Numerical Seasonal Prediction: Approaches and Challenges

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Acknowledgments: Huug van den Dool (CPC), Suru Saha (EMC), Yuejian Zhu (EMC), NMME, IMME, CTB teams

THORPEX Workshop; September 19-20, 2012
Content

• Brief history of NWP and NCP
• State-of-the-Art Operational NCPs: Bias, Skill
• Hindcasts and post-processing methods
• NMME, IMME and consolidation approaches
• Initial conditions and model errors in NCP
• Broader challenges: seamless weather-climate forecasts; Earth system models
Brief History of NCP

1950
Charney, Fjortoft and Von Newmann (1950)

1954
Birth of NWP

1963
Epstein (1969)

1969
Lorenz (1963)

1970
Manabe and Bryan (1969)

1975
Lorenz (1975) - Forecast errors of the second kind

1979
Charney et al (1979) - Doubling CO₂ experiments

1980
Talagrand (1981) - 4DVar

1990
Gates et al (1999) - AMIP
Toth and Kalnay (1993) - Breeding
Parrish and Derber (1992) - NMC method

2000
THORPEX

2010
EnKF exp
T-PARC
TIGGE
YOTC, IPY

NWP and NCP system are built with the same physical principles, common ancestry
Brief History

• NCEP has lead some of these developments.
• NCEP models have incorporated most, if not all of these NWP, DA methods in its GFS DA-forecast system.
• Based on the GFS, two global operational ensemble prediction systems are currently in place: GEFS (and NAEFS) and CFS, each with distinct emphasis: Medium Range and Seasonal forecasts
• CFS is now producing subseasonal forecasts; GEFS is experimenting with forecasts beyond 2 weeks
The NCEP CFS v2

• Upgraded Data Assimilation and Forecast System
• Creation of new Reanalysis of the atmosphere, ocean, land and ice
• Creation of Reforecast over 29 years (1982-2010)
• Operational implementation (2011)

http://cfs.ncep.noaa.gov
CFSR execution: Atmospheric (GSI) analysis is made at 00, 06, 12 and 18UTC using a 9h Coupled FG; likewise ocean and sea-ice analysis from the same FG. GLDAS analysis using observed precip is made only at 00UTC

Saha et al, BAMS, Aug 2010
Coupled ocean-atmosphere reanalysis (CFSR)

Distinct and static background error covariances $B$
Reforecast Configuration for CFSv2 (T126L64)

- 9-month hindcasts initiated from every 5th day and run from all 4 cycles of that day, beginning from Jan 1 of each year, over a 29 year period from 1982-2010. **This is required to calibrate the operational CPC longer-term seasonal predictions (ENSO, etc)**
- In addition, a single 1 season (123-day) hindcast run, initiated from every 0 UTC cycle between these five days, over the 12 year period from 1999-2010. **This is required to calibrate the operational CPC first season predictions for hydrological forecasts (precip, evaporation, runoff, streamflow, etc)**
- In addition, three 45-day (1-month) hindcast runs from every 6, 12 and 18 UTC cycles, over the 12-year period from 1999-2010. **This is required for the operational CPC week3-week6 predictions of tropical circulations (MJO, PNA, etc)**

Jan 1: 0 6 12 18  
Jan 2: 0 6 12 18  
Jan 3: 0 6 12 18  
Jan 4: 0 6 12 18  
Jan 5: 0 6 12 18  
Jan 6: 0 6 12 18

- **9 month run**
- **1 season run**
- **45 day run**

Saha et al 2011
Operational Configuration for CFSv2 real time forecasts (T126L64)

- There will be 4 control runs per day from the 0, 6, 12 and 18 UTC cycles of the CFS real-time data assimilation system, out to 9 months.
- In addition to the control run of 9 months at the 0 UTC cycle, there will be 3 additional runs, out to one season. These 3 runs per cycle will be initialized as in current operations.
- In addition to the control run of 9 months at the 6, 12 and 18 UTC cycles, there will be 3 additional runs, out to 45 days. These 3 runs per cycle will be initialized as in current operations.
- There will be a total of 16 CFS runs every day, of which 4 runs will go out to 9 months, 3 runs will go out to 1 season and 9 runs will go out to 45 days.
### CFSv2 OPERATIONAL IMPLEMENTATION

