

Fundamentals in Atmospheric Modeling

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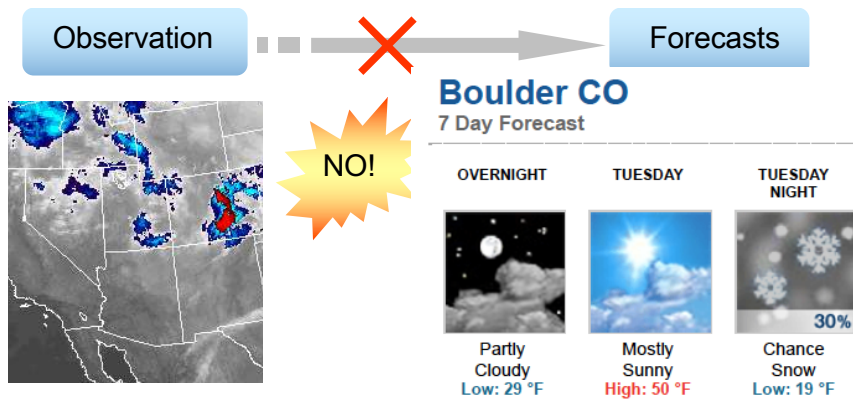
(KIAPS: Korea Institute of Atmospheric Prediction Systems)

(Also NCAR affiliate scientist)

List of presentations

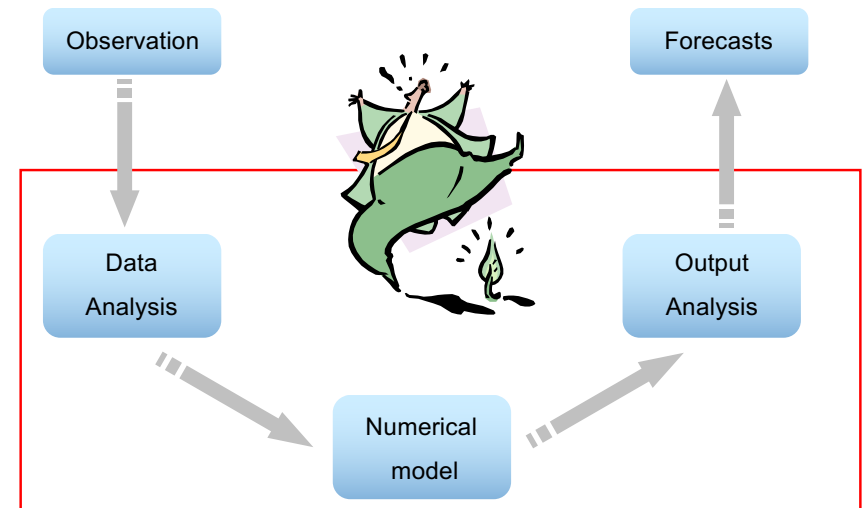
- Concept of modeling
- Structure of models
- Predictability
- Regional modeling

How were the today's forecasts made ?



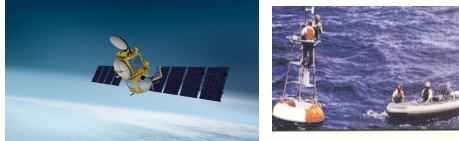
Then, what ?

Numerical model is a crucial component

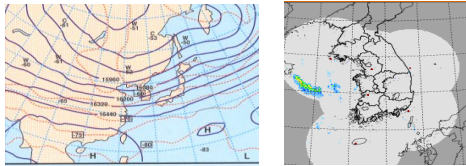


Then, how ?

Step1:
Observation



Step2:
Data analysis



Theory of NWP

Thermodynamics

Heat = Energy + Work

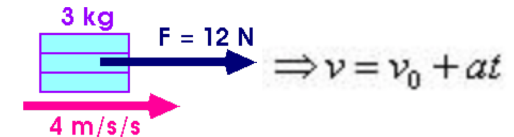
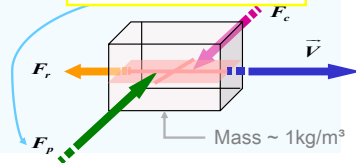


Dynamics

Force = Mass × Acceleration

- Mass $\approx 1 \text{ kg/m}^3$
- Force: PGF, Coriolis, Friction...

