Fundamentals in Atmospheric Modeling

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• Concept of modeling
• Structure of models
• Predictability

List of presentations

How were the today’s forecasts made?

Numerical model is a crucial component

Then, what?
Step 1: Observation

Step 2: Data analysis

Then, how?

Thermodynamics

\[ \Delta H = c_v \Delta T - \alpha \Delta p = c_v \Delta T + p \Delta \alpha \]

Dynamics

\[ \text{Force} = \text{Mass} \times \text{Acceleration} \]

- Mass \( \approx 1 \text{ kg/m}^3 \)
- Force: PGF, CO, Friction...

Theory of NWP

Theory of NWP: Atmosphere is conserved

- Momentum \( F = ma \)
- Mass \( \frac{1}{M} \frac{dM}{dt} = 0 \)
- Moisture \( \frac{dq}{dt} = E - C \)
- Ideal gas \( p \alpha = RT \)
- Energy \( Q = C_v \frac{dT}{dt} + p \frac{d\alpha}{dt} \)

V. Bjerknes (1904) pointed out for the first time that there is a complete set of 7 equations with 7 unknowns that governs the evolution of the atmosphere:

\[
\begin{align*}
\frac{dv}{dt} &= -\alpha N^2 \phi - \nabla \cdot F + 2 \Omega \times v \\
\frac{dp}{dt} &= -\nabla \cdot (\rho v) \\
p &= \rho RT \\
\frac{ds}{dt} &= C_v \frac{1}{T} \frac{dT}{dt} = \frac{Q}{T} \\
\frac{dq}{dt} &= E - C
\end{align*}
\]

7 equations, 7 unknown (u,v,w,T, p, den and q)
**History of numerical weather forecasts**

1904: Norwegian V. Bjerknes (1862-1951): Setup the governing equations

1922: British L. F. Richardson (1881-1953): Integrate model → failed

1939: Swedish C.-G. Rossby


1950: Princeton Group (Charney, Fjortoft, von Newman)

ENIAC (Electrical Numerical Integrator and Computer) → first success

**Computer Age (1946–)**

- von Neumann and Charney
  - Applied ENIAC to weather prediction

- Carl-Gustaf Rossby
  - The Swedish Institute of Meteorology
  - First routine real-time numerical weather forecasting. (1954)
  - (US in 1958, Japan in 1959)

**Factors for the improvement (Kalnay 2002)**

- Supercomputers
- Physical processes
- Initial conditions

**History of NWP skill: ECMWF**

![Anomaly correlation of 500 hPa Geopotential](image)

- Northern hemisphere extratropics
- Southern hemisphere extratropics

1 day / 10 yrs

**Super-computer for weather models**

- ENIAC, 1946
- NEC SX-5
- Cray T90
- Fujitsu VPP700E
- Cray SV1
- Cray T3E
Initial condition (data assimilation)

Data Assimilation

- Model 1°X 1° resolution, 20 levels
  \[ u, v, T, q, Ps, Tg \]
  \[ 360 \times 180 \times 20 = 1.3 \times 10^9 \times 4 \quad \text{var iabt} = 5 \times 10^9 \]
- Observation: \( 10^{-1} - 10^1 \) non-uniform distribution ±3 hour window
- Data assimilation cycle:
  1) data checking
  2) objective analysis
  3) Initialization: dynamical adjustment
  4) short-range fcst for first guess

Observation (+/-3hrs) → Background of FG →
Global analysis (statistical interpolation) and balancing →
Initial Conditions →
Global forecast model →
6 hour forecast (operational forecasts)

Various observations

Model

- Dynamics: Identity (Speed)
- Physics: Components (Predictability)
**Dynamics**

- **Numerical method (temporal)**
  a) \( \frac{u^{n+1} - u^n}{\Delta t} = F(u^n) \): leap-frog 
good for hyperbolic unstable for parabolic
b) \( \frac{u^{n+1} - u^n}{\Delta t} = F(u^n) \): Euler-forward 
good for diffusion unstable for hyperbolic
c) \( \frac{u^{n+1} - u^n}{\Delta t} = F\left(\frac{u^n + u^{n+1}}{2}\right) \): Crank-Nicholson
d) \( \frac{u^{n+1} - u^n}{\Delta t} = F(u^{n+1}) \): Fully implicit, backward
e) \( \frac{u^n - u^{n+1}}{\Delta t} = F(u^n) \): Euler-backward (Matzuno)
f) \( \frac{u^n - 2u^{n+1} + u^{n+2}}{\Delta t} = F(u^n) \): RK(Runge-Kuta)-4th order
  \( \frac{u^{n+1} - u^n}{\Delta t} = \frac{1}{6} F(u^n) + 2F\left(\frac{u^n + u^{n+1}}{2}\right) + 2F\left(\frac{u^{n+1} + u^{n+2}}{2}\right) + \frac{1}{6} F\left(\frac{u^{n+2} + 4u^{n+1} + u^n}{2}\right) \)
g) \( \frac{u^{n+1} - u^n}{\Delta t} = F_1(u^n) + \frac{1}{2} \frac{u^{n+1} - u^n}{\Delta t} \): Semi-Implicit
h) \( \frac{u^n - u^{n+1}}{\Delta t} = F_1(u^n) \); \( \frac{u^n - u^{n+1}}{\Delta t} = F_2(u^n) \): Fractional steps

