PROTOTYPE D'UN MODÈLE HYBRIDE STATISTIQUE / DYNAMIQUE POUR DES SIMULATIONS HYDRODYNAMIQUES À HAUTE RÉSOLUTION

Environnement et Changement climatique Canada (ECCC)

Pascal Matte, Caroline Sevigny, Silvia Innocenti

Polytechnique Montréal

Julie Carreau, Meryem Bousebata

12e Atelier de résolution de problèmes de Montréal
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Environnement et Changement climatique Canada | Environment and Climate Change Canada

Canada

PROTOTYPE OF A STATISTICAL / DYNAMICAL HYBRID MODEL FOR HIGH-RESOLUTION HYDRODYNAMIC SIMULATIONS

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12th Montreal Industrial Problem Solving Workshop
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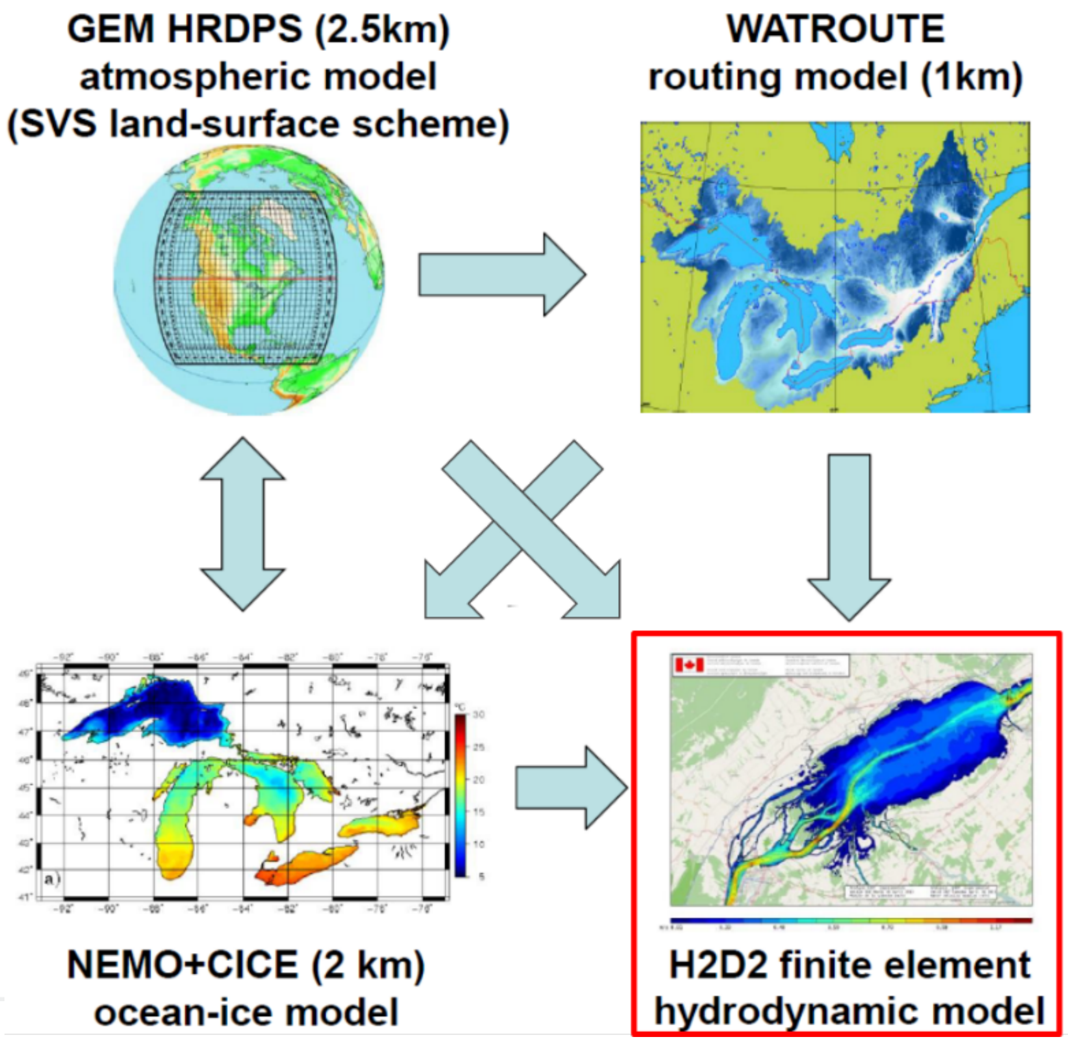
OUTLINE

- Context and motivation
  - Operational environmental prediction at ECCC
  - Modeling studies in the Great Lakes
  - Challenges and limitations
- Case study: Lake Erie
  - Hydrodynamic model
  - Wind setup and seiches
- Modeling approaches
  - Continuous simulations
  - Static scenarios
- Areas for improvement
  - Regional wind averaging
  - From static to continuous simulations
- Available data

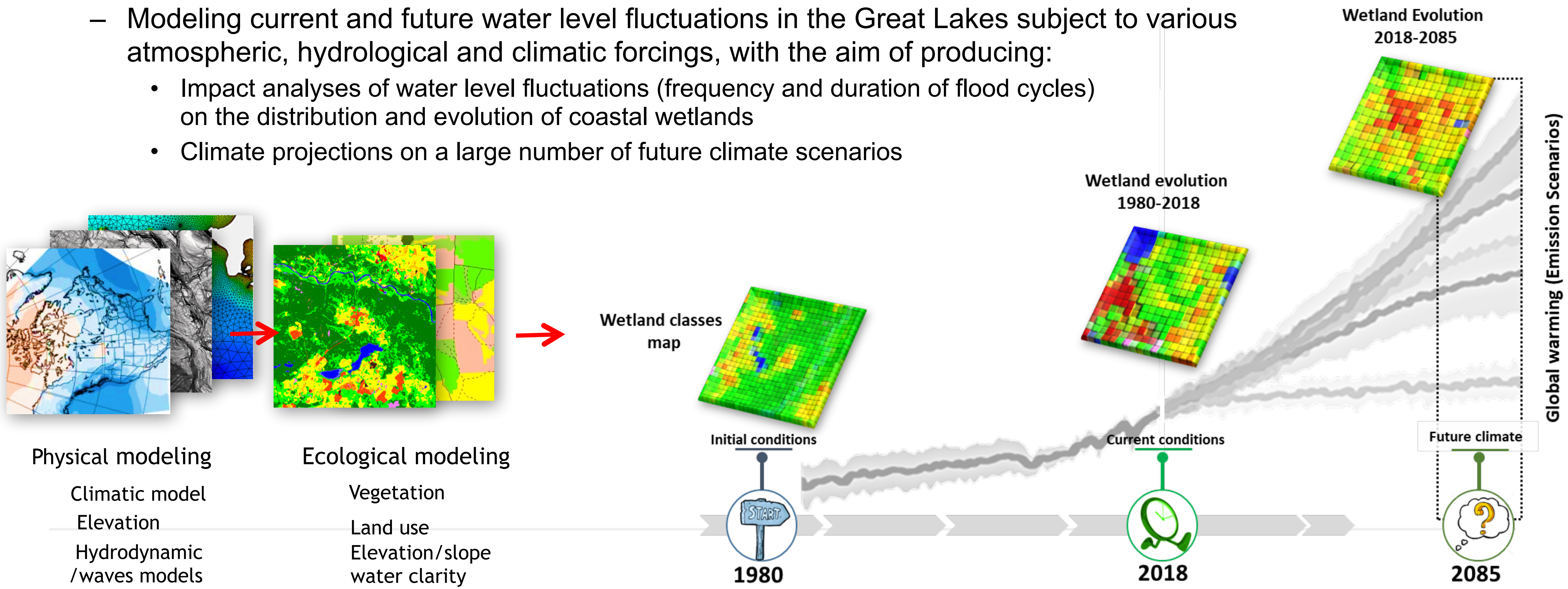
OPERATIONAL ENVIRONMENTAL PREDICTION AT ENVIRONMENT AND CLIMATE CHANGE CANADA (ECCC)

- ECCC's prediction systems provide 24/7 real-time analyses and forecasts of atmospheric, oceanic, ice, wave, hydrologic, and hydrodynamic conditions from global to local scales.
- Research and development focuses on improving ECCC's prediction capabilities and capacity to deliver and sustain environmental prediction products and services to Canadians, researchers, industry and government.
- Targeted outcomes include increased navigational safety, decision support, efficient search and rescue operations, and emergency response.



