Supporting Transport & Dispersion Modeling with Stochastic Weather

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Overview

■ Background
  ■ Definitions
  ■ Why ensembles?

■ Theory
  ■ Deterministic vs. Stochastic Weather
  ■ Limitations

■ Development
  ■ Joint Ensemble Forecast System (JEFS)
  ■ Ensemble Prediction System (EPS)

■ Application & Education
  ■ Forecast Process
  ■ Warfighter Decision Making
Background
Definitions

- **Stochastic Weather**: Description of the spectrum of possibilities for the state of the atmosphere

- **Ensemble Forecast**: (General) Multiple, unique forecasts for the same event
  - (Rigorous) Multiple, unique numerical weather prediction runs (*members*) for same valid period, capturing all sources of uncertainty

Sample Rigorous Ensemble
UK Met Office Global and Regional Ensemble Prediction System (MOGREPS)
- 25km Grid
- 36h Forecasts
- 24 Members
- Varied Analyses (EtKF)
- Varied Model (Stoch. Phys.)
<table>
<thead>
<tr>
<th>Year</th>
<th>Operational Center / Current Ensemble as of Dec 2007</th>
</tr>
</thead>
</table>
| 1992 | **The National Center for Environmental Prediction (NCEP)**  
  • **Global**: 30 members, 4/day, T126/L28 (~110 km), 15-day forecast  
  • **Limited Area**: 21 members, 32 km, 60-hour forecast |
| 1992 | **The European Centre for Medium-Range Weather Forecasts (ECMWF)**  
  • **Global**: 51 members, 2/day, T399/L40 (~35 km), 14-day forecast |
| 1995 | **Fleet Numerical Meteorology and Oceanography Center (FNMOC)**  
  • **Global**: 18 members, 1/day, T119/L24 (~120 km), 10-day forecast |
| 1996 | **Canadian Meteorological Center (CMC)**  
  • **Global**: 16 members, 2/day, 10-day forecast |
| 1996 | **China Meteorological Agency (CMA)**  
  • **Global**: 21 members, 1/day, T213/L31 (~65 km), 10-day forecast |
| 2000 | **Australian Bureau of Meteorology (BoM)**  
  • **Global**: 33 members, 2/day, T119/L19 (~120 km), 10-day forecast |
| 2001 | **Japan Meteorological Agency (JMA)**  
  • **Global**: 51 members, 1/day, T159/L40 (~90 km), 9-day forecast |
| 2001 | **Korean Meteorological Administration (KMA)**  
  • **Global**: 32 members, 1/day, T213/L40 (~65 km), 8-day forecast |
| 2007 | **United Kingdom Meteorology Office (UKMet)**  
  • **Global**: 24 members, N114/L38 (~120 km), 72-hour forecast  
  • **Limited Area**: 24 members, 25 km, 36-hour forecast |
Why Ensembles for USAF?

- Ensemble Forecasting (EF) provides objective, high quality stochastic weather to enable optimal decision making for:
  - **Effectiveness**: Maximize Mission Capability
  - **Efficiency**: Conserve Resources

- **Letter to Airmen: Air Force Smart Operations 21** (SECAF, Mar06)
  “…a dedicated effort to maximize value and minimize waste in our operations.”

  “AFSO 21 signifies a shift in our thinking…innovative ways to use our material and personnel more effectively.”

- **AF Policy Directive 90-9** – “All Air Force personnel will apply ORM principles, concepts, and techniques to assess the risks associated with their daily mission and duty-related activities.”
### Deterministic Wx vs. Stochastic Wx Application

**Mission:** C17 needed to deliver urgent equipment and supplies from CONUS to Pakistan for covert, special ops anti-terrorism operation. Air Refueling required.

#### Current Scenario (deterministic wx support)
- **Wx fcst for primary AR track:**
  - Sky: CLR
  - Vis: 7+ miles
  - Turb: MDT-SVR FL180-300
  - Icing: Neg
  - TSTMS: ISOLD
- **Action:** C17 plans to use alternate refueling track. Refueling successful.
- **Result:** Mission accomplished
- **Cost:** Supplemental KC10 costs due to alternate track
  - flight time: 2.5 hr (crew stress)
  - fuel: 42,000 lbs ($27K)

#### Future Scenario (stochastic wx support)
- **Wx fcst for primary AR track:**
  - Sky: CLR
  - Vis: 7+ miles
  - Turb: 25% chance > MDT
  - Icing: Neg
  - TSTMS: 15% chance
- **Action:** C17 plans to use primary track (accept known risk). Refueling successful.
- **Result:** Mission accomplished
- **Cost:** Maximized efficiency and minimized cost through enabling of ORM
Theory
Causes of NWP Uncertainty

Source Data

- **Initial Conditions**
  - Erred Observations
  - Incomplete Observations
  - Limitations to Data Assimilation

- **Lateral Boundary Conditions (for LAM)**
  - Inaccuracies
  - Discontinuous

- **Lower Boundary Conditions**
  - Incomplete and Erred Surface Temperature, Soil Moisture, Albedo, Roughness Length, …

Computational

- **Upper Boundary Modeling Limitations**
- **Model Core**
  - Primitive Equations
  - Assumptions
  - Numerical Truncation
  - Limited Resolution

- **Model Physics Limitations**
  - Assumptions
  - Parameterizations

NWP Model

**Integrity - Service - Excellence**
Deterministic Forecasting Limitations

An analysis produced to run an NWP model is somewhere in a cloud of likely states.

