1. Week 14 Lecture 22: NWP Models and Products of the U.S.
   - Models of the Environmental Modeling Center
   - Weather Research and Forecasting (WRF) Model
   - The Fleet Numerical Meteorology and Oceanography Center (FNMOC) NWP Models

2. Week 14 Lecture 23: Forecast Verification
The operational models are developed and maintained by the Environmental Modeling Center (Camp Springs, MD)

- **EMC** is part of Central Operations at the National Centers for Environmental Prediction (NCEP)
- **NCEP** is part of the National Weather Service (NWS)
- **NWS** is under the National Oceanic and Atmospheric Administration (NOAA)
- **NOAA** is under the Department of Commerce

The raw EMC model products are turned into forecasts by the prediction centers that form NCEP
NCEP Prediction Centers

- **Climate Prediction Center**: week 2, monthly, seasonal and multi-seasonal forecasts
- **Hydrometeorological Prediction Center**: 0-7 day weather and 0-5 day QPF for US
- **Storm Prediction Center**: 0-72 hour severe weather and 0-48 hour fire weather for continental US
- **Space Environment Center**: 0-3 days warnings and forecasting
- **Tropical Prediction Center/National Hurricane Center**: 0-5 day Tropical Cyclone Watches and Warnings for Atlantic and Pacific
- **Ocean Prediction Center**: 0-5 day marine boundary layer and ocean surface warning, North of 30°N
- **Aviation Weather Center**: domestic and international aviation
NOAA Model Products

NOAA’s NWS Model Production Suite

Global Analysis

Global Forecasts

- Global Ensemble Forecast System (w/ Canada)
- Climate Forecast System

Regional Analysis

- Regional Forecasts
- Short-Range Ensemble Forecast

- Hurricane Forecasts

- Dispersion
- Severe Weather
- Air Quality With EPA
- Rapid Update for Aviation

Real-Time Ocean Forecast System

Source: http://www.weatherchaos.umd.edu/
EMC Forecast Systems

Model Systems:

- Global Forecast System (GFS)
- North American Mesoscale (NAM)
- Rapid Update Cycle (RUC)

In 2010-2011 EMC will introduce the new modeling framework NOAA Environmental Modeling System (NEMS), which is compatible with the Earth System Modeling Framework (ESMF) adopted by all major US model developing institutions.
GFS

Current System:

- **Model:** GFS Model–Based on the Spectral Transform Method
- **Data Assimilation:** Gridspace Statistical Interpolation (GSI)–A 3D-Var Scheme
- **Number of Analyses Per Day:** 4
- **Number of Medium Range Forecasts Per Day:** 2
- **Forecast Time:** 16 days
- **Horizontal Resolution:** T382 (about 35 km) to 7.5 days, T190 (about 70 km) after that
- **Number of Vertical Levels:** 64

Changes Planned for 2010-2011:

- **Horizontal Resolution:** T574 Eulerian or T878 Semi-Lagrangian
See material on NAEFS in Lecture Note for Week 13 Lecture 20!
Current System:

- **Model**: WRF-NMM model (E-grid)
- **Data Assimilation**: GSI
- **Number Analyses and Forecasts Per Day**: 4
- **Forecast Time**: 84 hours
- **Horizontal Resolution**: 12 km
- **Number of Vertical Levels**: 60 with top at 2 hPa

Changes Planned for 2010-2011:

- **Model**: NEMS based NMM (B-grid)
- **Resolution**: Multiple Nests out to 48-hr (CONUS: 4 km, Alaska: 6 km, Hawaii: 4 km)
**Current System:**

- **Model:** RUC (Non-WRF and not developed at EMC)
- **Data Assimilation:** RUC 3D-Var
- **Number of Analyses Forecasts Per Day:** 24
- **Forecast Time:** 18 hours
- **Horizontal Resolution:** 13 km
- **Number of Vertical Levels:** 50 with top at 50 hPa

**Changes Planned for 2010-2011:**

- **Model:** WRF-based ARW
- **Data Assimilation:** GSI
- **Domain:** Expanded to include Alaska
Short Range Ensemble Forecast (SREF)

- **Number of Ensemble Members**: 21
- **Multi-Model Ensemble**: NMM, ARW, RSM (Regional Spectral Model)
- **Resolution**: 32-35 km (depending on the model)
Weather Research and Forecasting (WRF) Model

- It would be more accurate to call WRF a framework or a standard than a model.
- When the project started it was meant to end a situation where the research community and the operational community used different limited area models (the academic community used MM5 at the time, while NCEP used the Eta model).
- The result: Two different models both called WRF. The two dynamical cores are:
  - Advanced Research WRF (ARW) developed and maintained by the Mesoscale and Microscale Meteorology Division of the National Center for Atmospheric Research (NCAR MMM)
  - Nonhydrostatic Mesoscale Model (NMM) developed and maintained by NCEP (NCEP is about to abandon the WRF framework for NEMS)
The Future of WRF?

- It is safe to say that WRF will not be used by NWS (NCEP). In the best case, it will be used in SREF, but the purpose of having a limited area ensemble is not clear either. (I am not aware of any good scientific justification for having SREF in addition to NAEFS.)

- ARW will probably be used by some of the other agencies, maybe some other countries and universities for real time forecasting.

- ARW also has a **bright future as a research model**.

- WRF documentation, codes, etc. can be found at [http://www.wrf-model.org](http://www.wrf-model.org)
FNMOC provides model based meteorology and oceanography support to US and coalition forces; it is located in Monterey, CA.

