ENSEMBLE POST-PROCESSING

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Acknowledgements:
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http://wwwt.emc.ncep.noaa.gov/gmb/ens/index.html

OUTLINE

- INTRODUCTION TO ENSEMBLE POST-PROCESSING
  - MOTIVATION, OBJECTIVE, METRICS
- APPROACH
  - SYSTEMATIC COLLABORATIVE / TEAM EFFORT
- METHODOLOGY
  - BAYESIAN PROCESSOR, DOWNSCALING
- ISSUES
  - PROXY FOR TRUTH, HINDCASTING, WHAT'S MOST IMPORTANT?
- RESULTS
  - COMPARISON WITH RAW OUTPUT, GMOS, NDFD

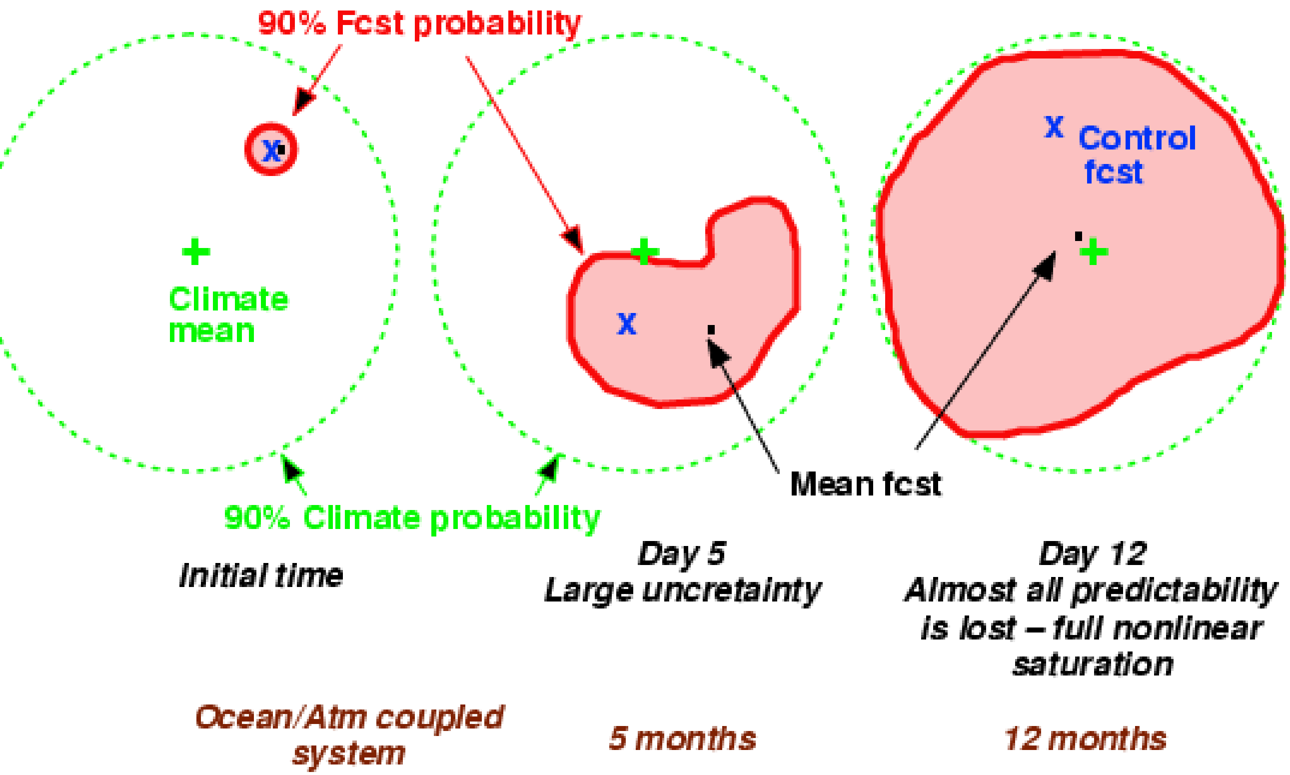
CHAOS + INITIAL + MODEL ERRORS = LOSS OF PREDICTABILITY

ORIGIN OF FORECAST UNCERTAINTY

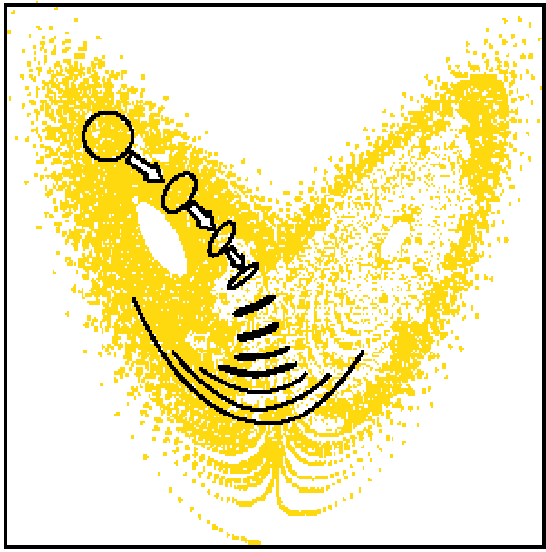
1) The atmosphere is a **deterministic system** *AND* has at least one direction in which **perturbations grow**

