Fundamentals in Atmospheric Modeling

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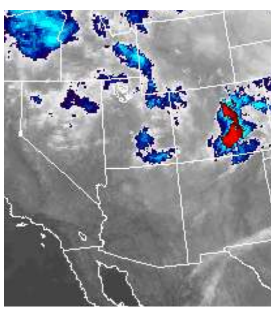
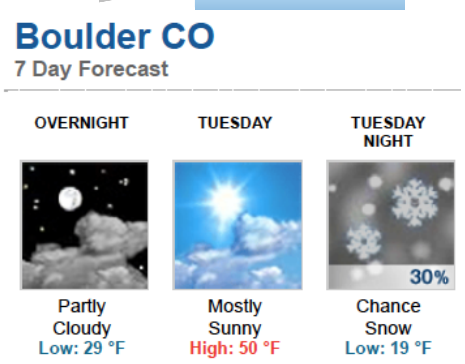
List of presentations

- Concept of modeling
- Structure of models
- Predictability
- Regional modeling

How were the today's forecasts made ?

Observation → ✗ → Forecasts





Then, what ?

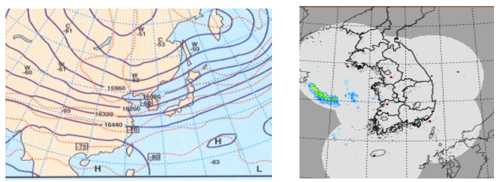
Numerical model is a crucial component

Observation → Data Analysis → Numerical model → Output Analysis → Forecasts

Then, how ?

Step1:
Observation

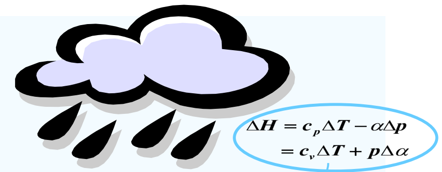
Step2:
Data analysis



Theory of NWP

Thermodynamics

Heat = Energy + Work

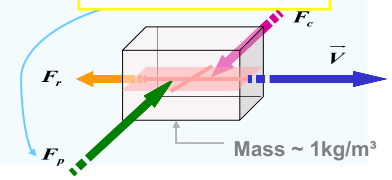


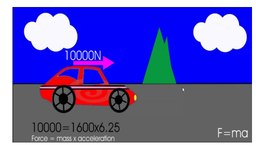
Nonlinear interaction

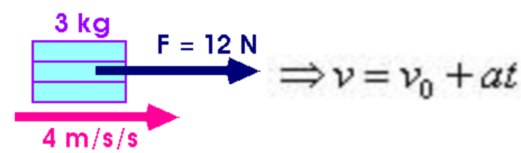
Dynamics

Force = Mass × Acceleration

- Mass ≒ 1 kg/m³
- Force: PGF, Coriolis, Friction…







Theory of NWP : Atmosphere is conserved

- **Momentum** $F = ma$ — Force = mass x acceleration
- **Mass** $\frac{1}{M}\frac{dM}{dt} = 0$ — Mass of a fluid is conserved
- **Moisture** $\frac{dq}{dt} = E - C$ — Moisture change = evaporation - condensation
- **Energy** $Q = C_v \frac{dT}{dt} + p\frac{d\alpha}{dt}$ — Heat = internal energy change − work done
- **Ideal gas** $p\alpha = RT$ — Pressure x specific volume = gas constant x temperature

The governing equations

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:*

$$\frac{d\mathbf{v}}{dt} = -\alpha\nabla p - \nabla\phi + \mathbf{F} - 2\Omega\times\mathbf{v} \quad \text{(1-3), East-west, North-south, and vertical}$$

$$\frac{\partial\rho}{\partial t} = -\nabla.(\rho\mathbf{v}) \quad (4)$$

$$p = \rho RT \quad (5)$$

$$\frac{ds}{dt} = C_p\frac{1}{\theta}\frac{d\theta}{dt} = \frac{Q}{T} \quad (6)$$

$$\frac{dq}{dt} = E - C \quad (7)$$

7 equations, 7 unknown (u,v,w,T, p, den and q)

solvable

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** :

1948, 1949, **J. G. Charney** (1917-1981)

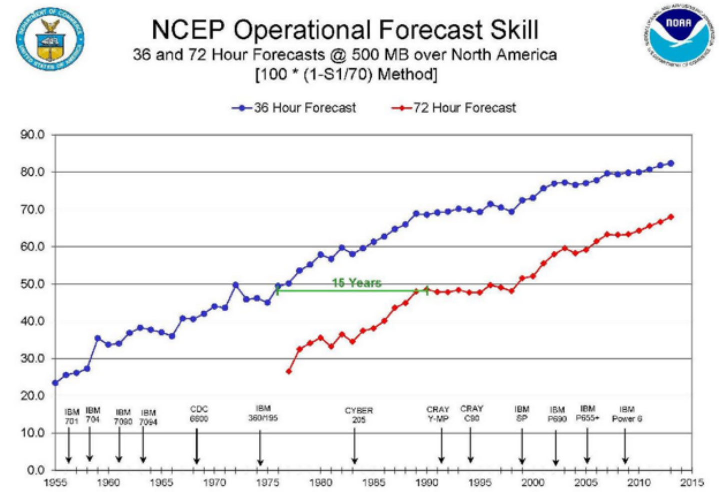
1950 : **Princeton Group**
(Charney, Fjortoft, von Newman)
ENIAC
(Electrical Numerical Integrator and Computer)
➔ first success

