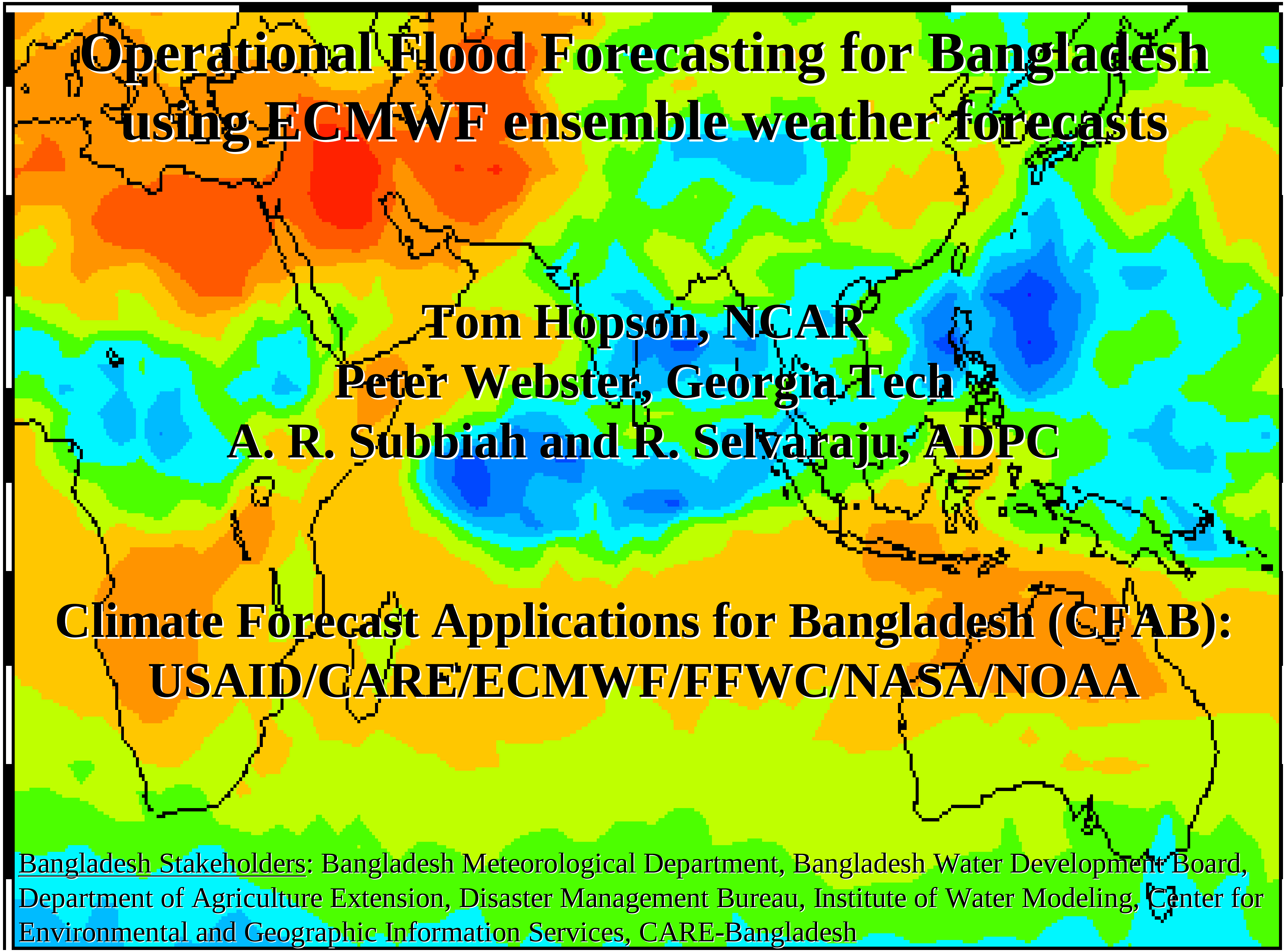

Operational Flood Forecasting for Bangladesh using ECMWF ensemble weather forecasts

Tom Hopson, NCAR
Peter Webster, Georgia Tech
A. R. Subbiah and R. Selvaraju, ADPC

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

Three-Tier Overlapping Forecast System Developed for 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.

Asia

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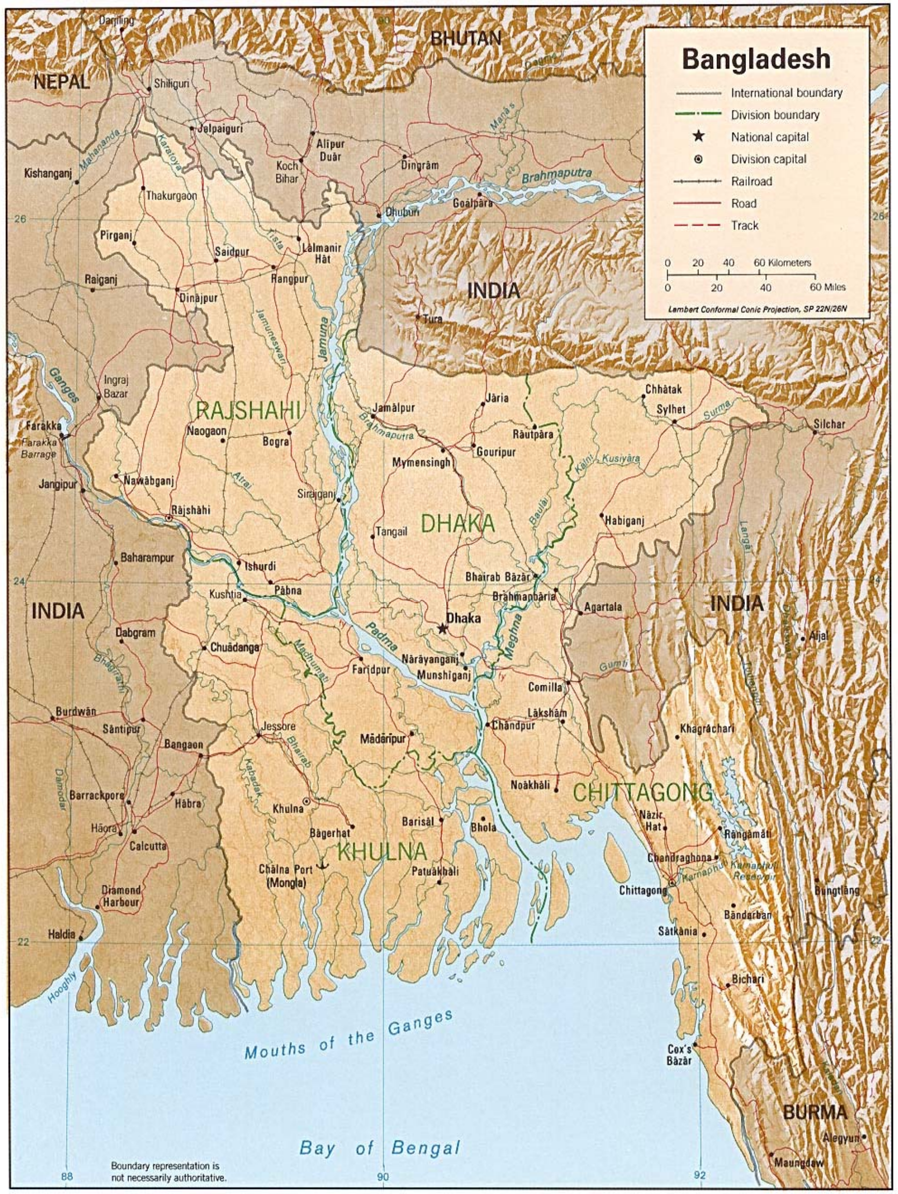
Bangladesh



Base 802491 (544488) 5-96

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

<u>Natural disasters:</u>

- 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

River Flooding

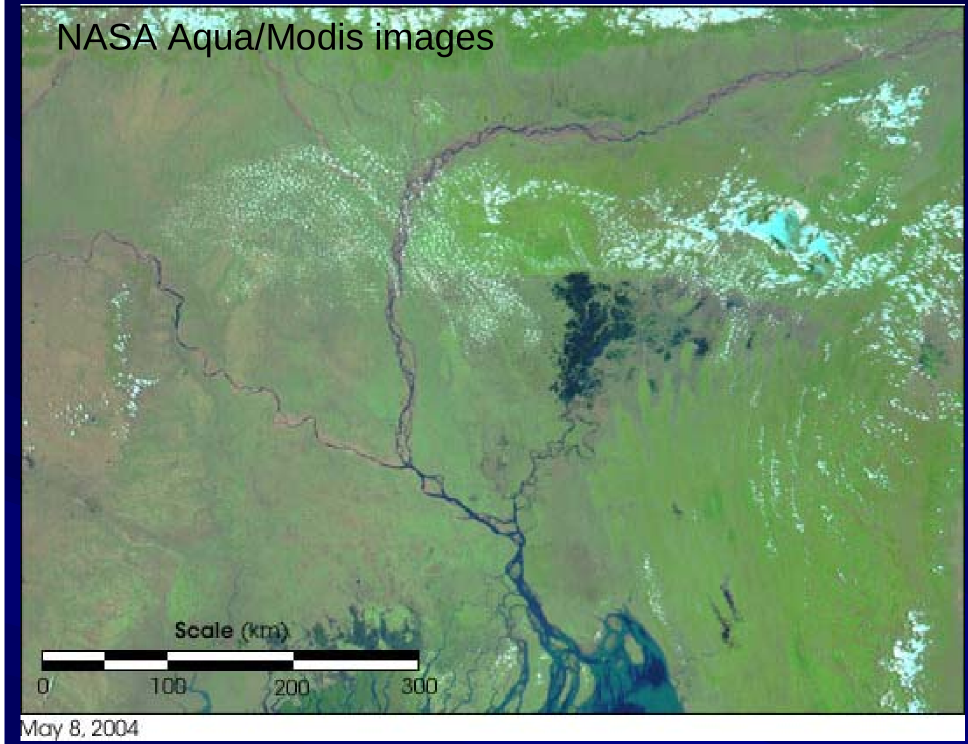
Damaging Floods:

- **large peak or extended duration**
- **Affect agriculture: early floods in May, late floods in September**

Recent severe flooding: 1974, 1987, 1988, 1997, 1998, 2000, 2004, and 2007

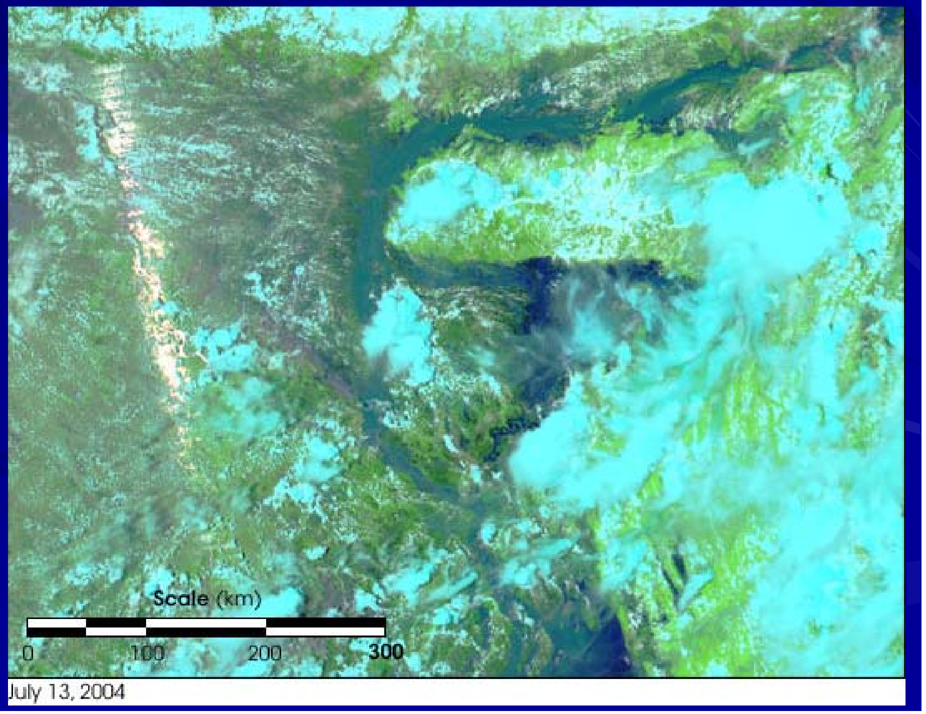
- **1998: 60% of country inundated for 3 months, 1000 killed, 40 million homeless, 10-20% total food production**
- **2004: Brahmaputra floods killed 500 people, displaced 30 million, 40% of capitol city Dhaka under water**
- **2007: Brahmaputra floods displaced over 20 million**

(World Food Program)



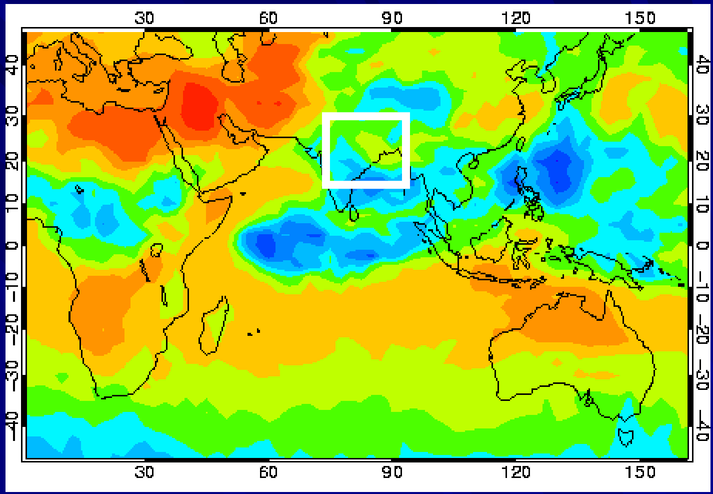
2004 dry season river flows …

… 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

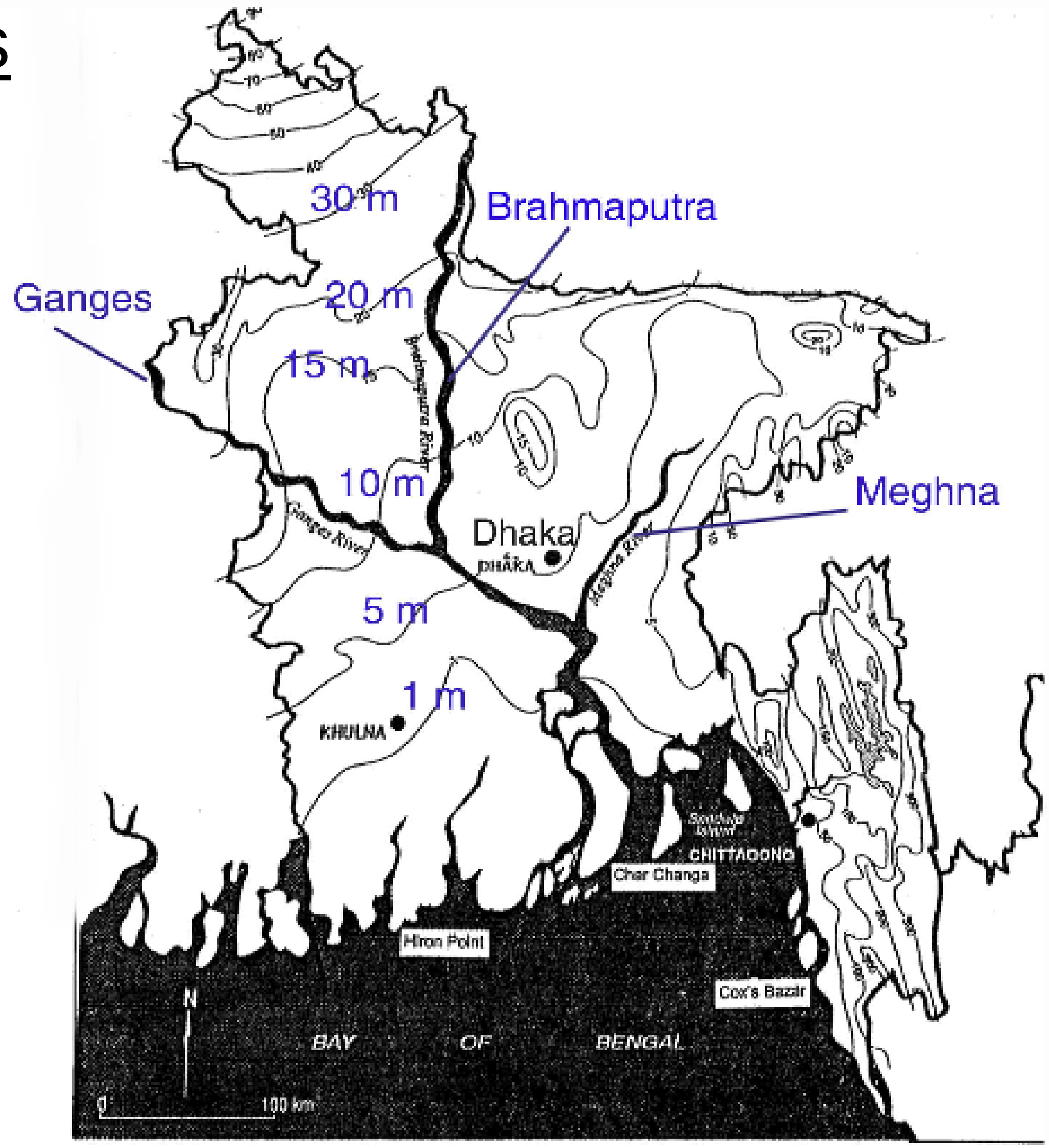
III. 2007 Floods and Warning System Pilot Areas

