Using atmospheric models and land surface schemes for hydrological prediction (hindcasting and forecasting)

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P3: Putting PUB into Practice
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There might soon be no such thing as a truly ungauged basin

PERSIANN rainfall estimated from geostationary satellites

SMOS: surface soil moisture

Water storage anomalies from GRACE satellite
Modelling the atmosphere over your basin is easier than you think

- Landscape
  - Saskatchewan
  - Northern Territories
  - Toronto
  - Central Quebec

- Atmosphere
  - Saskatchewan
  - Northern Territories
  - Toronto
  - Central Quebec

05/13/11
Consider using atmospheric (re-)analysis products for your prediction problems

- Modern data-assimilation systems ingest massive amounts of data on the state of the atmosphere and provide physically-based gridded datasets which can be used for hydrological prediction.
- Real-time products with global or regional coverage as well as reanalysis products are available from many atmospheric prediction agencies around the world.
Outline

• EC's Numerical Weather Prediction System based on the GEM atmospheric model

• CaPA: a near real-time precipitation analysis system

• MESH: a framework for surface and hydrology prediction

• Using GEM, CaPA and MESH for predicting changes to water level in the Great Lakes basin

• Accessing GEM, CaPA and MESH (products and code)
Numerical weather prediction: Think globally, predict locally

The only (proven) method to forecast the weather for more than a few days is to forecast it everywhere.

This is done by running a numerical weather prediction model (NWP) from initial conditions estimated from observations of the earth's atmosphere, oceans, and land surface.
Numerical weather prediction: Think globally, predict locally

There are limits to what we can afford in terms of horizontal resolution: CMC: 33km for 10 days

But we can zoom on a region of interest using a limited-area model (LAM)
Numerical weather prediction: Think globally, predict locally

The Global Environmental Multiscale (GEM) model developed by Environment Canada is one of the few NWP models which can do both.
Deterministic forecasting

- Single estimate of initial conditions
- Single model
- Single forecast
- That does not mean a perfect forecast:
  - observations are uncertain and coverage is limited
  - numerical models are fairly simple approximations of the actual physical processes
  - computers have limited capacities

Uncertainty can be estimated from forecast errors (a posteriori)
Ensemble forecasting

- **Multiple**
  - initial conditions
  - numerical models
  - weather forecasts

- Ensemble forecasting aims to represent uncertainty dynamically

- Differences in forecasts should reflect uncertainty
  - in our estimates of initial conditions
  - in the limitations of our numerical models

Uncertainty can be estimated from divergence of forecasts (a priori)
Environment Canada's Deterministic forecasting systems

- **Global Deterministic Prediction System (GDPS)**
  - 10 days, 33 km horizontal resolution at mid latitudes
  - 2 runs per day

- **Regional Deterministic Prediction System (RDPS)**
  - North America (Canada + US + Mexico)
  - 2 days, 15 km horizontal resolution
  - 4 runs per day

- **High-Resolution Deterministic Prediction System (HRDPS)**
  - 1 day, 2.5 km horizontal resolution on smaller domains
  - 1 run per day
  - Currently: Quebec-Windsor corridor, Southern BC, Atlantic, Arctic
  - System can easily be run anywhere within the RDPS domain, and at higher resolutions given adequate computing power
Environment Canada's Ensemble forecasting systems

• Global Ensemble Prediction System (GEPS)
  – 15 days, 100 km horizontal resolution (soon 60 km)
  – 20 members in order to represent uncertainty in initial conditions and in GEM's physical parameterizations
  – 2 runs per day
  – Every ten days a 30-day forecast is made (experimental)

• Regional Ensemble Prediction System (REPS)
  – North America (Canada + US + Mexico)
  – 3 days, 15 km horizontal resolution
  – 20 members
  – 2 runs per day
12h precipitation accumulation
24h forecast valid on Mar 31, 2011 00 UTC

Verification:
Canadian Precipitation Analysis (CaPA)
Forecasts of the past are almost as useful as forecasts of the future!

• Environment Canada keeps outputs from its operational forecasting system for five years

• They provide a consistent estimate of the state of the atmosphere and of the land-surface

• Past forecasts can be combined with existing observations to obtain a better estimate than either forecasts or observations alone (data assimilation)

• The Canadian Precipitation Analysis (CaPA) is a simple example of what data assimilation can do in data-sparse regions for estimating precipitation in near real-time
CaPA: operational configuration

Precipitation network

Analysis valid at 12Z, 12 May 2011 combining observations with GEM model
24h accumulation shown here
6h and 24h accum. available

Short-term precip. forecast (6-12h), GEM model (RDPS)
Precipitation as seen by CaPA: April 2nd - 3rd, 2011
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Skill, bias and uncertainty in CaPA products

- Verifications against gauges are made through data-denial experiments
- Strict quality control for solid precipitation
  - bias correction algorithms currently being tested
  - for now we end up rejecting most automatic gauges in winter
- Confidence index based on kriging variance provided
Land surface models provide surface runoff and groundwater recharge, and include a parameterization for lateral flow along hillslope. Routing model includes surface runoff routing, river routing and baseflow estimation.

