Seasonal Prediction Based on Dynamical Methods

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(Some Slides are taken from Web)

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Model Definition

- A model is only a representation of reality (e.g. a street plan of reality)
- Good modellers know the strong AND weak points of their models

Some quotations:

- All models are wrong, but some are useful - George Box
- The purpose of models is not to fit the data but to sharpen the questions - Samuel Karlin
- A theory has only the alternative of being right or wrong. A model has a third possibility, it may be right, but irrelevant. - Manfred Eigen
Why Modelling?

- To **ESTIMATE** the state of the system:
  - **ANALYSES** = **OBSERVATIONS** + **MODEL**
- To **FORECAST** the future state
- To **SUMMARISE** our understanding
  - **(MODEL** = **THEORY/**MAP OF REALITY)**
Introduction
What is a weather or climate model?

Numerical models are a sets of equations describing processes within a fluid

- Earth System Models are sets of equations describing processes within and between the atmosphere, ocean, cryosphere, and the terrestrial and marine biosphere
- Numerical weather prediction (NWP) uses current weather conditions as input into mathematical models of the atmosphere to predict the weather
Modelling Driving Factors

- Forecasting needs:
  - Nowcasting (up to 6 hours lead)
  - Short-range (6h-3days)
  - Medium-range (3-10 days)
  - Extended-range (10-30 days)
  - Long-range (>30 days) – seasonal/climate forecasts

- Computer technology – speed and memory

- Availability of more data e.g. satellite measurements
Physical Phenomena Associated with Seasonal Climate Variations

1. El-Nino Southern Oscillation (ENSO)
   a. SST variability in central and eastern equatorial Pacific
   b. Global teleconnections forced by changes in convective heating (rainfall) associated with SST variability in central and eastern Pacific

2. Indian Ocean Dipole

3. Soil moisture anomalies

4. Stratosphere-troposphere interactions

5. Sea-ice variability

ENSO is the dominant factor in seasonal climate variations. It has an irregular period of 3 to 5 years. Fortunately, it is also the phenomena we can model “most” skillfully but there is still room for improving these forecasts.
The interactions between atmosphere and oceans in the tropics dominate the variability at interannual scales. The main player is the variability in the equatorial Pacific. Wavetrains of anomaly stem from the region into the mid-latitudes, as the Pacific North American Pattern (PNA). The tropics are connected through the Pacific SST influence on the Indian Ocean SST and the monsoon, Sahel and Nordeste precipitation. It has been proposed that in certain years the circle is closed and a full chain of teleconnections goes all around the tropics. Also shown is the North Atlantic Oscillation a major mode of variability in the Euro_atlantic sector whose coupled nature is still under investigation.
The interactions between atmosphere and ocean in the high latitudes drive the long term circulation of the deep ocean. Cold, dense water sinks in the North Atlantic and in the Antarctica and fills the ocean basins before reemerging as warm surface waters.

Model studies have shown that other circulation are possible with sinking taking place in the North Pacific as well. We do not know if this possibility has ever been realized during the history of the planet.
Dynamical Equations

- **Molecular dynamics** – predict the motion of $10^{45}$ molecules using Newton’s laws (not feasible!)
- **Navier-Stokes equations** – use the continuum approximation to treat gas as a continuous fluid. Includes sound, gravity, inertial, and Rossby waves.
- **Euler equations** – use the incompressible or anelastic approximations to filter out sound waves that have little relevance to meteorology (speeds $> 300\text{m/s}$)
- **Primitive equations** – use the hydrostatic approximation to filter out vertically propagating gravity waves (speeds $>30\text{m/s}$)
- **Shallow water equations** – linearise about a basic steady flow in order to describe horizontal flow for different vertical modes. Each mode has a different equivalent depth external mode (e.g. tsunami) + barotropic mode + baroclinic modes
- **Vorticity equations** – assume geostrophic balance to remove gravity waves. Useful in understanding extra-tropical dynamics.
- **More conceptual models:** 0d (low order), 1d, and 2d models.
### Basic equations