Any point in the cloud is equally likely to be the truth.

The true state of the atmosphere exists as a single point in phase space that we never know exactly.

A point in phase space completely describes an instantaneous state of the atmosphere. (pres, temp, etc. at all points at one time.)
Ensemble Forecasting, a Stochastic Approach

An ensemble of likely analyses leads to an ensemble of likely forecasts

Ensemble Forecasting:
- Encompasses truth
- Reveals flow-dependent uncertainty
- Yields objective stochastic forecast

PHASE
SPACE

48h forecast Region

Analysis Region
Limitations

- Stochastic Weather is **not** a panacea
  - Only required when *uncertainty* exceeds operational *sensitivity*
  - Ensembles *quantify* uncertainty…doesn’t ELIMINATE it!
  - Operator still susceptible to unfavorable outcomes
  - **KEY:** Minimize impact from unfavorable outcomes

- Short Falls of raw ensemble (*or deterministic*) output
  - Limited # of members
  - Model bias
  - Insufficient accounting for initial and model error
  - Insufficient model resolution
  - **ANSWER:** Calibrate to adjust raw output
Development
Ensemble Forecast Process

N Analyses
(equally likely)

N 48hr Forecasts
(equally likely)

Products

Model Confidence

Consensus

Data Range

Probability

Analysis

Perturbations

DATA ASSIMILATION

Ensemble Forecast Process:

- **N Analyses**: These are the initial analysis datasets, equally likely.
- **N 48hr Forecasts**: These are forecasts generated from the analyses, equally likely.
- **Products**: The final products include:
  - **Model Confidence**
  - **Consensus**
  - **Data Range**
  - **Probability**
The Joint Ensemble Forecast System

GOAL: Prove the value, utility, and operational feasibility of EF to DoD operations.

FOCUS: How to best exploit EF output within forecasting and decision processes.
Joint Global Ensemble (JGE)

• **Description**: Combination of current GFS and NOGAPS global, medium-range ensemble data. Possible expansion to include ensembles from CMC, UKMET, JMA, etc.

• **Initial Conditions**: Ensemble Transform (GFS) and Breeding Modes\(^1\) (NOGAPS)

• **Model Variations/Perturbations**: Two unique models, but no model perturbations

• **Model Window**: Global

• **Grid Spacing**: 1.0°× 1.0° (~80 km)

• **Number of Members**: 46 at 00Z  
  30 at 12Z

• **Forecast Length/Interval**: 10 days/6 hours

• **Timing**
  • Cycle Times: 00Z and 12Z  
  • Products by: 07Z and 19Z

Joint Mesoscale Ensemble (JME)

- **Description**: Multiple high resolution, mesoscale model runs at FNMOC and AFWA

- **Initial Conditions**: Ensemble Transform Filter² run on short-range (6-h), mesoscale data assimilation cycle driven by GFS and NOGAPS ensemble members

- **Model variations/perturbations**:
  - Multimodel: WRF-ARW, COAMPS
  - Varied-model: various configurations of physics packages
  - Perturbed-model: perturbed surface boundary conditions (e.g., SST)

- **Model Window**: East Asia (COPC directive, Apr ’04)

- **Grid Spacing**: 15 km for baseline JME (fall ’06)
  - 5 km nest (in summer ’07)

- **Number of Members**: 20-30 (½ AFWA, ½ FNMOC)

- **Forecast Length/Interval**: 60 hours/3 hours

- **Timing**
  - Cycle Times: 06Z and 18Z \{ \text{~5h production} /cycle \}
  - Products by: 11Z and 23Z

Need Tools to Bridge the Gap

Characterize the Environment
(Stochastic Forecast)

Integrate and Exploit
(Binary Decisions/Actions)

Integrated Weather Effects Decision Aid (IWEDA)

<table>
<thead>
<tr>
<th>Stochastic Forecast</th>
<th>Weapon System Weather Thresholds*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt; 13kt</td>
</tr>
<tr>
<td></td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>10-13kt</td>
</tr>
<tr>
<td></td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>0-9kt</td>
</tr>
<tr>
<td></td>
<td>70%</td>
</tr>
</tbody>
</table>

*AFI 13-217
Application & Education
Weather Risk Analysis and Portrayal (WRAP)

Stochastic Weather Data

WRAP
- ORM calculations
- Stop-light style decision inputs
- Portrayal Techniques

Warfighter Risk Tolerance

IWEDA Rules

Given uncertain weather, lower acceptable risk means less certainty in the desired outcome.

