The Impacts of Urbanization/Urban Development in the Climate of Puerto Rico

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Abstract

A detailed analysis of century-scale climate change for Puerto Rico was done to assess the degree to which some of this change might be related to LULCC. We used long-term data, Geographic Information Systems (GIS), statistical analysis and Regional Atmospheric Modeling Systems (RAMS) to detect and assess the impact of local urban development on temperature and precipitation. We found strong evidence of a relationship linking temperature and precipitation magnitudes to local urban development. Findings for maximum, average and minimum temperature are robust showing that urbanization has increased local temperatures and levels of impact found here represent minimum estimates since they were based on data that had some prior adjustment intended to control for urban signals. Strong evidence of this relationship was also found in the precipitation data analysis, but no clear correlation was found in the direction, magnitude, period and location of rain with urban development implying that other factors dominate or are playing some role in this relationship. RAMS numerical modeling results were inconclusive suggesting that further tuning of settings and parameters are needed before model results can be used to guide decision-making.

Dissertation Research

- **1st part (Statistical Analysis)**
  - Long term observational study
    - **Temperature** (Maximum, Average and Minimum)
    - **Precipitation** (Monthly Average, Yearly Total Average)
- **2nd part (Computer simulations)**
  - Computational experiments
    - Regional Atmospheric Modeling System (RAMS)
      - Precipitation computer simulations

Study Questions

I. Long Term Observational Study

A. Have urbanization / urban development impacted local **temperatures**?, if so…

i. What is the **magnitude** of the temperature impacts?

B. Have urbanization / urban development impacted **precipitation** quantities?, if so…

i. What is the **magnitude** of the precipitation impacts?

II. Computational Experiments

A. What are the major land features and processes controlling local precipitation events?

Previous Work

- **Land Use / Land Cover Change**
  - Forest Regeneration
  - Urban Heat Island (UHI) in San Juan
- **Temperature**
  - Parameter-elevation on Independent Slopes Model (PRISM)
  - Climate Change Scenarios
  - RAMS
- **Precipitation**
  - PRISM
  - Rain Regionalization
  - RAMS
- **Vegetation**
  - Holdridge Ecological Life Zones (HELZ)
  - Puerto Rico GAP

Data & Methods

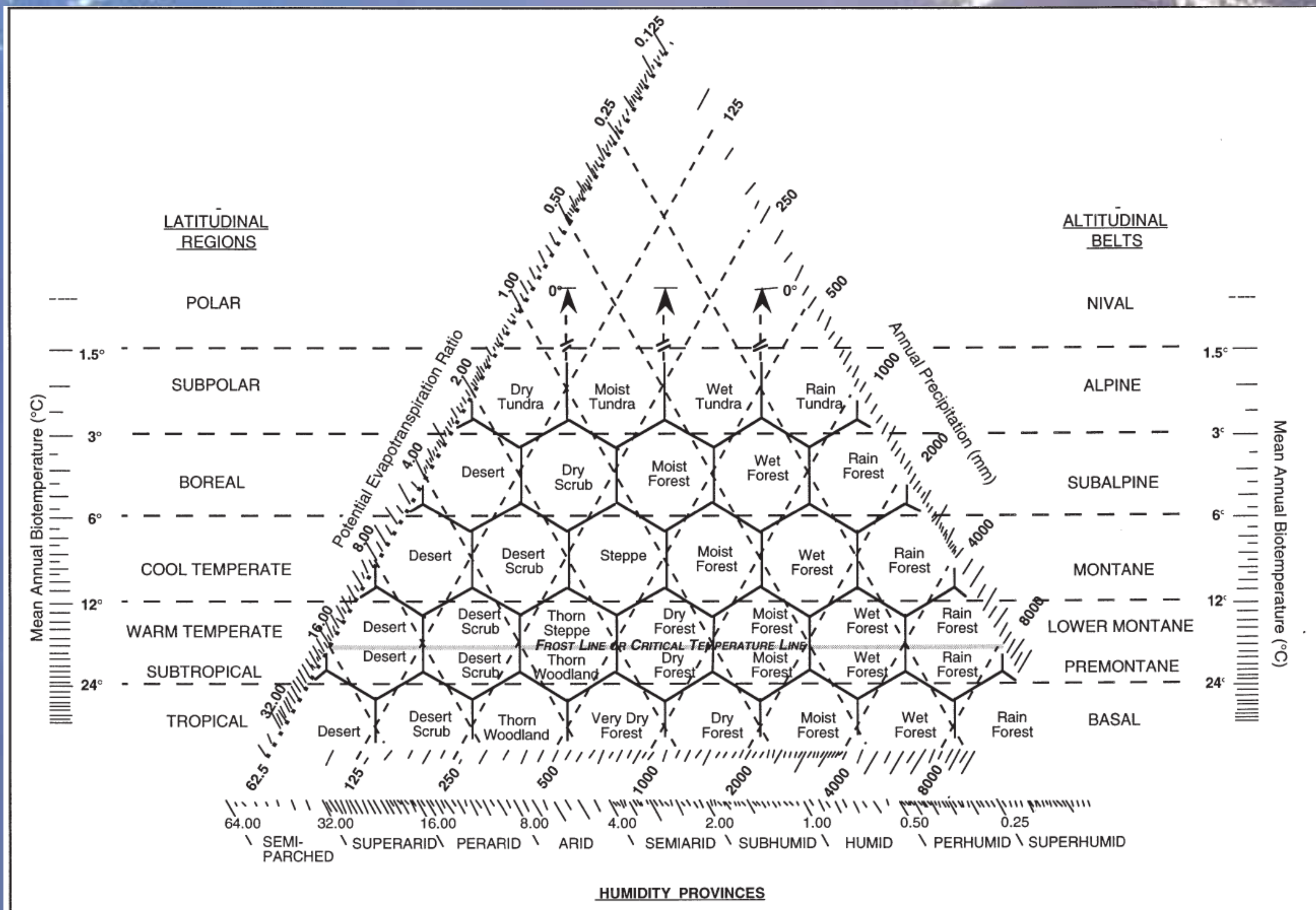
- **Digital Maps**
  - Land use / Land cover (Puerto Rico GAP Project 2004)
  - Holdridge Ecological Lifezones (HELZ)
- **Long term weather station data**
  - Temperature (adjusted)
  - Precipitation (raw)
- **Geographic Information Systems (GIS)**
- **Statistical Analysis (ANOVA, T-test; α *=0.05*)**
- **Regional Atmospheric Modeling System (RAMS)**

Holdridge Ecological Lifezones

- Geo-climatic plant classification system
- Uses **physiographic, climatic and physiological** characteristics of plants
  - Elevation
  - Precipitation
  - Humidity
  - Potential evapotranspiration
    - Water availability for ecosystem function
  - Bioemperature
    - Range of temperatures for vegetation grow (0°C to 30 °C)

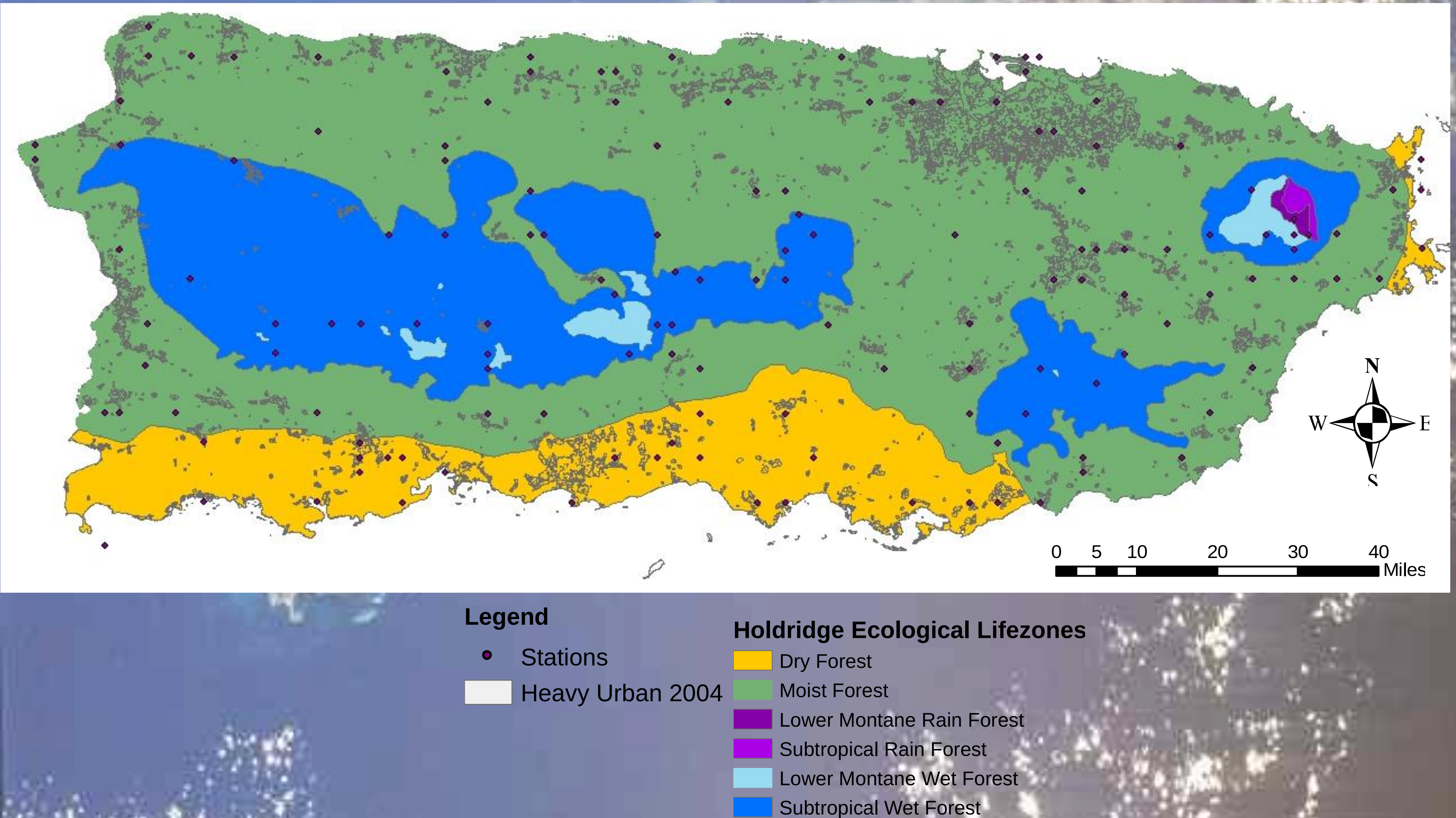
Holdridge, 1967

Holdridge Ecological Lifezones



Holdridge, 1967

Puerto Rico Holdridge Ecological Lifezones, urban areas and weather stations.



