Fundamentals in Atmospheric Modeling

Song-You Hong

(KIAPS: Korea Institute of Atmospheric Prediction Systems)

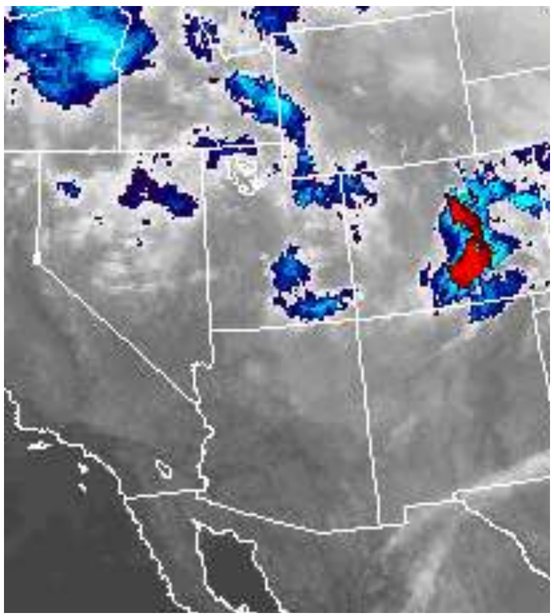
(Also NCAR affiliate scientist)

List of presentations

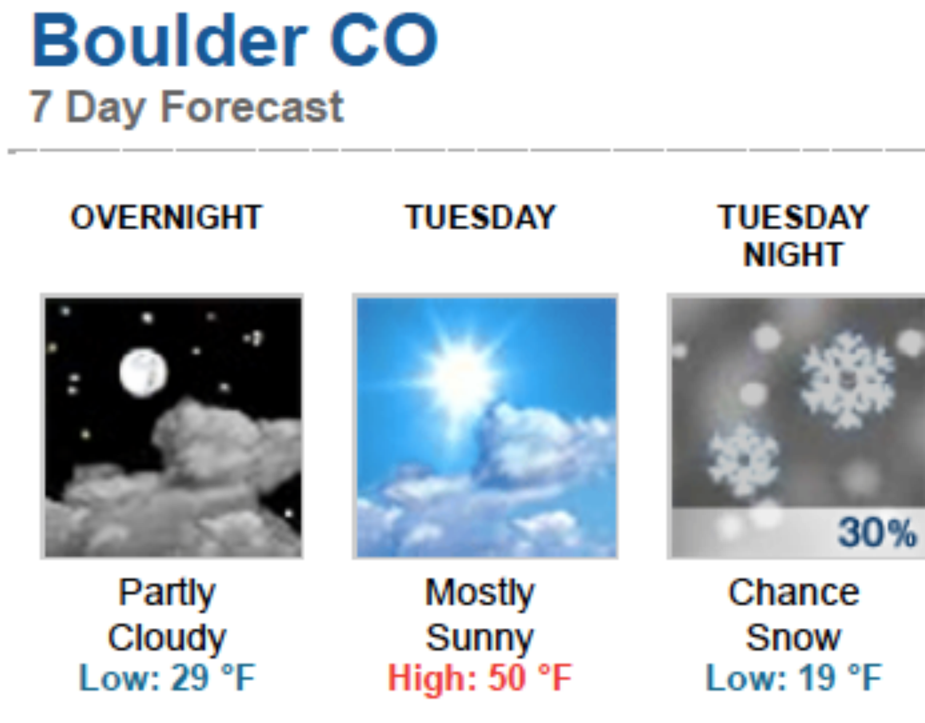
- Concept of modeling
- Structure of models
- Predictability

How the today's forecasts were made ?

Observation♪ → **Forecasts♪**

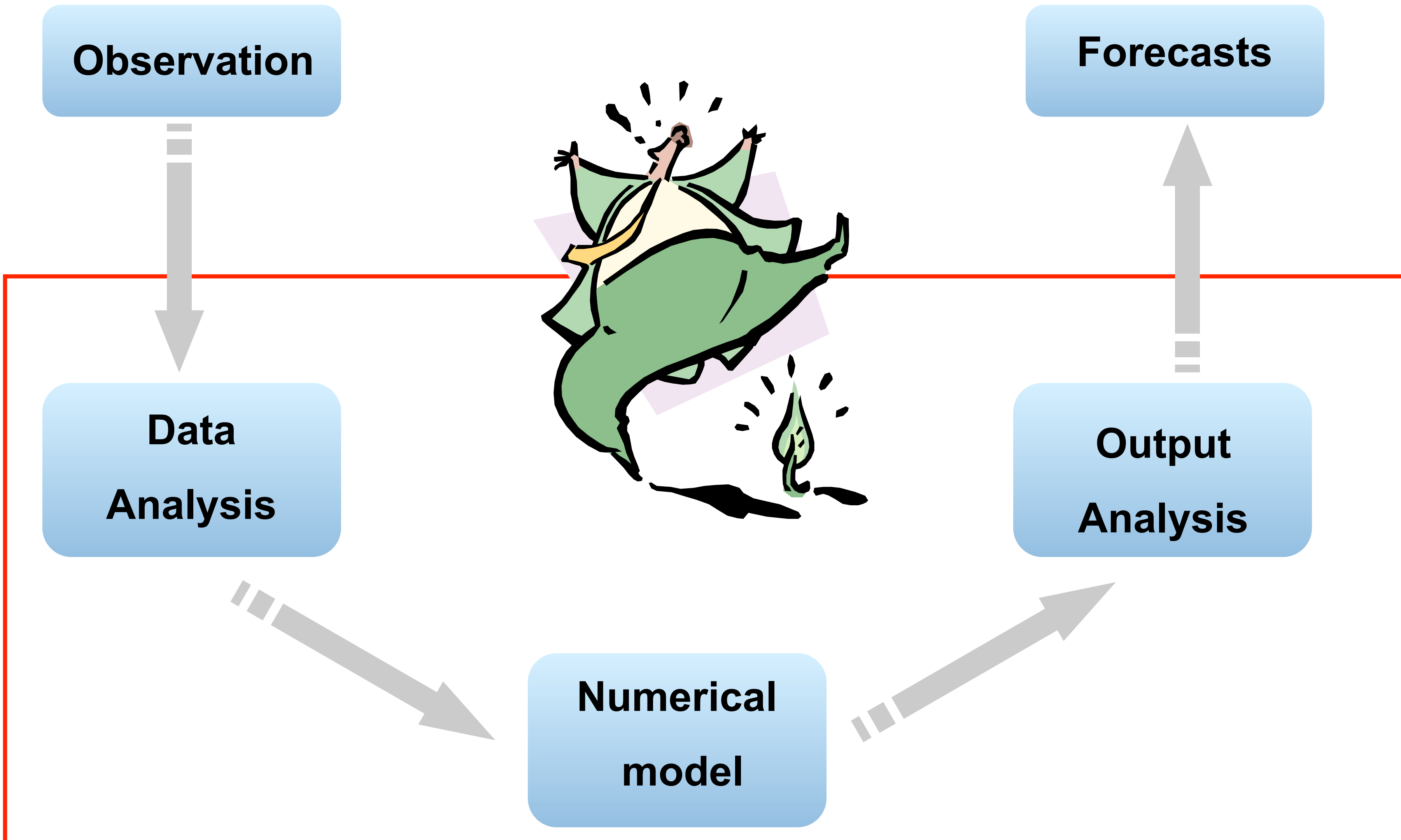


NO!

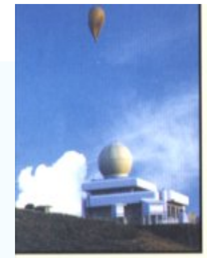


Then, what ?

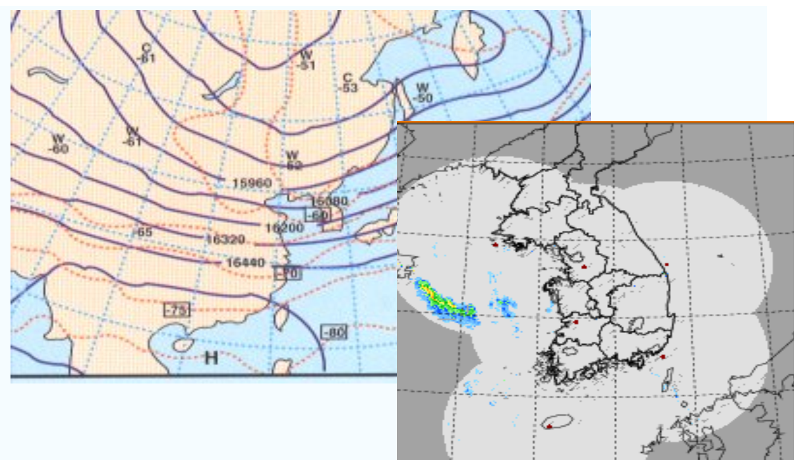
Weather forecasts ….



Step1: Observation



Step2: Data analysis



Theory ?

Thermodynamics

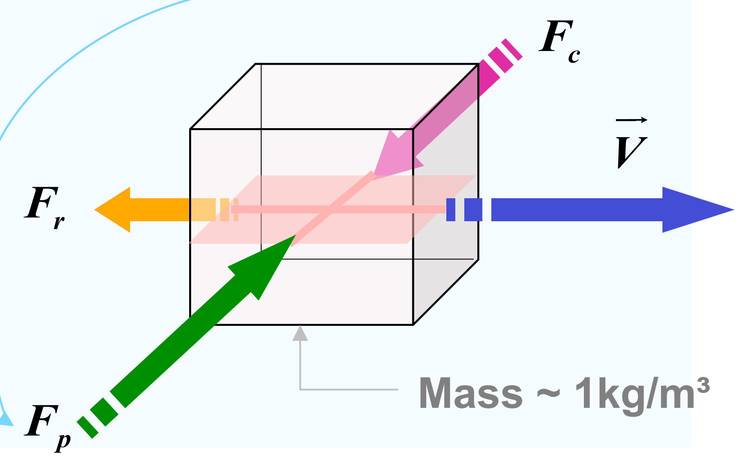
$\boxed{\text{Heat} = \text{Energy} + \text{Work}}$

$$\Delta H = c_p \Delta T - \alpha \Delta p$$
$$= c_v \Delta T + p \Delta \alpha$$

Dynamics

$\boxed{\text{Force} = \text{Mass} \times \text{Acceleration}}$

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



Theory ?

