CLIMATE?
Weather is what we get,
Climate is what we expect!
Weather summary = Climate

Expectation= mean condition of atmosphere (temp. & Prcp.)
Climate  =  Expectation
Climate Change = Expectation Should be changed!
Climate = Expectation of Expectation

How uncertain!
Prediction

: a rigorous (often quantitative,) statement forecasting what will happen under specific conditions

(in meteorology)
- What : atmospheric state (weather)
- Conditions: current state, physical rules, external forcing factors

Atmosphere is dynamical system!

\[
\frac{d\vec{X}}{dt} = F(\vec{X}, a)
\]

\[
\vec{X}(t_0 + \tau) = \vec{X}(t_0) + \int_0^\tau F(\vec{X}(t), a(t))
\]
Determinism

Perfect prediction is possible when we have knowledge of all necessary “conditions”

\[
\frac{d\vec{X}}{dt} = F(\vec{X}, a)
\]

Chaos

Small difference in the initial state cause huge difference later even in the deterministic nonlinear system.

Our knowledge is never perfect!

→ perfect forecast is impossible...
Predictability

Depends on **what to predict**

**Lead time**($\tau$)
- Temperature of this room tomorrow
- Temperature of this room in 30 days later
- Temperature of this room in 30 years later

**Location**
- Temperature of Busan (Korea)
- Temperature of Ho Chi Minh (Vietnam)
- Temperature of Villa Las Estrellas (Antarctica)

**Physical variables**
- Temperature
- Rainfall
- Wind speed

**Time-scale of predictand**
- Mean Temperature during a day
- Mean Temperature during a month
- Mean Temperature during a century
Signal & Noise

Two scales

• Fast and small scale processes: noise
  – Weather by tropical cyclone etc.

• Slow and large processes: signal
  – Climate by ENSO, ITCZ, monsoon, MJO and so forth

• What is the Signal? (How we can “see”?)
  – Tendency of weather that has to be physically caused by slow varying processes
Potential predictability

Matter of Signal & Noise

\[ X = X_s + X_n \]

Measured by relative magnitude (variance) of signal and noise

Signal >> Noise : more predictable

Signal << Noise : less predictable
Climate prediction

- Time mean of weather
- How long (time domain)?
- Seasonal forecast
- Subseasonal forecast
Weather statistics

Primary seasonal weather statistics: seasonal mean

Seasonal mean
2002 summer (JJA) rainfall

Monthly prec. Anomaly (Aug)

Summer mean prec. anomaly

Typhoon “RUSA” passed at 8/31 (1000mm a day)
Methods

- **Statistical (Empirical)**
  - Use observed relationship of climate system to predict future
  - Linear

- **Dynamical**
  - Based on “physical law” of climate system and expect to mimic “the memory”
  - Nonlinear
Pros/Cons

Statistical/Empirical
• Simple and cheap
• Based on (observation) data
• Short observing history. Do we have enough?
• Unprecedented events predictable ????

Dynamical
• Complex and expensive
• Based on Law
• Is our understanding accurate?
Statistical forecasting

(0) Climatology
- Baseline of seasonal forecasting
- “Nothing particular, Sir.”
  \[ x(t + 1) = x \]
- Rainfall amount will be similar to 30 year average.
- I don’t know? (33%:33%:33%) or Near Normal?

(1) Persistence
- Assume that future will be same as it is now.
  \[ x'(t + 1) = x'(t) \]
- Often Close to people’s expectation.
- Effective when the autocorrelation is large (e.g. ENSO forecast)

(2) Regression
- The most popular method and many variations
  \[ x'(t + 1) = ay(t) + b \]
  \[ x : \text{predictand (e.g. rainfall at a station)} \]
  \[ y : \text{predictor (e.g. NINO3.4 SST)} \]
Regression based forecast

Question #1: Predictor selection
- How to define predictor \( y \)?
- By definition, predictor should cause some changes in variation of predictand.

\[
x'(t+1) = ay(t) + b
\]

\( x' \) (t + 1) = ay(t) + b
\( x'(t + 1) = a_1y_1(t) + a_2y_2(t)b \)
A_1' (t + 1) + x_2'(t + 1) = a_1y_1(t) + a_2y_2(t)b

- One to One: often not very satisfactory
- One to Multi: easy to overfit (lie)
- Multi to Multi: looks nice but often produce nothing practical

✓ If they give similar results, the simpler is the better!

Question #2: appropriate Function
- How to define \( a \) and \( b \)?
- Your choice: linear, nonlinear, single, multi... complex ones are not necessarily better.