Nonlinear interaction



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:

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

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

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

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

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

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~)

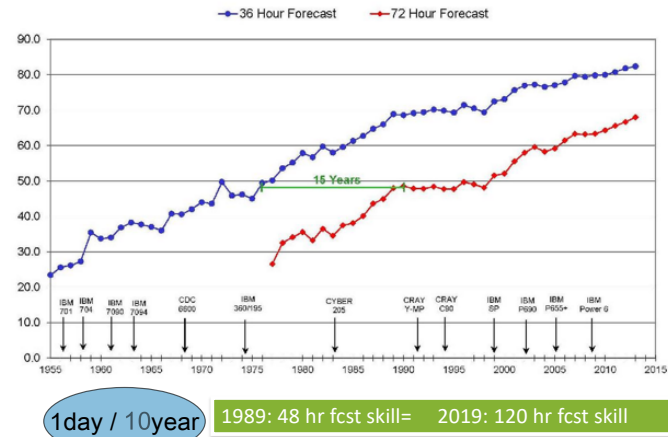
- von Neumann and Charney
 - Applied ENIAC to weather prediction
- Carl-Gustaf Rossby
 - The Swedish Institute of Meteorology
 - First routine real-time numerical weather forecasting. (1954)
(US in 1958, Japan in 1959)



History of NWP skill : NCEP GFS



NCEP Operational Forecast Skill
36 and 72 Hour Forecasts @ 500 MB over North America
[100 * (1-S1/70) Method]



Factors for the improvement (Kalnay 2002)

- Supercomputers
- Physical processes
- Initial conditions

Super-computer for weather models

ENIAC, 1946 (500 FLOPS)



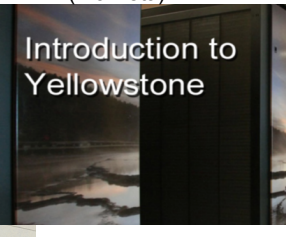
Sunway (125 Peta=10**15FLOPS)



XC40 (2.9 Peta)



IBM (1.5 Peta)

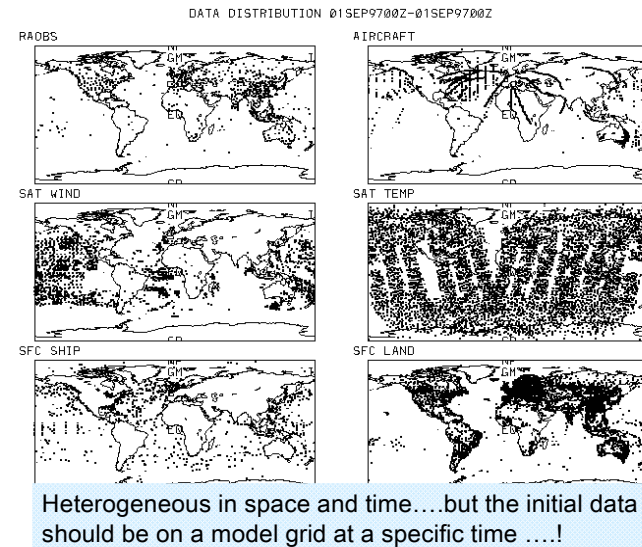


K-computer (11.2 Peta)



Initial condition (data assimilation)