2) **Initial** state (and model) has **error** in it ==>

Chaotic system + Initial error =(Loss of) Predictability



Buizza 2002



USER REQUIREMENTS:
PROBABILISTIC FORECAST INFORMATION IS CRITICAL

ECONOMIC VALUE OF FORECASTS

Given a particular forecast, a user either does or does not take action (eg, protects its crop against frost) *Mylne & Harrison, 1999*

FORECAST

OBSERVATION	*YES*	*NO*
YES	H(its) ***Mitigated Loss***	M(isses) ***Loss***
NO	F(alse alarms) ***Cost***	C(orrect rejections) ***No Cost***

$$Mean\ Expense_{fc} = hML + mL + fC$$

$$Mean\ Expense_{perf} = oML$$

$$ME_{cl} = \min[oL,\ oML + (1-o)C]$$

$$Value = \frac{ME_{cl} - ME_{fc}}{ME_{cl} - ME_{perf}}$$

o=climatological frequency

Optimum decision criterion for user action: P(weather event)=C/L

(Murphy 1977)

ENSEMBLE FORECASTING

- **Objective**
  - Generate finite sample of solutions representing underlying forecast pdf
    - Likelihood of solutions (equal or not equal) must be known to estimate pdf

- **Metrics**
  - Better (more informative) estimate of future pdf and its characteristics
    - Maximize statistical resolution
      - Narrow pdf as much as possible WHILE
    - Providing good statistical reliability
      - Forecast vs. observed distributions match
        - Realism/fidelity of solutions
        - Statistical corrections

WHAT'S NEEDED TO ACHIEVE GOAL?

- Estimate & sample initial pdf
  - Dynamically conditioned perturbations
    - Link with DA
- Represent model related uncertainty
  - Consider each model component
    - Link with numerical modeling
- Statistically correct ensemble output
  - Remove lead-time dependent bias
    - How large sample do we need?
  - Downscale bias-corrected forecasts
    - Relationship between high & low-res analysis fields OR
    - LAM
- Apply statistically corrected ensemble output
  - Inter / extrapolate ensemble data for continuous pdf
  - Drive downstream applications with ensemble trajectories

NCEP ENSEMBLE SYSTEMS – NOV. 2007

SYSTEM / COMPONENT	**SEASONAL**	**GLOBAL**	**REGIONAL**	**HIGH IMPACT (Under design)**
Model	GFS+MOM3 Coupled model	GFS	ETA (10), RSM (5), WRF(2*3)	Relocatable WRF
Initial uncertainty	*Lagged*	*ET with Rescaling*	*Breeding*	*?*
Boundary perturbations	*None*	*Fixed SST*	*From global ensemble*	*From regional ensemble*
Model diversity	None	None	Mult. conv. schemes	Yes
Stochastic physics	None	None (Planned)	None	?
Tropic. storm spec.	None	Relocation	None	Hurricane WRF
Schedule	Twice/day	00, 06, 12, 18 UTC	03, 09, 15, 21 12UTC	On demand
Spatial resolution / Output freq.	T62L64 (atm), 1/3-1 deg (ocean), daily	T126L28 (d0-d16) ~90km 6, hrly	32-45 km, 3 hrly	5-10 km, 1 hrly
Control member(s)	Yes	Yes (hi-lo)	Yes (5)	Yes
Perturbed members	Lagged	20	16+5	?
Forecast length	10 mos	16 days (384 hours)	87 hrs	6-12 hrs
Post-processing	Based on 25 yrs hindcasts	Bias correction (Recursive filter, all members)	Bias correction (Recursive filter, each member	?
Implementation	2004	March 27th 2007	Nov. 2007	2010?

ENSEMBLE TEAM APPROACH

- Common scientific principles - Chaos affects all spatial/temporal scales
  - Quantify all forecast uncertainty - Inseparable from forecasting in general
      - Links with observing system, data assimilation, numerical modeling, user applications
  - Represent all forecast uncertainty at their source - Otherwise poor reliability
    - Only chance to propagate true uncertainty through forecast process
- Unified approach
  - Common techniques across applications wherever appropriate / possible
- Ensemble team members
  - Work in implementation teams, coordinated with rest of EMC & NCO
  - Interact with broader research and user communities

COMPONENT		Adaptive Observations	Initial Perturbations	Model Perturbations	Statistical Post-Proc.	Product Generation	Verification
FORECAST SYSTEM LINK		*Obs. System Design*	*Data Assimilation*	*Numerical Modeling*			
APPLICATION	PEOPLE	Masutani, Song,	Wei	Hou, Du	Cui, Pena	Zhou, Zhu	Zhu, Zhou, Hou
Coupled	Pena						
Global	Zhu, Wobus						
Regional	Du						
High-Impact							
Ocean wave	Chen/Cao						
Sea Ice	Grumbine						
Riverflow/ Land-surface	Hou						

