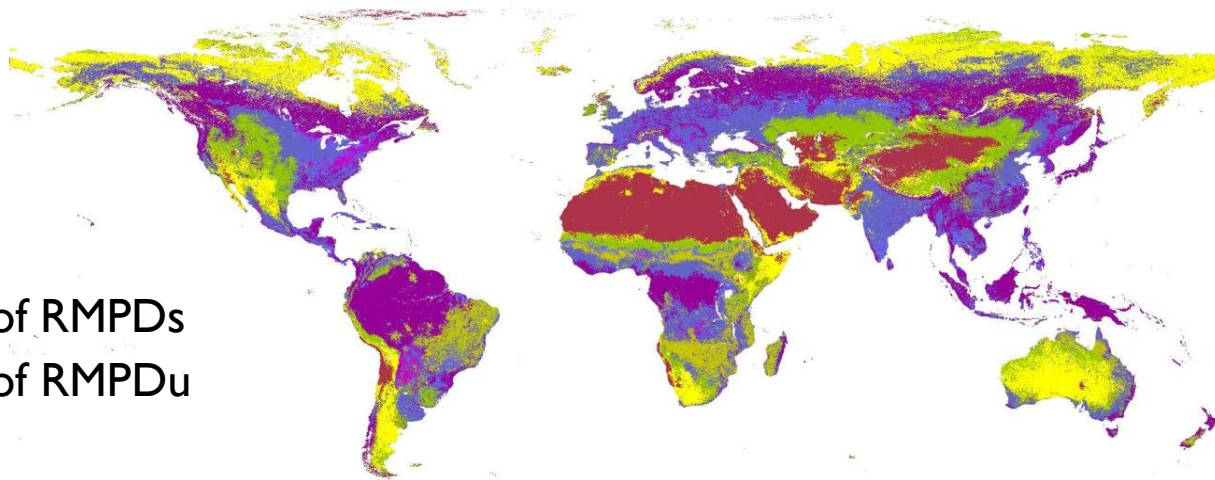




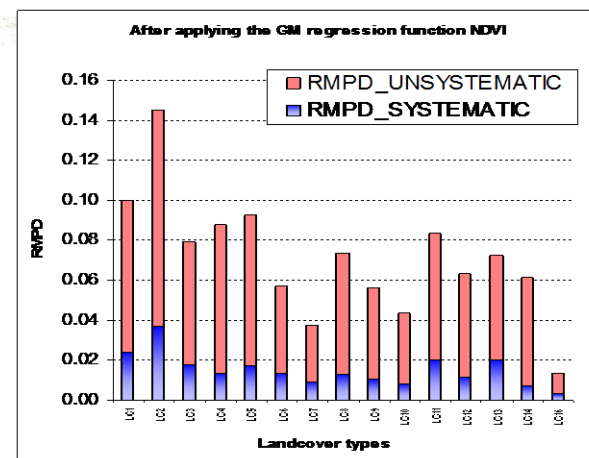
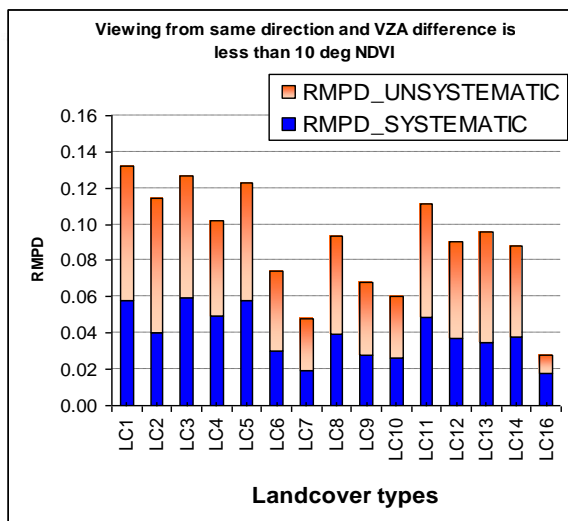
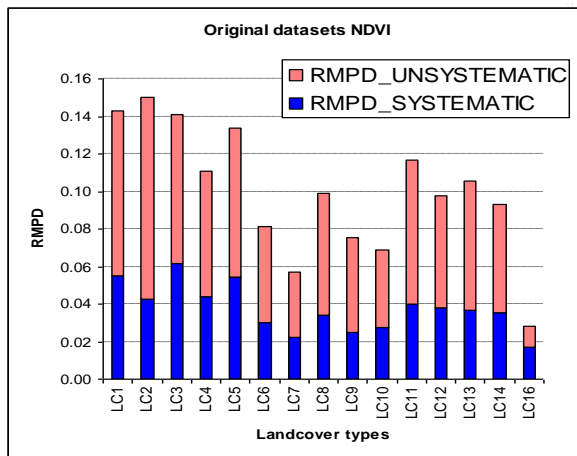
# Root Mean Square Difference of VGT-NDVI and MODIS-NDVI