✓ Should be based on Physical relationship between predictors and predictands
✓ Predictor cannot be tiny signal in the seasonal forecast
✓ Keep “doubt” on the possibility of selection by chance
✓ Selected predictor should be validated with separate data
Dynamical forecast

- Use GCM: Global Climate Model
  - It used to be called “General Circulation Model”
Dynamical forecast

- **Governing Equations → Written as computer program code (NWP)**

\[
\begin{align*}
\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} &= \nabla \Phi - 2\Omega \times \mathbf{u} - \frac{1}{\rho} \nabla p + \mathbf{f} \\
\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{u}) &= 0 \quad \Leftrightarrow \quad \frac{D \rho}{D t} = -\rho \nabla \cdot \mathbf{u} \\
\frac{\partial \theta}{\partial t} + \bar{u} \cdot \nabla \theta &= l
\end{align*}
\]
GCMs

- Coupled GCM
  - Atmosphere
  - Ocean
  - Sea-Ice
  - Land surface
  - Chemistry
  - Biosphere
Numerical modeling

- **Issue**
  - Digitization (physical variable is continuous, but computer needs digitization”)
    - Resolution, subgrid-scale parameterization
  - Unknown processes, tunable parameters
  - Initialization (for forecasting)

NOT the same with NATURE
NO perfect GCM
Initialization

Estimating Current status of climate system

- Preparing the beginning climate state of GCM with available observation
  - Balance between Wrong GCM vs Wrong OBS.
  - Balance between components (Atm, Ocn)
Ensemble Forecasting

- Run many times
  - Starts from slightly different initial conditions
Multi Model Ensemble Forecasting

- Run with many models

Which one??
A way to reduce prediction uncertainties generated when any single model is selected (to avoid extremely wrong forecast), in the end, to improve overall prediction skill!
Collection of Dynamic ensemble seasonal prediction data from NMHS and research institutes (16 operations/institutions from 10 countries)
# List of available models

(as of March 2018)

<table>
<thead>
<tr>
<th>Nation</th>
<th>Organization</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>Bureau of Meteorology</td>
<td>BoM</td>
</tr>
<tr>
<td>Canada</td>
<td>Meteorological Service of Canada</td>
<td>MSC</td>
</tr>
<tr>
<td>Chinese Taipei</td>
<td>Central Weather Bureau</td>
<td>CWB</td>
</tr>
<tr>
<td>Italy</td>
<td>Centro Euro-Mediterraneo sui Cambiamenti Climatici</td>
<td>CMCC</td>
</tr>
<tr>
<td>Japan</td>
<td>Japan Meteorological Agency</td>
<td>JMA</td>
</tr>
<tr>
<td>Korea</td>
<td>APEC (Asia-Pacific Economic Cooperation) Climate Center</td>
<td>APCC</td>
</tr>
<tr>
<td></td>
<td>Pusan National University</td>
<td>PNU</td>
</tr>
<tr>
<td>USA</td>
<td>National Centers for Environmental Prediction, NOAA</td>
<td>NCEP</td>
</tr>
<tr>
<td></td>
<td>National Aeronautics and Space Administration</td>
<td>NASA</td>
</tr>
</tbody>
</table>
APCC operational forecast

Collecting model data

Preprocessing
(data reconstruction, QC and so forth)

Calculation & visualization
(MME & verification)

Issuing prediction
(& graphics)

Middle of month (-1)
Second half of month (-1)
First half of month (0)
Middle of month (0)
APCC Climate Information

Seasonal outlook (global)

Climate Outlook for May - October 2017

BUSAN, 25 April 2017 – Synthesis of the latest model forecasts for May to October 2017 (MJJASO) at the APEC Climate Center (APCC), located in Busan, Korea, indicates persistent positive temperature anomaly across the tropical Pacific with the positive El Niño-Southern Oscillation (ENSO) phase. The forecast for the whole period shows a warm tendency over most of Eurasia and North and South America. Above normal temperature is highly probable over the tropical Pacific, eastern subtropical Pacific, the western and southern Indian Ocean, and the Barents Sea. For the same period, below and near normal rainfall is probable over the Great Australian Bight and the central Pacific, respectively. The forecast for MJJSO 2017 suggests a negative temperature anomaly over the northeastern Pacific and the central Indian Ocean. Below normal rainfall is highly probable for the central Indian Ocean. The forecast for ASO 2017 shows dry conditions over the maritime continent and the Caribbean Sea.

