A WATER CYCLE PREDICTION SYSTEM FOR THE GREAT LAKES AND ST. LAWRENCE RIVER

V. Fortin[1], D. Durnford[2], G. Smith[1], P. Matte[1], M. Mackay[1], N. Bernier[1]
... and many others

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Coastal Hydrology and Surface Processes linked to Air/Sea Modeling:
1st community of users workshop
Funchal, Madeira, Sept. 26-27 2017

Authors work for units of the Meteorological Research Division (MRD) or the Meteorological Service of Canada (MSC)

located at the Canadian Meteorological Centre (CMC)

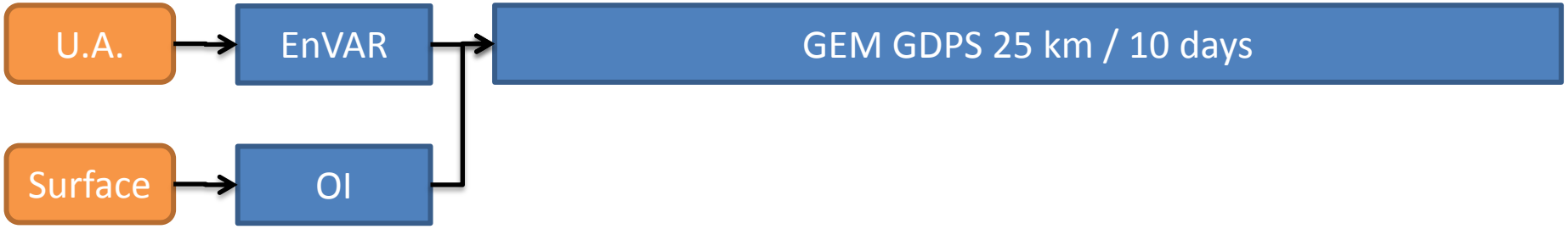
of Environment and Climate Change Canada (ECCC)

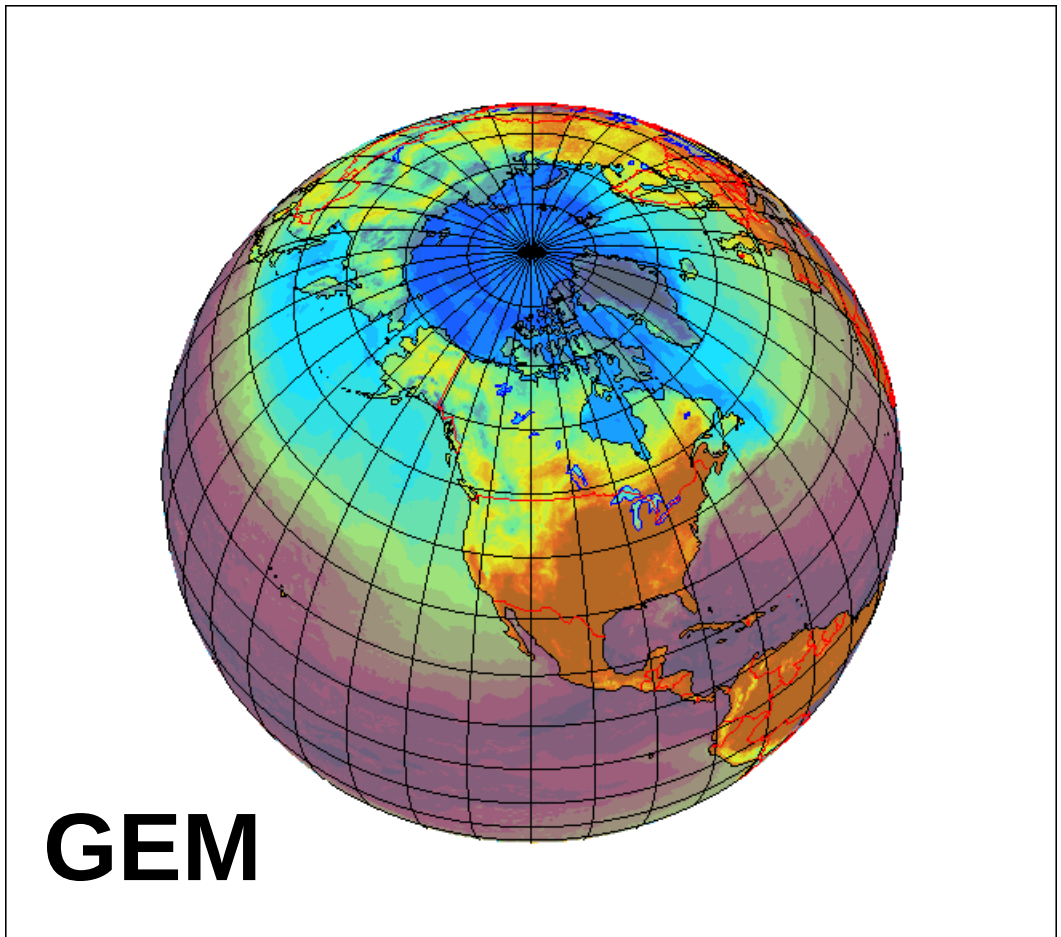
Dorval, Québec, close to Montreal's main airport

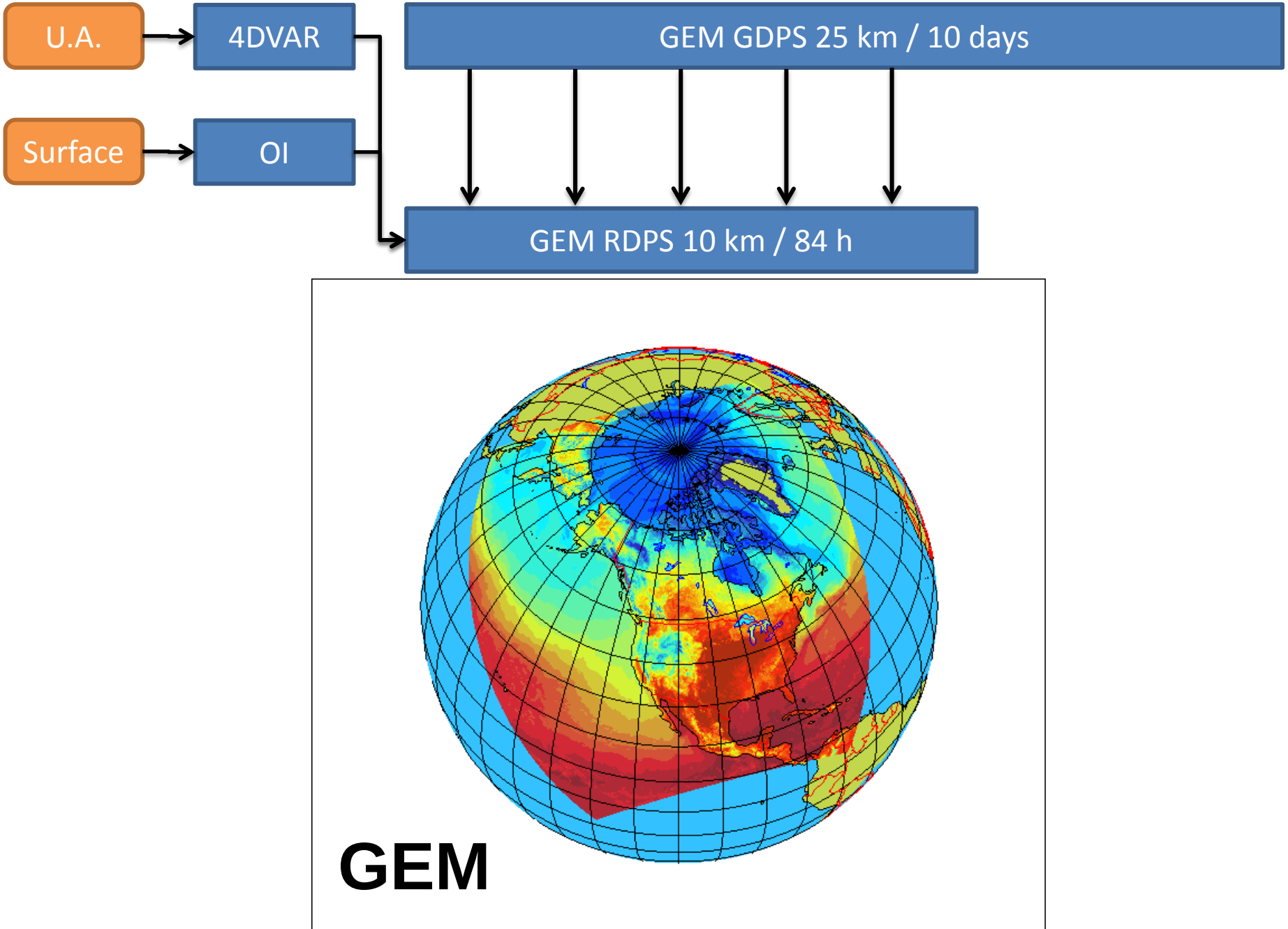
- National Weather Forecasting
- Global Ocean Forecasting
- Hydrological Forecasting (G.L.+St.L. for now)
- National Support for Environmental Emergency Response (e.g. oil spills)

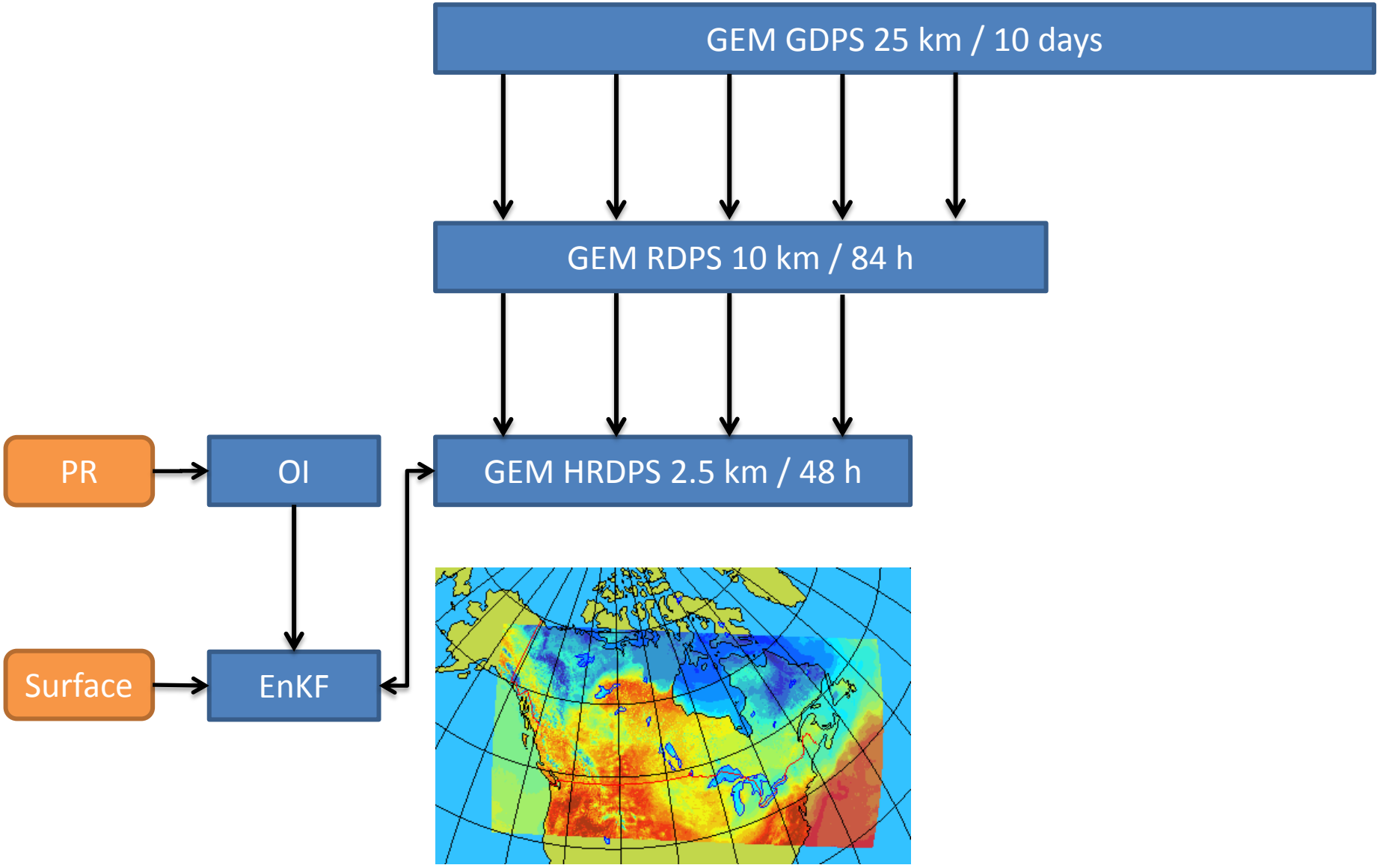
Water Cycle Prediction

- Forecasting the processes that impact the continental water cycle at scales of hours to days
  - the atmosphere, and in particular precipitation
  - the land surface (vegetated land, wetlands, glaciers, urban areas), and in particular, soil moisture, snowpack, evapotranspiration and runoff
  - the continental water surface (lakes, rivers, ocean), and in particular water levels, water velocity, water temperature and ice cover

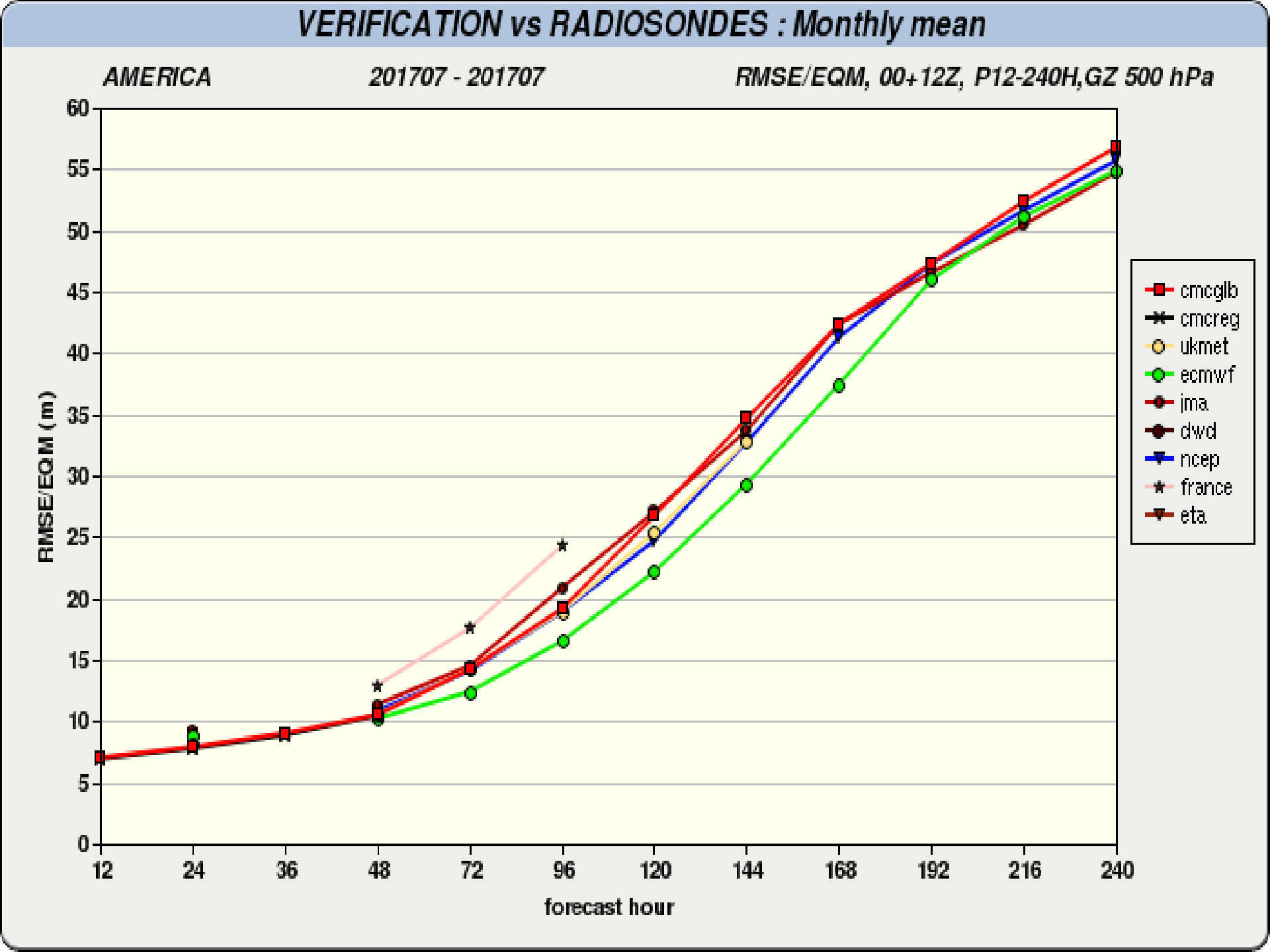

U.A.
EnVAR
GEM GDPS 25 km / 10 days
Surface
OI

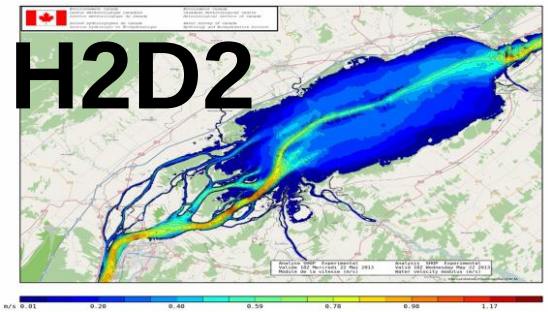

GEM

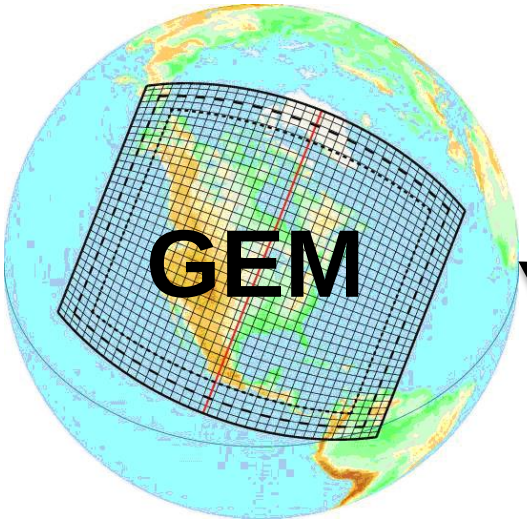

U.A.
4DVAR
GEM GDPS 25 km / 10 days
Surface
OI
GEM RDPS 10 km / 84 h
GEM


GEM GDPS 25 km / 10 days
GEM RDPS 10 km / 84 h
PR
OI
GEM HRDPS 2.5 km / 48 h
Surface
EnKF