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)

History of NWP skill : NCEP GFS



1day / 10year

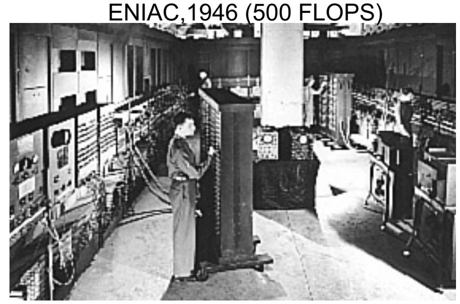
1988: 48 hr fcst skill= 2018: 120 hr fcst skill

Factors for the improvement (Kalnay 2002)

- Supercomputers
- Physical processes
- Initial conditions

Super-computer for weather models

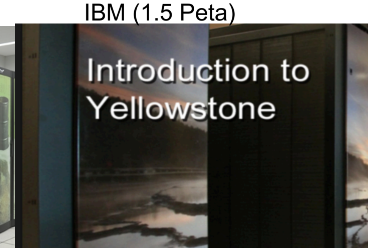
ENIAC,1946 (500 FLOPS)



Sunway (125 Peta=10**15FLOPS)

XC40 (2.9 Peta)

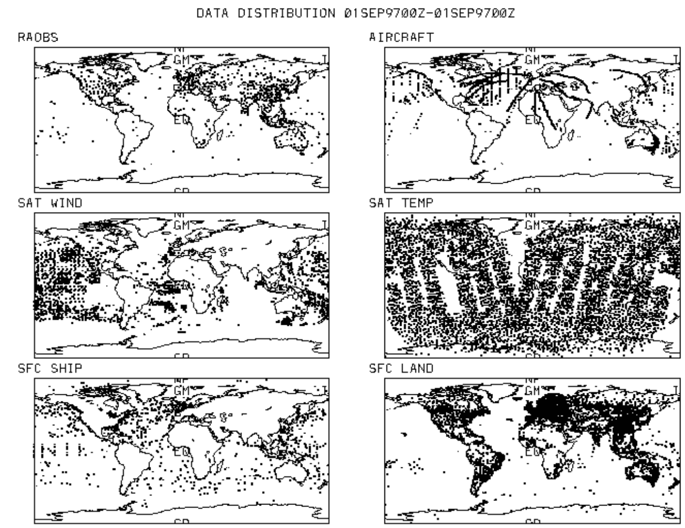
IBM (1.5 Peta)



K-computer (11.2 Peta)

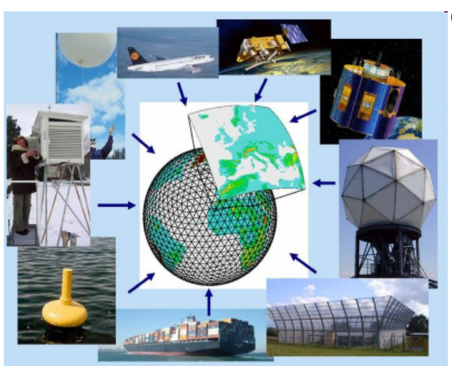
Initial condition
(data assimilation)

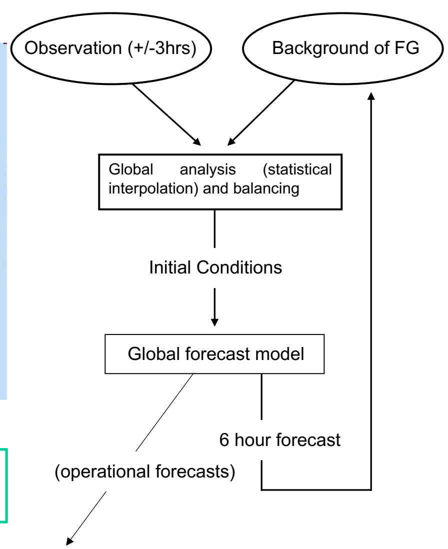
Various observations



Heterogeneous in space and time….