Topography of Bangladesh

Sea Level Impacts

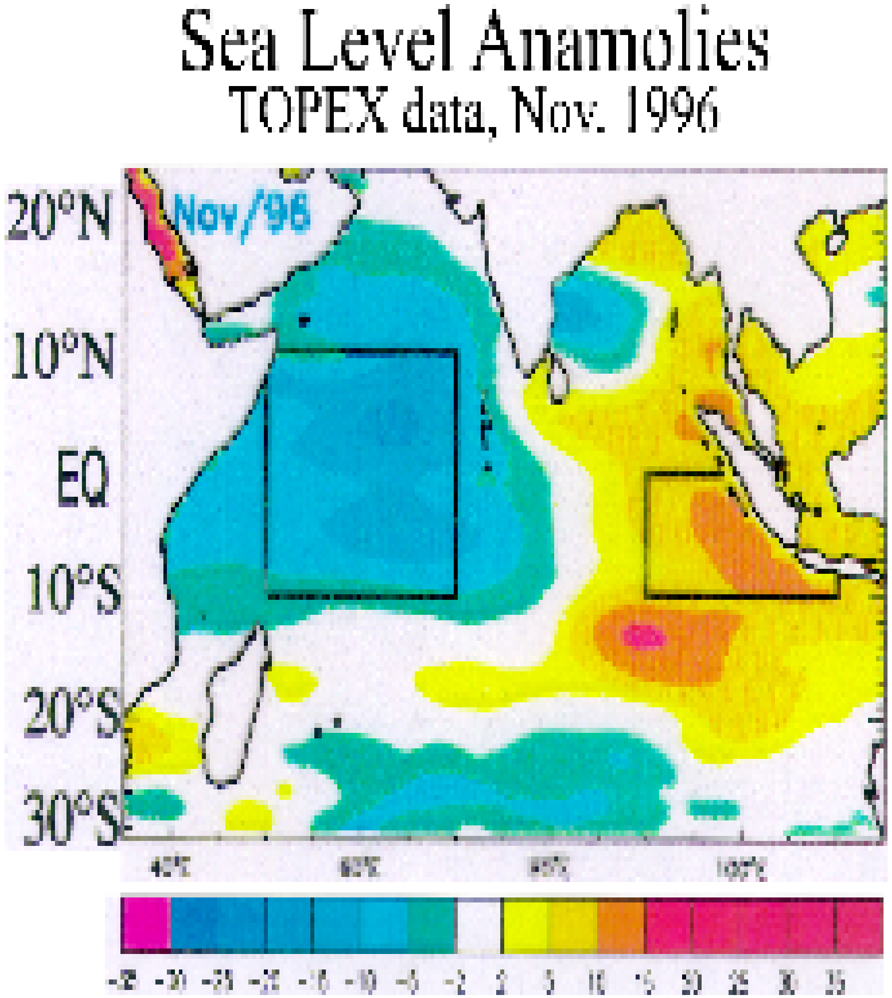
-Very flat topography

-Can changes in Bay of Bengal sea level height significantly affect river flooding over the whole country?

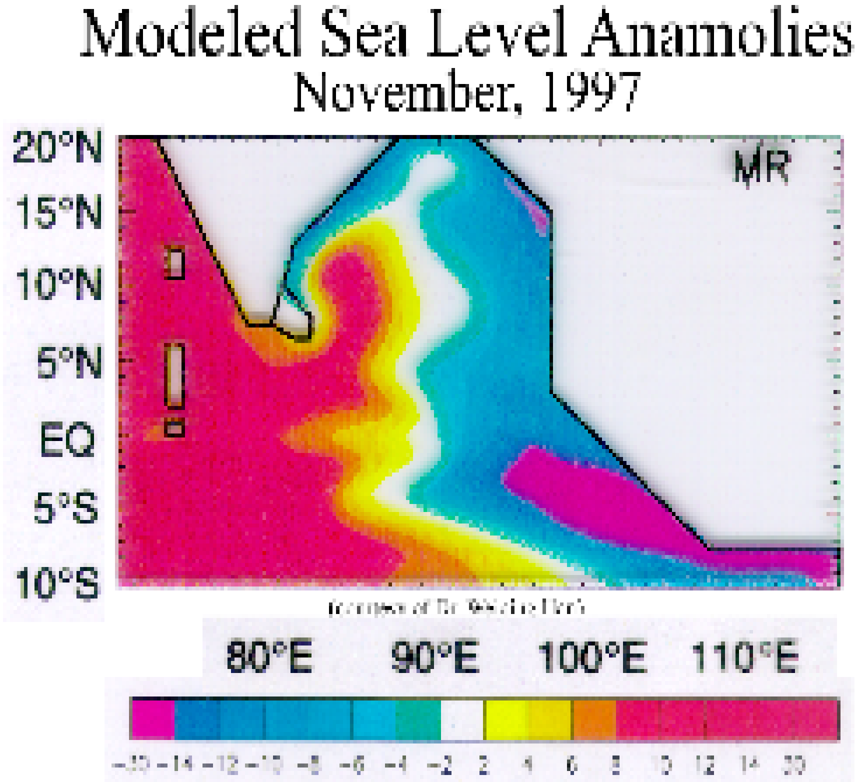


Ocean Dynamics Effecting Sea-Level in the Bay of Bengal

Indian Ocean Zonal Mode

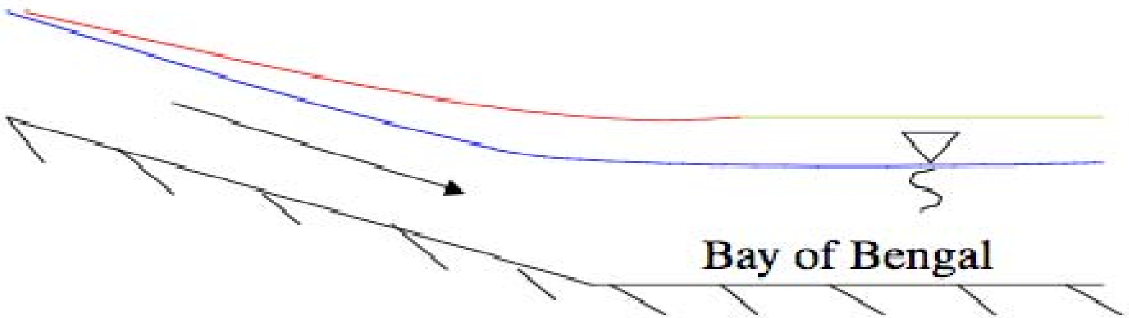


Baroclinic Coastal Kelvin Wave



(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

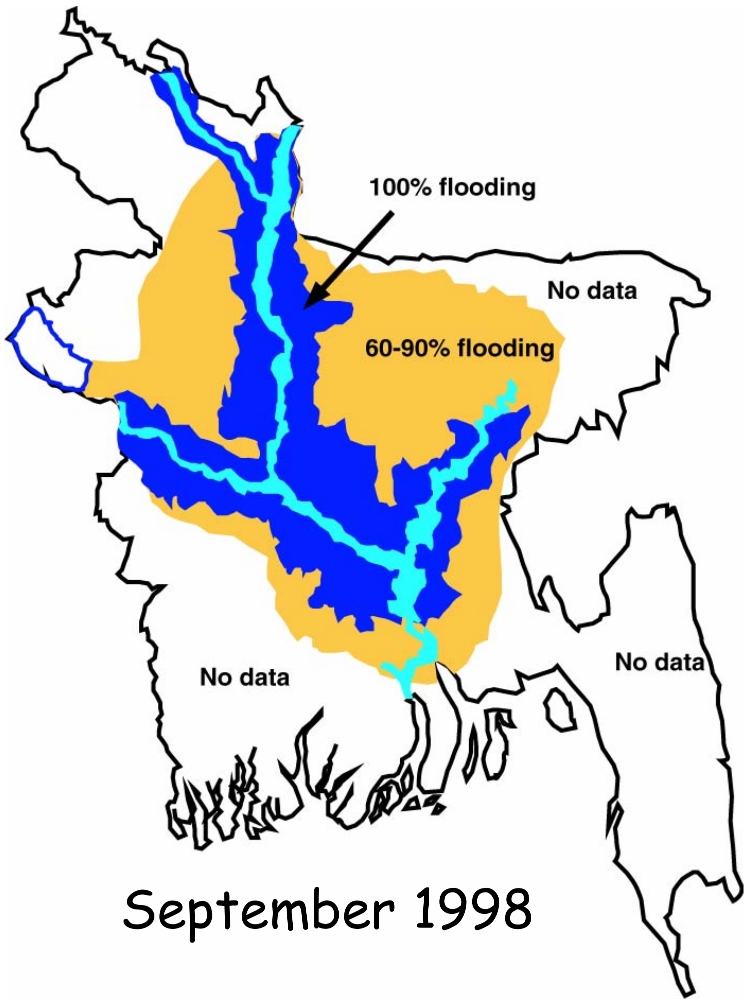
Calculation: linearize the depth-integrated Navier-Stokes equation about the "normal depth" D_n

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

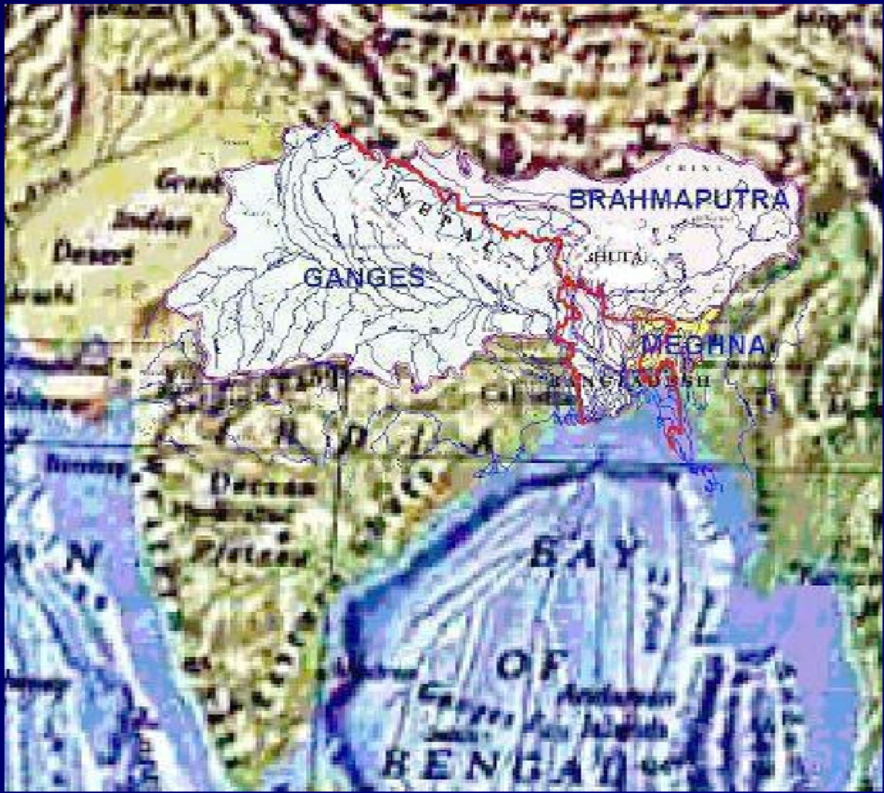
- Backwater effects limited to lower third of country and bounded by roughly 30cm
- Severe flood years affect whole country, with water depth variations of O(1m)

=> Look at precipitation-driven effects on flooding

disasterous flood year



CFAB Project: Improve flood warning lead time



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

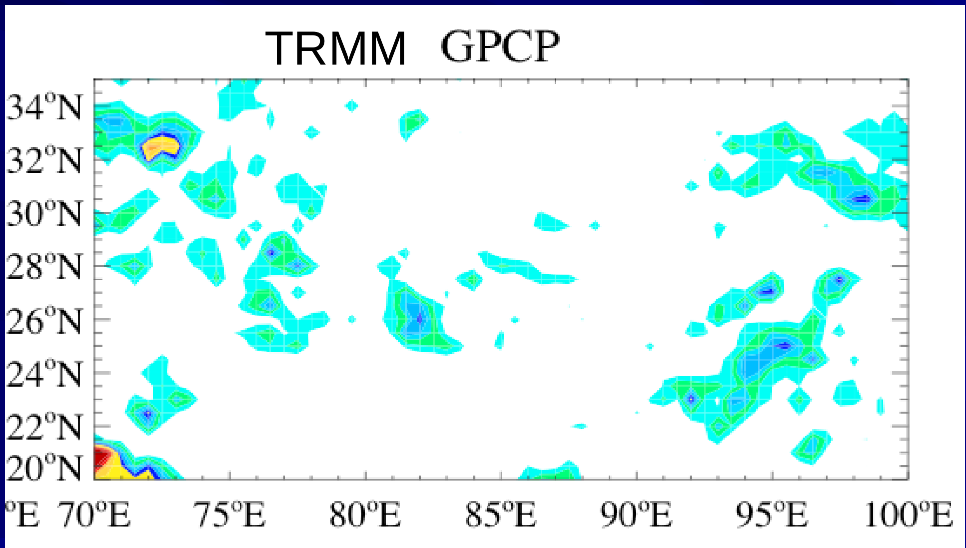
1) Rain gauge estimates: NOAA CPC and WMO GTS
   0.5 X 0.5 spatial resolution; 24h temporal resolution
   approximately 100 gauges reporting over combined catchment
   24hr reporting delay

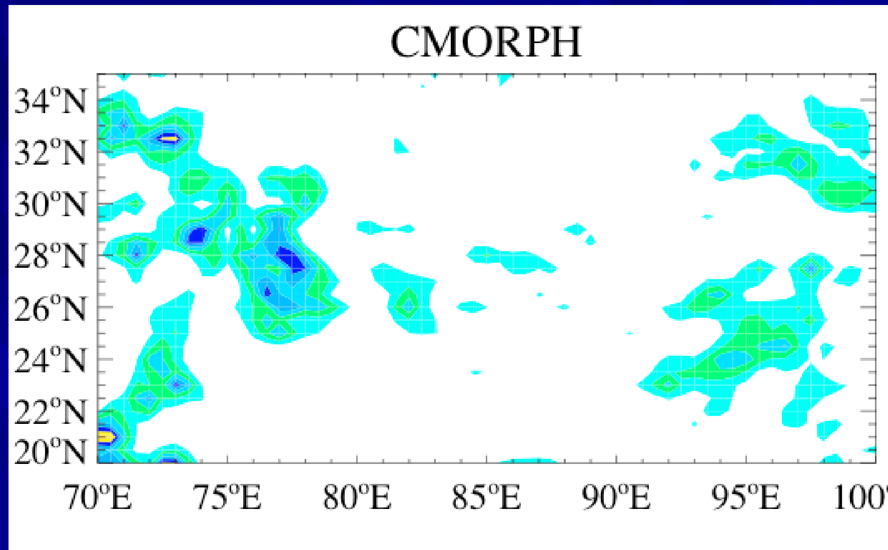
2) Satellite-derived estimates: Global Precipitation Climatology Project (GPCP)
   0.25X0.25 spatial resolution; 3hr temporal resolution
   6hr reporting delay
   geostationary infrared “cold cloud top” estimates calibrated from SSM/I and TMI microwave instruments