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

CONSERVATION

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:*

$$\frac{d\mathbf{v}}{dt} = -\alpha\nabla p - \nabla\phi + \mathbf{F} - 2\Omega\times\mathbf{v} \qquad \text{(1-3)}$$

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

$$p = \rho RT \qquad \text{(5)}$$

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

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

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**

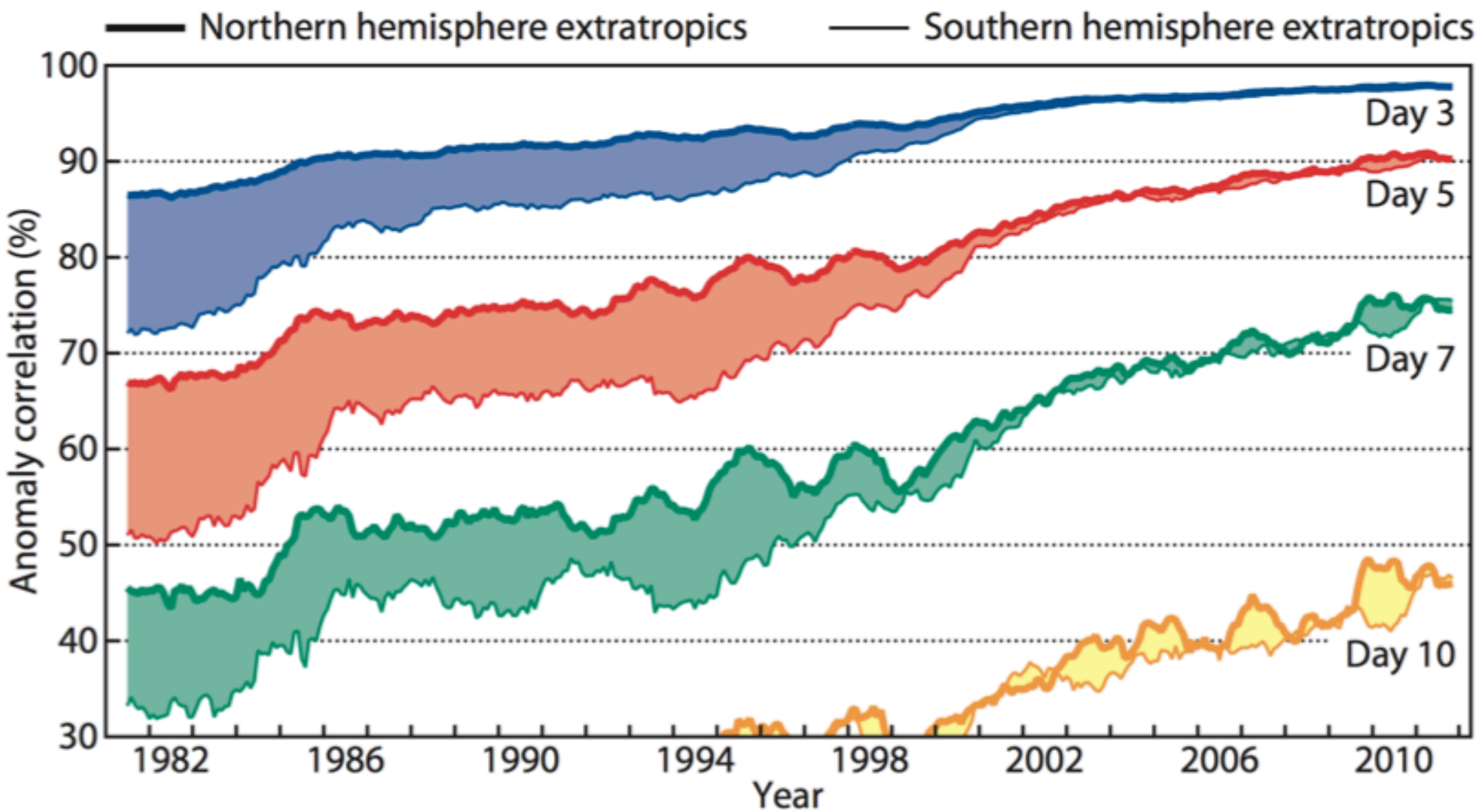
Computer Age (1946~)

- 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)

ECMWF MR-Forecast

Anomaly correlation of 500 hPa Geopotential

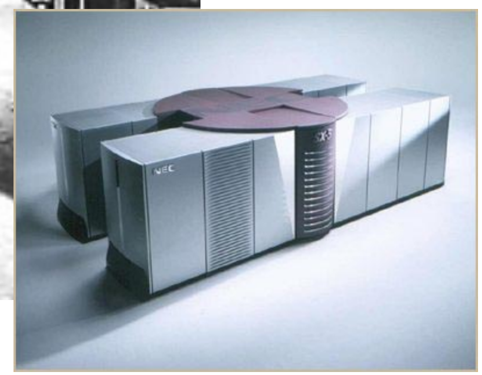


1day / 10 yrs

Factors for the improvement (Kalnay 2002)

- Supercomputers
- Physical processes
- Initial conditions

Super-computer for weather models



Cray T3E

ENIAC,1946

NEC SX-5

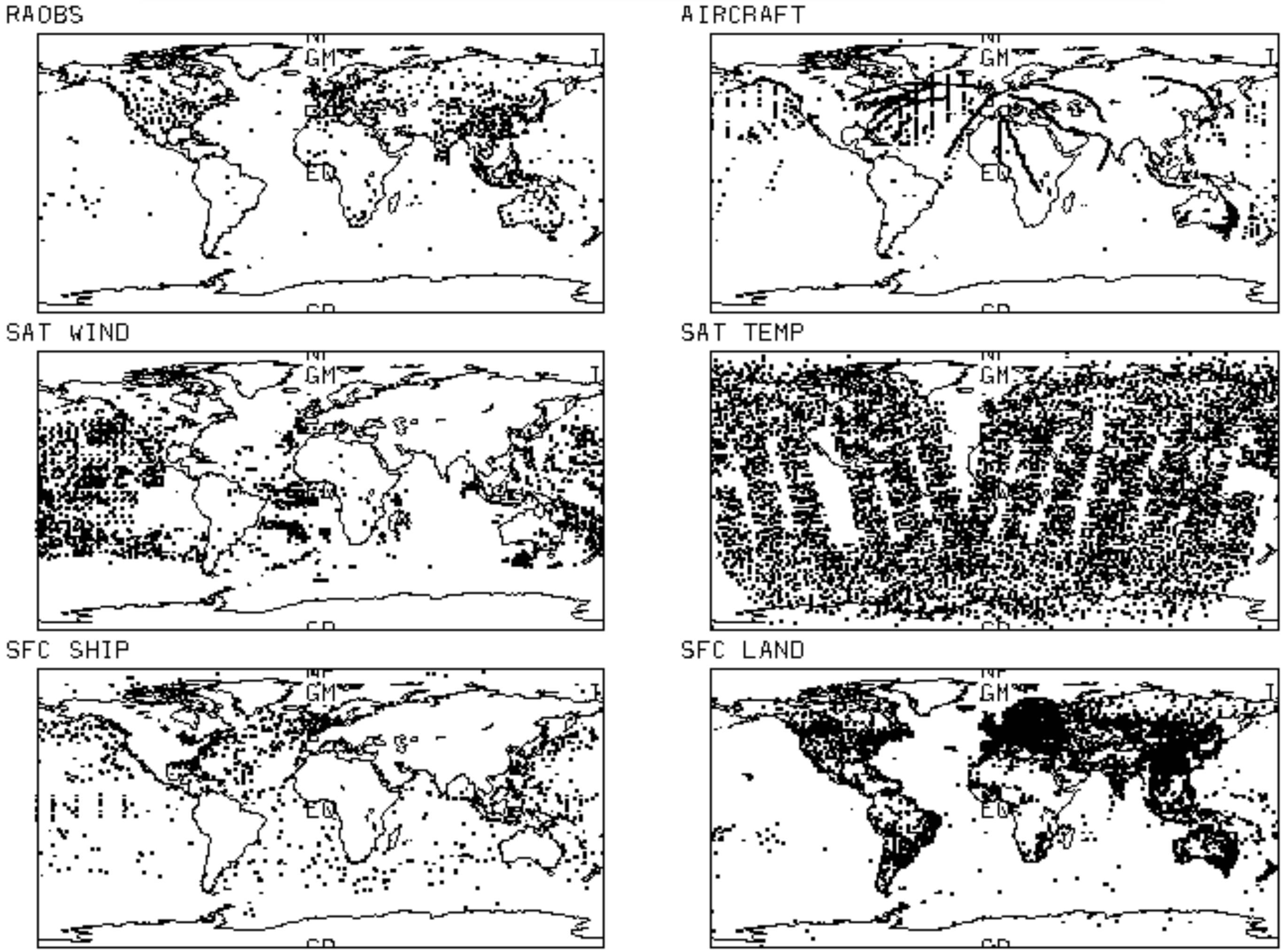
Cray SV1

Fujitsu VPP700E

Cray T90

Initial condition
(data assimilation)

Various observations



heterogeneous in space and time….