**PERTURBATION OF Members 2, 3 and 4 at each cycle**

<table>
<thead>
<tr>
<th>6Z</th>
<th>0 0 Z</th>
<th>G D A S</th>
<th>Dy A-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0</td>
<td>M2Dy-2 00Z= 0.85xA-2 + 0.1xA-3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 Z</td>
<td>M3Dy-2 00Z = A-2 + M1Dy-3 – M2Dy-3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G D A S</td>
<td>M4Dy-3 00Z = A-2 – M1Dy-3 + M2Dy-3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dy A-2</td>
<td>M1Dy-2 00Z dy-1 9mth control</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6Z</th>
<th>0 0 Z</th>
<th>G D A S</th>
<th>Dy A-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0</td>
<td>M2Dy-1 00Z= 0.85xA-1 + 0.1xA-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 Z</td>
<td>M3Dy-1 00Z = A-1 + M1Dy-2 – M2Dy-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G D A S</td>
<td>M4Dy-1 00Z = A-1 – M1Dy-2 + M2Dy-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dy A-1</td>
<td>M1Dy-1 00Z dy-1 9mth control</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6Z</th>
<th>0 0 Z</th>
<th>G D A S</th>
<th>Dy A0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0</td>
<td>M2Dy0 00Z= 0.85xA0 + 0.1xA-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 Z</td>
<td>M3Dy0 00Z = A0 + M1Dy-1 – M2Dy-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G D A S</td>
<td>M4Dy0 00Z = A0 – M1Dy-1 + M2Dy-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dy A0</td>
<td>M1Dy0 00Z dy0 9mth control</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Saha et al 2011
SST Anomalies

1982-2010

High skill in tropical SST
SST Anomalies

All initial months, all leads average
Gridpoint-wise Anomaly Correlation

1982-2010

PERS

MME Average (Split Clim)

Area Average AC=0.392164

Area Average AC=0.493145

Systematic Error [K]

PERS

MME Average

SE=-0.00281714, Abs SE=0.00718846

SE=-0.25248, Abs SE=0.364789
Correctly Removing systematic errors

Useful skill out to 8 months for Nino 3.4 Index
2m Temperature

Notice so low values
All initial months

Models have not been able to propagate adequately good SST skills to other critical variables.
### IMME= CFSv2+ EURO SIP MODELS

<table>
<thead>
<tr>
<th></th>
<th>NCEP/CFSv2</th>
<th>ECMWF</th>
<th>UKMET</th>
<th>METF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atmospheric Model</strong></td>
<td>T126L64</td>
<td>Syst 4: T255L91</td>
<td>Glosea4 (120km) L85</td>
<td>T42L91 (T63-linear grid)</td>
</tr>
<tr>
<td><strong>Ocean Model</strong></td>
<td>MOM4 L40 0.25 deg Eq, 0.5 deg global</td>
<td>NEMO 0.3 deg Eq 1 deg global</td>
<td>NEMO L75 0.3 deg Eq 1 deg global</td>
<td>ORCA 0.5 deg Eq 2 deg global</td>
</tr>
<tr>
<td><strong>Atmosphere/Ocean Coupling Frequency</strong></td>
<td>30 minutes</td>
<td>3 hr</td>
<td>IN</td>
<td>IN</td>
</tr>
<tr>
<td><strong>Land Model</strong></td>
<td>NOAA 4-layer</td>
<td>IN</td>
<td>IN</td>
<td>IN</td>
</tr>
<tr>
<td><strong>Sea Ice Model</strong></td>
<td>3-layer interactive Seaice model</td>
<td>IN</td>
<td>IN</td>
<td>IN</td>
</tr>
<tr>
<td><strong>Period of Hindcasts</strong></td>
<td>1982-2010 (29 years)</td>
<td>1981-2010 (30 years)</td>
<td>1989-2002 (14 years)</td>
<td>1981-2009 (29 years)</td>
</tr>
<tr>
<td><strong>Number of hindcast members</strong></td>
<td>24(28)</td>
<td>15</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td><strong>Number of Leads</strong></td>
<td>0-9 months</td>
<td>0-7 months</td>
<td>0-6 months</td>
<td>0-6 months</td>
</tr>
</tbody>
</table>