ENSEMBLE POST-PROCESSING

- **Goal**
  - Produce **best numerical guidance** with adaptive statistical methods requiring
      - Small sample (lessen need for hind-casts) & Little software maintenance
- **Approach**
  - **Combine all information** relevant to forecast problem

    No separate guidance for NGM, NAM, GFS, etc etc
    - Climatological pdf
    - Single NWP center
      - Global
        - » Hires (single value)
        - » Lower res (ensemble)
      - Regional
        - » Hires (single value)
        - » Lower res (ensemble)
    - Same info from multiple centers
    - Any other relevant info (conditional climate, etc)
  - ***Benefit for product suite design***
    - Objective guidance for optimal design of NWP system
      - How much each component contributes determines their relative weight in production suite
- **Output**
  - ***Single set of guidance*** (not a multitude of guidance)
  - Derived products from pdf (NAEFS products available now)
    - Eg, 10, 50, 90 percentile of univariate pdf
  - Full ensemble (from all sources, ftp access possible soon)
    - All information can be derived by users (joint probability of heavy precip & strong wind)

METHODS FOR POST-PROCESSING ENSEMBLES

- **Bias correction**
  - *Techniques*: Bayesian, to remove lead-time dependent syst. error on model grid
    Compares favorably with traditional MOS guidance
    - Unconditional systematic error
      - Proper "ensemble structure" (Coldest pattern appears with lowest temp)
    - Systematic error in selected pdf characteristics (eg, spread, etc)
      - Reliability ensured
  - *Need sample for forecast* – "proxy for truth" pairs
  - *Output* is bias-free (posterior) pdf
- **Ensemble adjustment**
  - *Technique*: Adjust ensemble members to represent posterior pdf
  - *Output*: Bias-free ensemble members on model grid (like coarse res. analyses)
- **Downscaling**
  - *Techniques*
    - Use relationship between coarse (model) and fine resolution (RTMA) analyses
      - Climate mean statistics
      - Regime dependent climate statistics
      - Case dependent
        Dual resolution ensemble approach, Smartinit for derived variables
    - Add sub-model-grid scale temporal/spatial variability
  - *No need for forecast sample* – needs only hires analysis/observations
  - *Output*: Downscaled bias-free ensemble members
    - Ready for deriving any user info

NCEP COLLABORATIVE EFFORTS (NOT INCLUSIVE)

- Meteorological Service of Canada (MSC)
  - North American Ensemble Forecast System (NAEFS)
    - Evolve into National Unified Operational Prediction Capability (NUOPC)
      - FNMOC & AFWA
- THORPEX
  - End-to-end probabilistic forecast process
    - National / international collaborators
- Univ. Virginia - Prof. Roman Krzysztofowicz
  - Bayesian methods
- GSD/ESRL – Paul Schultz et al.
  - Downscaling methods
- OHD / RFCs – DJ Seo et al.
  - Test statistically post-processed data in hydrometeorological ensemble applications
    - XEFS connection
- MDL – Kathy Gilbert et al.
  - Joint evaluation of numerical guidance (NDGD)
  - Other opportunities?
    - Eg, proxy for truth

ENSEMBLE POST-PROCESSING ISSUES

- **What should "proxy for truth" be?**
  - NWS should adapt high resolution gridded analysis as proxy for truth
    - Need consensus effort/choice to
      - Improve product
      - Eliminate confusion on developers' and users' sides
    - Example: RTMA (currently 5x5 km)
      - Draw close to observations
      - Eliminate bias of first guess wrt observations
        - » Exact choice may not be critical above certain quality?

ENSEMBLE POST-PROCESSING ISSUES - 2

- **How large sample of <forecast – proxy for truth> pairs needed for *bias correction*?**
  - Depends on statistical method used
    - Frequentist's approach
      - Uses joint forecast – truth pairs for bias-correcting forecasts
        - » Large joint sample needed to remove sampling noise from climatology of corrected forecasts
    - Bayesian methods (theoretically sound)
      - Combine info from long observed climate and small joint (fcst – truth) sample
        - » **Can work with much (3-5 times?) smaller joint sample**
  - Experience
    - Using most recent 60-days data with frequentist's approach
      - Excellent results out to 3-5 days lead time compared with using large hind-cast dataset
        - » Bo et al. 2004, Hamill 2007
  - Anticipation
    - Bayesian methods will work well beyond 5 days with small but representative hind-cast sample
  - Note
    - ***No need for hindcasts for downscaling***

