MAGEEP Education Network

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Water System Adaptation To Hydrological Changes

Module 11
Methods and Tools: Computational Models

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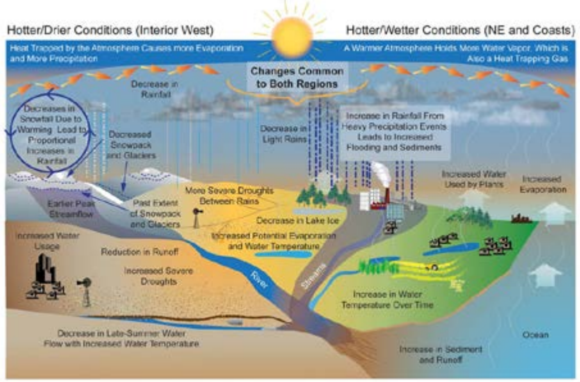
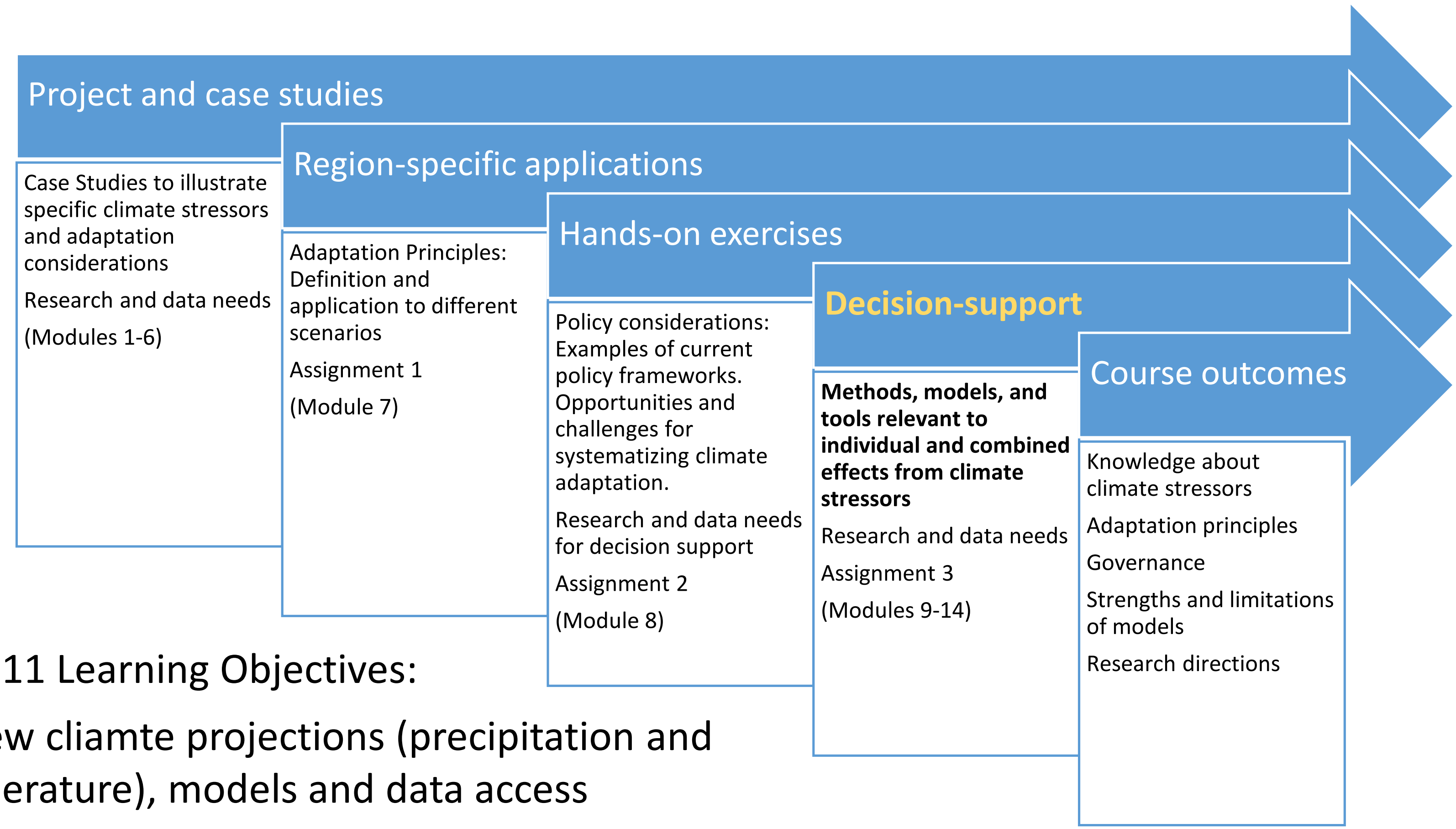


Course Roadmap

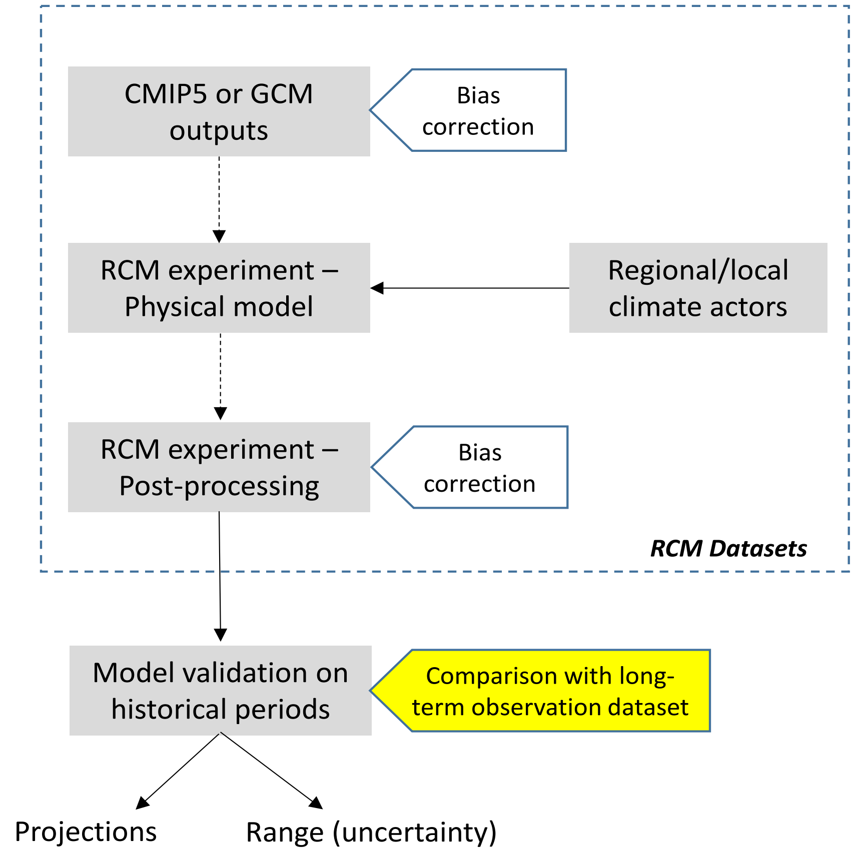


Module 11 Learning Objectives:

- Review cliamte projections (precipitation and temperature), models and data access
- Understand uncertainties and implication for adaptation planning and engineering

Key topics: Module 11

- Future hydrological design basis for a non-stationarity climate. Refer to adaptation principles in Modules #9-10
- Understanding climate models: Basic considerations and assumptions
  - Well defined warmer temperature in future, but precipitation change varies and is region-specific
  - Inland watersheds: Precipitation projection using GCM followed by RCM downscaling
  - Coastal areas: Storm surge height and sea level rise projections, and wind projections
  - For both inland and coastal areas, ***rigorous*** model validation are needed



Hydrological Design Basis and Climate Models

Precipitation

Temperature

Winds

Climate Modeling and Technical Data Development

→ Design storm and hydrological parameters

- Design runoff
- Design evapotranspiration
- Design winds (average and gust)

→ Design engineering parameters

- Storage facility sizing
- Conveyance pipe sizing and capacity specification
- Structural integrity against flood and wind damage
- Facility resilience under disruptive meteorological events (e.g., storm surge)

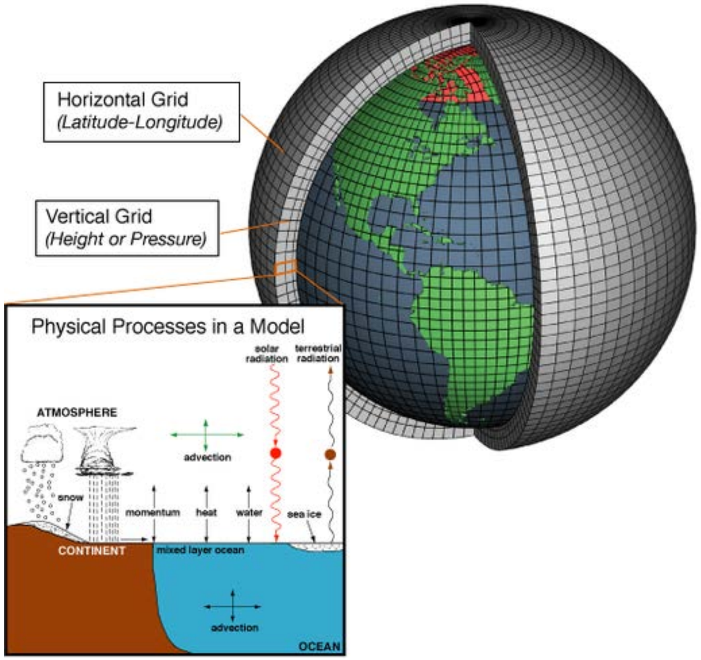
What are Climate Model and Climate Experiments?

Basic Property of a Global Circulation Model (GCM):

- Computing energy budget and heat flux in 3-D cells
- Dividing atmosphere and ocean into model cells in a physical model, and balancing solar energy and heat flux in form of air and water circulations
- Model-calibration often against the global 1950-2000 observation data
- Model outputs including temperature, precipitation, and wind in course spatial resolution (~125 by 125 km)

Future projection and emission pathways:

- Project future climate as monthly or daily averages for future period (until 2100)
- GHG emission as the major future variable specified in emission pathways (IPCC AR5), or formerly emission scenarios in IPCC AR4
- Presence of GHG in atmosphere traps heat; GCM projections are model simulation runs (a.k.a., climate experiments) for a given emission pathway



https://en.wikipedia.org/wiki/General_circulation_model

Climate Modeling Improvements with Time

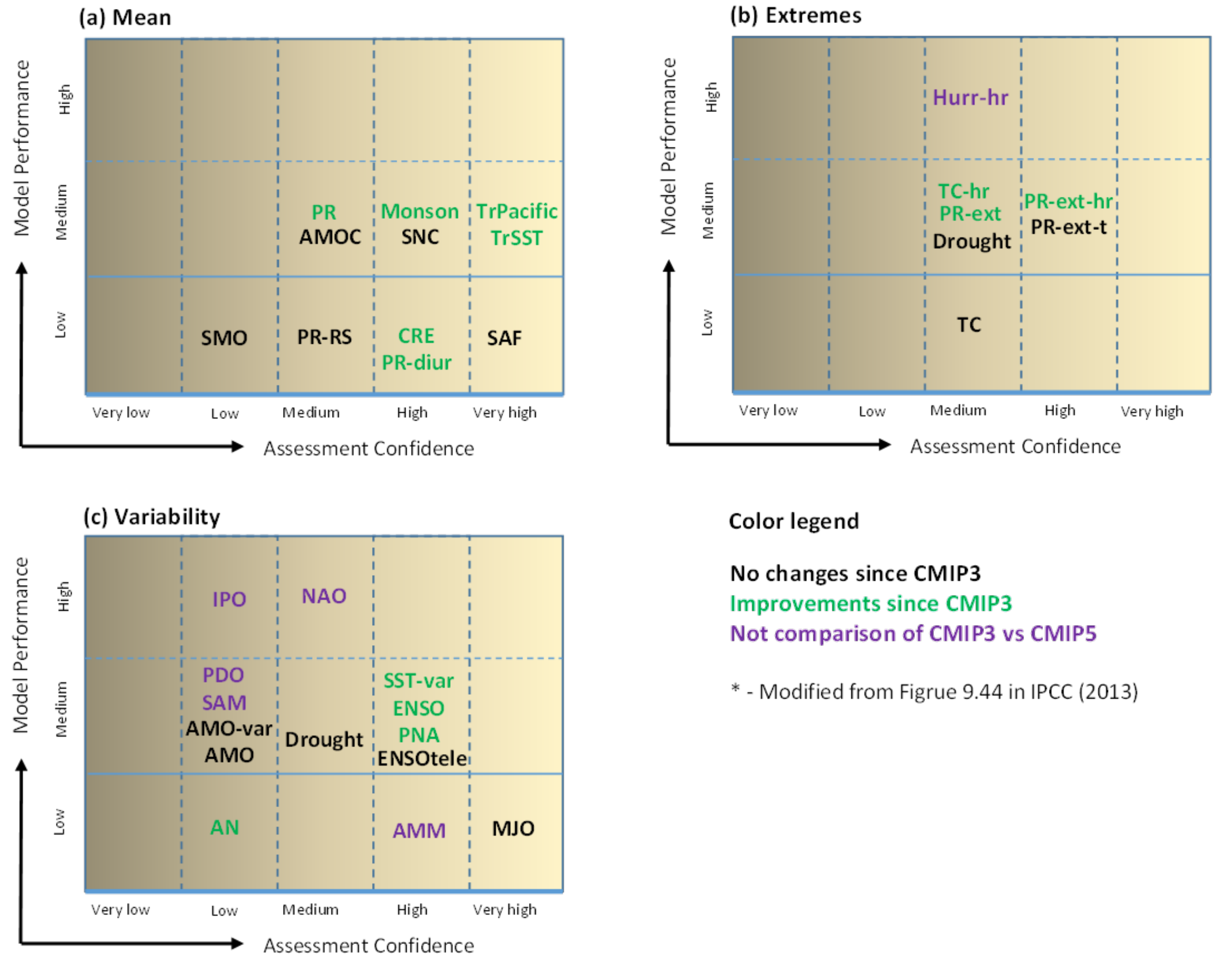
Mid-1970s	Mid-1980s	Early 1990s	Late 1990s	2000s
Atmosphere	Atmosphere	Atmosphere	Atmosphere	Atmosphere
	Land surface	Land surface	Land surface	Land surface
		Ocean, sea ice	Ocean, sea ice	Ocean, sea ice
			Sulphate aerosol	Sulphate aerosol
				Carbon cycle
				Vegetation
				Atm chemistry