Data Assimilation





Data assimilation best combines observations and a model

Model

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

Step3: Integration

Dynamics : Grid system

$$u_t + uu_x + vu_y + wu_z = -\frac{1}{\rho}p_x + \left(f + \frac{u}{a\tan\phi}\right)v + F_x$$

$$v_t + uv_x + vv_y + wv_z = -\frac{1}{\rho}p_y - \left(f + \frac{u}{\tan\phi}\right)u + F_y$$

$$w_t + uw_x + vw_y + ww_z = -\frac{1}{\rho}p_z - g + F_z$$

$$\rho_t + u\rho_x + v\rho_y + w\rho_z = -\rho\left(u_x + v_y + w_z\right)$$

$$T_t + uT_x + vT_y + wT_z - \frac{1}{\rho C_p}\left(p_t + up_x + vp_y + wp_z\right) = \boxed{\frac{1}{C_p}Q}$$

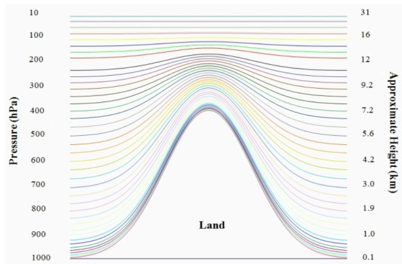
$$q_t + uq_x + vq_y + wq_z = \boxed{M}$$

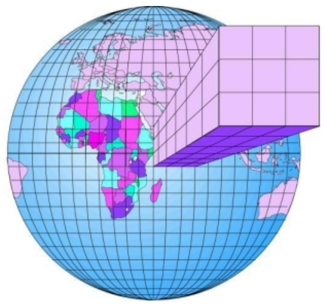
PHYSICS

$$p = \rho RT$$

unknown : $[u, v, w, \rho, T(\theta), q, p]$

If we consider O_3, $C_t + uC_x + vC_y + wC_z = \boxed{O_3}$





Dynamics : Numerical method (spatial)

Finite difference method (FDM) :

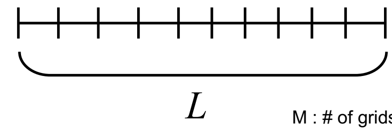
Spectral method (SPM) :

Finite element method (FEM) :

Ex) $\frac{\partial\phi}{\partial t} = -c\frac{\partial\phi}{\partial x}$; advection eq.

1) FDM (Finite difference)

$$\frac{\Delta\phi}{\Delta t} = \frac{\phi_2 - \phi_1}{t_2 - t_1}$$



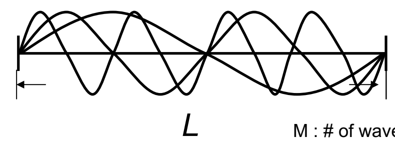
M : # of grids

2) Spectral Method

- Determine basis function to get $H(\phi(x))$

$e_m(x)$ (basis funct), $m = m_1 \cdots m_n$ → infinite

$$\Rightarrow \phi(x,t) = \sum_{m=m_1}^{M} \phi_m(t)e_m(x)$$



M : # of waves

* Resolution Increases $\begin{cases} \Delta x \to decreases \\ (\Delta x = L/M) \\ M \to increases \end{cases}$

Dynamics : Numerical method (temporal)

a) $\frac{u^{n+1} - u^{n-1}}{2\Delta t} = F(u^n)$: **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) $\frac{u^* - u^n}{\Delta t} = F(u^n)$; $\frac{u^{n+1} - u^n}{\Delta t} = F(u^*)$: **Euler-backward (Matzuno)**

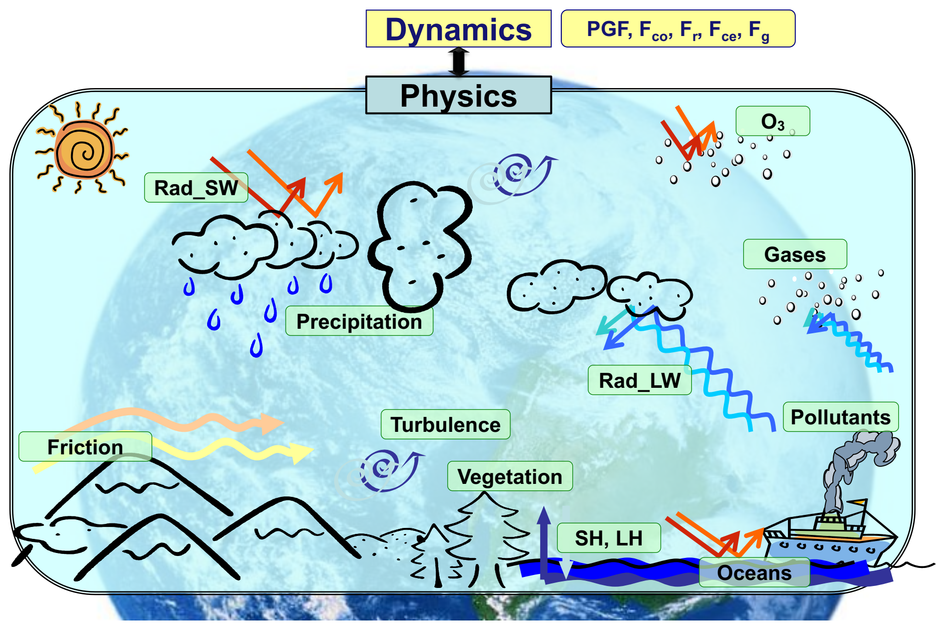
f) $\frac{u^{n+\frac{1}{2}*} - u^n}{\Delta t/2} = F(u^n)$; $\frac{u^{n+1*} - u^n}{\Delta t} = F\left(u^{n+\frac{1}{2}*}\right)$