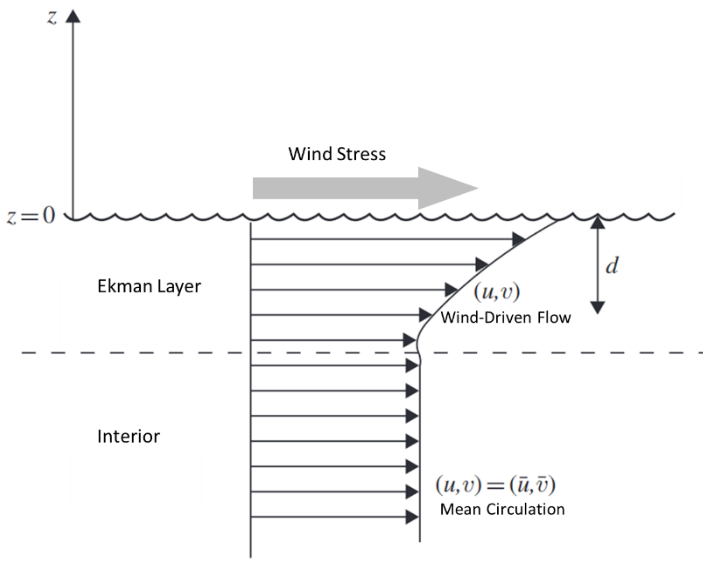
MODELING STUDIES IN THE GREAT LAKES

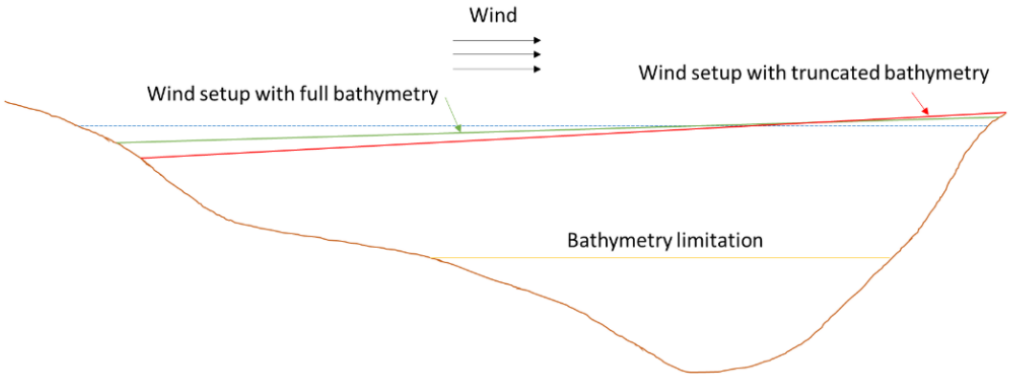
- Great Lakes – St. Lawrence River Adaptive Management
  - An evaluation of new transboundary water management plans based on the assessment of several scenarios
- Great Lakes Protection Initiative
  - Modeling current and future water level fluctuations in the Great Lakes subject to various atmospheric, hydrological and climatic forcings, with the aim of producing:
    - Impact analyses of water level fluctuations (frequency and duration of flood cycles) on the distribution and evolution of coastal wetlands
    - Climate projections on a large number of future climate scenarios



CHALLENGES AND LIMITATIONS

- This type of applications requires a large number of simulations:
  - At high spatial resolution, particularly near the coast
  - At a sufficiently small time step (sub-hourly) to capture high frequency variations
  - Over long periods (30+ years)
- In order to reduce computational costs and the number of simulations to be produced, various simplifications have been made, in particular:
  - Two-dimensional (2D-horizontal) simulations, neglecting lake stratification and mixing
  - Static (time-invariant) simulations, using uniform and static scenarios to reconstruct temporal variability (unable to reproduce phenomena like seiches)
  - Neglect of some variables, like astronomical tides, atmospheric pressure and ice, not modeled but identified as having an impact on water level variations





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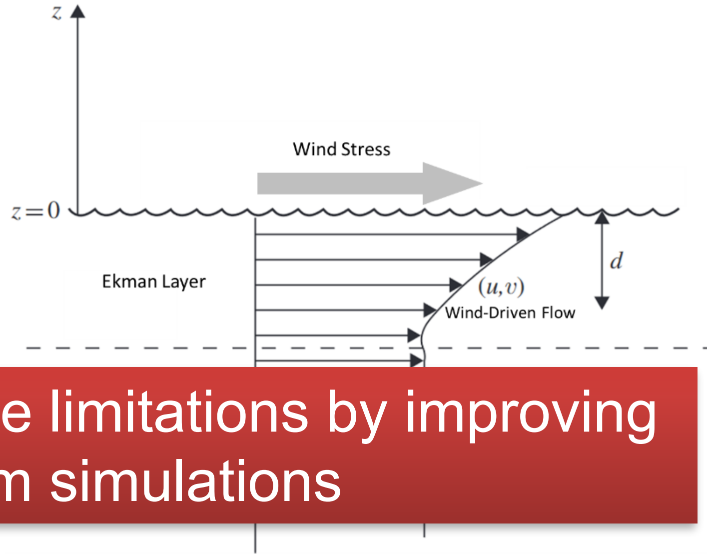

A statistical-dynamical solution is sought to alleviate some of these limitations by improving the physical representativeness and reducing the cost of long-term simulations

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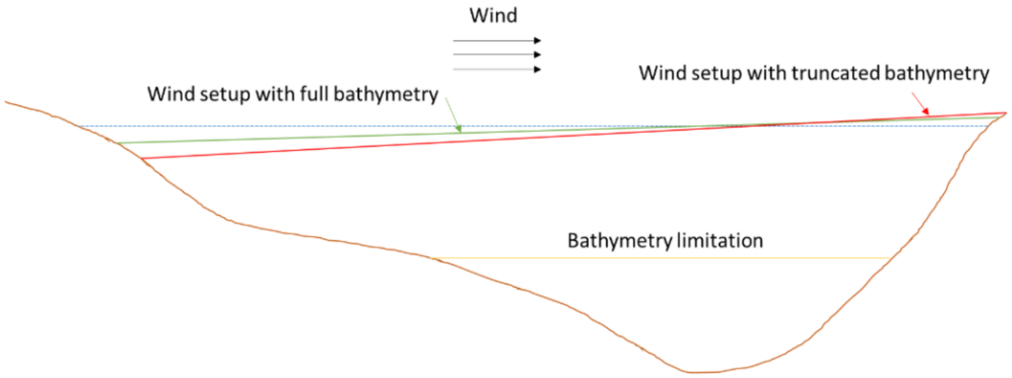
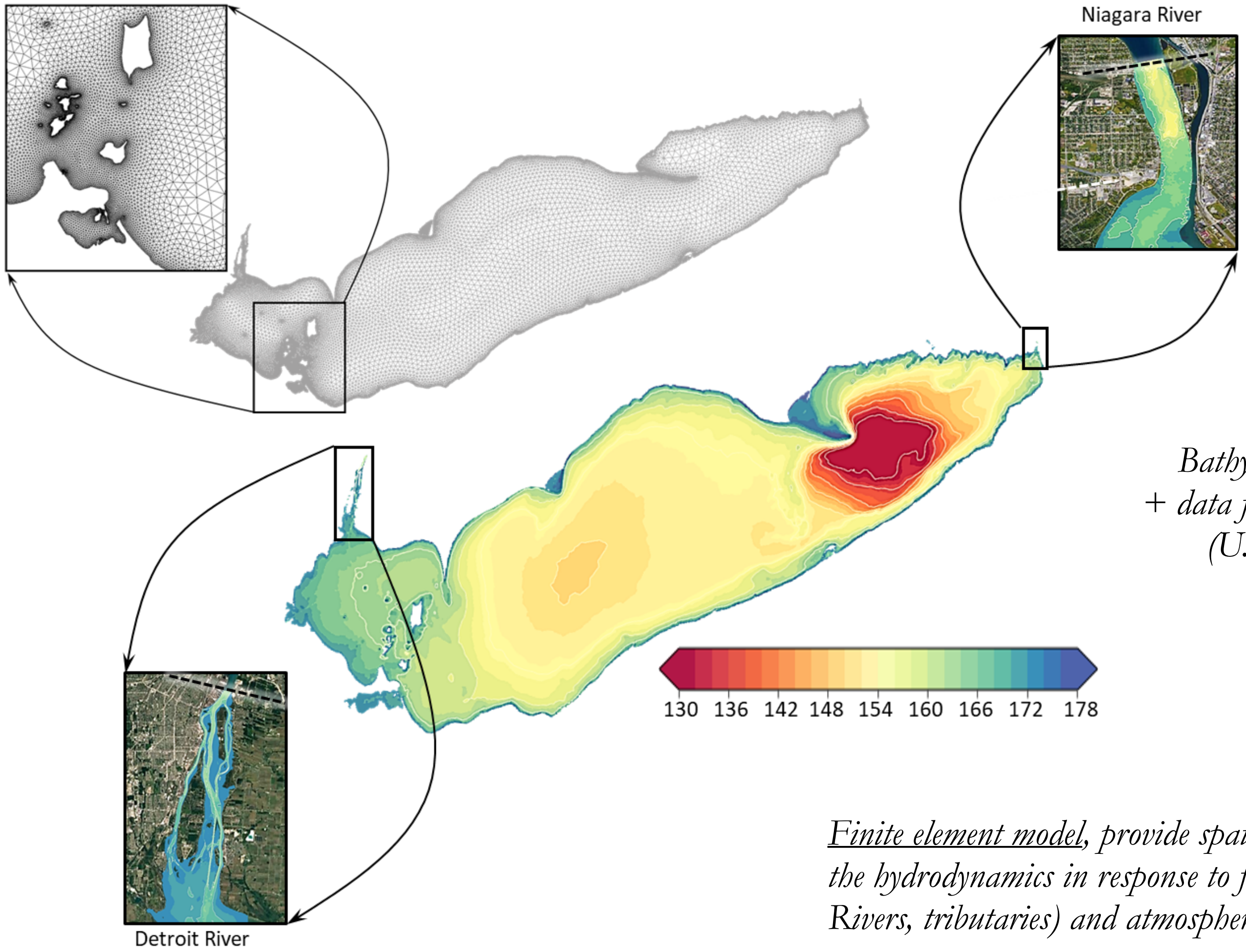