GEM


VERIFICATION vs RADIOSONDES : Monthly mean
AMERICA
201707 - 201707
RMSE/EQM, 00+12Z, P12-240H,GZ 500 hPa
RMSE/EQM (m)
forecast hour
0
5
10
15
20
25
30
35
40
45
50
55
60
12
24
36
48
72
96
120
144
168
192
216
240
cmcglb
cmcreg
ukmet
ecmwf
jma
dwd
ncep
france
eta

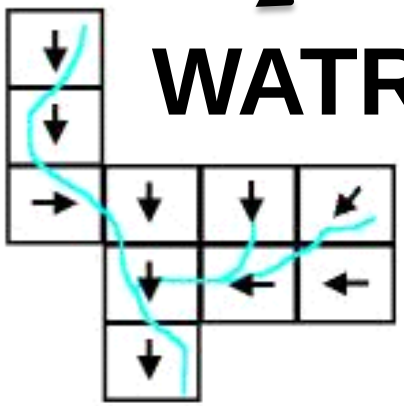




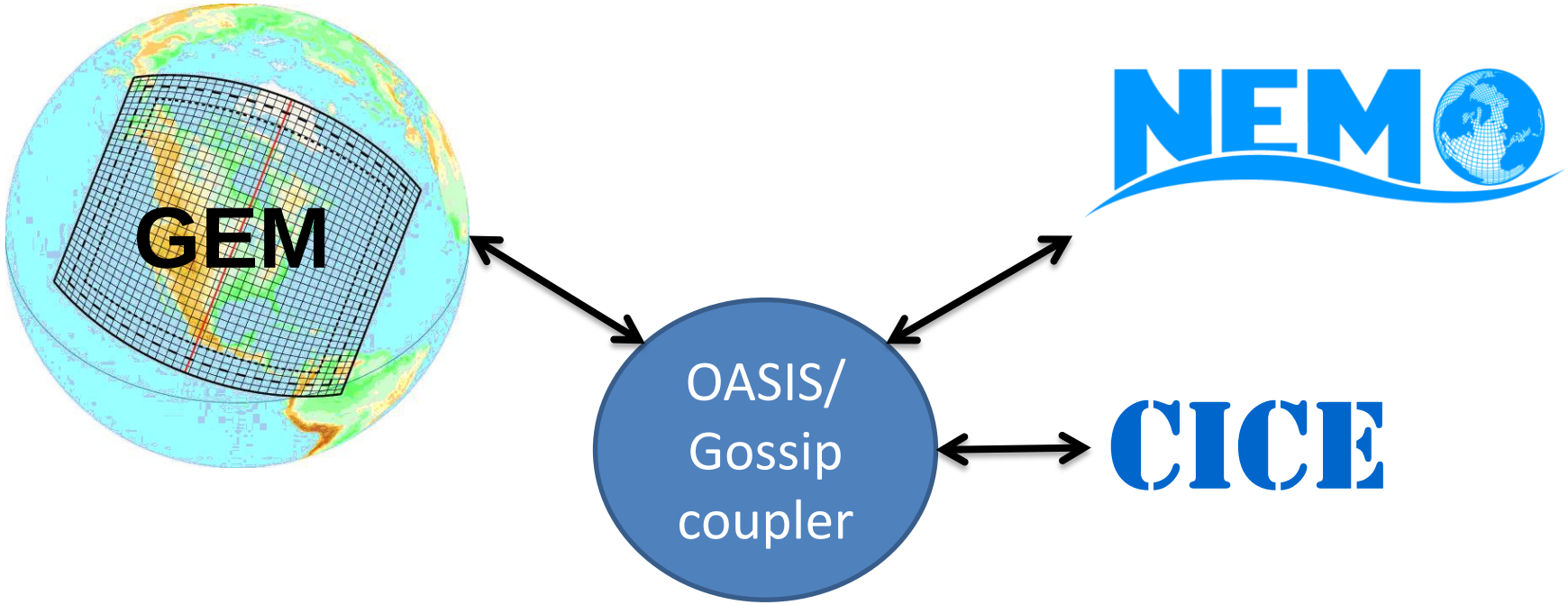
NEMO

OASIS/
Gossip
coupler

CICE

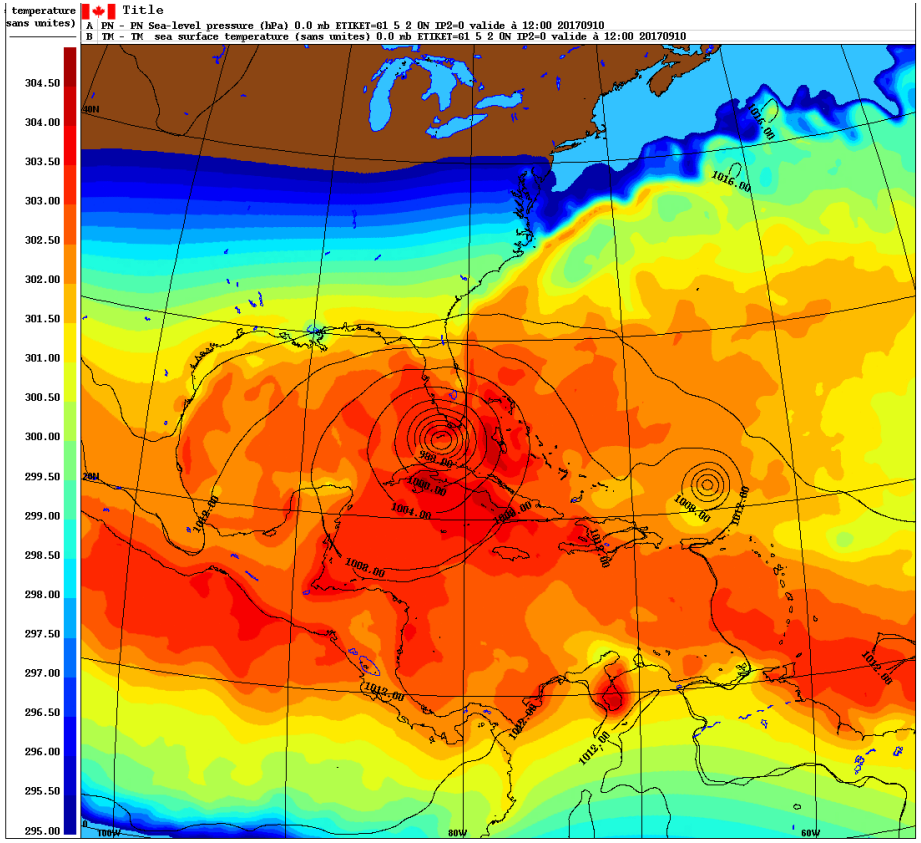


WATROUTE

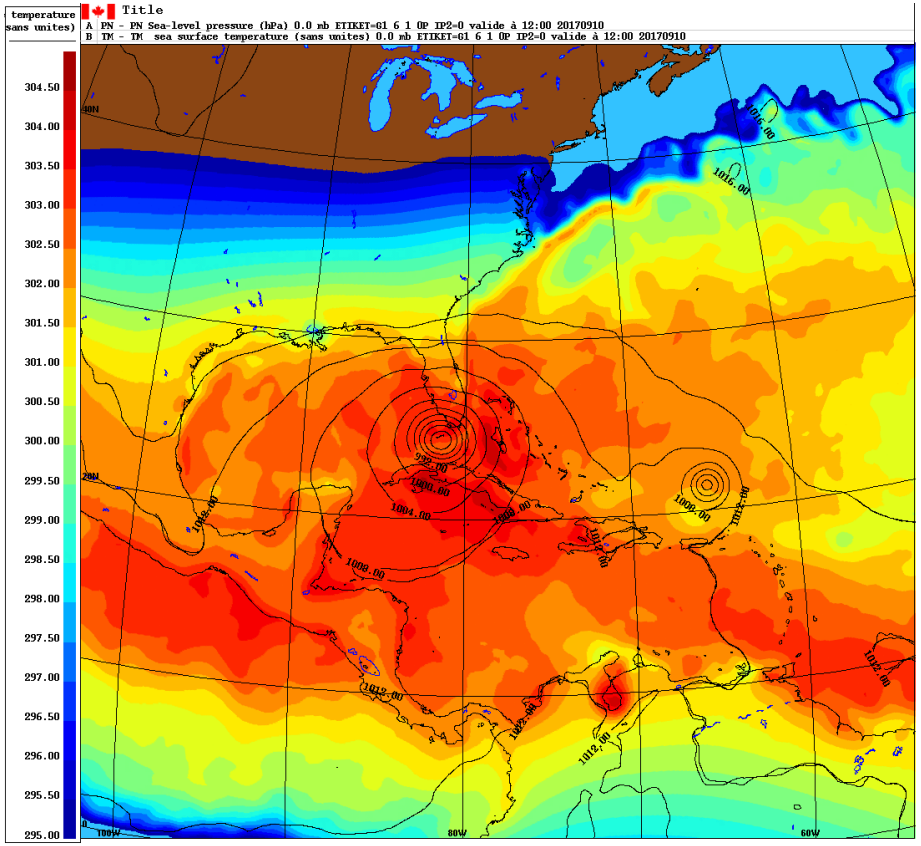

GEM
NEMO
OASIS/
Gossip
coupler
CICE

Surface pressure and water surface temperature in 10-day uncoupled and coupled global weather forecasts issued 2017-09-09 12 UTC (Hurricanes Irma and José)

Uncoupled (GEM only)

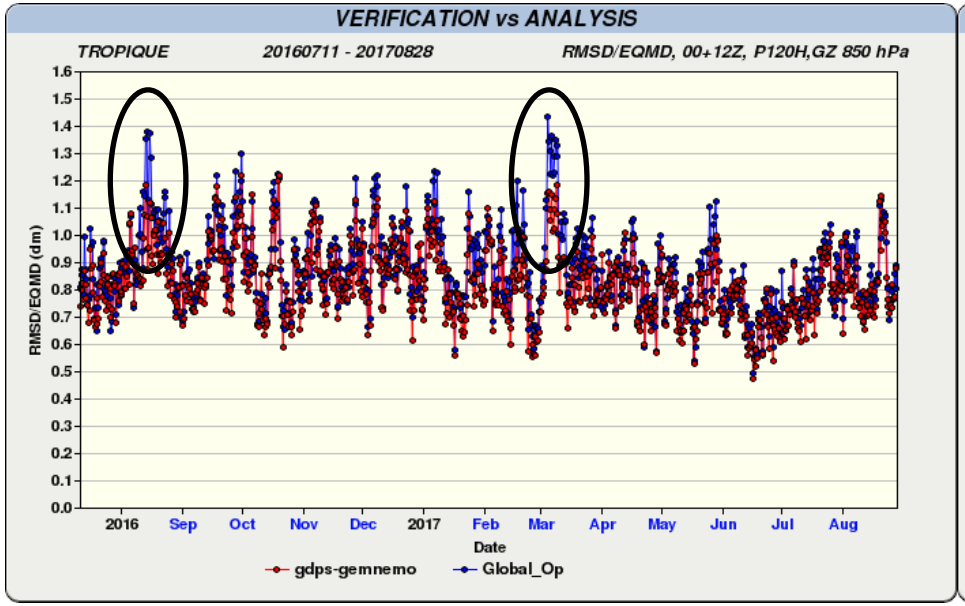


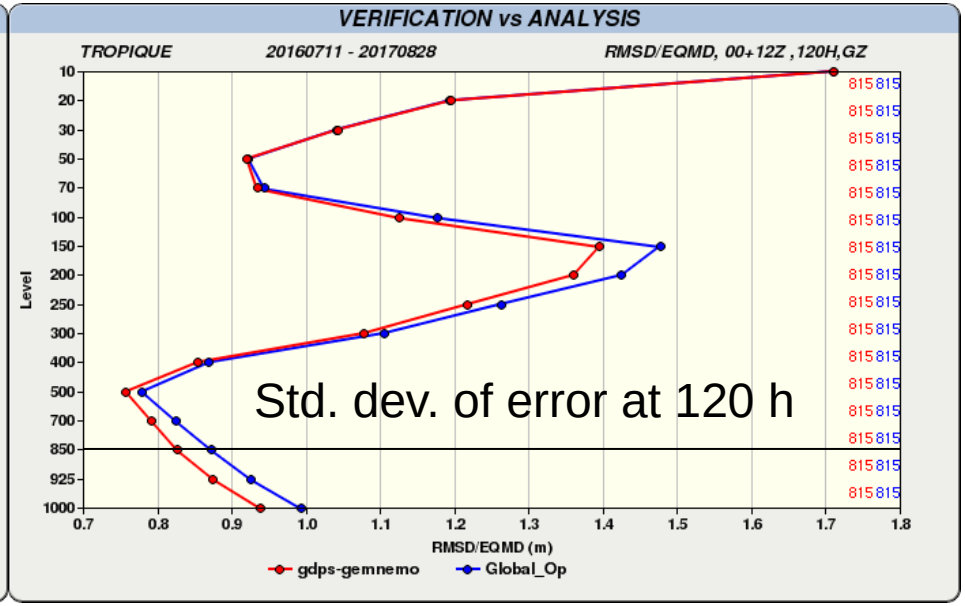
Coupled (GEM+NEMO+CICE)

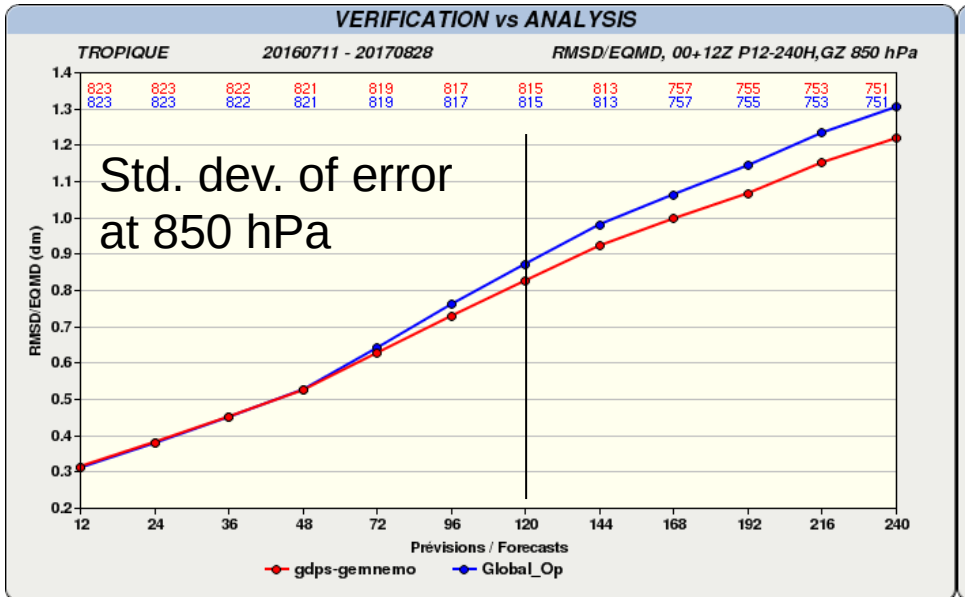


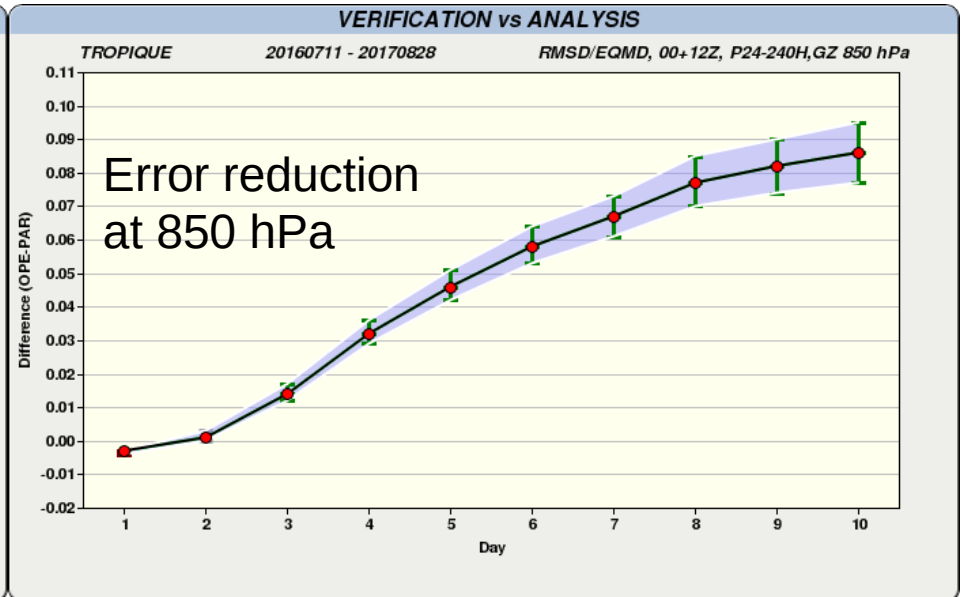
Accepted for operational implementation on September 19, 2017
see Smith et al. (2015) QJRMS and Smith et al. (2017) MWR (submitted)

Impact of GEM+NEMO+CICE coupling
Tropics, Geopotential Height, August 2016 - August 2017

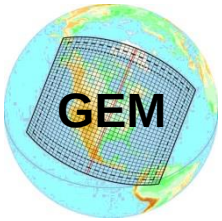








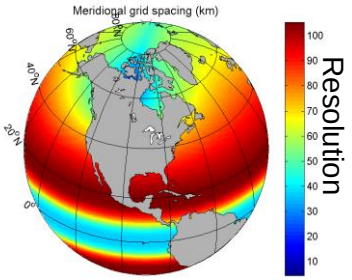
Applications and domains



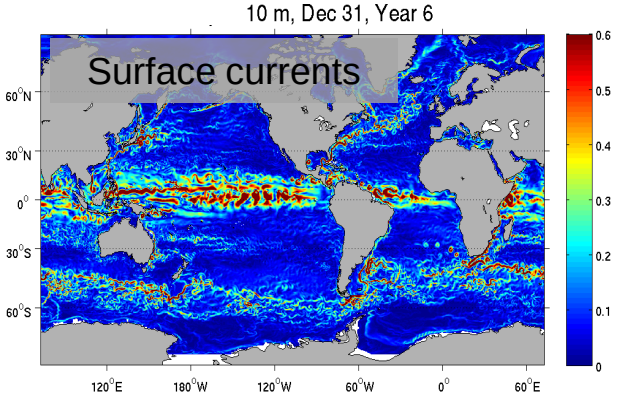
+ NEMO + CICE

- Global 1° resolution
  - Seasonal ensemble forecast
- Global 1/4° resolution
  - 10 day forecast
- Gulf of St. Lawrence: 5 km
  - 2 day forecast
- Great Lakes : 2 km
  - 3.5 day forecast