Data Assimilation

- Model 1°X 1° resolution, 20 levels

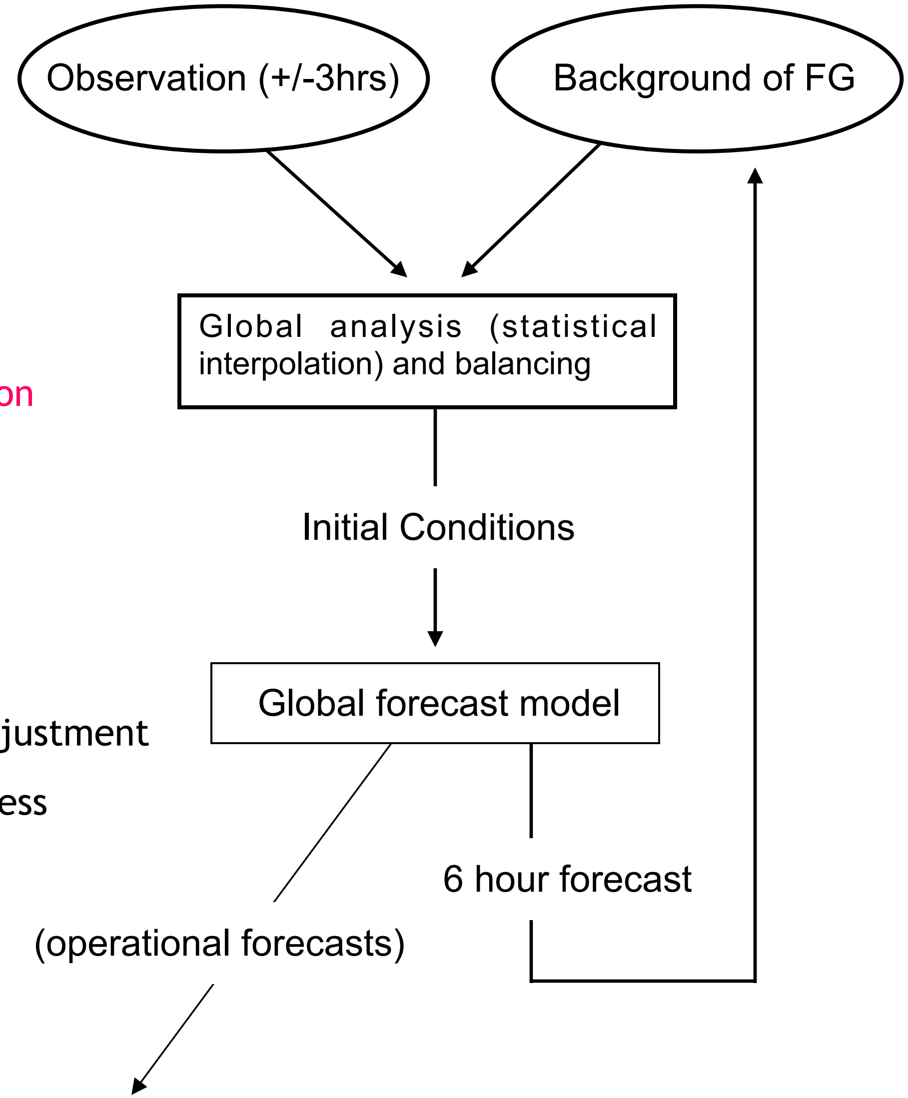
  u, v, T, q, Ps, Tg

  $$360\times180\times20=1.3\times10^6\times4\ \mathrm{var}\,iabl\ =5\times10^6$$

- observation : $10^4\sim10^5$ non-uniform distribution

  ±3 *hour window*

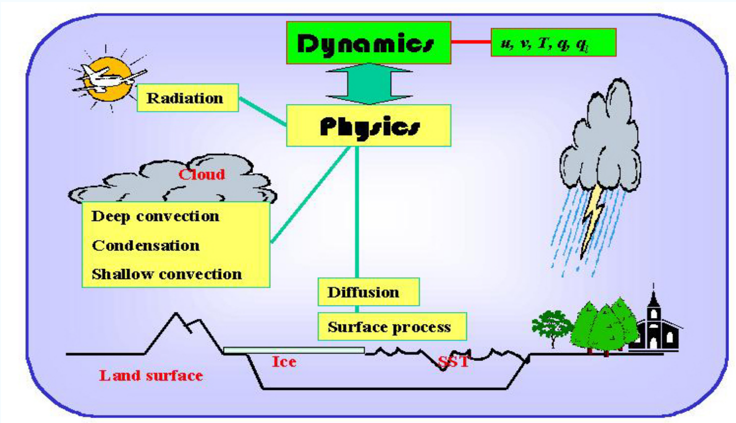
- Data assimilation cycle 1) data checking
  2) objective analysis
  3) Initialization: dynamical adjustment
  4) short-range fcst for first guess



Model

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

Step3: Integration



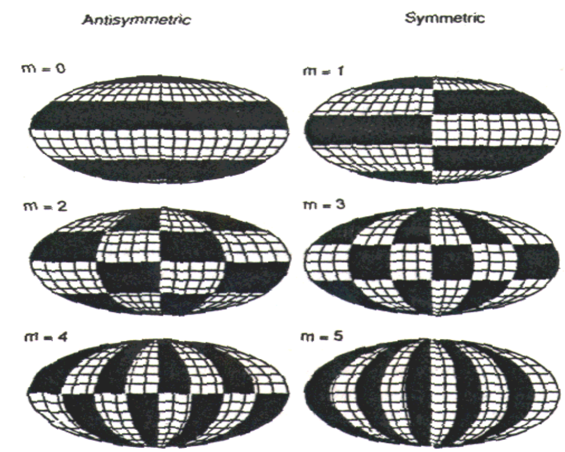
$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - \omega\frac{\partial u}{\partial p} - \frac{\partial \Phi}{\partial x} + fv + F_x$$

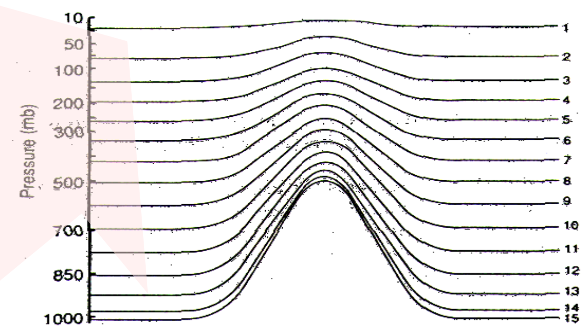
$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - \omega\frac{\partial v}{\partial p} - \frac{\partial \Phi}{\partial y} - fu + F_y$$

$$\frac{\partial \Phi}{\partial t} = -\frac{RT}{p}$$

$$\frac{\partial T}{\partial t} = -u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} + \omega\left(\frac{\kappa T}{p} - \frac{\partial T}{\partial p}\right) + \frac{\dot{H}}{c_p}$$

$$\frac{\partial \omega}{\partial p} = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$$





15-level sigma-coordinate model

Dynamics : model frame

Finite difference method (FDM) :

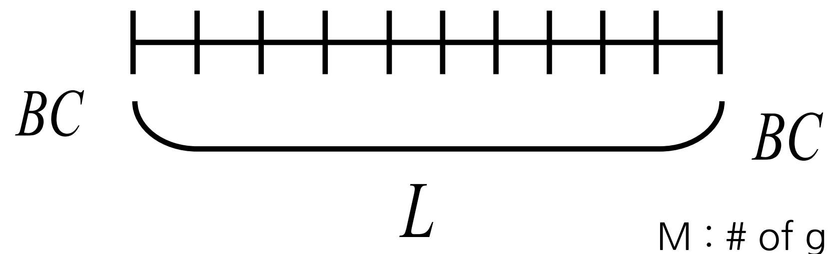
Spectral method (SPM) :

Finite element method (FEM) :

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

1) FDM (Finite difference)

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



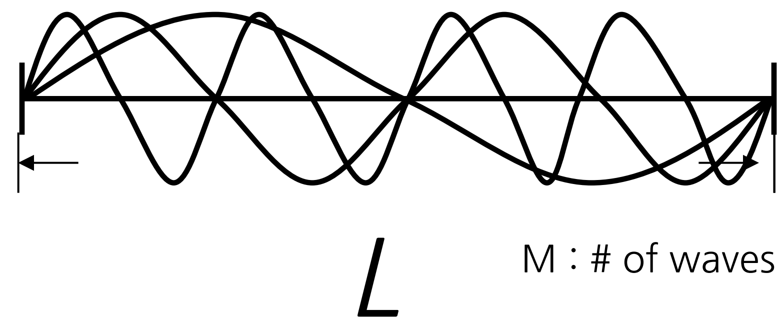
M : # of grids

2) Spectral Method

- Determine basis function to get $H\left(\phi(x)\right)$
- Expand ϕ in terms of a time series

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

$$\Rightarrow \phi\left(x,t\right) = \sum_{m=m_1}^{m_2} \phi_m(t) e_m(x)$$



M : # of waves

* Resolution Increases $\left(\begin{array}{l} \Delta x \rightarrow decreases \\ m \rightarrow increases \end{array} \right.$

Integration scheme …

a) $$\frac{u^{n+1}-u^{n-1}}{2\Delta t}=F\left(u^n\right)$$: leap-frog **good for hyperbolic**

unstable for parabolic

b) $$\frac{u^{n+1}-u^{n}}{\Delta t}=F\left(u^n\right)$$: 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) $$\frac{u^{n+1}-u^{n}}{\Delta t}=F\left(u^{n+1}\right)$$: **Fully implicit, backward**