CASE STUDY: LAKE ERIE

<u>H2D2 model:</u>
Solves the 2D shallow water (St-Venant) equations over an unstructured finite element grid.

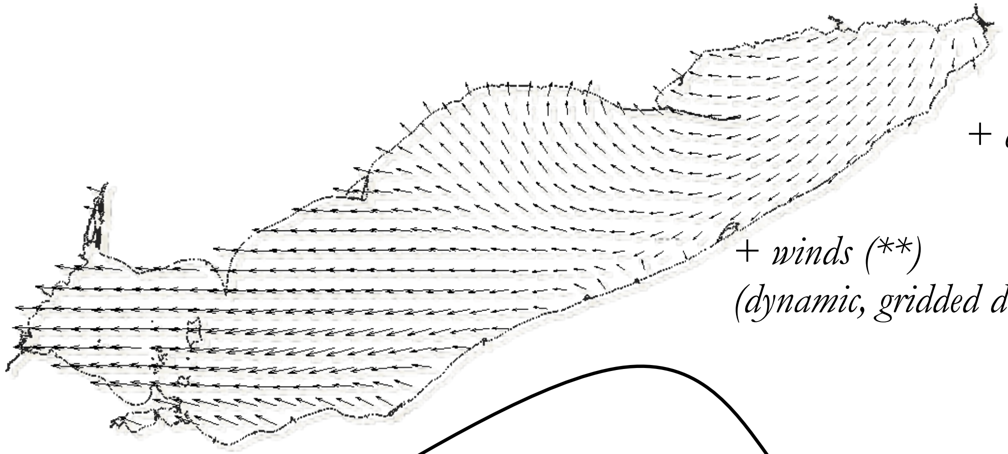
<u>Mesh:</u>
323k nodes
150k elements
Resolution: ~10m to 3km
Computation time: ~ 20 min./ 6 hrs
Time step: 6 min.



Bathymetry, NOAA (~90-100 m)
+ data from USACE, Niagara River
(U.S. Army Corps of Engineers)

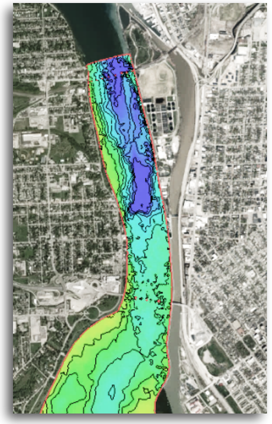
<u>Finite element model</u>, provide spatial and temporal description of the hydrodynamics in response to fluvial (e.g. Detroit and Niagara Rivers, tributaries) and atmospheric (winds) forcing

CASE STUDY: LAKE ERIE



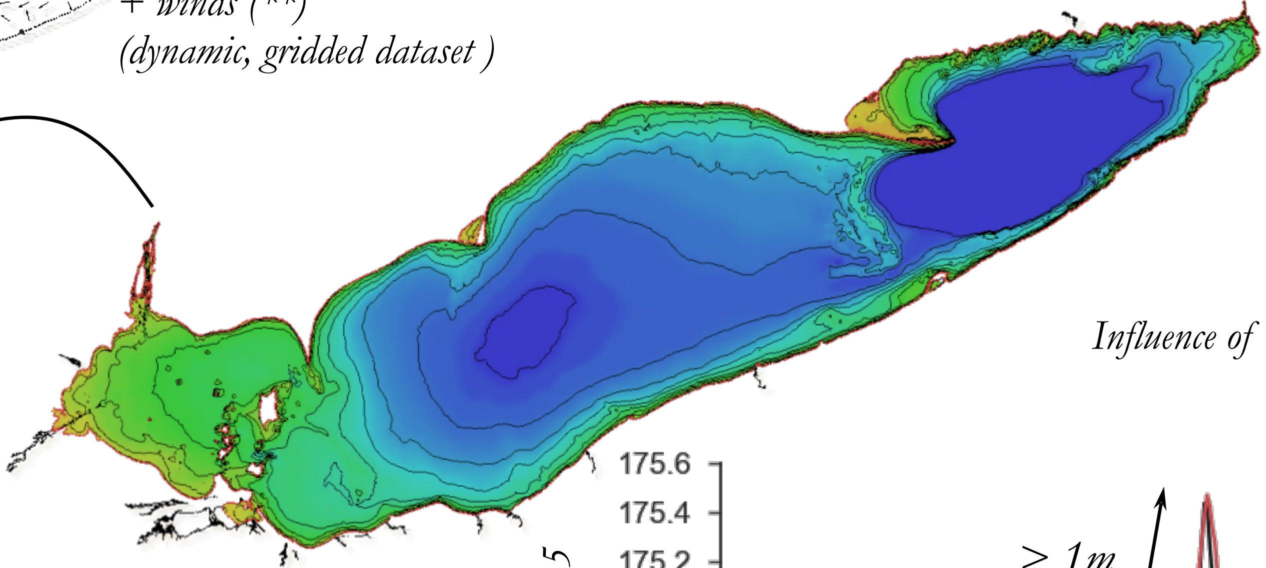
<u>Inputs :</u>

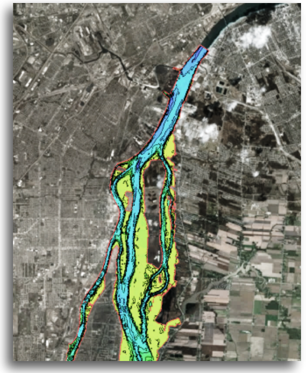
+ all the secondary watersheds
(19 boundary conditions, including Welland Canal)
+ evaporation (1D model, LLTM) / precipitation (CaPA)*



<u>Downstream condition</u>:
water level Fort Erie (Niagara River)