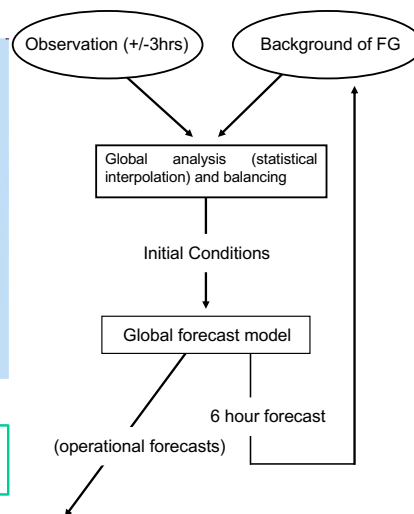
Various observations



Data Assimilation



Data assimilation best combines
observations and a model



Model

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

Step3: Integration

Dynamics : Grid system

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

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

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

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

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

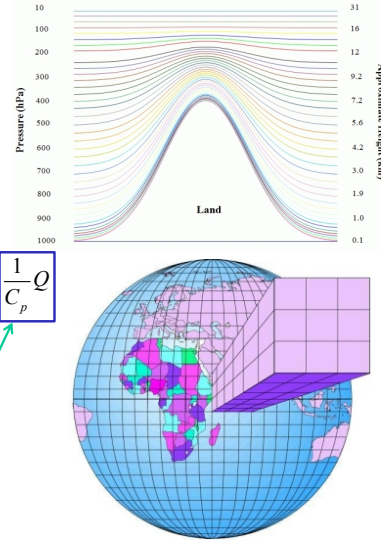
$$q_t + uq_x + vq_y + wq_z = M$$

$$p = \rho RT$$

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

If we consider O_3 , $C_t + uC_x + vC_y + wC_z = O_3$

PHYSICS



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)

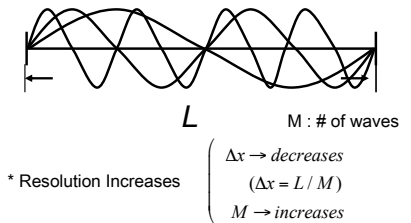
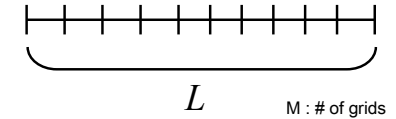
$$\frac{\Delta \phi}{\Delta t} = \frac{\phi_2 - \phi_1}{t_2 - t_1}$$

2) Spectral Method

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

$e_m(x)$ (basis funct), $m = m_1 \dots m_n \dots \rightarrow$ infinite

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



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

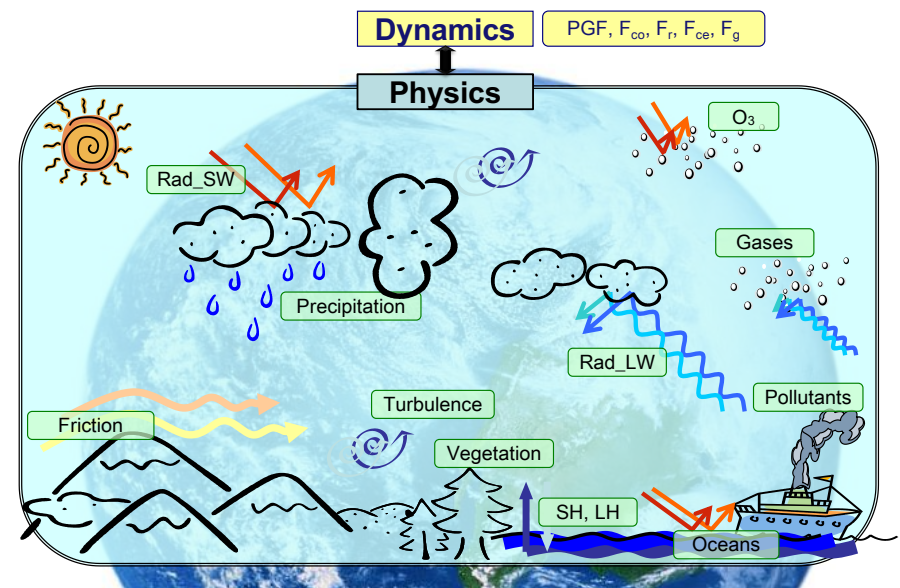
e) $\frac{u^* - u^n}{\Delta t} = F(u^n)$; $\frac{u^{n+1} - u^n}{\Delta t} = F(u^*)$: Euler-backward (Matzuno)