ENSEMBLE POST-PROCESSING ISSUES - 3

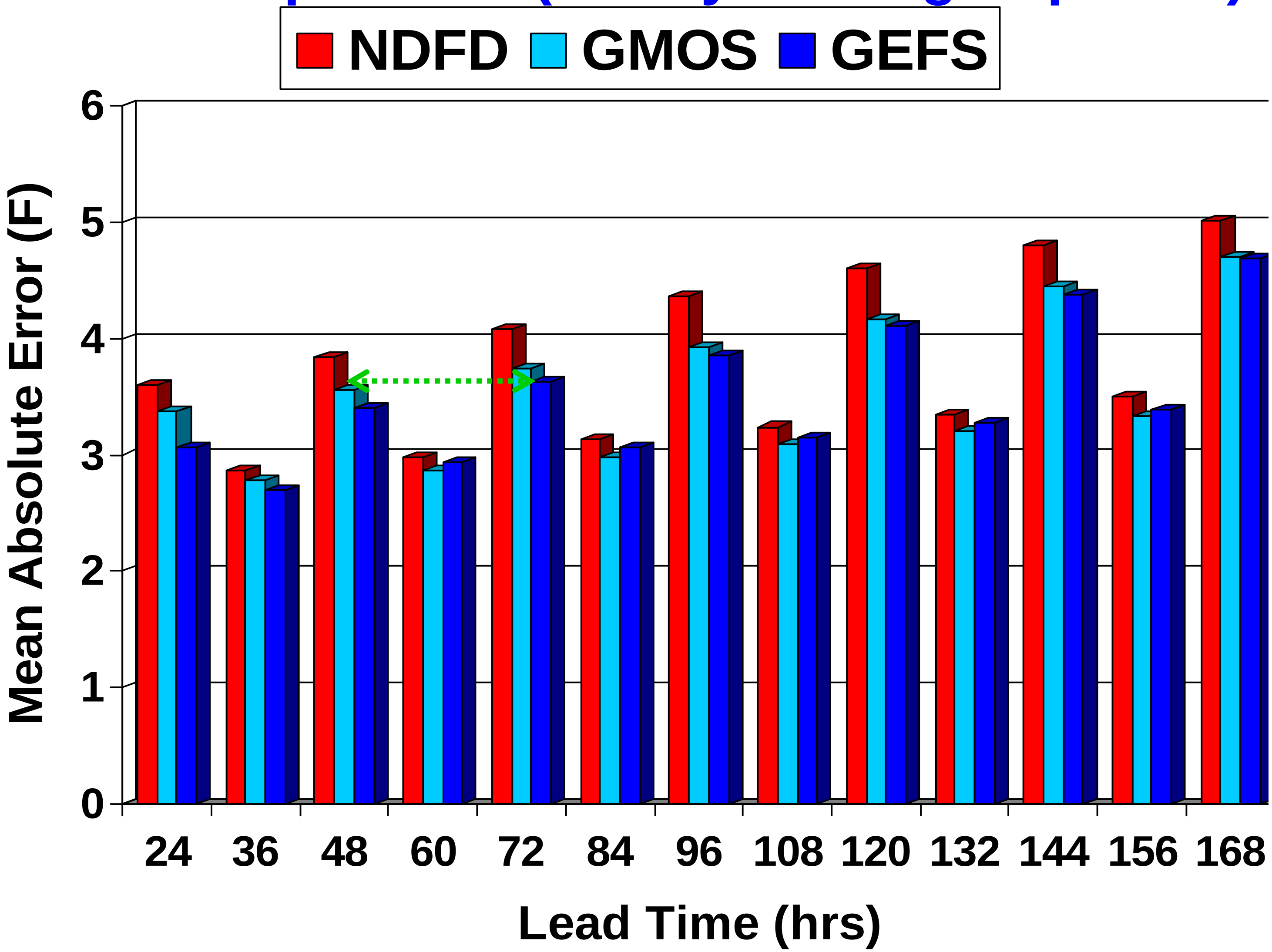
- **What are relative contributions for bias correction vs. downscaling?**
  - Depends on sophistication of NWP methods (DA, model, ensemble)
    - Crude NWP methods (20 yrs ago)
      - Lead-time dependent bias correction was critical to remove drift on model grid
        - » Need for joint sample
    - Current NWP methods
      - Downscaling may be more important
        - » **No need for forecast sample**
  - Experience
    - Downscaling dominates positive results when both methods applied
      - Other studies combine bias correction / downscaling, attribute good results to use of large hindcast dataset
        - » Must consider effect of inherent downscaling

Large hindcast data needed due to choice of combined frequentist bias correction / downscaling method

OFFICIAL NDFD FORECAST, GMOS & GEFS GUIDANCE VERIFIED *AGAINST RTMA* OVER CONUS

2-m Temperature (40 days in Aug-Sep 2007)