Courtesy of IPCC (2013)

- Climate modeling is evolving as a coordinated effort among world-wide climate research centers
- More climatic processes and Earth physical systems are now incorporated in model simulation than ever before
- All models have large uncertainties in precipitation projections (See next slide)
- To address model uncertainty, model ensembles (from a set of individual models) commonly used as a temporary solution
- Coupled Model Intercomparison Project (CMIP) coordinates individual modeling efforts for better interpretability of climate experiments. Two sets of datasets produced: CMIP Phase 3 (CMIP3) and Phase 5 (CMIP5)

Climate Modeling Improvements with Time

- Despite coordinated efforts, some major climate processes and Earth systems are not fully described in GCMs
- Model improvement made from CMIP3 to CMIP5 in the past years.
- CMIP5 projections still have low confidence on the precipitation mean, extremes, and variability associated with several prominent climate processes (See figure on the right)
- Notables include SMO, PR-RS, TC, AN, AMM, and MJO, for example. This yields model uncertainties in GCM projections



* - Modified from Figrue 9.44 in IPCC (2013)

Three Approaches in Climate Projection

Top-down climate projections

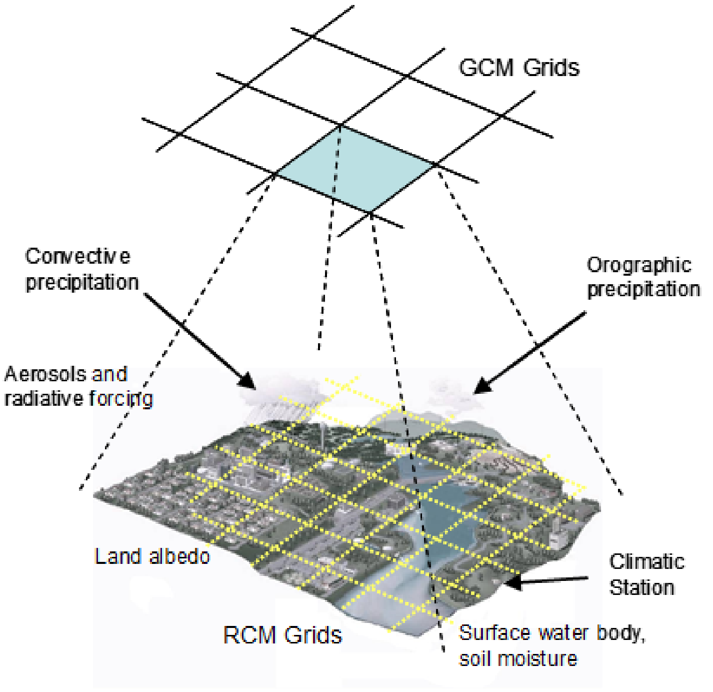
- Project future precipitation and temperature using GCM and RCM simulations;
- Project future land use projections;
- Quantify watershed hydrological responses with quantifiable uncertainties

Bottom-up vulnerability analysis

- Define hydrological threshold in functional deterioration of water infrastructure and water program services;
- Analyze potentials for hydrological change and thus define the hydrological threshold.

Scenario-based quantitative analysis

- Assume degrees of precipitation and temperature changes in future climate; or
- Assume future emission scenarios
- Model watershed response for vulnerability assessment and adaptation design/planning.



Schematic illustration of climate downscaling

Approaches in Climate Projection

Key Considerations for All Approaches

- Define time of model projection
- Define physical domain for projection (e.g., watershed, a city location
- Define projection parameters
  - Temperature (daily mean, diurnal, monthly mean)
  - Precipitation (daily and monthly mean, form)
  - Other variables (wind, moisture, etc.)
- Determine climate models: RCM vs GCM, and individual models vs model ensemble
- Derive hydrological design basis

Top-Down Climate Projection for Adaptation

Inland watershed hydrological and water infrastructure adaptation:

- Precipitation intensity, depth and duration of a design storm
- Temperature, and wind
- Soil moisture or drought index
- All related to watershed hydrology and water availability

Coastal area inundation and disruptive climatic events:

- Sea level rise and storm surge height
- Precipitation intensity, depth and duration, also know as design storm, in coastal inlands
- All related to inundation and inland flooding

- RCM climate simulations at high spatial resolution for watershed-scale planning and engineering
- Rigorous climate model validation with long-range local historical data
- Significantly larger model uncertainty for projection time further into future
- Model uncertainty to be assessed and incorporated into adaptation planning and engineering

Top-Down Climate Projection for Adaptation

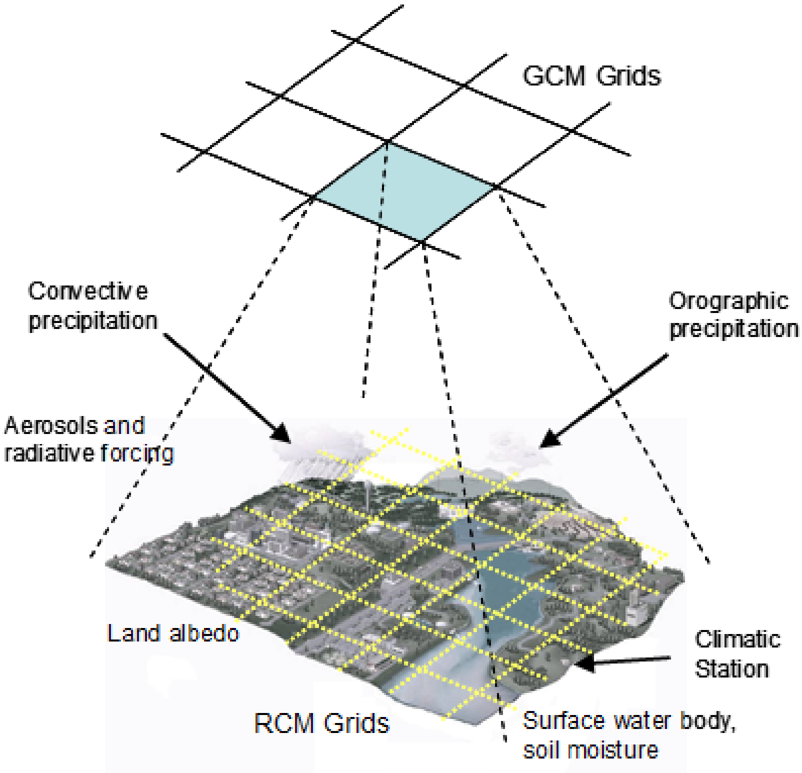
Projections for adaptation planning and engineering in inland areas:

- Precipitation intensity, depth and duration, also know as design storm
- Temperature, and to a lesser degree, wind
- Soil moisture or drought index
- All related to watershed hydrology and water availability

Projections for adaptation planning and engineering in coastal areas:

- Precipitation intensity, depth and duration, also know as design storm
- Sea level rise, storm surge and winds
- All related to inundation and acute disruptive impacts

Climate Models and Downscaling



Say the area for mid latitude

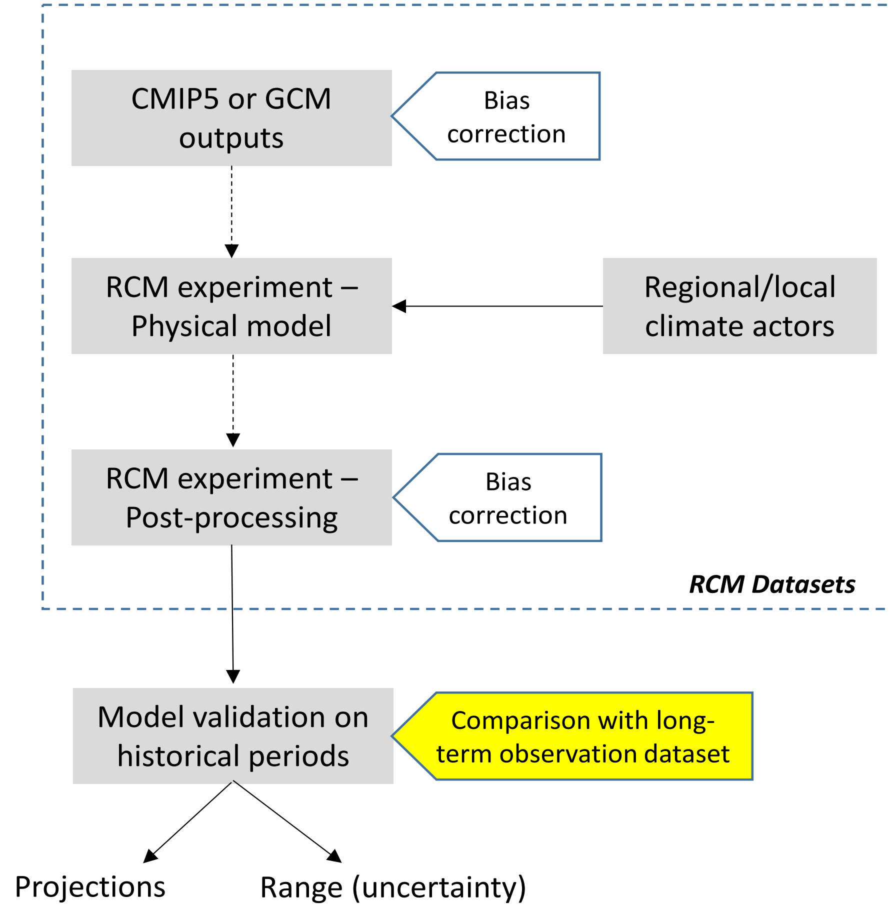
- For watershed applications, GCM-generated future precipitation projections are further “downscaled” using RCM simulations
- A RCM simulation is based on GCM results, but details precipitation at higher spatial resolution at which local climate factors can be considered.
- Local climate factors such as land albedo, aerosols, topography, etc, can significantly affect orographic and convective precipitation.
- They are important to precipitation variability in watershed scales.

Top-Down Climate Projection for Inland Watersheds

For hydrological and water infrastructure adaptation in inland watersheds:

- Precipitation projection of high-confidence for next 30-50 years
- High-spatial resolution for local watersheds
- Temperature, wind and soil moisture helpful in ET and water demand analysis
- Uncertainty range known if no accurate projections are available

✓ Available modeling techniques: Bias correction and model validation against local historical observations (See diagram on right)



Climate Projection at Watershed Scales

Methods and Database for Top-down Precipitation Projections

CMIP3 or CMIP5 datasets

GCM ensembles for all major future emission pathways

Data access through World Climate Research Programme (http://cmip-pcmdi.llnl.gov/cmip5/data_getting _started.html) .

NetCD files for BCSD also available at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections

Statistically downscaled RCM datasets

BLM RCM datasets (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections) :

Bias-corrected statistical desegregation (BCSD) using CMIP3 output

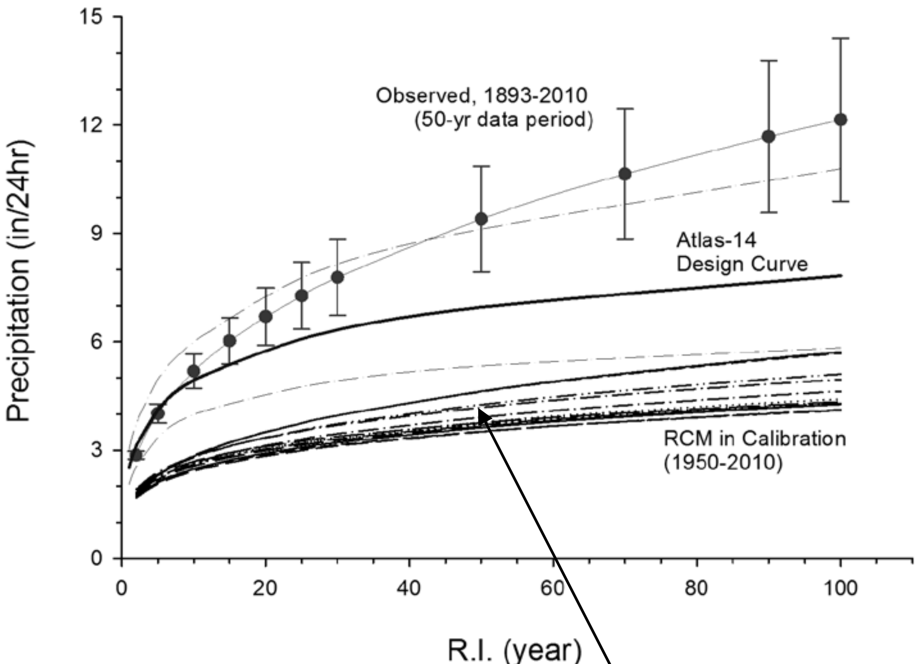
Bias-correction and constructed analog (BCCA) using CMIP5 output

NARCCAP RCM datasets (http://www.narccap.ucar.edu/about/index.html)