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

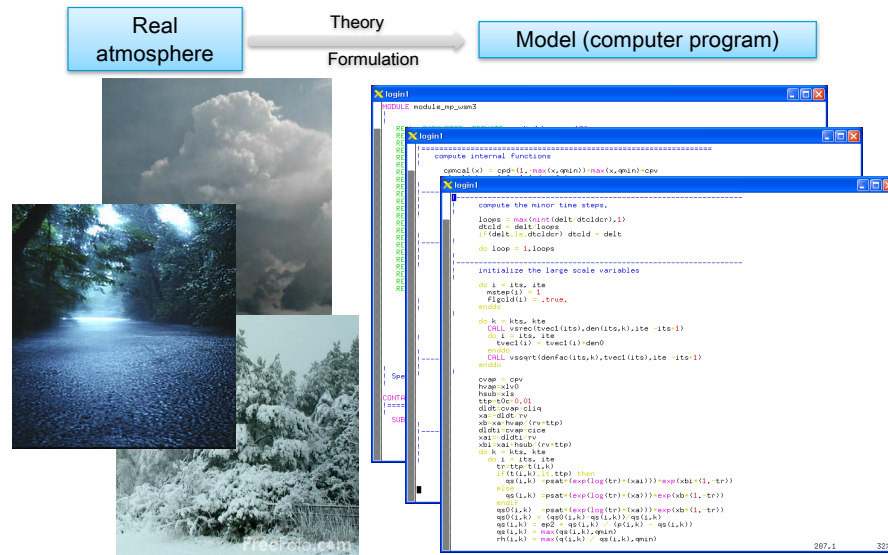
g) $\frac{u^{n+1} - u^{n-1}}{2\Delta t} = F_1(u^n) + F_2\left(\frac{u^{n+1} - u^{n-1}}{2}\right)$: Semi-Implicit

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

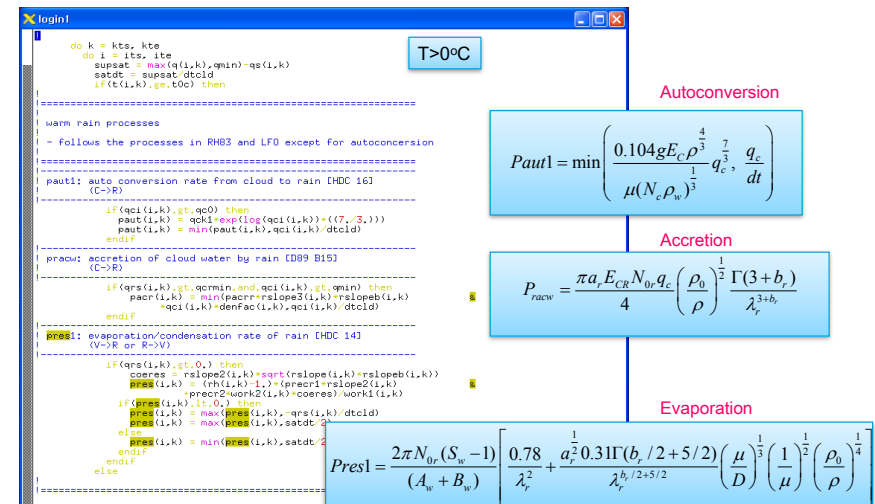
Physics modules : Branches of atmospheric sciences