$\frac{u^{n+1} - u^n}{\Delta t} = \frac{1}{6}\left[F(u^n) + 4F\left(u^{n+\frac{1}{2}*}\right) + F\left(u^{n+1*}\right)\right]$: **RK(Runge-Kuta)-3rd order**

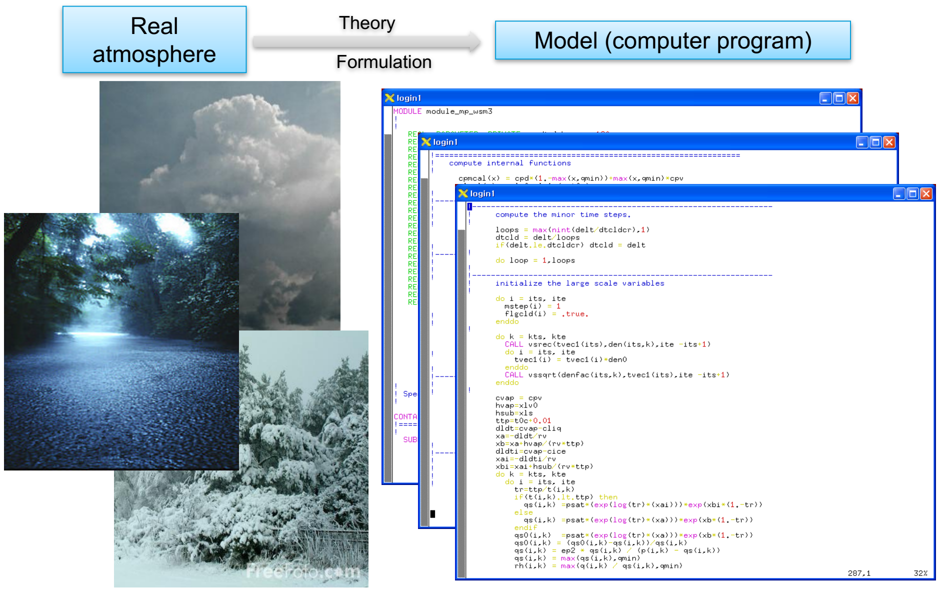
g) $\frac{u^{n+1} - u^{n-1}}{2\Delta t} = F_1(u^n) + F_2\left(\frac{u^{n+1} - u^{n-1}}{2}\right)$: **Semi-Implicit**

h) $\frac{u^* - u^n}{\Delta t} = F_1(u^n)$; $\frac{u^{n+1} - u^*}{\Delta t} = F_2(u^*)$: **Fractional steps**

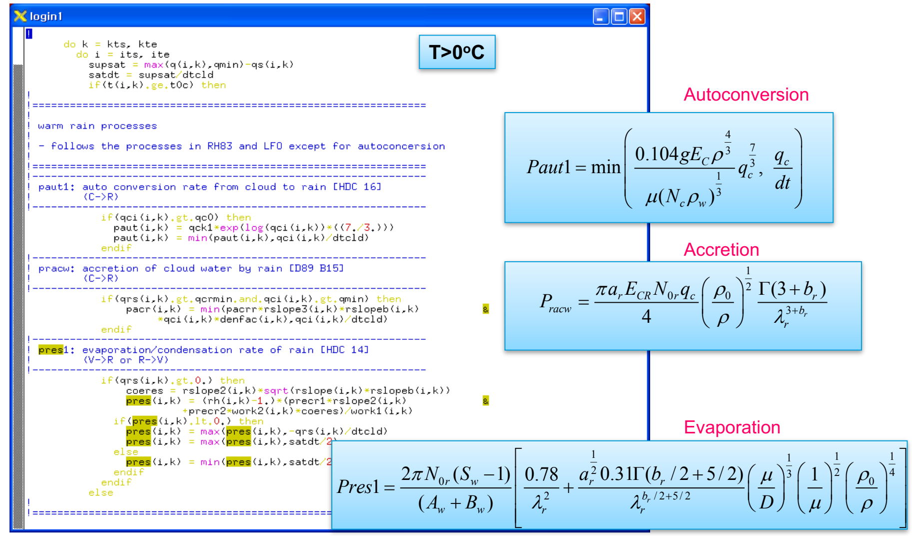
Physics modules : Branches of atmospheric sciences