1° Global

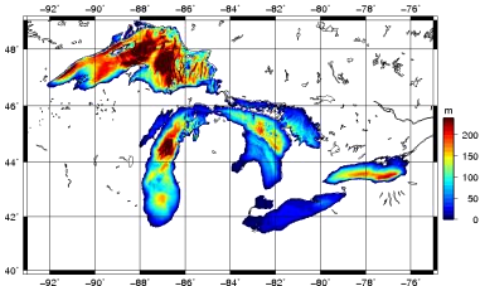


1/4° Global



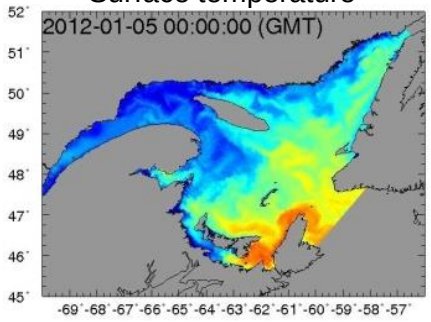
2-km Great Lakes

Bathymetry



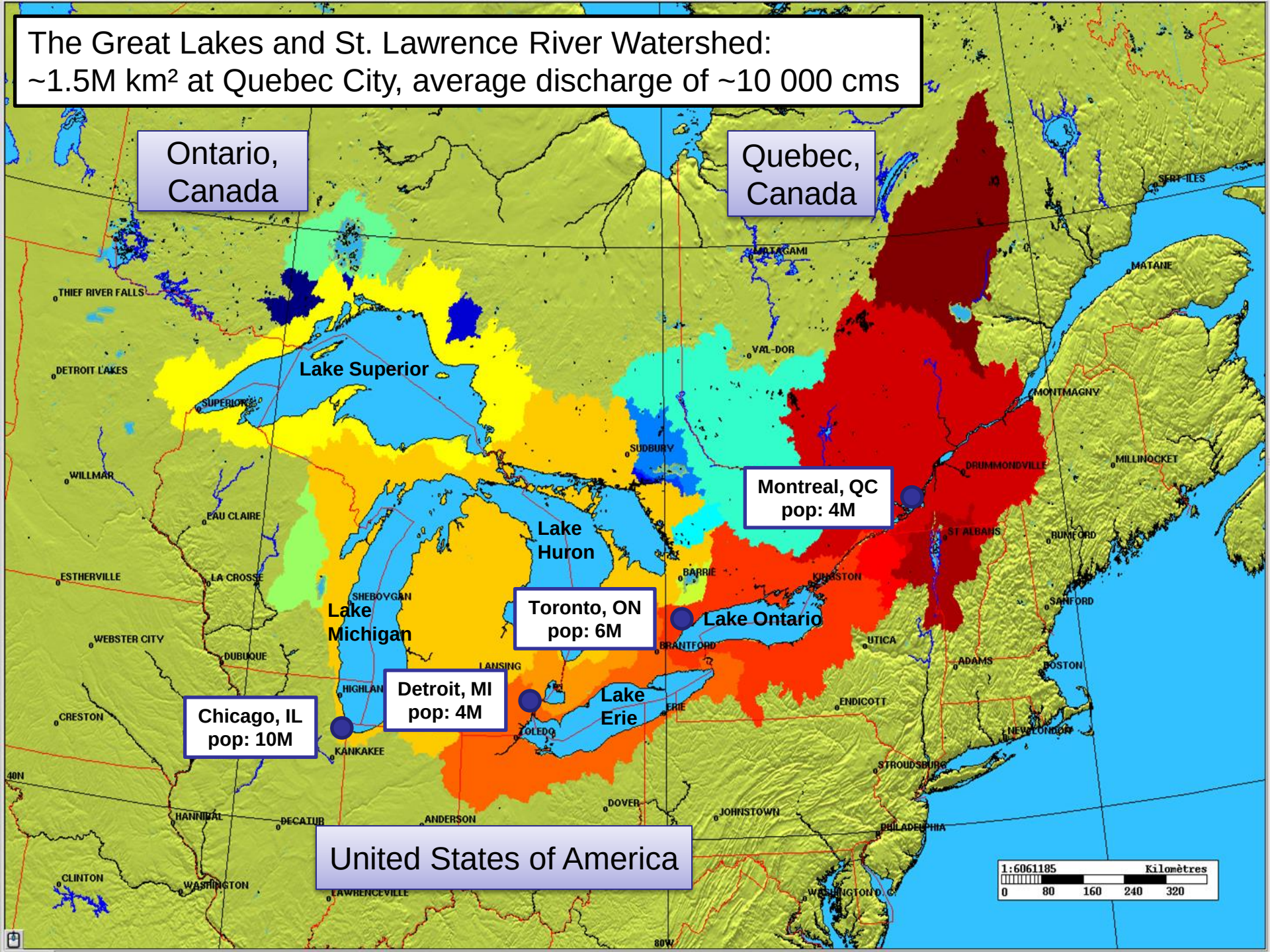
5-km Gulf of St. Lawrence

Surface temperature



Needs for water cycle prediction systems at ECCC

- To help manage transboundary watersheds (including locks, dams, and hydropower facilities shared with the United States)
- To improve weather forecasting, incl. marine forecasts for large lakes and rivers
- To help respond to environmental emergencies (e.g. oil spills)


The Great Lakes and St. Lawrence River Watershed:
~1.5M km² at Quebec City, average discharge of ~10 000 cms
Ontario, Canada
Quebec, Canada
Lake Superior
Lake Huron
Lake Michigan
Lake Erie
Lake Ontario
Montreal, QC pop: 4M
Toronto, ON pop: 6M
Detroit, MI pop: 4M
Chicago, IL pop: 10M
United States of America
THIEF RIVER FALLS
DETROIT LAKES
WILLMAR
EAU CLAIRE
LA CROSSE
ESTHERVILLE
WEBSTER CITY
DUBUQUE
CRESTON
HANNIBAL
DECATUR
CLINTON
WASHINGTON
ANDERSON
LAWRENCEVILLE
SHEBOYGAN
HIGHLAN
KANKAKEE
LANSING
TOLEDO
ERIE
SUDBURY
BARRIE
BRANTFORD
KINGSTON
VAL-D'OR
MATAGAMI
SEPT-ÎLES
MATANE
MONTMAGNY
DRUMMONDVILLE
MILLINOCKET
ST ALBANS
RUMFORD
SANFORD
UTICA
ADAMS
BOSTON
ENDICOTT
NEW LONDON
STROUDSBURG
DOVER
JOHNSTOWN
PHILADELPHIA
WASHINGTON D.C.
1:6061185
Kilomètres
0 80 160 240 320

Kaniatarowanenneh: the Great Waterway

Duluth, MN

Sault Ste-Marie, ON

Quebec City, QC

Chicago, IL

Kaniatarowanenneh: the Great Waterway

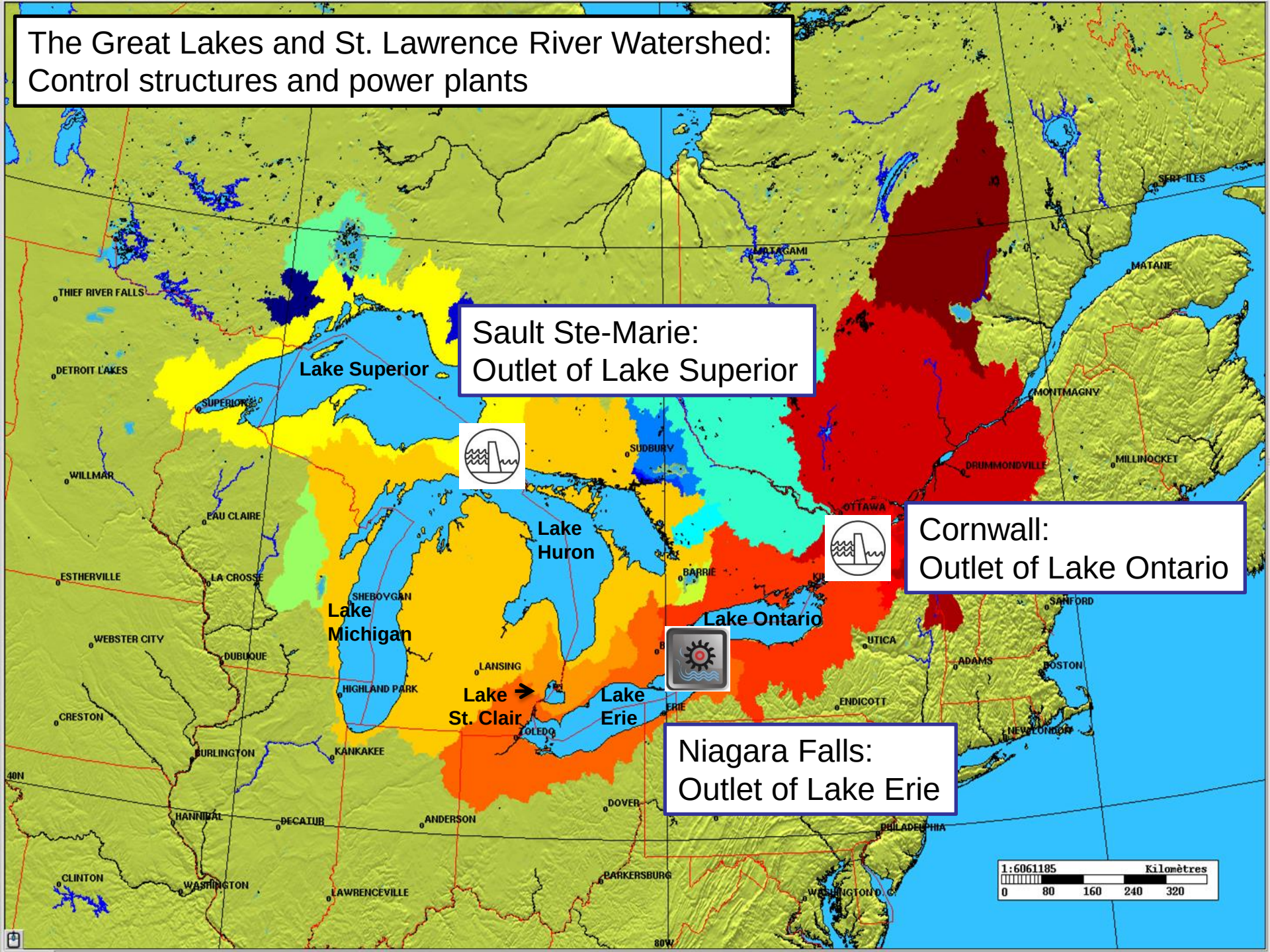
Nantes, FR

Geneva, CH

Budapest, HU

Barcelona, ES

1:6061185 Kilomètres
0 80 160 240 320


The Great Lakes and St. Lawrence River Watershed:
Control structures and power plants
Sault Ste-Marie:
Outlet of Lake Superior
Cornwall:
Outlet of Lake Ontario
Niagara Falls:
Outlet of Lake Erie
Lake Superior
Lake Huron
Lake Michigan
Lake St. Clair
Lake Erie
Lake Ontario
THIEF RIVER FALLS
DETROIT LAKES
SUPERIOR
WILLMAR
EAU CLAIRE
ESTHERVILLE
LA CROSSE
WEBSTER CITY
DUBUQUE
CRESTON
BURLINGTON
KANKAKEE
HANNIBAL
DECATUR
CLINTON
WASHINGTON
LAWRENCEVILLE
ANDERSON
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TOLEDO
ERIE
SUDBURY
BARRIE
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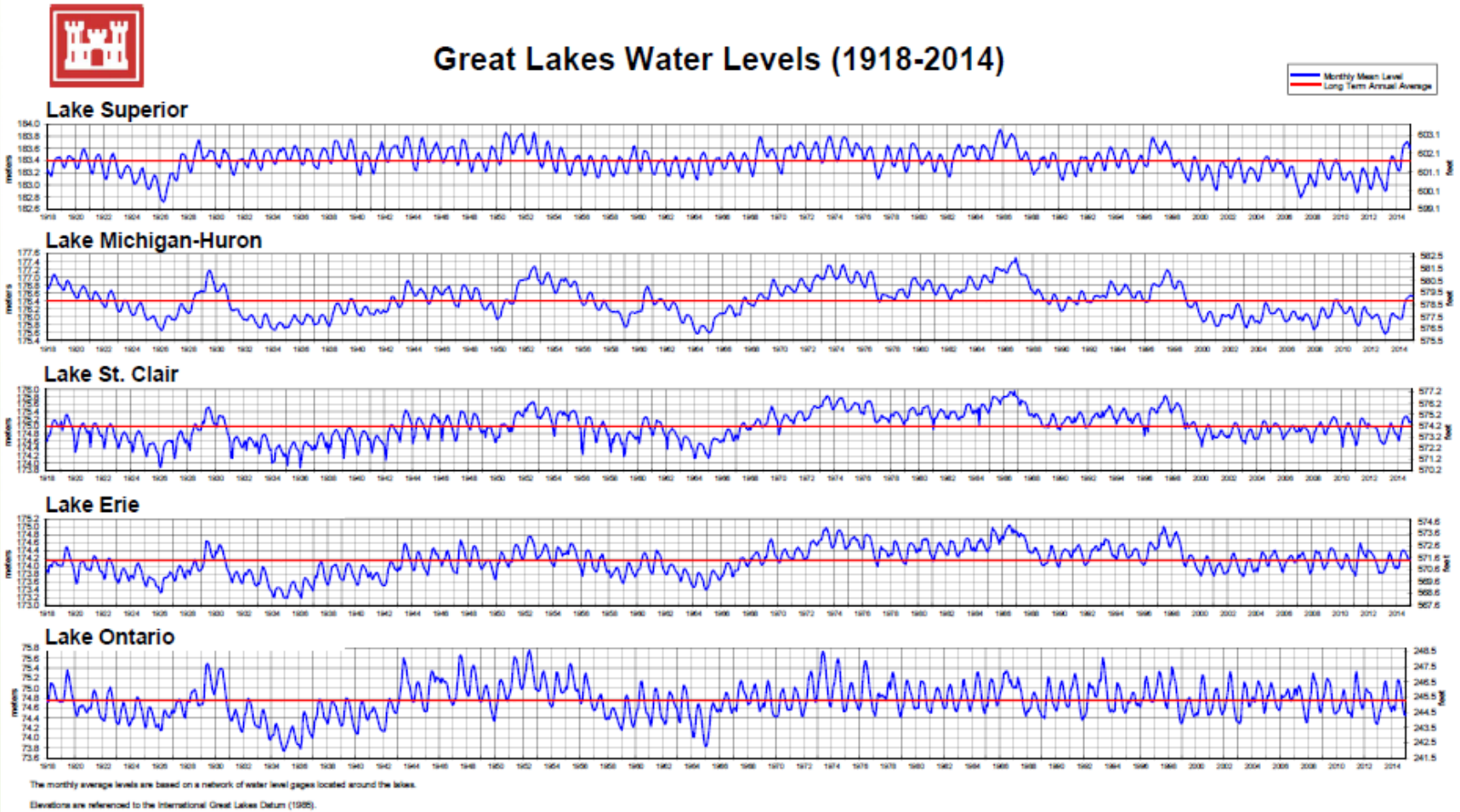
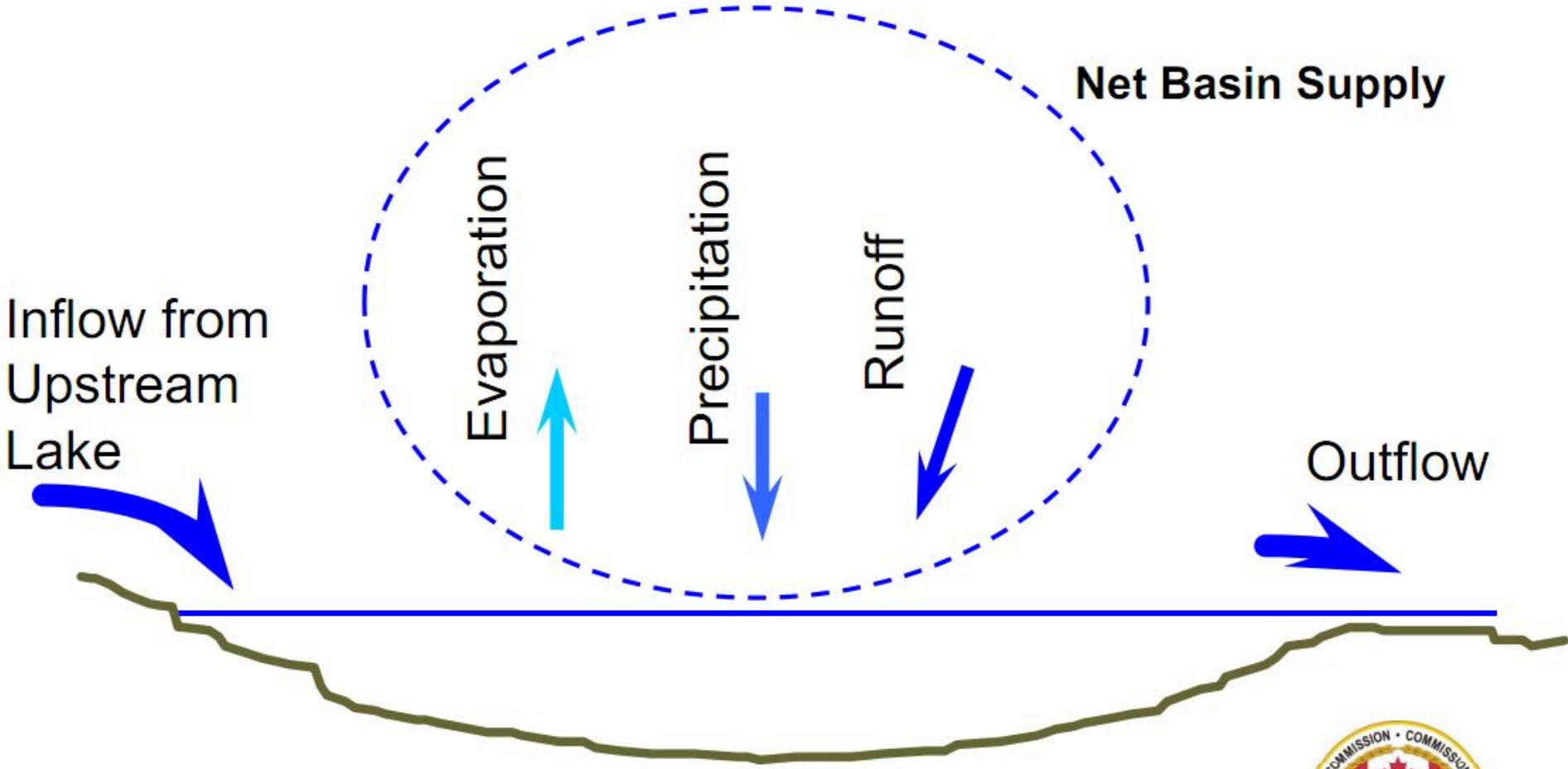
MONTMAGNY
MATANE
SEPT-ILES
MILLINOCKET
SANFORD
UTICA
ADAMS
BOSTON
ENDICOTT
NEW LONDON
DOVER
PHILADELPHIA
BARKERSBURG
WASHINGTON D.C.
1:6061185
Kilomètres
0
80
160
240
320