IN: Information needed
MME Mean Outperforms Individual Models

**EUROSIP T2m AC over Land**

T2M AC Global Land Average

**NMME Precipitation Forecast Skills**

NMME Forecast Skills (AC) for PRA Aug 1C Ave 30°S-30°N

- **Model 1**
- **Model 2**
- **Model 3**
- **Model 4**
- **MMEave**
# US NMME Phase-I Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Hindcast Period</th>
<th>Ensemble Size</th>
<th>Lead Times</th>
<th>Arrangement of Ensemble Members</th>
<th>Contact and reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFSv1</td>
<td>1981-2009</td>
<td>15</td>
<td>0-8 Months</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; 0Z +/-2 days, 21&lt;sup&gt;st&lt;/sup&gt; 0Z +/-2d, 11&lt;sup&gt;th&lt;/sup&gt; 0Z +/- 2d</td>
<td>Saha (Saha et al. 2006)</td>
</tr>
<tr>
<td>CFSv2</td>
<td>1982-2009</td>
<td>24(28)</td>
<td>0-9 Months</td>
<td>4 members (0, 6, 12, 18Z) every 5&lt;sup&gt;th&lt;/sup&gt; day</td>
<td>Saha (Saha et al. 2010)</td>
</tr>
<tr>
<td>GFDL-CM2.2</td>
<td>1982-2010</td>
<td>10</td>
<td>0-11 Months</td>
<td>All 1&lt;sup&gt;st&lt;/sup&gt; of the month 0Z</td>
<td>Rosati (Zhang et al. 2007)</td>
</tr>
<tr>
<td>IRI-ECHAM4-f</td>
<td>1982-2010</td>
<td>12</td>
<td>0-7 Months</td>
<td>All 1&lt;sup&gt;st&lt;/sup&gt; of the month 0Z</td>
<td>DeWitt (DeWitt 2005)</td>
</tr>
<tr>
<td>IRI-ECHAM4-a</td>
<td>1982-2010</td>
<td>12</td>
<td>0-7 Months</td>
<td>All 1&lt;sup&gt;st&lt;/sup&gt; of the Month 0Z</td>
<td>DeWitt (Dewitt 2005)</td>
</tr>
<tr>
<td>CCSM3.0</td>
<td>1982-2010</td>
<td>6</td>
<td>0-11 Months</td>
<td>All 1&lt;sup&gt;st&lt;/sup&gt; of the Month 0Z</td>
<td>Kirtman (Kirtman and Min 2009)</td>
</tr>
<tr>
<td>GEOS5</td>
<td>1981-2010</td>
<td>6</td>
<td>0-9 Months</td>
<td>1 Member every 5&lt;sup&gt;th&lt;/sup&gt; day</td>
<td>Schubert (Vernieres et al. 2011)</td>
</tr>
</tbody>
</table>
## NMME

### One-tier Coupled Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Atmosphere</th>
<th>Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFSv1</td>
<td>T62L64</td>
<td>MOM3 L40, 0.3° Eq</td>
</tr>
<tr>
<td>CFSv2</td>
<td>T126L64</td>
<td>MOM4 L40, 0.25° Eq</td>
</tr>
<tr>
<td>GFDL-CM2.2</td>
<td>2x2.5° L24</td>
<td>MOM4 L50, 0.3° Eq</td>
</tr>
<tr>
<td>IRI-ECHAM4 -f</td>
<td>T42L19</td>
<td>MOM3 L25 0.5° Eq</td>
</tr>
<tr>
<td>IRI-ECHAM4-a</td>
<td>T42L19</td>
<td>MOM3 L25 0.5° Eq</td>
</tr>
<tr>
<td>CCSM3.0</td>
<td>T85L26</td>
<td>POP L40, 0.3° Eq</td>
</tr>
<tr>
<td>GEOS 5</td>
<td></td>
<td>MOM4</td>
</tr>
</tbody>
</table>
Real Time:
Real time integrations are collected from the respective ftp sites at 5pm COB 8th of the month.

Desire: Robust scripts that can handle any number of models and members
DJF Season [Temperature]
NA Prate

IMME prate_us forecast

Season 1

Season 3

Season 2

Season 4
Nino 3.4 Plume

Ensemble averages of each model in NMME plus IMME

Q. Zhang (CPC)

All NMME Members (~100)
Current developments

- Skill Masks (Evaluation strategies)
- Consolidation methods
- Probabilistic forecast products
- Trends
- Extremes
Notes

• IMME and NMME share similar scripts for data handling
• NMME became operational in August 2011, IMME in December 2011
• Sanity Check: First Friday after the 8th of the month, thus, UKL ensemble is usually not included
• NMME is voluntary. Funding is uncertain.
• NMME and IMME becoming major products to guide operational seasonal forecasts
• Gradually incorporating essential products (Nino 3.4 plumes, skill masks, etc.)
## Purpose of hindcast:

<table>
<thead>
<tr>
<th></th>
<th>activity</th>
<th>Data requirements</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Correct the mean</td>
<td>15-20 (30) years</td>
<td>WMO says 30</td>
</tr>
<tr>
<td>2</td>
<td>Correction pdf</td>
<td>45</td>
<td>WMO says 45</td>
</tr>
<tr>
<td>3</td>
<td>Estimate of AC-skill to 0.15 accuracy</td>
<td>45</td>
<td>CPC rejects local forecasts &lt;=0.30</td>
</tr>
<tr>
<td>4</td>
<td>To test whether we can tell AC-skill Mdl A &gt; Mdl B by 0.1</td>
<td>More</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Attempt to assign non-equal weights to models</td>
<td>100’s to 1000’s of years</td>
<td>Unless we become smarter</td>
</tr>
</tbody>
</table>
MME: Better than the sum of the parts?