Physics module (example): Cloud and precipitation



Physics module (example): Cloud and precipitation

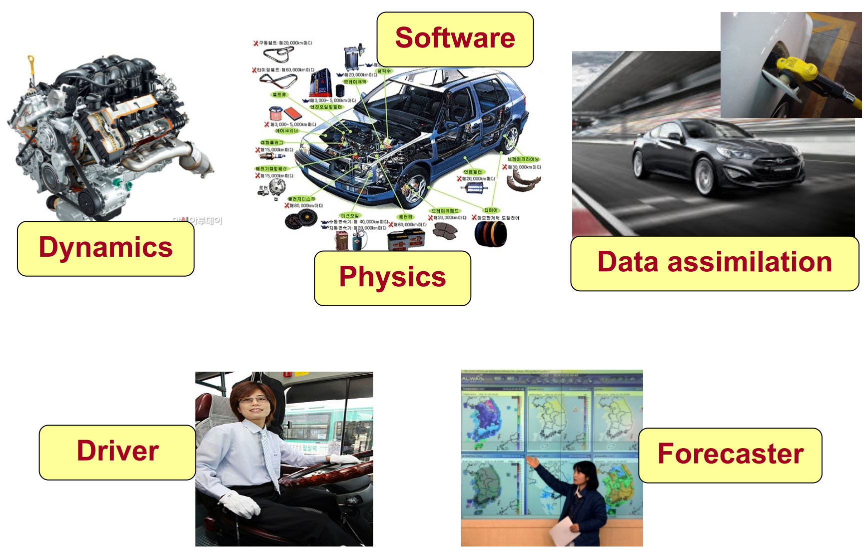


$$Paut1 = \min\left(\frac{0.104 g E_C \rho^{\frac{4}{3}}}{\mu (N_c \rho_w)^{\frac{1}{3}}} q_c^{\frac{7}{3}}, \frac{q_c}{dt}\right)$$

$$P_{racw} = \frac{\pi a_r E_{CR} N_{0r} q_c}{4}\left(\frac{\rho_0}{\rho}\right)^{\frac{1}{2}} \frac{\Gamma(3+b_r)}{\lambda_r^{3+b_r}}$$

$$Pres1 = \frac{2\pi N_{0r}(S_w - 1)}{(A_w + B_w)}\left[\frac{0.78}{\lambda_r^2} + \frac{a_r^{\frac{1}{2}} 0.31 \Gamma(b_r/2 + 5/2)}{\lambda_r^{b_r/2+5/2}}\left(\frac{\mu}{D}\right)^{\frac{1}{3}}\left(\frac{1}{\mu}\right)^{\frac{1}{2}}\left(\frac{\rho_0}{\rho}\right)^{\frac{1}{4}}\right]$$

Car and model



Classification of models

- **Dynamic core**

Hydrostatic	Non-hydrostatic
Large-scale	Small-scale (heavy rainfall, complex mountain)

- **Scale**

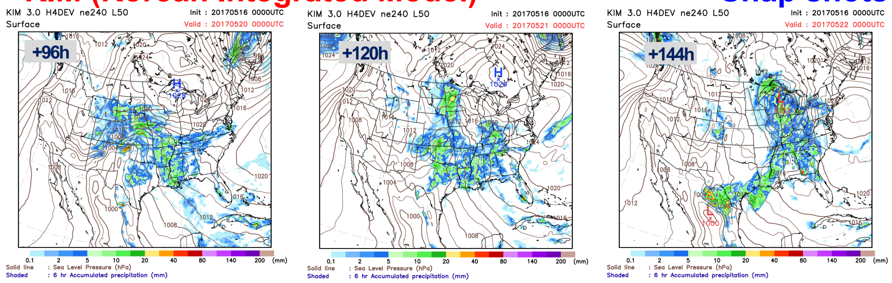
Global	Regional
10 km – 100 km (NWP – Climate)	1 km - 10 km (NWP-Climate)

- **Purpose**

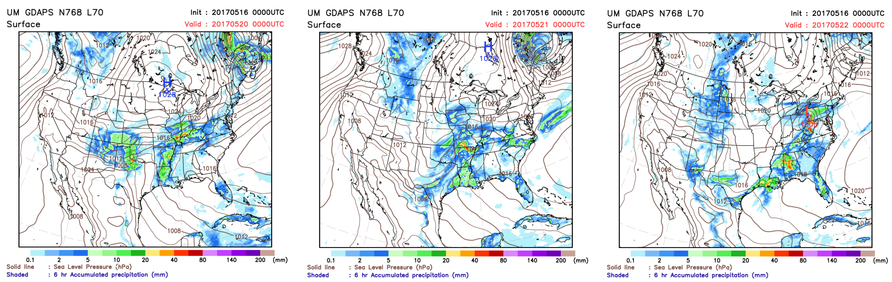
Initial data-> FORECAST	Forcing → RESPONSE
NWP : upto 2 weeks	**GCM** (General circulation model)