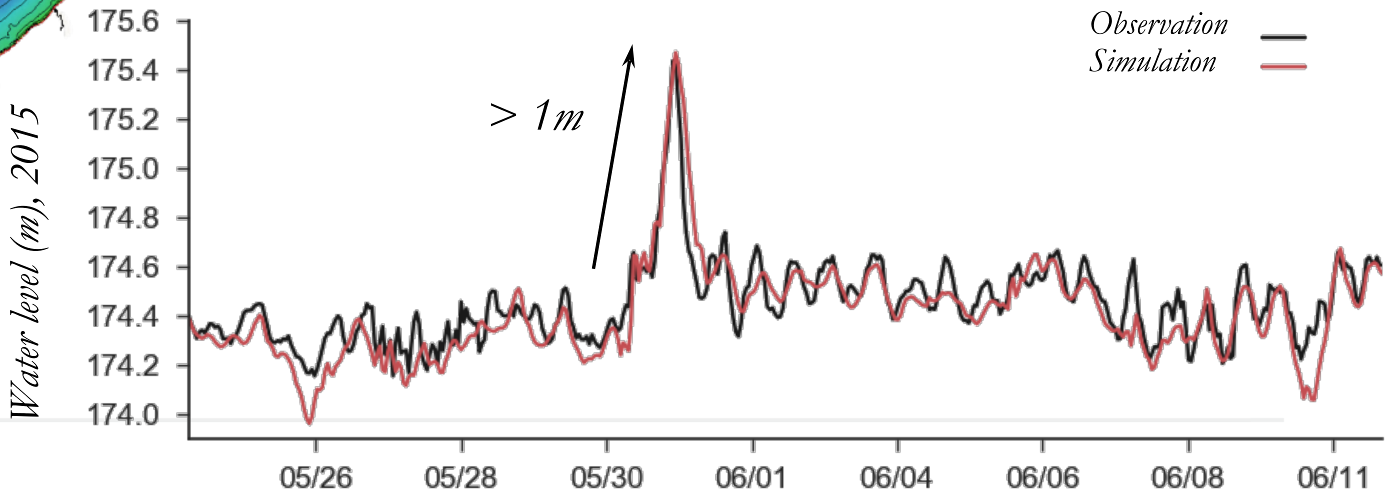
+ winds (**)
(dynamic, gridded dataset)





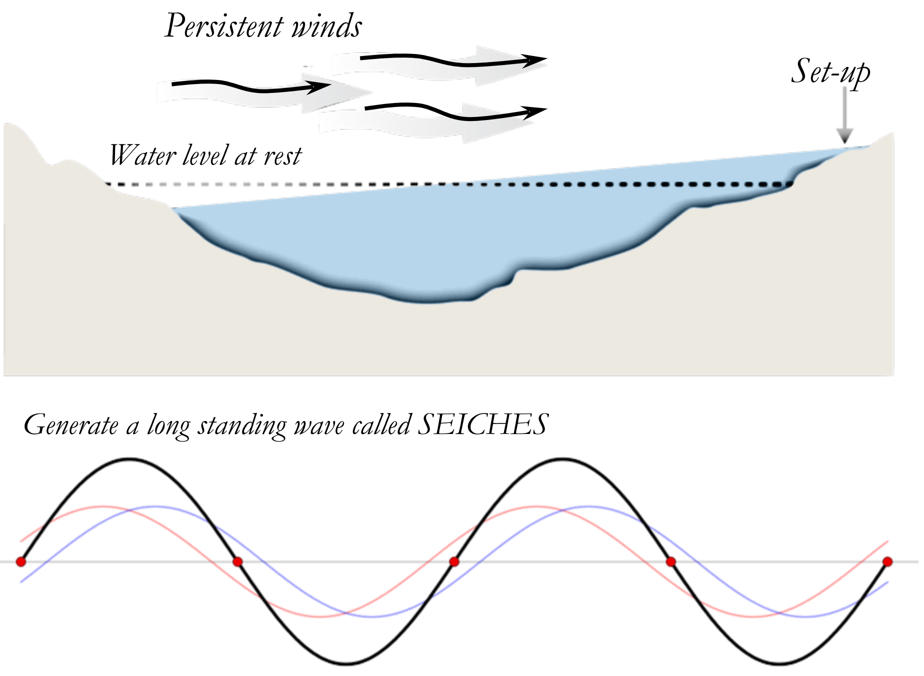
<u>Upstream condition</u>:
discharge Fort Wayne (Detroit River)

Influence of winds, set-ups and seiches (historical mean variation, between ~ 40 and 100 cm)

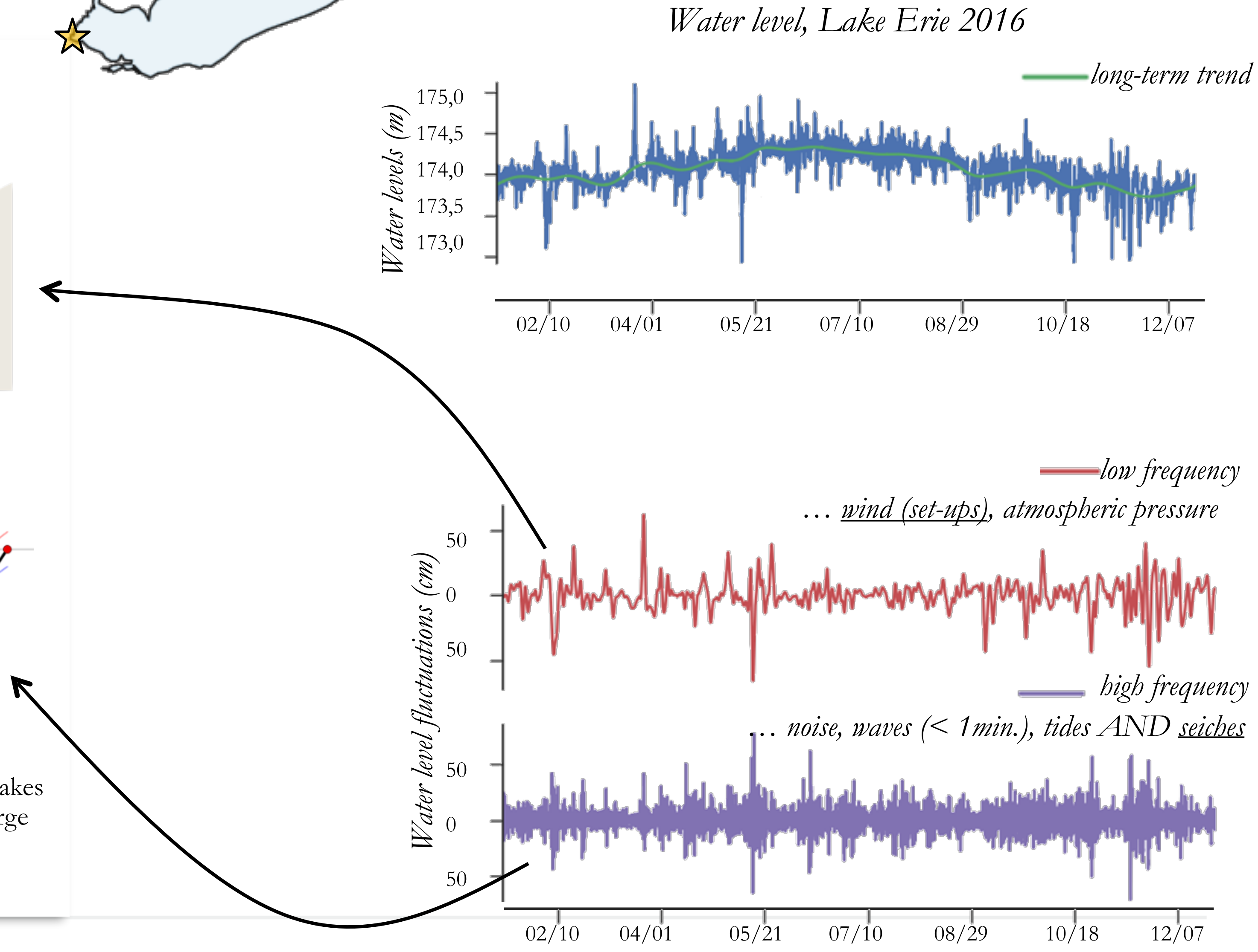


(*) LLTM, Large Lake Thermodynamic Model (NOAA)
(**) historical: Climex, ~ 12km, 3hrs.

