Introduction to Quantitative Precipitation Forecasts (QPF) and Numerical Weather Prediction (NWP) Products

Submitted by: Nanjing University
Introduction to Quantitative Precipitation Forecasts (QPF) and Numerical Weather Prediction (NWP) Products

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Acknowledgements: NOAA/ESRL/GSD, NOAA/NCEP, NCAR
Introduction to QPF

- QPF and current status
- Mesoscale modeling
- Ensemble forecasting and PQPF
- Numerical Weather Prediction (NWP) Products
- Summary and discussions
Damage from Hydrometeorological disasters in 2010
Storm: 29%
Hydrological events: 32%
Natural disasters by heavy rainfall

Aug 8, 2010, landslides, Zhouqu, Gangsu, China

Summer 2010, Pakistan floods

Typhoon Morakot, 2009

January 2008, winter storms, China
Annual QPF Skill of HPC

24-Hour 1-Inch Day 1 QPF Verification
Annual Threat Scores

NOAA
Percent Improvement Over NWP

HPC % Improvement to NCEP models
1-Inch Day 1 QPF Forecast

NOAA
## Threat Score (TS)

<table>
<thead>
<tr>
<th></th>
<th>obs</th>
<th>Yes</th>
<th>No</th>
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<td>fect</td>
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<tr>
<td>Yes</td>
<td></td>
<td>Hits (a)</td>
<td>False alarms (b)</td>
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<tr>
<td>No</td>
<td></td>
<td>Misses (c)</td>
<td>Correct rejection (d)</td>
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\[ TS = \frac{a}{a + b + c} \]

\[ Hit \ rate = \frac{a}{a + c} \]

\[ False \ alarm \ rate = \frac{b}{b + d} \]
Uncertainty in NWP and QPF

850hPa 24h wind fcst

Analysis

EC 24h QPF

Station obs
Microphysics of QPF

Condensation nuclei, a very slow process, cloud droplets
From droplets to raindrops:
• Collision-coalescence process
• Ice-crystal (Bergeron) process
Microphysics of QPF

- Warm clouds: Collision-coalescence process
- “Cold” clouds: Ice-crystal (Bergeron) process
Precipitation in Clouds

- Starts quickly
- Most Precipitation formed through accretion
- Many times rain starts as ice
Precipitation types

Virga

Rime

Freezing rain

Hail

Sleet

Boulder, Colorado
December 21, 2006
Possible thunderstorm areas

Challenges in QPF:

- Short predictability limits (strong nonlinear, complicated thermodynamical and physical processes, etc)
- Initial conditions, model error/uncertainties
- Observation/verifying uncertainties
- Complex topography, vegetation, and hydrology
Introduction to QPF

• QPF and current status

• **Mesoscale modeling**

• Ensemble forecasting and PQPF

• Numerical Weather Prediction (NWP) Products

• Summary and discussions
Goal is to improve forecasts of rain and snow
Uses local-state-federal, and private-public-academic partnerships

Benefits: Accelerates improvements in QPF and flood forecasting, with impacts on transportation, ecosystems, emergency management, flood control and water supply. Science and field tests will advise on how best to fill gaps in observational and modeling systems.

Status:
- Recommended by USWRP
- Implementing regionally
- HMT-prototype 2003-04
- HMT-West 2005-09
- Addresses Sacramento flood risk

Next Steps:
- Provide state-of-the-art QPE to evaluate hydrologic models
- Winter QPF in mountains
- HMT-East (2009-12)
- HMT-Central (2012-16)

http://hmt.noaa.gov
During the winter season significant precipitation events in California are often caused by land-falling “atmospheric rivers” associated with extratropical cyclones in the Pacific.

Due to the terrain steepness and soil characteristics in the area, a high risk of flooding and landslides is often associated with these events.
The study domain – American River Basin (ARB)
Hydrological conditions during HMT-West-2006

- Indicates heavy precipitation events selected for study

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**USGS 11427000 NF AMERICAN R A NORTH FORK DAM CA**

- **DAILY Discharge, cubic feet per second**
  - Median Daily Streamflow based on 63 years of record
  - Daily Mean Discharge

Provisional Data Subject to Revision
Number of ensemble members \( (N) = M (Model) \times T (Time-lagged) \)

\[
N = M \times T = M \times INT \left( \frac{\text{Maximum forecast projection - Lead time (h)}}{\text{Model initial interval (dt)}} + 1 \right)
\]
LAPS diabatic initialization scheme

Local Analysis and Prediction System (LAPS)