Wx Risk Visualization
(low risk tolerance)
Sample JME Product: Multimeteogram

Misawa AB, Japan

AFWA Forecast Multimeteogram
JME Cycle: 11Nov06, 18Z

RWY: 100/280
15km Resolution

Wind Speed (kt)

90% CI

Extreme Max

Mean

Valid Time (UTC)

11/18 12/00 06 12 18 13/00 06 12 18 14/00 06

Wind Direction
Sample JME Product: Probagram *(Probabilistic Meteogram)*

**Probability of Weather Warning Criteria at Osan AB, Korea**

- Probability of Lethality for Several Agents
- Probability of Threshold Concentration for Several Agents
Application to Dispersion Modeling

Ensemble of Wx Fcsts  HPAC Variations  Ensemble of Plumes

A

A1

A2

A3

A4

...etc.

B

B1

B2

B3

B4

...etc.

C

C1

C2

C3

C4

...etc.

etc.

I n t e g r i t y  -  S e r v i c e  -  E x c e l l e n c e
Application to Dispersion Modeling

Ensemble of Wx Fcsts

A
B
C
D
E
F
etc.

“Best Guess” Forecast Winds + Variance

HPAC With Uncertainty Information

Critical Concentration Plume, hr 0-3

Forecast Confidence

HIGH

LOW
Application to Dispersion Modeling

 Ensemble of Wx Fcsts

 A
 B
 C
 D
 E
 F
 etc.

 "Best Guess" Forecast Winds + Variance

 HPAC With Uncertainty Information

 Critical Concentration Plume, hr 4-6

 Forecast Confidence

 HIGH LOW

 Integrity - Service - Excellence
Currently Available Forecaster Training

**Strengths**
- Good for initial exposure
- Starts brainstorm for products and applications ideas
- Available, accessible, free...

**Weaknesses**
- Too scientific in places
- Weak on some key concepts
- Leaves forecaster hanging…
  - Limited application to today’s forecast process
  - Missing customer interface

**Webcast by COMET**

**COMET module**

**National Weather Service training manual**

**ENSEMBLE PREDICTION SYSTEMS**

A training manual targeted for meteorologists wanting to know more about the ensemble technique

"Unfortunately when you most need predictability, that's usually when the atmosphere is the most unpredictable." – C. McElroy (NWS)
This ensemble stuff is useless! Last time they said 80% chance of snow we didn’t get a flurry. This time they said only 40%!
Warfighter Education on using Stochastic WX

- Warfighters should understand:
  - Benefits of stochastic vs. deterministic weather to ORM decision making
  - Optimal use of stochastic weather in both M2M and human decision making

- Recommend integration with warfighter training (i.e. schools, exercises, etc.)
Stochastic WX Optimizes ORM

The Goal: Efficient Mission Success

Max Combat Capability
Conserve Personnel & Resources
Prevent or Mitigate Losses
Evaluate and Minimize Risks
Identify, Control, and Document Hazards

Advance or Optimize Gain
Evaluate and Maximize Gain
Identify, Control, and Document Opportunities

Defensive Mindset
Offensive Mindset
**Defensive ORM: Resource Protection**

*Scenario – Typhoon Approach at Kadena AB, Japan*

Critical Event: Surface Winds $\geq 50$ kt  
-- Damaging to aircraft parked on the apron

Loss (if damaged): $1$M  
Cost (of protecting): $150$K  
-- Redeployment (fuel, TDY costs, etc.)

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### *Example Expense Over 2 Year Period*

<table>
<thead>
<tr>
<th>Typhoon Approach</th>
<th><strong>Deterministic Operator</strong> (Decision Threshold = 50kt)</th>
<th><strong>Stochastic Operator</strong> (Decision Threshold = 15%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forecast Wind (kt)</td>
<td>Observed Wind (kt)</td>
</tr>
<tr>
<td>1</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>36</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>77</td>
<td>81</td>
</tr>
<tr>
<td>4</td>
<td>43</td>
<td>62</td>
</tr>
<tr>
<td>5</td>
<td>52</td>
<td>41</td>
</tr>
<tr>
<td>6</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>27</td>
</tr>
<tr>
<td>8</td>
<td>32</td>
<td>23</td>
</tr>
</tbody>
</table>

*Generated by computer simulation*
**Defensive ORM: Resource Protection**

**Scenario – Typhoon Approach at Kadena AB, Japan**

Critical Event: Surface Winds ≥ 50kt -- Damaging to aircraft parked on the apron

Loss (if damage): $1M

Cost (of protecting): $150K -- Redeployment (fuel, TDY costs, etc.)