CASE STUDY: LAKE ERIE



ref. National Weather Service
standing wave oscillation of water in large lakes usually created by strong winds and/or a large barometric pressure gradient



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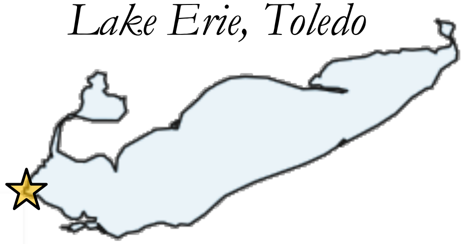
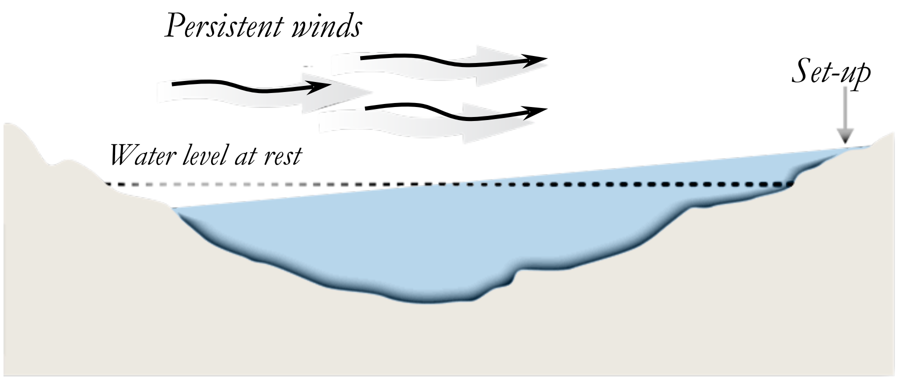
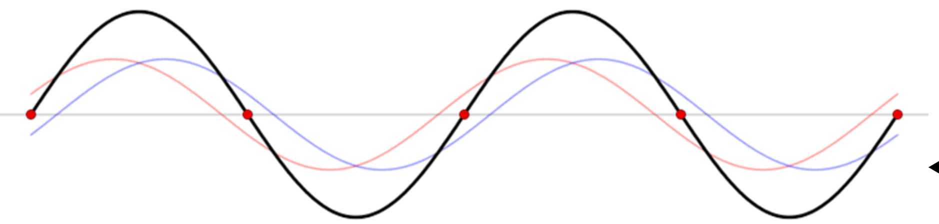




Generate a long standing wave called SEICHES



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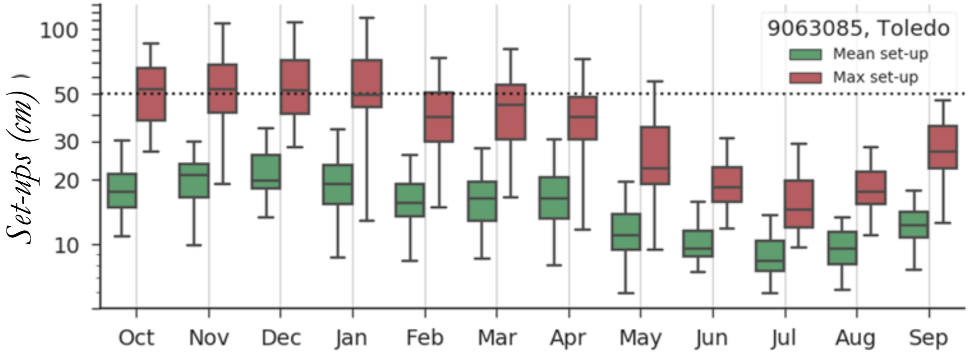
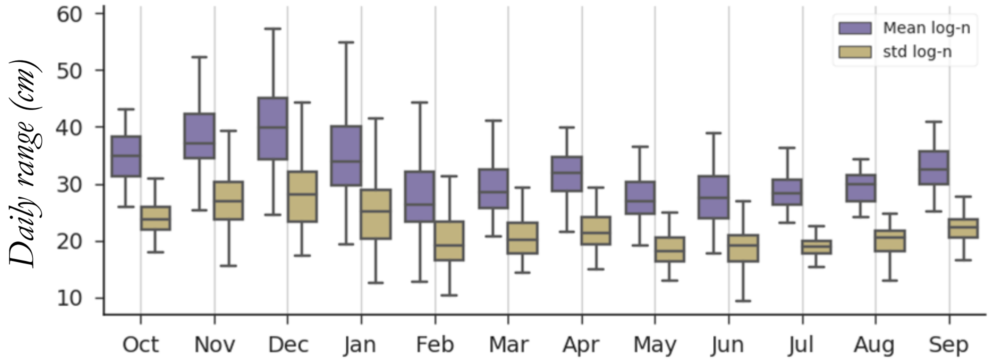
set-ups between ~20 et 50 cm

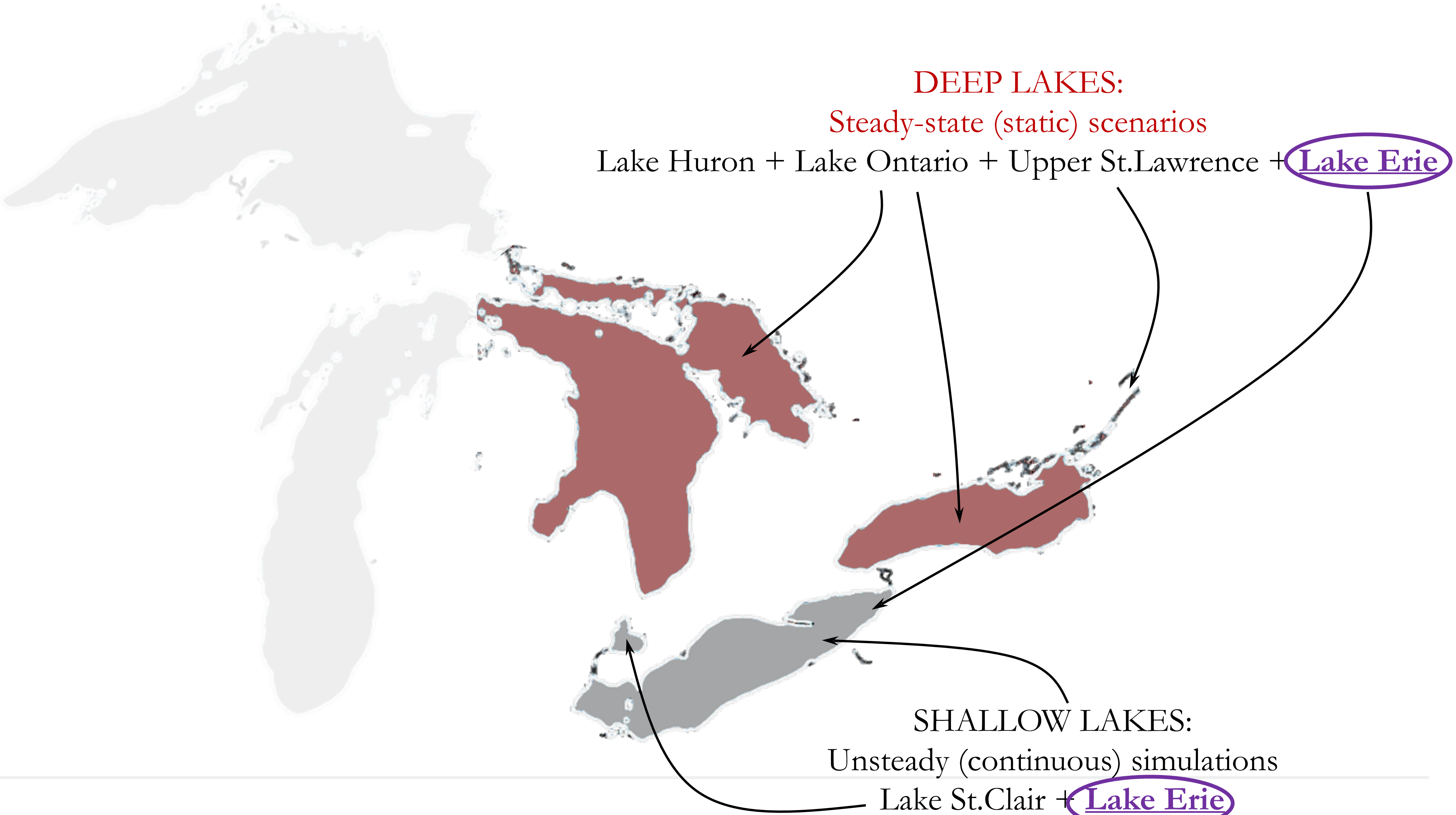


~25 et 40 cm daily variations (mainly seiches)