Long-term fluctuations in water levels



Great Lakes Water Supplies

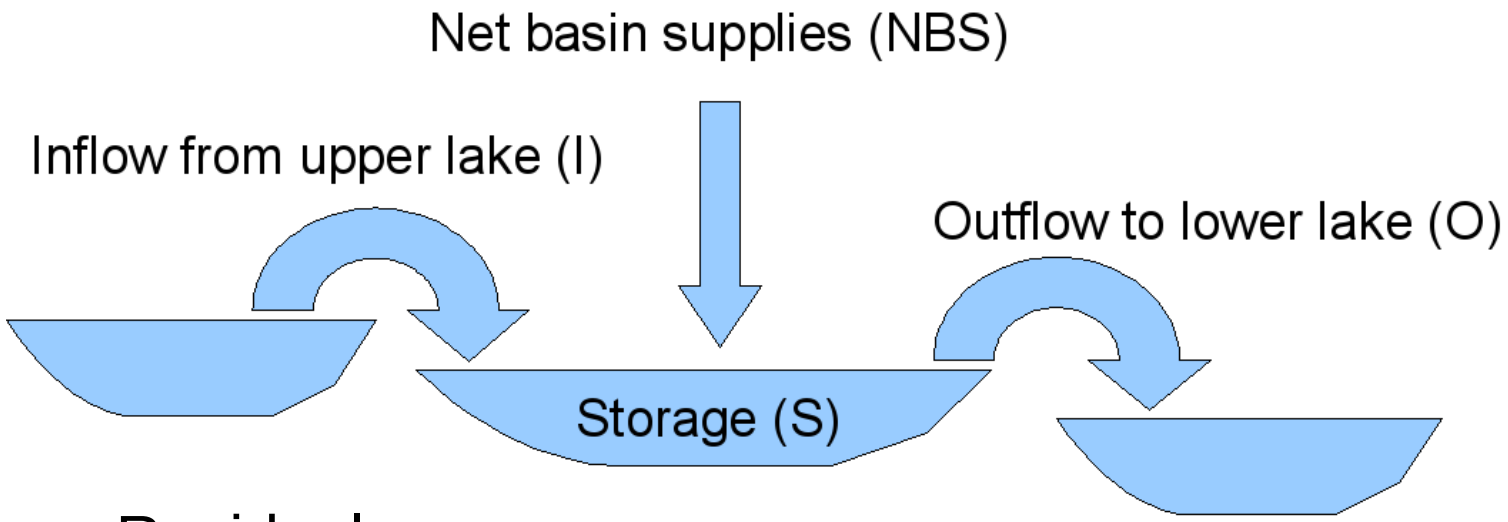
(Factors Affecting Water Levels)



International Lake Superior Board of Control

30 August 2011

Net basin supplies: component vs residual method

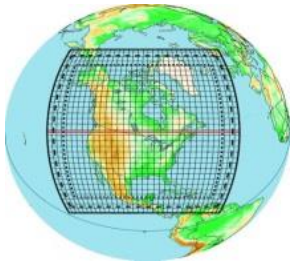


Residual $NBS = \Delta S + O - I$

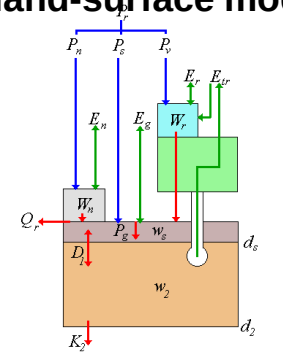
Component $NBS = P_{Lake} - E_{Lake} + R_{Basin}$

Water Cycle Prediction System for the Great Lakes: the starting point

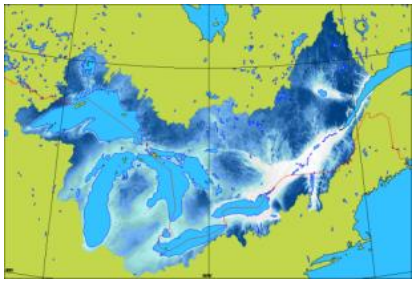
GEM RDPS (15 km)
atmospheric model

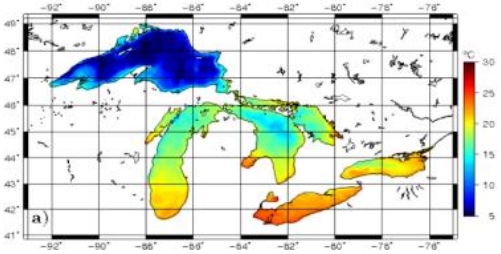


ISBA
land-surface model



WATROUTE
routing model (1km)

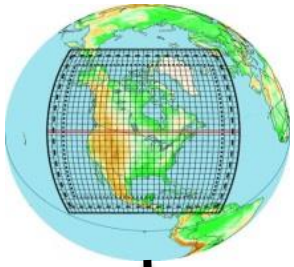




Open ocean bulk formula
for evaporation

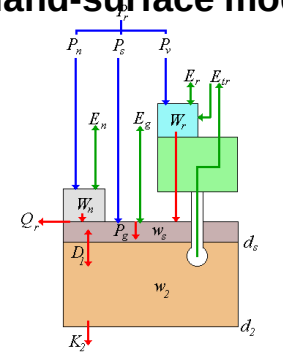
Water Cycle Prediction System for the Great Lakes: the starting point

GEM RDPS (15 km) atmospheric model

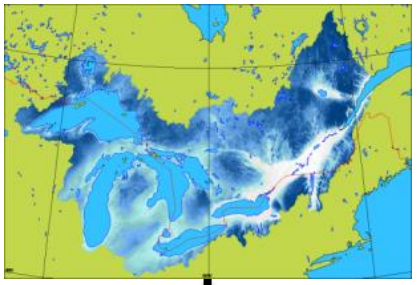


P_{Lake}

ISBA land-surface model

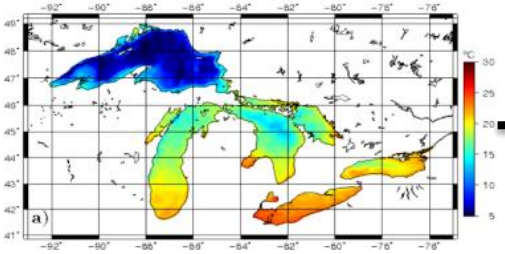


WATROUTE routing model (1km)



R_{Basin}

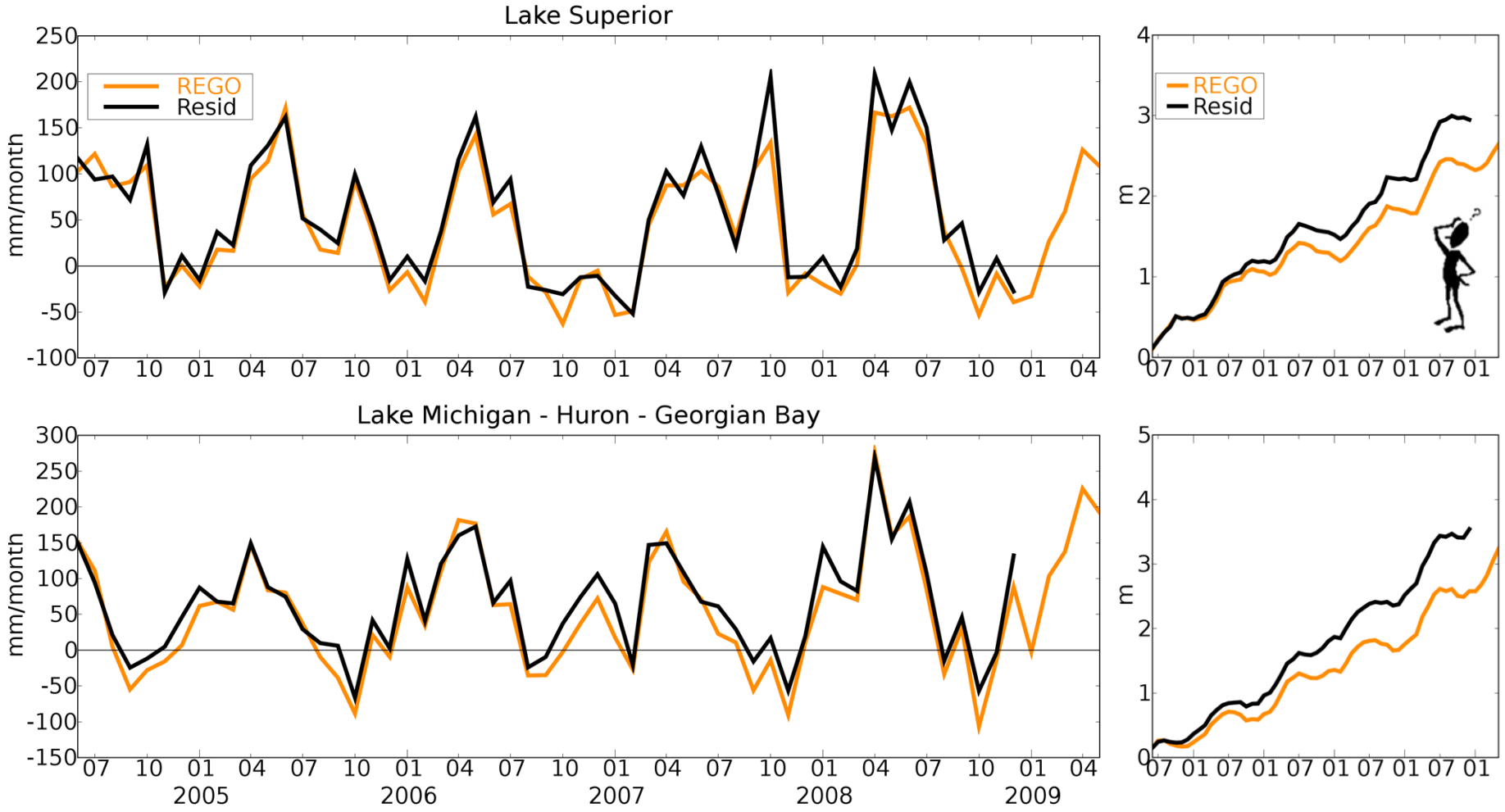
$$NBS = P_{Lake} - E_{Lake} + R_{Basin}$$



E_{Lake}

Open ocean bulk formula for evaporation

Monthly NBS, June 2004 - May 2009



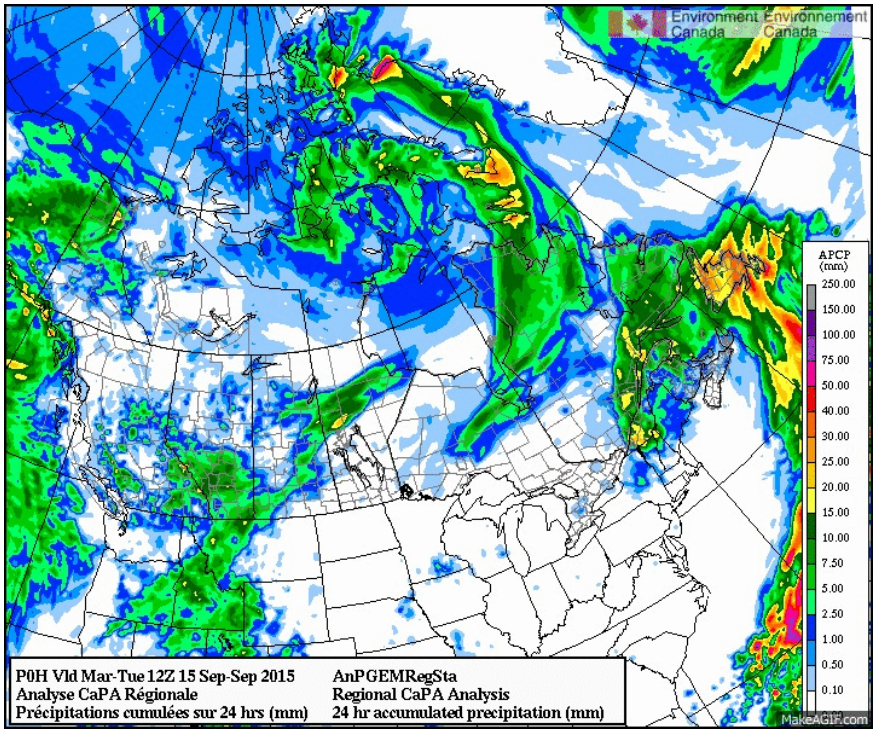
Residual NBS (observed)

Component NBS (modelled)

Deacu et al. (2012), Journal of Hydrometeorology

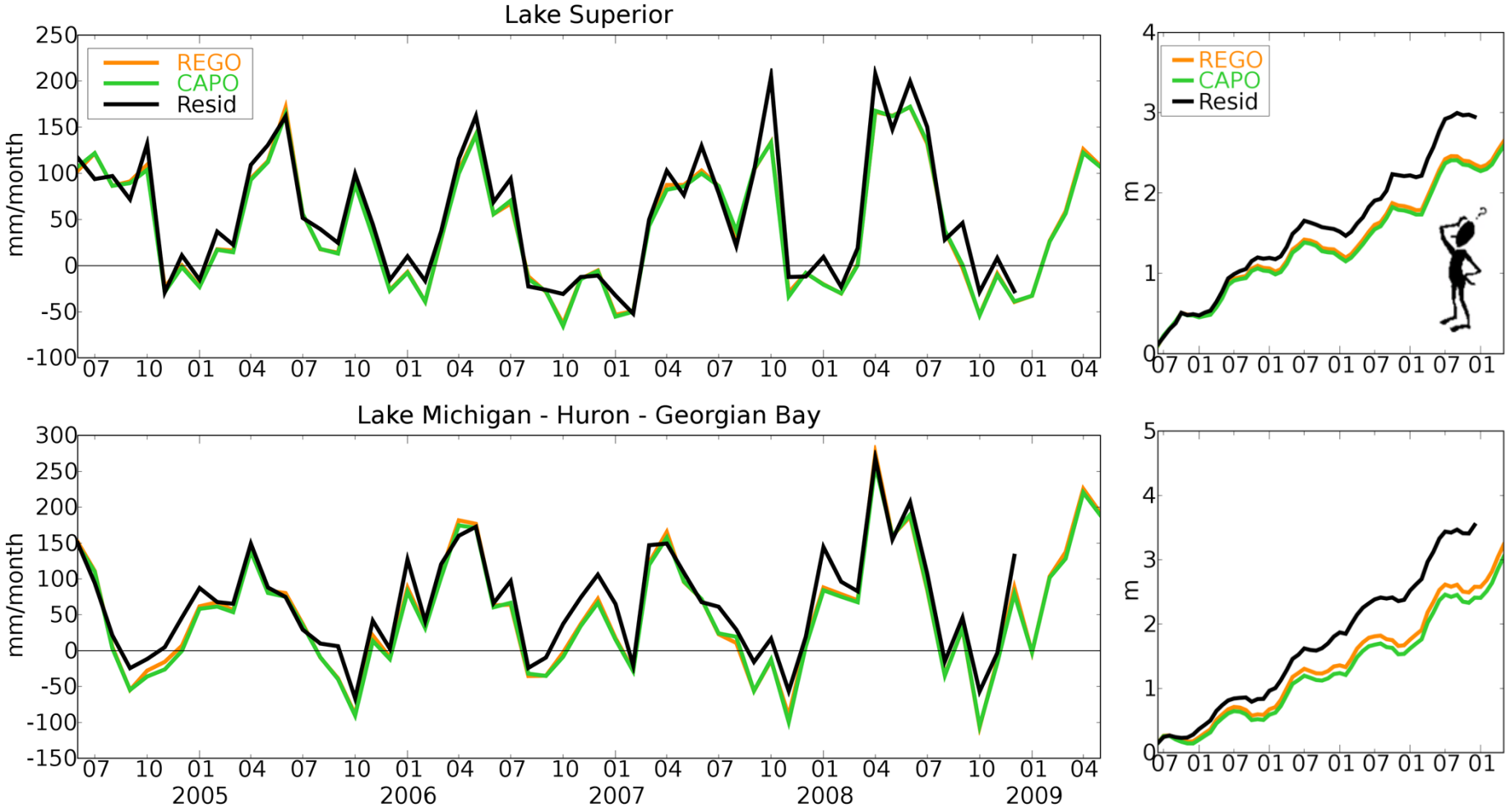
Canadian Precipitation Analysis: real-time QPE for North America

- Optimal interpolation technique used to merge gauges and radar data with a background provided by the GEM model
- Fully automated quality control
- 6-h and 24-h accumulations
- 2.5 km and 10 km horizontal resolutions now available
- Early (T+1h) and late (T+7h) analyses
- Archive going back to 2002 also available online



Mahfouf et al. (2007) A.-O.
Lespinas et al. (2015) J. Hydromet.
Fortin et al. (2015) J. Hydrology