- **Numerical method (spatial)**
  - Finite difference method (FDM):
  - Spectral method (SPM):
  - Finite element method (FEM):

- **Physics modules**
  - **Dynamics**
  - PGF, F_{co}, F_{n}, F_{ex}, F_{g}
  - **Physics**
  - Precipitation, Rad_SW, Turbulence, Vegetation, SH, LH, O3, O
  - **Branches of atmospheric sciences**
  - Oceans, Gases, Pollutants, Rad_LW, Vegetation, O3, O
Physics module (example): Cloud and precipitation

Real atmosphere → Theory → Model (computer program)

Physics module (example): Cloud and precipitation

\[ P_{\text{net}} = \frac{\pi a E \rho_{\text{c}} q}{4} \left( \frac{\rho_{\text{c}}}{\rho} \right)^{2} \left( \Gamma + \frac{b}{\lambda} \right) \]

\[ P_{\text{net}} = 2 \pi \left( S_{\text{r}} - 1 \right) \frac{\rho_{\text{c}}}{\rho_{\text{w}}} \frac{0.78}{2} \left( 0.3 H b \right) \left( \frac{1}{\rho_{\text{w}}} \right) \left( \frac{0.104}{\rho} \right) \]

\[ \frac{1}{N_{\text{c}}} \left( \frac{\rho_{\text{c}}}{\rho} \right) \left( \frac{1}{\rho_{\text{w}}} \right) \left( \frac{0.104}{\rho} \right) \]

\[ \frac{1}{N_{\text{c}}} \left( \frac{\rho_{\text{c}}}{\rho} \right) \left( \frac{1}{\rho_{\text{w}}} \right) \left( \frac{0.104}{\rho} \right) \]

Classify of models

- Dynamic frame
  - Hydrostatic
  - Non-hydrostatic
  - Purpose
- Scale
  - Global
  - Regional
  - Initial data → FORECAST
  - Forcing → RESPONSE

Hydrostatic

Non-hydrostatic

Small-scale
(heavy rainfall, complex mountain)

Large-scale

10 km – 100 km

1 km-10 km

NWP: up to 2 weeks

GCM (General circulation model)
Predictability

- Charney (1951): Uncertainties in initial condition and model
- Lorenz (1962, 1963): Unstable nature of atmosphere

**Purpose**: NWP is better than statistical forecast
- **Tool**: 4 K memory computer
- **Model**: 12 variables (heating and dissipation forcing)
- **Results**: differences -> non-periodicity
- **Initial condition (3 decimal point)**: different after 2 month
- **Round-off error**: cause of non-periodicity

**Chaos theory (Lorenz)**
- Atmosphere is unstable

**Ensemble forecasts**: Seasonal and beyond
- **Deterministic**
- **Stochastic**
- Different initial conditions
- Increase of spread
- Forecast (time)

**NWP (Initial value)**
- Seasonal forecasts (External forcing such as SST)
**Climate prediction**: RCP scenarios

- **RCP8.5**: high greenhouse gas concentration levels
- **RCP4.5**: stabilization scenario

**Target simulation period**

**Radiative Forcing (W/m^2)**

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(Meinshausen et al. 2011)

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**Global versus Regional**

- **GCM**: Global Climate Model
- **RCM**: Regional Climate Model

- Water Resource Management
- Human Health
- Agriculture
- Disaster Protection

Regional model is a magnifying glass

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**Benefit? **---- Very clear!

**Climate prediction**: Climate system sensitivity

1. **Forcing**
2. **Climate System**
3. **Response**

- **CO2**, **Aerosol**, **Volcanic**
- **Water vapor feedback**, **Ice-albedo feedback**, **Vegetation feedbacks**, **Cloud (radiative) feedback**

(Great debate!, Mostly still uncertain)
Another inherent issue in regional modeling:
lateral boundary treatment is empirical

Buffer zone

F(n) : weighting of global

\[ \frac{\partial A}{\partial t} = F(n)F(A_{CM} - A_{GB}) - F(n)F\n\] So, empirical

Domain size sensitivity: Pattern correlation with global

Domain size sensitivity: A mid-latitude cyclone

Observed

Large

Away from OBS

Small

Close to OBS

Thanks for your attention!
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