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^{o} X 1.125^{o} (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^{o} X 1.125^{o} (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^{o} X 0.5^{o} (TL255L40), 80km

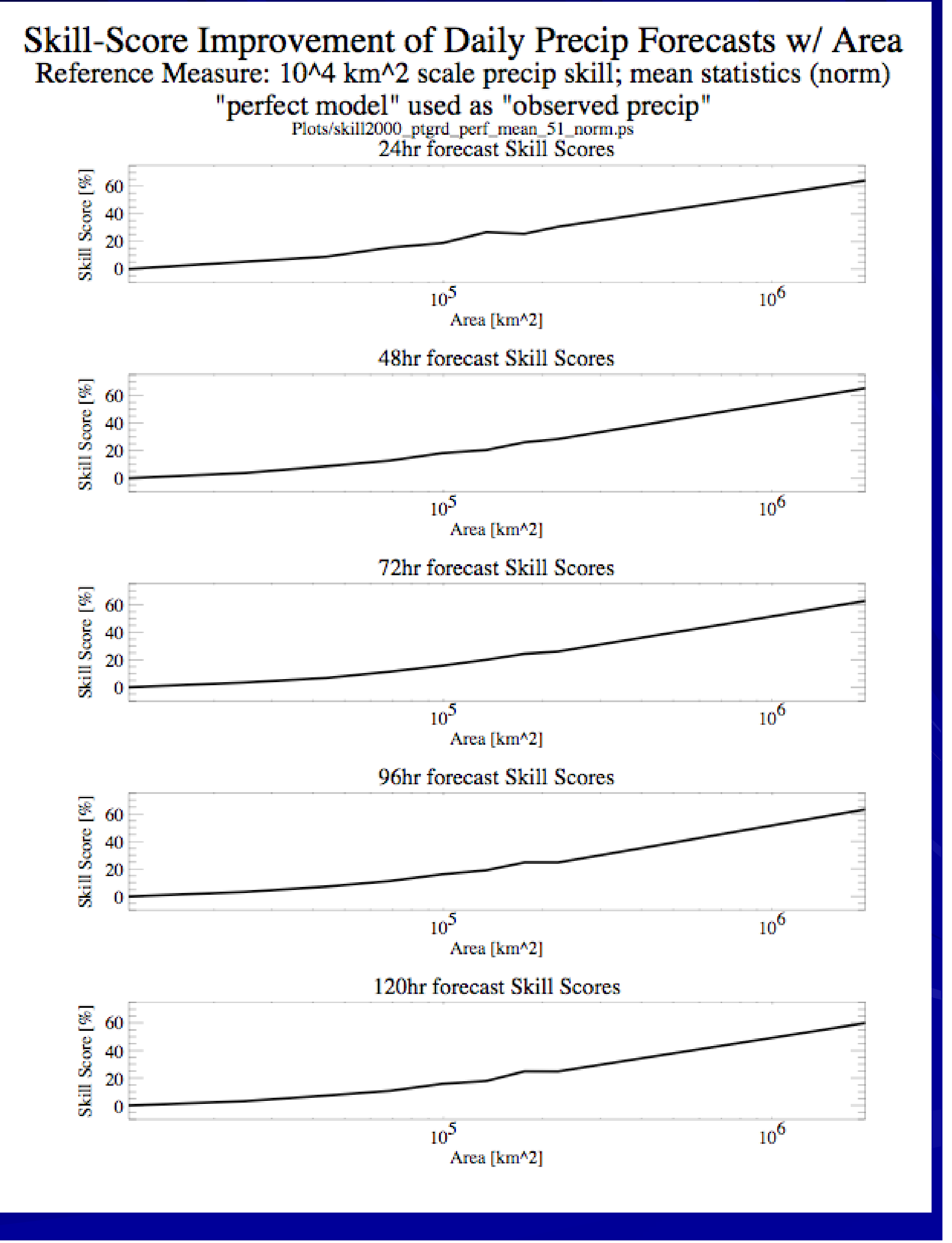
Motivation for generating ensemble forecasts (weather or hydrologic):
$\Rightarrow$ a well-calibrated ensemble forecast provides a prognosis of its own uncertainty or level of confidence

Rule of Thumb:

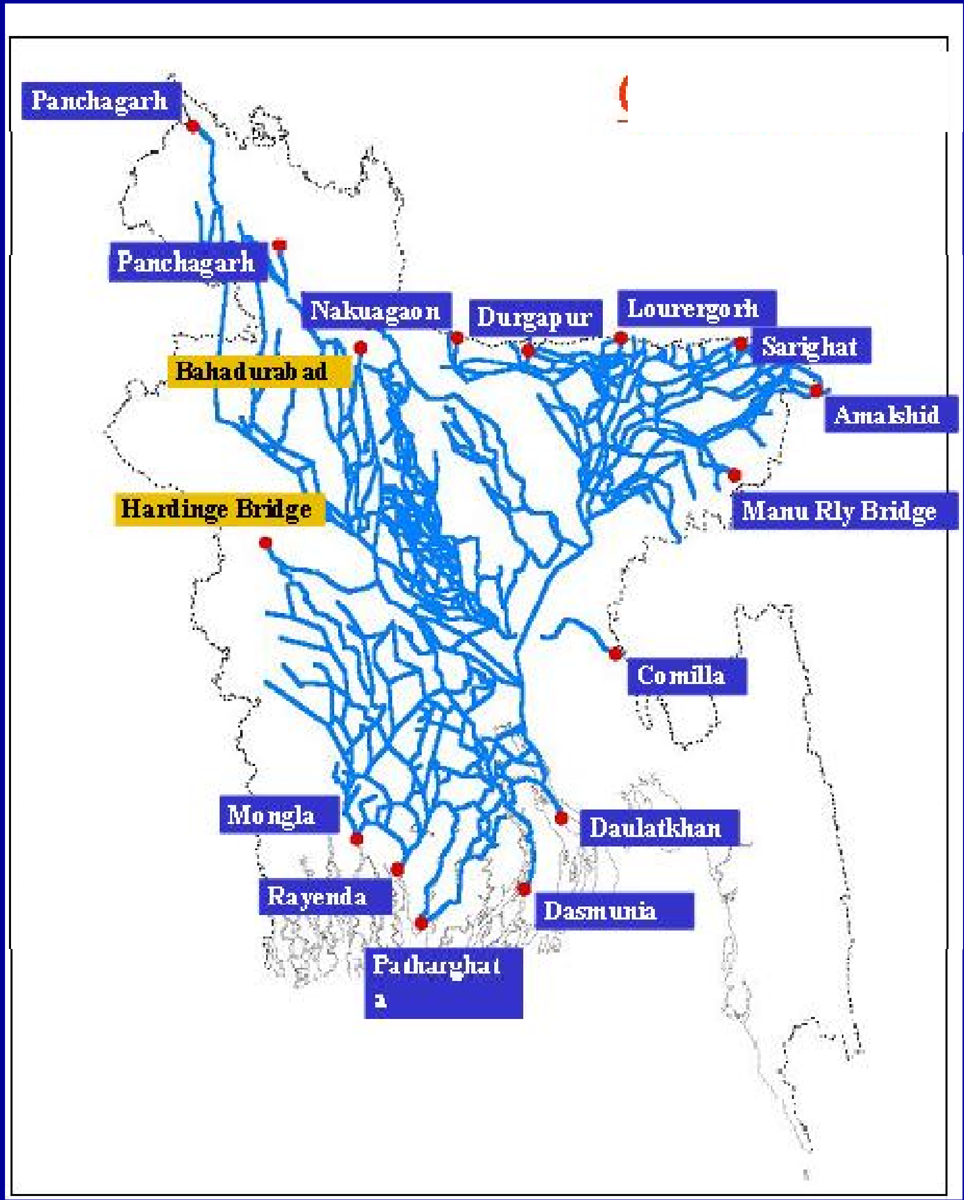
-- Weather forecast skill (RMS error) increases with spatial (and temporal) scale

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

-- Logarithmic increase



Merged FFWC-CFAB Hydraulic Model Schematic



Primary forecast boundary conditions shown in gold:

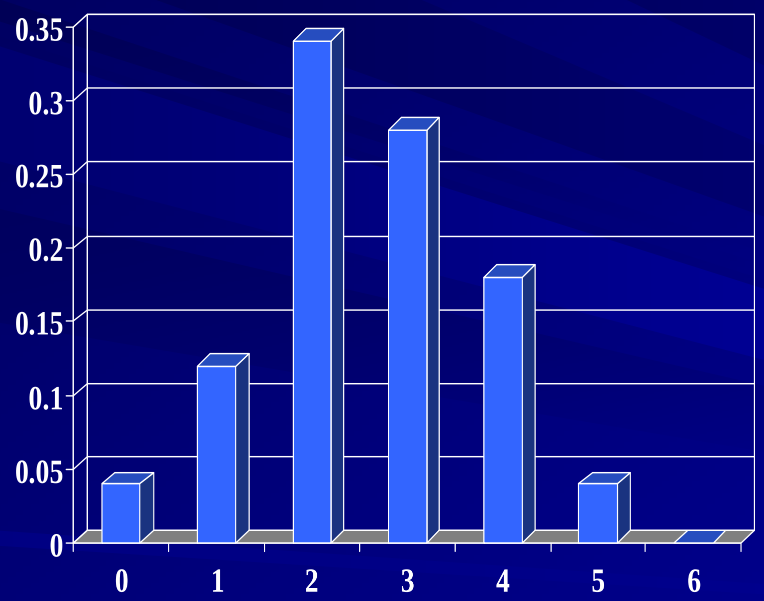
Ganges at Hardinge Bridge

Brahmaputra at Bahadurabad

<u>3) Benefit:</u> FFWC daily river discharge observations used in forecast data assimilation scheme (Auto-Regressive Integrated Moving Average model [ARIMA] approach)

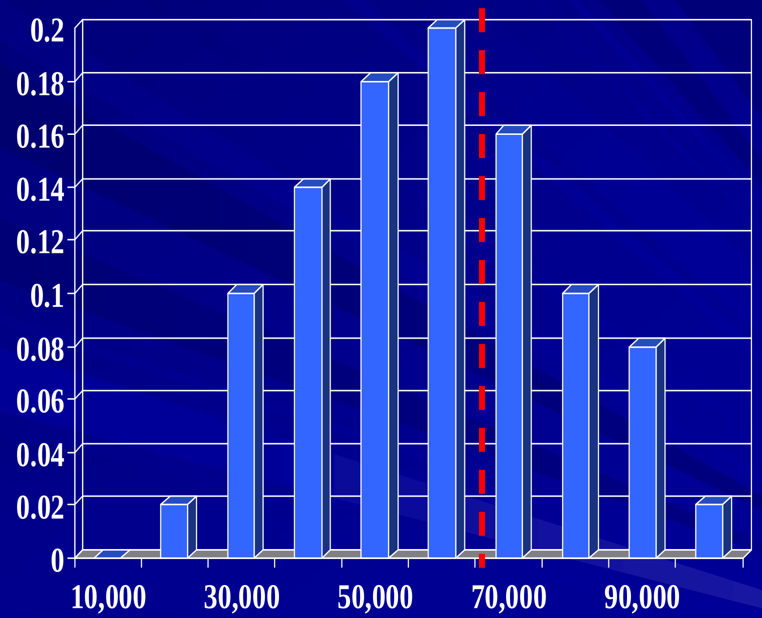
Transforming (Ensemble) Rainfall into (Probabilistic) River Flow Forecasts

Rainfall Probability



Rainfall [mm]

Discharge Probability

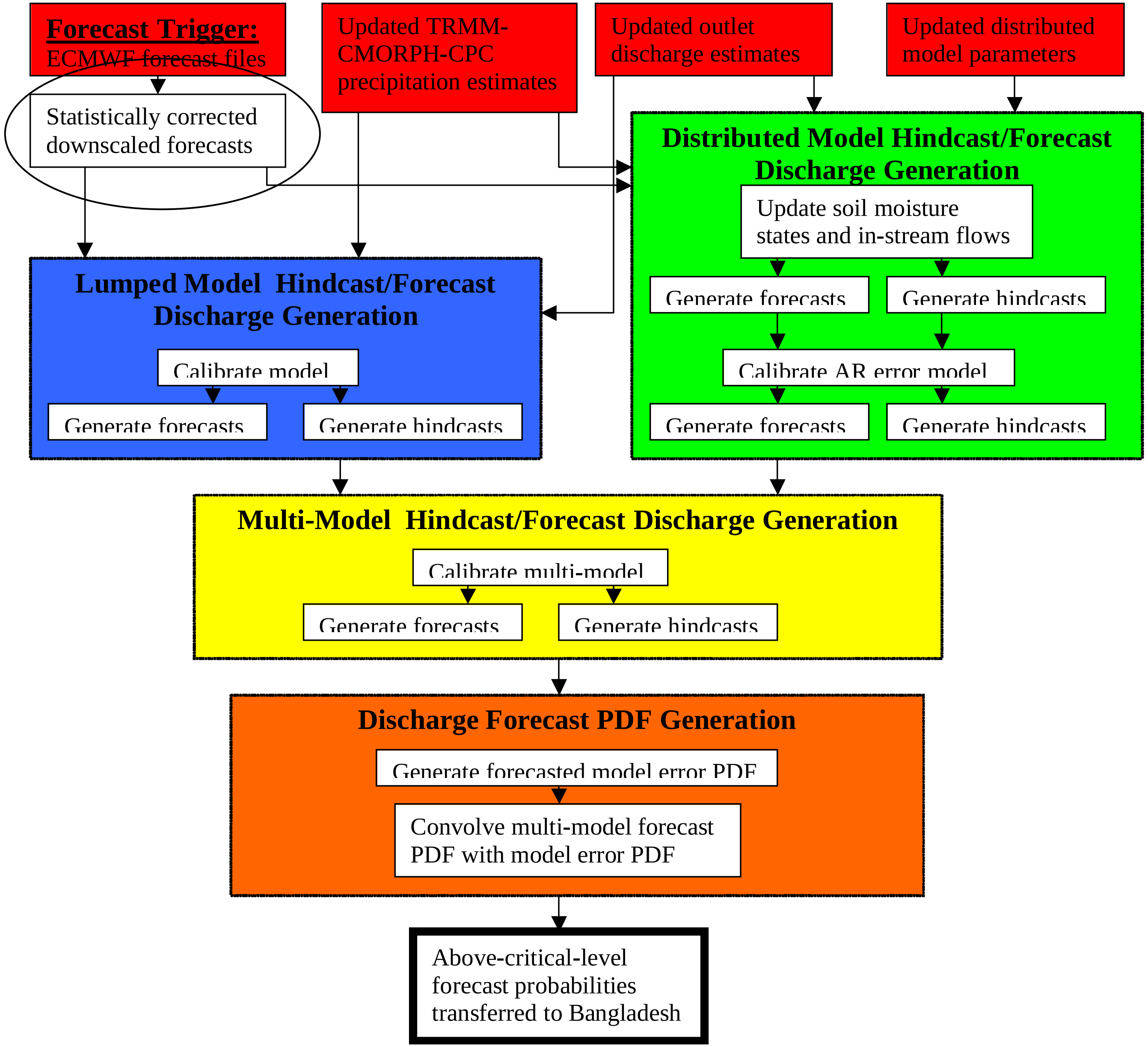


Discharge [m^3/s]

Above danger level probability 36%

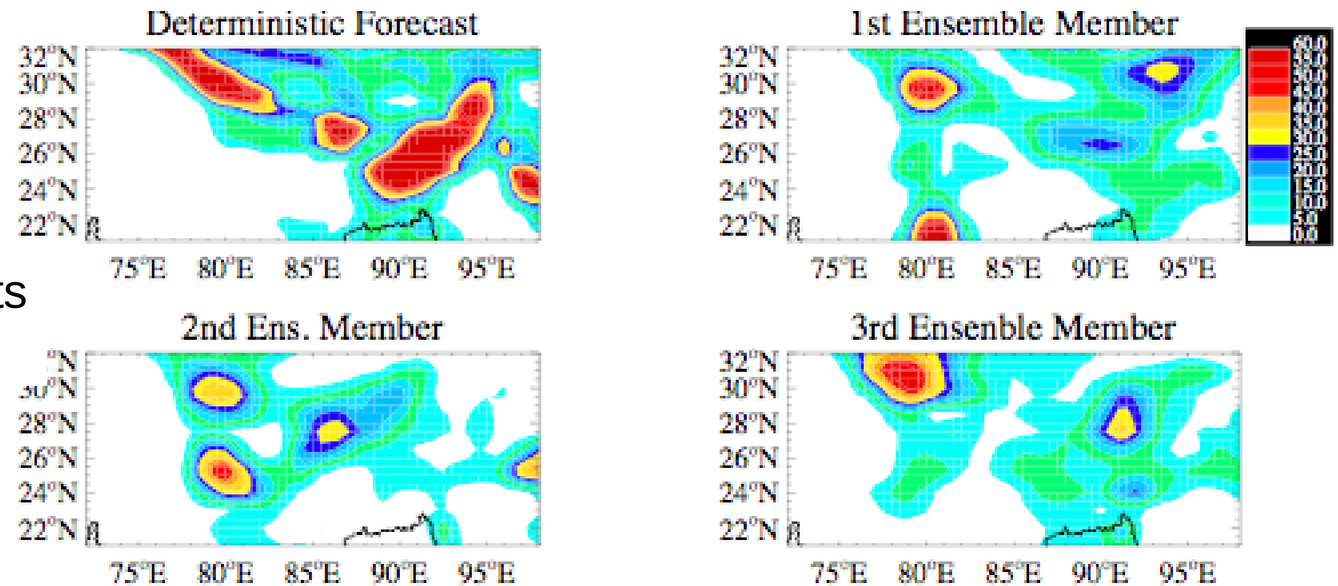
Greater than climatological seasonal risk?