UNIVERSITY  
of HAWAII  
MĀNOA



Need a map of RMPDs  
Need a map of RMPDu

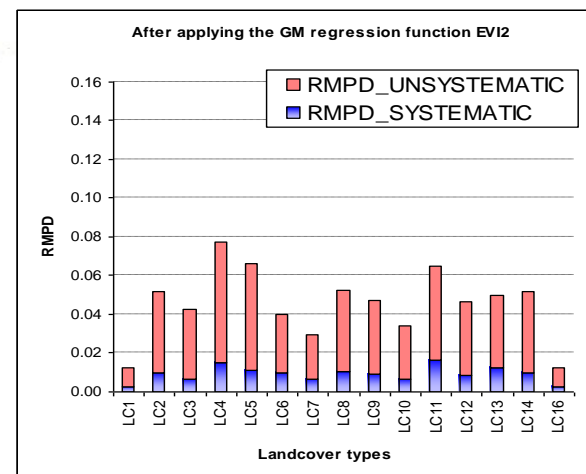
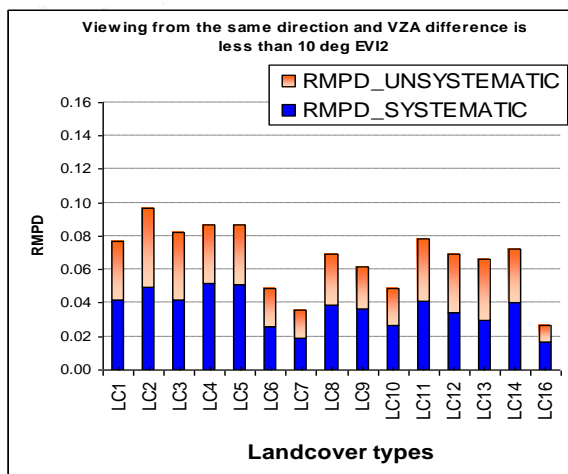
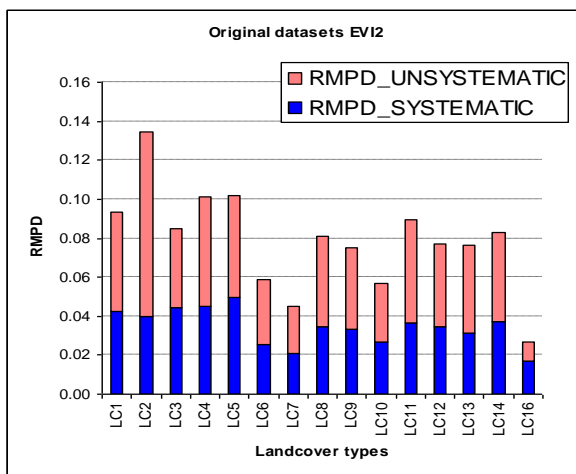
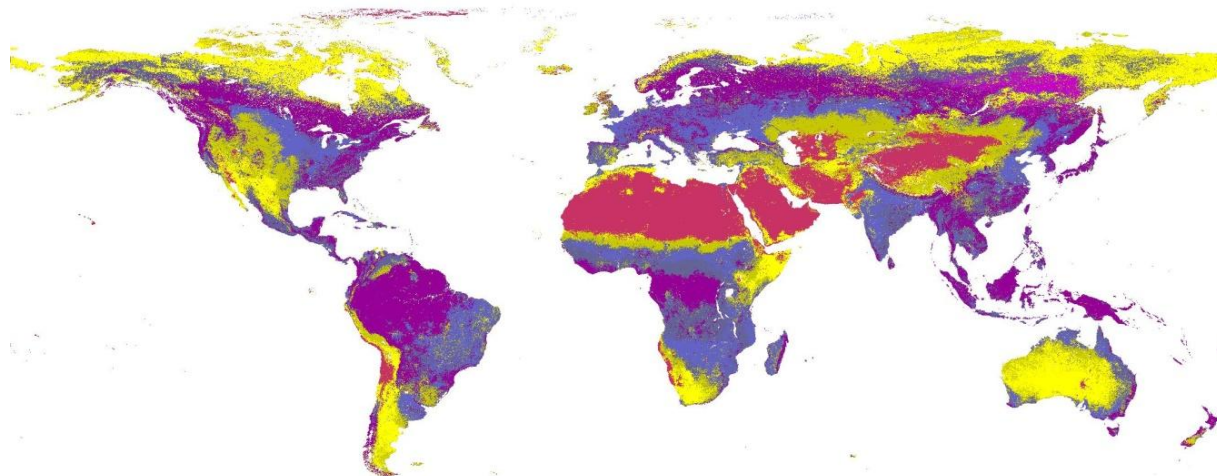