**Primitive equations**

\[
\frac{Du}{Dt} + f\hat{z} \times u + \nabla_p \Phi = 0
\]

\[
\frac{\partial \Phi}{\partial t} + \frac{RT}{p} = 0
\]

\[
\nabla_p u + \frac{\partial \omega}{\partial p} = 0
\]

\[
\frac{D \log T}{Dt} - \frac{\kappa \omega}{p} = 0
\]

**Shallow water eqns**

\[
\frac{\partial u}{\partial t} + f v + \frac{\partial \Phi}{\partial x} = 0
\]

\[
\frac{\partial v}{\partial t} - f u + \frac{\partial \Phi}{\partial y} = 0
\]

\[
\frac{\partial \Phi}{\partial t} + g H \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = 0
\]

**Barotropic vor. eqn**

\[
\frac{D \xi}{Dt} + \beta v = 0
\]
Basic Equation Set

Horizontal Momentum Equations

\[
\frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - w \frac{\partial u}{\partial z} + \frac{uv \tan \phi}{a} - \frac{uw}{a} - \frac{1}{\rho} \frac{\partial p}{\partial x} - 2\Omega (w \cos \phi - v \sin \phi) + F_x
\]

\[
\frac{\partial v}{\partial t} = -u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - w \frac{\partial v}{\partial z} - \frac{u^2 \tan \phi}{a} - \frac{uw}{a} - \frac{1}{\rho} \frac{\partial p}{\partial y} - 2\Omega u \sin \phi + F_y
\]

\[\phi = \text{latitude}, \ a = \text{radius of the Earth}, \ \Omega = \text{rotational frequency of Earth}, \ F = \text{friction}\]
Basic Equation Set

Vertical Momentum Equation

\[
\frac{\partial w}{\partial t} = -u \frac{\partial w}{\partial x} - v \frac{\partial w}{\partial y} - w \frac{\partial w}{\partial z} - \frac{u^2 + v^2}{a} - \frac{1}{\rho} \frac{\partial p}{\partial z} - 2\Omega u \cos \phi - g + F_z
\]

\(\phi = \) latitude, \(a = \) radius of the Earth, \(\Omega = \) rotational frequency of Earth, \(F = \) friction
Basic Equation Set

**Thermodynamic Equation**

\[
\frac{\partial T}{\partial t} = -u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} + w(\gamma - \gamma_d) + \frac{1}{c_p} \frac{dH}{dt}
\]

or, alternately...

\[
\frac{\partial T}{\partial t} = -u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} - w \frac{\partial T}{\partial z} - w \gamma_d + \frac{Q}{c_p}
\]

\(\gamma =\) lapse rate of temperature, \(\gamma_d =\) dry adiabatic lapse rate, \(Q =\) diabatic heating rate
Basic Equation Set

Continuity Equations

(i.e., mass – top – and water vapor – bottom – are neither created nor destroyed)

\[
\frac{\partial \rho}{\partial t} = -u \frac{\partial \rho}{\partial x} - v \frac{\partial \rho}{\partial y} - w \frac{\partial \rho}{\partial z} - \rho \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right)
\]

q\_v = water vapor mixing ratio, Q\_v = source/sink of q\_v due to phase changes
Basic Equation Set

Ideal Gas Law

\[ p = \rho RT \]
If you can solve the set of equations (often referred to as the *primitive equations*) given in the past few slides, you can do NWP!

...but...

...how do we actually *solve* these equations???
What Do We Need?

• How do we represent these equations on a map?
• How do we integrate them in time?
• How do we integrate them in space?
• How do we handle resolvable versus unresolvable processes?
• How do we handle diabatic processes?
• How do we handle friction?
• How do we handle microphysical phase changes (water vapor as well as other species – cloud, ice, graupel, rain, etc.)?
• How do we obtain our initial atmospheric state?

...all among many relevant questions we will address!
Another scary thought:

Nearly *everything* we describe from here on out involves some sort of *approximation*.