HELZ Temperature Data Analysis

	Maximum Temperature		Average Temperature		Minimum Temperature	
HELZ	**Station Data**		**Station Data**		**Station Data**	
Decadal	(°C)	**Sig.**	(°C)	**Sig.**	(°C)	**Sig.**
Wet Forest	27.19	**0.000**	22.26	**0.000**	17.33	**0.000**
Moist Forest	30.41	0.315	25.41	**0.000**	20.41	**0.000**
Dry Forest	30.66	0.315	26.12	**0.000**	21.58	**0.000**
HELZ	**GIS**		**GIS**		**GIS**	
Century	(°C)	**Sig.**	(°C)	**Sig.**	(°C)	**Sig.**
Wet Forest	28.16	**0.000**	23.07	**0.000**	17.98	**0.000**
Moist Forest	29.25	**0.000**	24.54	**0.000**	19.84	**0.000**
Dry Forest	29.86	**0.000**	25.37	**0.000**	20.87	**0.000**

α =0.05

HELZ GIS Maps Precipitation Data Analysis

	1900-1929		1930-1959		1960-1989		1990-2007	
	cm/year	Sig.	cm/year	Sig.	cm/year	Sig.	cm/year	Sig.
WF	342.33	**0.000**	399.18	**0.000**	407.50	**0.000**	214.27	**0.000**
MF	341.78	**0.000**	331.36	**0.000**	362.92	**0.000**	181.69	**0.000**
DF	220.54	**0.000**	242.41	**0.000**	253.72	**0.000**	152.68	**0.000**

α =0.05

Temperature Results

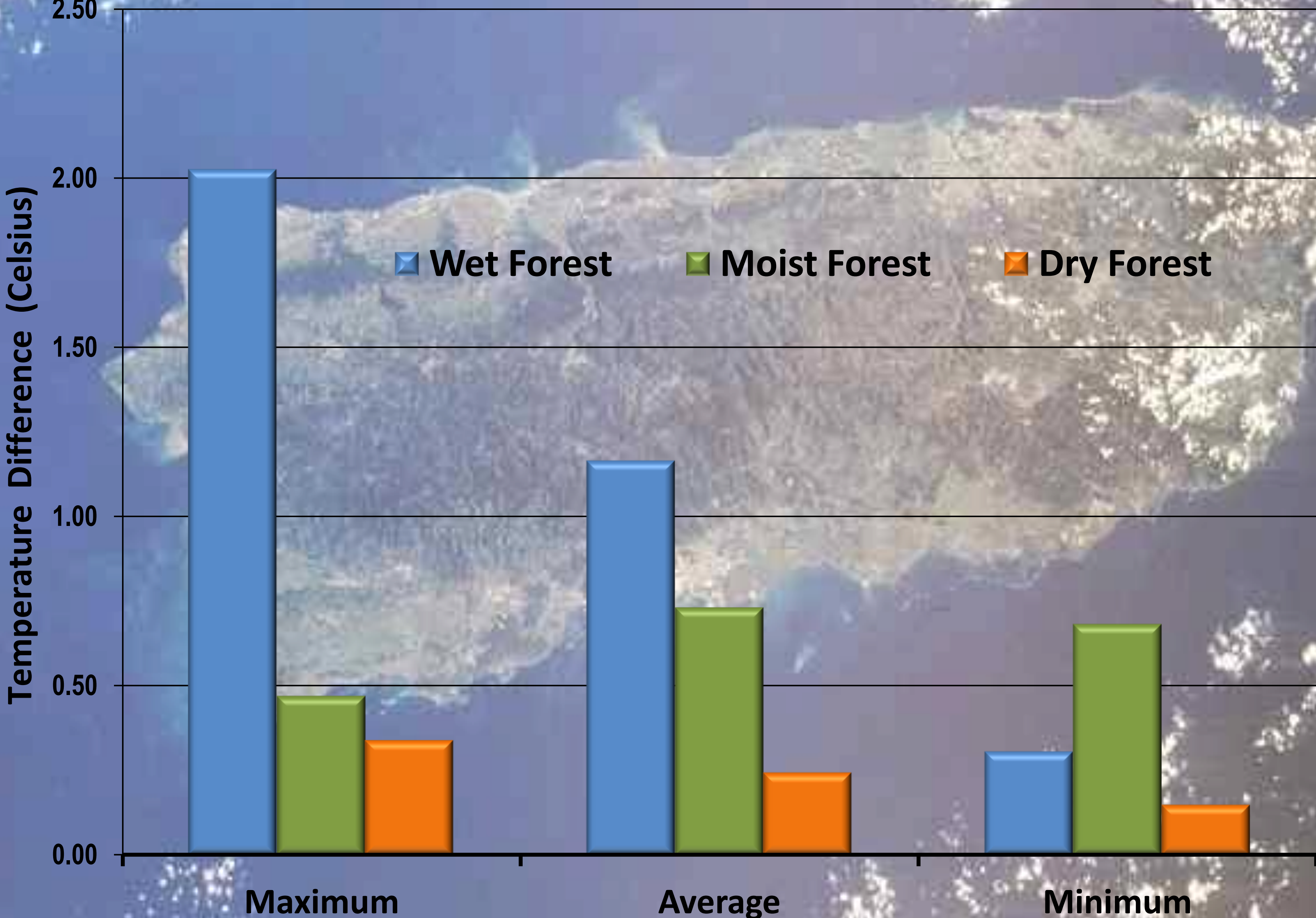
Statistical Analysis of long term observational data from surface stations

Urban Temperature Data Analysis

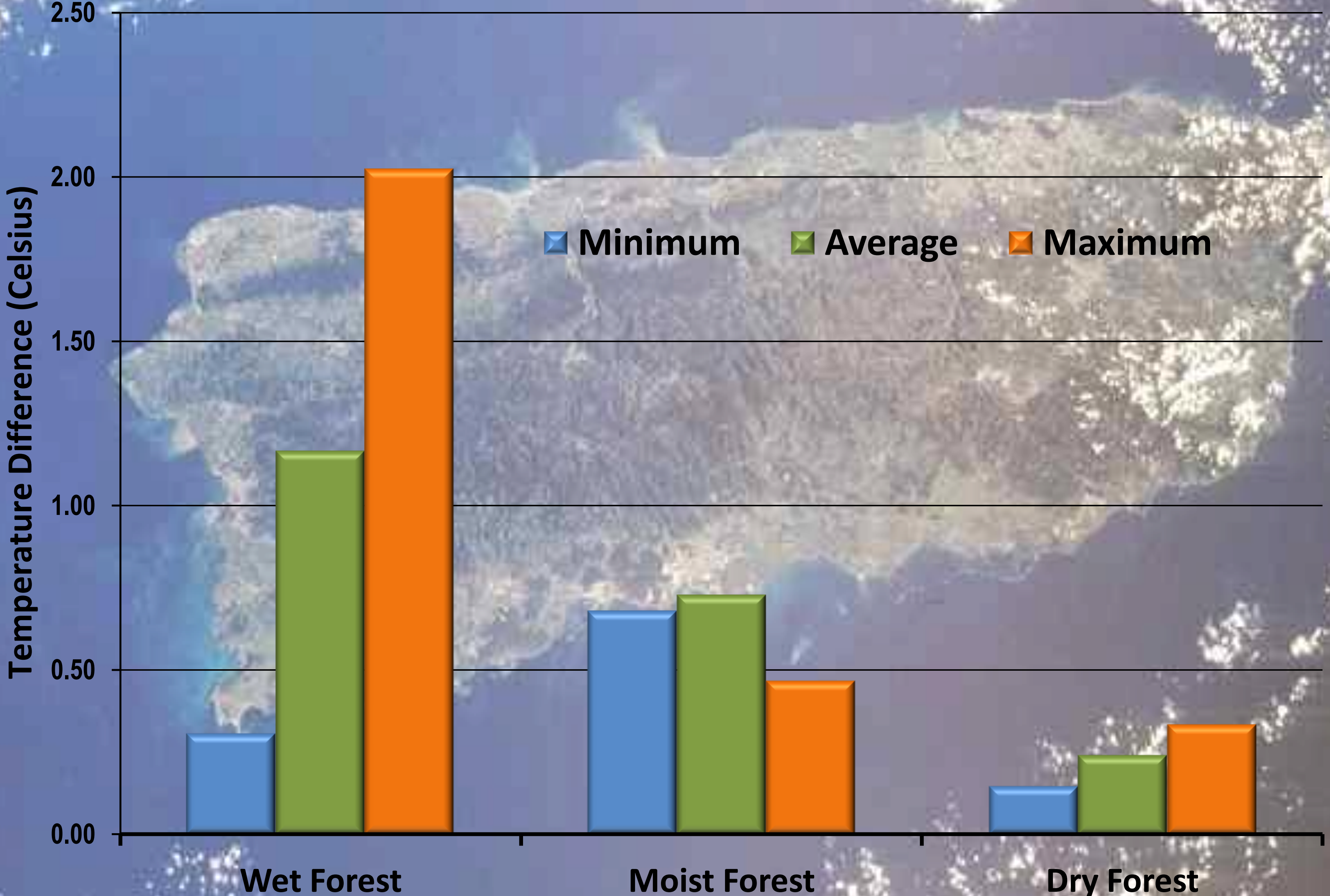
	Maximum Temp. (°C)			Average Temp. (°C)			Minimum Temp. (°C)		
HELZ	**Station Data**			**Station Data**			**Station Data**		
Decadal	**U**	**NU**	**Sig.**	**U**	**NU**	**Sig.**	**U**	**NU**	**Sig.**
Wet Forest	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Moist Forest	29.00	29.76	**0.000**	24.92	24.63	0.242	20.84	19.51	**0.000**
Dry Forest	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HELZ	**GIS**			**GIS**			**GIS**		
Century	**U**	**NU**	**Sig.**	**U**	**NU**	**Sig.**	**U**	**NU**	**Sig.**
Wet Forest	30.16	28.13	**0.000**	24.22	23.05	**0.000**	18.28	17.98	**0.000**
Moist Forest	29.62	29.15	**0.000**	25.00	24.27	**0.000**	20.37	19.70	**0.000**
Dry Forest	30.13	29.80	**0.000**	25.56	25.32	**0.000**	20.99	20.85	**0.000**

α =0.05

GIS Maps Urban - Non Urban Temperature Differences by Temperature



GIS Maps Urban - Non Urban Temperature Differences by HELZ



Temperature Results Summary

- Station data analysis (ANOVA; *α = 0.05*)
  - **Statistical differences** between Urban & Non Urban temperatures (maximum & minimum) in the **Moist Forest**
    - **Urban areas greatest impact found on minimum temperatures**
  - Average Urban & Non Urban temperatures statistically similar in the **Moist Forest**
- GIS maps data analysis (T-Test; *α = 0.05*)
  - Statistical difference between Urban & Non Urban detected in **all temperatures at all HELZ's** (FILNET 2 data & PRISM)