Monthly NBS, June 2004 - May 2009



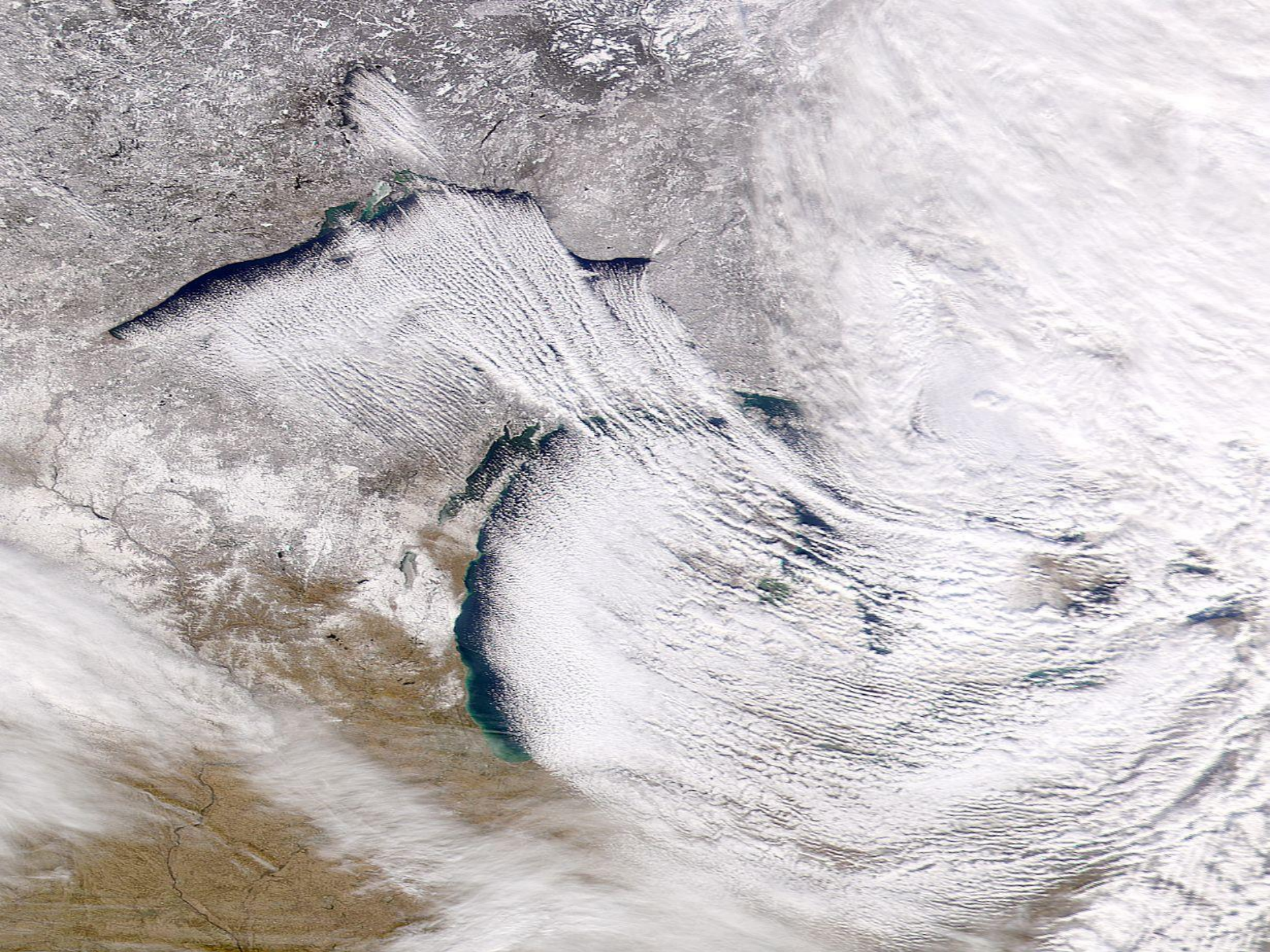
Residual NBS

Component NBS

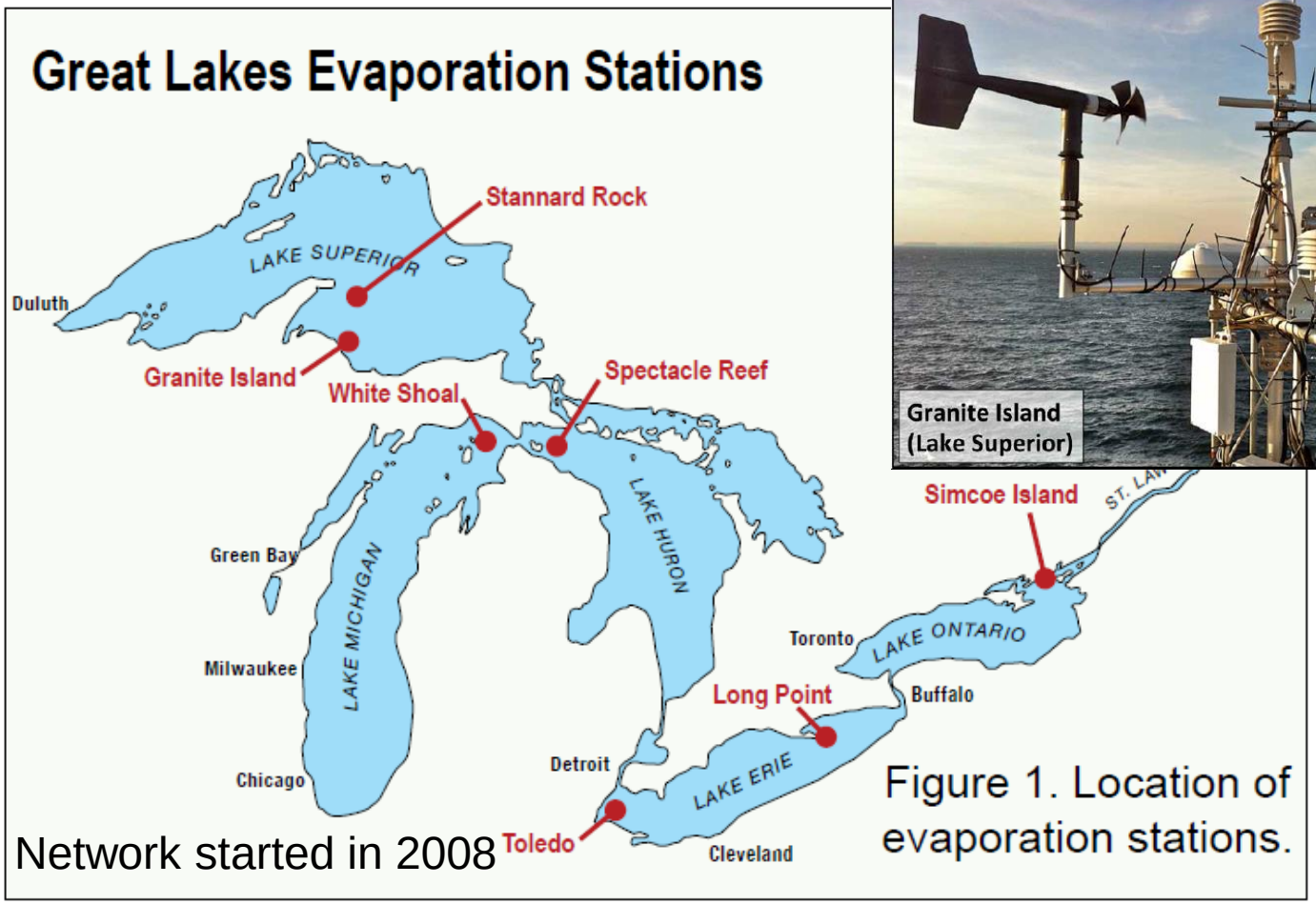
GEM precip

CaPA precip

Deacu et al. (2012), Journal of Hydrometeorology

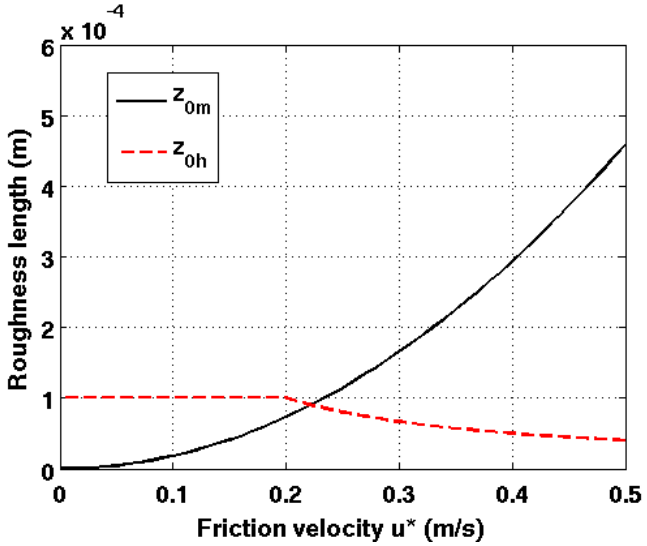


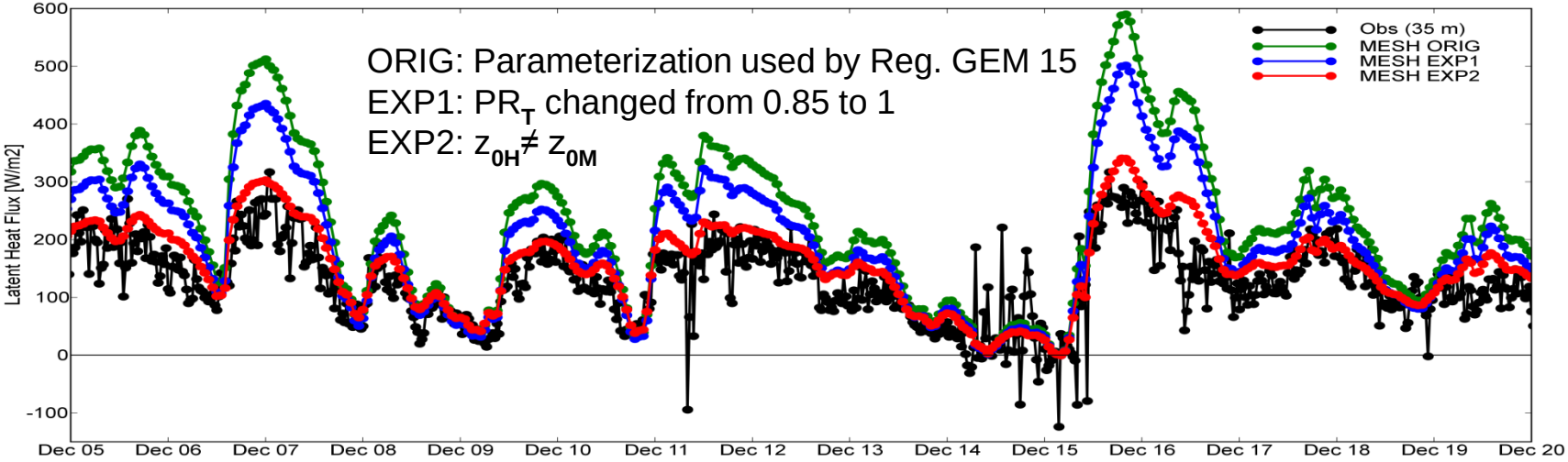
Monitoring of evaporation on the Great Lakes



Improving the turbulent flux parameterization over water

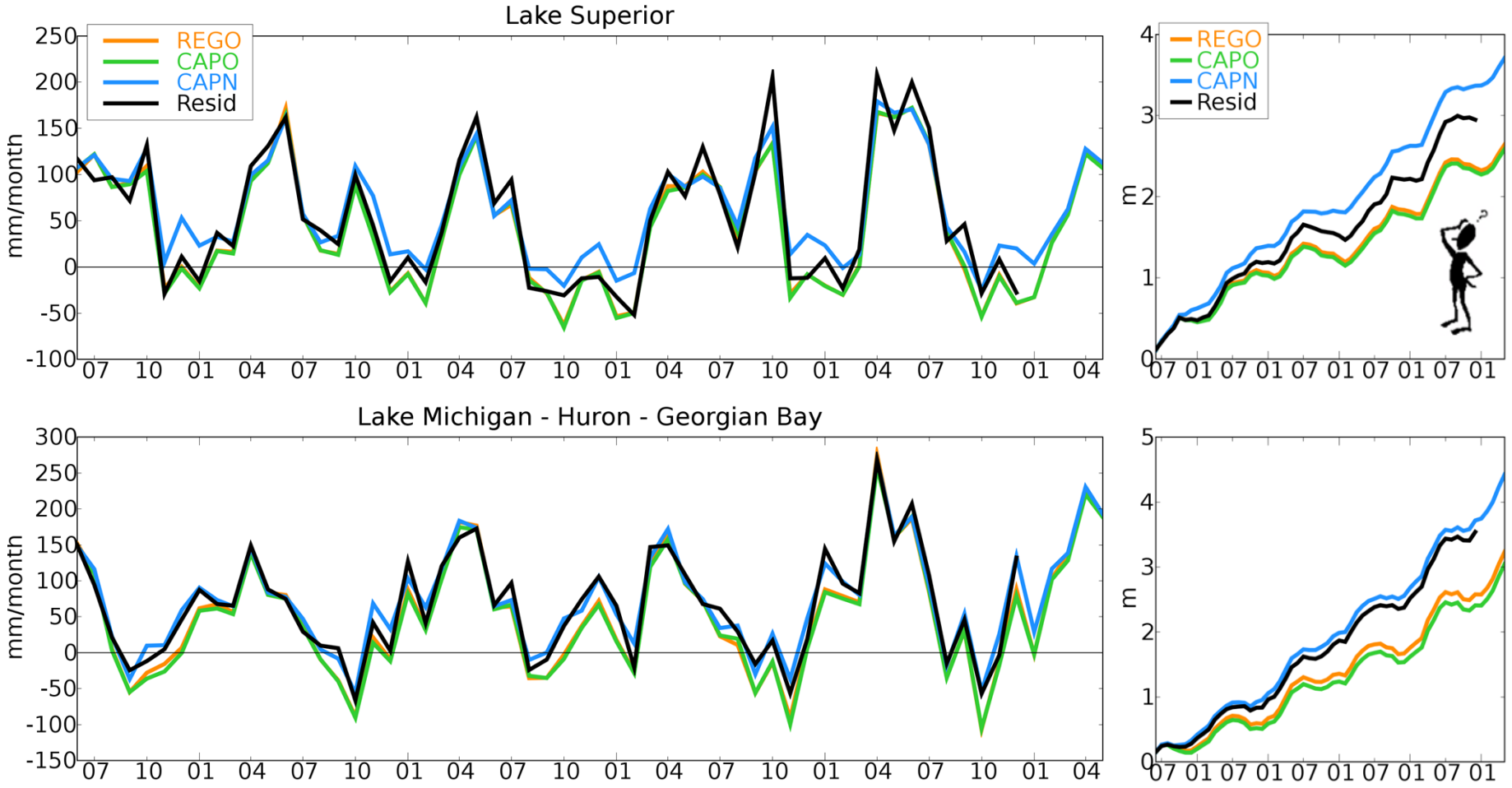
Eddy-covariance data used to improve evaporation prediction





Deacu et al. (2012), Journal of Hydrometeorology

Monthly NBS, June 2004 - May 2009



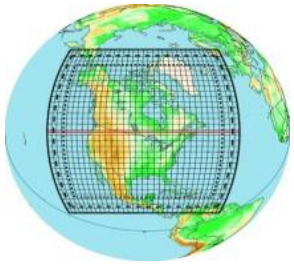
Residual NBS

Component NBS
- GEM precip
- CaPA precip
- Improved FPW

Deacu et al. (2012), Journal of Hydrometeorology

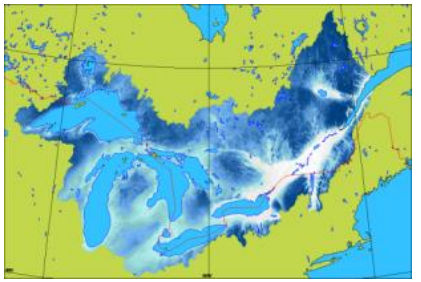
Water Cycle Prediction System for the Great Lakes: the starting point

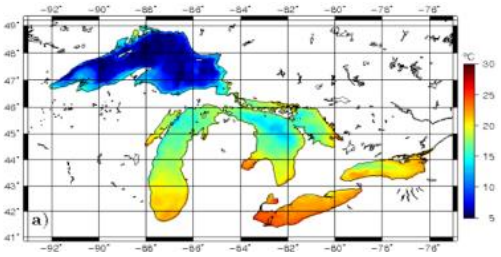
GEM RDPS (15 km) atmospheric model



GEM LAM (15 km) atmospheric model (ISBA land-surface scheme)

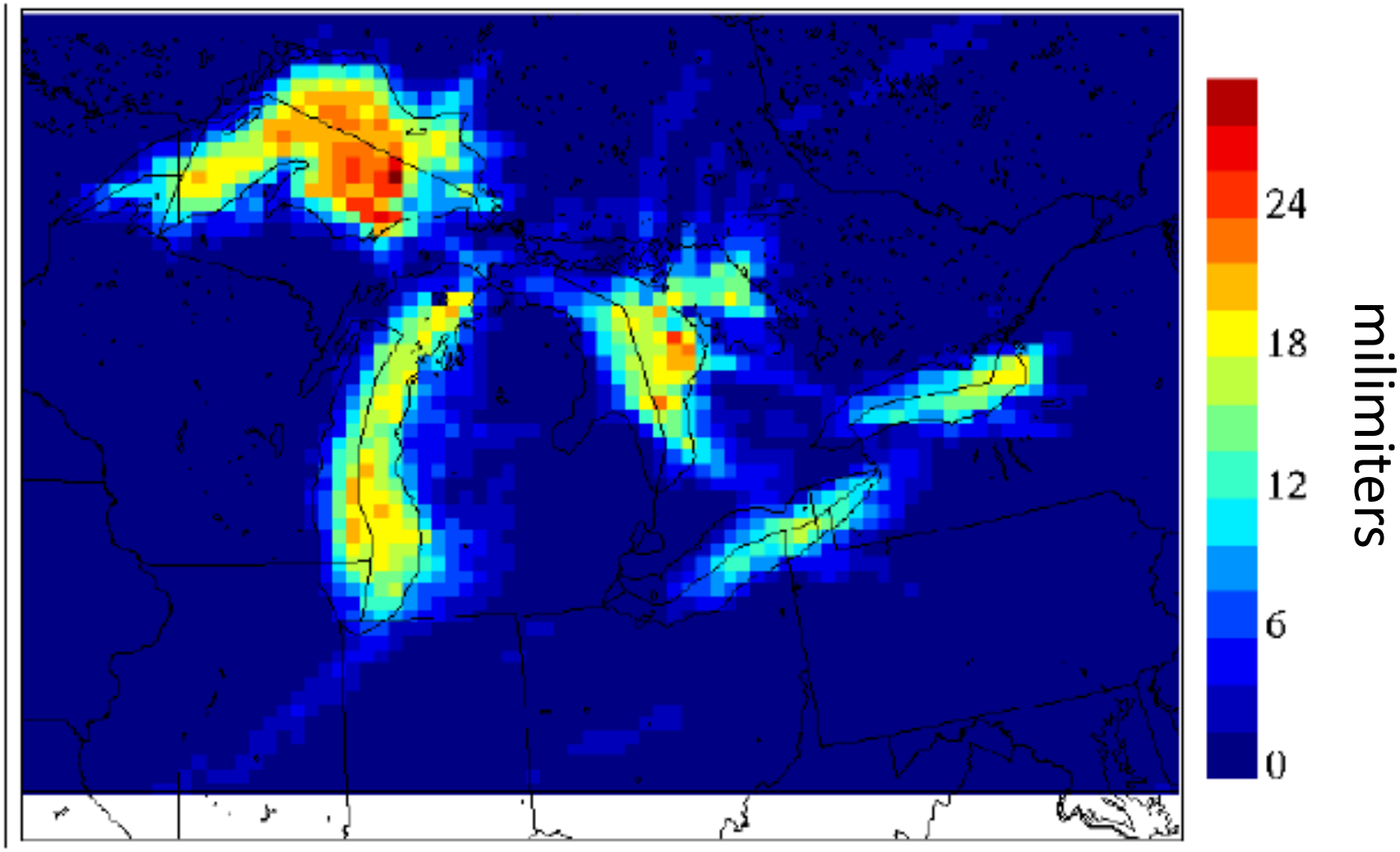
WATROUTE routing model (1km)