Example, Toledo (Lake Erie), 1980-2010

MODELING APPROACHES:
CONTINUOUS SIMULATIONS VS. STATIC SCENARIOS

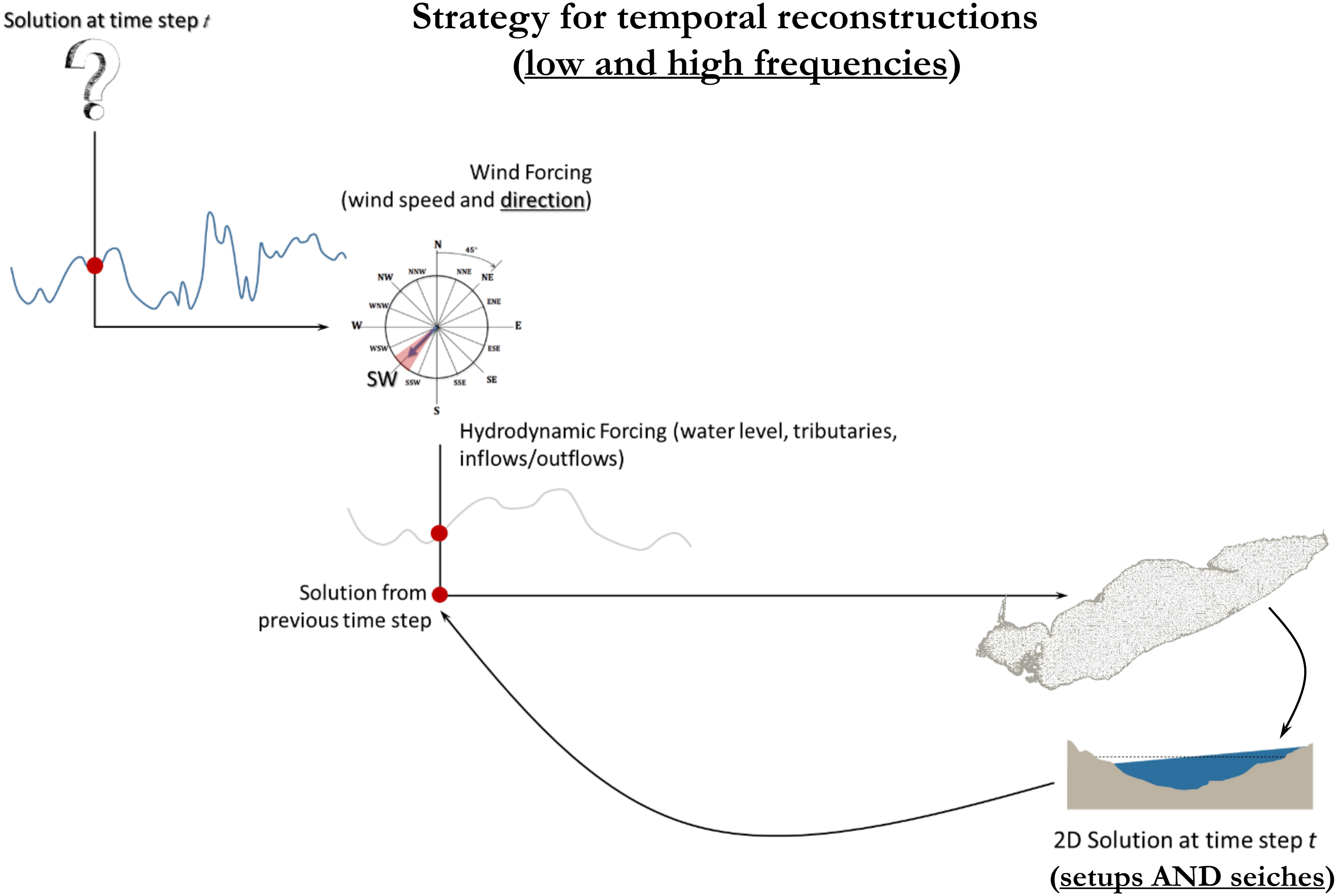


MODELING APPROACHES:
CONTINUOUS SIMULATIONS VS. STATIC SCENARIOS

Reference real-time simulations:

- Solves the full 2D unsteady St-Venant equations
- Calibrated based on 2 years of observations
- Data assimilation with frequent restarts for accurate mean water levels
- Continuous simulation over 1980-2018
- Accurate representation of water level **setups** AND **seiches**
- 2 climatic periods:
  - Historic conditions 1980-2009
  - Future conditions 2070-2099
    - RCP 4.5, RCP 8.5

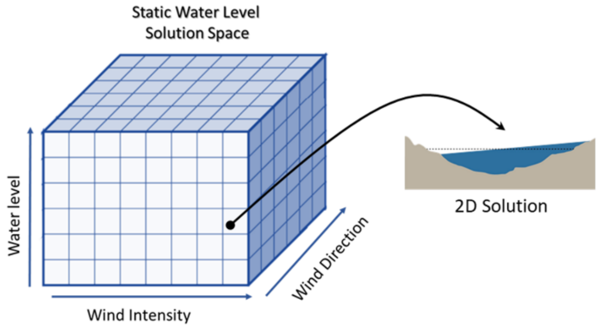
Strategy for temporal reconstructions (low and high frequencies)



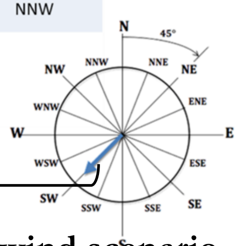
MODELING APPROACHES:

CONTINUOUS SIMULATIONS VS. STATIC SCENARIOS

Solution space for water levels

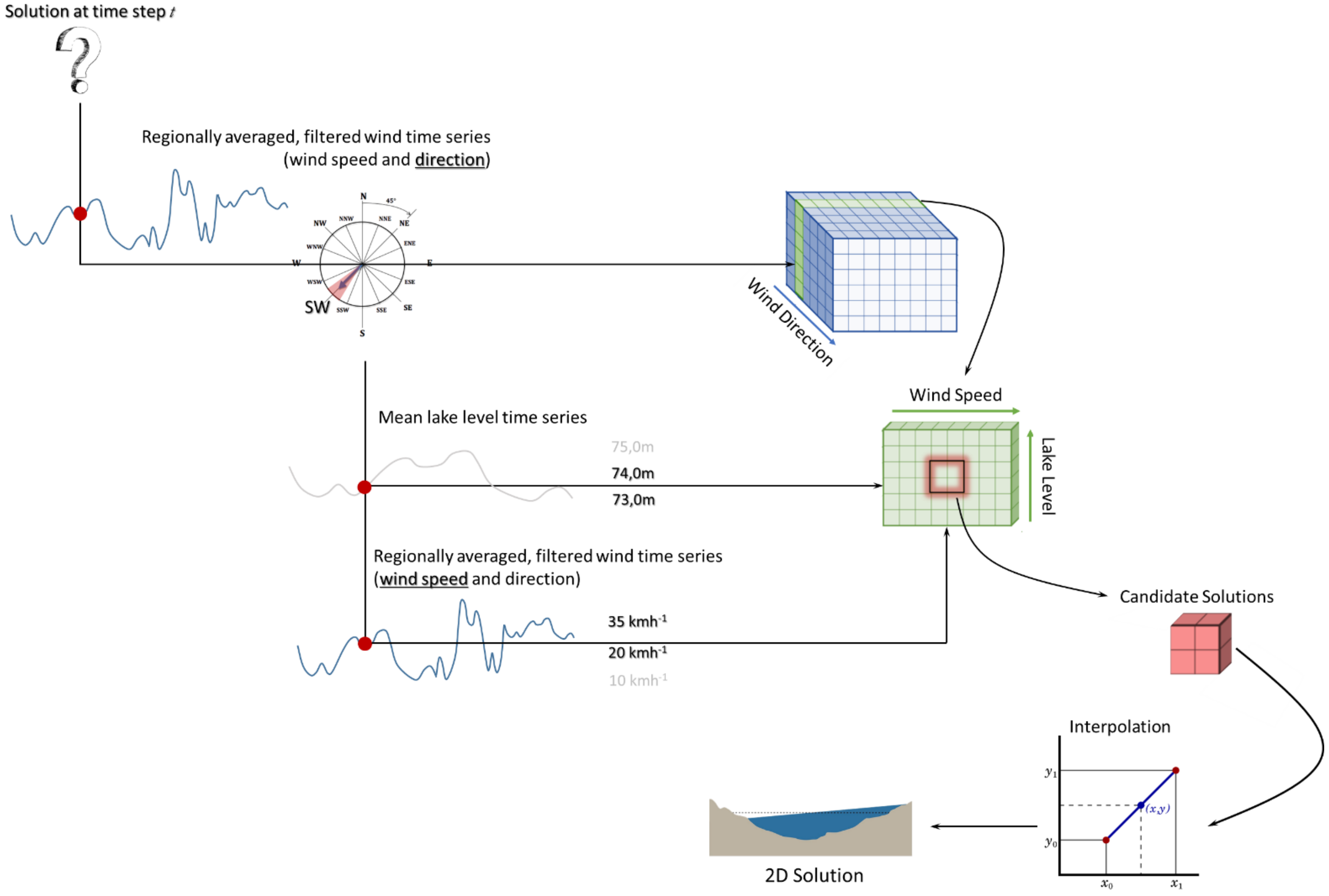


	STATIC FORCING							
	Mean Lake Level			Winds				
	Lake Ontario (m)	Lake Huron (m)		Wind Intensity				Wind Direction
					Speed Classes km h⁻¹	Forcing km h⁻¹ (ms⁻¹)		
1	73.75	175.40						
2	74.0	175.78	1	No Wind	< 7	0 (0)	1	N
3	74.5	176.18	2	Gentle	7–12	10 (2.8)	2	NNE
4	75.0	176.59	3	Low	12–27	20 (5.6)	3	NE
5	75.5	177.0	4	Moderate	27–43	35 (9.7)	...	...
6	76.0	177.42	5	High	43–57	50 (13.9)	16	NNW
7	76.5	177.83	6	Strong	57–73	65 (18.1)		
8	77.0	178.24	7	Extreme	> 73	80 (22.2)		
9	77.5	178.67						
10	78.0	179.09						



One effective depth defined for each wind scenario

Strategy for temporal reconstructions (<u>low-frequencies only</u>)

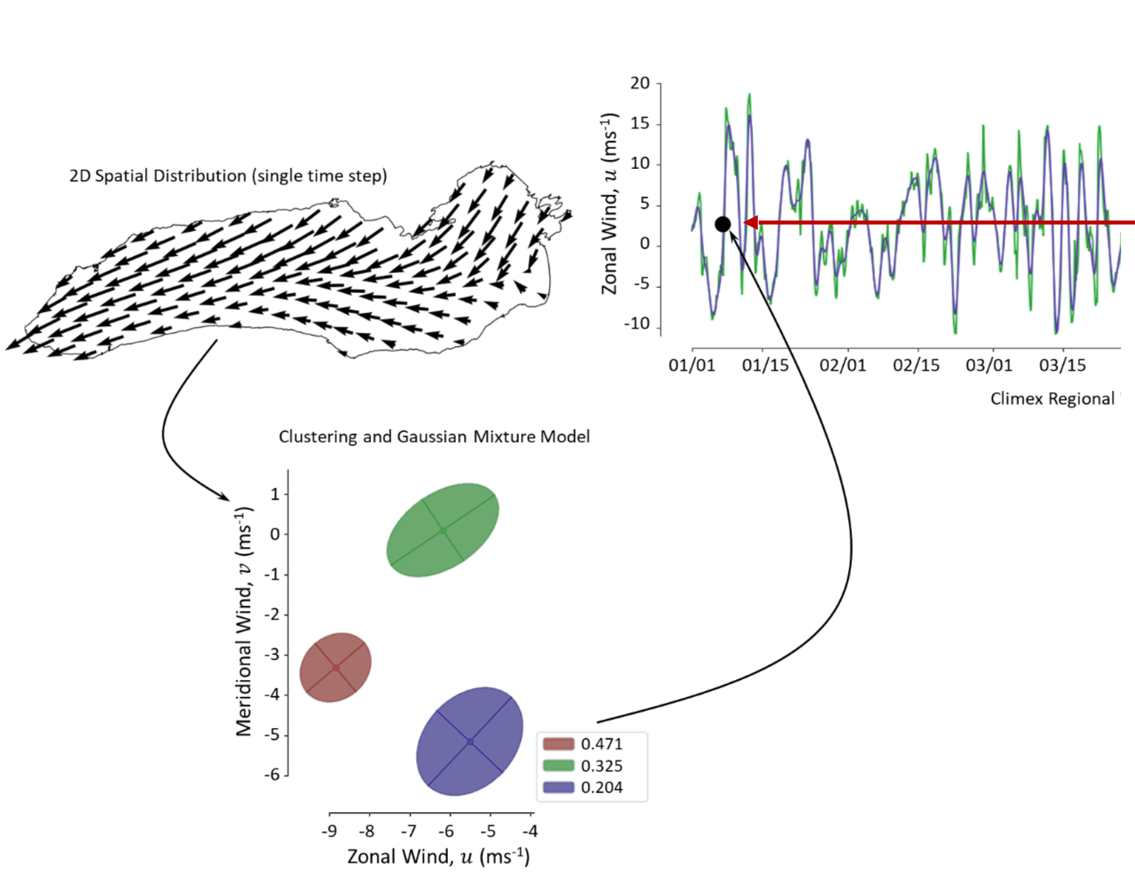


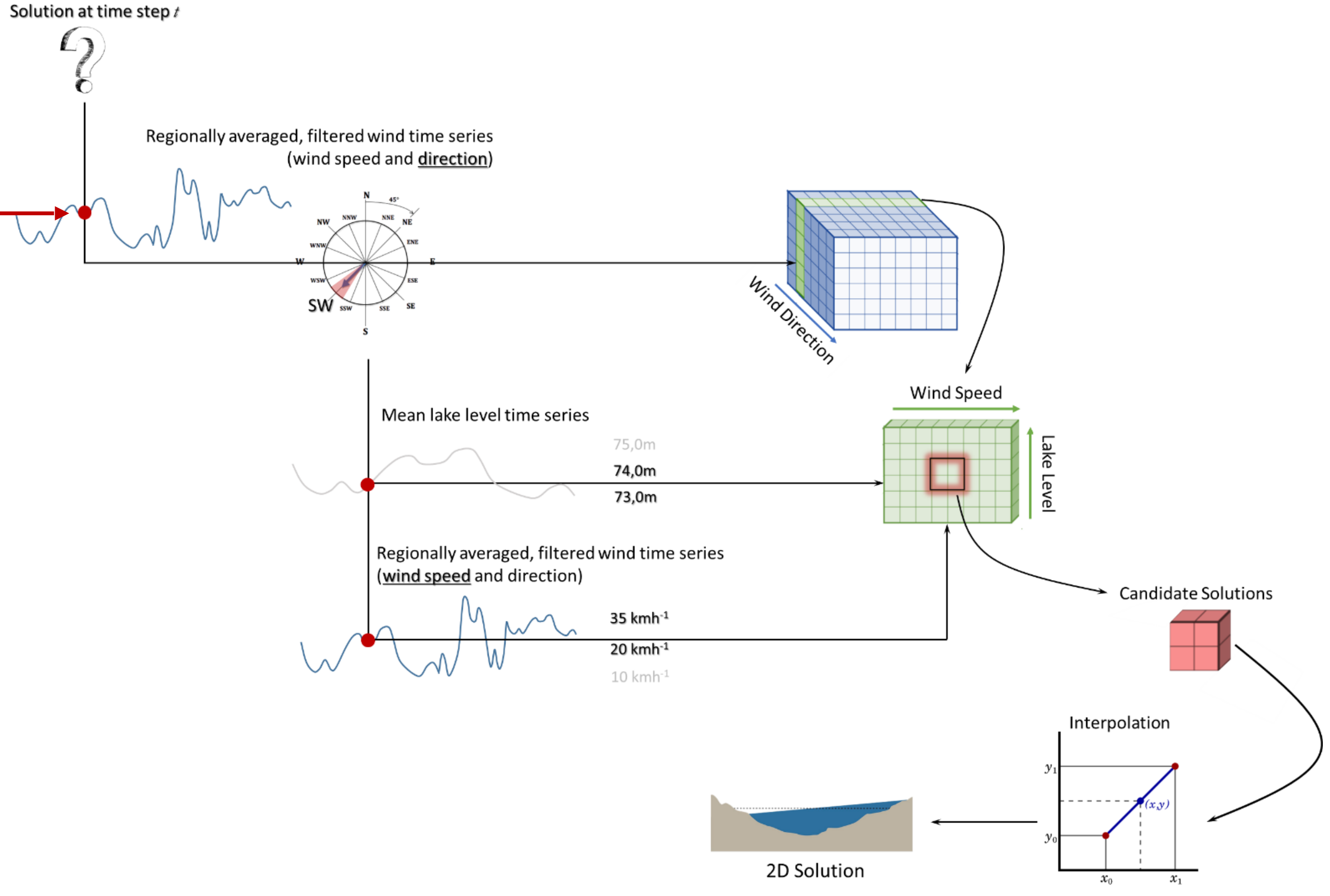
(<u>setups ONLY</u>)