This is true for the equations themselves, the methods used to solve them, the initial and boundary data used to drive the model, and so on.
Prognostic vs. Diagnostic

• Prognostic: any equation with a time-derivative is a prognostic equation; it can be integrated in time to produce a *prediction*

• Diagnostic: any equation without a time-derivative is a diagnostic equation; it can only be used to *diagnose* what is happening at a given time
Finite Difference methods

Idea: Replace all derivatives by finite difference approximations:

For example:

\[ \frac{\partial \phi}{\partial t} + u \frac{\partial \phi}{\partial x} = 0 \]

1-dimensional advection equation

\[ \phi_j^{(n)} = \phi(x_j, t_n) = \phi(j\Delta, nh) \]

\[ \frac{(\phi_j^{(n+1)} - \phi_j^{(n-1)})}{2h} + u_i^n \frac{(\phi_{j+1}^{(n)} - \phi_{j-1}^{(n)})}{2\Delta} = 0 \]

Centered Time Centred Space (CTCS)

n = "time level"  \quad j = "grid point"  

h = "time step" \quad \delta = "grid spacing"
Real World Problem

PV on 315K
18:00 23/12/04
Thursday

× 10^{-6} K m^2 kg^{-1} s^{-1}
What should be parameterized?

Model Physics include:

- Radiation transfer.
- Surface processes.
- Vertical turbulent processes.
- Clouds and large-scale condensation.
- Cumulus convection.
- Gravity wave drag.

16 major physical processes in climate system. (from http://www.meted.ucar.edu/nwp/pcu1/ic4/frameset.htm)
How do we do parameterization in numerical models?

- Ignore some processes (in simple models).
- Simplifications of complex processes based on some assumptions.
- Statistical/empirical relationships and approximations based on observations.
- **Nested models and super-parameterization:** Embed a cloud model as a parameterization into climate models.
Cumulus convective Parameterization schemes

- Manabe moist convective adjustment scheme.
- Arakawa – Schubert scheme.
- Betts – Miller scheme.
- Kuo scheme.

This storm has reached an upper-level inversion, forming an anvil-shape to the cloud.
There are several ways to produce probabilistic information but the most viable and popular is ensemble prediction.

Instead of running one forecast, run a collection (ensemble) of forecasts, each starting from a different initial state or with different physics.

The variations in the resulting forecasts can be used to estimate the uncertainty of the prediction.

The ensemble mean is on average more skillful than any individual member.
Kinetic Energy Spectrum for the Atmosphere and the Ocean
(Woods, 1985; Bryan, 1990)

Most energy at 2000-4000km scales

Most energy at 100-200km scales

Energy ($m^2/s$)

Log E

Large scale

Small scale

Typical climate models resolution: 200-500km

Wave Number (cycle/km)
Dynamical Predictions (Tier-2 or Tier-1?)

- Tier-Two Models: Atmospheric General Circulation Models
  - Integration with prescribed SST boundary conditions
  - Atmospheric Initial Conditions
- Tier-One Models: Coupled Ocean-Land-Atmosphere Models
Oceans -- Soil -- Cyosphere -- Biosphere
Numerical Models: Coupling

**Atmosphere**
- Wind Stress
- Precipitation
- Atmospheric Radiation
- Air Temperature
- Solar Radiation
- Surface Temperature

**Oceans -- Sea Ice**
- Wind Stress
- Fresh Water Flux
- Sensible Heat Flux
- Latent Heat Flux
- Sea Surface Temperature

**COUPLER:**
1. Interpolate from the atmospheric grid to the ocean grid and viceversa.
2. Compute fluxes
Very Large Computers are needed

Project of the Earth Simulator Computer (Japan) :
objective, a global coupled model with 5km resolution
Positive Attributes of Different Approaches to Seasonal Forecasting

2-Tiered Forecast Systems:
- Relatively inexpensive computationally
- Potentially more accurate SST data due to input from multiple sources
- No drift of SST annual cycle on which anomalies are superimposed

1-Tiered Forecast Systems:
- Potentially more accurate representation of physical interaction between ocean and atmosphere: Transient (waves) and time mean
## Tier-Two models used for prediction of Indian Monsoon