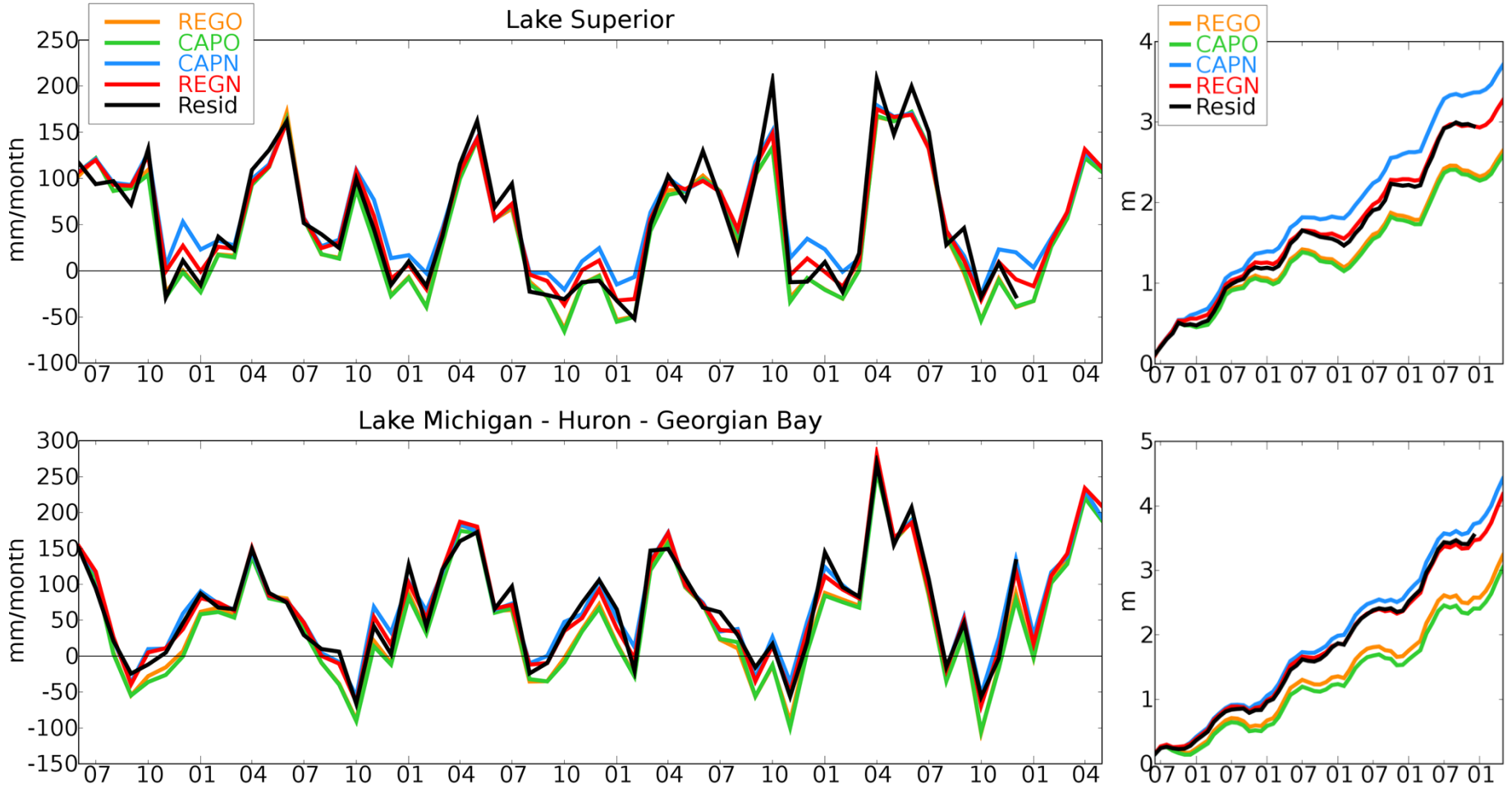


Improved flux parameterization over water

Impact of coupling(using improved flux parameterization) on precipitation forecasts (sum of 31 daily forecasts, Dec ember 2009)



Monthly NBS, June 2004 - May 2009



Residual NBS

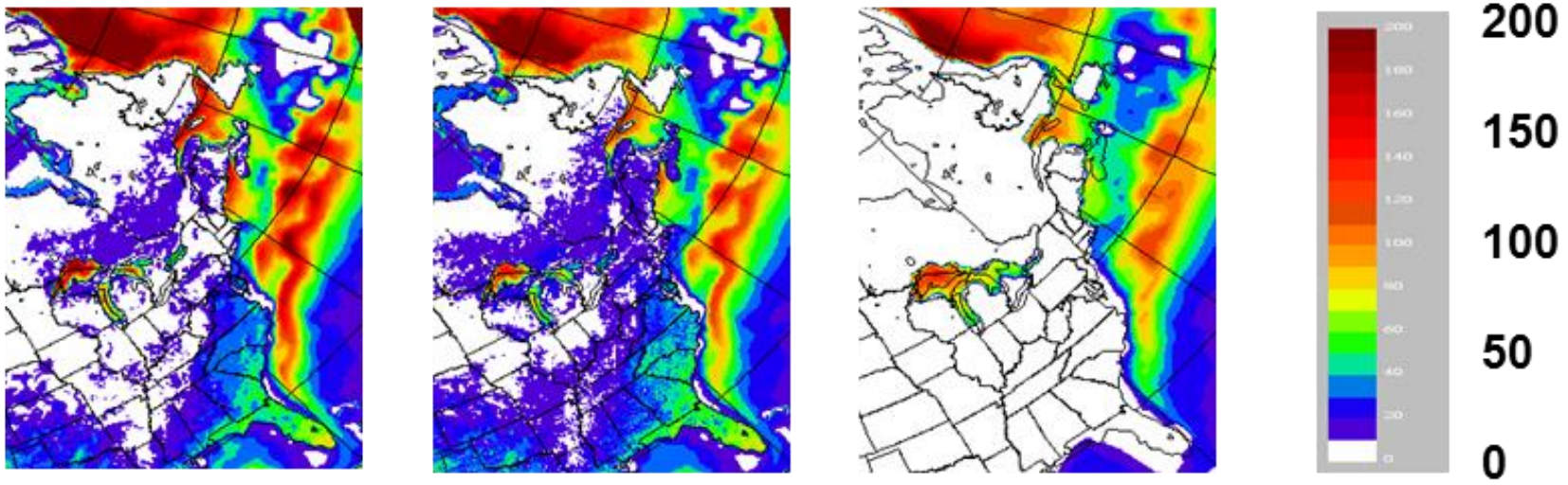
Component NBS

- GEM precip
- CaPA precip
- Improved FPW
- Coupled system

Deacu et al. (2012), Journal of Hydrometeorology

Operational implementation of improved flux param. in Fall 2012

Average latent heat flux, winter 2011 (W/m²)



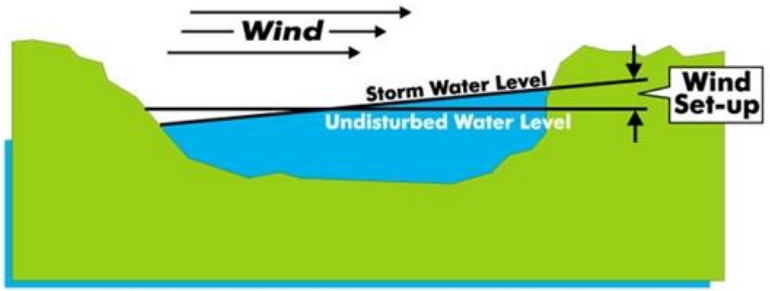
GEM 15km (old)

GEM 10km (new)

OAFlux

Short-term fluctuations in water levels

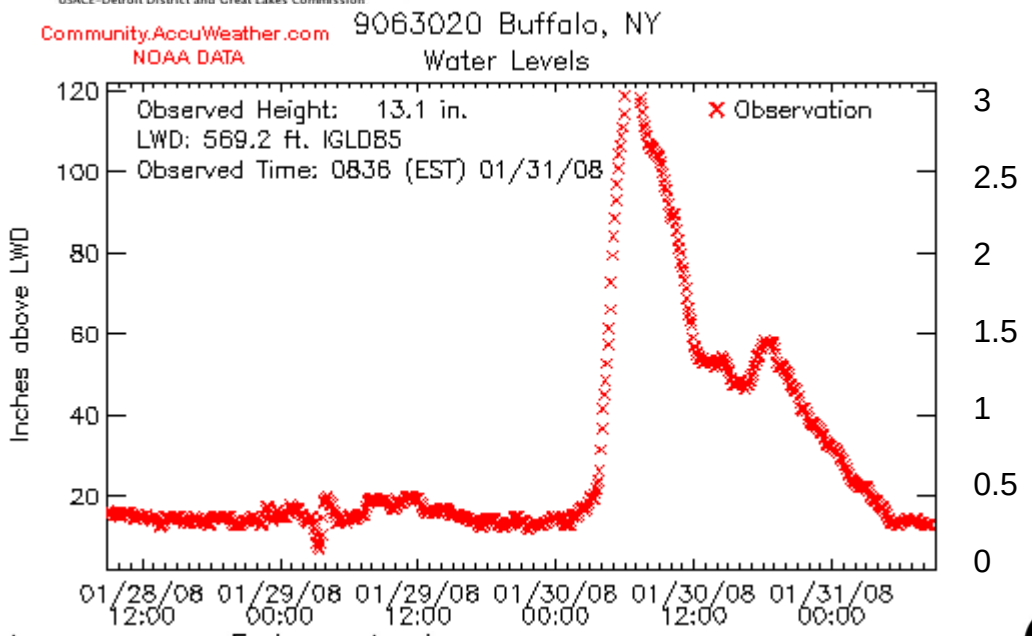
- Storm surge



Lake profile showing wind set-up

Courtesy *Living with the Lakes*, copyright 2000
USACE-Detroit District and Great Lakes Commission

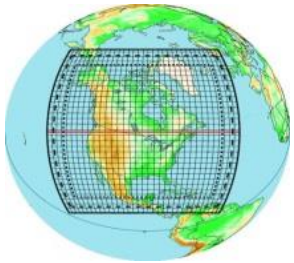
12 h



Meters above mean water level

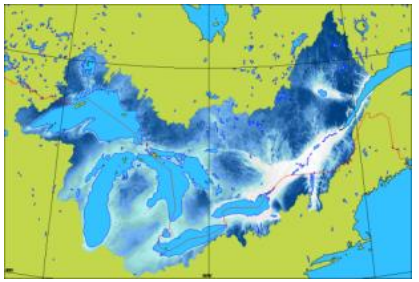
Water Cycle Prediction System for the Great Lakes

GEM RDPS (10 km)
atmospheric model



GEM LAM (10 km)
atmospheric model
(ISBA land-surface scheme)

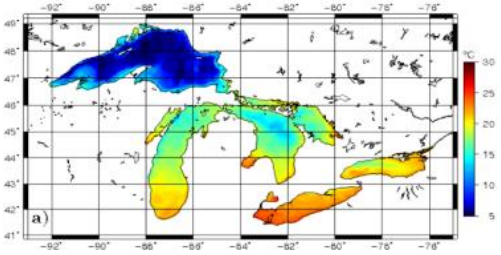
WATROUTE
routing model (1km)



In production since June 2016:

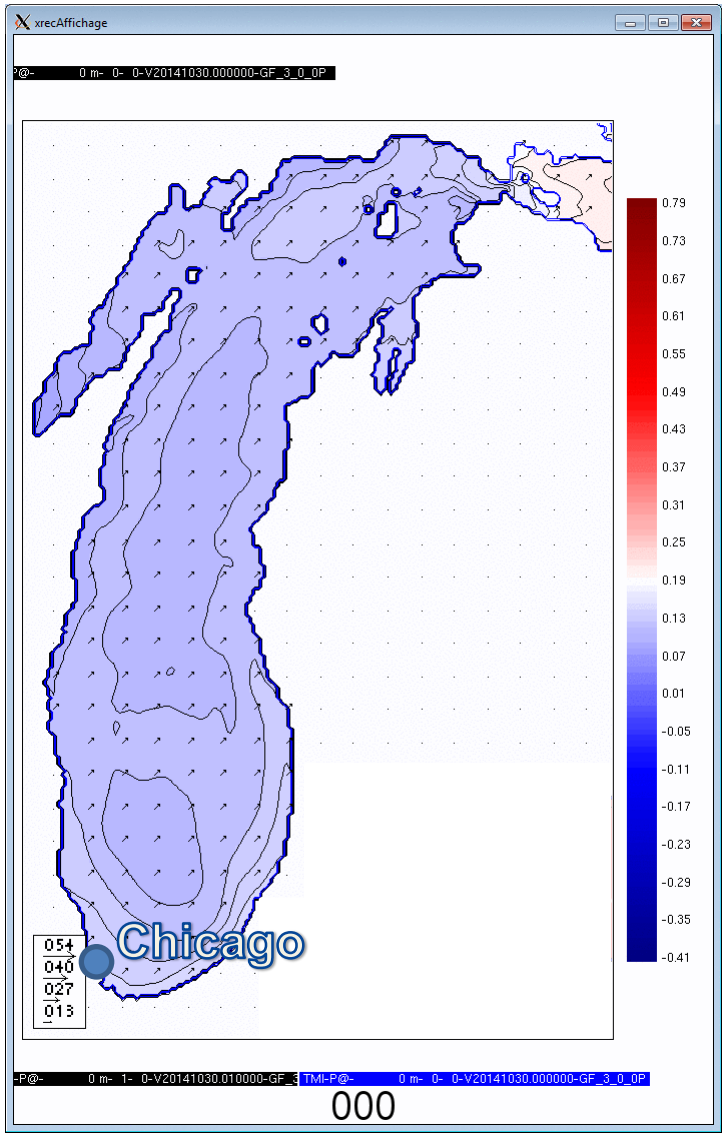
- 2 runs per day
- 3.5 day forecasts

Durnford et al. (2017) submitted to BAMS



NEMO+CICE (2 km)
ocean-ice model
over the Great Lakes

Halloween storm, 2014: NEMO forecast

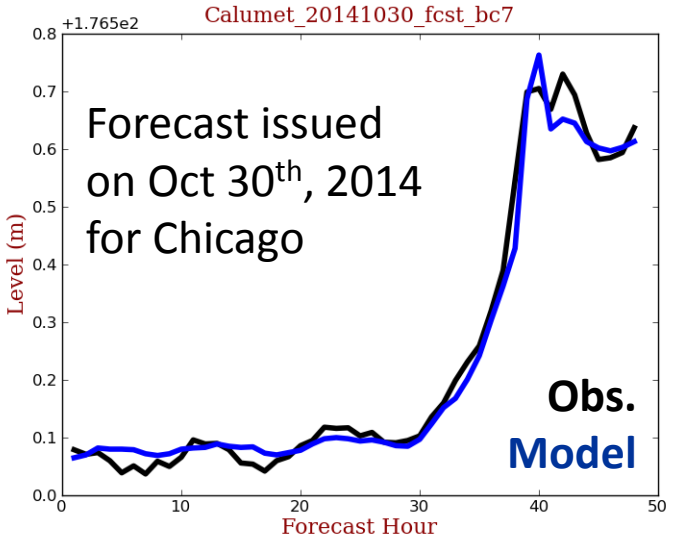


+80 cm

+60 cm

+40 cm

+20 cm

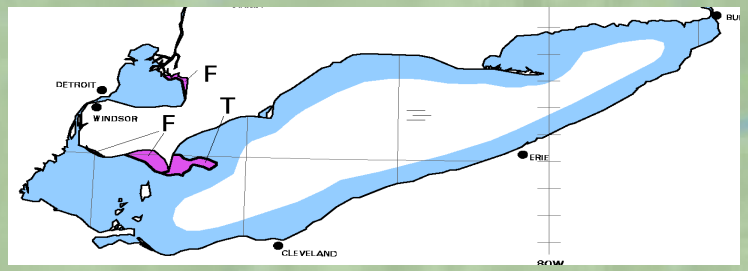


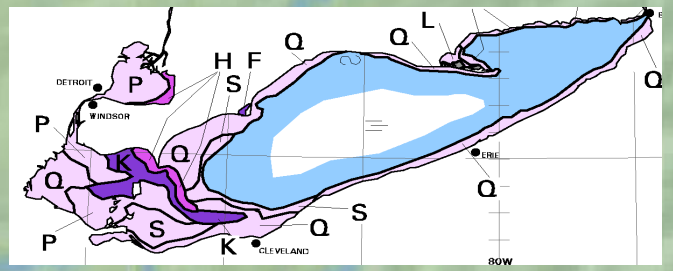
0h 24h 48h

NEMO ice and surface current forecast
2016-02-12 00Z - 2016-02-14 00Z

Layer	time	elevation
Map	2016-02-12T00:00:00Z	-1
LAKES.GL - Sea ice fraction (NIL)	2016-02-12T00:00:00Z	-1
LAKES.GL - Ocean current (m/s)	2016-02-12T00:00:00Z	-1