# Root Mean of Square Difference of VGT-EVI2 and MODIS-EVI2



UNIVERSITY  
of HAWAII  
MĀNOA



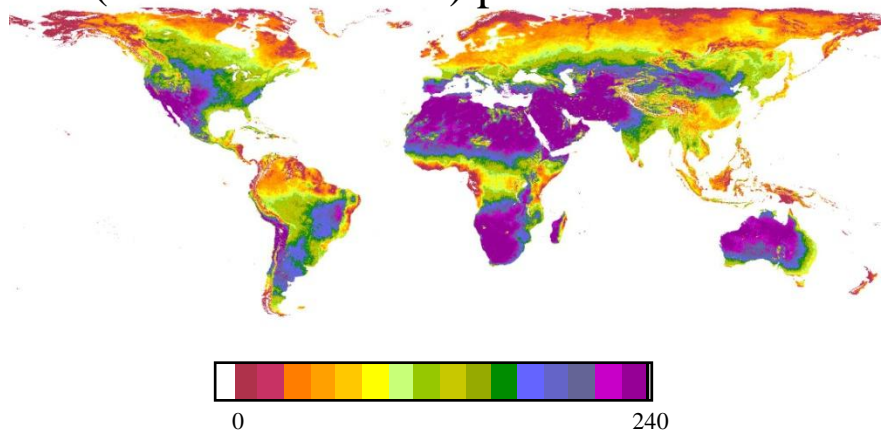


# Error Analysis: VGT – AVH (v.3)

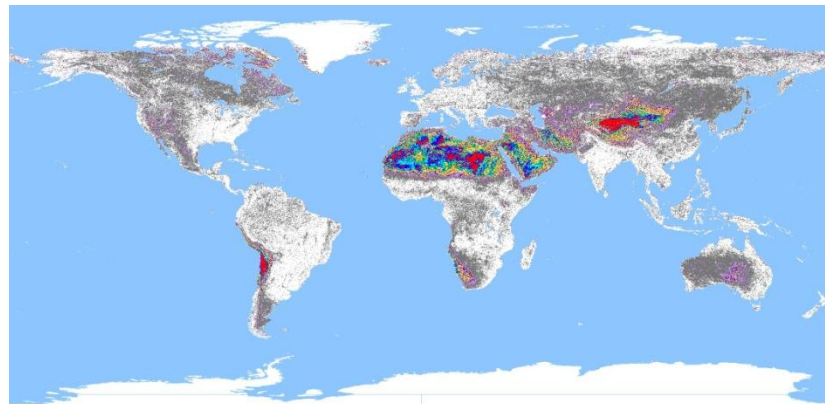


UNIVERSITY  
of HAWAII  
MĀNOA

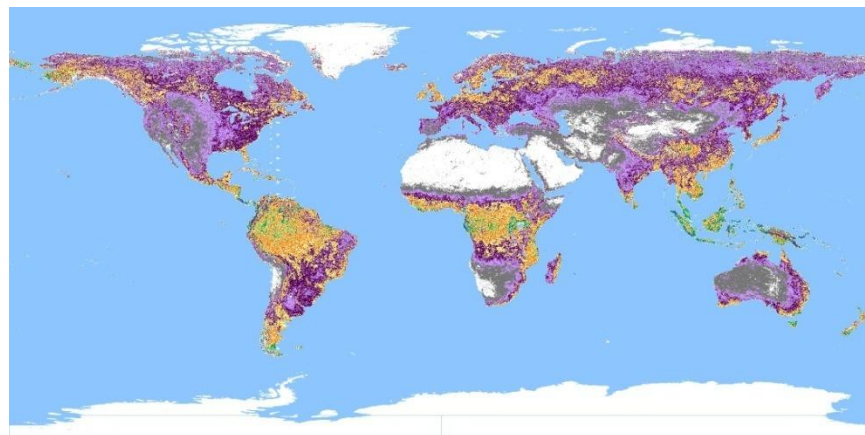
Number of available observation pairs  
(VGT4-AVH14v.3) per location