The FNMOC models have been developed in collaboration with the Naval Research Laboratory (NRL)

- **Global Model**: Navy Operational Global Atmospheric Prediction System (NOGAPS) (T159, 24 levels)
- **Limited Area Model**: Coupled Ocean Atmosphere Prediction System (COAMPS) (15 km resolution)
- **Global Ensemble Forecast System**: Ensemble Forecast System (EFS) (10-member NOGAPS ensemble)
Operational NWP centers verify their forecasts based on a **daily basis** using objective verification scores. The goal is

- To detect problems with the model
- To measure progress
- To compare performance between models
Root-Mean-Square Error

Recap:

\[ RMS = \sqrt{(x_f - x_v)^2} \]

- \(x_f\): forecast
- \(x_v\): verification data (typically an analysis or a set of observations)
- \((x_f - x_v)^2\): mean of the square of the difference over all verification locations (e.g., over all model grid points all over all observation locations)

**Main Challenge:** The real state of the atmosphere is not known (not even in the hindsight!): \(x_v\) is always a **proxy** to the true state. Thus we can compute only an estimate of the error.
Decomposition of the RMS Error

Let $x_c$ be the climatology, then

$$MS = (x_f - x_v)^2 = \left[ (x_f - x_c) - (x_v - x_c) \right]^2$$

$$= (x_f - x_c)^2 + (x_v - x_c)^2 - 2(x_f - x_c)(x_v - x_c)$$

$$= (x_f - x_c)^2 + (x_v - x_c)^2 - 2C$$

- The last term $C = (x_f - x_c)(x_v - x_c)$ is the covariance between $(x_f - x_c)$ and $(x_v - x_c)$.

- In a good forecast model: $(x_f - x_c)^2 \approx (x_v - x_c)^2$ and the two terms change little with forecast time.

- At analysis time: $C = (x_f - x_c)(x_v - x_c) \approx 2(x_f - x_c)^2$, thus $MS \approx 0$, which is an artifact due to using a proxy; in reality $MS > 0$, which we would obtain if the true state $x_t$ was used instead of $x_v$. 

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Errors of the Error Estimate

A slightly different decomposition of the mean-square error:

\[
MS = (x_f - x_v)^2 = \left[ (x_f - x_t) - (x_v - x_t) \right]^2 \\
= (x_f - x_t)^2 + (x_v - x_t)^2 - 2(x_f - x_t)(x_v - x_t)
\]

- The first term, \((x_f - x_t)^2\), is the true error we try to estimate. The two other terms are the sources of error in the error estimate.
- The second term, \((x_v - x_t)^2\), is always positive, thus if it is a source overestimation of the error.
- The last term is the covariance between the error in the forecast and the error in the proxy. This term is typically a source of underestimation of the error.
How Can We Reduce the Error in the Error Estimate?

- This is a serious **problem only for the verification of short term forecasts**, because in that case \((x_v - x_t)^2\) is comparable to \((x_f - x_t)^2\) and the covariance between the errors in the verified and the verification data sets can be large.

- One possibility is to use the **analysis from a different center** for the verification. This will reduce the covariance. It is also useful to use a good analysis, because in that case \((x_v - x_t)^2\) is also small.

- Another possibility is to use **observations not used in the analysis**. This condition is automatically satisfied when we verify forecasts. The problem is that the observation coverage is not uniform, thus the verification will be biased to densely observed regions. Typically done using radiosonde observations.
Example: NCEP Verification Against Radiosondes

Source: http://wwwt.emc.ncep.noaa.gov/gmb/ssaha/
Comparison of the Accuracy of Forecasts: A Piece of Good News

- Let $MS_1$ be the mean-square error of forecast $x_{f1}$ and $MS_2$ the mean-square error of $x_{f2}$.

$$\begin{align*}
MS_1 - MS_2 &= \frac{(x_{f1} - x_t)^2 - (x_{f2} - x_t)^2}{2(x_{f1} - x_t)(x_v - x_t) + 2(x_{f2} - x_t)(x_v - x_t)}
\end{align*}$$

- Notice that the term $(x_v - x_t)^2$ cancelled out by taking the difference.
- The two correlation terms have opposite sign and similar magnitude (0 when the verification is against observation).
- Changes in the forecast accuracy, which are much smaller than the accuracy of the verification data, can be safely detected.
Anomaly Correlation

- **Formula**: 
  \[ AC = \frac{(x_f - x_c)(x_v - x_c)}{\| (x_f - x_c) \| \| (x_v - x_c) \|} = \frac{C}{\| (x_f - x_c) \| \| (x_v - x_c) \|} \]

- **Interpretation**: Correlation between predicted and actual deviation from climatology. Often computed after a spectral truncation of the fields to retain only the sub-synoptic (few hundred km) and large scale features.

- **Significance**: One of the oldest verification score for NWP forecasts, thus long records are available. This is important to see longer term trends in the forecast improvement.

- **Cautionary Note**: Even an imperfect forecast can have perfect score if the error is in the magnitude \( \| (x_f - x_c) \| \).
Example: ECMWF Landmark Performance

Source: http://www.ecmwf.int/publications/cms/get/ecmwfnews/1268389540174
A Concluding Remark on Verification

We did not discuss the following important verification issues:

- Verification of precipitation forecasts (require different measures than what we discussed)
- Verification of ensemble based probabilistic forecasts (very hot research topic, a variety of scores used by operational centers)
- Verification of weather parameters as opposed to verification of the atmospheric flow
- Tropical cyclone specific verification scores (e.g., accuracy of track forecasts, intensity, etc)