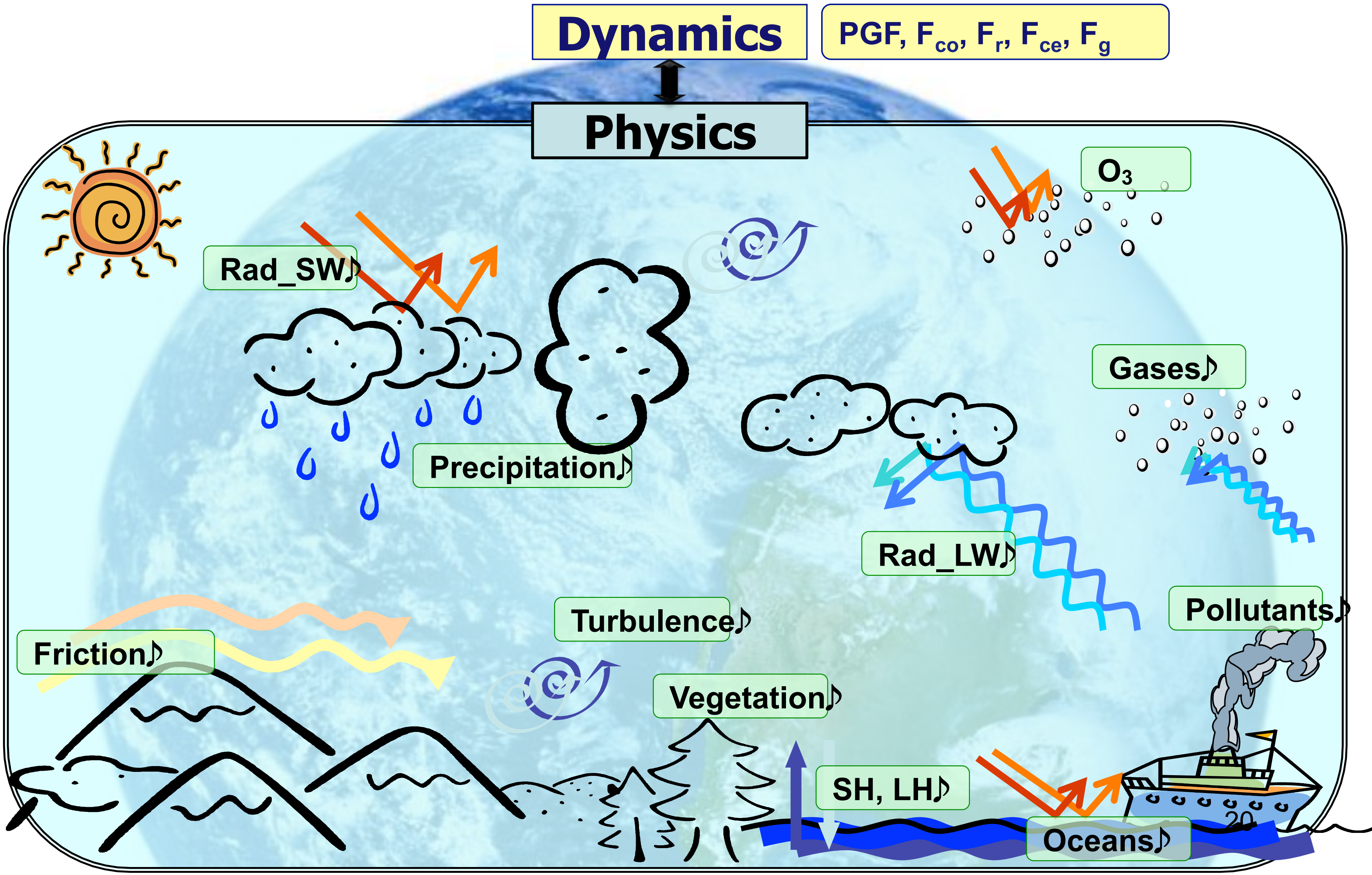
e) $$\frac{u^{*}-u^{n}}{\Delta t}=F\left(u^n\right) \quad : \quad \frac{u^{n+1}-u^{n}}{\Delta t}=F\left(u^*\right)$$: **Euler-backward (Matzuno)**

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

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

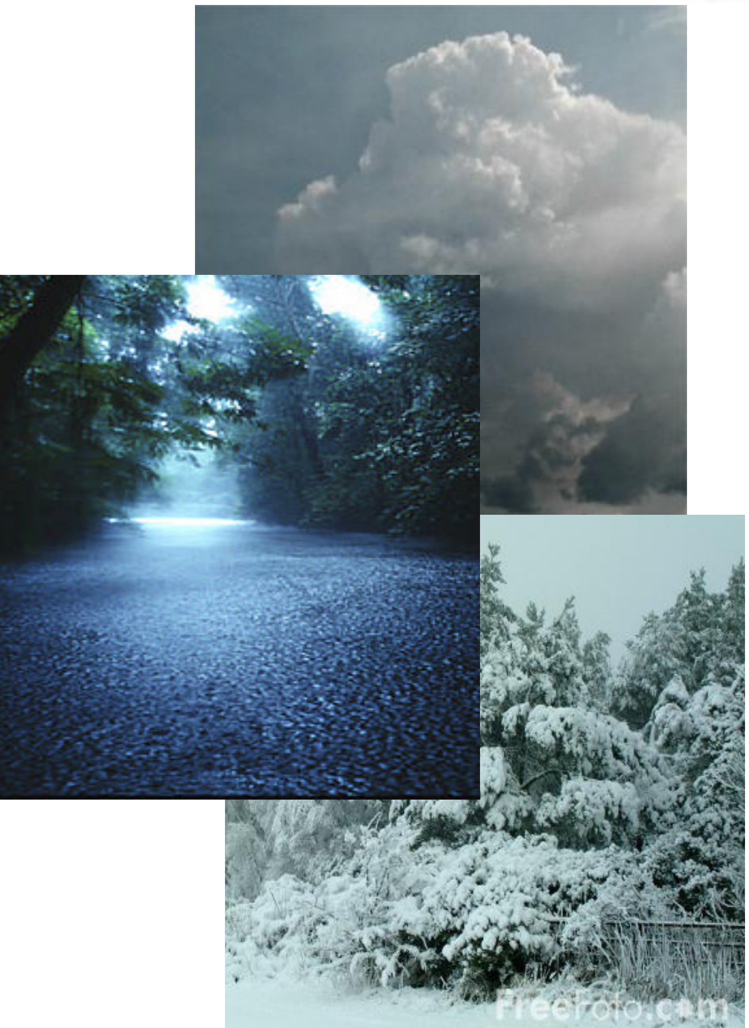
g) $$\frac{u^{n+1}-u^{n-1}}{2\Delta t}=F_1\left(u^n\right)+F_2\left(\frac{u^{n+1}-u^{n-1}}{2}\right)$$: **Semi-Implicit**

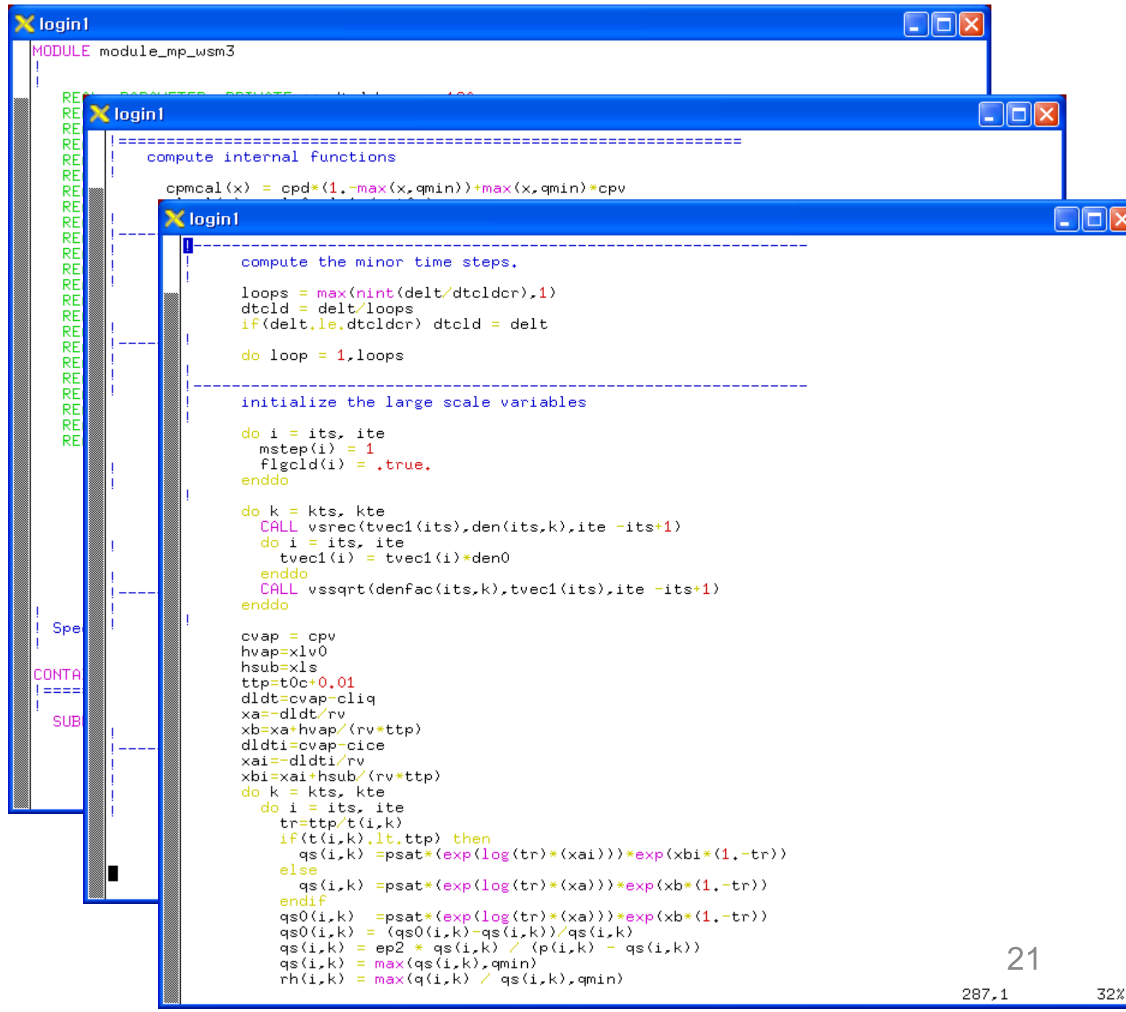
h) $$\frac{u^{*}-u^{n}}{\Delta t}=F_1\left(u^n\right); \qquad \frac{u^{n+1}-u^{*}}{\Delta t}=F_2\left(u^*\right)$$: **Fractional steps**