Radar/Satellite Aircraft/Surface

Background Analyses

Environmental conditions (T, rh)

Cloud grid Synthesizer

Cloud Typing Algorithm

Cloud Table Database

Ice/snow Mixing Ratios
Rainwater mixing ratio
Cloud water mixing ratio

1-D Cloud Model

Constraints

Var Balance and Continuity Scheme

Interpolation to model grid

Adjusted U, V, $\omega$, T
CloudSat Verification of LAPS Cloud Analysis
QPF

0-6-h QPF

Stage IV

MM5.nam Schultz

WRF.nam Ferrier

WRF.ruc Lin

WRF.nam Lin

WRF.nam Thompson

RAMS.nam, no LAPS

RAMS.ruc, no LAPS

RAMS.nam

Four rerun models

Five operational models

Yuan et al. 2008, JHM

Valid at 1800 UTC, Feb 27, 2006
Nested domain:
• Outer/inner nest grid spacing 9 and 3 km, respectively,
• 6-h cycles,
• 9 members
• Mixed models, physics and boundary conditions
48-hr forecast starting at 12 UTC, 18 January 2010
QPF

Example of 24-h QPF
9-km resolution

9 members:
ARW-TOM-GEP0
ARW-FER-GEP1
ARW-SCH-GEP2
ARW-TOM-GEP3
NMM-FER-GEP4
ARW-FER-GEP5
ARW-SCH-GEP6
ARW-TOM-GEP7
NMM-FER-GEP8
ETS of 6-h QPF

Equitable threat score (ETS) of 6-h QPF
9-km resolution
Dec 2009 - Apr 2010 (some missing data)
Verification data: Stage IV

6-h QPF verified 4 times per day (00, 06, 12, 18 UTC)
6-114 h lead times

Ensemble mean is much better than individual members.
Gep0 (control) is also better.
ETS of 24-h QPF

Equitable threat score (ETS) of 24-h QPF
9-km resolution
Dec 2009 - Apr 2010 (some missing data)
Verification data: Stage IV

24-h QPF verified for 12 UTC cycle
24-96 h lead times
Ensemble mean is much better, especially for higher thresholds.
Example of 24-h PQPF
9-km resolution
Probability is defined as the ratio of the number of members exceeding the precipitation thresholds of 9 total members.

Left column: observed probability based on the NCEP Stage IV data
For a given threshold, occurred event, obs probability is 1, otherwise 0.
Right column: PQPF
SSM/I satellite image shows an atmospheric-river (AR) plume of integrated water vapor (IWV) impacting California.

Stream gauge data (>30 years) show the regional extent of high streamflow covering roughly 500 km of coast (Ralph et al., 2006, GRL).

SSM/I IWV analysis shows there were 35 ARs impacting CA during the last 8 winters.

Storms with imbedded ARs produced more rain and snow than other storms (Neiman et al., 2007, JHM).

SSM/I does not provide IWV measurements over land, hence automated ground-based detection is required to track ARs over CA.
- 10 km horizontal grid spacing
- Hourly update, 12-hr forecast
- LAPS initial conditions
- NAM LBCs
- HRRR
NOAA/ Hydrometeorological Testbed (HMT) Program

HMT Major Activity Areas

- **Verification**
- **Obs Network**
- **QPE**
- **QPF**
- **DSTs**
- **Debris Flow**
- **Snow Info**
- **Hydro Apps**

HMT WEST - Cool Season (2004-2010)

HMT CENTRAL - Warm Season (TBD)

HMT EAST - All Season (2010-2015), including Hurricane Landfall
Two-Dimensional Runoff Erosion and Export (TREX) model

TREX Model Framework (Velleux et al. 2008)

A spatially distributed model to access watershed hydrology, sediment transport, and chemical contaminant transport and fate
Event-Based Streamflow Simulation using TREX

- Precipitation input:
  - 150 m x 150 m grids
  - QPF: ensemble forecasts (3-km) from HMT-West project
  - 0-6 h
  - QPE: NCEP Stage IV (4-km) precipitation analysis

Test:
- (a) parameter sensitivity
- (b) QPF sensitivity
- (c) Comparison with operational CNRFC QPF
Average skill scores for 14 IOPs

The RPS is computed for the simulations using the 0-6 h ensemble mean QPF, 6-h Stage IV, CNRFC day 1 to day 3 forecasts and averaged for 14 IOPs during three winters (HMT-West 2006, 2007, 2008).