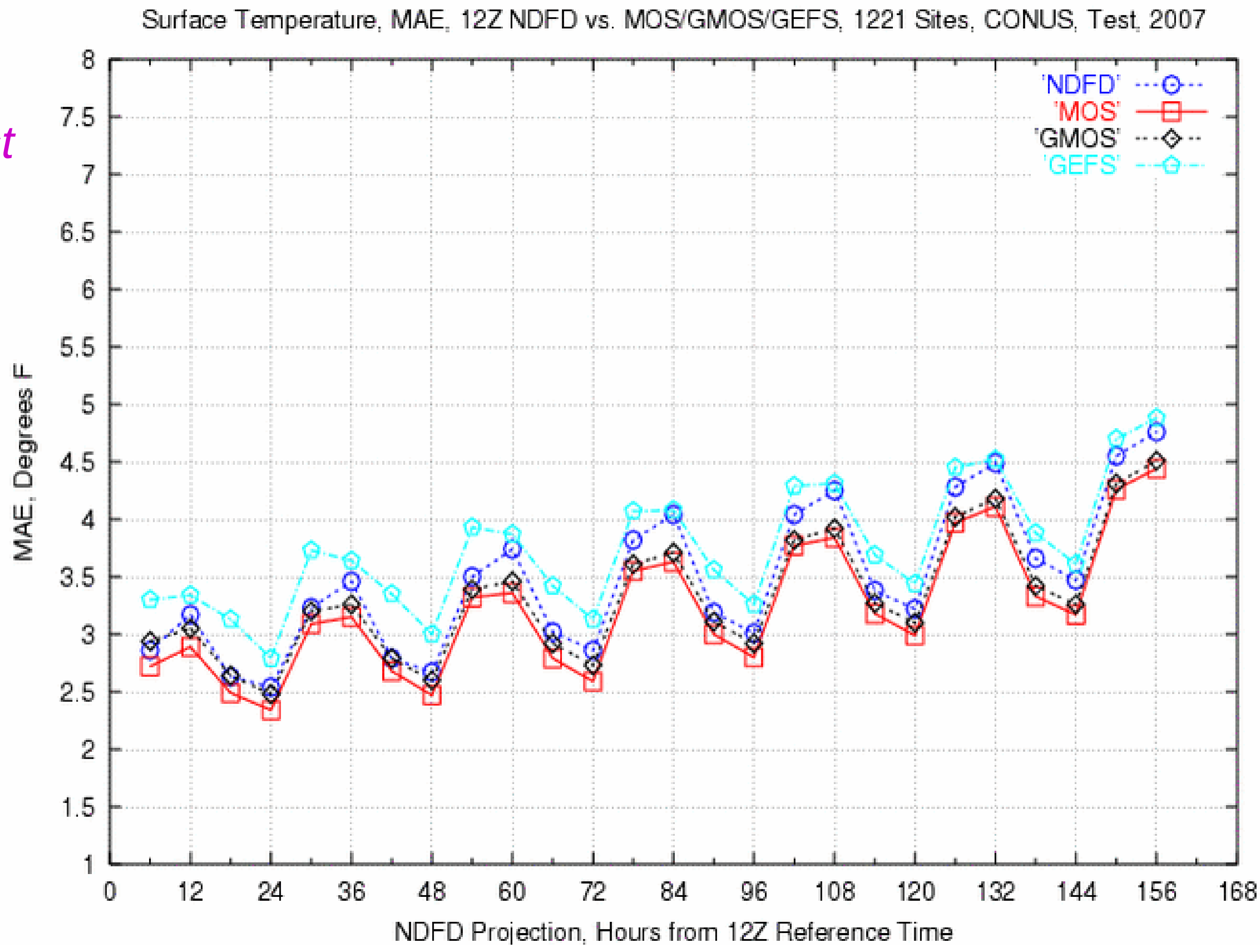
- *GMOS & GEFS guidance superior to official NDFD forecast*
  - *1-day advantage in skill*
- *GEFS/GMOS trained against RTMA / Obs*
- *GENS better than GMOS up to 48 hrs, similar afterwards*