Temperature and Precipitation Outlook:

1. Forecast for May - July 2017

Strong enhanced probability for above normal temperature is predicted for the tropical and subtropical Pacific and Atlantic, the Barents Sea, the Norwegian Sea, the Bering Sea, the Sea of Okhotsk, the Arabian Sea, the Bay of Bengal, the western and southern Indian Ocean including Madagascar, the Mediterranean Sea, the Gulf of Mexico, and the Caribbean Sea. Enhanced probability for above normal temperature is predicted for the eastern Indian Ocean, the maritime continent, Mongolia, the western and northeastern China, the Middle East, and southern Africa. A warm tendency is expected for the Arctic, Greenland, most of Eurasia, and North and South America. Enhanced probability for below normal temperature is predicted for the northeastern Pacific and the central Indian Ocean. Enhanced probability for above normal precipitation is predicted for the southern Philippine Sea, central Africa, and southern South America. Strong enhanced probability for below normal precipitation is predicted for the central Indian Ocean and the Great Australian Bight. Enhanced probability for below normal precipitation is predicted for the eastern Indian Ocean, Australia, the northern Philippine Sea, and the central off-equatorial North Pacific. Precipitation in the central and eastern equatorial Pacific, the Middle East, and the northern and southern Africa is predicted to be near normal.

ENSO & IOD prediction

Nino3.4 Index for 2017 MJJSO

Temperature at 2m for May - July 2017

IOD Index for 2017 MJJSO
APCC MME skill improvement

Hindcast Skill: ACC

By YM Min (APCC)

RT Forecast Skill: T850, ACC
Evaluation of Seasonal Prediction

Yun-Young Lee
How GOOD?

- Evaluation of forecast: verification

- Excellent
- Good
- Satisfactory
- Poor
Verification

- Evaluation: measure of **closeness**
Verification

• Evaluation: depends on Dimension/Viewpoint
Deterministic forecast

- Various measures
  - **MSE** (Mean Square Error), **RMSE** (Root MSE)
    \[ MSE = \frac{1}{N} \sum_{i} (F_i - O_i)^2 \]
  - **MSSS** (Mean Square Skill Score)
    - Conventional form of “skill score”
    - \( 1 - \frac{MSE}{MSE_c} \), MSE : error/penalty, MSE<sub>c</sub> : error of climatology forecast
  - **ACC** (Anomaly correlation, Pattern), **TCC** (Temporal correlation)
    \[ ACC = \frac{\sum_{i=1}^{N} w_i (f_i - f) (o_i - o)}{\sqrt{\sum_{i=1}^{N} w_i (f_i - f)^2 \sum_{i=1}^{N} w_i (o_i - o)^2}} \]

- skill score = \( \frac{SCORE_{forecast} - SCORE_{reference}}{SCORE_{perfect forecast} - SCORE_{reference}} \)
  - Which is designed to give an answer for the question “What is the relative improvement of the forecast over some reference forecast?”
Verification

- Evaluation: depends on Dimension/Viewpoint
Examples

\[ F(t) \]
\[ G(t) = F(t) + 100 \]

RMSE?
But, Correlation?
Probabilistic forecast

Brier score (BS)

- MSE of prob. forecast
  \[ BS = \frac{1}{N} \sum_i (F_i - O_i)^2 \]
  
  F=probability(forecast),
  O=1/0 (actual outcome of instance)
  Eg. Binary events such as “rain” or “no rain”
  Range: 0 to 1, Perfect score = 0
  Intuitively, Higher score = Better skill?

Brier Skill Score (BSS)

\[ BSS = 1 - \frac{BS}{BS_c} \]

BS : error/penalty,
BS_c: BS of climatology forecast
Range: -infinity to 1
Perfect score = 1

skill score = \[ \frac{SCORE_{forecast} - SCORE_{reference}}{SCORE_{perfect\ forecast} - SCORE_{reference}} \]

Which is designed to give an answer for the question “What is the relative improvement of the forecast over some reference forecast?”
Probabilistic forecast (Categorical)

- Reliability curve

Accurate probability forecast system
- Reliability
- Sharpness
- Resolution

Underforecasting

Overforecasting
## Probabilistic forecast (Categorical)

<table>
<thead>
<tr>
<th></th>
<th>“rain”</th>
<th>“no rain”</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Yes</td>
<td>Hit (H)</td>
<td>Miss (M)</td>
</tr>
<tr>
<td>No</td>
<td>False Alarm (F)</td>
<td>Correct Rejection (C)</td>
</tr>
</tbody>
</table>

- **HR (Hit rate)** = $\frac{H}{H+M}$
  
  0 to 1, perfect score = 1

- **FAR (False Alarm rate)** = $\frac{F}{F+C}$
  
  0 to 1, perfect score = 0

**Good forecast**: $HR \uparrow$, $FAR \downarrow$
Probabilistic forecast (Categorical)

- ROC (Relative Operating Characteristics)

ROC score
= Area Under ROC curve

Range: 0 to 1
perfect: ROC score = 1
no skill: ROC score = 0.5
(no added value)
Probabilistic forecast (Categorical)

- ROC (Relative Operating Characteristics)

ROC score
= Area of ROC curve

Range: 0 to 1
perfect: ROC score = 1
no skill: ROC score = 0.5
(no added value)
Probabilistic forecast (Categorical)