**Hydrological forecasting with MESH**

- **GEM Atmospheric model**
  - "On-line" mode
  - "Off-line" mode

- **Surface scheme**
  - CLASS 3.4 or ISBA

- **WATROUTE Routing model**

**Offline mode: forcing with short-term forecasts**
(with precipitation forecast replaced by an analysis)

**Community model, source code available upon request**
Soulis, Craig, Fortin et Liu (2011)
Hydrological Processes

4 feet
Using MESH on the Great Lakes to predict net basin supply

Grid cell size: ~ 225 km²
Land surface scheme: ISBA
Net basin supplies: component vs residual method

Net basin supplies (NBS)

Inflow from upper lake (I)

Outflow to lower lake (O)

Storage (S)

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

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

Component NBS makes it possible to gain understanding as to why lake levels are changing and (eventually) forecast these changes.
Objectives of the project

• Build a gridded dataset covering a 5-year period (June 2004 to May 2009) describing the spatial and temporal evolution of the watershed
  – contribute to explaining why lake levels dropped
• Assess whether it is possible using GEM and MESH to close the water balance of the Great Lakes on a monthly time scale, given the uncertainty in each term of the water balance
  – build confidence in the residual method for estimating NBS
  – compare components (especially P and E) to estimates from other sources (in particular GLERL)
• Assess whether it is possible using GEM and MESH to forecast net basin supplies
MESH - the movie:
November 1-20, 2008
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MESH “calibration”

- **REGO**: Initial results, GEM forcings from CMC archive
- **Resid**: Residual NBS (from lake levels)
**MESH “calibration”**

- **REGO:** Initial results, GEM forcings from CMC archive
- **CAPO:** CaPA methodology used to improve precip
- **Resid:** Residual NBS (from lake levels)

Lake Superior monthly Net Basin Supplies

Cumulative NBS
Verification of Overlake Evaporation

Eddy-correlation system

Verification of daily mean flux (June 2008 – January 2009)

Observations courtesy of Chris Spence, NWRI

Verification of half-hourly fluxes for December 2008: changes to operational configuration were required

ORIG: Parameterization used by Reg. GEM 15
EXP1: PRₜ changed from 0.85 to 1
EXP2: z₀H ≠ z₀M

Stable conditions

Unstable conditions

All cases

Observations courtesy of Chris Spence, NWRI
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Offline mode: forcing with short-term forecasts (with precipitation forecast replaced by an analysis).

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Lake Superior monthly Net Basin Supplies

Cumulative NBS
An additional trick for the final hindcast: streamflow nudging

- Simulated flows replaced by observations where there is a gauge
  - 169 locations across the basin, 2/3 of the basin
- Flows are still predicted by MESH for the ungauged portion of the watershed
  - including downstream of a gauge

Lake Superior monthly Net Basin Supplies

Cumulative NBS
MESH vs residual NBS: Superior and Michigan-Huron
MESH vs residual NBS: Erie and Ontario
How do GEM+MESH compare to a hindcast based on obs. alone?

GEM+MESH hindcast:
- Overlake precip:
  - short-term forecast (6-18h)
  - CaPA not helping much
- Overlake evaporation:
  - short-term forecast (6-18h)
- Runoff:
  - ISBA land-surface scheme
  - WATROUTE routing model
  - Streamflow nudging (optional, but does give better results)

GLERL hindcast (NOAA):
- Overlake precip:
  - Thiessen polygons using near-shore stations
- Overlake evaporation:
  - Empirical model based on observations of wind and temperature from near-shore stations
- Runoff:
  - Pro-rating by area of observed streamflow to estimate runoff from the whole watershed
MESH vs GLERL component NBS: Superior and Michigan-Huron
MESH vs GLERL component NBS: Erie and Ontario
Can errors be explained by uncertainty in atmospheric forcings?

- Probabilistic hydrological prediction:
  - Uncertainty in (deterministic) hindcast estimated from variability of day-1 ensemble forecasts of NBS
- 90% C.I. too often fails to cover the obs.
What difference does the land-surface model make?

- Both land-surface models available in MESH lead to confidence intervals of similar quality.
- Best results are obtained from multi-model ensemble.
Predicting daily flows

- 81 non-regulated gauged watersheds identified
Nash-Sutcliffe of daily mean flow (4 year verification period)

- Raw forecast
  - Hydrographs are too flashy

- After post-processing
  - Unit hydrograph calibrated based on 1st year of data

39 basins off the chart

14 basins off the chart

There is still room for improvement!
Access to Environment Canada's models, analyses and forecasts

- **Product guide:**

- **Images:** the Analysis & Modelling web page

- **Gridded forecasts:** the datamart

- **GEM model** and utilities for pre- and post-processing:

- **CaPA products (until the next update to weatheroffice):**

- **MESH model:**