MODELING APPROACHES:
CONTINUOUS SIMULATIONS VS. STATIC SCENARIOS

Regional wind averaging (Gaussian Mixture Model)

Strategy for temporal reconstructions (low-frequencies only)

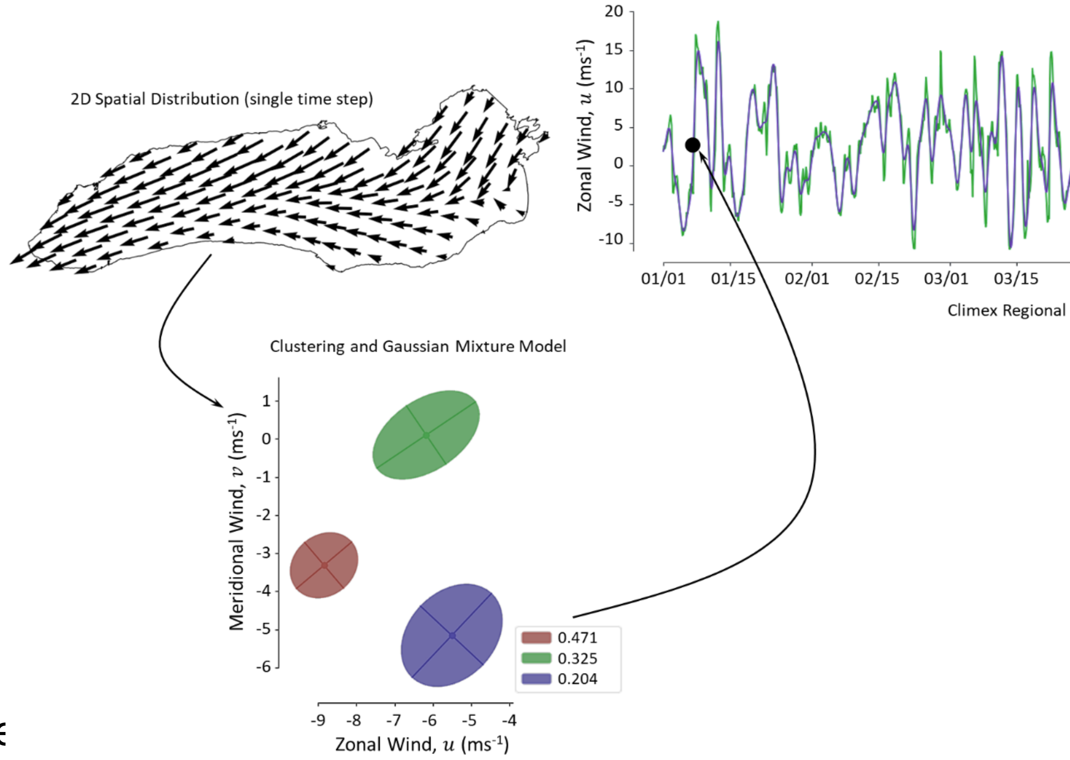




(setups ONLY)

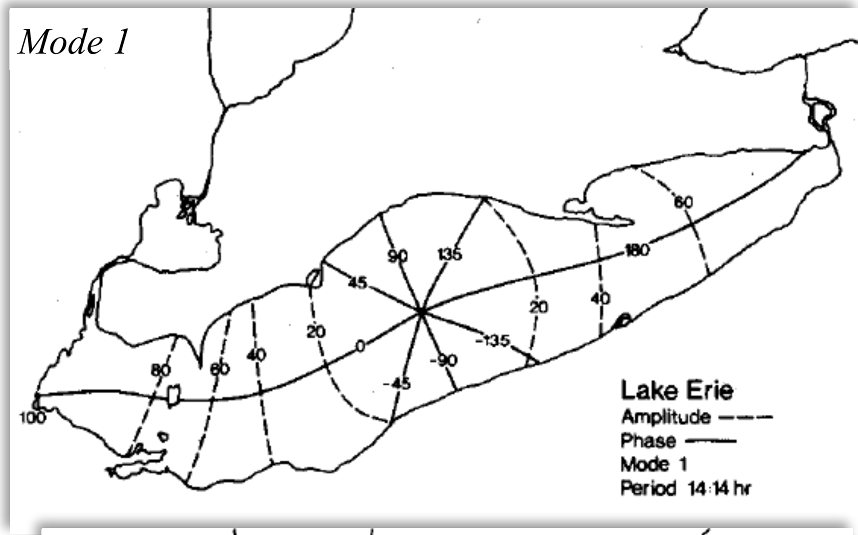
AREAS FOR IMPROVEMENT
STATISTICAL / DYNAMICAL HYBRID SOLUTIONS

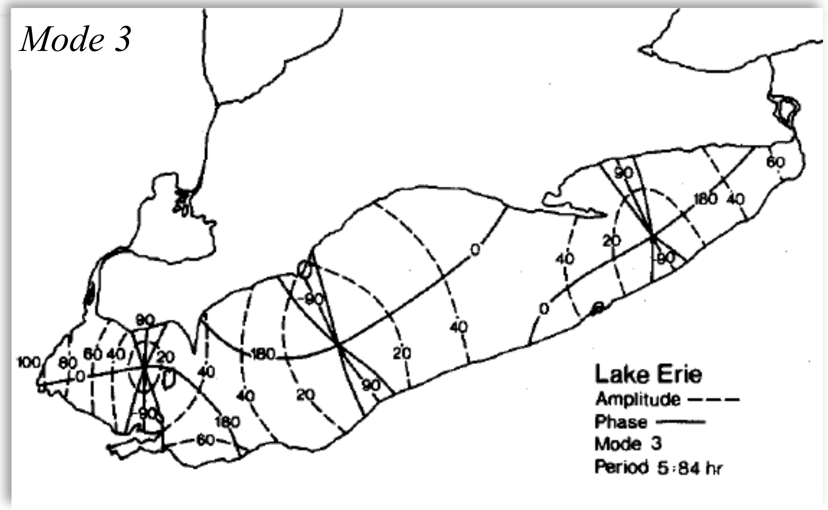
1. Regional wind averaging
   - Current solution:
     - Gaussian Mixture Model with 3 clusters
     - Hydrodynamic model forced using spatially uniform winds
     - Time series reconstruction based on bilinear interpolation between simulated water levels from uniform wind scenarios
   - Sought solution:
     - Identification of 2D wind patterns through dimension reduction techniques
     - Definition of hydrodynamic scenarios using static 2D (i.e. non-uniform) winds
     - Time series reconstruction based on a weighting between the various water level responses to 2D wind scenarios



AREAS FOR IMPROVEMENT
STATISTICAL / DYNAMICAL HYBRID SOLUTIONS

2. From static to continuous simulations
   - Current solution:
     - For deep lakes, a strategy based on static scenarios is employed for temporal reconstructions
     - Only the low-frequency variability (water level setups) is captured
     - For Lake Erie, both static and continuous simulations are available, allowing for a direct comparison between the two approaches
   - Sought solution:
     - Using the Lake Erie models, establish the foundations of a machine-learning prototype aimed at reproducing seiches from static simulations along with physics- or ecology-based metrics
     - Explore ways to separate low and high frequencies
     - Potentially exploit available 2D wind fields (or principal patterns from step 1) to inform the model
     - Consider a synthetic representation of the seiche phenomenon, for example, by mode decomposition of the amplitudes and phases or similar techniques as used for winds (step 1)





ref. Hamblin (1987)

AVAILABLE DATA
5 YEARS: 1990-1994

- **Water level observations**:
  - *.csv files with hourly station observations (unfiltered water levels) + mean water levels (seasonal mean) from NOAA
- **Winds**:
  - netCDF files created from the Climate Forecast System Reanalysis (CFSR)
    - 0.312° spatial resolution
    - hourly time step
- **Hydrodynamics (continuous run)**:
  - netCDF files regridded from H2D2 simulation results (34 GB/year)
    - 500 m resolution
    - 24 min time step
- **Hydrodynamics (static scenarios)**:
  - *.dat files (SMS software) containing H2D2 outputs including water levels
    - File name convention: LKE_<direction>_<wind speed (p=point)>_h<mean water level>.dat.
- **Native hydrodynamic model**:
  - .*2dm H2D2 unstructured grid (SMS software) and related coordinates (*.cor) and elements (*.ele) files

QUESTIONS?