Val Dagostaro

OFFICIAL NDFD FORECAST, GMOS & GEFS GUIDANCE VERIFIED *AGAINST MOS OBS* DATA

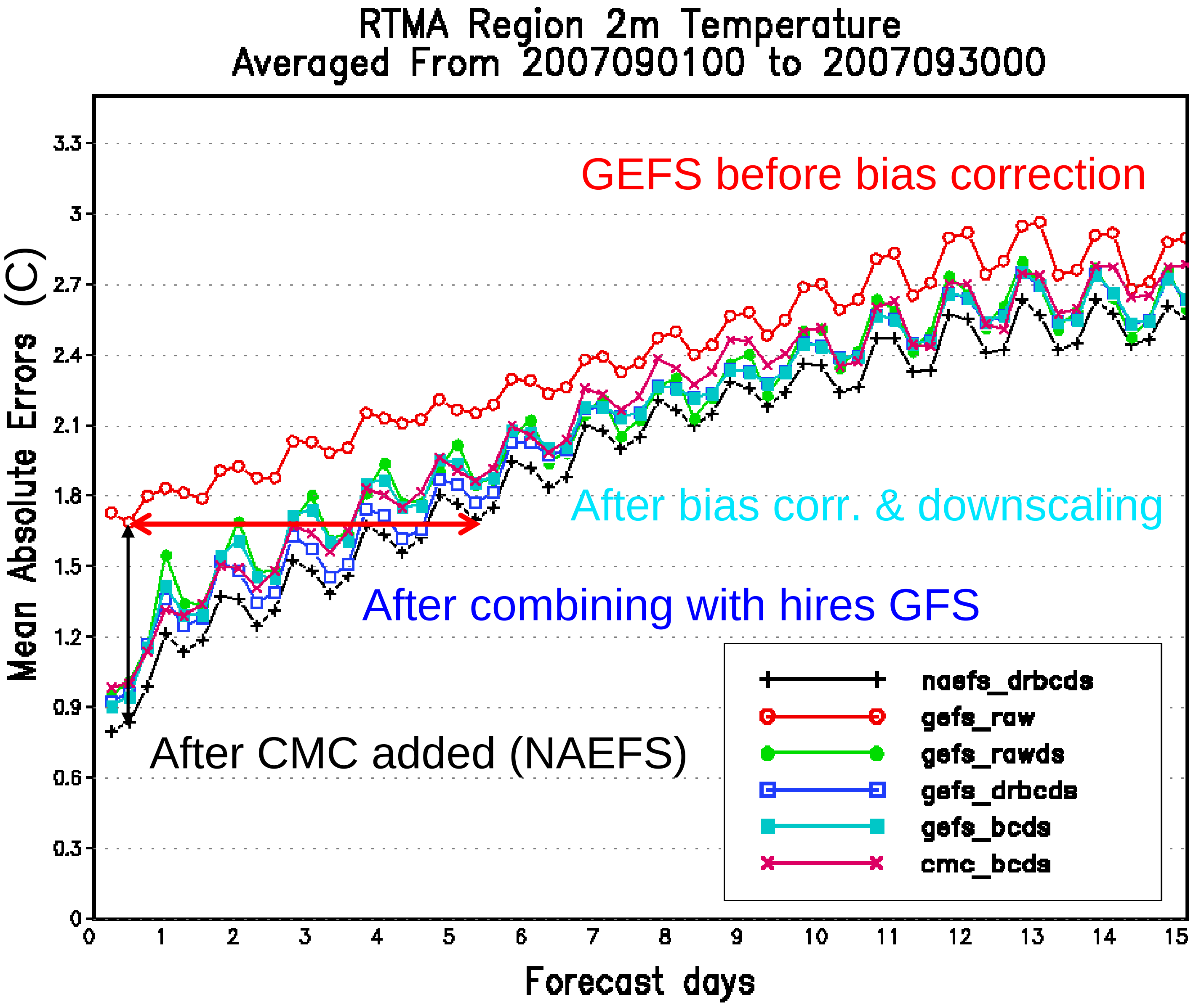
- *GEFS/GMOS trained against RTMA / Obs*
- *GMOS better than GEFS*



Val Dagostaro

NAEFS PRODUCT EVALUATION

- *5-day gain compared to raw guidance*
  - *Up to 40% error reduction*
- *Downscaling most important*
  - *Bias correction, dual resolution, NAEFS combination contributes with 1.5 day gain*
- *Operationally available*



Bo Cui

FORECASTER'S ROLE

- Background
  - New demands
    - Significant extension of product/service suite (NDFD, etc)
  - New tools
    - High quality numerical guidance (can be made) available

- Traditional role
  - Routinely prepares forecast (eg, modifies NWP guidance)
    - What should be maintained from these tasks if all relevant forecast info is combined in statistically sound fashion?
      - Objective guidance favorably compares with official temperature forecasts
        - » NDFD vs. GMOS & NCEP temperature forecasts (MDL verification stats) – Fig below
        - » "Official" vs. MOS temperature forecasts (R. Krzysztofowicz)

          Including cases with extreme changes

- New roles for forecaster?
  - Directs forecast process
    - Allocates adaptively configurable resources
      - Adaptive observational, DA, NWP procedures based on anticipated user impact
    - Quality Controls NWP process
      - Feedback to NWP
  - Interprets statistically post-processed unified NWP guidance
    - Interacts with user community

SUMMARY - NCEP POST-PROCESSING EFFORTS

- Theoretically sound
  - Based on Bayesian theorem
    - Can be expanded in various directions
      - Eg, regime dependent corrections
- Combines information from diverse sources
  - Different centers, forecast systems, statistical methods, etc
    - Add FNMOC, ECMWF, UKMET, etc
- Fast convergence of statistical estimates
  - Efficient with small samples
    - Minimum needs for training forecast sample (hind-casts)
- Adaptive
  - Bias estimates based on recent past
    - Regime dependent estimates for short range
    - DA / Modeling / Ensemble suite can evolve
      - Pre-implementation test data used for training prior to DA/model/ensemble upgrades
- Low maintenance
  - Part of operational suite
    - Upgrades to any system naturally feeds into final product with minimal human intervention

BACKGROUND

PROPAGATING FORECAST UNCERTAINTY

OLD PARADIGM: Reduce Uncertainty	***FORECAST PROCESS***	**NEW PARADIGM:** Reduce & Assess Uncertainty
Misconstrued determinism	NATURE	Critical sensitivity to initial conditions - Chaos
Reduce obs. uncertainty	OBSERVING SYSTEM	Quantify obs. uncertainty
Estimate expected value	DATA ASSIMILATION	Estimate distribution
Reduce model errors	NWP MODELING	Reduce & represent model errors
Ad hoc opportunities	**ENSEMBLE FORECASTING**	Systematic approach
Reduce systematic error	STATISTICAL POST-PROCESSING	Calibrate uncertainty
Single value	BASIC PRODUCTS	Distributional characteristics
Yes or No forecasts tailored for decisions	USER SUPPORT SYSTEMS	Incorporate forecast uncertainty info
Limited forecast info - Restricted usage	SOCIETY	All forecast info – Optimal user decisions