- **ROC (Relative Operating Characteristics)**

  - **ROC score**
    - $\text{ROC score} = \text{Area of ROC curve}$
    - **Range**: 0 to 1
    - **Perfect**: ROC score $= 1$
    - **No skill**: ROC score $= 0.5$
    - (no added value)

- Biased forecast with high ROC score
- A measure of *potential usefulness*

**ROC Curve**: PREC, JAS (1983-2005)

- **Hit Rate** vs **False Alarm Rate**
- **ROC Scores**:
  - AN: 0.70
  - NN: 0.59
  - BN: 0.68

**Perfect?**

**No skill**

**ROC score**

= Area of ROC curve

- Range: 0 to 1
- perfect: ROC score $= 1$
- no skill: ROC score $= 0.5$
  - (no added value)
Probabilistic forecast (Categorical)

HSS (Heidke Skill Score)

Giving the answer for the question “What was the accuracy of the forecast in predicting the correct category, relative to that of random chance?”

<table>
<thead>
<tr>
<th>F</th>
<th>O</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Hit (H)</td>
<td>False Alarm (F)</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>Miss (M)</td>
<td>Correct Rejection (C)</td>
<td></td>
</tr>
</tbody>
</table>

\[
\text{HSS} = \frac{\text{SCORE}_{\text{forecast}} - \text{SCORE}_{\text{by chance}}}{\text{SCORE}_{\text{perfect forecast}} - \text{SCORE}_{\text{by chance}}}
\]

\[
= \frac{\left\{ \frac{(H + C)}{n} - \frac{[(H + F)(H + M) + (F + C)(M + C)]}{n^2} \right\}}{\left\{ 1 - \frac{[(H + F)(H + M) + (F + C)(M + C)]}{n^2} \right\}}
\]

Range: - infinity to 1, 0=no skill, 1=perfect skill
Money Problem!

Drought expected!

<table>
<thead>
<tr>
<th>Preparing (reservoir)</th>
<th>Drought happens?</th>
<th>Net cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes (cost)</td>
<td>No (No money loss because of drought)</td>
<td></td>
</tr>
<tr>
<td>No (no cost)</td>
<td>Yes (money loss)</td>
<td></td>
</tr>
</tbody>
</table>
Forecast economic value

\[ V = \frac{E_{cli} - E_{fore}}{E_{cli} - E_{per}} \]

- **V=1**: perfect forecast
- **V=0**: climatological forecast

\[ V = \begin{cases} 
\frac{E_{cli} - E_{fore}}{E_{cli} - E_{per}} & \text{if } V=1 \\
\frac{E_{cli} - E_{per}}{E_{cli} - E_{fore}} & \text{if } V=0 
\end{cases} \]

- **E_{fore}**: Expected expense of forecast
- **E_{per}**: Expected expense of perfect forecast
- **E_{cli}**: Expected expense of climatological forecast

<table>
<thead>
<tr>
<th>Observation (real event)</th>
<th>Forecast (action)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Hit (h) Cost (C)</td>
</tr>
<tr>
<td>No</td>
<td>False alarm (f) Cost (C)</td>
</tr>
<tr>
<td></td>
<td>Miss (m) Loss (L)</td>
</tr>
<tr>
<td></td>
<td>Correct rejection (c) 0</td>
</tr>
</tbody>
</table>

- When the forecast is **perfect**, \( f = m = 0 \) and \( h = \bar{o} \). Then,

\[ E_{per} = hC = \bar{o}C \]

- When the forecast is **climatology**. The only one kind of action will be kept.

If Yes : \( E \rightarrow C \), otherwise \( E \rightarrow \bar{o}L \).

**Decision: action of low expense.** Thus,

\[ E_{cli} = \min(C, \bar{o}L) \]

\[ V = \frac{\min(C, \bar{o}L) - (h + f)C - mL}{\min(C, \bar{o}L) - \bar{o}C} = \frac{\min\left(\frac{C}{L}, \bar{o}\right) - (h + f)\frac{C}{L} - m}{\min\left(\frac{C}{L}, \bar{o}\right) - \bar{o}\frac{C}{L}} \]
Value of Probabilistic forecast (Above normal) : GCMs

\[ V = \frac{\min \left( \frac{C}{L}, \bar{o} \right) - (h + f) \frac{C}{L} - m}{\min \left( \frac{C}{L}, \bar{o} \right) - \frac{C}{L} \bar{o}} \]

(a) Monsoon(40E-160E,20S~40N)

(b) ENSO (160E-280E,20S~20N)
Forecast Verification

- Multi aspect evaluation is necessary.
- A single verification score (e.g. $R=0.5$, explaining 25% variance) cannot tell everything.

- User oriented verification would be useful.
- If not clear, use popular one.

- Difficulties in “translating” meteorological skill score into Public wording.

- Let’s see some results!!!
APCC MME (TCC)

Rainfall (JJA)

SLP (JJA)