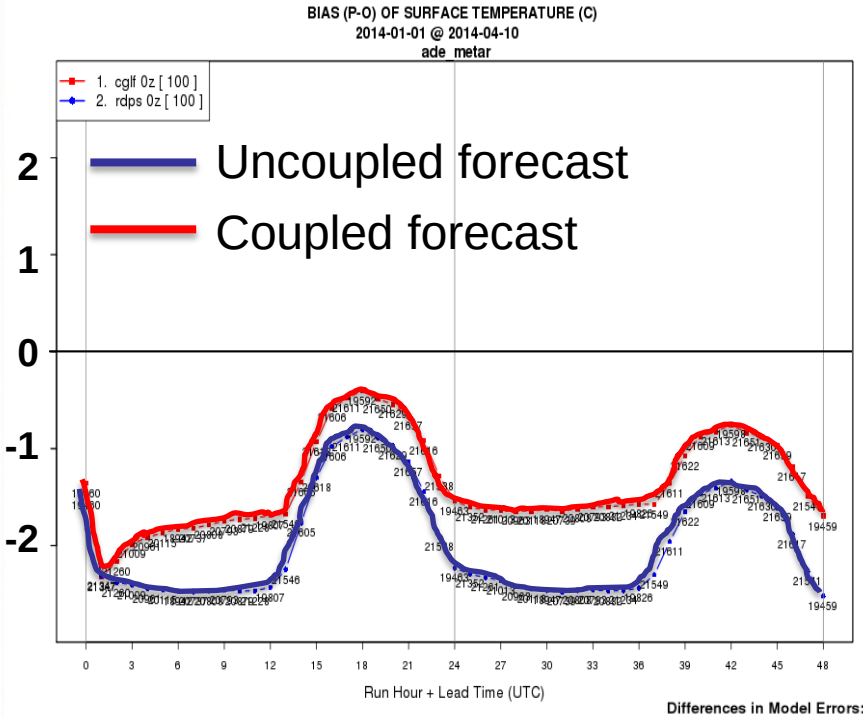
[48/48]

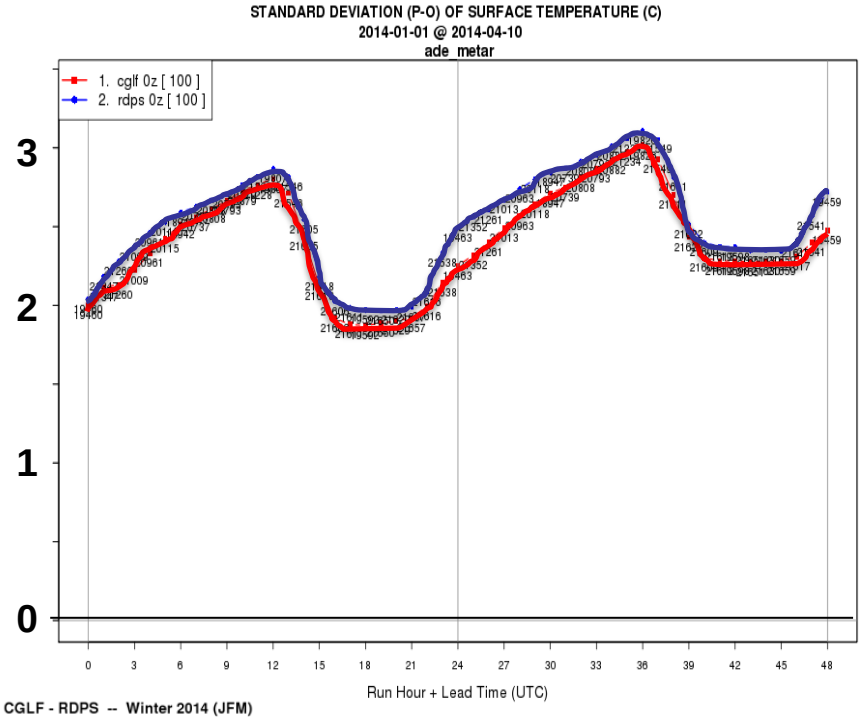




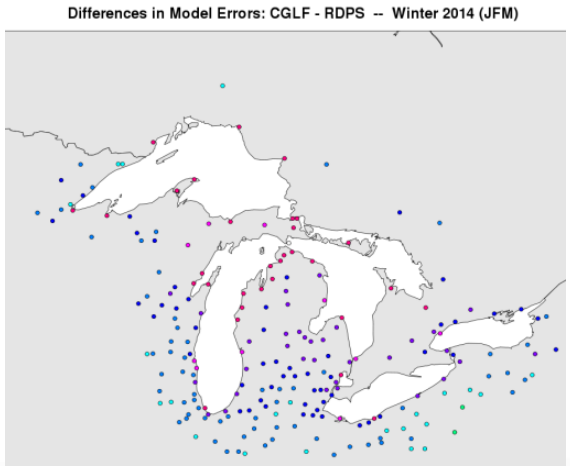
LonLat (-79.02,43.78)

Impact of coupling: Winter 2014 temperature forecasts





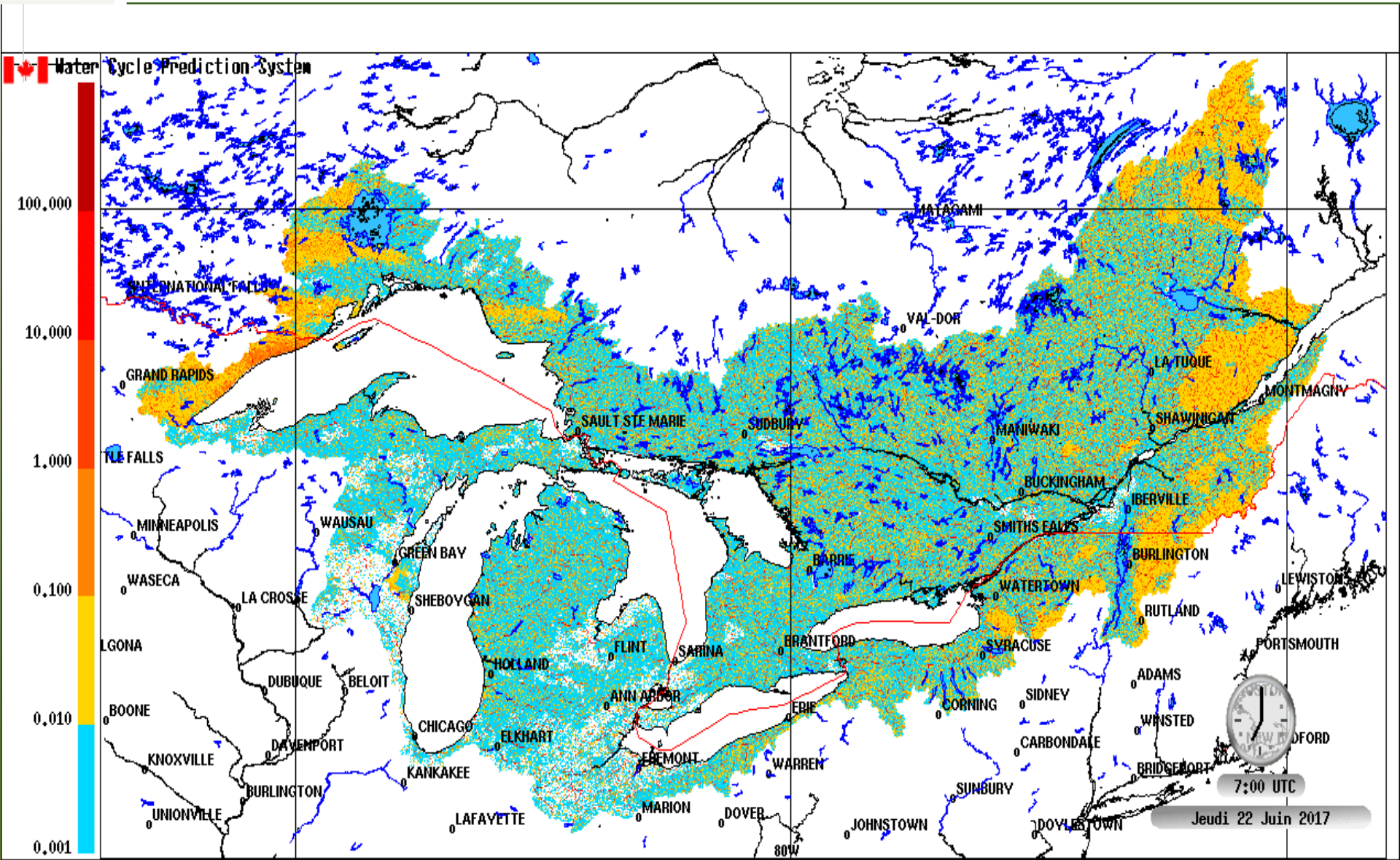
Bias improved by 1C at night, 0.5C during the day



Standard deviation improved by 0.1 C

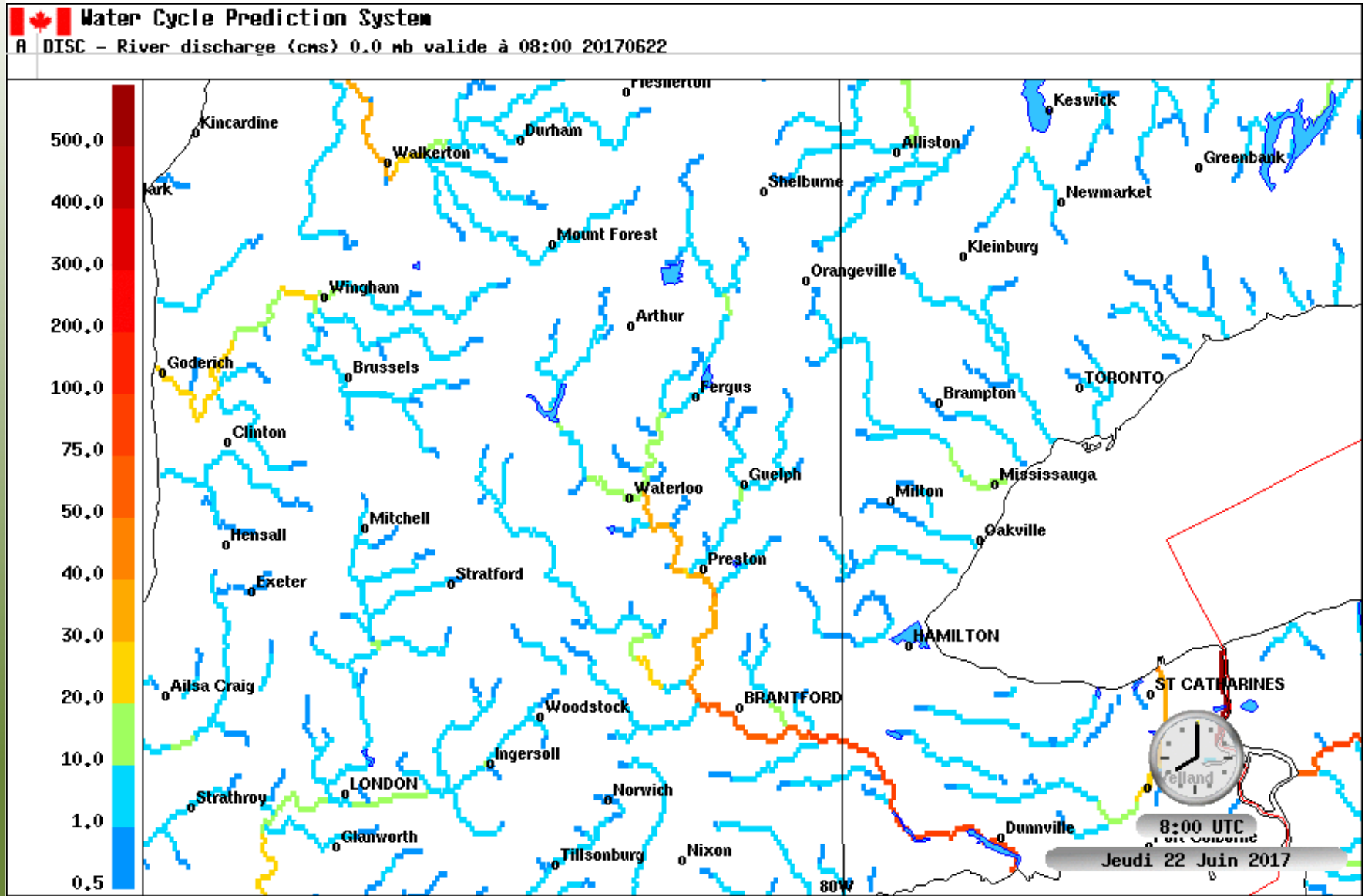
Streamflow analysis cycle

2017-06-22 06Z - 2017-06-24 06Z

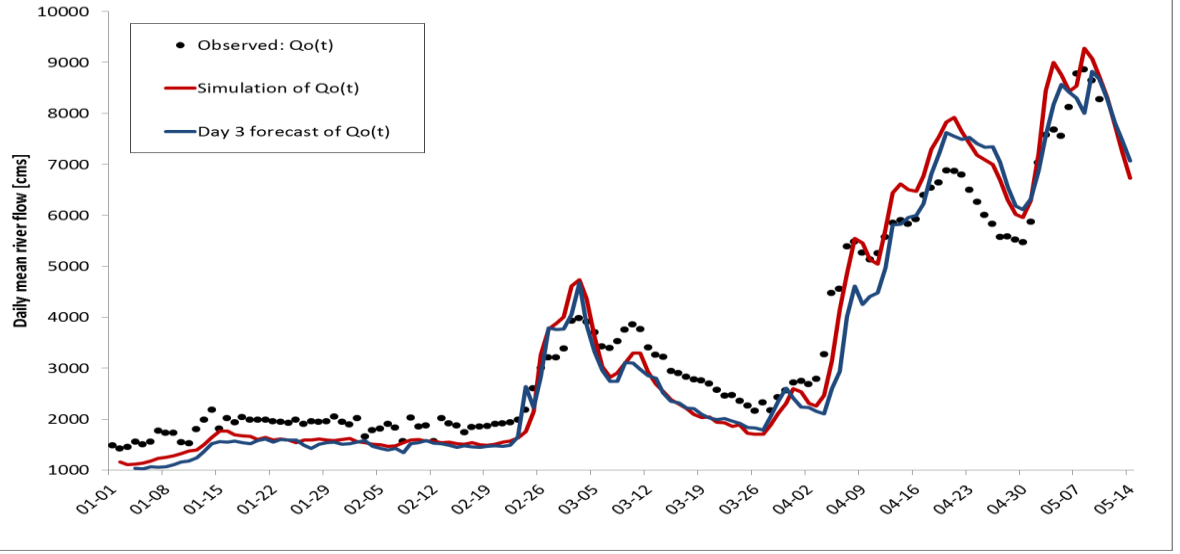


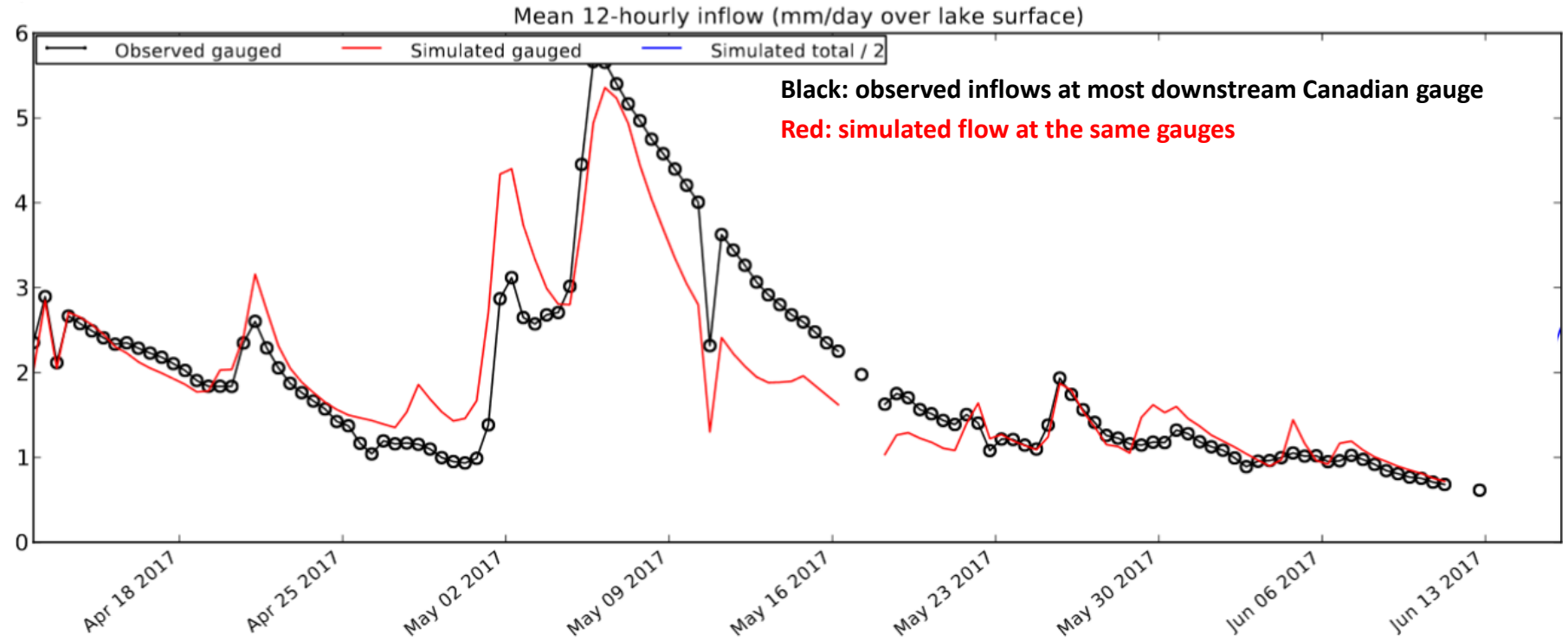
Streamflow analysis cycle

2017-06-22 06Z - 2017-06-26 06Z



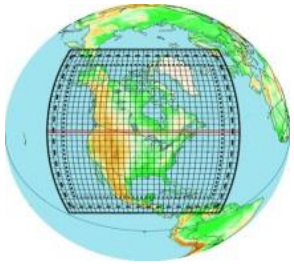

Ottawa River
(outlet @ Carillon Dam)
Ottawa River
Lake St. Lawrence
(outlet @ Moses Saunders &
Long Sault Dam)
Ottawa, ON
Montreal, QC
Cornwall, ON
Massena, NY
Ogdensburg, NY
St. Lawrence River
Lake St Louis
(outlet @ Lasalle)
Kingston, ON
Cobourg, ON
Toronto, ON
Lake Ontario
Port Weller, ON
Niagara River
Buffalo, NY
Rochester, NY
Oswego, NY
Syracuse, NY
Lake Erie


