Operational Flood Forecasting for Bangladesh using ECMWF ensemble weather forecasts

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Climate Forecast Applications for Bangladesh (CFAB):
USAID/CARE/ECMWF/FFWC/NASA/NOAA

Bangladesh Stakeholders: Bangladesh Meteorological Department, Bangladesh Water Development Board, Department of Agriculture Extension, Disaster Management Bureau, Institute of Water Modeling, Center for Environmental and Geographic Information Services, CARE-Bangladesh
SEASONAL OUTLOOK: “Broad brush” probabilistic forecast of rainfall and river discharge. Updated each month. Produced out to 6 months, currently most useful skill out 3 months.

20-25 DAY FORECAST: Forecast of average 5-day rainfall and river discharge 3-4 weeks in advance. Updated every 5 days.

1-10 DAY FORECAST: Forecast of rainfall and precipitation in probabilistic form updated every day. Considerable skill out to 5-days. Moderate skill 5-10 days.
Bangladesh background

- About 1/3 of land area floods the monsoon rainy season
- Size: roughly the size of UK (144,000 sq km)
- Border countries: Burma (193 km), India (4,053 km)
- Population: 140 million
- 36% of population below poverty line
- Within the top 5 of: poorest and most densely populated in the world

Natural disasters:
- Nov 1970 Bhola cyclone -- at least 300,000 died in 20 min (12m)
- April 1991 Bangladesh cyclone -- 138,000 died (6m)
- Nov 2007 Sidr cyclone -- 5-10,000 died
Damaging Floods:
- large peak or extended duration
- Affect agriculture: early floods in May, late floods in September

- 1998: 60% of country inundated for 3 months, 1000 killed, 40 million homeless, 10-20% total food production
- 2004: Brahmaputra floods killed 500 people, displaced 30 million, 40% of capitol city Dhaka under water
- 2007: Brahmaputra floods displaced over 20 million

(World Food Program)
2004 dry season river flows ...

... and during the July flooding event
Overview:
Bangladesh flood forecasting

I. CFAB History -- Sea-level impacts on flooding

II. 1-10 day Discharge Forecasting
   1. precipitation forecast bias removal
   2. multi-model river forecasting
   3. accounting for all error: weather and hydrologic errors

III. 2007 Floods and Warning System Pilot Areas
Sea Level Impacts

- Very flat topography
- Can changes in Bay of Bengal sea level height significantly affect river flooding over the whole country?
Ocean Dynamics Effecting Sea-Level in the Bay of Bengal

Indian Ocean Zonal Mode

Baroclinic Coastal Kelvin Wave

(results by Weiqing Han)
How important are (“forecastable”) interannual sea level variations (and climate change impacts) on country-wide extreme flooding events?

Approach: without extensive knowledge of river hydraulic properties, instead do simplified “scale analysis” (linearization) of the governing equation (“dynamic equation of gradually-varied flow”) to get approximate solution.

(Answer: effects impact river heights roughly 200km upstream, but *not* over the whole country)
Sea Level Impacts

Calculation: linearize the depth-integrated Navier-Stokes equation about the “normal depth” $D_n$

Results: exponential decrease of sea-level impacts with e-folding length $D_n / (3S_0) \approx 150 km$

- Backwater effects limited to lower third of country and bounded by roughly 30cm
- Severe flood years affect whole country, with water depth variations of $O(1m)$

=> Look at precipitation-driven effects on flooding

September 1998
Problems:

1. Limited warning of upstream river discharges
2. Precipitation forecasting in tropics difficult

Good forecasting skill derived from:
1. good data inputs: ECMWF weather forecasts, satellite rainfall
2. Large catchments => weather forecasting skill “integrates” over large spatial and temporal scales
3. Partnership with Bangladesh’s Flood Forecasting Warning Centre (FFWC) => daily border river readings used in data assimilation scheme
1) Rainfall Estimates

1) Rain gauge estimates: NOAA CPC and WMO GTS
0.5 X 0.5 spatial resolution; 24h temporal resolution
approximately 100 gauges reporting over combined catchment
24hr reporting delay