Dynamics
PGF, F_{co}, F_r, F_{ce}, F_g
Physics
O_3
Rad_SW♪
Precipitation♪
Gases♪
Rad_LW♪
Pollutants♪
Turbulence♪
Friction♪
Vegetation♪
SH, LH♪
Oceans♪

Example : Cloud and precipitation

Real atmosphere → Theory / Formulation → Model (computer program)





Cloud and precipitation

login1

```
!
      do k = kts, kte
        do i = its, ite
          supsat = max(q(i,k),qmin)-qs(i,k)
          satdt = supsat/dtcld
          if(t(i,k).ge.t0c) then
!
!===============================================================
!
! warm rain processes
!
! - follows the processes in RH83 and LFO except for autoconcersion
!
!===============================================================
!---------------------------------------------------------------
! paut1: auto conversion rate from cloud to rain [HDC 16]
!        (C->R)
!---------------------------------------------------------------
            if(qci(i,k).gt.qc0) then
              paut(i,k) = qck1*exp(log(qci(i,k))*((7./3.)))
              paut(i,k) = min(paut(i,k),qci(i,k)/dtcld)
            endif
!---------------------------------------------------------------
! pracw: accretion of cloud water by rain [D89 B15]
!        (C->R)
!---------------------------------------------------------------
            if(qrs(i,k).gt.qcrmin.and.qci(i,k).gt.qmin) then
                pacr(i,k) = min(pacrr*rslope3(i,k)*rslopeb(i,k)      &
                     *qci(i,k)*denfac(i,k),qci(i,k)/dtcld)
            endif
!---------------------------------------------------------------
! pres1: evaporation/condensation rate of rain [HDC 14]
!        (V->R or R->V)
!---------------------------------------------------------------
            if(qrs(i,k).gt.0.) then
                coeres = rslope2(i,k)*sqrt(rslope(i,k)*rslopeb(i,k))
                pres(i,k) = (rh(i,k)-1.)*(precr1*rslope2(i,k)        &
                         +precr2*work2(i,k)*coeres)/work1(i,k)
              if(pres(i,k).lt.0.) then
                pres(i,k) = max(pres(i,k),-qrs(i,k)/dtcld)
                pres(i,k) = max(pres(i,k),satdt/2
              else
                pres(i,k) = min(pres(i,k),satdt/2
              endif
            endif
          else
!
!=================================================
```

T>0°C

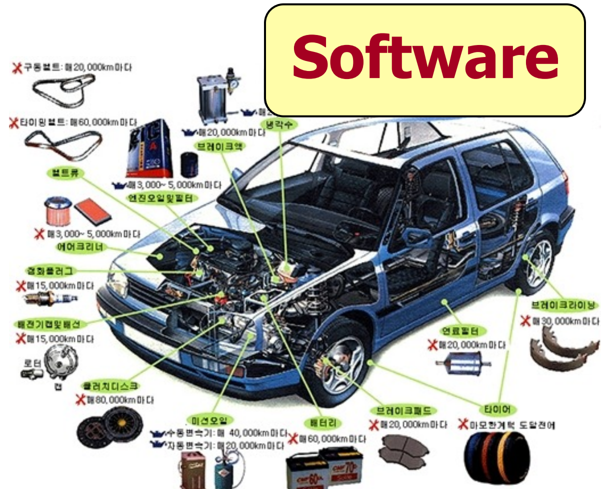
$$Paut1 = \min\left(\frac{0.104 g E_C \rho^{\frac{4}{3}}}{\mu (N_c \rho_w)^{\frac{1}{3}}} q_c^{\frac{7}{3}},\ \frac{q_c}{dt}\right)$$