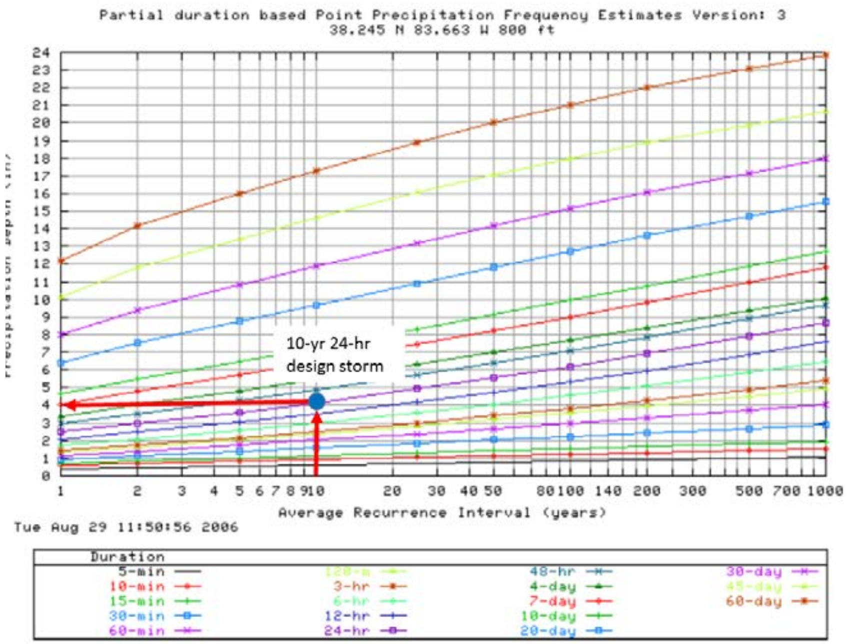
Projection using climate teleconnection

Various statistical methodologies linking SST anomalies to local or regional precipitation variability or long-term changes

Climate Projection for Adaptation



Atlas 14 Design Chart (NOAA NWS, 2004)



Courtesy of NWS (2015)

All RCMs significantly under-predict design precipitation at all storm return intervals. The degree of underestimation can be accurately determined

Transfer Climate Projections to Watershed Hydrological Design Parameters

Post-processing for local watershed applications:

- After downscaling of climate projections to a local watershed, post-processing helps determine the design storm for planning and design
- The process involves:
  - Deriving model projections from RCM (or if not available, CMIP5 ensemble data) for both calibration and projection periods;
  - Running statistical analysis against calibration precipitation data
  - Deriving bias correction factor using statistical analogue for calibration
  - Correcting projection bias in projections

Top-Down Climate Projection for Adaptation

Projections for adaptation planning and engineering in inland:

- Precipitation intensity, depth and duration, also know as design storm
- Temperature, and to a lesser degree, wind
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- All related to watershed hydrology and water availability

Projections for adaptation planning and engineering in coastal areas:

- Precipitation intensity, depth and duration, also know as design storm
- Sea level rise, storm surge and winds
- All related to inundation and acute disruptive impacts

Systems Modeling for Coastal Area Adaptation

Emission Pathways
GCM climate experiments

Sea Level Rise Projection

Storm surge modeling

Outputs for Impact modeling and adaptation analysis

- Salt water intrusion modeling
- SLR and storm surge modeling of coastal wetlands
- Wave and wind propagation simulation
- Coastal flooding modeling
- Traffic and evacuation modeling in storm surge
- Drinking water supply simulation in SLR and storm surge
- Stormwater and wastewater systems modeling and adaptation
- Flooding risk modeling and analysis

Local Storm Surge Projections for Adaptation

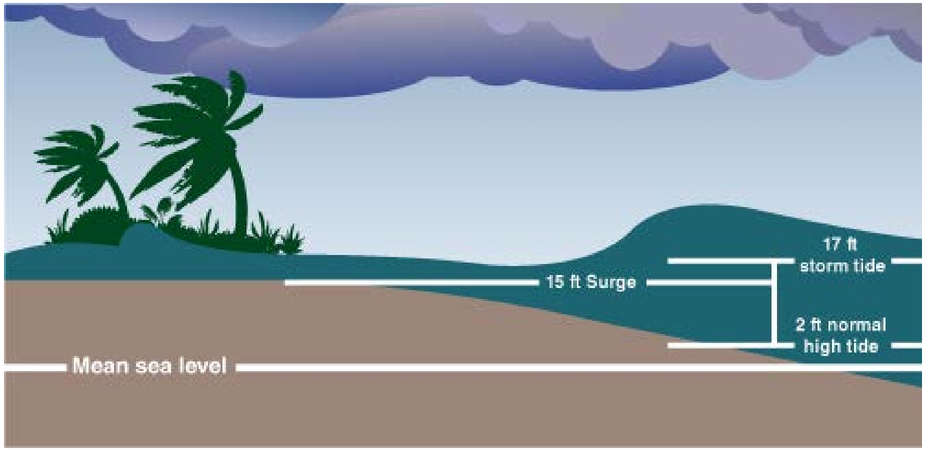
SLOSH model and governing equations

- Sea, land, and overland surge from hurricanes (SLOSH) model estimates the degree of storm surge in term of maximum envelope of water (MEOM) and the maximum of MEOWs (MOM). Both MEOM and MOM used for emergency planning
- SLOSH is computationally efficient, 2-D explicit, finite-difference model, formulated on a semi-staggered Arakawa B-grid.

- Major model parameters affecting outputs
  - Surface drag coefficient, C_D
  - Bottom slip coefficient, s
  - Vertical eddy viscosity coefficient

Basic model-projection steps

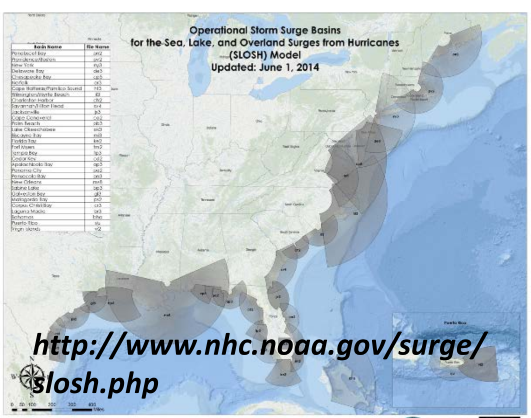
- Use regional SLOSH model outputs as boundary conditions;
- Use local topography and bathometry at current and projected future sea levels (in DTM data)
- Calibrate against past storm surge events
- Conduct modeling and projection results analysis in GIS



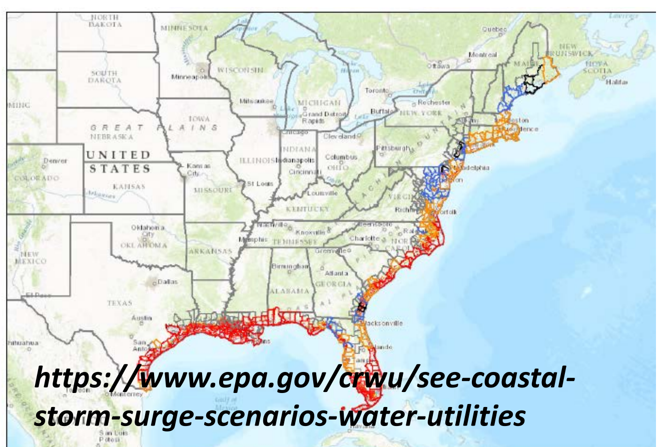
Top-Down Emergency Planning and Engineering Basis for Acute Hydroclimatic Events