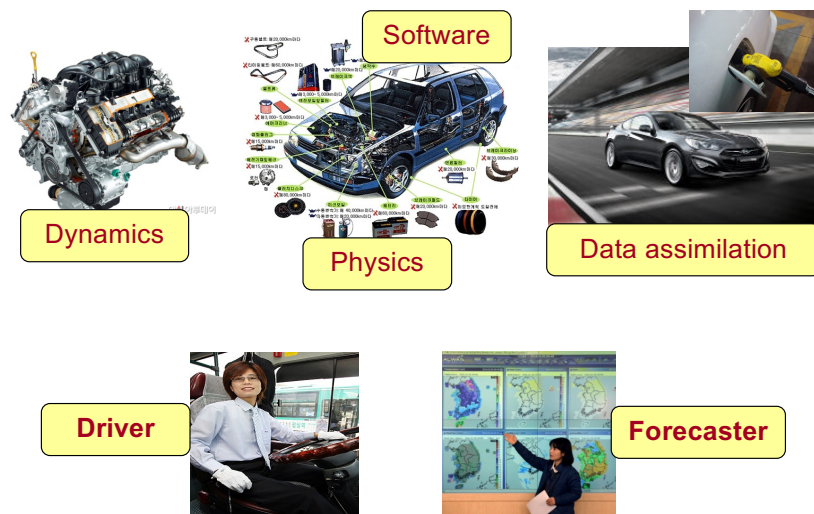
Physics module (example): Cloud and precipitation



Physics module (example): Cloud and precipitation



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)

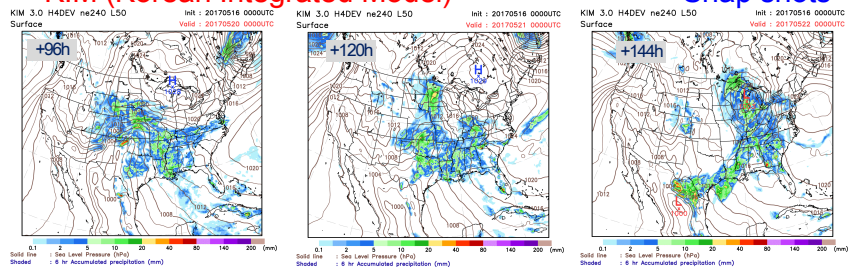
- Purpose

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

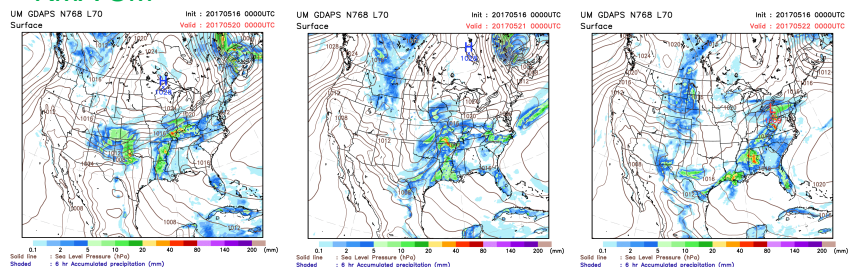
KIAPS real time forecasts (INIT 2017051600) : 12 km global NWP

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)

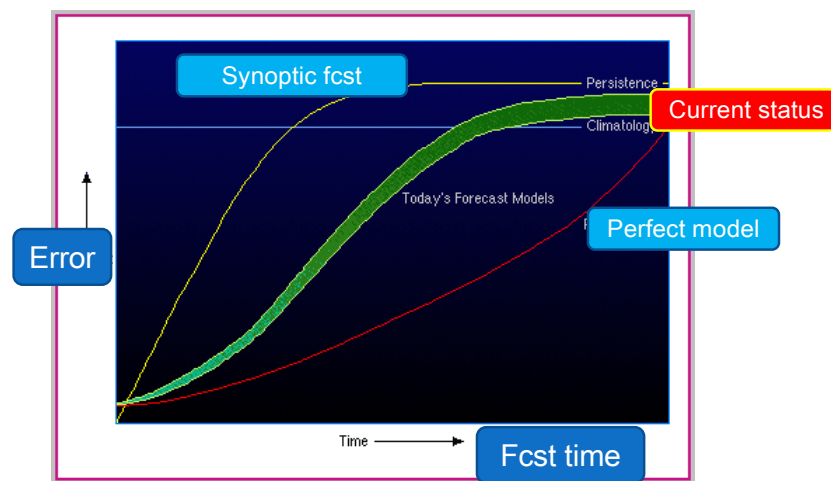
Results : differences -> non-periodicity