Precipitation Results

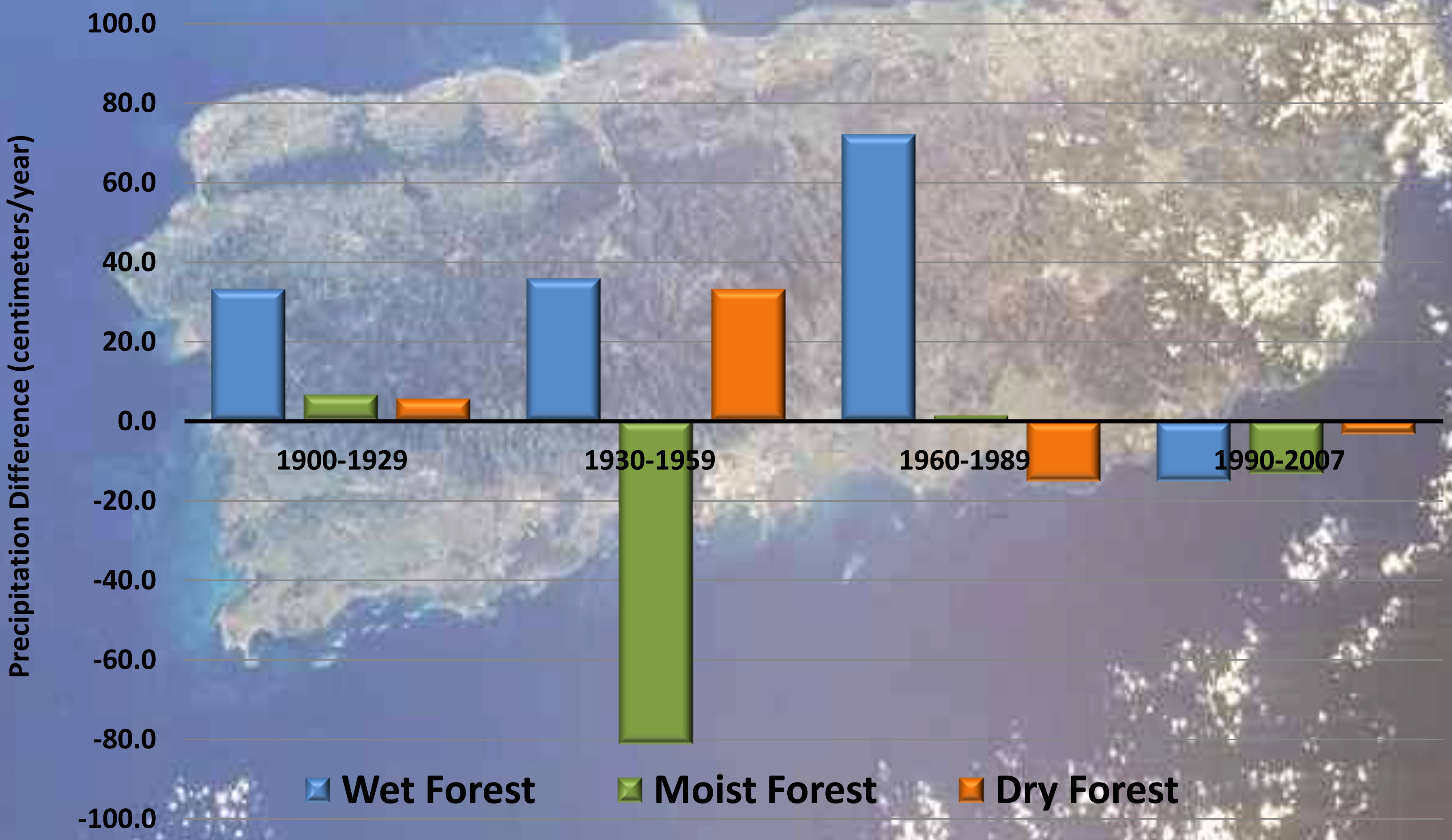
Statistical Analysis of long term observational data from surface stations

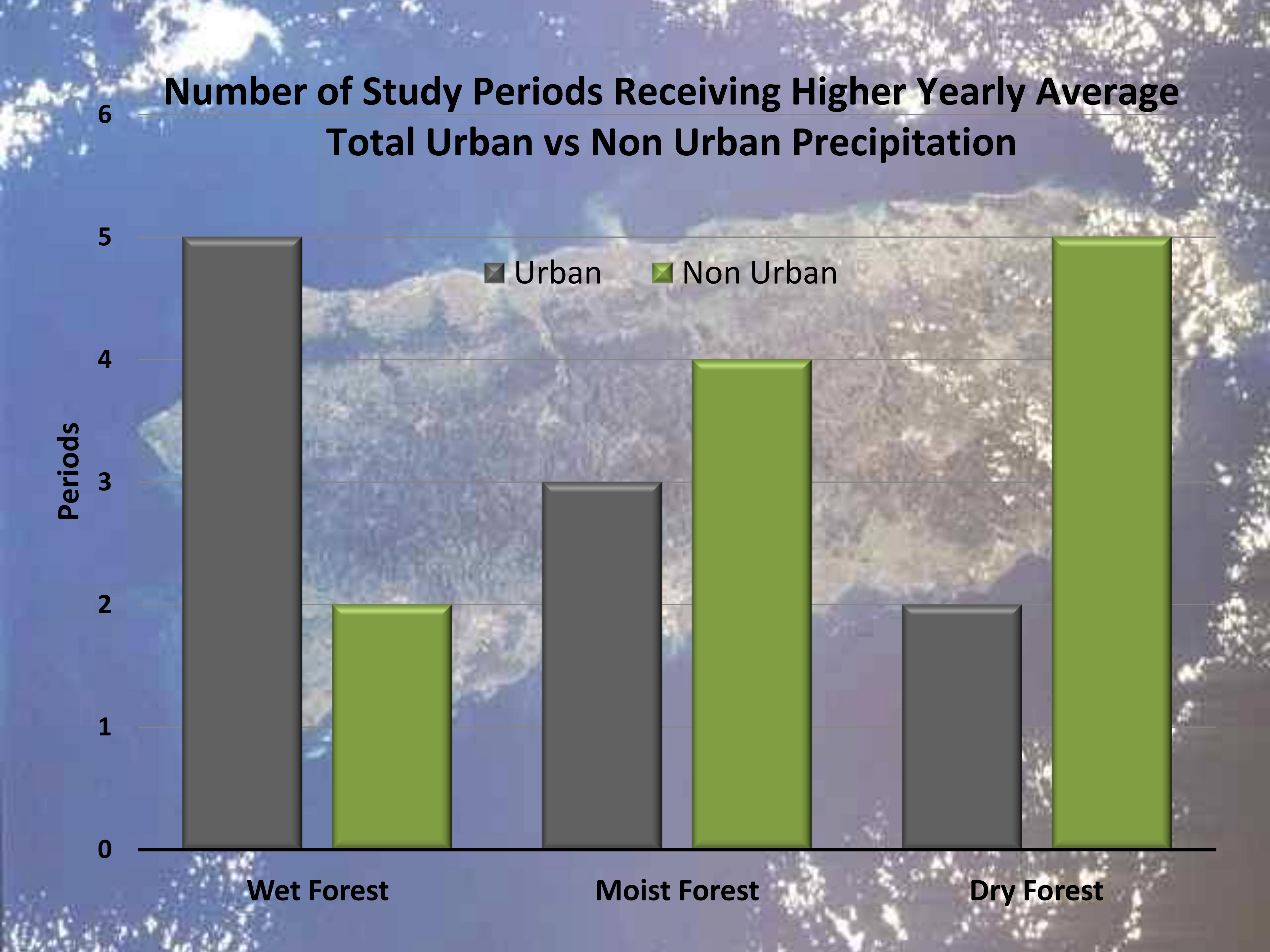
GIS Maps Urban versus Non Urban Precipitation Data Analysis by HELZ

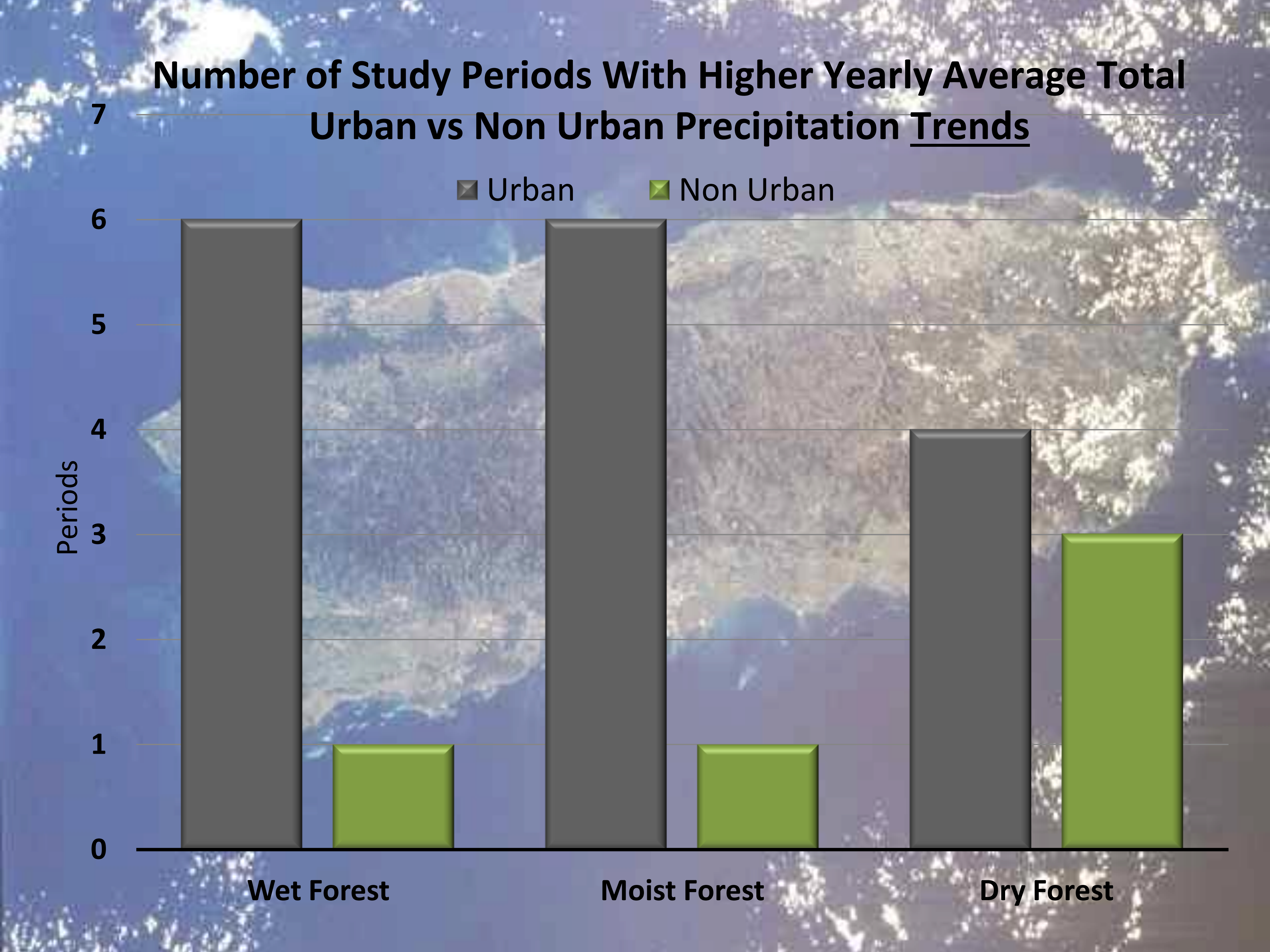
	1900-1929 (cm/y)			1930-1959 (cm/y)			1960-1989 (cm/y)			1990-2007 (cm/y)		
	U	NU	Sig.	U	NU	Sig.	U	NU	Sig.	U	NU	Sig.
WF	**375.33**	342.11	**0.000**	**434.80**	398.95	**0.000**	**479.00**	407.02	**0.000**	199.31	**214.37**	**0.000**
MF	**347.45**	341.00	**0.000**	260.05	**341.21**	**0.000**	**364.02**	362.77	**0.000**	169.90	**183.31**	**0.000**
DF	**225.54**	219.91	**0.000**	**271.75**	238.65	**0.000**	240.31	**255.44**	**0.000**	149.74	**153.06**	**0.000**

α =0.05

Yearly Average Total Precipitation Urban - Non Urban Differences By HELZ




Number of Study Periods Receiving Higher Yearly Average
Total Urban vs Non Urban Precipitation
Urban
Non Urban
Periods
0
1
2
3
4
5
6
Wet Forest
Moist Forest
Dry Forest


Number of Study Periods With Higher Yearly Average Total
Urban vs Non Urban Precipitation Trends
Urban
Non Urban
Periods
0
1
2
3
4
5
6
7
Wet Forest
Moist Forest
Dry Forest

Precipitation Results Summary

- Station data analysis (ANOVA; *α = 0.05*)
  - **No statistical differences** detected or similar Urban & Non Urban **monthly average precipitation**
- GIS generated data analysis (T-test; *α = 0.05*)
  - **Statistical differences** found between Urban & Non Urban **yearly average total precipitation** in all periods and all HELZ
  - **No clear correlation** between time period, HELZ, magnitudes or direction of precipitation differences.
  - **Higher** precipitation **trends are more prevalent over urban** than non urban areas at most study periods.