Daily Operational Flood Forecasting Sequence



ECMWF 51-member Ensemble Precipitation Forecasts

5 Day Lead-time Forecasts
=> Lots of variability



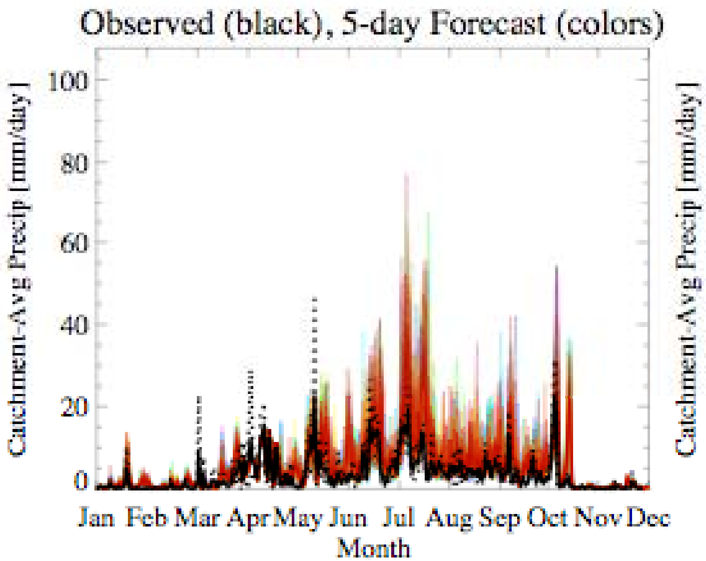
<u>2004 Brahmaputra Catchment-averaged Forecasts</u>

-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



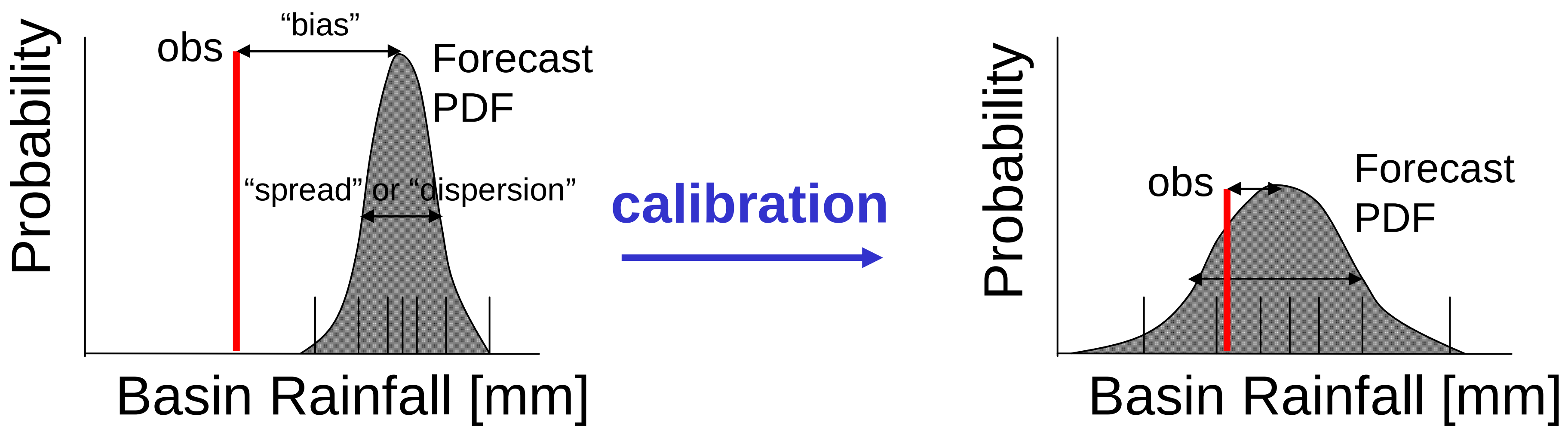
Specific Necessity of Post-Processing Weather Forecasts for Hydrologic Forecasting Applications

- 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”?



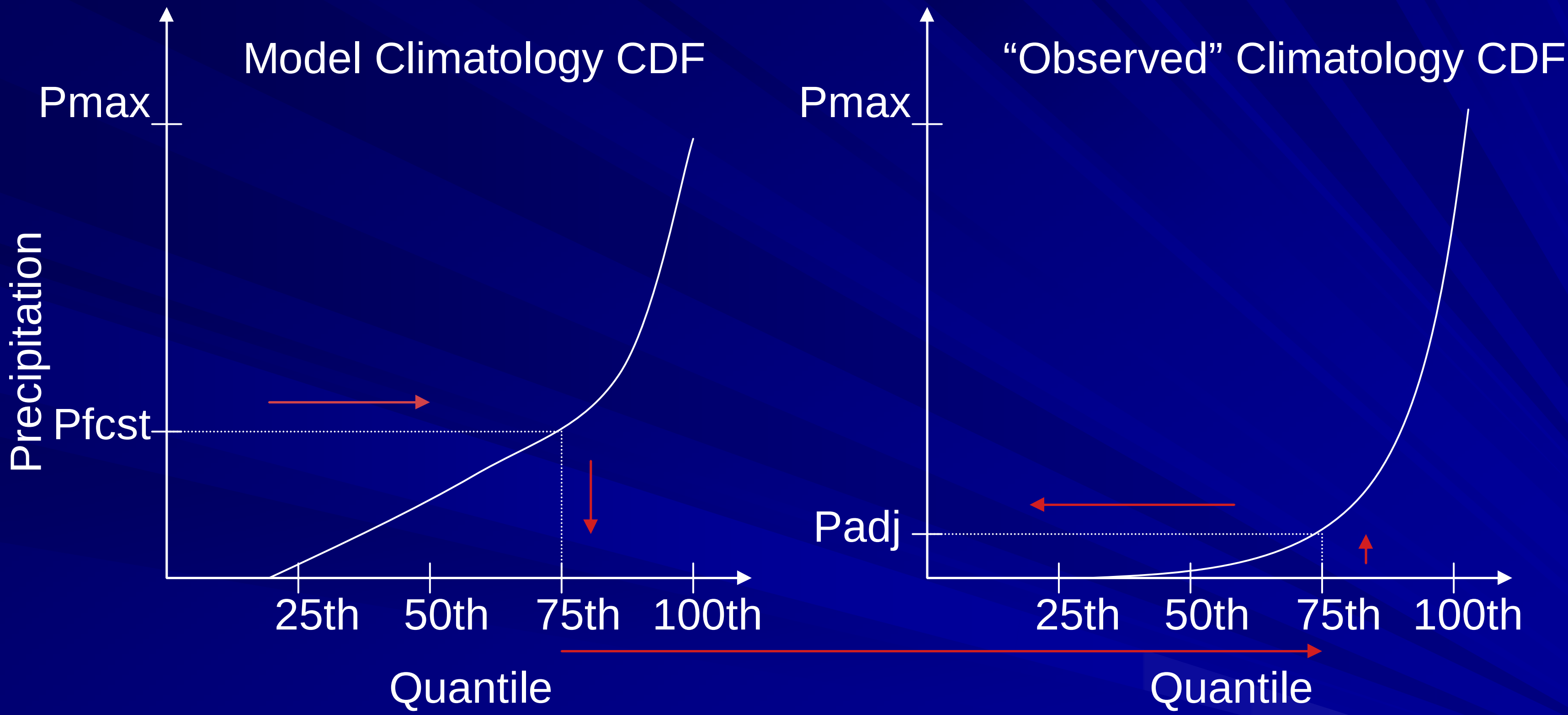
<u>Post-processing has corrected:</u>

- 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”)

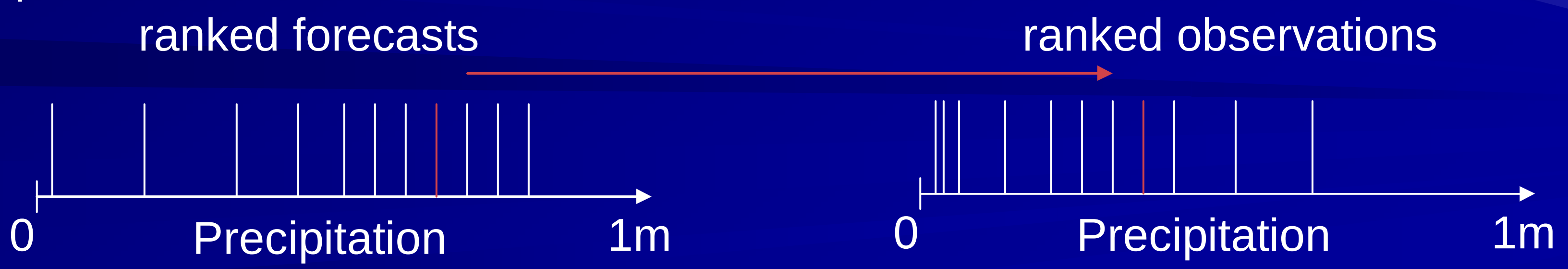
Forecast Bias Adjustment

-done independently for each forecast grid

(bias-correct the whole PDF, not just the median)

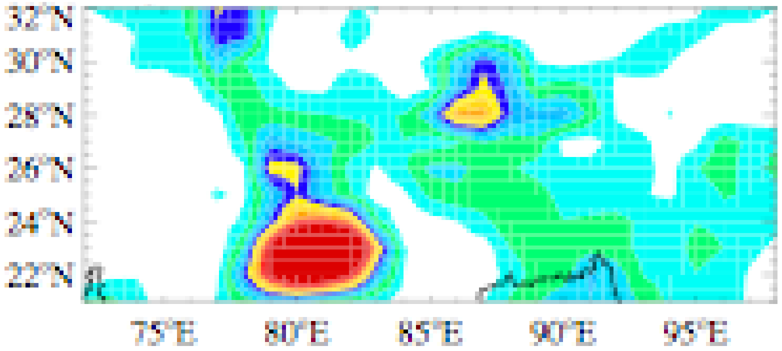


In practical terms …

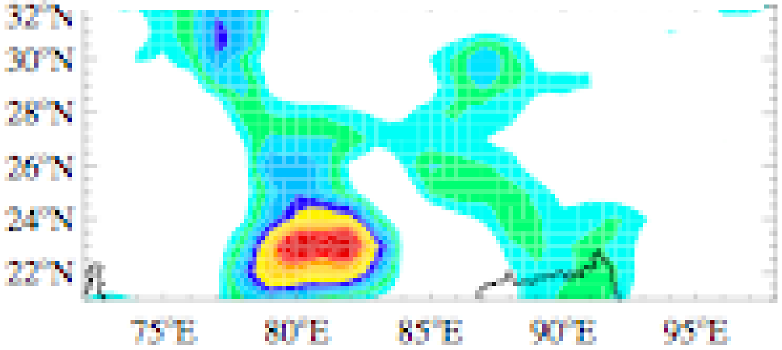


Bias-corrected Precipitation Forecasts

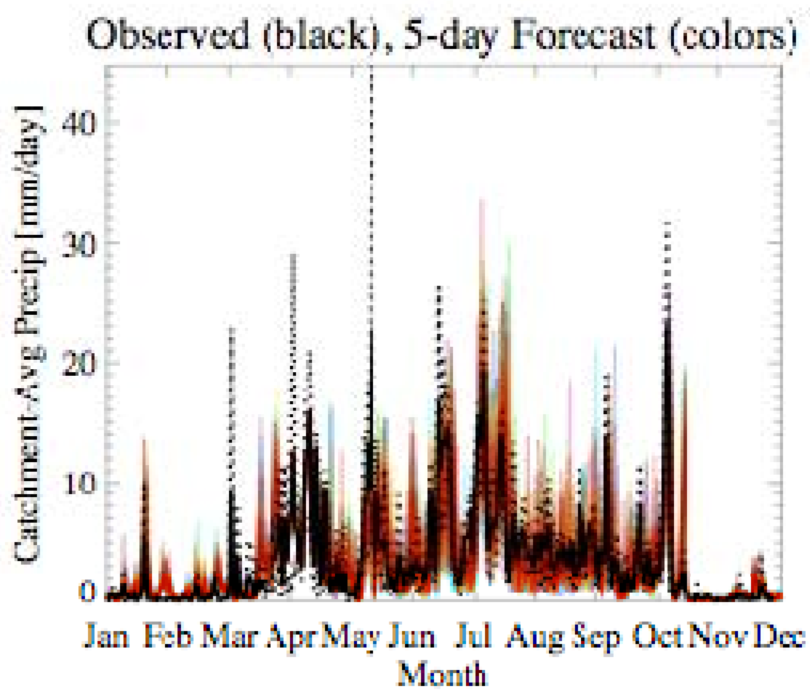
Original Forecast



Corrected Forecast



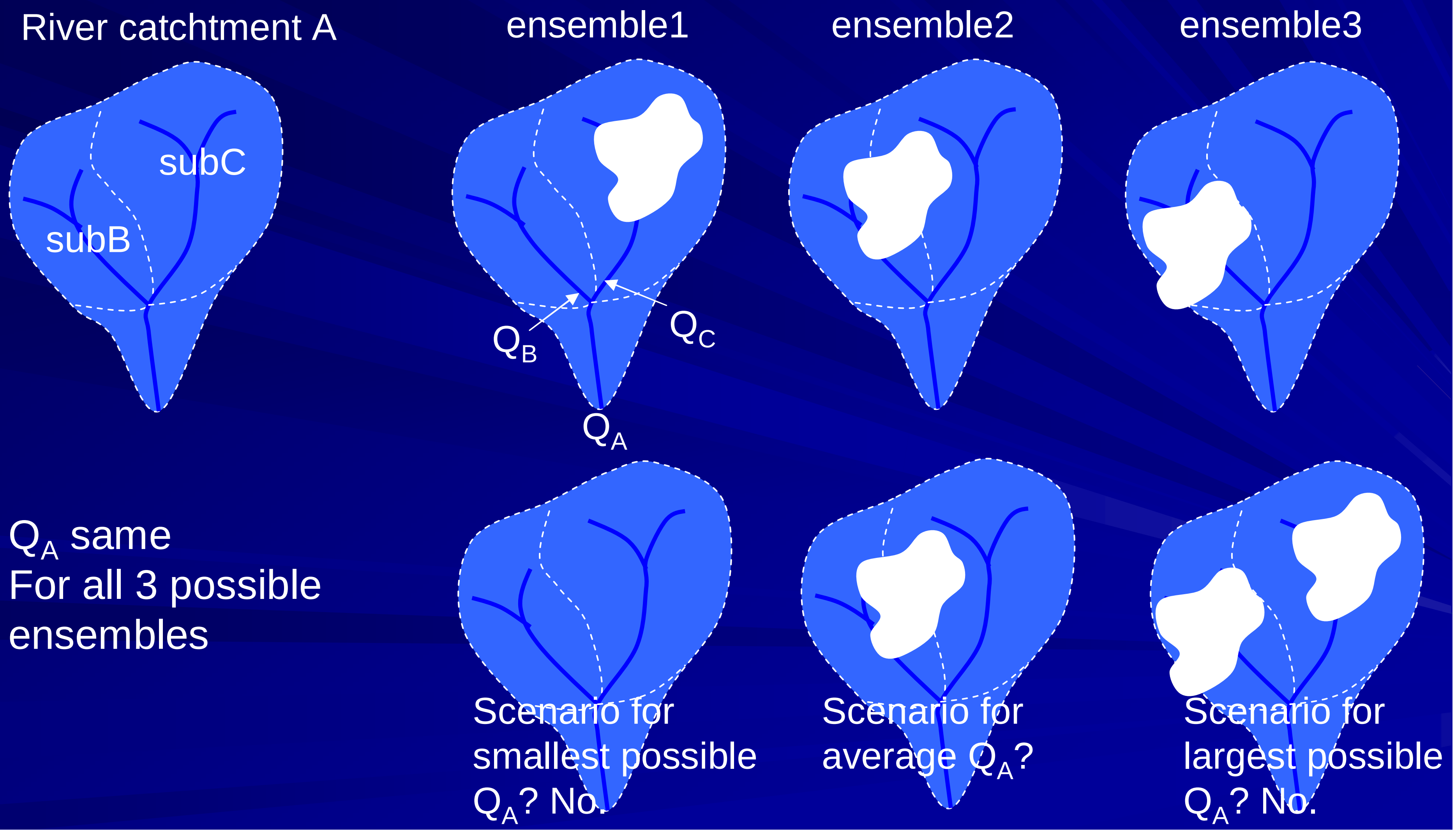
Brahmaputra Corrected Forecasts



=> Now observed precipitation within the "ensemble bundle", and preserving spatial and temporal covariances

