Numerical Atmospheric Modeling

Song-You Hong

songyouhong@gmail.com

List of presentations

- **Concept of modeling**
- **Structure of models**
- **WRF model**

Modeling experience

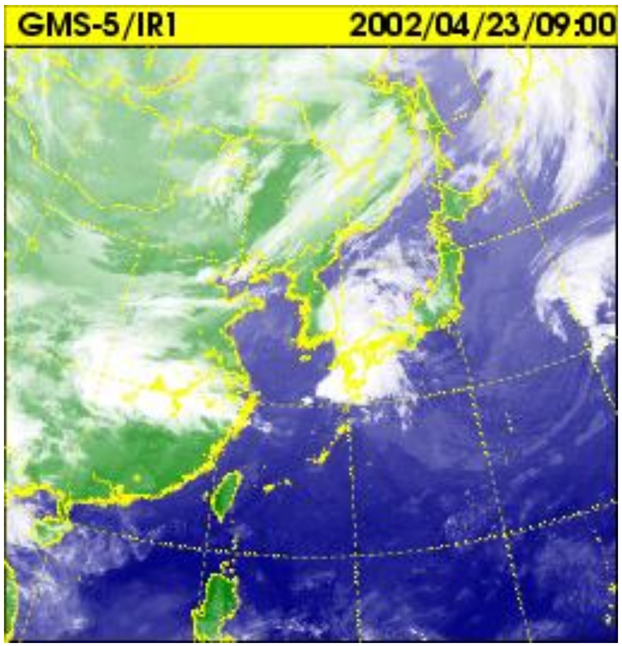
Papers : about 100

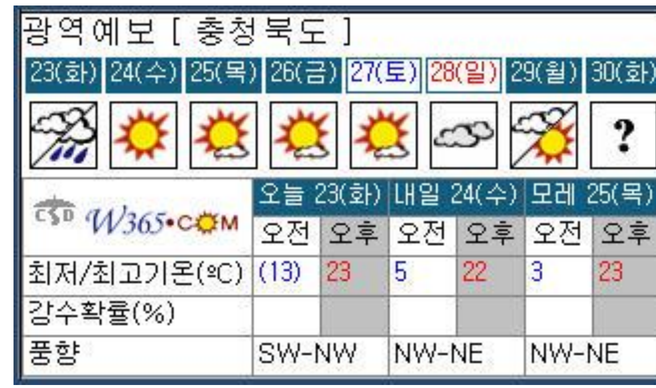
- MM5 – KMA (SNU, 1986-1989)
- NCEP/EMC (MRF, ETA, RSM, 1993-2000)
  - **Cumulus convection (Hong and Pan 1998, MWR): 1998**
  - **Cloud scheme (Hong et al. 1998, MWR) : 1996**
  - **PBL scheme (Hong and Pan 1996, MWR) : 1995**
  - **Lateral boundary (Hong and Juang, MWR) : 1996**
  - **COMPARE (Nagata et al. 2001, BAMS) : NCEP representative**
  - **PIRCS (Takle et al. 1999, JGR) : NCEP representative**
- NCEP SFM (1998-2000)
- WRF (2000-)
- GRIMs (2000-)

How the today's forecasts were made ?

Observation → **Forecasts**

NO!