Research Results Summary

- Temperature impacts of urban development detected across the entire island (**strong evidence**).
- Precipitation impacts of urban development detected across the island but lees clear (**good evidence**).
- RAMS simulation results inconclusive (**need more studies**)

Temperature Remarks

- **<u>Temperature</u>**
  - – Specific **ecological and environmental impacts** are currently unknown.
    - Ecosystem and species resiliency **studies are needed**.
    - Potential **risks to human health**, if any, are **unknown**
  - – Urban **sustainable policies and practices** could help mitigate impacts.
    - Some practices could also have mitigation value for precipitation impacts

Precipitation Remarks

- Has been **decreasing** for the entire century.
- Climate change models predict the **increase of dry periods and heavy precipitation** events.
  - Combines water storage issues with floods, landslides, etc
  - Water management plan is critical
    - Must account for **drainage, storm water and runoff** management
- Mitigation unlikely, adaptation through watershed management may be only option

Precipitation Remarks

- Evidence of urban **impacts detected but unclear**
  - Further studies important to assist decision making.
- Computational experiments results were **inconclusive**.
  - More fine-tuning required to assist decision making
- Some practices could also have mitigation value for temperature impacts.

Impact Management

- **Temperature Mitigation**
  - Further studies to monitor impacts
  - Implement urban **greening policies and practices**
    - **Urban reforestation**, agriculture, gardening & landscaping
    - Reduce fossil fuel **transportation** dependence
      - Promote collective transportation
      - Improve public transportation
      - Account for and coordinate with private collective transportation
      - Promote walking and reclaim sidewalks (become **walk friendly**)
      - Promote bicycle use (become **bicycle friendly**)

Impact Management

- **Precipitation Adaptation**
  - Detailed **studies to measure** magnitude of impacts
  - **Sustainable** Watershed **Management**
    - Educate public, government officials and companies
    - Reduce water reservoir capacity loss and control sedimentation
    - Control and avoid rural upland deforestation
  - Account for **natural drainage**
    - Study, manage, increase and protect natural permeable areas
    - Protect and expand natural wetlands
    - Develop constructed wetlands as retention ponds
  - Urban **runoff control** projects
    - Account and manage urban runoff
    - Create urban wetlands and artificial drainage sinks
    - Protect urban green areas

The End

Questions and Comments

HELZ Temperature Data Analysis

α =0.05	Maximum Temperature		Average Temperature		Minimum Temperature	
HELZ	Station Data		Station Data		Station Data	
Decadal	(°C)	Sig.	(°C)	Sig.	(°C)	Sig.
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Moist Forest	30.41	0.315	25.41	0.000	20.41	0.000
Dry Forest	30.66	0.315	26.12	0.000	21.58	0.000
HELZ	GIS		GIS		GIS	
Century	(°C)	Sig.	(°C)	Sig.	(°C)	Sig.
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Moist Forest	29.25	0.000	24.54	0.000	19.84	0.000
Dry Forest	29.86	0.000	25.37	0.000	20.87	0.000
HELZ	PRISM		PRISM		PRISM	
1963-1995	(°C)	Sig.	(°C)	Sig.	(°C)	Sig.
Wet Forest	28.05	0.000	22.79	0.000	17.59	0.000
Moist Forest	29.83	0.000	24.76	0.000	19.76	0.000
Dry Forest	30.87	0.000	25.61	0.000	20.39	0.000

Urban Temperature Data Analysis

α =0.05	Maximum Temp. (°C)			Average Temp. (°C)			Minimum Temp. (°C)		
HELZ	Station Data			Station Data			Station Data		
Decadal	U	NU	Sig.	U	NU	Sig.	U	NU	Sig.
Wet Forest	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Moist Forest	29.00	29.76	0.000	24.92	24.63	0.242	20.84	19.51	0.000
Dry Forest	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HELZ	GIS			GIS			GIS		
Century	U	NU	Sig.	U	NU	Sig.	U	NU	Sig.
Wet Forest	30.16	28.13	0.000	24.22	23.05	0.000	18.28	17.98	0.000
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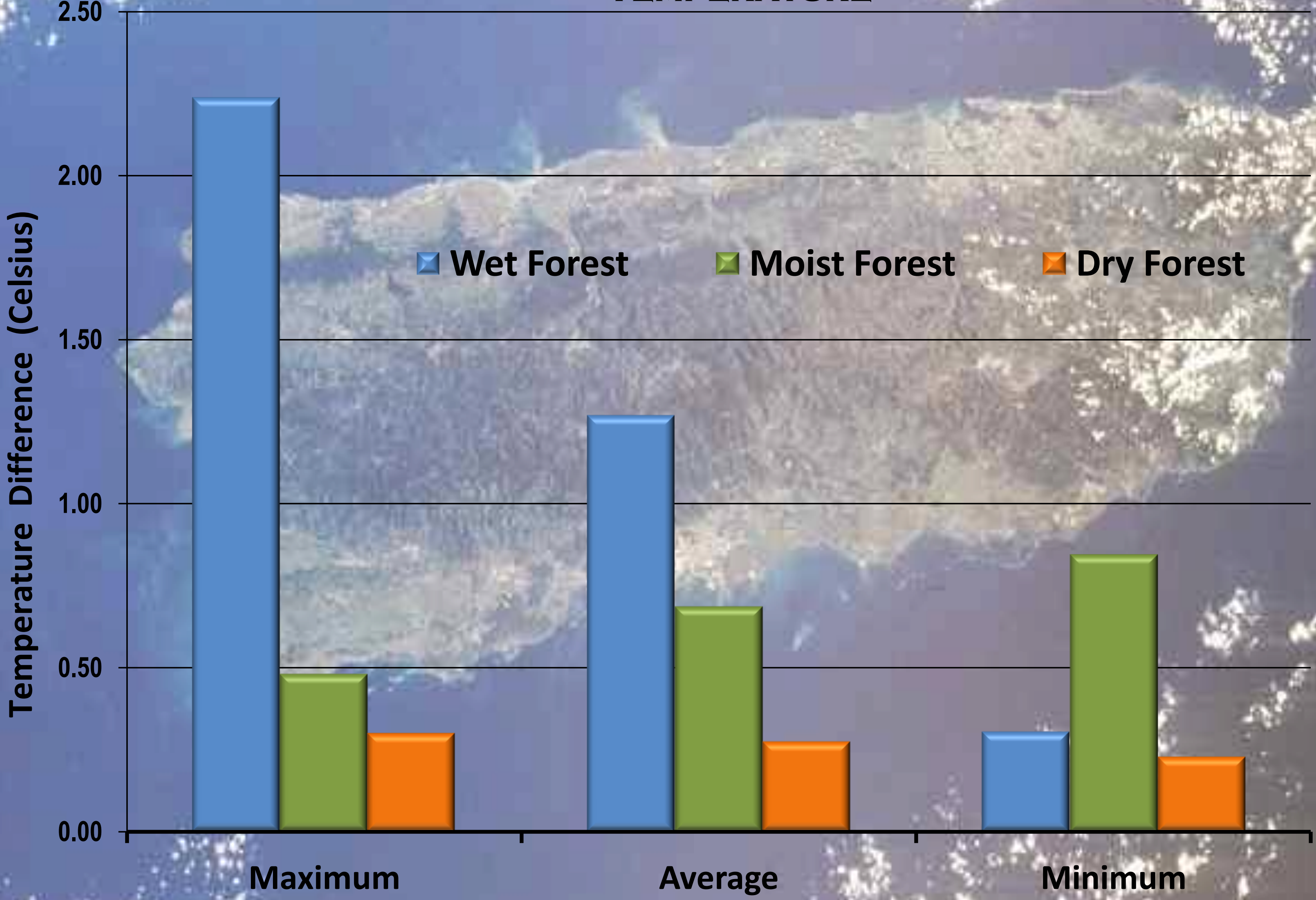
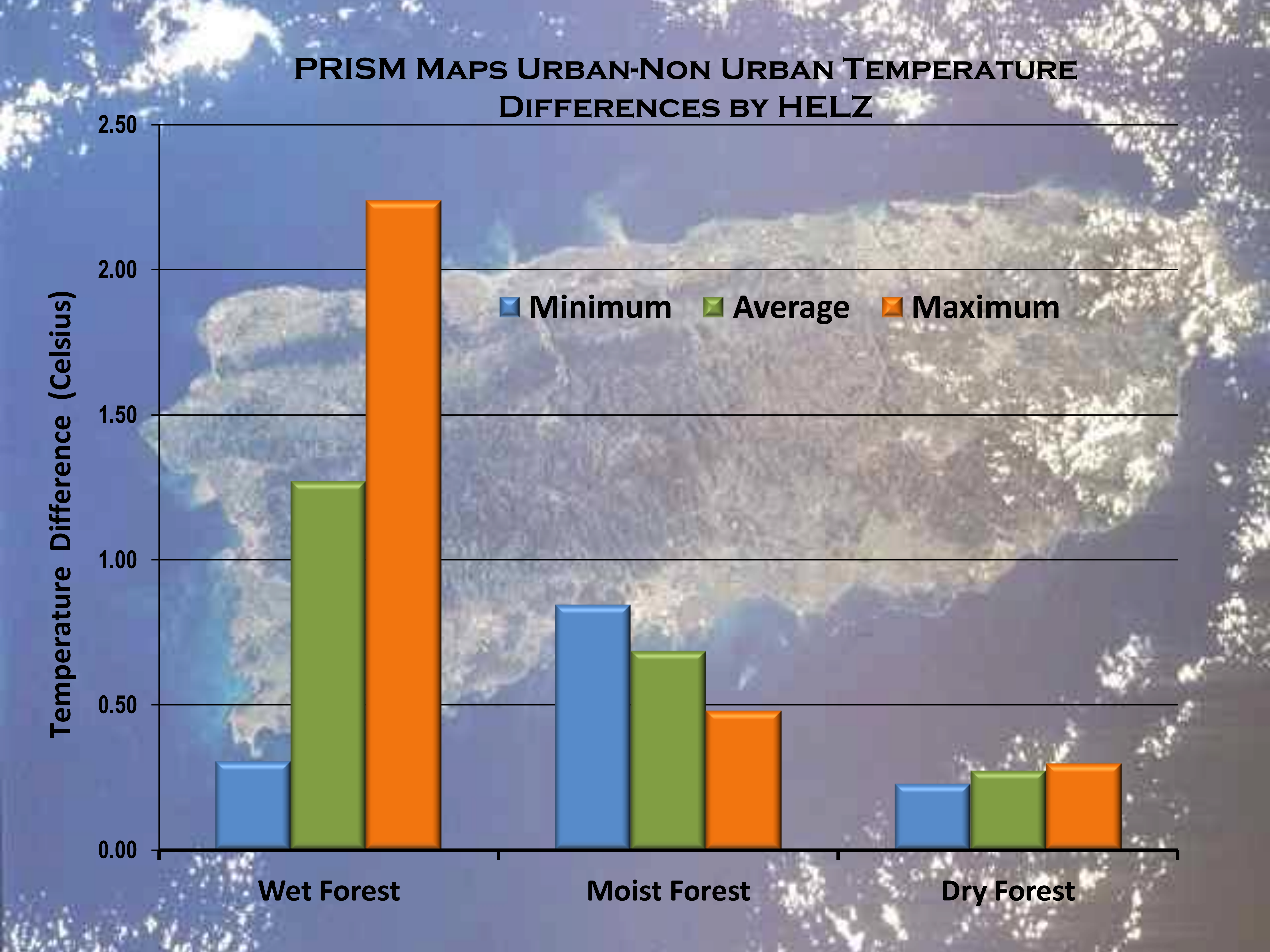
Dry Forest	30.13	29.80	0.000	25.56	25.32	0.000	20.99	20.85	0.000
HELZ	PRISM			PRISM			PRISM		
1963-1995	U	NU	Sig.	U	NU	Sig.	U	NU	Sig.
Wet Forest	30.21	27.97	0.000	24.02	22.75	0.000	17.88	17.58	0.000
Moist Forest	30.15	29.68	0.000	25.22	24.54	0.000	20.33	19.49	0.000
Dry Forest	31.08	30.78	0.000	25.80	25.53	0.000	20.55	20.32	0.000