*Expense Over 10-Year Period*

*Generated by computer simulation*
Summary

- Ensemble forecasting provides objective stochastic weather
  - Technology well advanced, and can enable ORM...not just in a military setting

- Ensemble Capability is Coming...
  - JEFS results late 2008 will pave the way for future operational EPS
  - Joint prototype with Navy will create a DoD asset

- Education and training required to fully realize advantages
  - Forecaster – retrain to stochastic thinking
  - Warfighter – foster integration and exploitation of stochastic weather

"Stochastic weather allows us to exploit uncertainty, ...rather than being at its mercy."

--- F. Anthony Eckel, Maj (PhD)
“Anticipate and Exploit the Weather for Battle”
### Notional Requirements for NWS Ensemble Data (by 2010)

<table>
<thead>
<tr>
<th></th>
<th>CONUS (WRF) Limited Area Ensemble</th>
<th>Global Mesoscale Ensemble</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model Domain</strong></td>
<td>1) CONUS (20N-55N, 135W-60W</td>
<td>Global</td>
</tr>
<tr>
<td></td>
<td>2) Alaska (55N-73N, 170W-130W)</td>
<td></td>
</tr>
<tr>
<td><strong>Grid Spacing</strong></td>
<td>10 km</td>
<td>25 km or spectral equivalent (~T565) with step down resolution beyond 48-h forecast lead time</td>
</tr>
<tr>
<td><strong>Number of Levels</strong></td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td><strong>Ensemble Size</strong></td>
<td>20 Members</td>
<td>20 Members</td>
</tr>
<tr>
<td><strong>Cycle Frequency</strong></td>
<td>4 per day</td>
<td>4 per day out to 72 h, with 2 of those cycles out to 240 h</td>
</tr>
<tr>
<td><strong>Forecast Length/Interval</strong></td>
<td>48 h / 3 h</td>
<td>72 h &amp; 240 h / 6 h</td>
</tr>
<tr>
<td><strong>Delivery Schedule</strong></td>
<td>Incremental delivery starting NLT 3h after initialization time, complete NLT 5h after initialization time</td>
<td><em>same</em></td>
</tr>
<tr>
<td><strong>Analysis Perturbations</strong></td>
<td>Robust initial conditions (Ex: Ensemble Transform Kalman Filter)</td>
<td><em>same</em></td>
</tr>
<tr>
<td><strong>Model Perturbations</strong></td>
<td>Robust accounting for model uncertainty using single model framework with multiple physics combinations, physics perturbations, and/or stochastic physics.</td>
<td><em>same</em></td>
</tr>
<tr>
<td><strong>Calibration</strong></td>
<td>Robust correction for systematic errors, both 1st moment (bias correction) and 2nd moment (spread correction) of the ensemble distribution</td>
<td><em>same</em></td>
</tr>
</tbody>
</table>
WRAP Decision Input Processing

Drop Zone #1
- Marginal: 99%
- Unfavorable: 0%
Surface Wind Speed:
- 5 kt: Low
- 10 kt: Med
- 15 kt: Med

Drop Zone #2
- Marginal: 1%
- Unfavorable: 68%
Surface Wind Speed:
- 5 kt: Low
- 10 kt: Med
- 15 kt: High

Drop Zone #3
- Marginal: 37%
- Unfavorable: 11%
Surface Wind Speed:
- 5 kt: Low
- 10 kt: Med
- 15 kt: High

Acceptable Risk
- Low (Accept 10%)
- Med (Accept 40%)
- High (Accept 70%)
WRAP Interface

Parameters and Preferences

Map View

Info Window

Temporal Controls
Long Term EF Vision (2020)

United Global Mesoscale Ensemble
- Runs/Cycle: $O(100)$
- Resolution: $O(10\text{km})$
- Length: 10 days

AFWA
- Global Mesoscale Ensemble
  - Runs/Cycle: $O(10)$
  - Resolution: $O(10\text{km})$
  - Length: 10 days

NCEP
- Global Mesoscale Ensemble
  - Runs/Cycle: $O(10)$
  - Resolution: $O(10\text{km})$
  - Length: 15 days

FNMOC
- Global Mesoscale Ensemble
  - Runs/Cycle: $O(10)$
  - Resolution: $O(10\text{km})$
  - Length: 10 days

Microscale Ensembles
- Runs/Cycle: $O(10)$
- Resolution: $O(100\text{m})$
- Length: 24 hours

Coalition Weather Centers
- Global Mesoscale Ensembles
  - MSC
  - JMA
  - Met Office
  - ABM
  - ...etc.