OR:

“A chain is only as strong as its weakest link”
<table>
<thead>
<tr>
<th>Method</th>
<th>Formula/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-model ensemble mean (MM)</td>
<td>$\alpha_i = 1/9$, $i=1,..K$, $K$ number of methods</td>
</tr>
<tr>
<td>Correlation (COR)</td>
<td>$\alpha_i = \frac{\text{cov}(\xi_i, O)}{\sigma_{\xi_i}^2}$, $\xi_i$ time series forecast of $i$-th method</td>
</tr>
<tr>
<td>Frequency of best (FRE)</td>
<td>$\alpha_i = {N_i/N}$, $N$ number of training years, $N_i = \left{ \sum_N \text{cases}(\xi_i) \mid \xi_i = \min{(\xi_k - O)^2, k = 1,..K} \right}$</td>
</tr>
<tr>
<td>Ridging (RID)</td>
<td>$\overline{\alpha} = (A + \lambda I)^{-1}b$</td>
</tr>
<tr>
<td>$A = Z^T Z$, $b = Z^T O$, $\lambda$ is such that $\alpha_i \geq -0.01$, $i=1,..K$ and sum alpha squared small</td>
<td></td>
</tr>
<tr>
<td>Double pass Ridging (RI2)</td>
<td>Set to zero any $\alpha_i &lt; 0$, $i=1,..K$ after first RID pass</td>
</tr>
<tr>
<td>RID with MM constraint (RIM)</td>
<td>$\overline{\alpha} = (A + \lambda I)^{-1}\left(b + \frac{\lambda}{K}1\right)$</td>
</tr>
<tr>
<td>RID with weighted mean constraint (RIW)</td>
<td>$\overline{\alpha} = (A + \lambda I)^{-1}b^*$</td>
</tr>
<tr>
<td>where $b^*<em>i = b_i\left(1 + \frac{\lambda}{a</em>{ii}f}\right)$ and $f = \sum_{i=1}^K \frac{b_i}{a_{ii}}$.</td>
<td></td>
</tr>
<tr>
<td>Unconstrained (UR)</td>
<td>$\overline{\alpha} = A^{-1}b$</td>
</tr>
</tbody>
</table>
Pattern Anomaly Correlation

Average over all leads and initial months

- D1
- D2
- D3
- D4
- D5
- D6
- D7
- CFS
- CA
- MMA
- COR
- FRE
- RID
- RI2
- RIM
- RIW
- UR

Consolidation methods

Dependent: CV-3RE
Historical RPSS for GEFS

20 Member Ensemble

- GEFS constantly improving: Better I.C., higher resolution, most recent GFS
- GEFS currently outperforms climatology beyond 16 days; slowly approaching to zero
Global ensemble systems at NCEP

• Coupled CFSv2 45 days currently in operations and associated hindcast
  – Initial conditions not optimized to represent weather forecast uncertainty
  – Frozen model and hindcast

• GEFS state of the art atmospheric model
  – Uncoupled model
  – No hindcast
Past evaluations

- Evaluations of experimental GEFS (in operations in 2007) showed AC > 0.5 at around 20 days for the two modes of MJO
- GEFS outperformed the CFSv1. With a limited sample size (two months) it there is a large uncertainty.
- The new CFSv2 now also outperforms the CFSv1
- No evaluations have been carried out of the two current ensemble systems

From Qin Zhang (CPC-NOAA)
**Experimental Design for BV**

- Model: GEOS5 Coupled GCM (Tag: Natanas-replay-7_21mom)
- Norm variable: Velocity Potential at 200hPa over 40-180E, 20S-20N
- Rescaling time scale: 1day, 2day, and 5day
- Rescaling norm magnitude: Variously tested

Chikamoto et al. 2007

BV: 1-day rescaling with 3.3% norm magnitude

Yoo Ham and Schubert (2010)

Space-time power spectrum
Correlation skill improvement of BV prediction is robust during unpredictable phase of CNTL prediction.

Yoo Ham and Schubert (2010)
WWRP (THORPEX) – WCRP Collaboration

- Seamless weather-climate EPS
- Multi-scale organization of tropical convection and its two-way interaction with the global circulation
- Data Assimilation of coupled systems
- Utilization of subseasonal and seasonal predictions for social and economic benefits
Challenges

• Operational Hybrid DA for the atmosphere is in place and there are some experiments with Local EnKF for the Ocean. How do we approach the problem of coupled DA in NCP in a systematic way?

• Representation of model errors in EPS for seasonal prediction systems are done *ad hoc*.

• Adequately couple Land and other climate components to the operational NCP

• Hindcast: 1000’s years of data that need to be exploited. What would be the appropriate length, ensemble size?