KIAPS real time forecasts (INIT 2017051600) : 12 km global NWP

KIM (Korean Integrated Model) **Snap shots**



KMA UM



Predictability

Chaos theory (Lorenz)

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

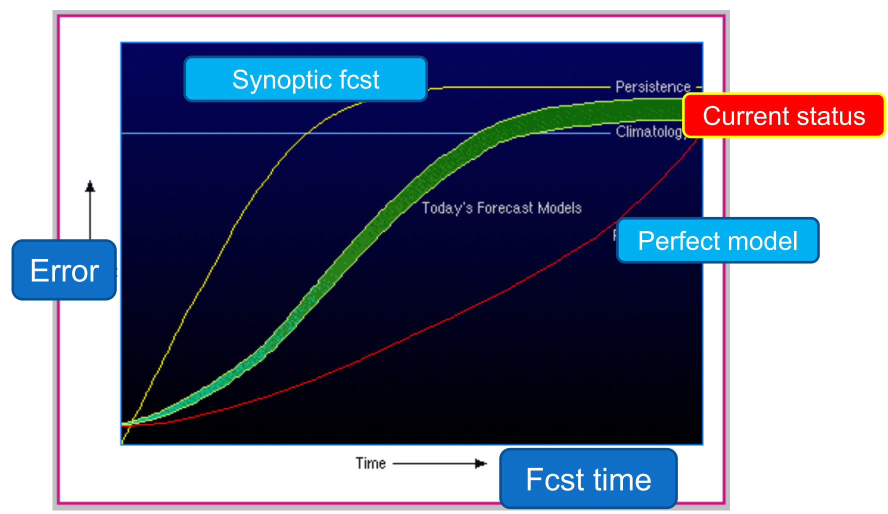
↓

Round-off error -> cause of non-periodcity

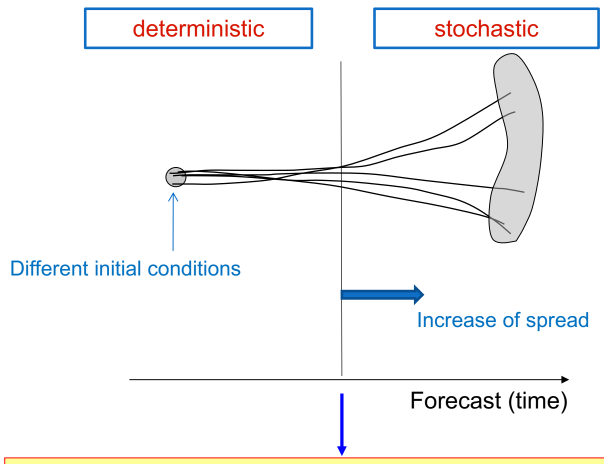
↓

Chaos theory– two weeks for NWP

Predictability : Atmosphere is chaotic



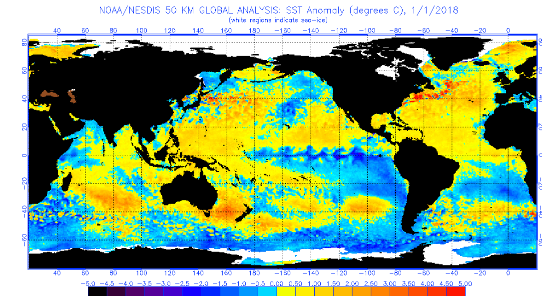
Ensemble forecasts : Seasonal and beyond



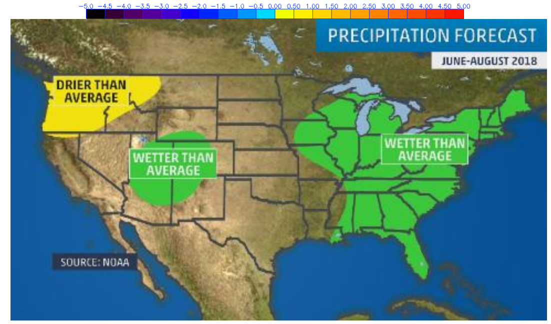
NWP
(Initial value)

Seasonal forecasts
(External forcing such as SST)