PRISM Maps Urban-Non Urban Temperature Differences by Temperature

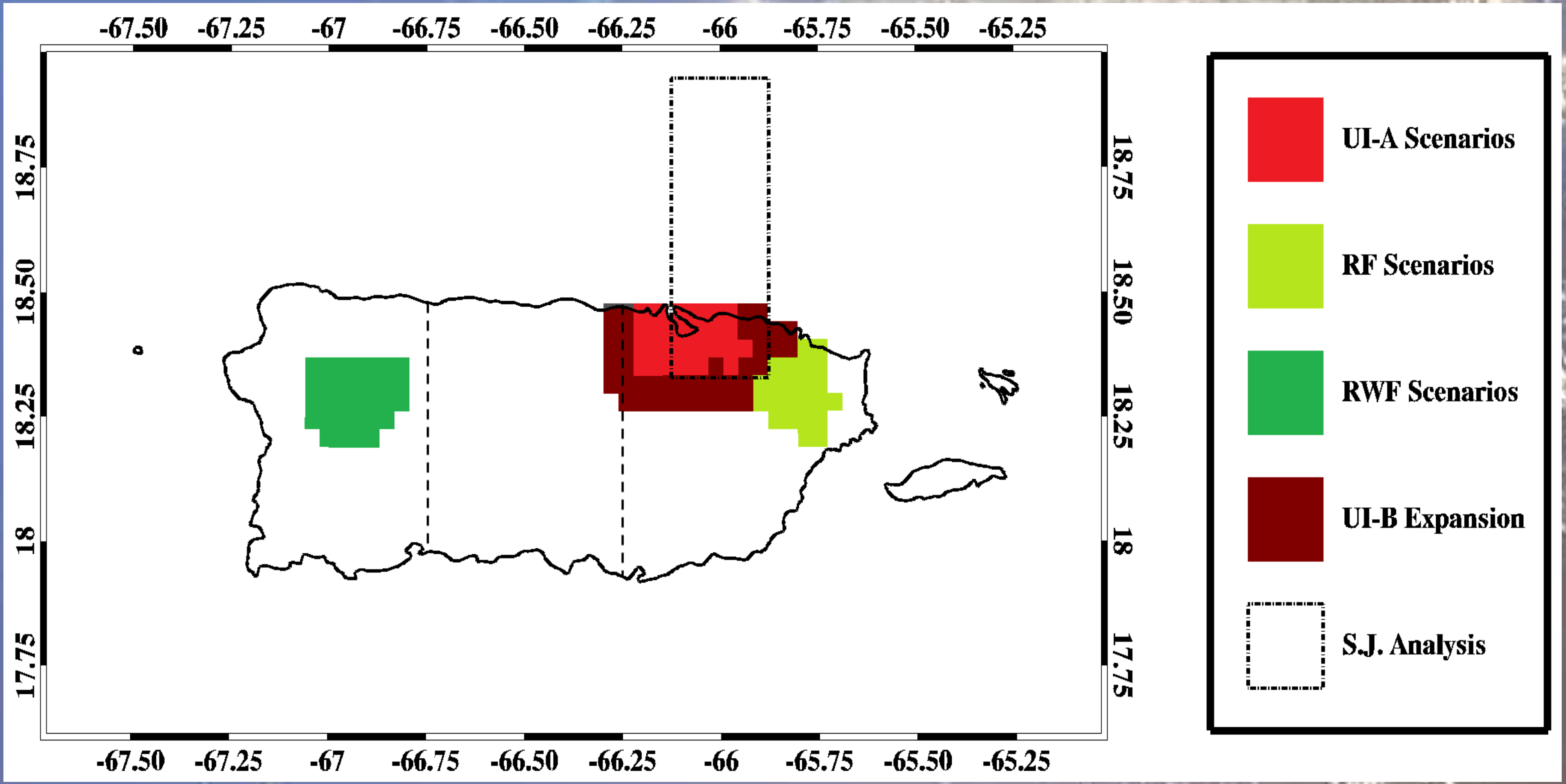



PRISM Maps Urban-Non Urban Temperature Differences by HELZ
Temperature Difference (Celsius)
2.50
2.00
1.50
1.00
0.50
0.00
Minimum
Average
Maximum
Wet Forest
Moist Forest
Dry Forest

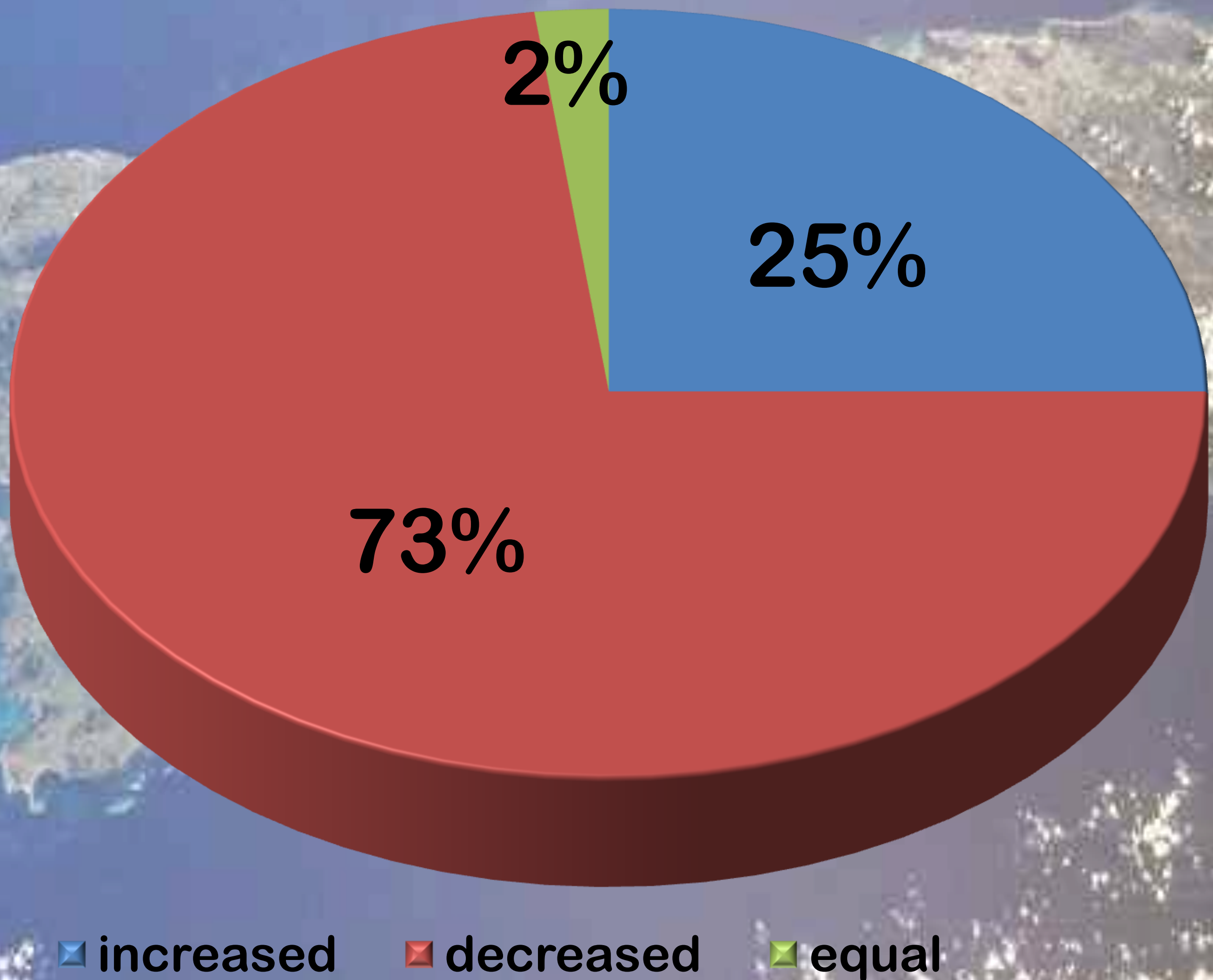
RAMS Results

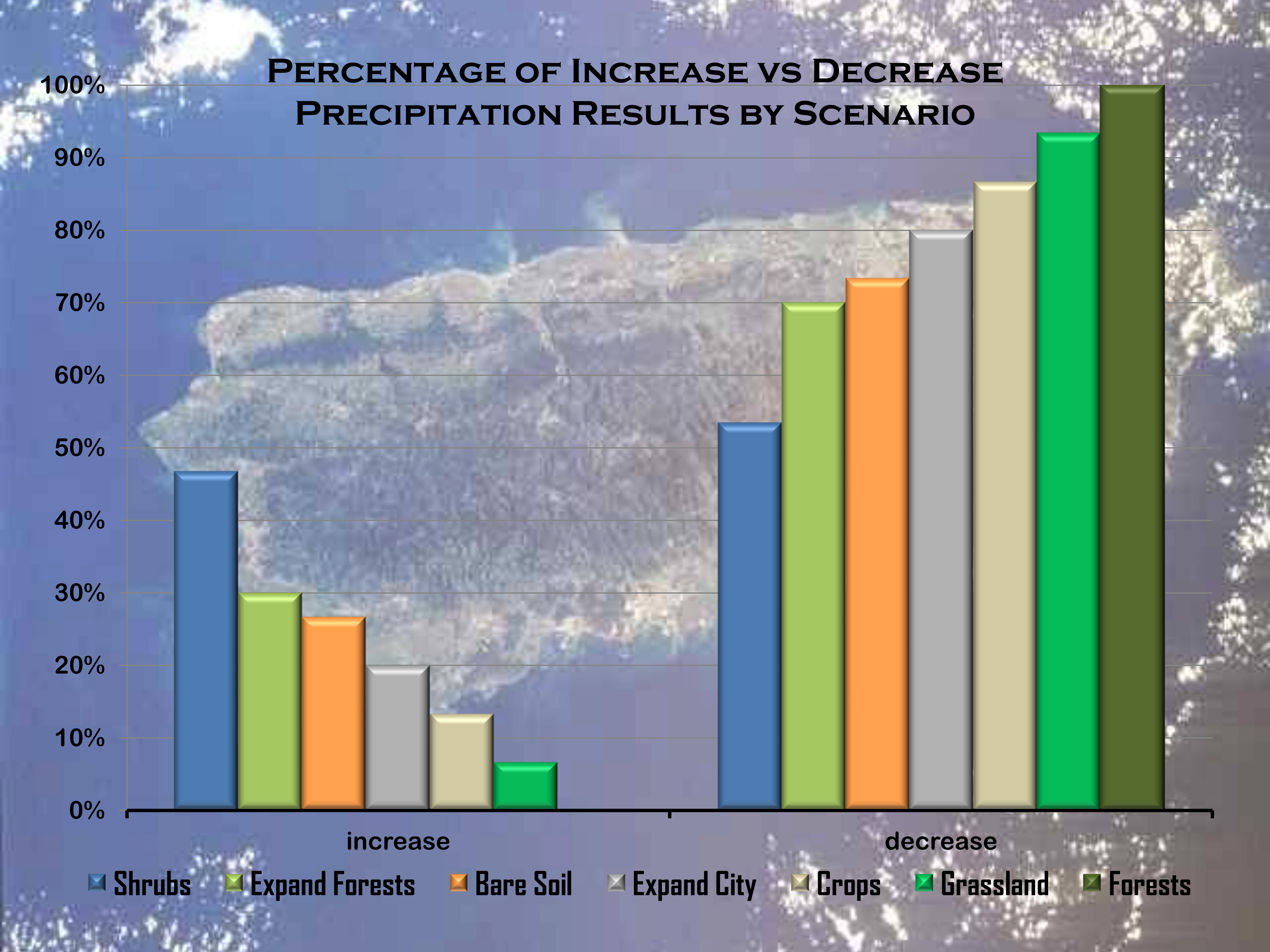
Computational experiments of potential scenarios based on real weather events