Smaller RPS is better.
Windsor tornado case, 22 May 2008

- Tornado touched down at Windsor, Colorado around 17:40 UTC, 22 May 2008
- Facts:
  Most expensive tornado in Colorado's history
  1 fatality, 15-20 injuries, 850 home damages
  ~$200 million
  F3 (wind as high as 130 to 150 mph)

NWS Doppler Radar Image at 11:44 AM MDT

http://www.crh.noaa.gov/bou/?n=news_116
http://rammb.cira.colostate.edu/case_studies/20080522/
00:00 hr 800mb reflectivity initialized at 17 UTC 22 May 2005, mosaic radar vs. WRF forecast (STMAS), 1.7 km
00-01 UTC 800 mb reflectivity initialized at 17 UTC 22 May 2005,
mosaic radar vs. WRF forecast (STMAS), 1.7 km
Hot start initialization is very important for tornado forecasting.
850 mb Analyzed and Simulated Reflectivity

Analysis

2hr HOT Fcst

2hr NO-HOT Fcst

16 June 2002

Initialized with LAPS

Initialized with NAM

Mature Squall Line Animation
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High resolution Forecasts

Advantages of Higher Resolution Models: An Illustration

- Precipitation Banding
- Isolated Cells
- Convective Clusters
- Linear

NOAA/NWS/NCEP
Development of ensemble forecasting

NWP history
First one-day NWP (1950, R. F. Charney and J. von Neuman)
NWP 1950s (NCEP), 1955-1973: north hemisphere; global since 1973
Chaos theory (Lorenz 1963ab,1965,1968)
1992 NCEP (Breeding of Growing Modes) and ECMWF (Singular Vector),
global ensemble system
Ensemble prediction system (EPS)

Short-range ensemble system (SREF) (Brooks et al. 1995)
NCEP SREF
Background: Chaos and ensemble system

**Predictability: Does the Flap of a Butterfly’s Wings in Brazil set off a Tornado in Texas?**

— Edward Lorenz (1972)

- The “Butterfly Effect”, the sensitivity to initial conditions, is the essence of chaos.

- The perfect atmospheric model has a predictability limit about two weeks.

- The predictability depends on the instability of the atmosphere.
Construction of Ensemble Prediction System (EPS)

Perturbations:

– **Initial conditions**
  
  **Different initial atmospheric states**
  
  e.g., Singular Vector (ECMWF), Bred Vector (Breeding, NCEP), Monte Carlo, data assimilation, perturbed observation

– **Models or physics**
  
  Different models or variations on the same model (perturbed physics, dynamics, parameters etc)
  
  e.g., dynamic core, convective parameterization scheme and internal closure scheme, PBL, microphysics, stochastic parameters/tendencies

– **Boundary conditions**
  
  Lateral or lower boundary conditions

– **Time-lagged**
  
  Different initialization time
ESTIMATING AND SAMPLING INITIAL ERRORS: THE BREEDING METHOD - 1992

- **DATA ASSIM:** Growing errors due to cycling through NWP forecasts
- **BREEDING:** - Simulate effect of obs by rescaling nonlinear perturbations
  - Sample subspace of most rapidly growing analysis errors
    - Extension of linear concept of Lyapunov Vectors into nonlinear environment
    - Fastest growing nonlinear perturbations
    - Not optimized for future growth –
      - Norm independent
    - Is non-modal behavior important?

References
1. Toth and Kalnay: 1993 BAMS
2. Tracton and Kalnay: 1993 WAF

Courtesy of Zoltan Toth
Concepts in ensemble forecasting

Ensemble forecasting:
A group of weather forecasts or multiple predictions

Ensemble mean: averaging all ensemble forecasts

Ensemble spread: standard deviation of ensemble members

Ensemble variance: variance of ensemble forecasts, square of ensemble spread

Forecast error: measure of the error of ensemble mean (absolute error or square error) or a member, single verification

Forecast uncertainty: uncertainty based on multiple forecasts, PDF

Spread-skill relationship misleading: (Houtekamer, 1993; Withaker and Loughe, 1998) ensemble spread – forecast error correlation

Spread-skill relationship: forecast uncertainty vs. actual uncertainty PDF
e.g., binned spread-skill correlation
THORPEX and NAEFS

The Observing System Research and Predictability Experiment (THORPEX)
the THORPEX Interactive Grand Global Ensemble (TIGGE)
EPS problems and cures

• Problems:
  – Biases.
  – Spread deficiencies
  – Lack of spread / skill relationship.
  – Etc.