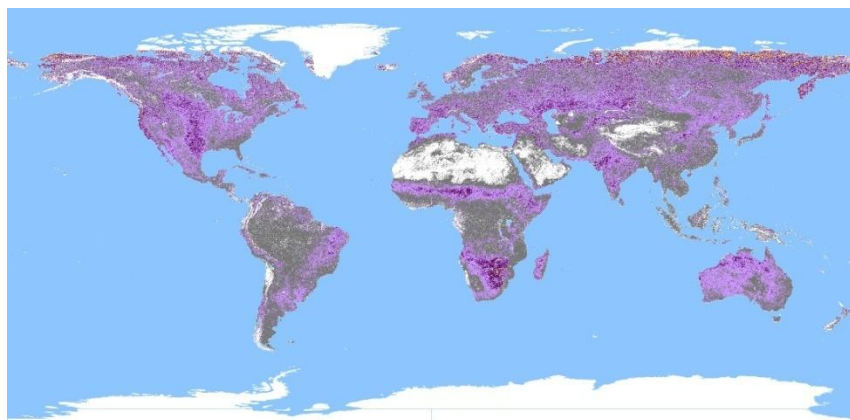
Cluster  $[100 * (vgt - avh) / vgt] < -45\%$



Cluster  $> 45$



Cluster  $< +/- 5$

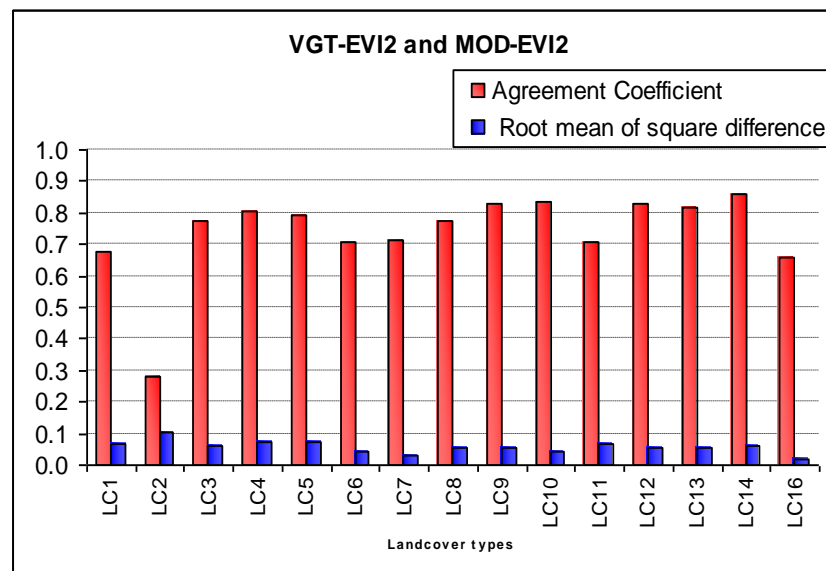
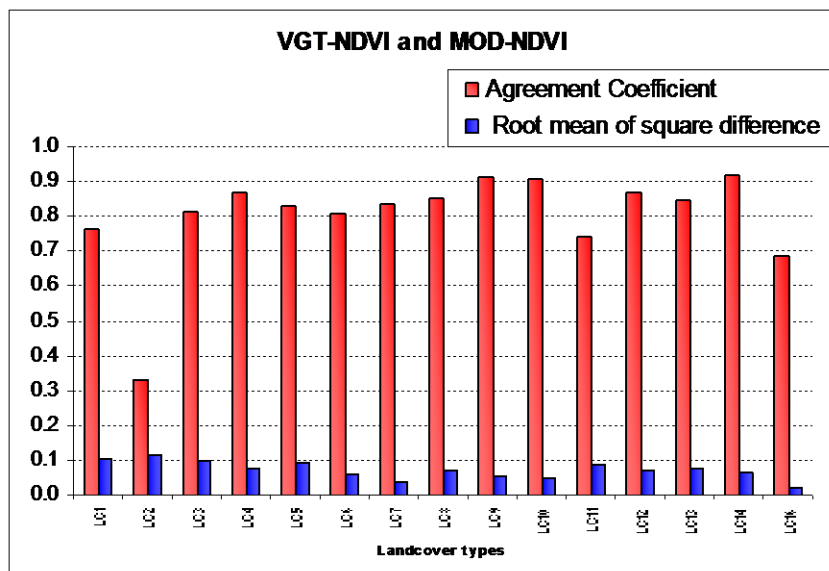




# Agreement Analysis



UNIVERSITY  
of HAWAII  
MĀNOA





# Agreement Analysis



UNIVERSITY  
of HAWAII  
MĀNOA