Areas of analyzed land-use change for each scenario and the Island response subdivisions



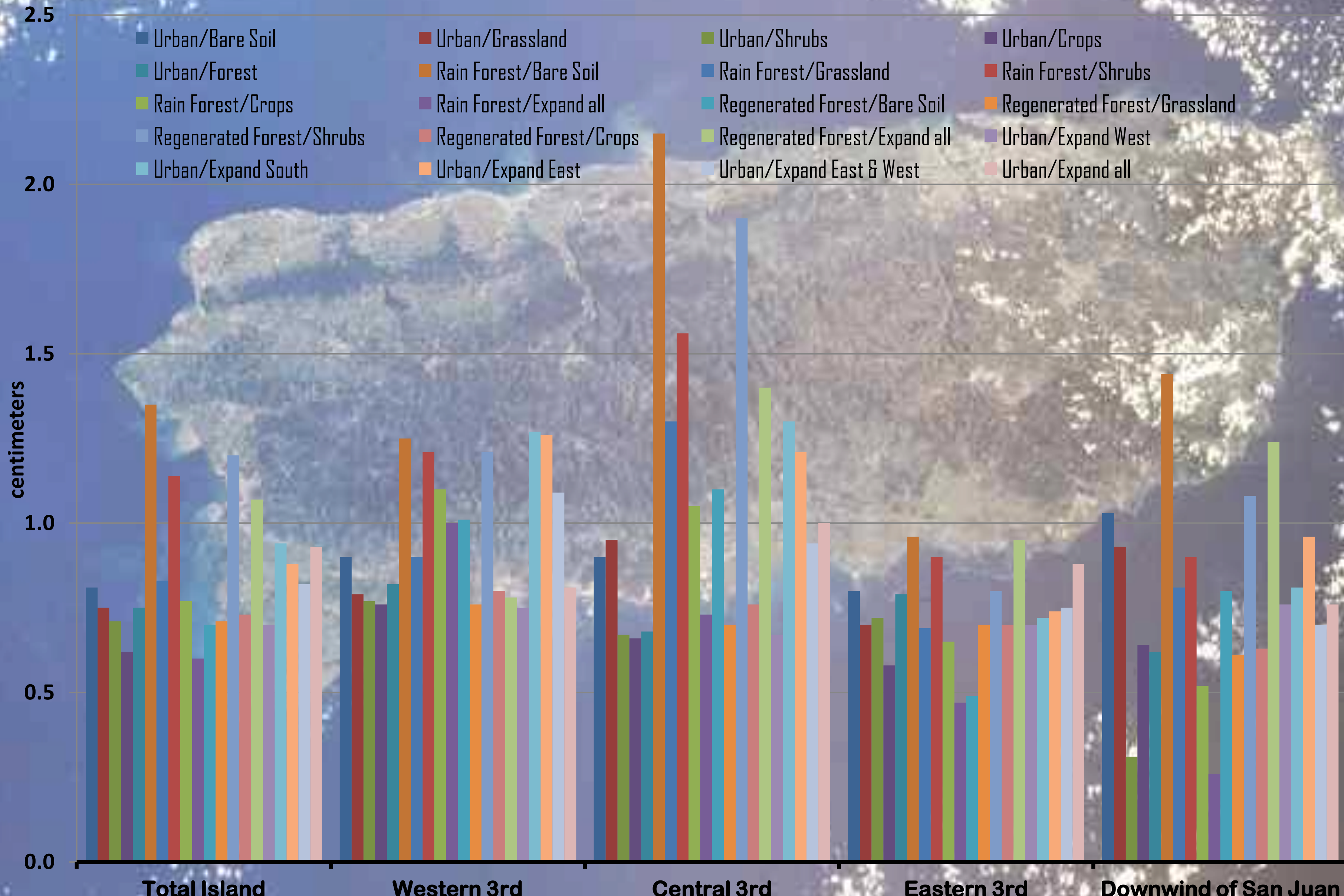
Percentage of resulting scenarios with increased vs decreased precipitation





Percentage of Increase vs Decrease Precipitation Results by Scenario
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
increase
decrease
Shrubs
Expand Forests
Bare Soil
Expand City
Crops
Grassland
Forests

Total Precipitation Response ratio for each scenario at each region relative to control



RAMS Results Summary

- Most scenarios (**73%**) resulted in decreased precipitation.
- Eastern part is the less responsive to LULCC simulations, Central part the most responsive
- Substitutions in both Forests (Rain Forests & Regenerated) caused the most cases of precipitation increase.
- Urban expansions caused more cases of precipitation increase than substitutions
- Substitutions in San Juan urban area decreased precipitation island wide.

Conclusions

- Urban development signals were detected in temperatures across the island.
  - **Strong supporting evidence** of urban impacts
    - Detected in surface stations
    - Detected in GIS generated maps
  - ANOVA and t-test effective detecting urban signals

Conclusions

- Urban development signals were detected on precipitation but less clear.
  - Not detected directly from stations but from GIS generated data.
  - Relationship is not constant
    - Exists in both directions depending on period and HELZ
    - Relationship is reversed in some periods
      - Precipitation over Urban areas dominate in the Wet Forest
      - Precipitation over Non Urban areas dominate in the Dry Forest
    - Magnitude is not constant

Conclusions

- RAMS
  - Pilot study suggests that land cover changes in one area impact precipitation elsewhere on the island.
  - Eastern part less responsive to LULCC simulations, Central part the most responsive
  - Additional events, parameterization and sensitivity analyses are required to produce reliable conclusions for decision making

Theoretical Implications

- Provided a method that small locations could use to asses land use/land cover impacts
  - Effective, reliable and low budget
    - Tackles the research question directly (no need for transformations or indirect methods)
    - Needs only station data, GIS and statistics
    - Statistical quantification of impact
  - Can be used for any land use/land cover and any climate variable
  - Findings mean impact exists; can no longer be ignored.

Theoretical Implications

- Urban signal has been detected in local temperatures across the entire island
  - The magnitude of the signal is at least half degree and has not exceeded much over 2 degrees of difference.
  - Urban Heat Island (UHI) effect highly probable in Wet Forest developed area.

Theoretical Implications

- Urban signal has been detected in local precipitation across the entire island
  - The signal was detected since the beginning of the century
  - The relationship exists in both directions
  - The magnitude and direction of the relationship has shifted through the century depending on HELZ and time period

Practical Implications

- Temperature results suggests….
  - Further studies needed to assess local ecological or environmental impacts of temperatures.
  - If further impacts are identified specific policies and practices like urban reforestation could mitigate it
- Precipitation results suggests…..
  - Ecological or environmental impacts currently unclear
    - Adaptation maybe the only alternative, mitigation unlikely

Future Suggestions

- Temperature
  - Need urban stations in WF and DF locations
  - Need stations around reservations and development stressed locations
- Precipitation
  - Complete and analyze station adjusted data
  - Use radar and satellite precipitation data
  - Filter data to isolate locally generated events

Final Remarks

- Theoretical findings contribute to **understanding of phenomena** and development of **scientific methods**.
  - Urban signals have been detected in local temperatures and precipitation.
  - Methods suitable for all scales but mostly needed at smaller scales
  - RAMS needs further tuning and development
- Practical findings contributes to **local management** and **mitigation policies and practices.**
  - Urban temperature impacts mitigation possible through urban reforestation and greening policies and practices.
  - Urban precipitation impacts mitigation unlikely, adaptation may be only option

Final Remarks

- Climate science can benefit from studies at smaller spatial scales
  - Provide answers at higher spatial and temporal resolution
  - Findings can feed larger scale models

Atmospheric Phenomena

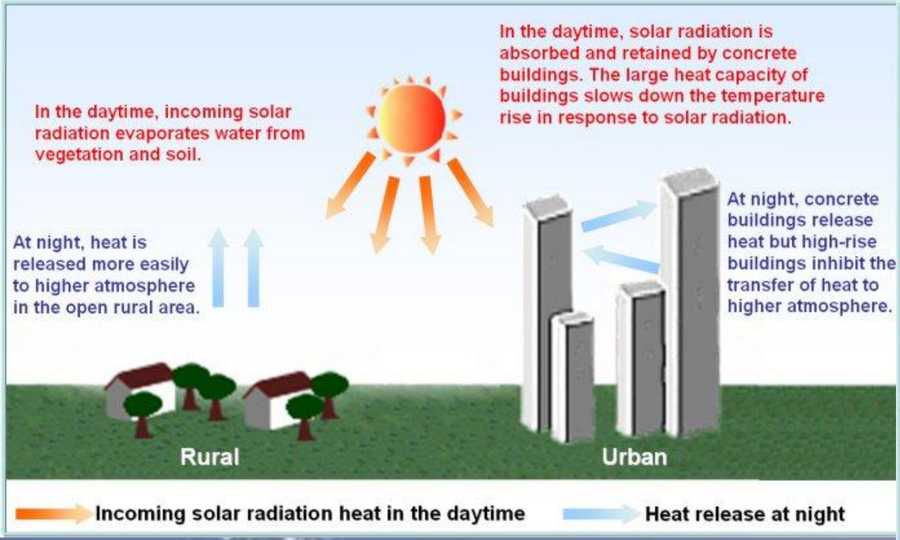
- Take place at different spatial scales
  - Global (Planetary)
  - Regional (Synoptic)
  - Local (Meso, Micro)
- Some phenomena have effects at particular scales
  - Green House Gases (Global)
  - Regional Oscillations (Synoptic)
  - Land Use/Land Cover Changes (Local)