Initial condition (3 decimal point) : different after 2 month

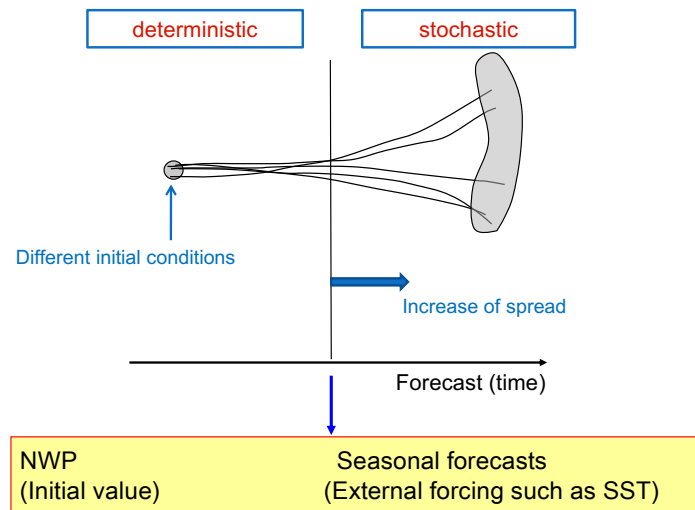
Round-off error -> cause of non-periodicity