Single value

Distribution

Ensemble Forecasting:
Central role – bringing the pieces together

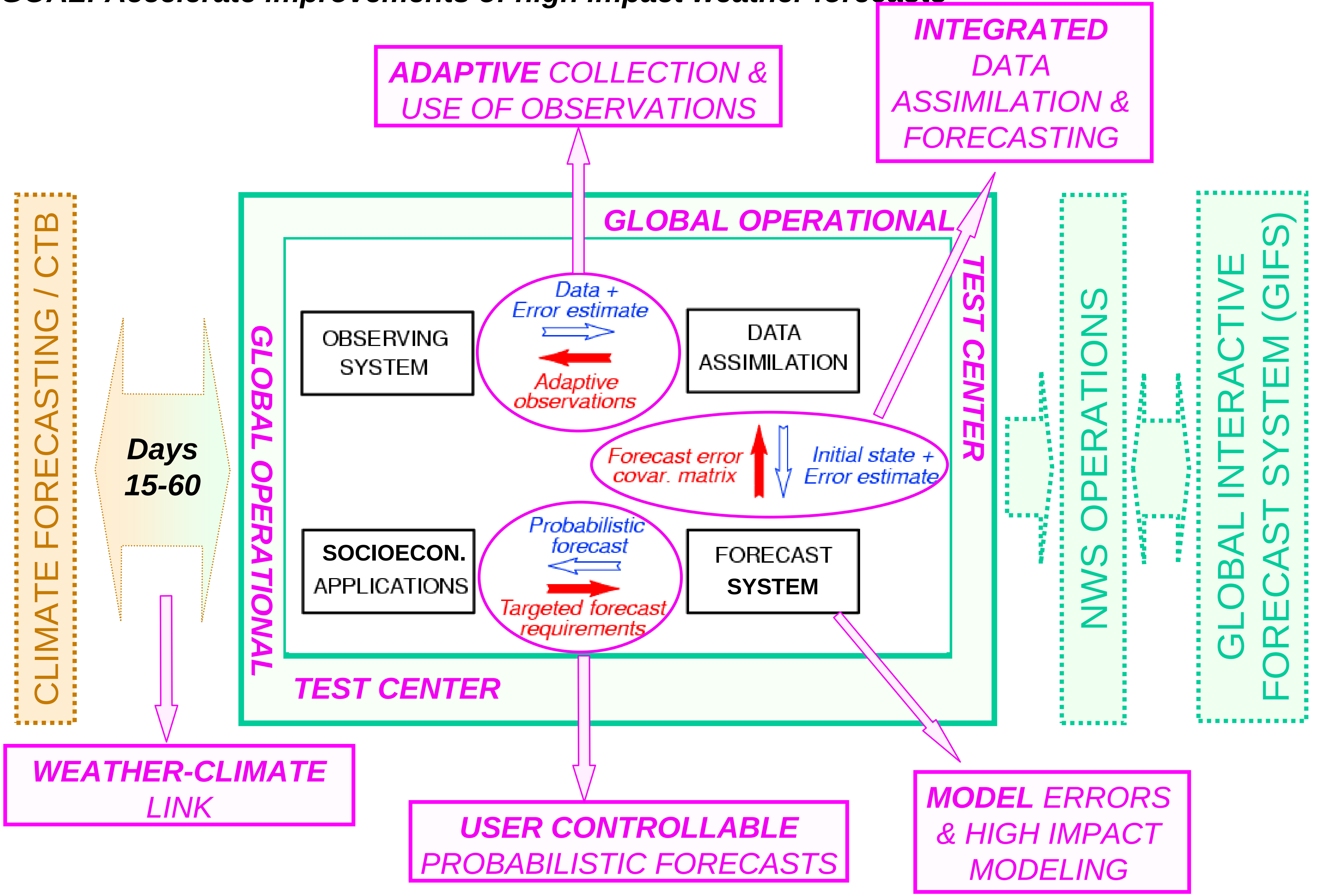
RESEARCH TO OPERATIONS TO APPLICATIONS FUNNEL

WHO		WHAT
Wide research community	RESEARCH & DEVELOPMENT	General basic & applied R&D
Research Labs, Grants	DIRECTED R&D	R&D directed toward operations
Environmental Modeling Center	RESEARCH TO OPERATIONS	Systematic transition to operations
NCEP Central Operations	OPERATIONS	7/24 Product generation
NCEP Service Centers	OPERATIONS TO APPLICATIONS	Systematic transition to applications
WFOs, Weather Enterprise	USER SUPPORT	Delivery of products to end users
Diverse user community	SOCIETAL APPLICATIONS	Decision making, feedback