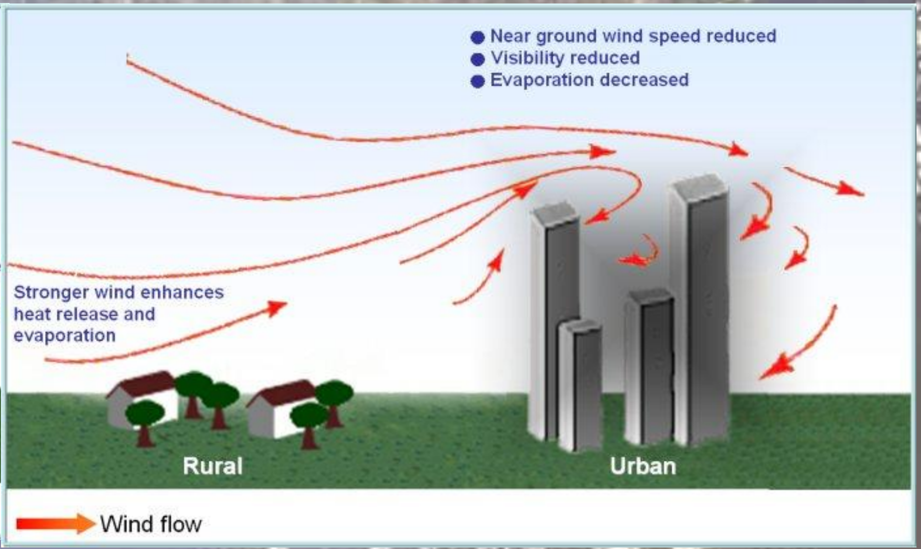
Climatology vs Meteorology

Meteorology	Subject	Climatology
Atmospheric (temperature, winds, precipitation, humidity)	**Study Phenomena**	Atmospheric (temperature, winds, precipitation, humidity)
Micro to Global (micro, meso, synoptic, planetary) (1 m – 1 Km) micro to (10^3 Km – 40^3 Km) global	**Spatial Scale**	Micro to Global (micro, meso, synoptic, planetary) (1 m – 1 Km) micro to (10^3 Km – 40^3 Km) global
Immediate conditions seconds to months	**Temporal Scale**	**Long term patterns** decades to geological periods

Microclimatology

- Local weather events are modified by natural and artificial biological, chemical and physical land features and processes.
  - Urbanization & deforestation induce dramatic changes to the land





Hong Kong Climate Change Observatory
http://www.hko.gov.hk/climate_change/urbanization_e.htm

Climate studies

- Most have been conducted in Continents
  - Continents do not represent all existing climates
    - Interaction between mixture of major air masses
    - Small tropical islands are dominated by tropical maritime mass
  - Fewer studies at small geographic places because of the lack of **long term data** and **high resolution information**
  - Climate science can greatly benefit from studies from smaller places (higher spatial resolution)

Study Site: Puerto Rico

- Long term climate data
  - Temperature
    - Yearly and monthly averages (FILNET 2 adjusted)
  - Precipitation
    - Yearly and monthly average totals (raw data)
- High resolution digital maps
- Relative high number of weather stations (high density)

Future Suggestions

- Temperature
  - Need urban stations in WF and DF locations
  - Need stations around reservations and development stressed locations
  - Generate maximum and minimum temperature Reanalysis data

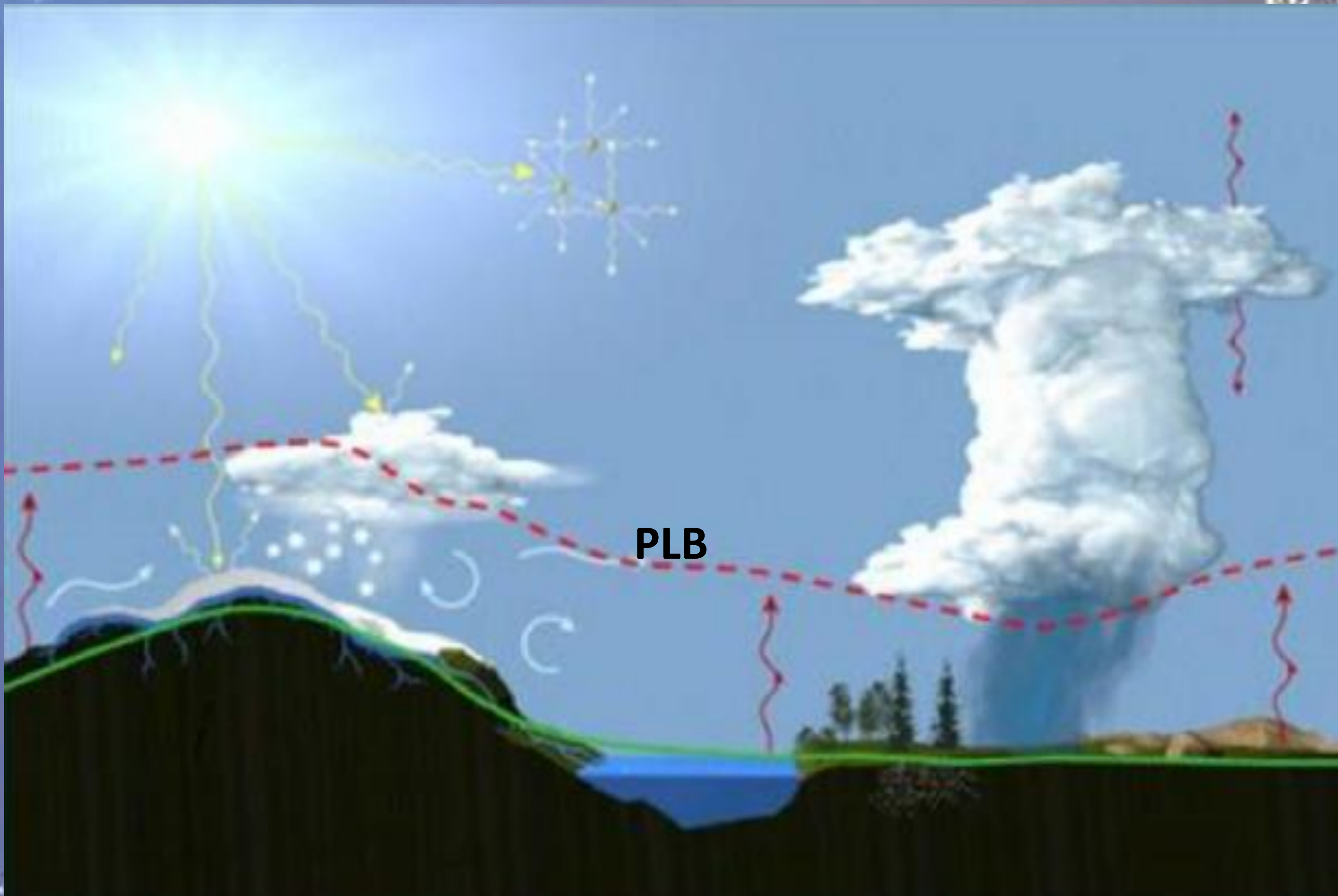
Future Suggestions

- Precipitation
  - Complete and analyze station adjusted data
  - Use radar and satellite precipitation data
  - Filter data to isolate locally generated events
  - Standardize land cover vegetation classification for climate and ecological research
  - Downscale to higher spatial resolution

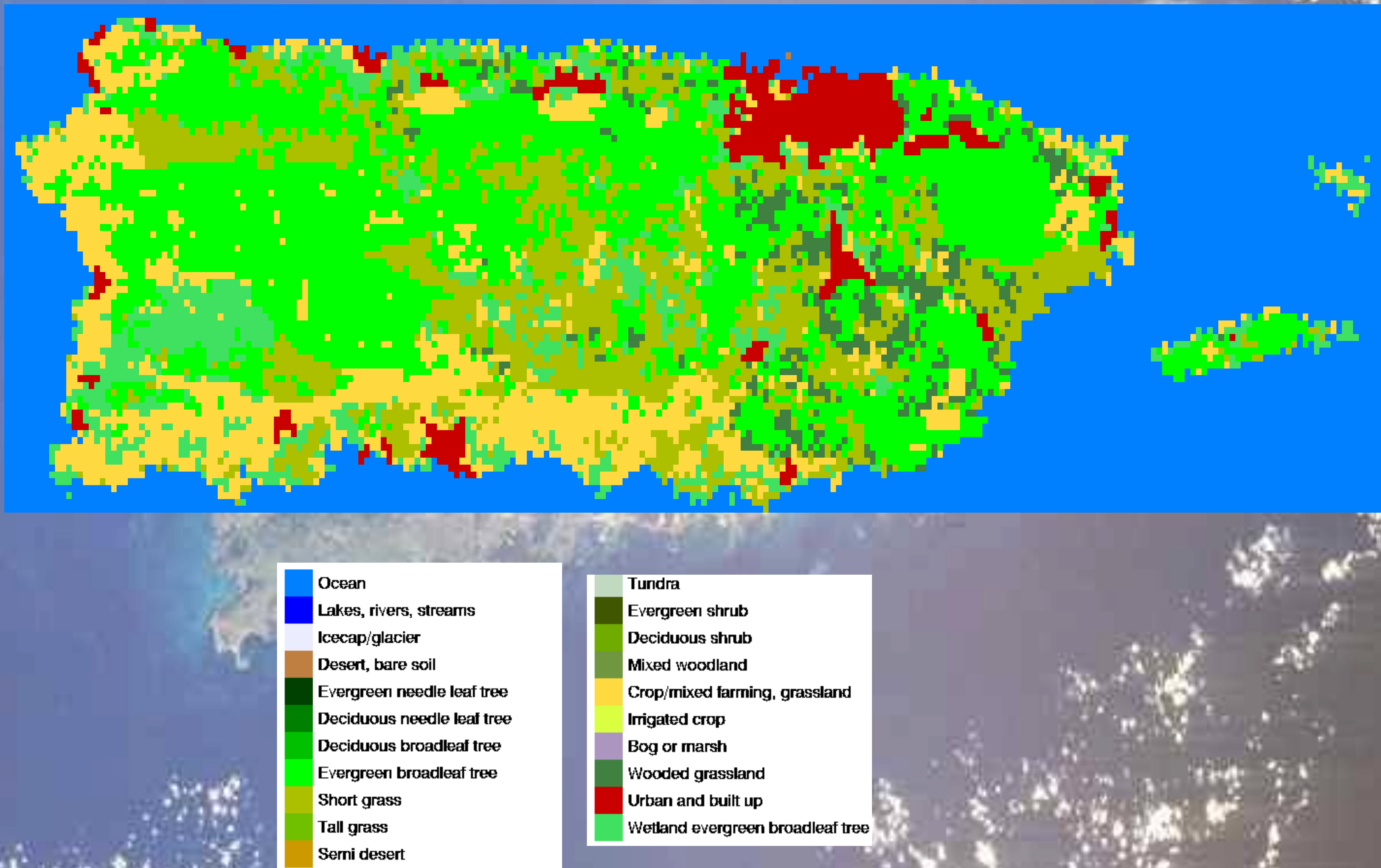
Microclimatology

- Studies **long term patterns** of atmospheric phenomena that develops within the **Planetary Boundary Layer** (PBL)
  - First several kilometers over the earth surface
  - Friction between earth's surface and atmosphere
  - Natural phenomena and anthropogenic activities change surface fluxes and energy balance.
  - Land features and processes affect weather events

Planetary Boundary Layer (PBL)



LEAF-3 land-use/and cover types



Conclusions

- RAMS
  - Eastern precipitation seems to respond to topographic and/or other forcings or be controlled by other factors than land use/land covers changes.
  - Central and Western parts responded more to Land Use/Land Cover simulations.
    - Precipitation at central part seems to benefit from Eastern, Western and Urban boundary mechanical uplift convergence.
  - Urban greening and climatization practices may decrease precipitation island wide
  - Many counterintuitive and unexpected results imply more studies are needed to reliably run RAMS.