A Cautionary Warning about using Probabilistic Precipitation Forecasts in Hydrologic Modeling

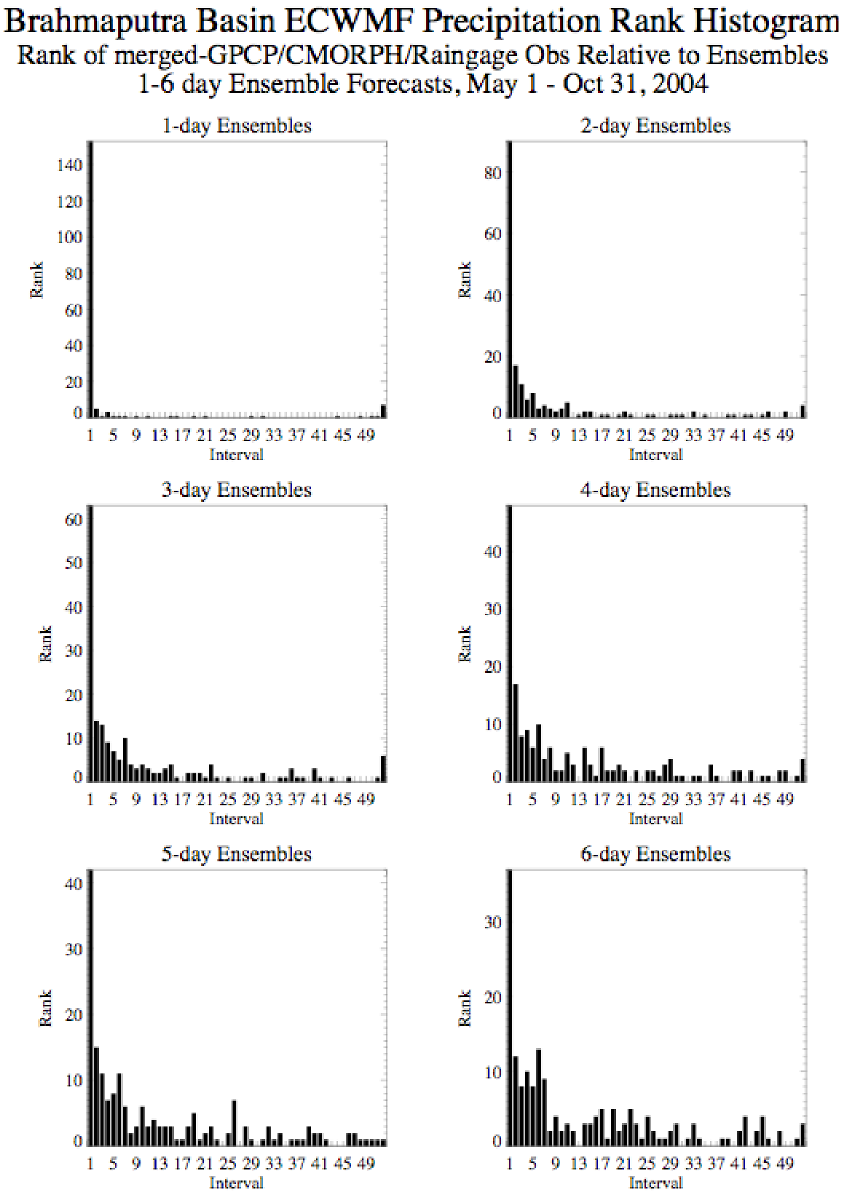
(Importance of Maintaining Spatial and Temporal Covariances for Hydrologic Forecasting => one option: “Schaake Shuffle”)



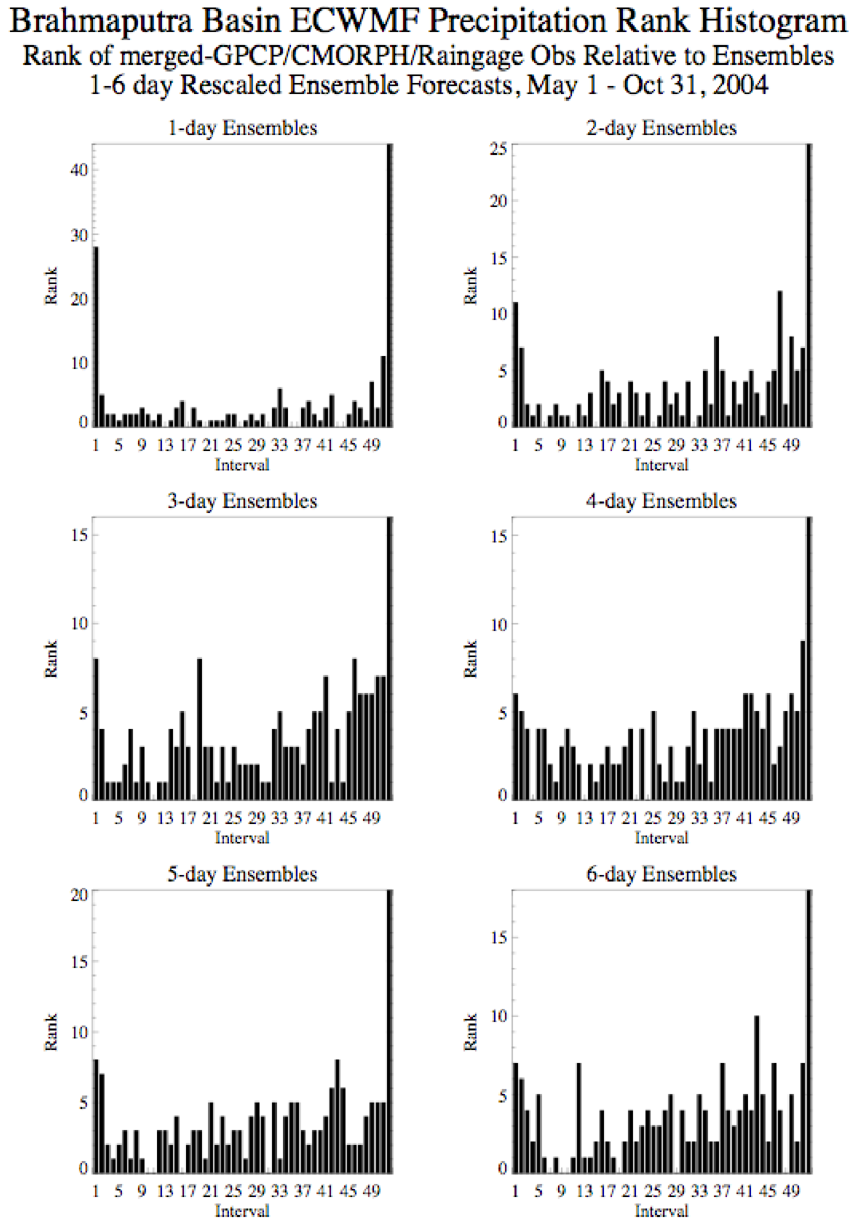
Rank Histogram Comparisons

(better but not perfect!)

Original



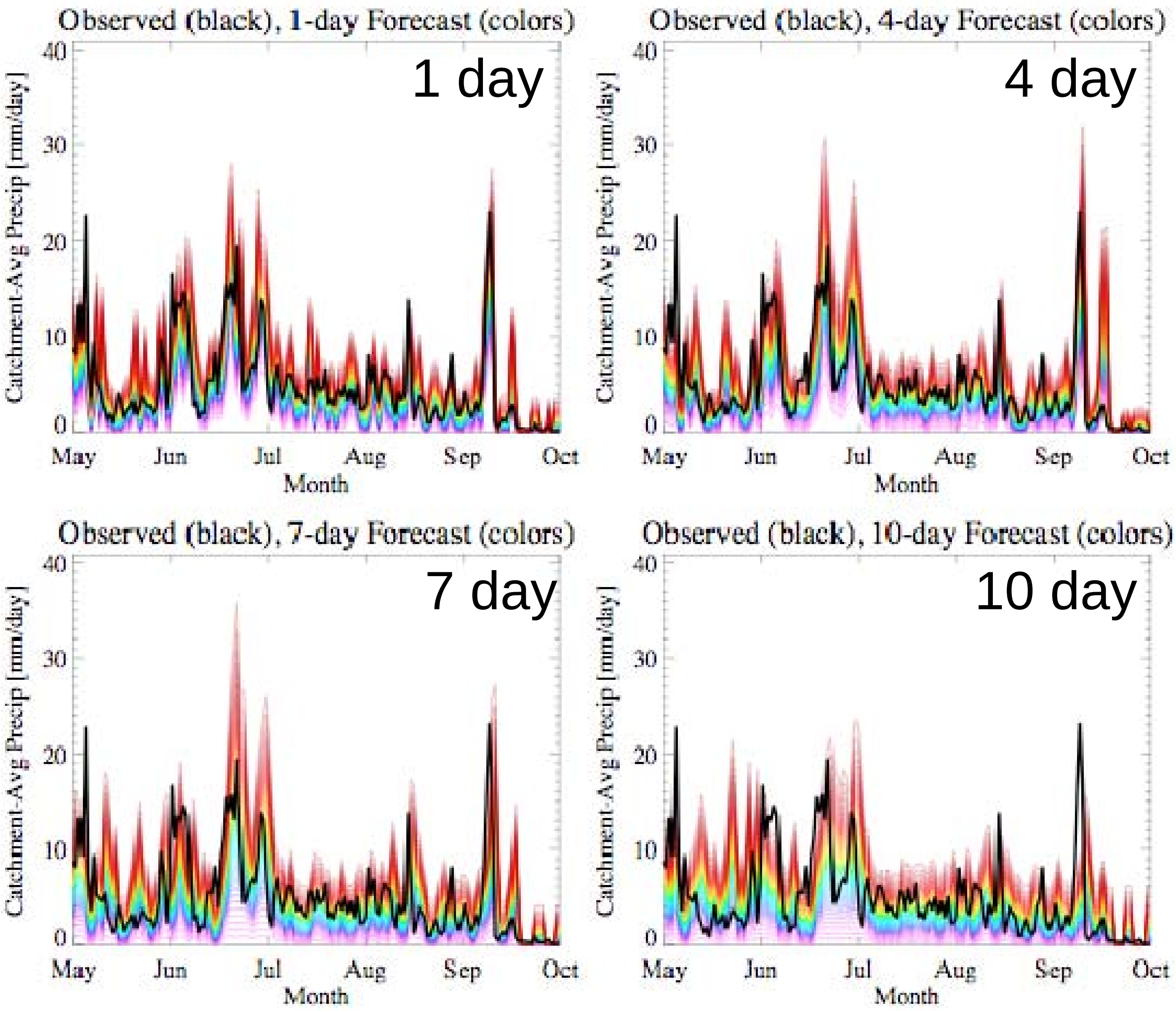
Adjusted



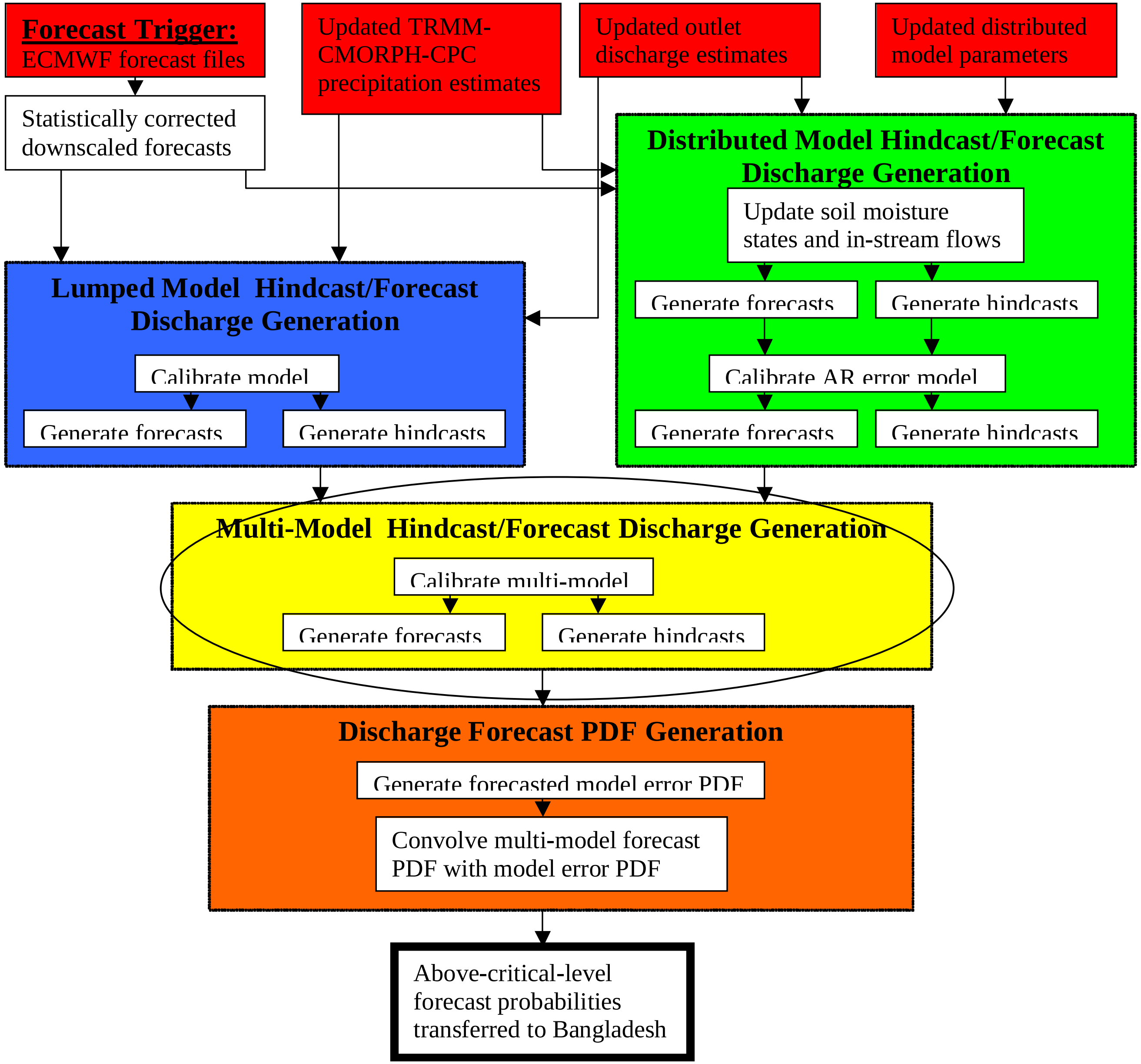
<u>Quantile Regression approach</u>:maintaining skill no worse than “persistence” for non-Gaussian PDF’s

(ECMWF Brahmaputra catchment Precipitation)

- “Multi-model” statistical approach applied to NCAR’s WRF mesoscale ensemble forecasts



Daily Operational Flood Forecasting Sequence



Discharge Multi-Model Forecast

Multi-Model-Ensemble Approach:

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

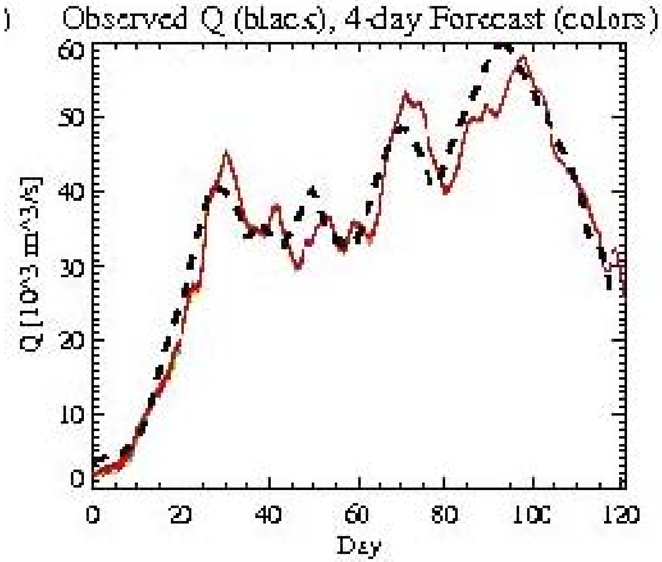
•Regress models' historic discharges to minimize historic residuals with observed discharge

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

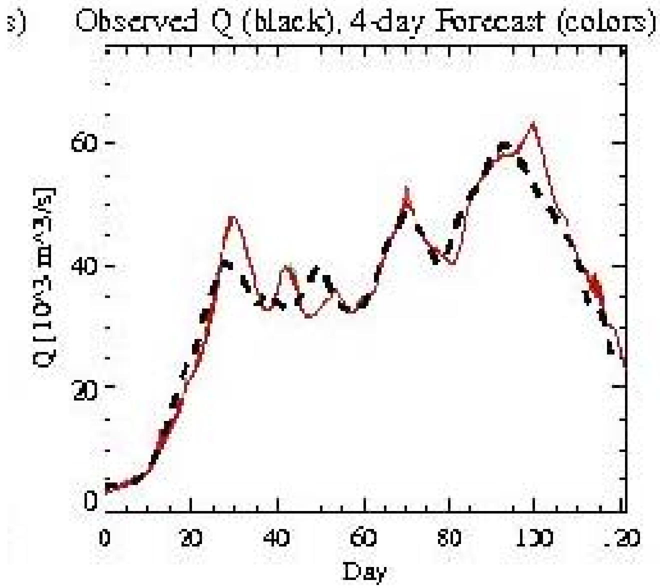
•If AIC minimized, use regression coefficients to generate "multi-model" forecast; otherwise use highest-ranked model => "win-win" situation!

2003 Model Comparisons for the Ganges (4-day lead-time)

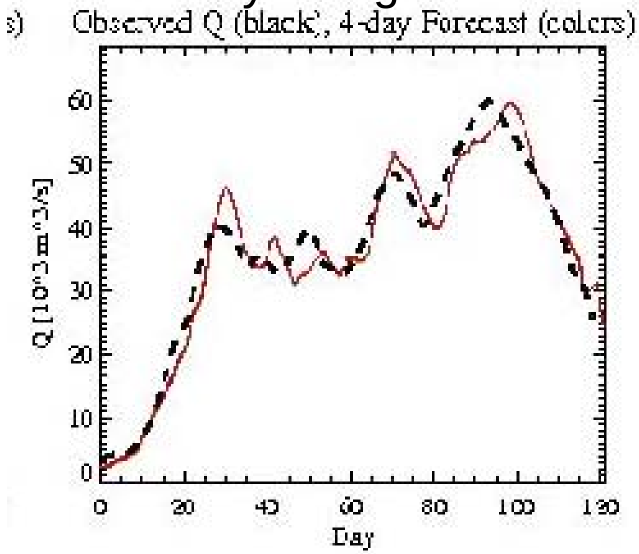
hydrologic lumped model



hydrologic distributed model



Resultant Hydrologic multi-model



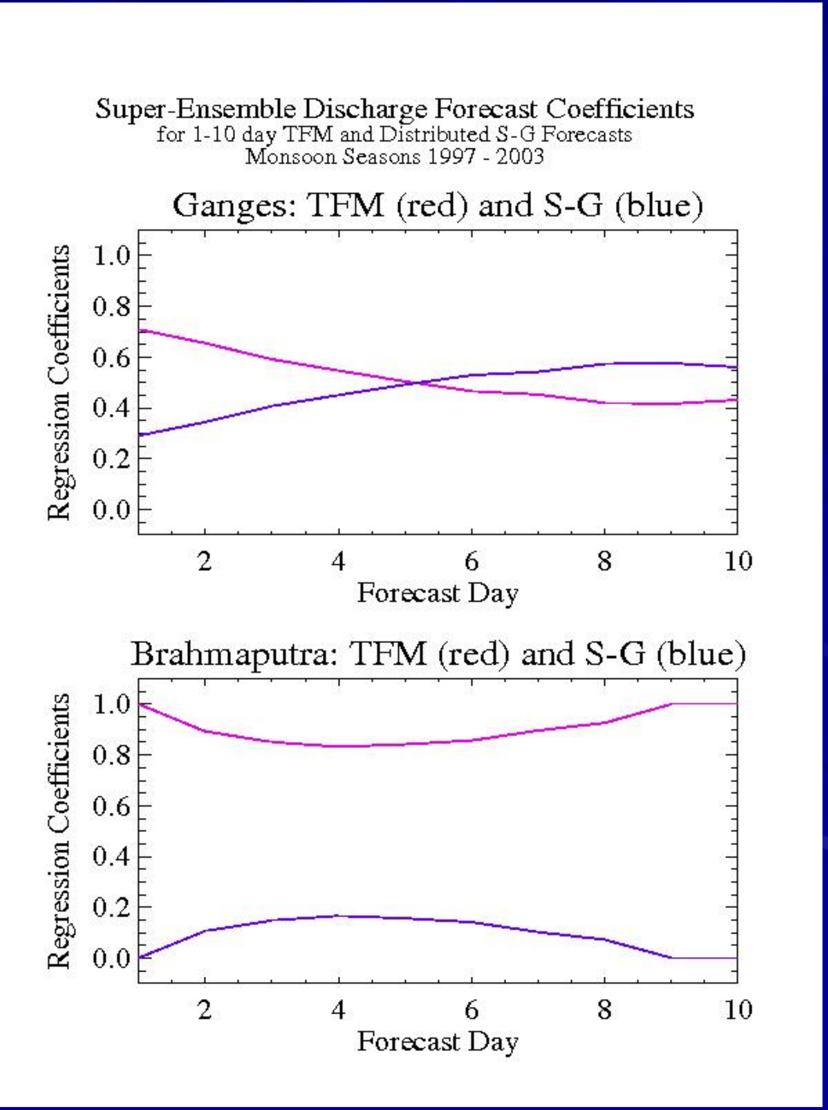
Multi-Model Forecast Regression Coefficients

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

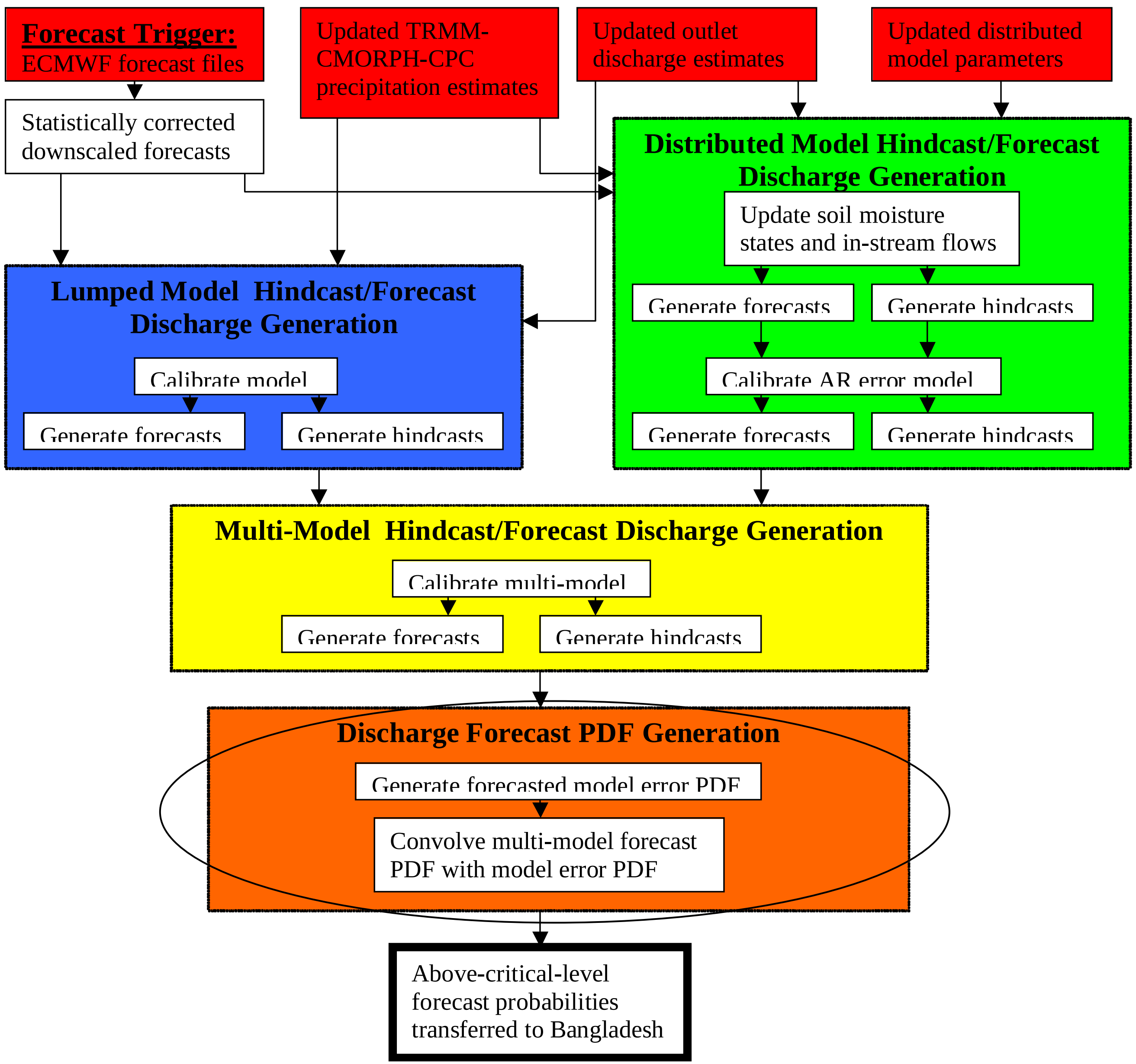
- Significant catchment variation
- Coefficients vary with the forecast lead-time
- Representative of the each basin's hydrology

-- Ganges slower time-scale response

-- Brahmaputra "flashier"

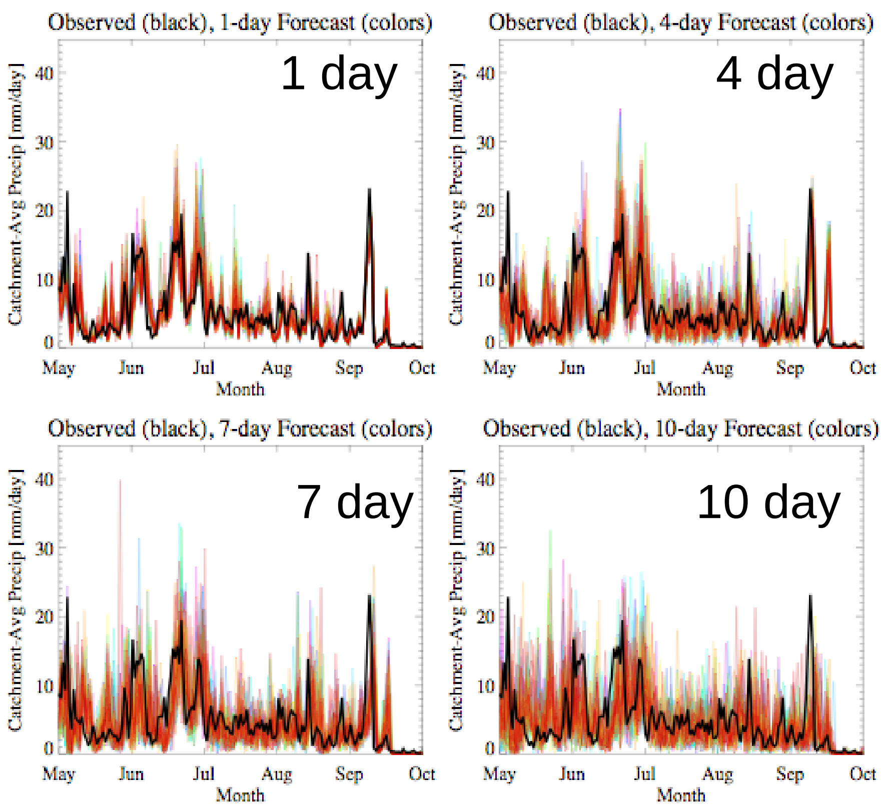


Daily Operational Flood Forecasting Sequence

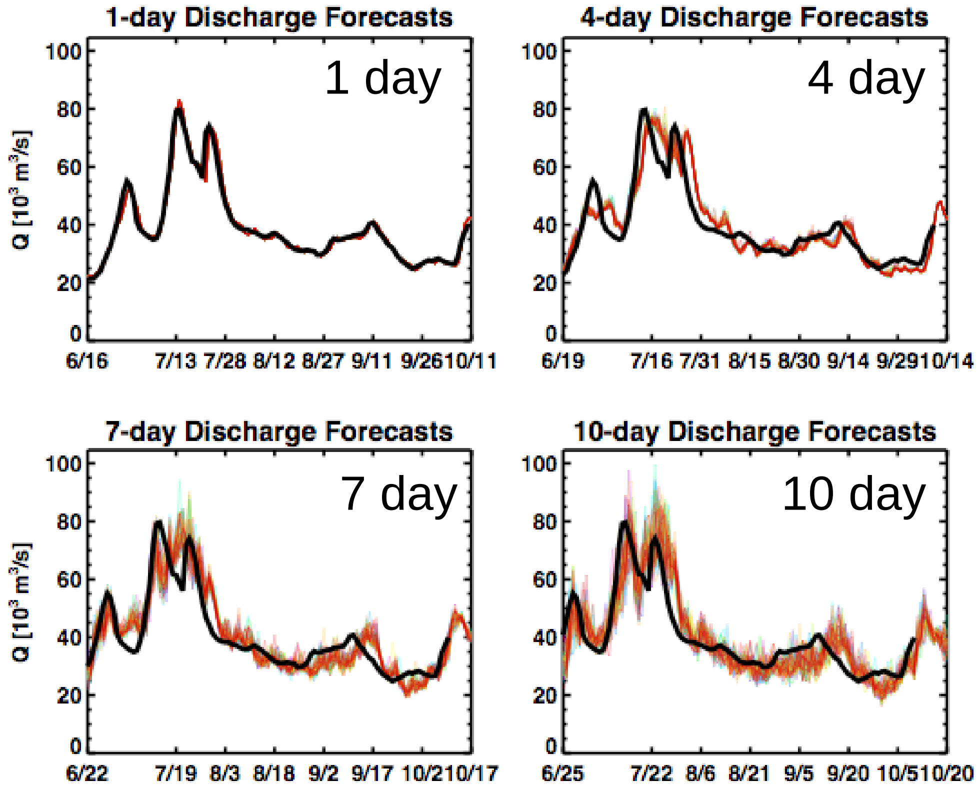


Significance of Weather Forecast Uncertainty Discharge Forecasts

Precipitation Forecasts

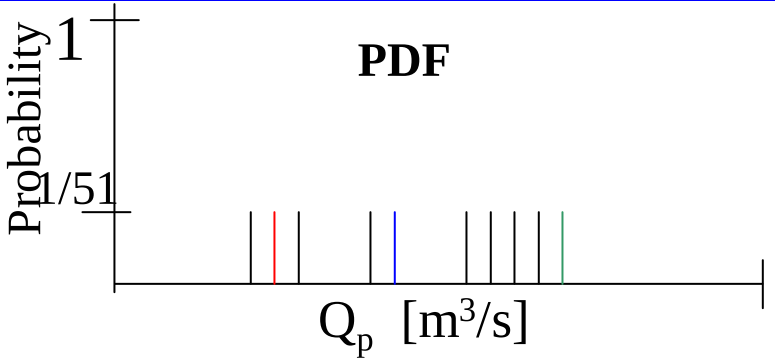


Discharge Forecasts

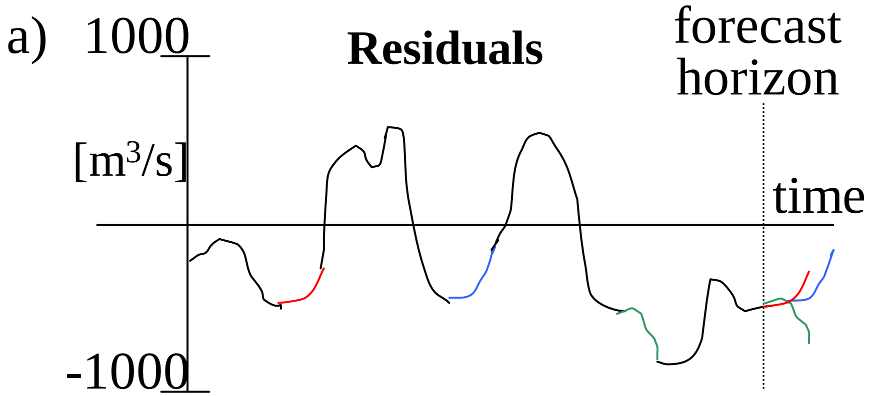


Producing a Reliable Probabilistic Discharge Forecast

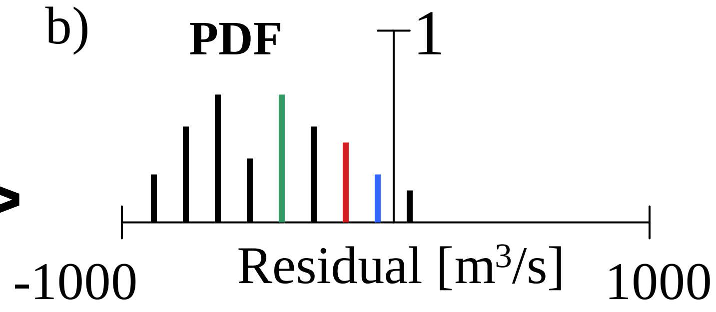
Step 1: generate discharge ensembles from precipitation forecast ensembles (Q_p):