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

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

Car and model

Dynamics

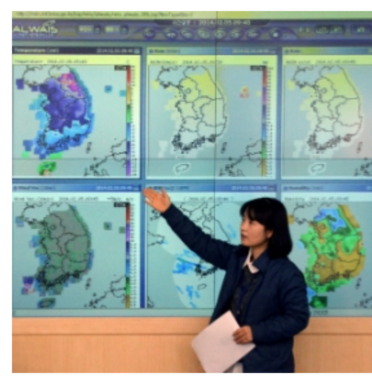


Software

Physics

Data assimilation

Driver



Forecaster

Classification of models

- Dynamic frame

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

- Scale

Global	Regional
10 km - 100 km	1 km-10 km

- Purpose

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

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

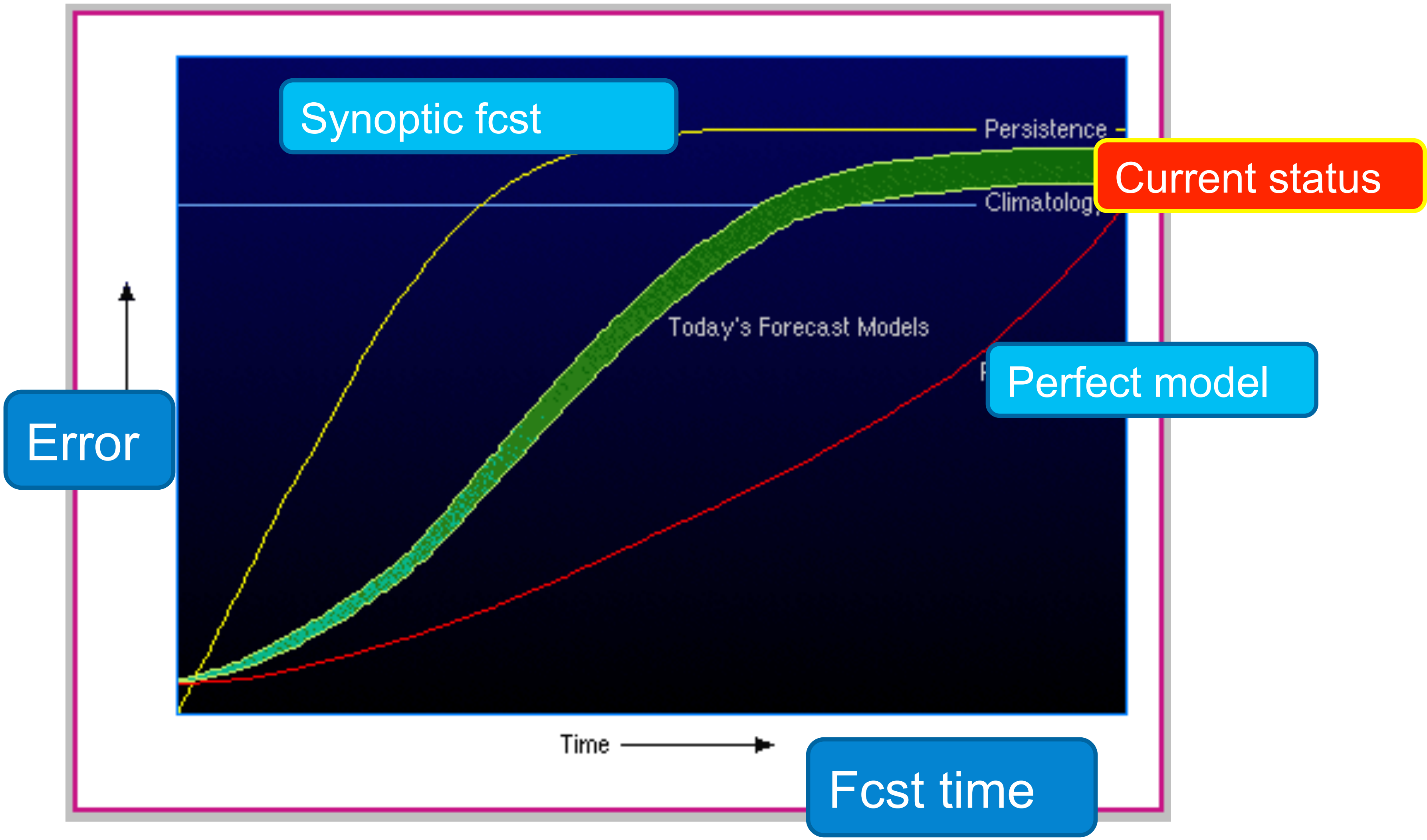
↓

Round-off error -> cause of non-periodcity

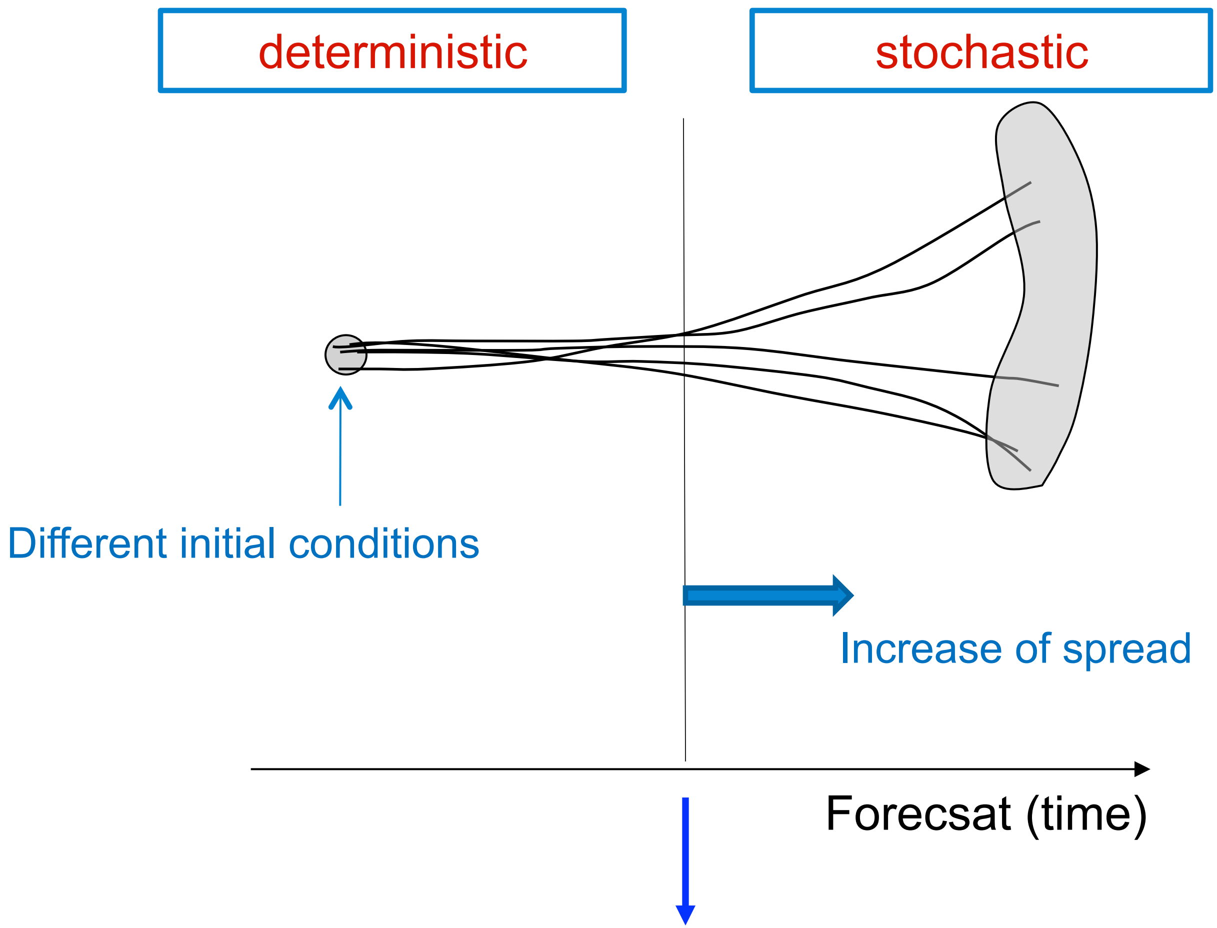
↓

Chaos theory– two weeks

Predictability

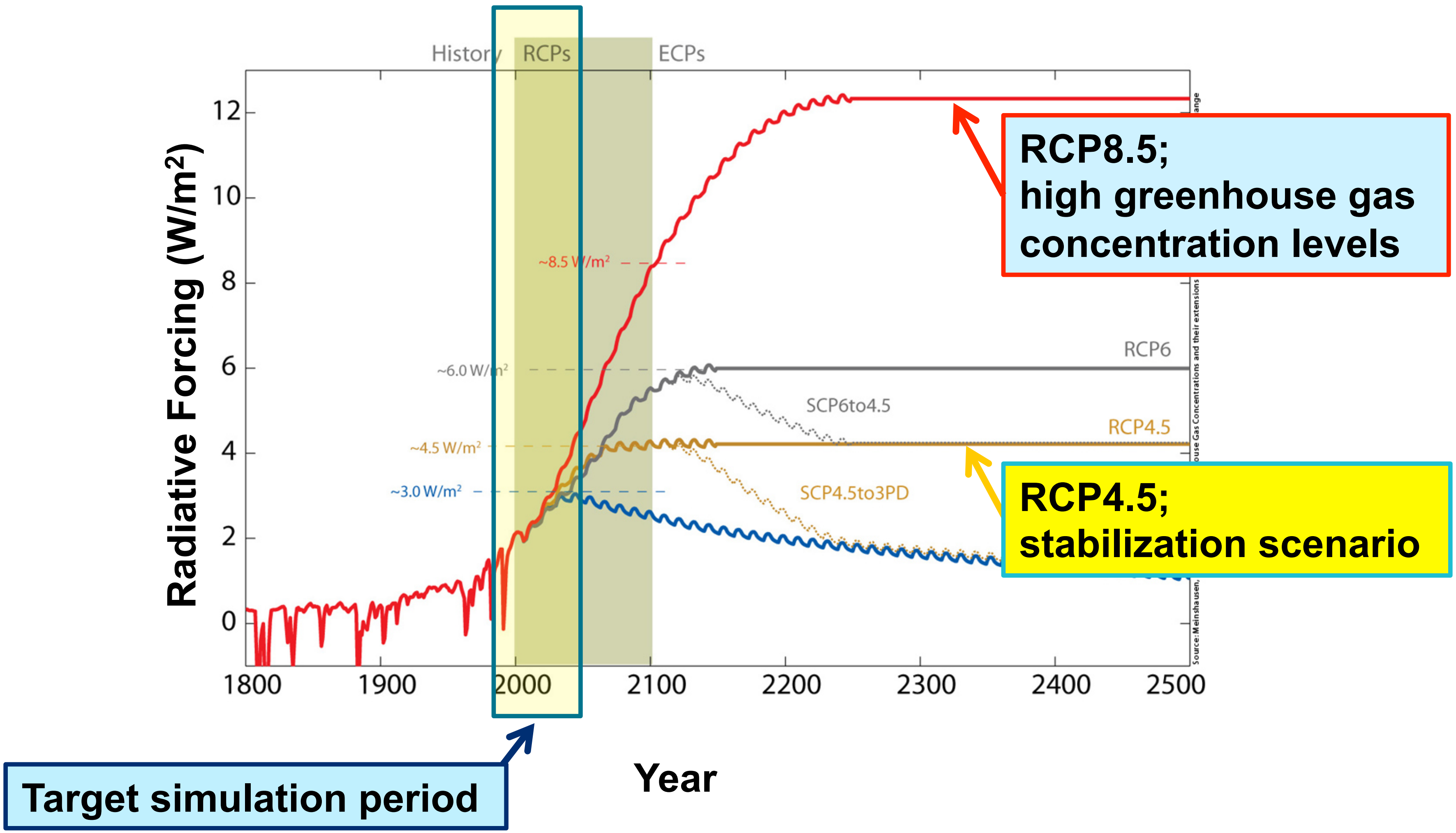


Ensemble forecasts



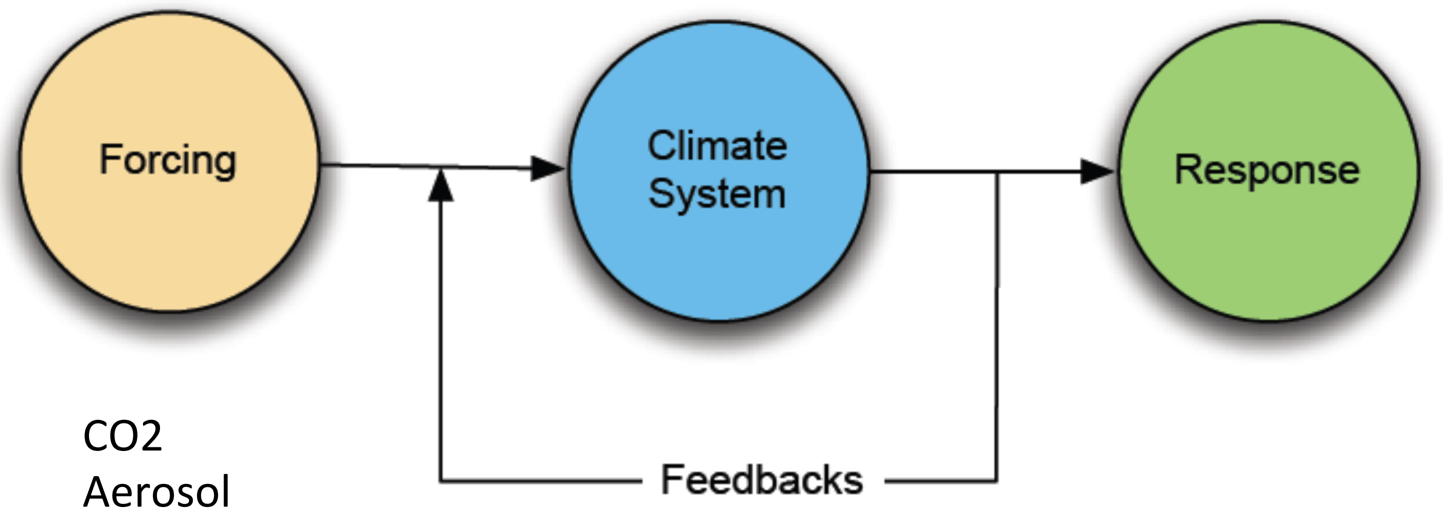
NWP (IVP) **SFS (BVP)**

RCP scenarios



(Meinshausen et al. 2011)