2) Satellite-derived estimates: Global Precipitation Climatology Project (GPCP)
0.25X0.25 spatial resolution; 3hr temporal resolution
6hr reporting delay
geostationary infrared “cold cloud top” estimates calibrated from SSM/I and
TMI microwave instruments

3) Satellite-derived estimates: NOAA CPC “CMORPH”
0.25X0.25 spatial resolution; 3hr temporal resolution
18hr reporting delay
precipitation rain rates derived from microwave instruments (SSM/I, TMI,
AMSU-B), but “cloud tracking” done using infrared satellites
Spatial Comparison of Precipitation Products

Monsoon season (Aug 1, 2004)
Indian subcontinent
Weather Forecasts for Hydrologic Applications

ECMWF example

• **Seasonal -- ECMWF System 3**
  - based on: 1) long predictability of ocean circulation, 2) variability in tropical SSTs impacts global atmospheric circulation
  - coupled atmosphere-ocean model integrations
  - out to 7 month lead-times, integrated 1Xmonth
  - 41 member ensembles, 1.125° X 1.125° (TL159L62), 130km

• **Monthly forecasts -- ECMWF**
  - “fills in the gaps” -- atmosphere retains some memory with ocean variability impacting atmospheric circulation
  - coupled ocean-atmospheric modeling after 10 days
  - 15 to 32 day lead-times, integrated 1Xweek
  - 51 member ensemble, 1.125° X 1.125° (TL159L62), 130km

• **Medium-range -- ECMWF EPS**
  - atmospheric initial value problem, SST’s persisted
  - 6hr - 15 day lead-time forecasts, integrated 2Xdaily
  - 51 member ensembles, 0.5° X 0.5° (TL255L40), 80km

Motivation for generating ensemble forecasts (weather or hydrologic):

⇒ a well-calibrated ensemble forecast provides a prognosis of its own uncertainty or level of confidence
Rule of Thumb:

-- Weather forecast skill (RMS error) increases with spatial (and temporal) scale

=> Utility of weather forecasts in flood forecasting increases for larger catchments

-- Logarithmic increase
Primary forecast boundary conditions shown in gold:

Ganges at Hardinge Bridge

Brahmaputra at Bahadurabad

3) Benefit: FFWC daily river discharge observations used in forecast data assimilation scheme (Auto-Regressive Integrated Moving Average model [ARIMA] approach)
Transforming (Ensemble) Rainfall into (Probabilistic) River Flow Forecasts

Above danger level probability 36%
Greater than climatological seasonal risk?
Daily Operational Flood Forecasting Sequence

Forecast Trigger: ECMWF forecast files
- Statistically corrected downscaled forecasts

Lumped Model Hindcast/Forecast Discharge Generation
- Calibrate model
  - Generate forecasts
  - Generate hindcasts

Distributed Model Hindcast/Forecast Discharge Generation
- Update soil moisture states and in-stream flows
  - Generate forecasts
  - Generate hindcasts

Multi-Model Hindcast/Forecast Discharge Generation
- Calibrate multi-model
  - Generate forecasts
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Discharge Forecast PDF Generation
- Generate forecasted model error PDF
- Convolve multi-model forecast PDF with model error PDF

Above-critical-level forecast probabilities transferred to Bangladesh
ECMWF 51-member Ensemble Precipitation Forecasts

5 Day Lead-time Forecasts
⇒ Lots of variability

2004 Brahmaputra Catchment-averaged Forecasts
- black line satellite observations
- colored lines ensemble forecasts
⇒ Basic structure of catchment rainfall similar for both forecasts and observations
⇒ But large relative over-bias in forecasts
Specific Necessity of Post-Processing Weather Forecasts for Hydrologic Forecasting Applications

- Hydrologic forecast model calibration can often implicitly remove biases in input weather variables (i.e. precipitation).

- However, if you use one product (i.e. satellite rainfall) to calibrate your hydrologic model, but use *more* than one product (i.e. satellite rainfall and numerical weather prediction rainfall) or weather forecasts at different lead-times (with different biases for each lead-time) to generate hydrologic forecasts, then biases *between* each product or forecast lead-time must be removed.