<table>
<thead>
<tr>
<th>Inst.</th>
<th>Model used</th>
</tr>
</thead>
<tbody>
<tr>
<td>IITM</td>
<td>COLA</td>
</tr>
<tr>
<td></td>
<td>PUM-Hadley centre</td>
</tr>
<tr>
<td>NCMRWF-SAC</td>
<td>NCMRWF <em>(version of NCEP)</em></td>
</tr>
<tr>
<td>IMD - IISC</td>
<td>SFM <em>(very recent version of NCEP)</em></td>
</tr>
<tr>
<td>IIT-Delhi</td>
<td>ECMWF <em>(old version)</em></td>
</tr>
<tr>
<td>NAL, Bangalore</td>
<td>VARSHA-version of NCMRWF model</td>
</tr>
<tr>
<td>CMMACCS</td>
<td>Version of LMD model</td>
</tr>
</tbody>
</table>
Seasonal Prediction of the Indian Monsoon (SPIM)

Observed and simulated mean monthly all-India rainfall 1985–2004

- **Rainfall (cm)**
  - Observed
  - PUM
  - SFM
  - COLA
  - NCMRWF
  - NAL-Varsha

**Month**
- May
- June
- July
- August
- September
Observed and simulated variation of all-India rainfall: 1985-2004

Seasonal Prediction of the Indian Monsoon (SPIM)

CC=0.39

Note: (1988, 2001, 2002) – consistency among the models; 1994 all models failed
Two-tier MME hindcast of summer Monsoon rainfall

Hindcast Skill is nearly Zero in ASM region

5-AGCM EM hindcast skill (21Yr)

- Two-tier system was unable to predict ASM rainfall.
- TTS tends to yield positive SST-rainfall correlations in SM region that are at odds with observation (negative).
- Treating monsoon as a slave to prescribed SST results in the failure.

OBS SST-rainfall correlation

Model SST-rainfall correlation

Wang et al. 2005
Effect of Coupling on Simulated Indian Summer Monsoon correlations (%) with CPC GSOD 1980–2003

Coupled

![Diagram of coupled model results](image1)

un-Coupled

![Diagram of uncoupled model results](image2)

(Taken from Dewitt)
Hindcast skill of CFS vs Simulation Skill of GFS

ACC of Coupled model

ACC of un-coupled model

Chaudhari et al., (2013)
ISMR simulation by GFS and hindcast by CFS

Chaudhari et al., (2013)
SST-Rainfall Correlation

Chaudhari et al., (2013)
SST-Rainfall correlation at different lag/leads
Teleconnections with Nino3.4

Observed

Coupled

Un-coupled

Chaudhari et al., (2013)
IITM CFS Model: Seasonal and Extended Range Prediction (IITM)

Atmospheric Model
GFS
T382 L64 levels

Land Model
Ice Model

COUPLER

Ocean Model
MOMv4
fully global
1/2°x1/2° (1/4° in tropics)
40 levels

ATMOSPHERE INITIAL CONDITIONS FROM GSI (NCMRWF)

OCEAN INITIAL CONDITIONS FROM GODAS (INCOIS)

(Original model is adopted from NCEP)
Comparison of performances of different climate models

<table>
<thead>
<tr>
<th>Forecasting system</th>
<th>Period</th>
<th>Correlation Coefficient (between Actual and predicted monsoon rainfall)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earlier Generation Models (DEMETER)</td>
<td>1960-2001</td>
<td>0.28</td>
</tr>
<tr>
<td>Latest Models (ENSEMBLES)</td>
<td>1960-2005</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1984-2005</td>
</tr>
<tr>
<td>NCEP CFS V2 (IITM Pune)</td>
<td>1984-2005</td>
<td>0.36</td>
</tr>
<tr>
<td>IMD STATISTICAL FORECASTING SYSTEM</td>
<td>1988-2011</td>
<td>0.23</td>
</tr>
</tbody>
</table>
1.1 Introduction: Books on numerical modelling


1.1 Introduction: Ocean books and other sources


3. + many articles in journals such as J. Climate, QJRMS, etc.
Thank you