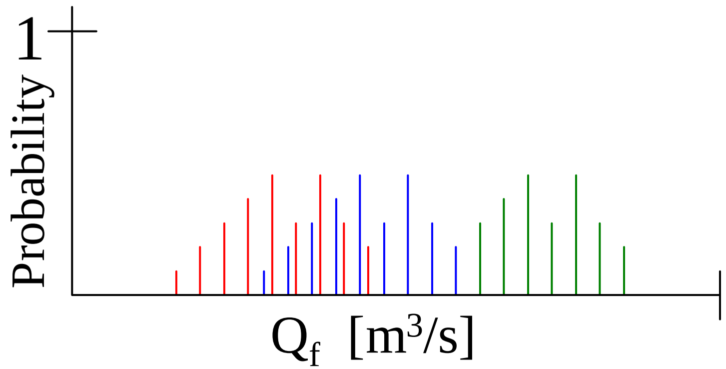
Step 2: a) generate multi-model hindcast error time-series using precip estimates; b) conditionally sample and weight to produce empirical forecasted error PDF:



=>

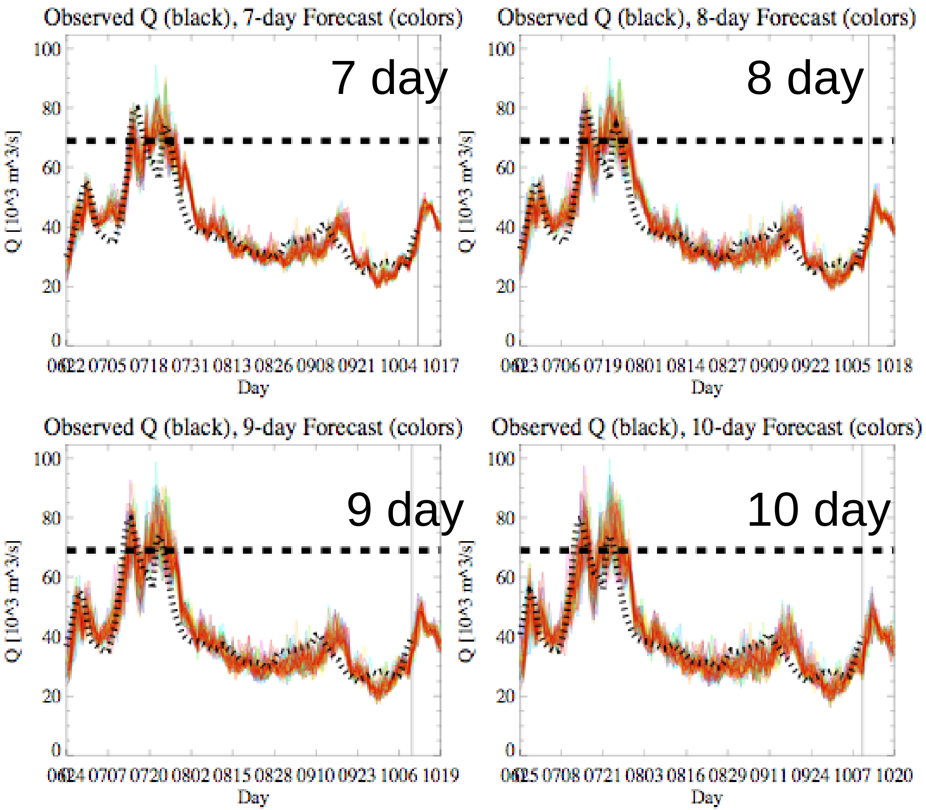


Step 3: combine both uncertainty PDF's to generate a "new-and-improved" more complete PDF for forecasting (Q_f):

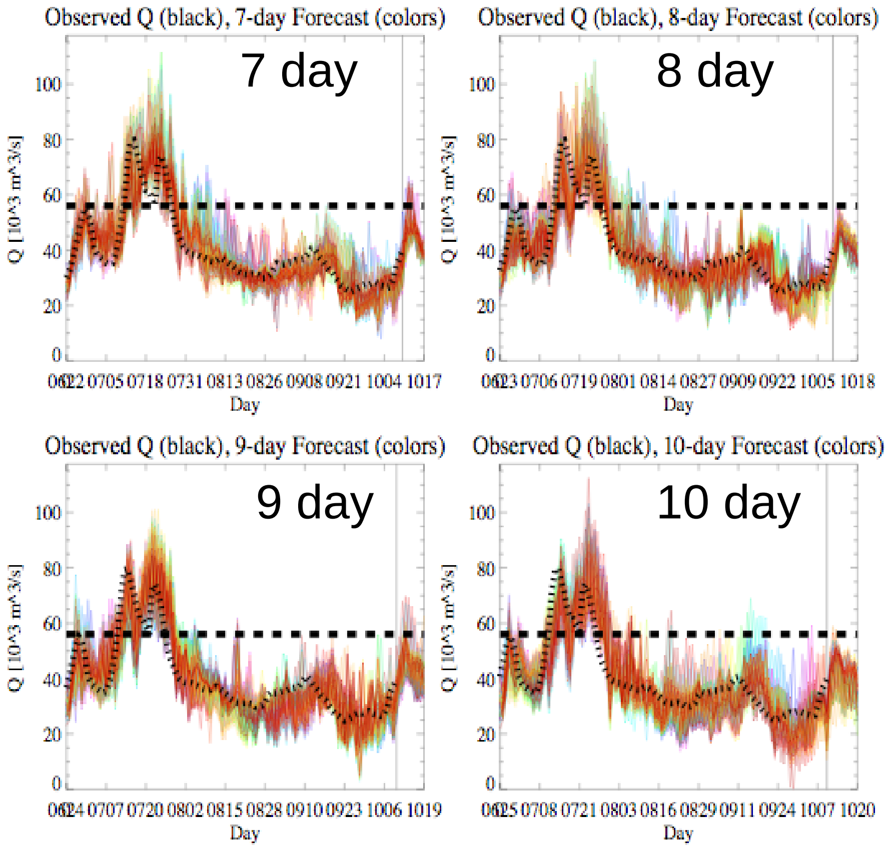


Significance of Weather Forecast Uncertainty Discharge Forecasts

2004 Brahmaputra Discharge Forecast Ensembles



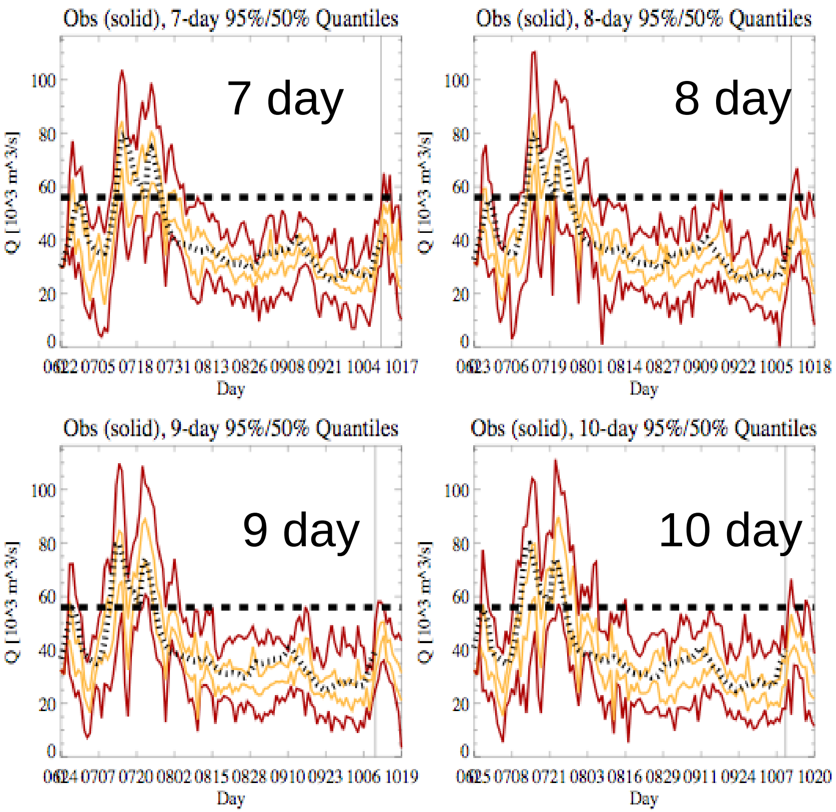
Corrected Forecast Ensembles



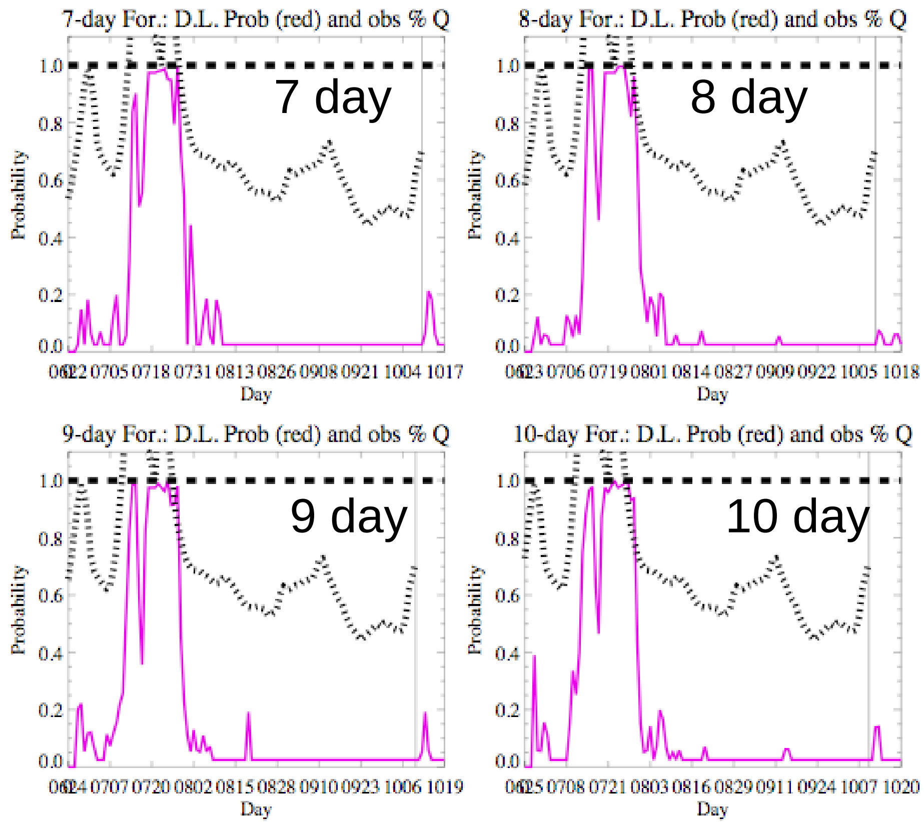
2004 Brahmaputra Forecast Results

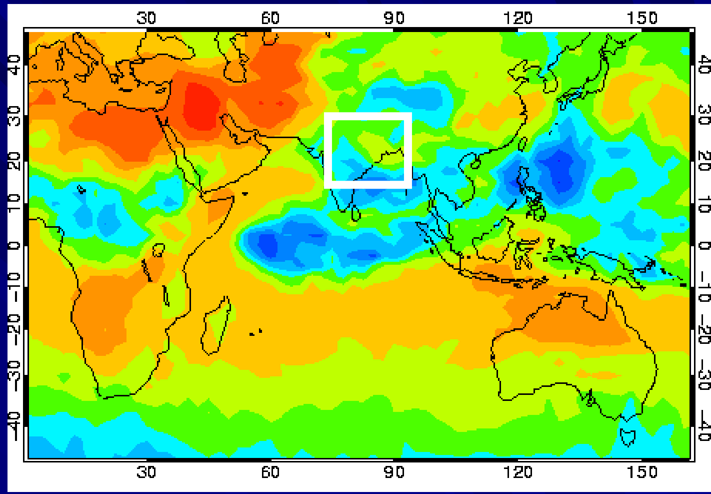
Confidence Intervals

50% 95%



Above-Critical-Level Cumulative Probability





Overview:

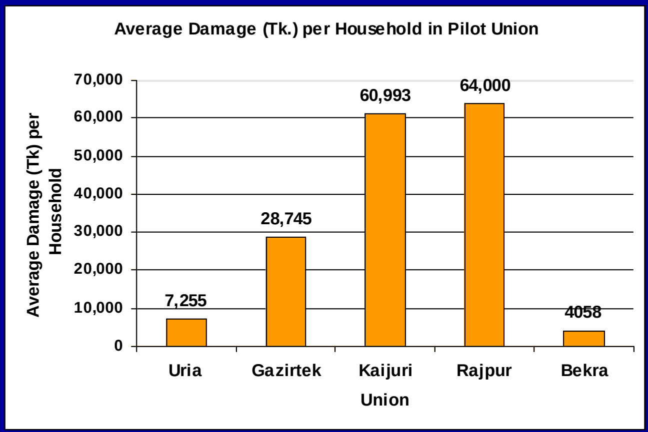
Bangladesh flood forecasting

I. CFAB History -- sea-level backwater effects

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

Five Pilot Sites chosen in 2006 consultation workshops based on biophysical, social criteria:



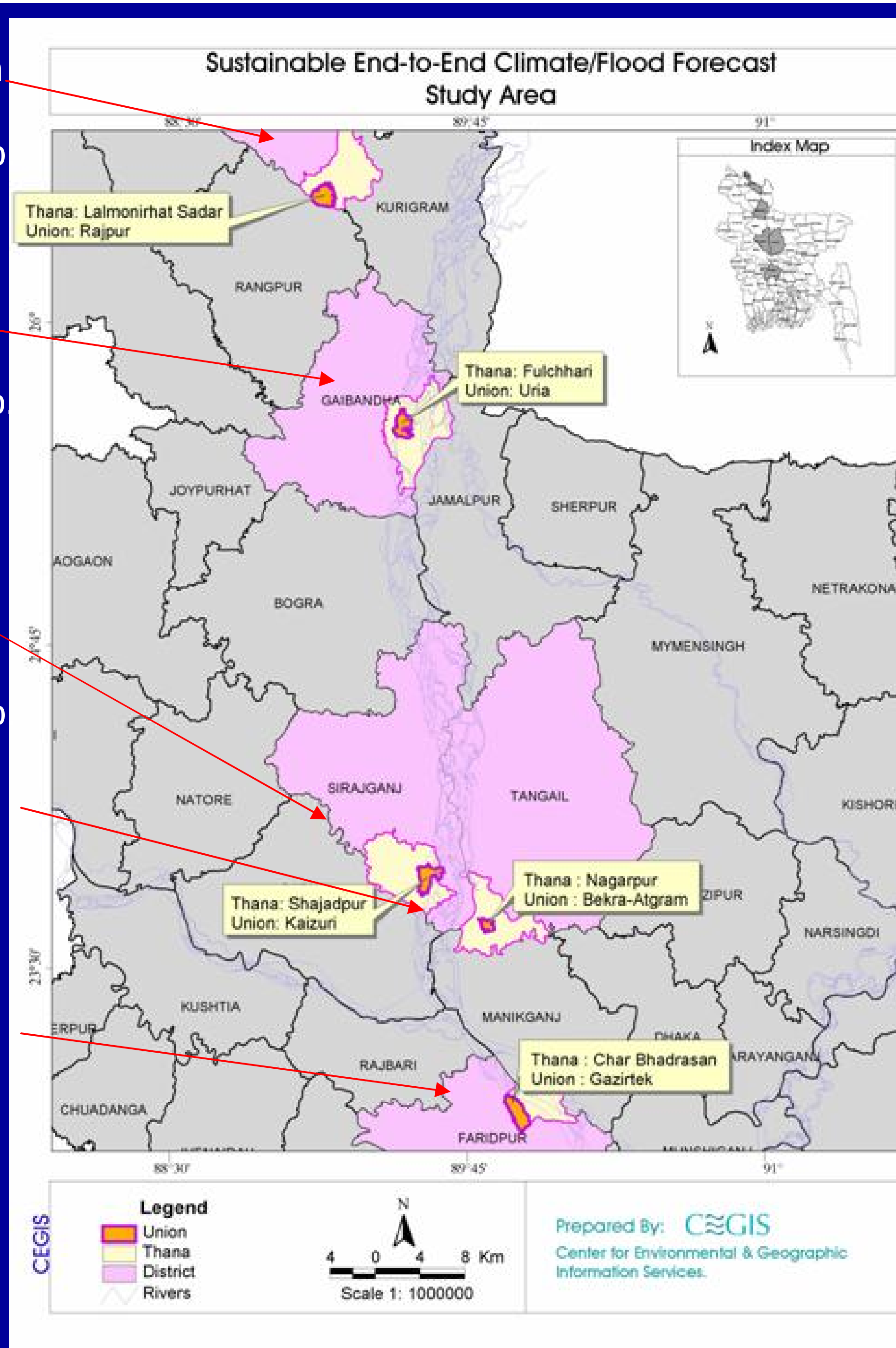
Rajpur Union
-- 16 sq km
-- 16,000 pop

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

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

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

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

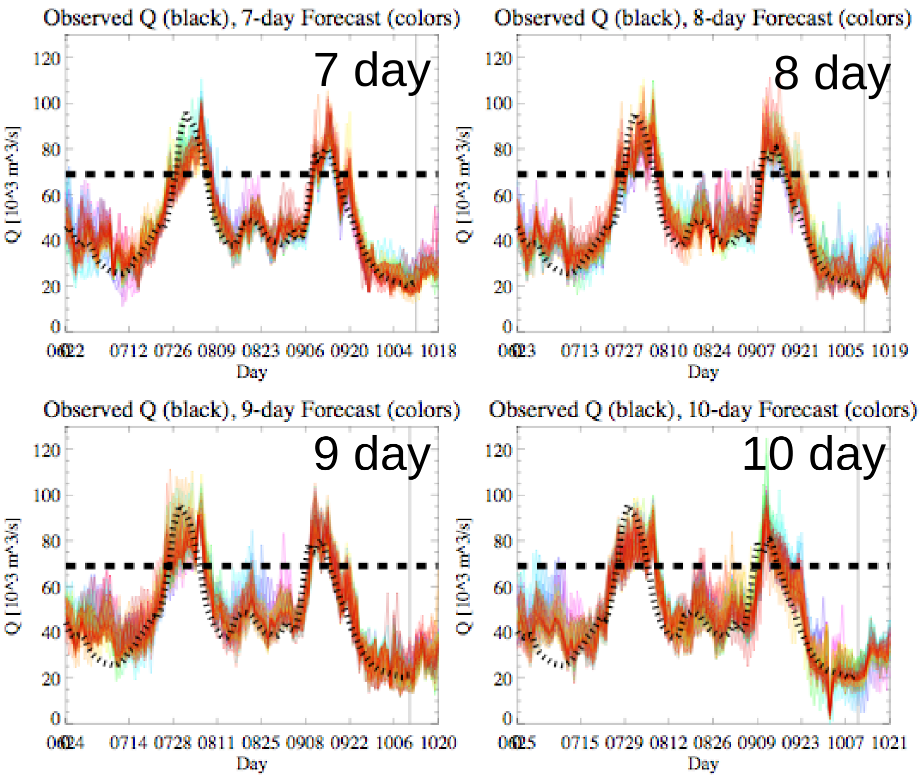


5.2 July/August 2007 floods in Bangladesh

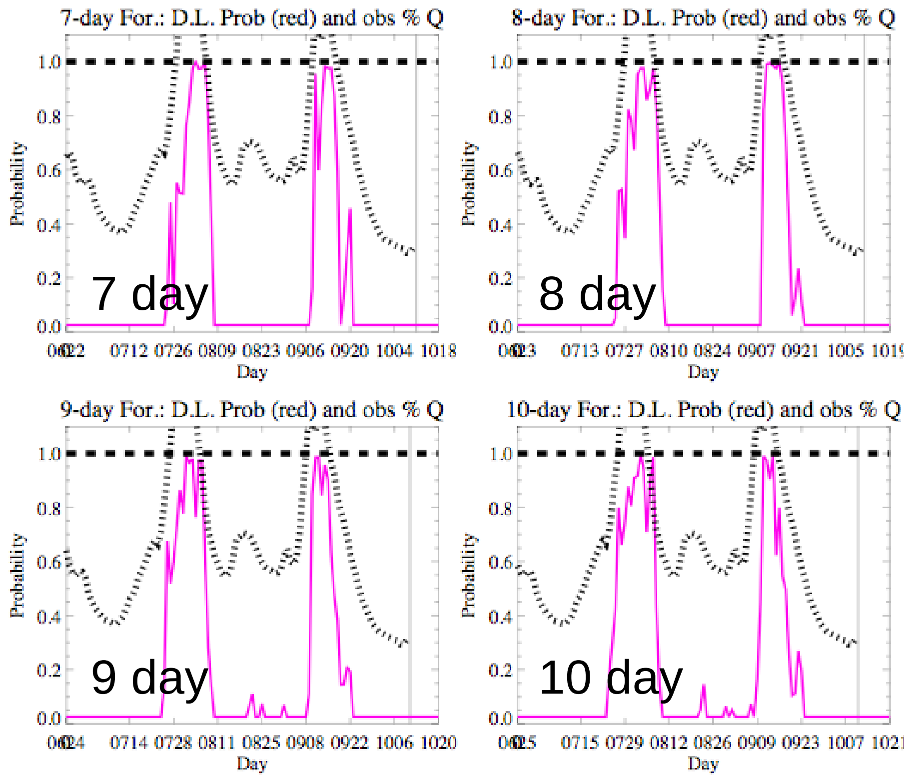
"Seven people had died and thousands have been forced to leave their homes in Bangladesh because of worsening floods. Officials said that nearly half a million people remained marooned in seven flood-hit districts in the country's north west and in the south." (8 August 2007, from *http://news.bbc.co.uk*).

2007 Brahmaputra Ensemble Forecasts and Danger Level Probabilities

7-10 day Ensemble Forecasts



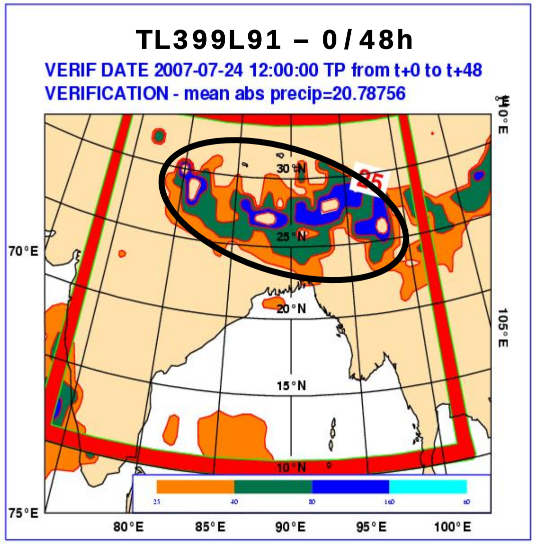
7-10 day Danger Levels

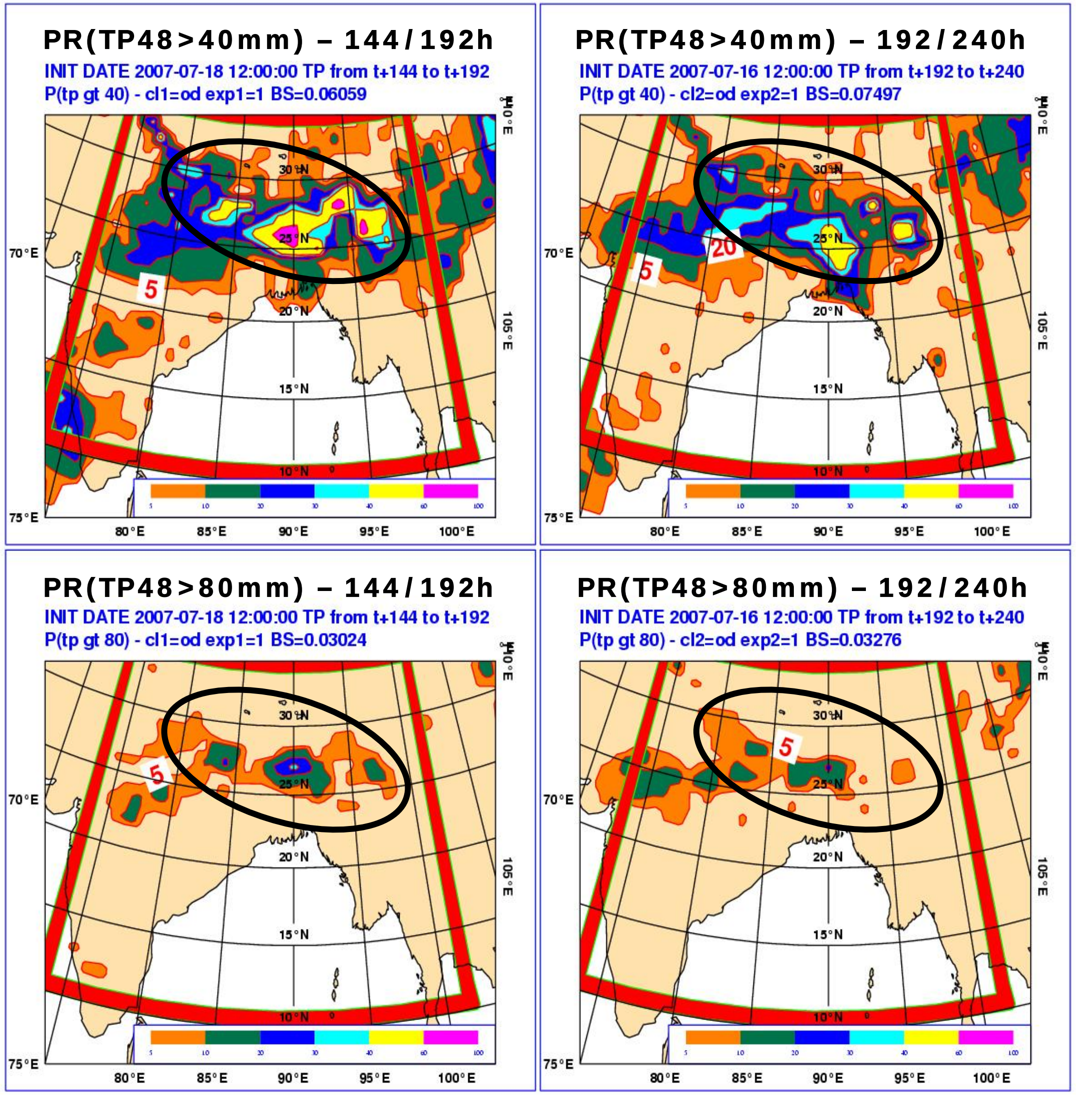


5.2 2007 floods in Bangladesh – fcs for 24/07-26/07

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."

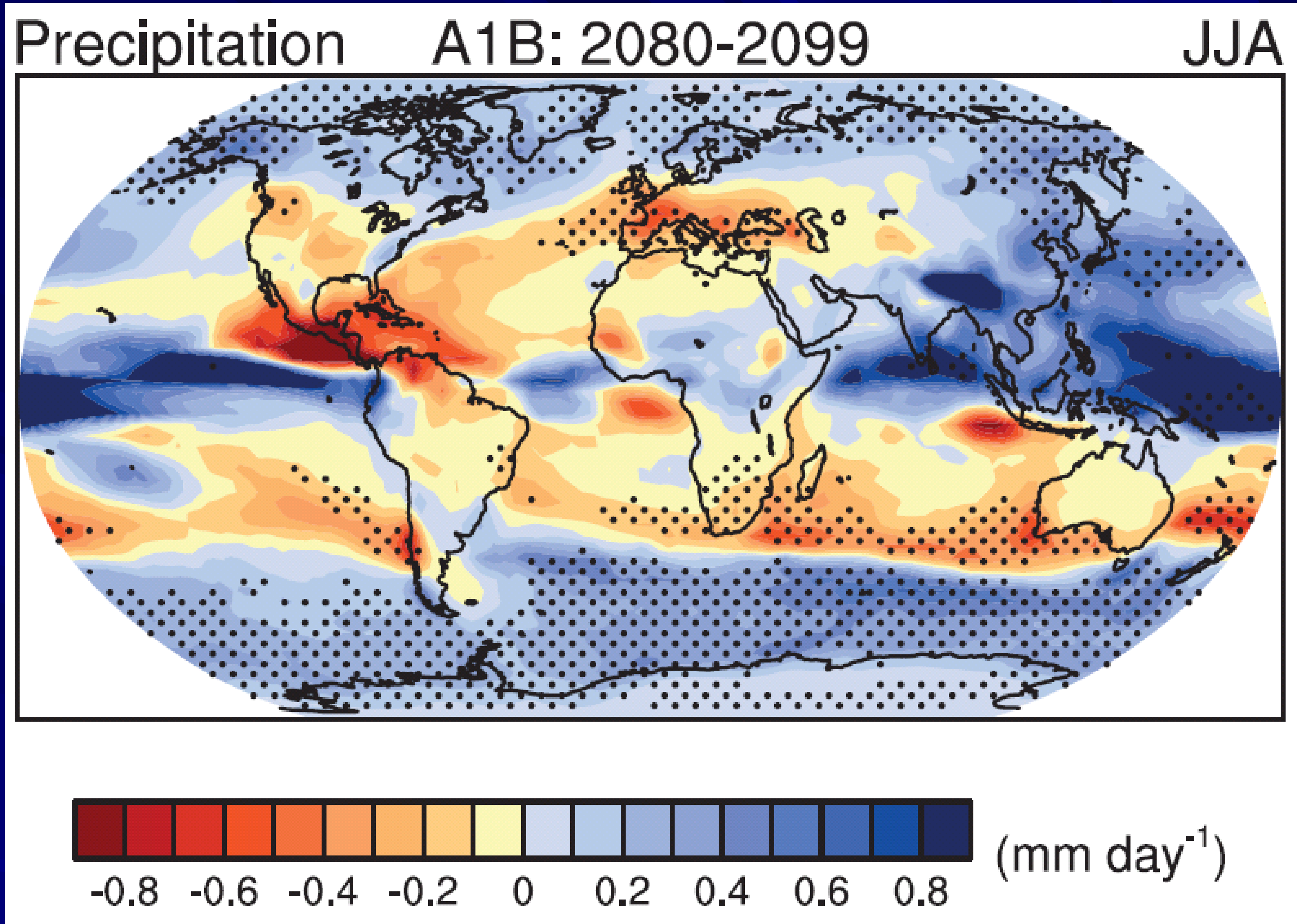
"The communities in Rajpur Union … were able to use the forecast for … mobilizing food, safe drinking water for a week to 10 days, protecting their … rice seedlings, fishing nets, and … fish pods."

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!