Three-Steps

Step	Product	Resources
Regional SLOSH-SS assessment for current and future emission	SLR and MEOWs for vulnerability analysis	NOAA SLOSH SS products [1] EPA SS inundation maps [2]
SLOSH-SS impact analysis at local scale by reanalysis of regional models	MEOWs, MOMs of hurricane grade for planning	Local MEOWs & MOMs modeling and probability analysis Hydrological modeling of impacts
Forecasting, warning, assessment / Emergency and mitigation actions	Emergency plan activation & consequence mitigation	MOMs updating & forecasting Emergency water services [3]



http://www.nhc.noaa.gov/surge/slosh.php

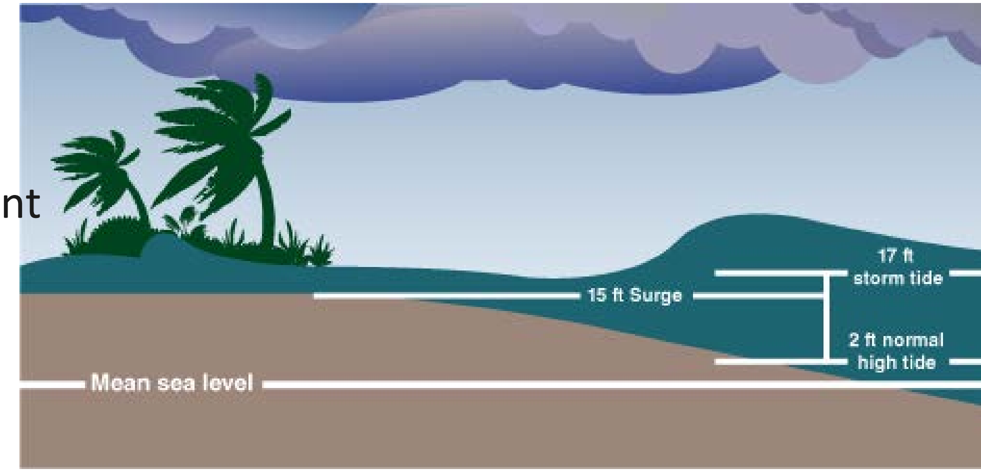

https://www.epa.gov/crwu/see-coastal-storm-surge-scenarios-water-utilities


Calibration and rerun for local topography, storm tracks and calibrations

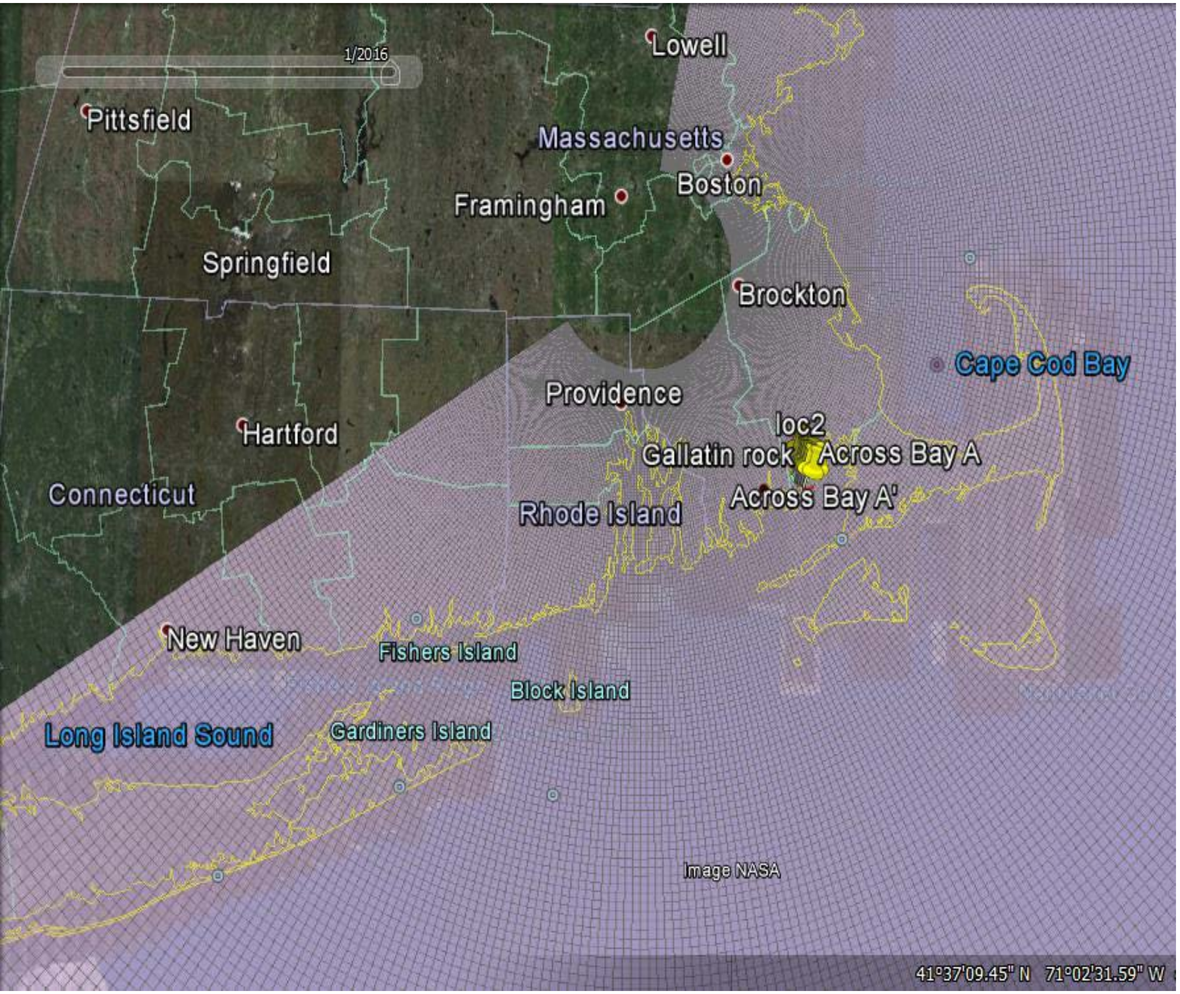
Basics: How to Develop Reliable Local Storm Surge Projections

SLOSH model and governing equations

- Governing differential equations for the transport of motion in Cartesian and Polar coordinate systems
- SLOSH is computationally efficient, 2-D explicit, finite-difference model, formulated on a semi-staggered Arakawa B-grid.
- Major model parameters affecting outputs
  - Surface drag coefficient, C_D
  - Bottom slip coefficient, s
  - Vertical eddy viscosity coefficient