- This is because hydrologic model calibration cannot (implicitly) remove all biases of all input weather products simultaneously.
What do we mean by “calibration” or “post-processing”?

Post-processing has corrected:
• the “on average” bias
• as well as under-representation of the 2nd moment of the empirical forecast PDF (i.e. corrected its “dispersion” or “spread”)

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Probabilty

Basin Rainfall [mm]

obs

“bias”

Forecast PDF

“spread” or “dispersion”

calibration

Probabilty

Basin Rainfall [mm]

obs

Forecast PDF
Forecast Bias Adjustment
-done independently for each forecast grid
(bias-correct the whole PDF, not just the median)

In practical terms …
ranked forecasts
ranked observations
Bias-corrected Precipitation Forecasts

Original Forecast

Corrected Forecast

Brahmaputra Corrected Forecasts

=> Now observed precipitation within the “ensemble bundle”, and preserving spatial and temporal covariances
A Cautionary Warning about using Probabilistic Precipitation Forecasts in Hydrologic Modeling

(Importance of Maintaining Spatial and Temporal Covariances for Hydrologic Forecasting => one option: “Schaake Shuffle”)

River catchment A

ensemble1

ensemble2

ensemble3

QA same
For all 3 possible ensembles

Scenario for smallest possible QA? No.

Scenario for average QA? No.

Scenario for largest possible QA? No.
Rank Histogram Comparisons
(better but not perfect!)

Original

Brahmaputra Basin ECWMF Precipitation Rank Histogram
Rank of merged-GPCP/CMORPH/Raingage Obs Relative to Ensembles
1-6 day Ensemble Forecasts, May 1 - Oct 31, 2004

Adjusted

Brahmaputra Basin ECWMF Precipitation Rank Histogram
Rank of merged-GPCP/CMORPH/Raingage Obs Relative to Ensembles
1-6 day Rescaled Ensemble Forecasts, May 1 - Oct 31, 2004
Quantile Regression approach: maintaining skill no worse than “persistence” for non-Gaussian PDF’s (ECMWF Brahmaputra catchment Precipitation)

“Multi-model” statistical approach applied to NCAR’s WRF mesoscale ensemble forecasts
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**Updated TRMM-CMORPH-CPC precipitation estimates**

**Updated outlet discharge estimates**

**Updated distributed model parameters**

**Distributed Model Hindcast/Forecast Discharge Generation**
- Update soil moisture states and in-stream flows
- Generate forecasts
- Generate hindcasts
- Calibrate AR error model

**Multi-Model Hindcast/Forecast Discharge Generation**
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**Above-critical-level forecast probabilities transferred to Bangladesh**
Discharge Multi-Model Forecast

Multi-Model-Ensemble Approach:

• Rank models based on historic residual error using current model calibration and “observed” precipitation

• Regress models’ historic discharges to minimize historic residuals with observed discharge

• To avoid over-calibration, evaluate resultant residuals using Akaike Information Criteria (AIC)

• If AIC minimized, use regression coefficients to generate “multi-model” forecast; otherwise use highest-ranked model => “win-win” situation!
2003 Model Comparisons for the Ganges (4-day lead-time)

hydrologic lumped model

hydrologic distributed model

Resultant Hydrologic multi-model
Multi-Model Forecast Regression Coefficients

- Lumped model (red)
- Distributed model (blue)

- Significant catchment variation
- Coefficients vary with the forecast lead-time
- Representative of each basin’s hydrology
  -- Ganges slower time-scale response
  -- Brahmaputra “flashier”
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Above-critical-level forecast probabilities transferred to Bangladesh
Significance of Weather Forecast Uncertainty
Discharge Forecasts

Precipitation Forecasts

Discharge Forecasts
**Producing a Reliable Probabilistic Discharge Forecast**

**Step 1:** generate discharge ensembles from precipitation forecast ensembles ($Q_p$):

**Step 2:** a) generate multi-model hindcast error time-series using precip estimates; b) conditionally sample and weight to produce empirical forecasted error PDF:

- a) Residuals
  - forecast horizon
  - time
  
- b) PDF

**Step 3:** combine both uncertainty PDF’s to generate a “new-and-improved” more complete PDF for forecasting ($Q_f$):
Significance of Weather Forecast Uncertainty
Discharge Forecasts