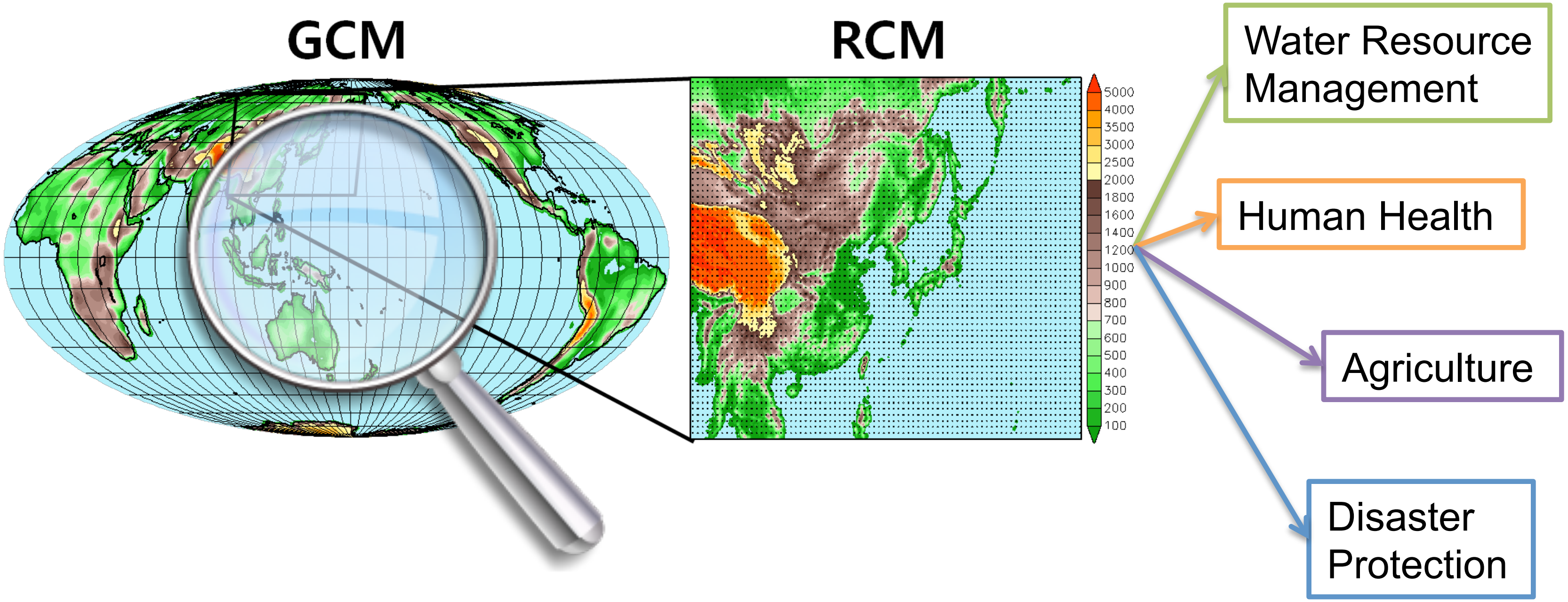
Climate system sensitivity



CO2
Aerosol
Volcanic

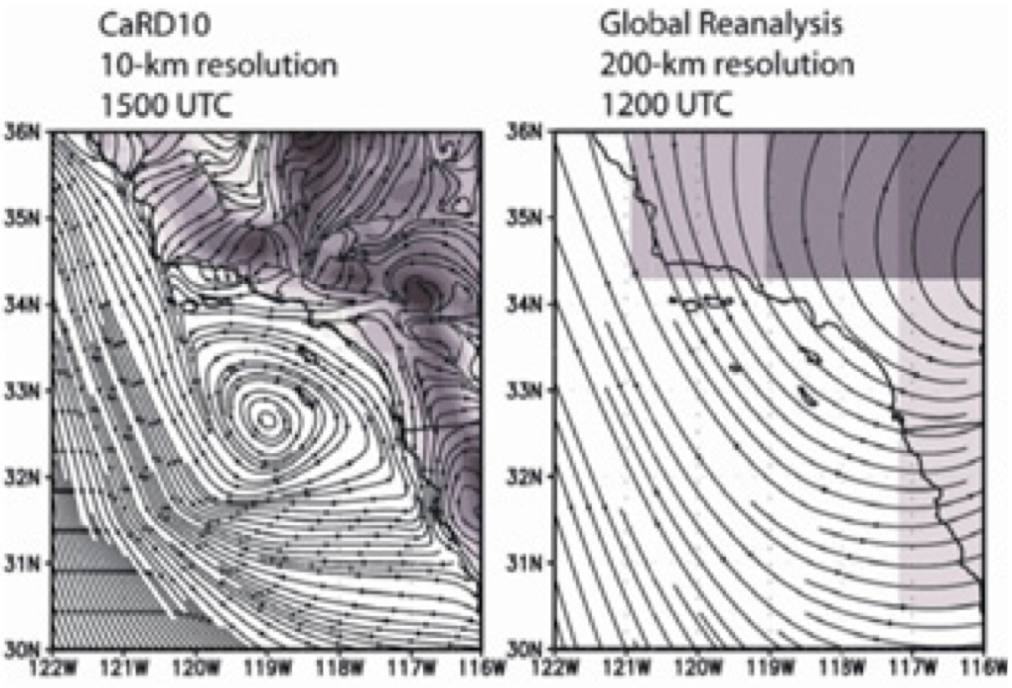
Water vapor feedback
Ice-albedo feedback
Vegetation feedbacks
Cloud (radiative) feedback
(Great debate!, Mostly still uncertain)
…

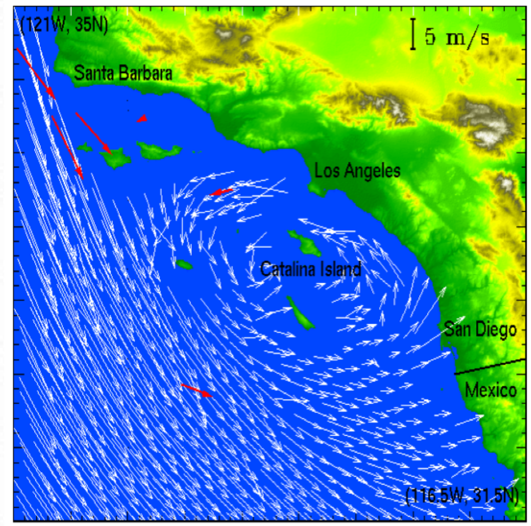
Global versus Rregional



Regional model is a magnifying glass

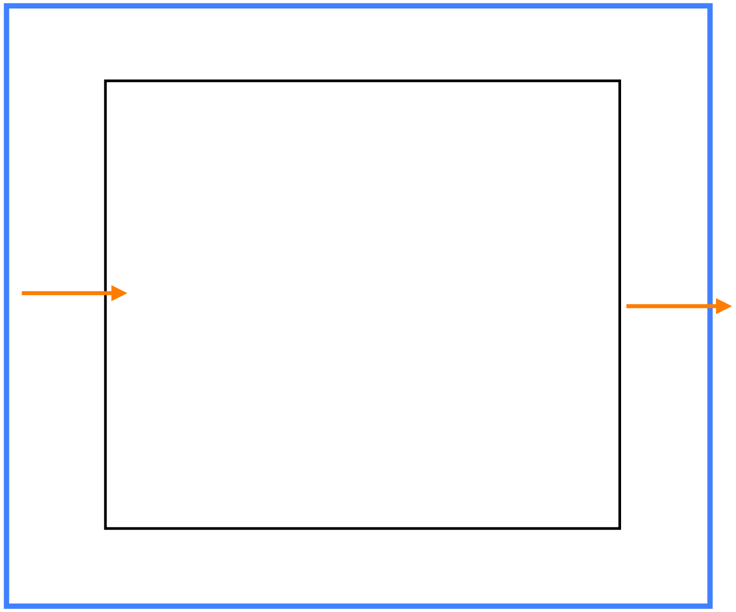
Benefit ?   ---- Very clear !



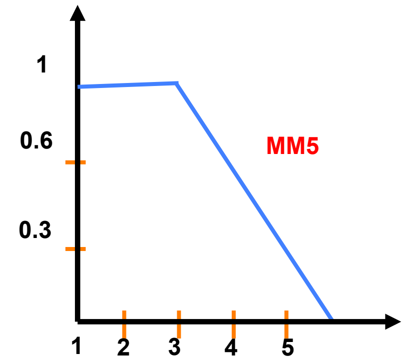


But, there is another issue on lateral boundary treatment

Buffer zone



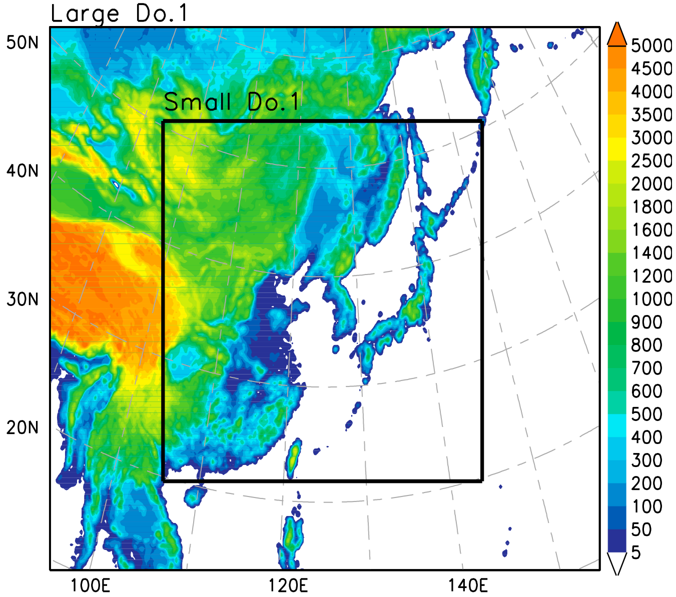
F(n) : weighting of global

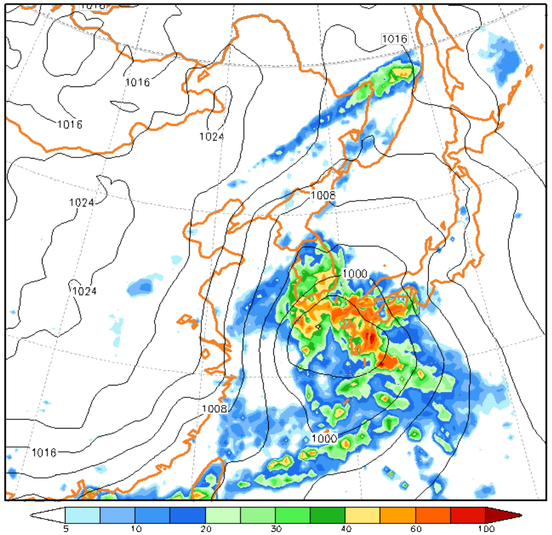


$$\left.\frac{\partial A}{\partial t}\right|_n = F(n)F_1(A_{CM} - A_{FM}) - F(n)F_2\nabla^2(A_{CM} - A_{FM})$$