Mattapoisett Example: Model Simulation for Current and Future Climates



- Reference NOAA's regional SLOSH setup and outputs
- Run model calibration – adjusting model parameters
- Projection for future scenarios for specified wind directions and sea level rise scenarios

- Taking sea level rise scenarios
  - Surface drag coefficient, C_D
  - Bottom slip coefficient, s
  - And water column height, H

- Specifying hurricane tracks and pressure gradients
  - Depending on local coastal features (channels, barrier islands, etc.)
  - Examining historical records

Mattapoisett Example: Model Simulation for Current and Future Climates

- ***Local Historical Wind Gradient and Tracks***

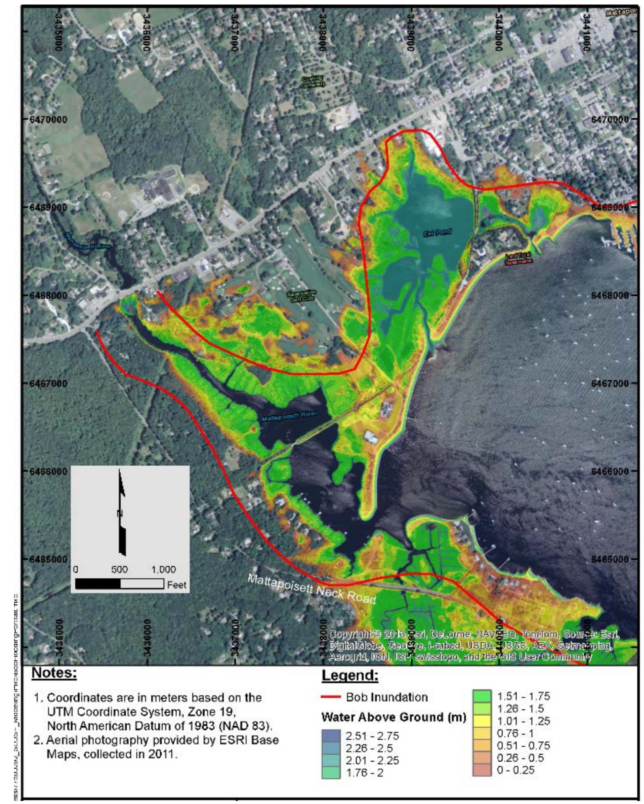
Table 1. SLOSH Model Inputs

Parameters	Values	Number of Variations
Landfall Location	1 (Hurricane Bob)	1
Pressure (mb)	40, 60, 80	3
Radius of Maximum Wind (mi)	25, 40, 55	3
Forward Speed (mph)	30,45,60	3
Track Direction (degree)	NNW, N, NNE, NE	4
Sea Level Rise (ft)	0, 1, 2, 4	4
Total Number of Runs		432

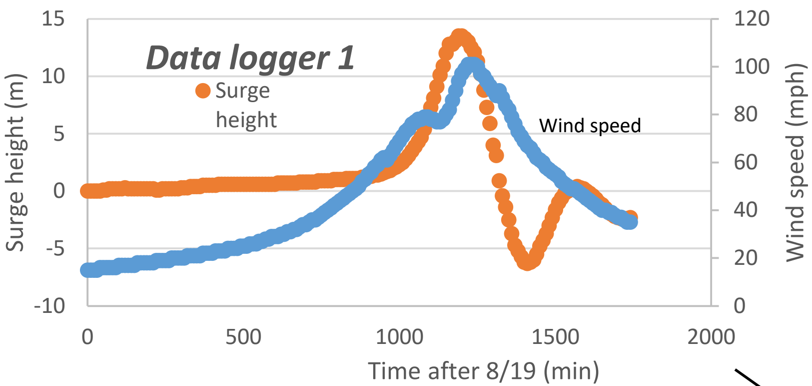
Table 1. Historical Storms for the Mattapoisett Area

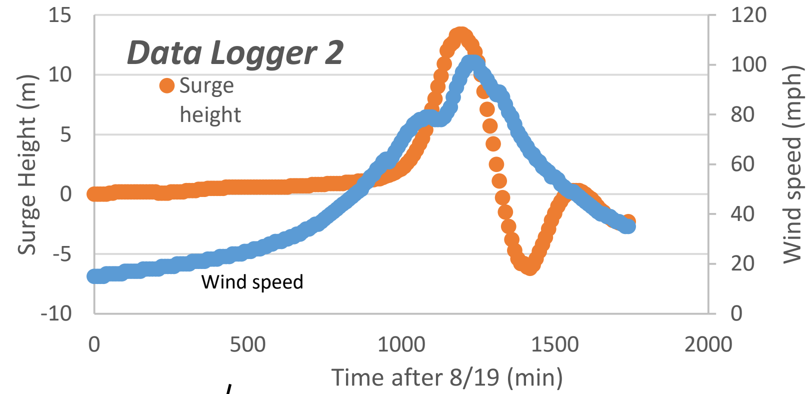
Name	ΔP (mb)	Rmax (mile)	1-min Vmax (knot)	Speed (mph)	Direction
1635	74	35	117	40	NNE - NE
1815	53	30	106	47	N - NNE
1938 First	73	57	104	48	NNW - N
1938 Second	77	30	135	62	NNW - N
1944 First	46	32	91	33	NNE - NE
1944 Second	54	38	98	39	NNE - NE
1954 Carol	58	25	115	45	N - NNE
1985 Gloria	36	24	105	36	NNE - NE
1991 Bob	56	48	88	31	NNE - NE
1999 Floyd	39	39	81	33	NNE - NE
Maximum	77	57	135	62	
Minimum	36	24	81	31	

- ***Local Topography and Historical Hurricane Calibration***



Mattapoisett Case: Model Simulation Results

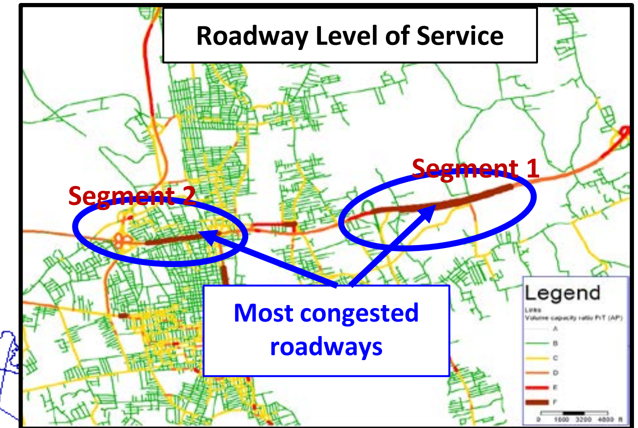




In Category-4 hurricane, it is projected that strong wind >80 mph in the study area could last over 5 hours, causing physical damage to above-ground structures including electrical grids