ENSEMBLES AND THE RESEARCH COMMUNITY

LINKED THROUGH THORPEX – MAJOR INTERNATIONAL RESEARCH PROGRAM

GOAL: Accelerate improvements of high impact weather forecasts



THORPEX

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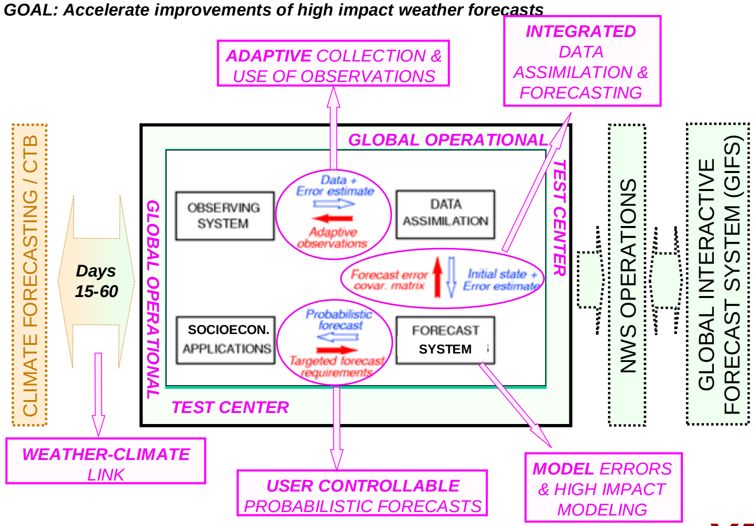
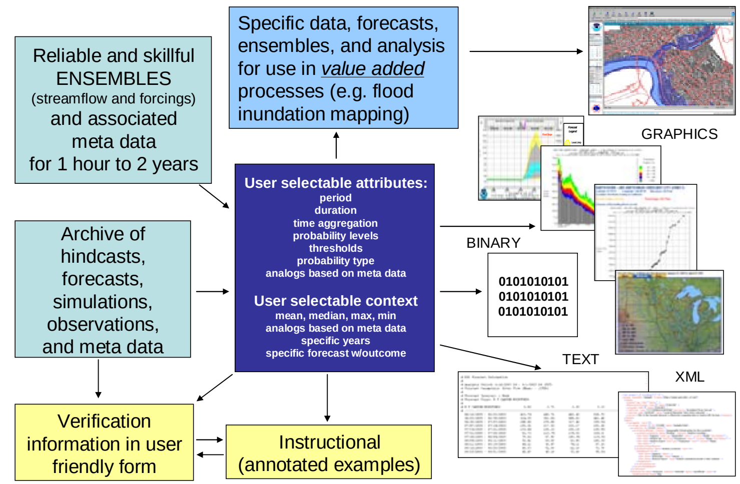
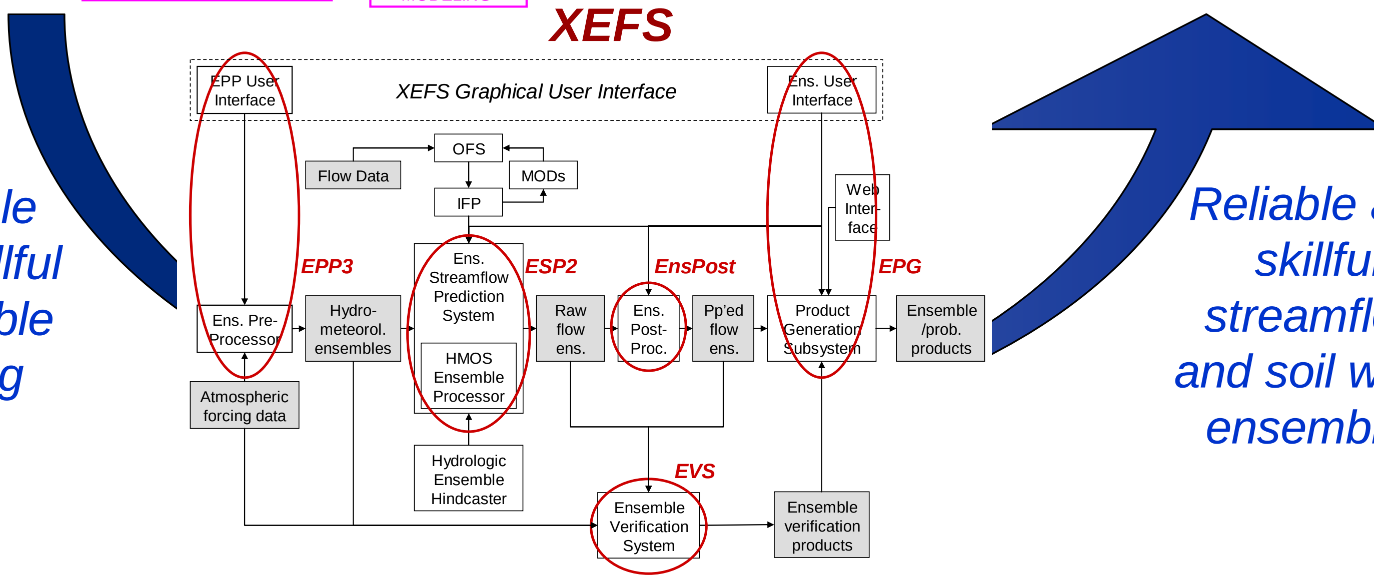


Ensemble Products & Services for Hydrology & Water Resources



XEFS



Reliable and skillful ensemble forcing

Reliable and skillful streamflow and soil water ensembles

BACKGROUND - 2