• Cures
  – Design a better ensemble forecast system
    • Improved methods of generating initial conditions
    • Methods for dealing with model errors
  – Post-process the ensemble forecasts to ameliorate these errors
Ranked histograms

Over dispersive

Under dispersive

Negative bias

Positive bias

Horizontal line: perfect ensemble
Motivation for generating ensemble forecasts:

1) Greater accuracy of ensemble mean forecast (half the error variance of single forecast)
2) Likelihood of extremes
3) Non-Gaussian forecast PDF’s
4) **Ensemble spread as a representation of forecast uncertainty**
Naturally Paired Spread-skill measures:

- Set I (L1 measures):
  - Error measures:
    - absolute error of the ensemble mean forecast
    - absolute error of a single ensemble member
  - Spread measures:
    - ensemble standard deviation
    - mean absolute difference of the ensembles about the ensemble mean

- Set II (squared moments; L2 measures):
  - Error measures:
    - square error of the ensemble mean forecast
    - square error of a single ensemble member
  - Spread measures:
    - ensemble variance
Ensemble “Spread” or “Dispersion”  
Forecast “Skill” or “Error”  

Probability  

“skill” or “error”  

“dispersion” or “spread”  

Rainfall [mm/day]
Spread-Skill Correlation...

- ECMWF spread-skill (black) correlation << 1
- Even “perfect model” (blue) correlation << 1 and varies with forecast lead-time

- 1 day
  - ECMWF
    - $r = 0.33$
    - “Perfect”
    - $r = 0.68$

- 4 day
  - ECMWF
    - $r = 0.41$
    - “Perfect”
    - $r = 0.56$

- 7 day
  - ECMWF
    - $r = 0.39$
    - “Perfect”
    - $r = 0.53$

- 10 day
  - ECMWF
    - $r = 0.36$
    - “Perfect”
    - $r = 0.49$
Ensemble spread – error correlation

Ensemble spread – error correlation, for a lognormal distribution,

\[ \rho_{\sigma,|E|} = \sqrt{\frac{2}{\pi} \left[ \frac{1 - \exp(-\beta^2)}{1 - \frac{2}{\pi} \exp(\beta^2)} \right]} \]

Highest value: \( \sqrt{\frac{2}{\pi}} \approx 0.8 \)
One option …

1) Assign dispersion bins, then:

2) Average the error values in each bin, then correlate

3) Calculate individual rank histograms for each bin, convert to a scalar measure

Tom Hopson       NCAR
Option 2: "binned" Spread-skill Correlation

- "perfect model" (blue) approaches perfect correlation
- "no-skill" model (red) has expected under-dispersive "U-shape"
- ECMWF forecasts (black) generally under-dispersive, improving with lead-time
- Heteroscedastic model (green) slightly better(worse) than ECMWF forecasts for short(long) lead-times
Conclusions about spread-skill relationship

• Spread-skill correlation can be misleading measure of utility of ensemble dispersion
  – Dependent on “stability” properties of environmental system
• 3 alternatives:
  1) “normalized” (skill-score) spread-skill correlation
  2) “binned” spread-skill correlation
  3) “binned” rank histogram
• ratio of moments of “spread” distribution also indicates utility
  -- if ratio --> 1.0, fixed “climatological” error distribution may provide a far cheaper estimate of forecast error
• Truer test of utility of forecast dispersion is a comparison with a heteroscedastic error model => a statistical error model may be superior (and cheaper)
• Important to account for observation and sampling uncertainties when doing a verification

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Spaghetti plot

Pros: Avoids the assumption of normally distributed data
      Ensemble mean and spread
      Cluster and outliers
      Mode (i.e. most frequently occurring solution)

Cons: One or only a few contours
      Cannot see full field of interest over the full domain
      Selection of the right contour
Spaghetti plot

Ensemble Spaghetti Diagram for 24 hr Precipitation Exceeding 0.5"
0000 UTC  19 Nov 2001 Forecast Valid 1200 UTC  22 Nov 2001

NCEP Data / The COMET Program
Plume diagram

SREF Ensemble Member Forecast Initialized 09 UTC 22Oct2009
Accumulated 3-hour precipitation Starting 12 UTC 20Oct2009
Green=rain; red=freezing rain; cyan/teal=ice pellets; blue=snow

Precip (inches)