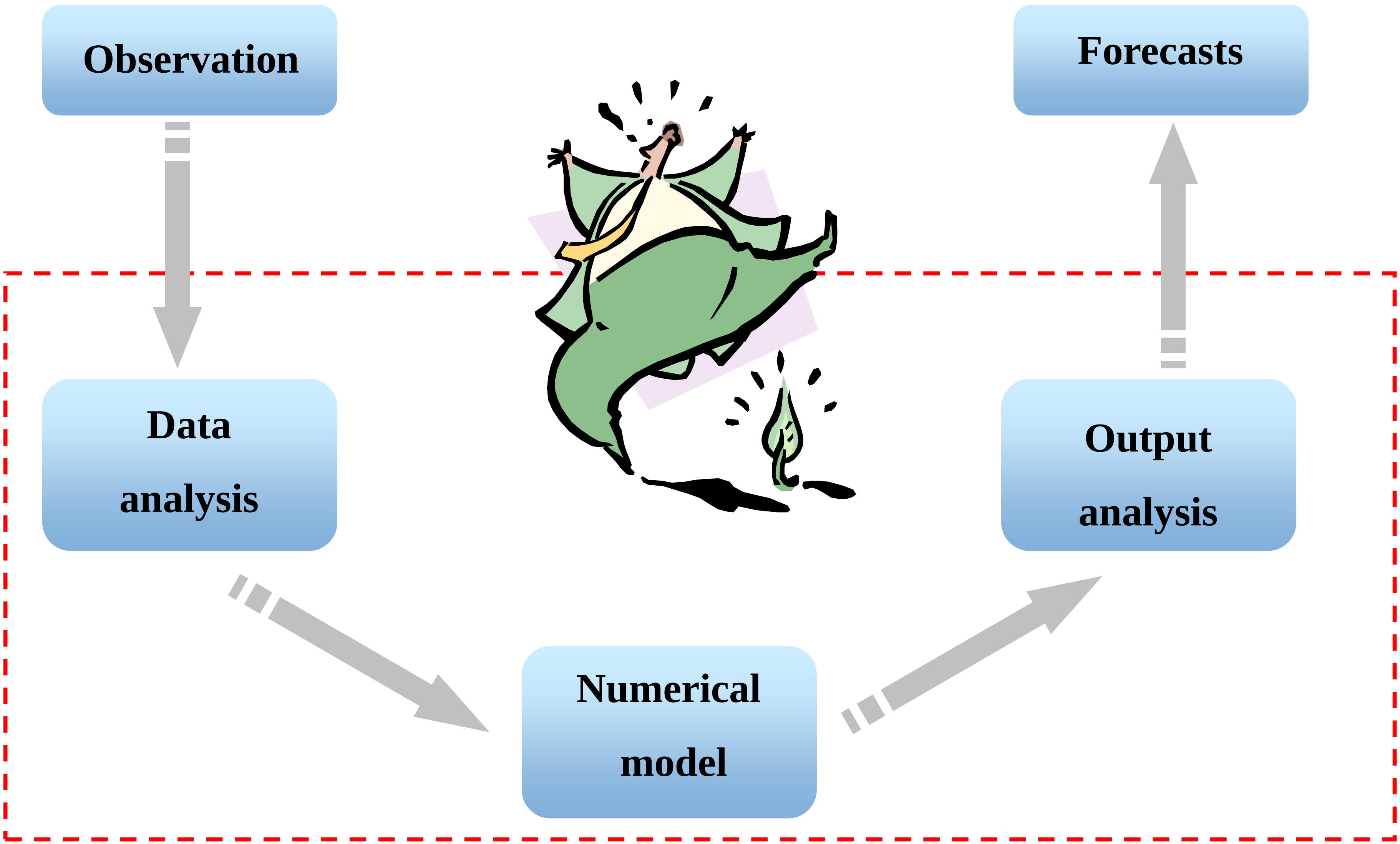
광역예보 [충청북도]

23(화)	24(수)	25(목)	26(금)	27(토)	28(일)	29(월)	30(화)

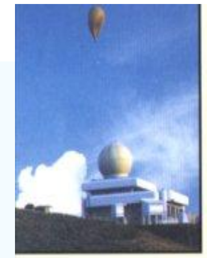
W365•COM	오늘 23(화)		내일 24(수)		모레 25(목)	
	오전	오후	오전	오후	오전	오후
최저/최고기온(℃)	(13)	23	5	22	3	23
강수확률(%)						
풍향	SW-NW		NW-NE		NW-NE	

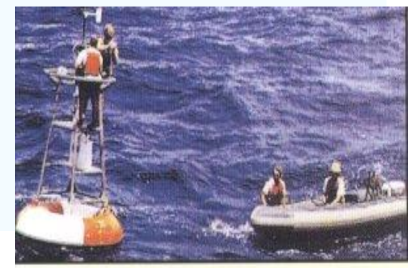
Then, what ?

Weather forecasts ….

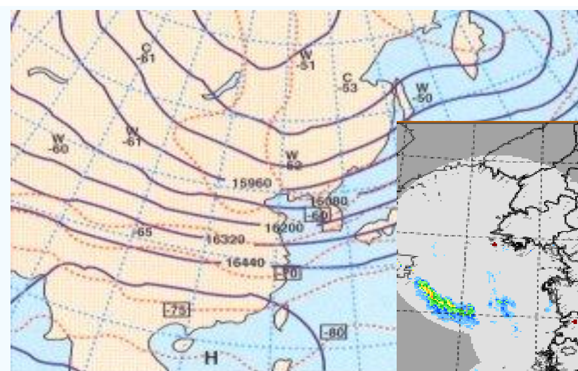


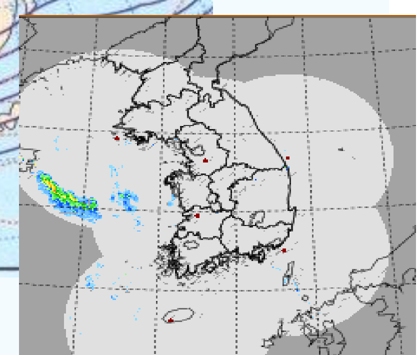
Step1: Observation





Step2: Data analysis





Theory ?