2004 Brahmaputra Discharge Forecast Ensembles

Corrected Forecast Ensembles
2004 Brahmaputra Forecast Results

Confidence Intervals

- 50%
- 95%

Above-Critical-Level Cumulative Probability

Days: 7 day, 8 day, 9 day, 10 day

Days: 7 day, 8 day, 9 day, 10 day
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Five Pilot Sites chosen in 2006 consultation workshops based on biophysical, social criteria:

- **Rajpur Union**
  - 16 sq km
  - 16,000 pop.

- **Uria Union**
  - 23 sq km
  - 14,000 pop.

- **Kaijuri Union**
  - 45 sq km
  - 53,000 pop.

- **Gazirtek Union**
  - 32 sq km
  - 23,000 pop.

- **Bhekra Union**
  - 11 sq km
  - 9,000 pop.

**Average Damage (Tk.) per Household in Pilot Union**

- **Uria**: 7,255
- **Gazirtek**: 28,745
- **Kaijuri**: 60,993
- **Rajpur**: 64,000
- **Bhekra**: 4058

**Legend**
- Union
- Thana
- District
- Rivers

*Prepared by: CEGIS Center for Environmental & Geographic Information Services.*
5.2 July/August 2007 floods in Bangladesh

“Seven people had died and thousands have been forced to leave their homes in Bangladesh because of worsening floods. Officials said that nearly half a million people remained marooned in seven flood-hit districts in the country’s north west and in the south.” (8 August 2007, from http://news.bbc.co.uk).
2007 Brahmaputra Ensemble Forecasts and Danger Level Probabilities

7-10 day Ensemble Forecasts

7-10 day Danger Levels
5.2 2007 floods in Bangladesh – fcs for 24/07-26/07

The right figure shows the 144/192h (left) and 192/240h (right) fc probabilities of 48h-accumulated rainfall in excess of 40 (top) and 80 (bottom) mm (CI 5/10/20/30/40/60/110%).

The left 1-panel figure shows a 0/48h TL399L91 forecast (CI 25/40/80/160/320mm).
Community level decision responses for 2007 flood forecasts (High lands)

- Protected homestead vegetables by creating adequate drainage facilities

- Livestock was protected in high lands with additional dry fodder (paddy straw)

- Early harvesting of B.aman rice and jute anticipating floods in Gaibandha and Sirajganj, respectively.

Selvaraju (ADPC)
Community level decision responses for 2007 flood forecasts (Low lands)

- Secured cattle, poultry birds, homestead vegetables, protected fishery by putting nets in advance

- Planed to evacuate and identified high grounds with adequate communication and sanitation facilities
Community level decision responses for 2007 flood forecasts (Low lands)

“… on 25th July we started communicating the information to as many people as possible … especially those people living in river islands (“chars”)…”

“On the 28th and 29th, meetings were organized in villages near Rangpur … they perceived that the river water level would fall, but our forecasts showed a rising trend…[with] significant chance of overflow and breaches [of weak] embankments … We engaged … an evacuation plan urgently”

“We communicated the forecast to another pilot union … on July 26th … to mobilize resources for evacuation … All the six villages in the union were later flooded to a height of 4-6 feet on July 29th… about 35% of the people in the union were evacuated in advance.”

“The communities in Rajpur Union … were able to use the forecast for … mobilizing food, safe drinking water for a week to 10 days, protecting their … rice seedlings, fishing nets, and … fish pods.”
Conclusions

2003: CFAB forecast went operational

2004:
-- Multimodel Forecasts fully-automated
-- CFAB became an entity of Bangladesh government
-- forecasted severe Brahmaputra flooding event

2006:
-- Forecasts incorporated into operational FFWC model
-- 5 pilot study dissemination areas trained

2007: 5 pilot areas warned many days in-advance during two severe flooding events

2008-2009:
-- Ongoing expansion of the warning system
-- Ongoing technological improvements
However, however, effects of aerosols could be important

=> Black carbon has caused decreased monsoon rainfall in 20th century
Thank You!