Chaos theory- two weeks for NWP

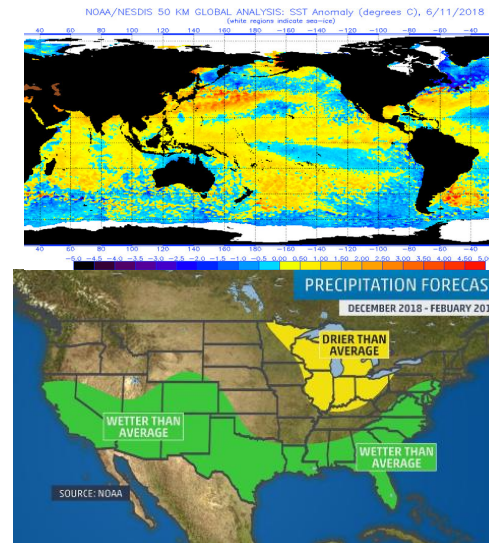
Predictability : Atmosphere is chaotic



Ensemble forecasts : Seasonal and beyond



Ensemble forecasts : Seasonal and beyond

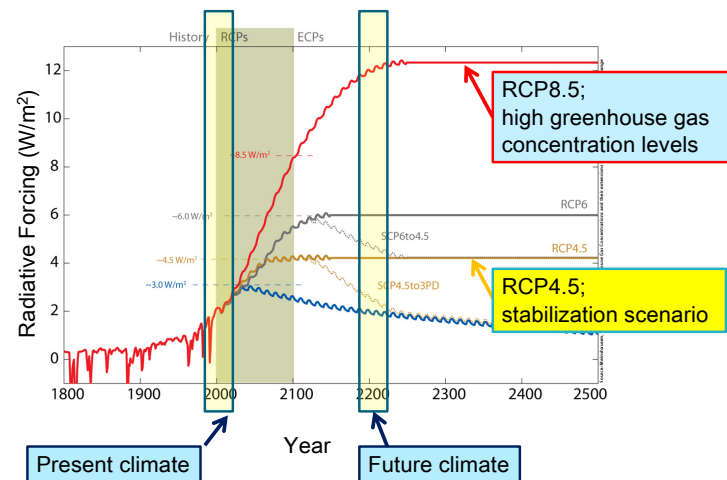


SST anomaly in
June 2018

Precipitation anomaly
in Winter 2018/2019

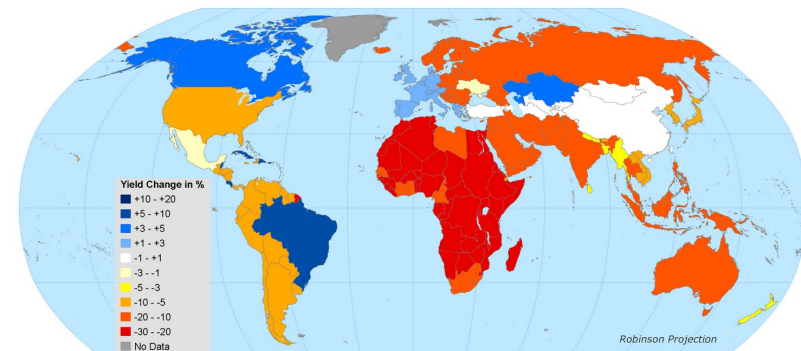
Climate prediction : For given RCP scenarios

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



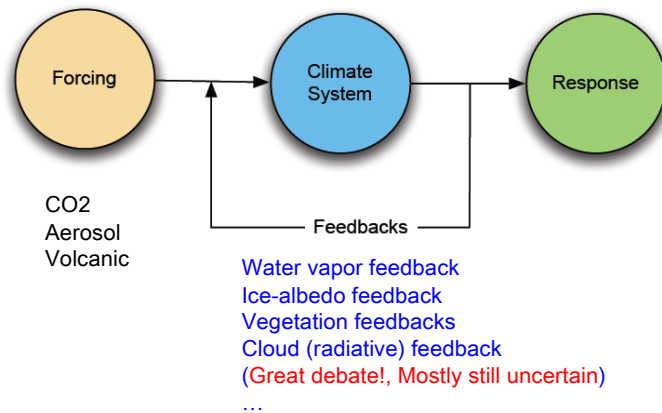
Copyright 2010, The Trustees of Columbia University in the City of New York
Source: Ignatov, A. and C. Rosenzweig, 2010. Effects of Climate Change
on Global Food Production. Data available at
<http://climate.columbia.edu/atocropmodel/>
Publish Date: March 2010

This map is for illustrative purposes and does not imply the expression of any opinion on the part of the co-authors, CIESIN, or their sponsors concerning the legal status of any country or territory or concerning the delimitation of frontiers or boundaries.



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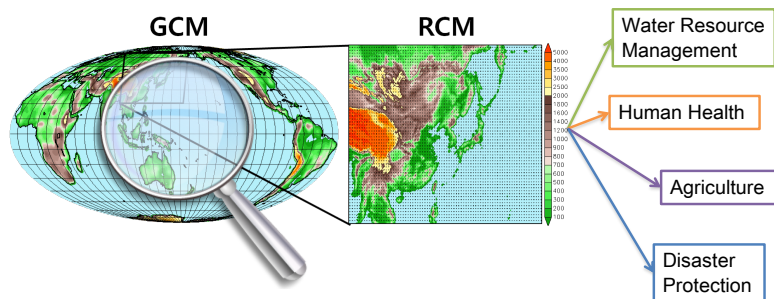
Climate prediction : Climate system sensitivity



NWP / GCM : models could be unified.

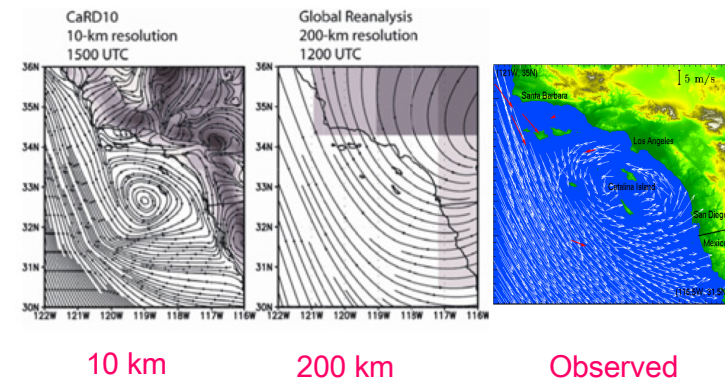
Global vs Regional

Regional modeling : need for applications



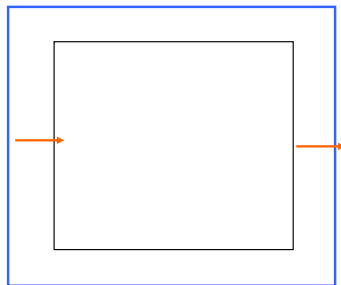
Regional model is a magnifying glass

High resolution benefit ? ---- Very clear !