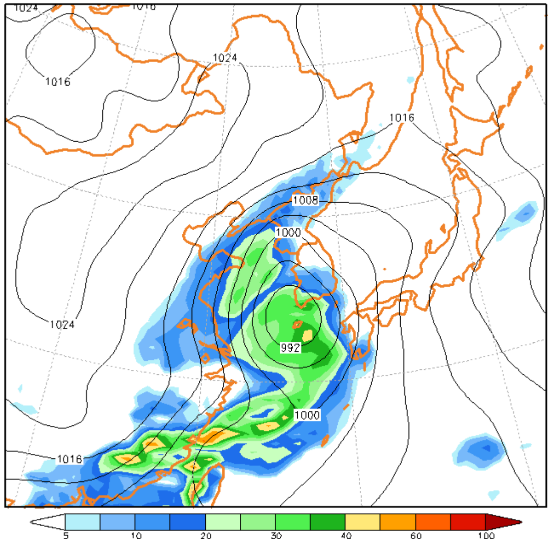
So, empirical

Domain size sensitivity





TMPA and FNL



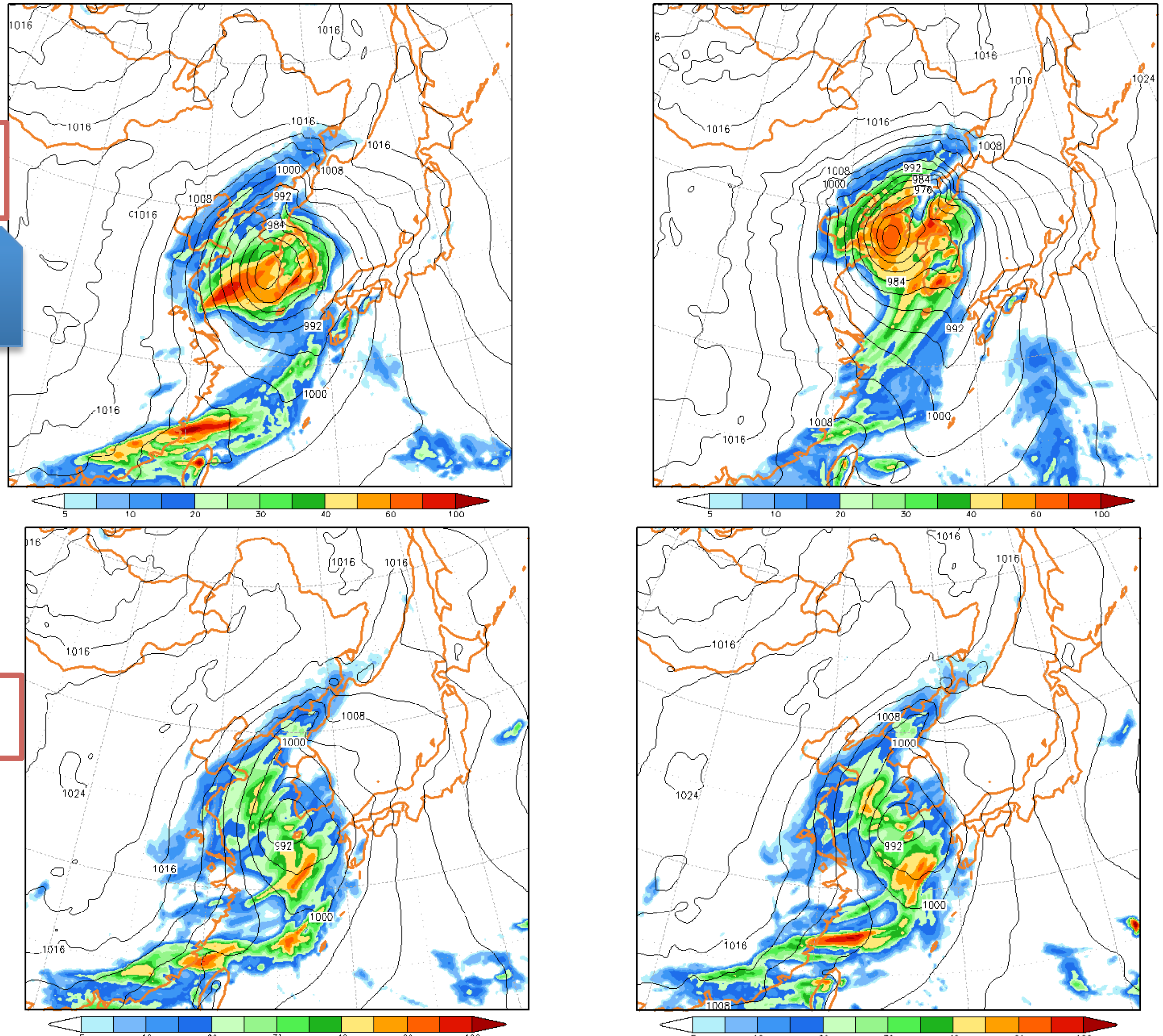
GFS 72 hr fcst

Mid-latitude cyclone on April 6th, 2013

WRF fcst driven by GFS fcst

Small

Close to GFS



Large

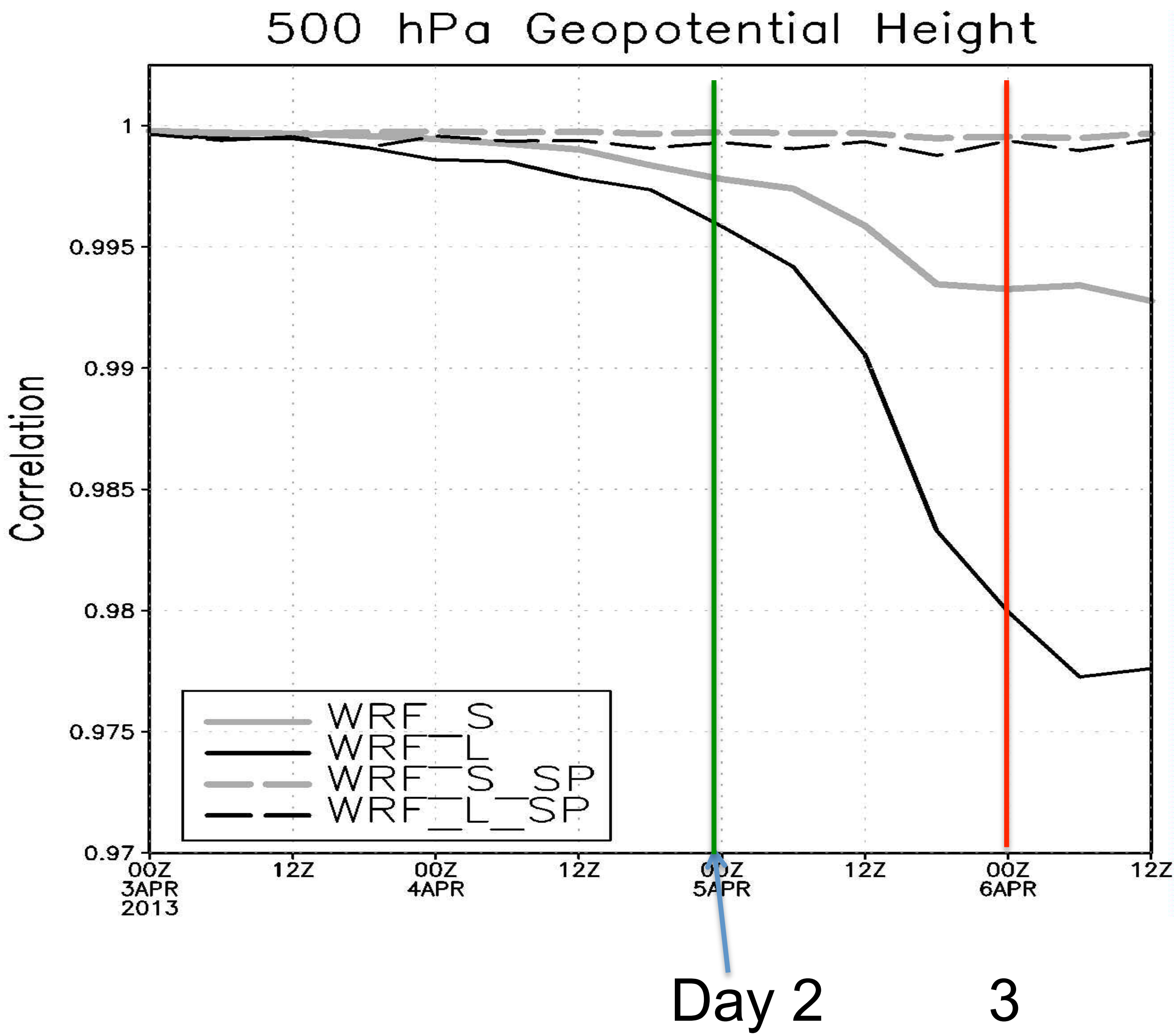
Away from GFS

Small_SP

Large_SP

Spectral nudging (SP): WRF approaches to GFS forecasts …but loses regional details

Domain-averaged PC



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 !
songyouhong@gmail.com

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.