RAIN
Mean: 0.09
Max.: 0.33
Min.: 0.00

SNOW
Mean: 0.08
Max.: 0.65
Min.: 0.00

FZRA
Mean: 0.00
Max.: 0.00
Min.: 0.00

ICEPELL
Mean: 0.00
Max.: 0.00
Min.: 0.00

Station Data Plot for Scottsbluff NE

NOAA/NCEP/NWS
Postage Stamps: 500 mb HGHT

14 members + CTRL

Note deeper troughs in some fcsts

GFS Ensemble at SPC: F216 valid 00 UTC 21 June 2006
Spread (sample standard deviation) quantifies the degree of uncertainty.
Box and Whisker diagram

![Box and Whisker Diagram for Ensemble Forecast from 0000 UTC 19 Nov 2001](Image)

- Median
- 25th %-ile
- 75th %-ile
- Warmest
- Coldest

2 m Temperature (°C)

Forecast Verification Time:
- 00 UTC 11/19
- 12 UTC 11/19
- 00 UTC 11/20
- 12 UTC 11/20
- 00 UTC 11/21
- 12 UTC 11/21
- 00 UTC 11/22
- 12 UTC 11/22

NCEP Data / The COMET Program
PROBABILITY CHARTS

Pros: Depicts probabilities for exceeding threshold
Display the full domain
Ensemble members $\rightarrow$ probabilities

Cons:
Do not get full PDF
Representativeness of probabilities (limited ensemble size)
One threshold
Does not provide maximum value

Percentage of members with QPF $> .25''/24h$
Highest QPF at each point exceeded by 60% of the ensemble members
Starting Point

Forecaster selected blends to generate starting point grids
QPF Confidence Interval

Max/Min QPF derived from HPC QPF and Characteristic uncertainty of current pattern

http://www.hpc.ncep.noaa.gov/qpfci/qpfci.shtml
CONVECTIVE OUTLOOKS

Categorical and Probabilistic: Operational through Day 3; Exp through Day 8

Tornado (Hatched area 10% ≥ F2)

Wind

Hail (Hatched area 10% ≥ 2”)

NCEP
Experimental Enhanced Thunderstorms Outlooks

Thunderstorm Graphic valid until 3Z

Thunderstorm Graphic valid 3Z to 12Z
Ensemble Guidance at the SPC

- Develop specialized guidance for the specific application (severe weather, fire weather, winter weather)

- Design guidance that…
  - Helps blend deterministic and ensemble approaches
  - Facilitates transition toward probabilistic forecasts
  - Incorporates larger-scale environmental information to yield downscaled probabilistic guidance
  - Aids in decision support of high impact weather
    - Gauge confidence
    - Alert for potentially significant events

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Commonly Used Ensemble Guidance at the SPC

• Mean, Median, Max, Min, Spread, Exceedance Probabilities, and Combined Probabilities
  – Basic Weather Parameters
    • Temperature, Height, MSLP, Wind, Moisture, etc.
  – Derived Severe Weather Parameters
    • CAPE, Shear, Supercell and Sig. Tornado Parameters, etc.
  – Calibrated Probability of Thunderstorms and Severe Thunderstorms

David Bright
SREF Combined or Joint Probability

\[ \text{Pr} \left[ P_{12I} \leq 0.01'' \right] \times \text{Pr} \left[ RH \leq 15\% \right] \times \text{Pr} \left[ \text{WSPD} \geq 20 \text{ mph} \right] \times \text{Pr} \left[ \text{TMPF} \geq 60 \text{F} \right] \]
SREF Likely PTYPE and Mean P03I (contours)

Czys Algorithm
WAF (1996)

FCST: F024 VALID: Sat 20061230/0900 UTC
NOAA/NWS Storm Prediction Center, Norman, OK

PMPCPN & 32F TMP [1 mem=dot;Mean=solid;All=dash]
061230/0900V024 LIKELY PTYPE [Czys:Grn=R;Blue=S;Red=ZR;Orange=IP;Pink=ZR/IP]
SREF Combined or Joint Probability: STP Ingredients

Probability of Significant Tornado Environment

Pr [MLCAPE $\geq$ 1000 J/kg] X
Pr [MLLCL $\leq$ 1000 m] X
Pr [0-1KM HLCY $\geq$ 100 m$^2$/s$^2$] X
Pr [0-6 KM Shear $\geq$ 40 kts] X
Pr [C03I $\geq$ 0.01"]
Summary and discussions

• Challenges in QPF

• Ensemble forecasting can improve short-range weather forecasts (including QPF) than a single deterministic run.

• Important factors in ensemble and model configurations:
  - Initialization
  - Physical schemes
  - Boundary conditions

• Discussions
  - Improvements of mesoscale modeling
  - Quality and usefulness of short-range ensembles for QPF and PQPF
  - Integration and applications of NWP products