Thermodynamics

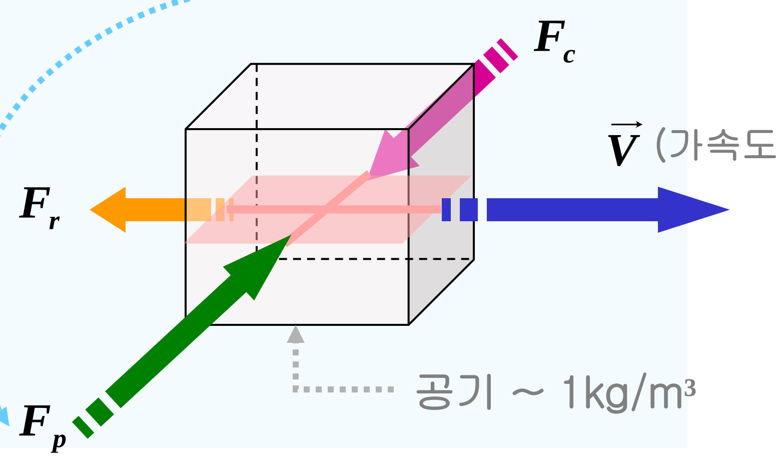
Heat = Energy + Work

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

Dynamics

Force = Mass × Acceleration

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



- 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:*

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

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

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

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

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

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

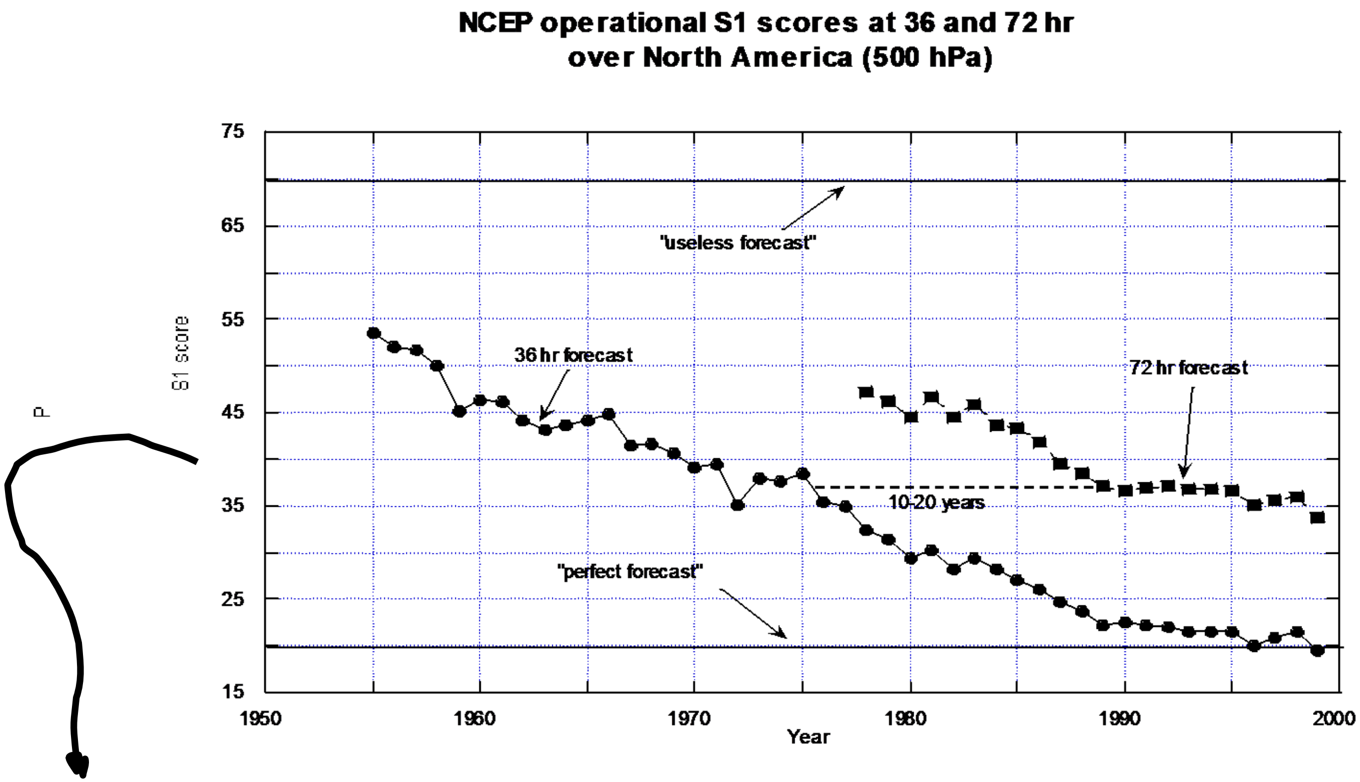
1922 : British L. F. Richardson (1881-1953) :
Integrate model → failed