Observed: Qo(t)
Simulation of Qo(t)
Day 3 forecast of Qo(t)
Daily mean river flow [cms]
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
01-01
01-08
01-15
01-22
01-29
02-05
02-12
02-19
02-26
03-05
03-12
03-19
03-26
04-02
04-09
04-16
04-23
04-30
05-07
05-14


Mean 12-hourly inflow (mm/day over lake surface)
Observed gauged
Simulated gauged
Simulated total / 2
Black: observed inflows at most downstream Canadian gauge
Red: simulated flow at the same gauges
6
5
4
3
2
1
0
Apr 18 2017
Apr 25 2017
May 02 2017
May 09 2017
May 16 2017
May 23 2017
May 30 2017
Jun 06 2017
Jun 13 2017

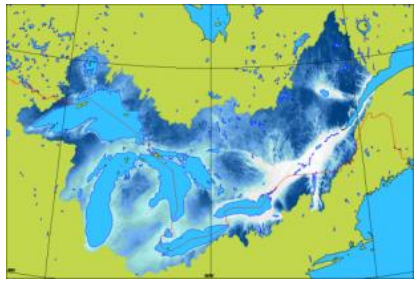
Water Cycle Prediction System for the Great Lakes and St. Lawrence

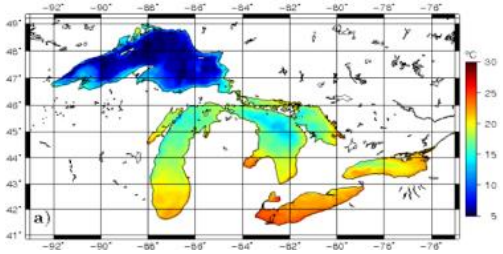
GEM RDPS (10 km)
atmospheric model



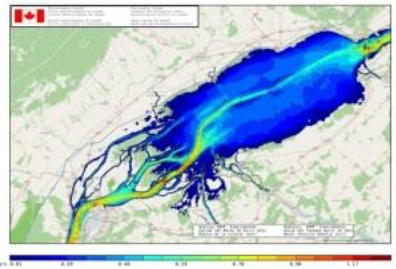
GEM LAM (10 km)
atmospheric model
(ISBA land-surface scheme)

WATROUTE
routing model (1km)



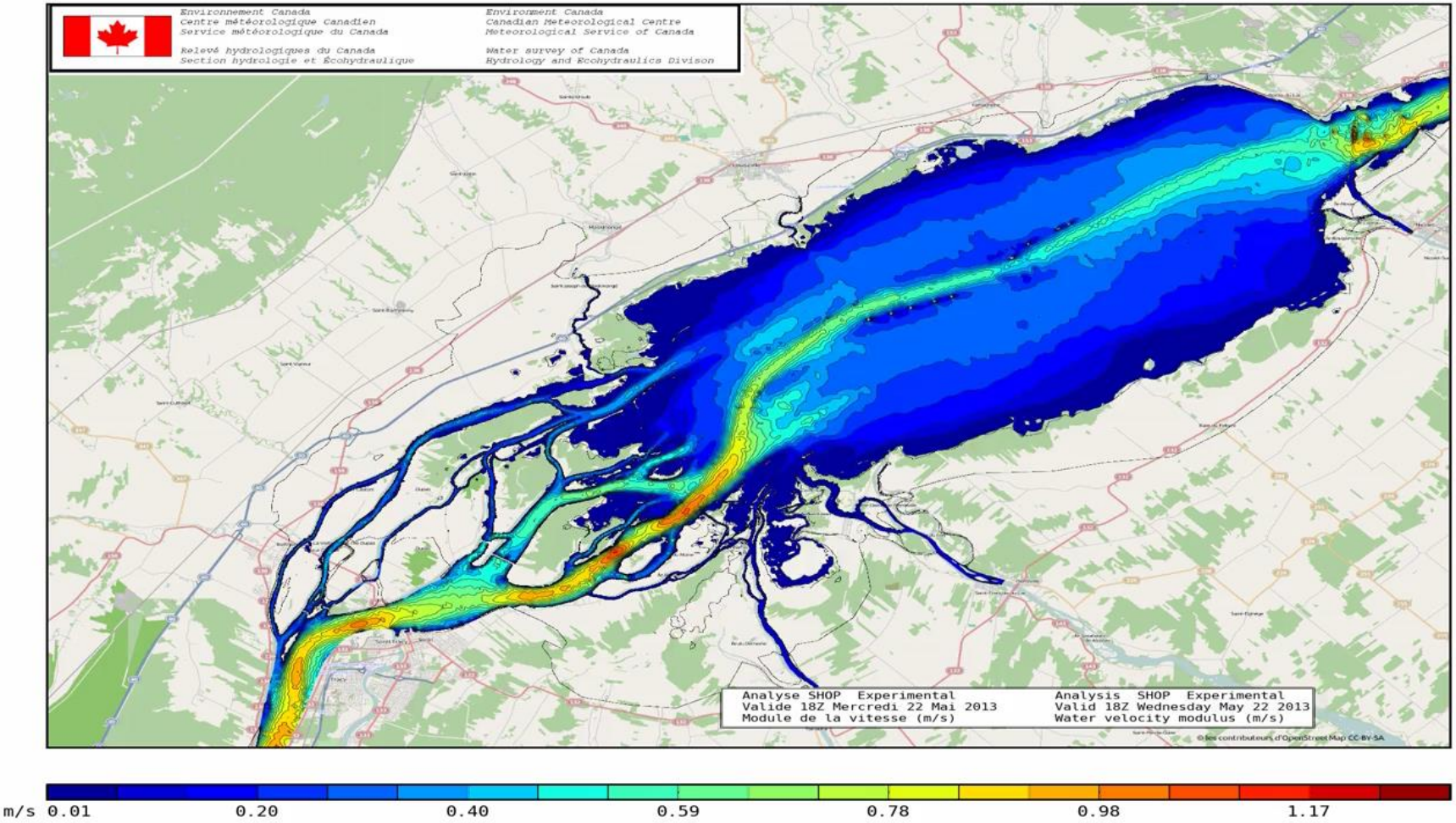


NEMO+CICE (2 km)
ocean-ice model
over the Great Lakes

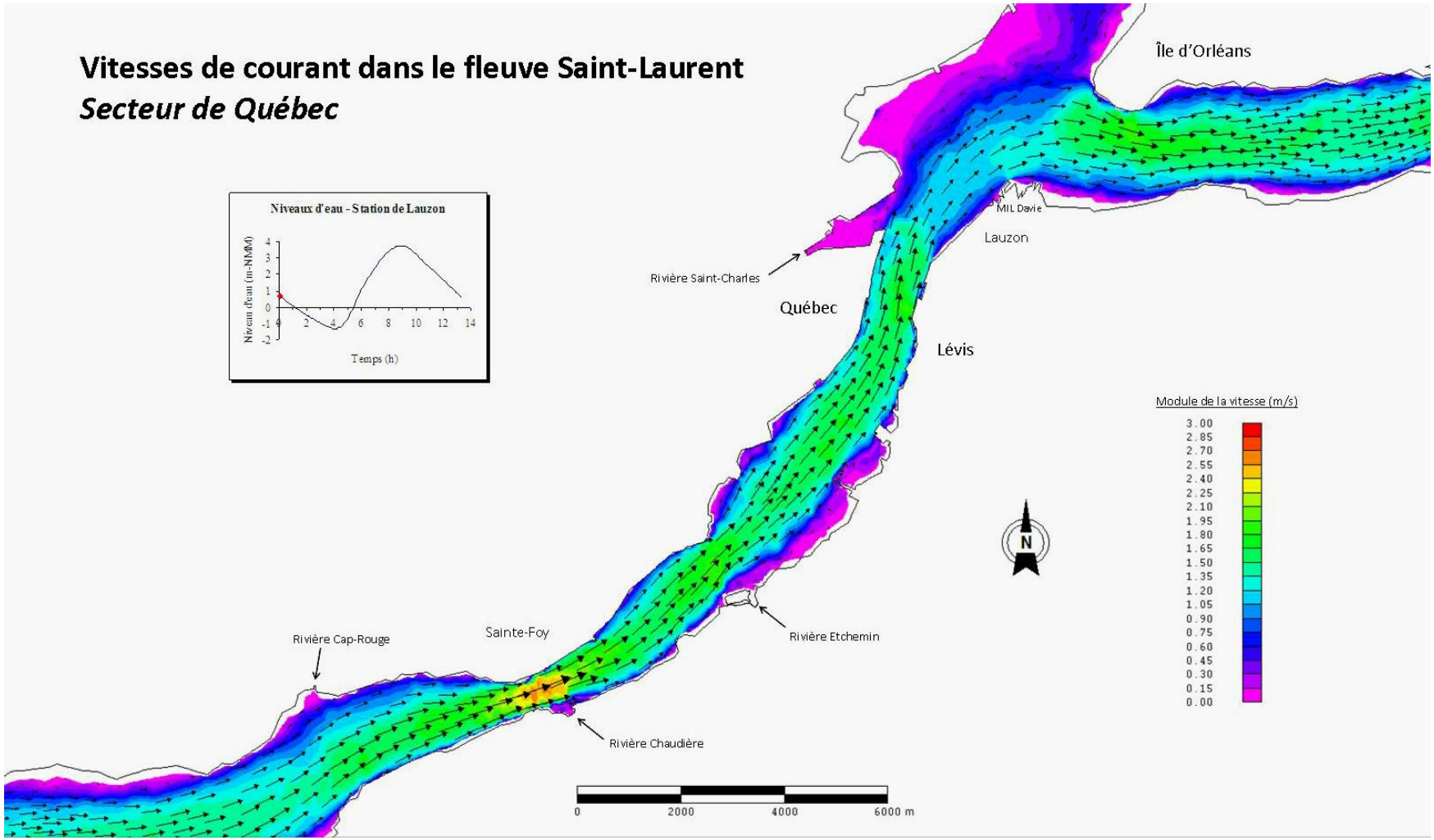


H2D2 finite element
hydrodynamic model
from Montreal to the
Gulf of St. Lawrence

Lake St. Pierre water extent and velocity, May 2013 - April 2014



Surface currents near Quebec City



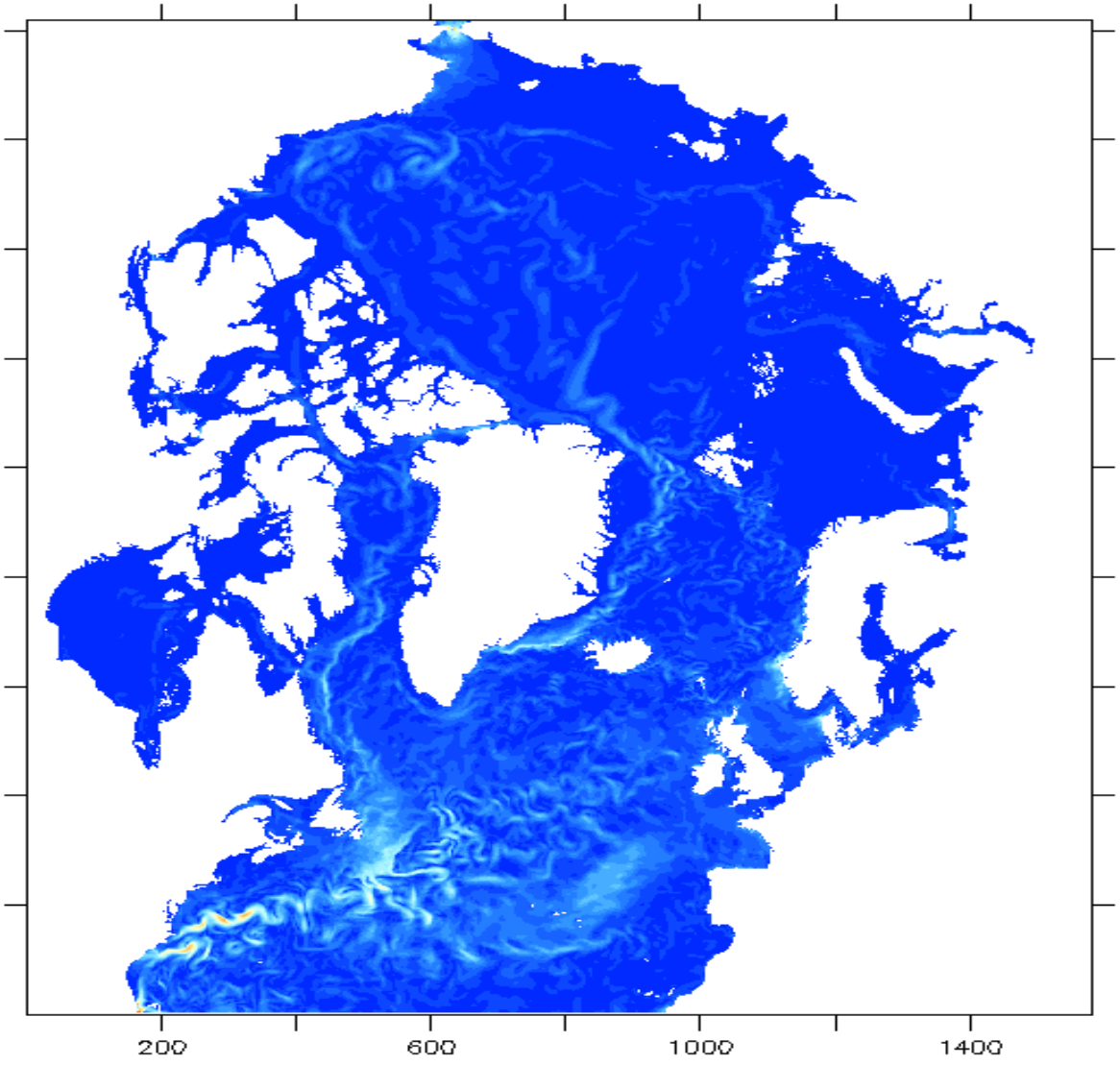
Advantages of using coupled environmental models

- Accuracy gains:
  - Capturing interactions between the atmosphere and the lakes, in particular in the presence of upwelling events and ice cover (Durnford et al., BAMS, 2017, submitted)
  - Tuning of the NWP model based on water supply and over-lake evaporation observations (Deacu et al., J. Hydrometeor., 2012)
- Consistency gains:
  - Evaporation and evapotranspiration are the same in the atmosphere, hydrology and lake models
- Efficiency gains:
  - Latency: environmental predictions are available at the same time as the weather forecast
  - Robustness: 24/7 support at almost no additional cost
  - Maintenance: a single land-surface model to maintain

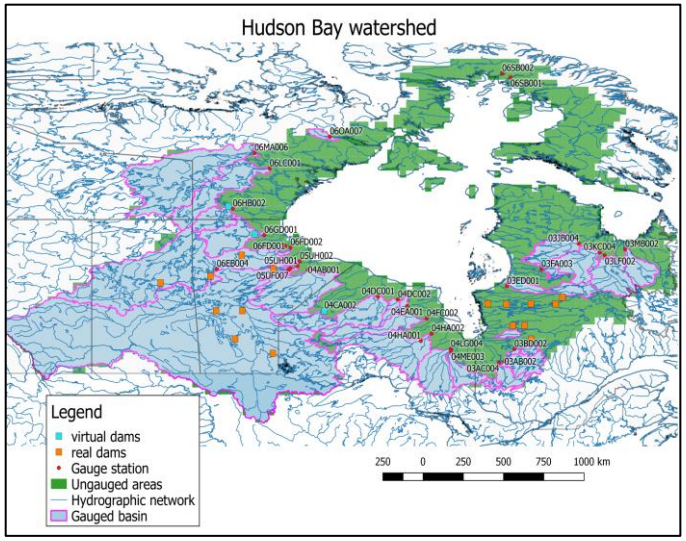
Next steps

- Deterministic system
  - increase resolution of atmospheric model component from 10-km to 2.5-km
  - increase resolution of lake model to hundreds of meters (TBD)
  - upgrade land-surface model (SVS) and land-data assimilation system (CaLDAS)
  - improved data assimilation of streamflow observations and lake levels (method TBD)
- Ensemble prediction system
  - increase lead time from 3.5 days to 30 days!
- Develop a similar system for the Arctic basin

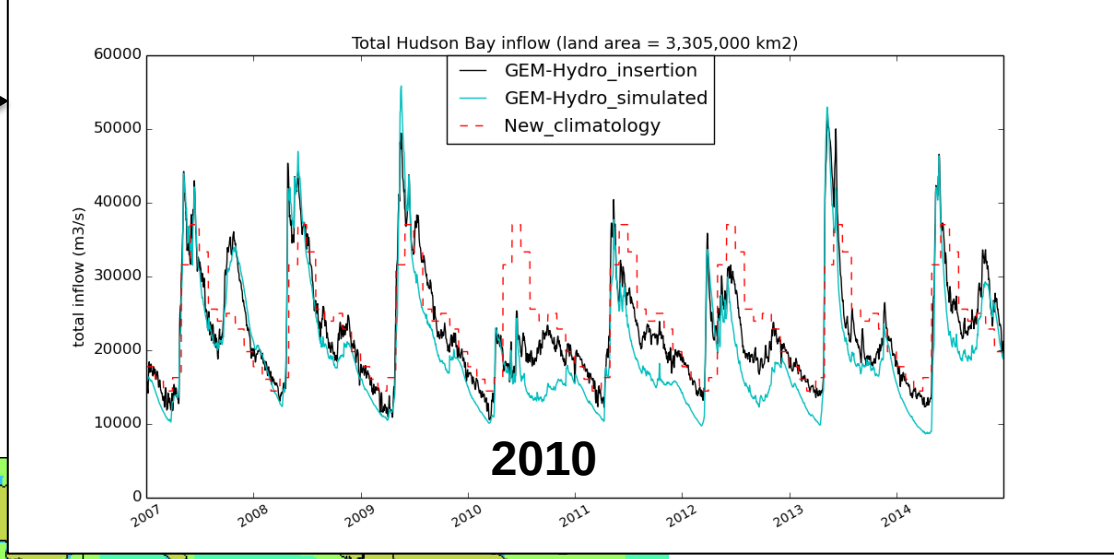
1/12° N. Atlantic and Arctic



Hudson Bay watershed



Total Hudson Bay Inflow



Changes in average salinity (PSU)