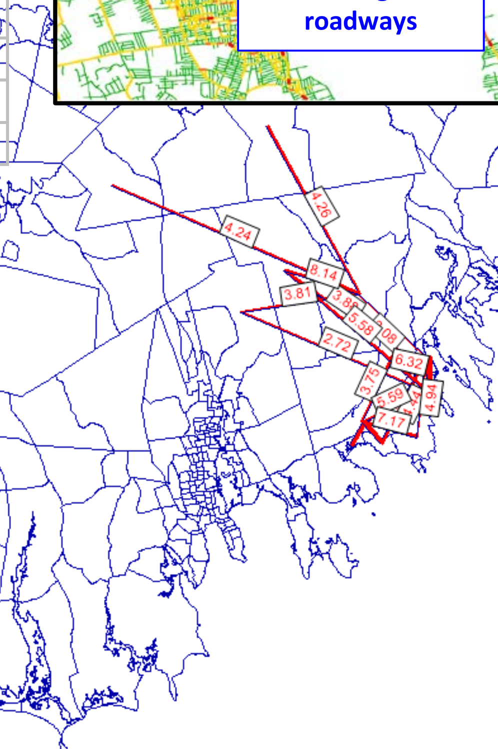
Mattapoisett Example: Systems Modeling for Storm Surge Evacuation

Sea level rise (meter)	Hurricane Category 1			Hurricane Category 2		
	Traffic analysis zones -	Affected Population	Affected Households	Traffic analysis zones -	Affected Population	Affected Household
SLR 0	121	15,995	8,429	136	28,117	14,589
SLR 1	122	16,086	8,487	136	28,235	14,675
SLR 2	122	16,196	8,561	136	28,335	14,735
SLR 4	122	16,380	8,677	136	28,514	14,845
Sea level rise (meter)	**Hurricane Category 3**			**Hurricane Category 4**		
	Traffic analysis zones -	Affected Population	Affected Households	Traffic analysis zones -	Affected Population	Affected Household
SLR 0	144	39,325	20,150	183	78,030	39,323
SLR 1	144	39,488	20,269	183	78,159	38,395
SLR 2	144	39,563	20,313	183	78,276	38,461
SLR 4	144	39,749	20,422	184	78,754	38,731



Integrated systems modeling includes SLOSH, sea level rise, population distribution, evacuation planning, and traffic analysis. It produces outputs in:

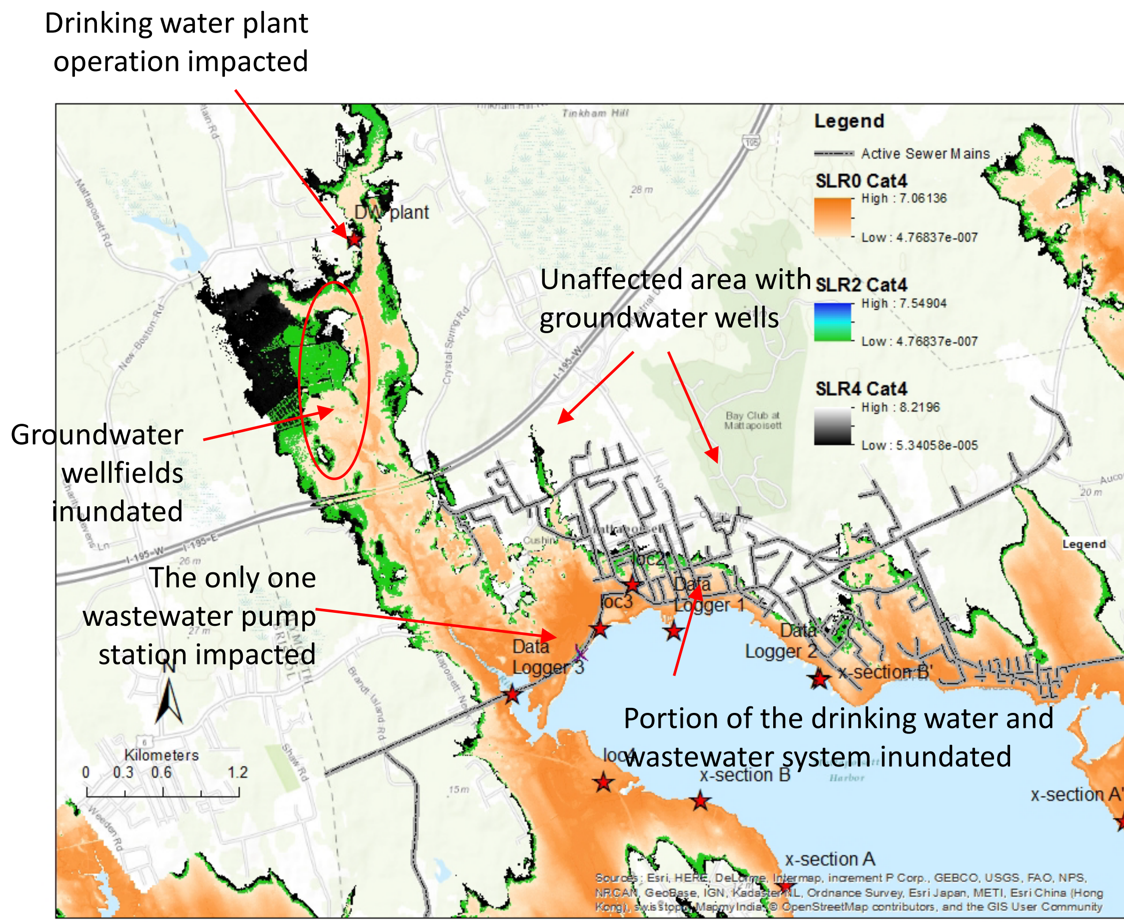
- Evacuated population and distribution
- Evacuation time needed and optimal routes
- Road traffic and management options
- Emergency water and food supplies



Mattapoisett Example: Emergency Water Supply and Wastewater Services

Water Infrastructure Impacts and Adaptation

- Wastewater collection system inundated in the south
- Wastewater transfer station is impacted, with potential damage to the pump house and equipment
- Drinking water plant is impacted, and may not be operational
- Wells and small drinking water systems in the north not affected, offering the resilience in emergency water supplies
- Only emergency water services during storm surge; but full services need to be resumed in recovery phase



Summary

- Three major approaches in climate modeling and all have their limitations
- In top-down approach, GCM and RCM outputs can be used for application in water system adaptation
- To use climate model results, model validation and knowledge of projection uncertainty are critical to adaptation success
- Provided climate model and data access with weblinks

Research Questions

- Give one example of using climate model for regional planning and local water adaptation in your country. If not available, search for one example in which precipitation has changed and describe how this may affect the function of water infrastructure.
- Are coarse-scaled GCM precipitation projection accurate enough for hydrological design basis of a local water utility?
- What are the steps in developing a hydrological design basis in top-down approach for water infrastructure adaptation?
- Find an appropriate climate downscaling database for precipitation, and list the reference or URL.

Looking ahead to the next module…..

- Next module: Models and Tools for Stormwater and Wastewater System Adaptation
- Scoping of project topics