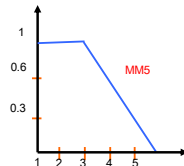


Another inherent issue in regional modeling : lateral boundary treatment is **empirical**

Buffer zone

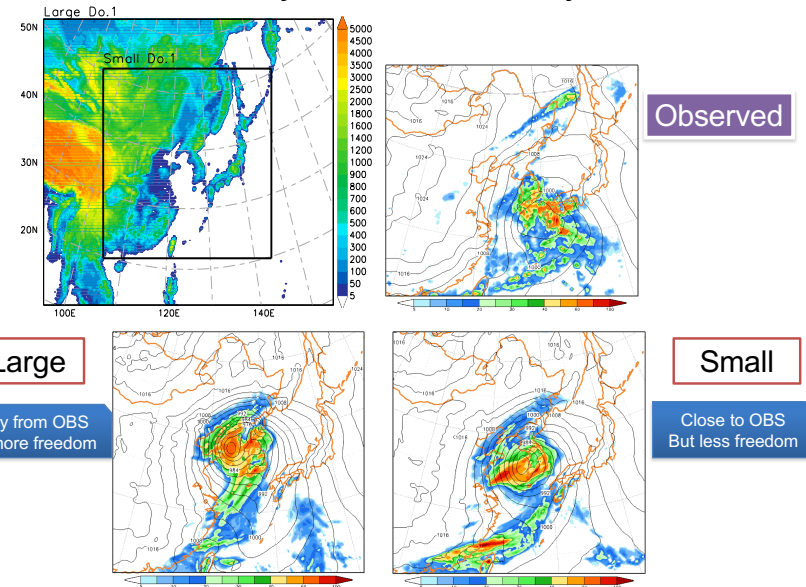


$F(n)$: weighting of global

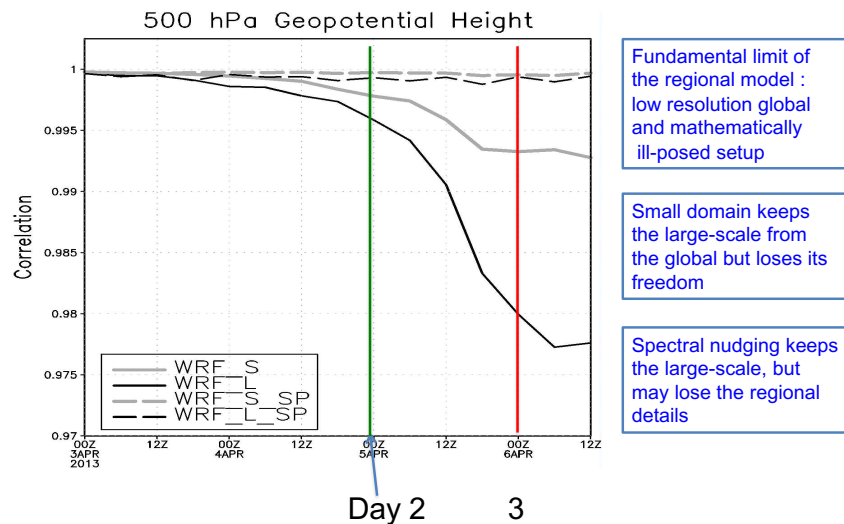


$$\frac{\partial A}{\partial t} \Big|_n = F(n)F_1(A_{CM} - A_{FM}) - F(n)F_2\nabla^2(A_{CM} - A_{FM}) \quad \text{So, empirical}$$

Domain size sensitivity : A mid-latitude cyclone



Domain size sensitivity : Pattern correlation with global



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.