Ensemble forecasts : Seasonal and beyond



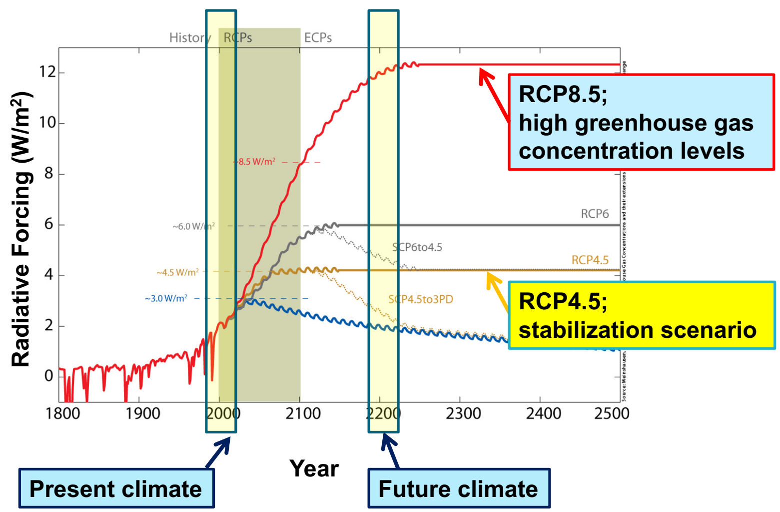
SST anomaly in January 2018



Precipitation anomaly in Summer 2018

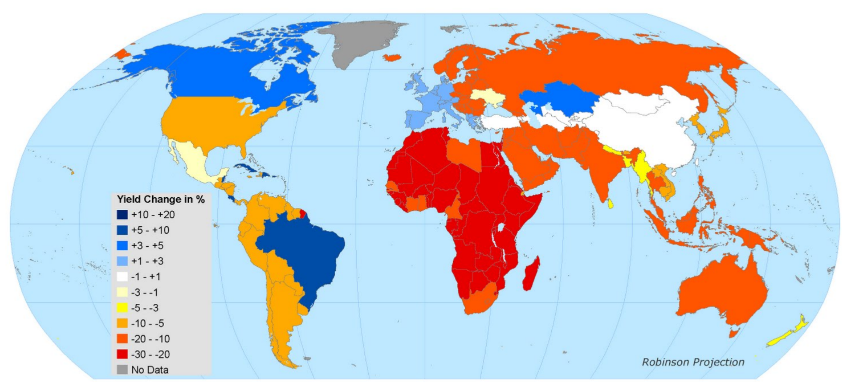
Climate prediction : For given RCP scenarios

Climate changes = future minus present



Climate prediction : For given RCP scenarios

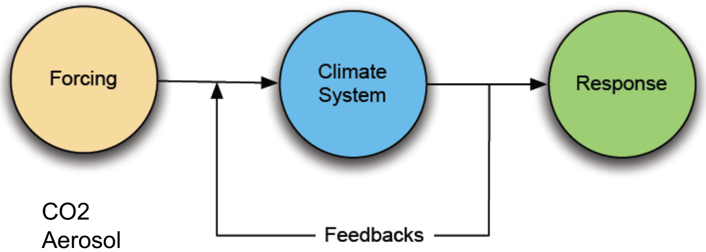
Effects of Climate Change on Global Food Production



Projected Maize Yield Change in %

1970-2000 Baseline to 2080, SRES A1F Scenario

Climate prediction : Climate system sensitivity



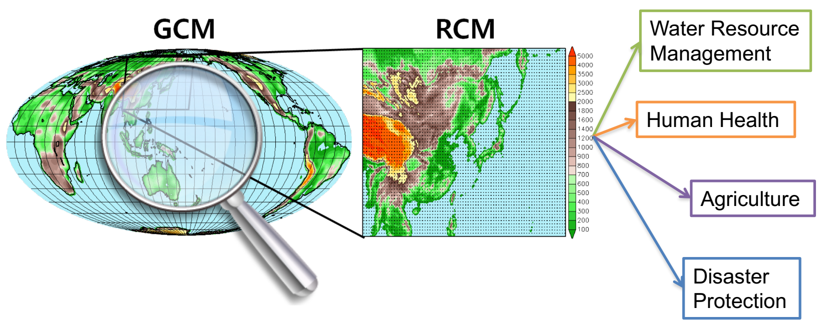
CO2
Aerosol
Volcanic

Water vapor feedback
Ice-albedo feedback
Vegetation feedbacks
Cloud (radiative) feedback
(Great debate!, Mostly still uncertain)
…

NWP / GCM : models could be unified.

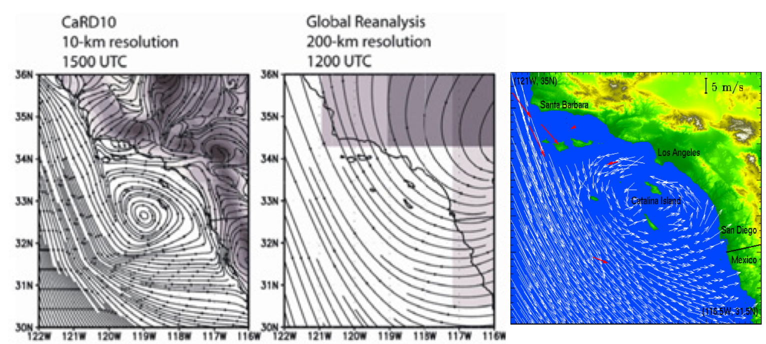
Global vs Regional

Regional modeling : need for applications



Regional model is a magnifying glass

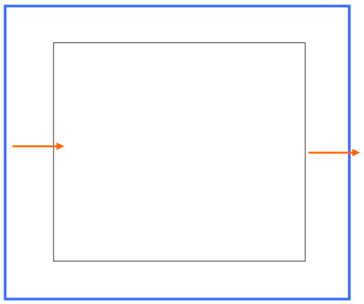
High resolution benefit ? ---- Very clear !