Conclusions

- RAMS
  - Expanding the Regenerated Wet Forest and the south expansion of the city are the most environmentally friendly and realistically plausible scenarios
    - Puerto Rico precipitation has been decreasing for the century and climate change scenarios for the region have predicted longer dry periods.
    - Expanding city east would increase precipitation but would threaten natural reserves, coastal expansion not desirable.
    - The combination of Regenerated Wet Forest expansion adding **shrubs** may increase precipitation for most of the island.

HELZ	Station Data Monthly Average			GIS Yearly Average Total (cm)			PRISM Yearly Average Total (cm)		
	U	NU	Sig.	U	NU	Sig.	U	NU	Sig.
Wet Forest									
Moist Forest									
Dry Forest									
	Trends			Trends			Trends		
	U	NU	Sig.	U	NU	Sig.	U	NU	Sig.
Wet Forest									
Moist Forest									
Dry Forest									

Practical Implications

- Computational experiments results suggest….
  - Any Land Cover changes around the island would reduce precipitation in Eastern Puerto Rico
  - Expand Western Forest using shrub type vegetation to increase local precipitation
  - Urban climate mitigation and greening of San Juan may result in island precipitation decrease.

Future Suggestions

- RAMS
  - Parameterize major vegetation types in Puerto Rico, in particular the Dry Forest.
  - Find and run more real events to fine tune better control run in RAMS
  - Develop local RAMS code and programming sensitive to local needs and interests

Precipitation Magnitudes

- Monthly Average Precipitation (cm)
  - Averages the precipitation that falls each month
    - Sums **precipitation totals** from each month and divides by number of months
      - Used for station data analysis
- Yearly Total Average precipitation (cm)
  - Averages the precipitation that falls each year
    - Sums **average monthly precipitation** each year
      - Used for GIS interpolation

Urban Stations 60m Radius Yearly Average Total Precipitation 2 Way ANOVA

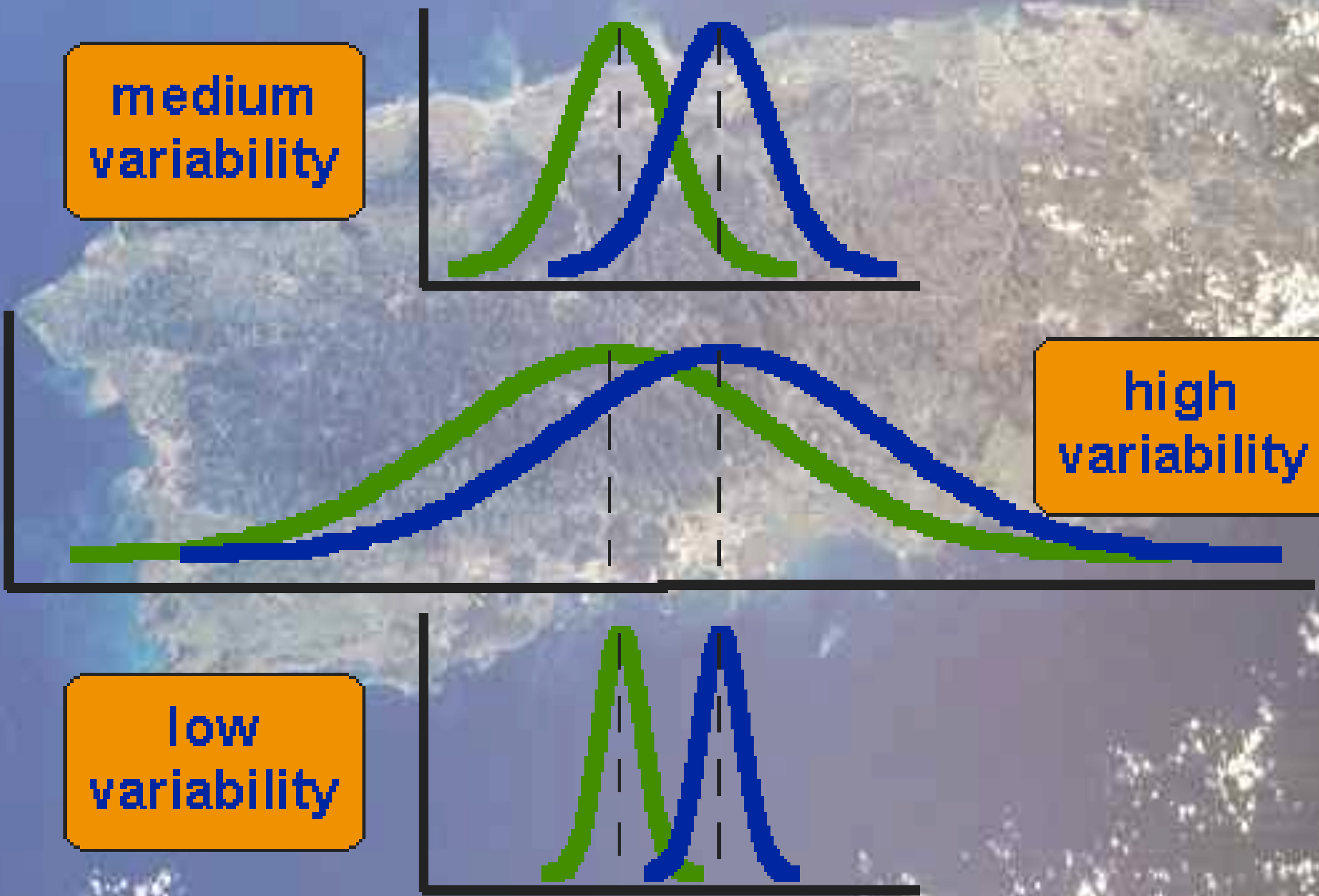
	Test for Combined Effects	1900-1929 cm/y	1930-1959 cm/y	1960-1989 cm/y	1990-2007 cm/y
2004	**Inter. Sig.**	**Comb Sig.**	**Comb Sig.**	**Comb Sig.**	**Comb Sig.**
*WF	0.056	N/A	N/A	N/A	N/A
MF	0.991	N/A	N/A	N/A	N/A
DF	**0.049**	1.000	**0.017**	**0.003**	0.532

* From 1992 Land Cover Map

Statistical Analysis T-test

- Analysis of Variance & T-Test
  - Significance level (α = 0.001; 0.05; 0.1)
    - Error Type I
      - Rejecting the null hypothesis (accepting alternative hypothesis) when is true
      - Increased chance with smaller α
    - Error Type II
      - Rejecting the alternative hypothesis (accepting the null hypothesis) when is true
      - Increased chance with larger α

T - Test



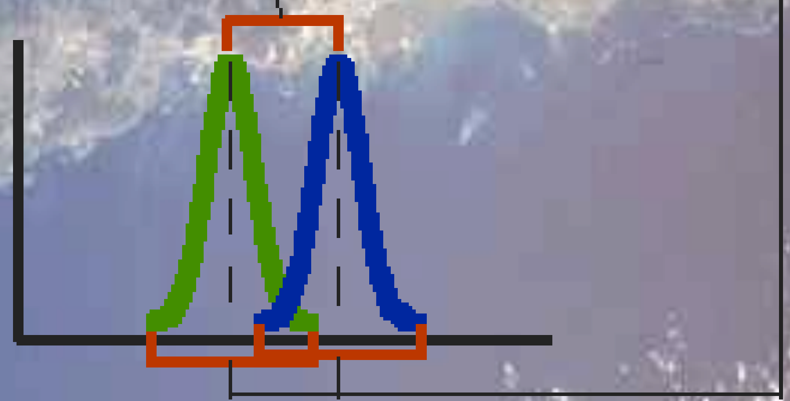
Research Methods Knowledge Base
http://www.socialresearchmethods.net/kb/stat_t.php

T - Test

$$\frac{\text{signal}}{\text{noise}} = \frac{\text{difference between group means}}{\text{variability of groups}}$$

$$= \frac{\bar{X}_T - \bar{X}_C}{SE(\bar{X}_T - \bar{X}_C)}$$

$$= \text{t-value}$$



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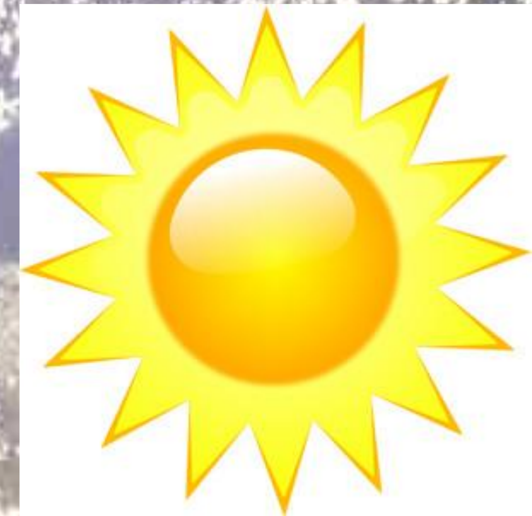
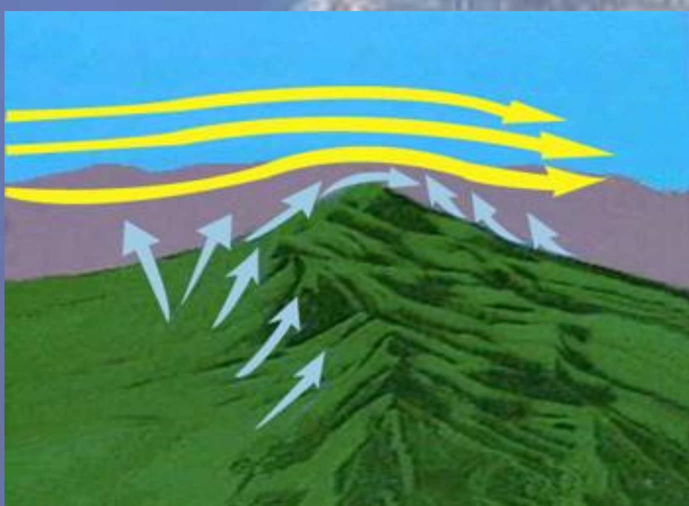

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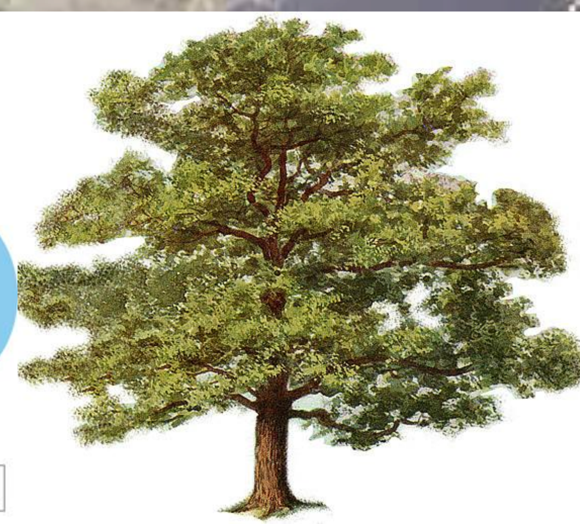


Holdridge Ecological Lifezones

- System of Vegetation Classification developed in 1967
- Combines plant physiology and environmental variables to map vegetation
  - Elevation
  - Evapotranspiration
  - Humidity
  - Precipitation
  - Biotemperature