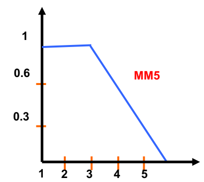
10 km | 200 km | Observed

Another inherent issue in regional modeling
: lateral boundary treatment is empirical

Buffer zone



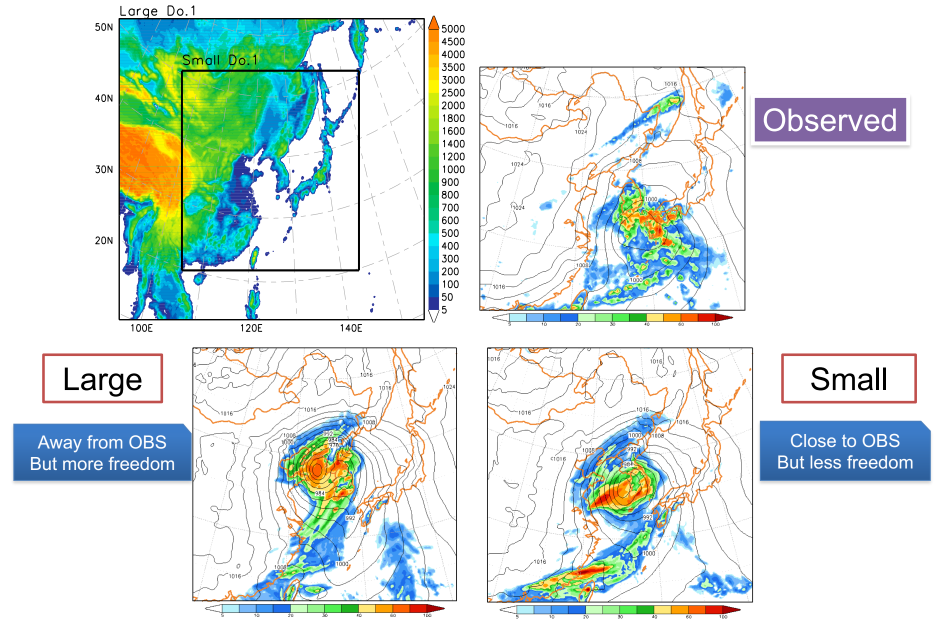
F(n) : weighting of global



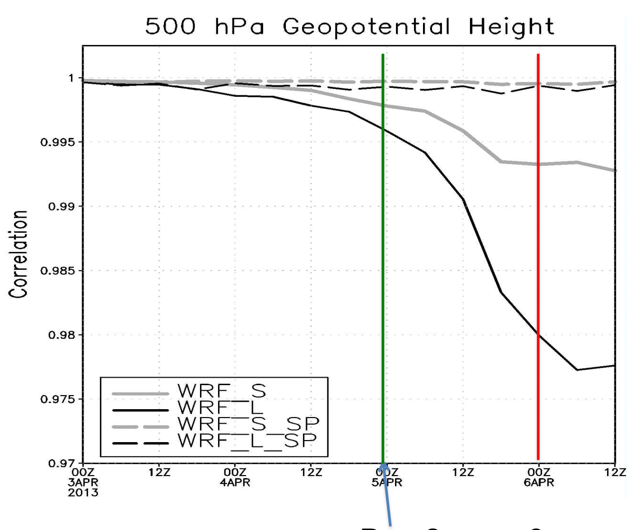
$$\frac{\partial A}{\partial t}\Big|_n = F(n)F_1(A_{CM} - A_{FM}) - F(n)F_2\nabla^2(A_{CM} - A_{FM})$$

So, empirical

Domain size sensitivity : A mid-latitude cyclone



Domain size sensitivity : Pattern correlation with global



Fundamental limit of the regional model : low resolution global and mathematically ill-posed setup

Small domain keeps the large-scale from the global but loses its freedom

Spectral nudging keeps the large-scale, but may lose the regional details

Thanks for your attention !

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Hong, S.-Y., and M. Kanamitsu, 2014: Dynamical downscaling: Fundamental issues from an NWP point of view and recommendations. *Asia-Pac. J. Atmos. Sci.*, **50,** 83-104, doi: 10.1007/s13143-014-0029-2.

Dudhia, J., 2014: A history of mesoscale model Development. *Asia-Pac. J. Atmos. Sci.*, **50,** 121-131.