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

Tendency of forecast error (1955-1998) : NCEP

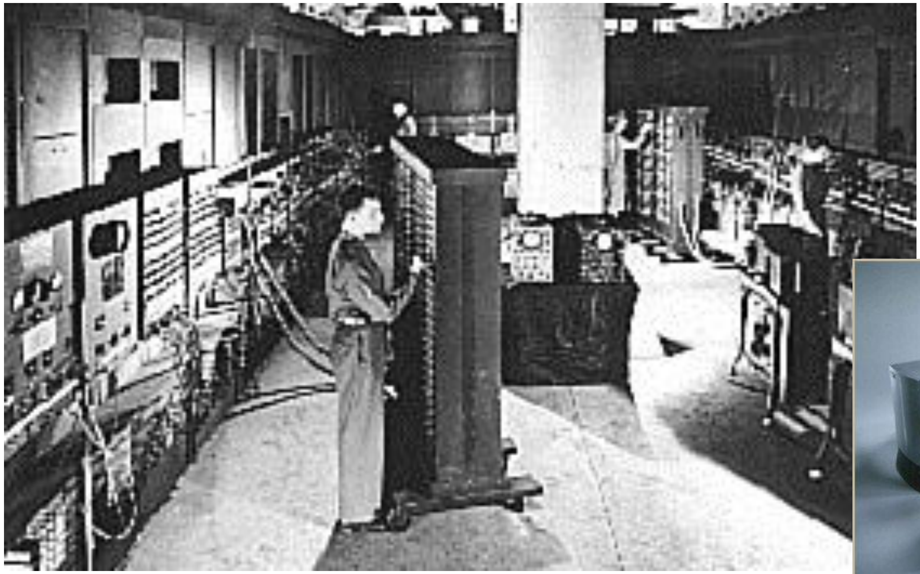


1day / 8 yrs

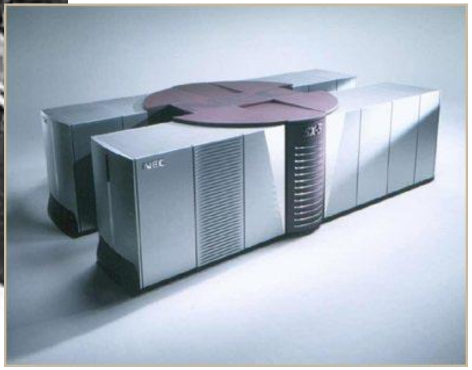
Factors for the improvement

- supercomputers
- physical processes
- initial conditions

Super-computer for weather models



ENIAC,1946



NEC SX-5

Cray T3E

Cray SV1

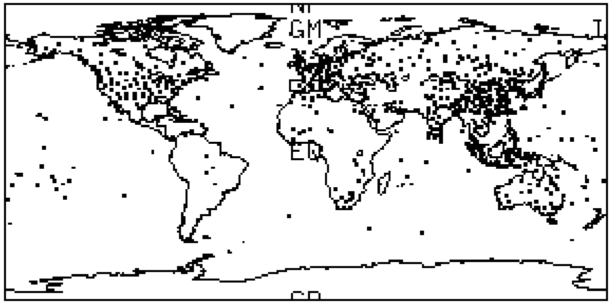
Fujitsu VPP700E

Cray T90

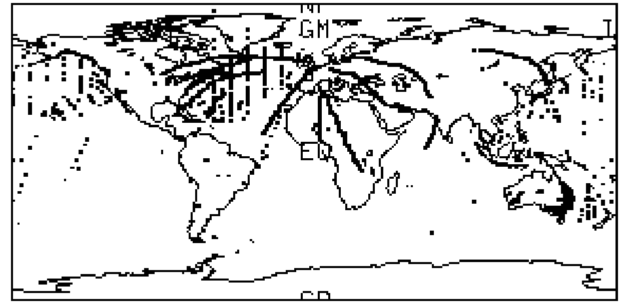
Initial condition
(data assimilation)

Various observations

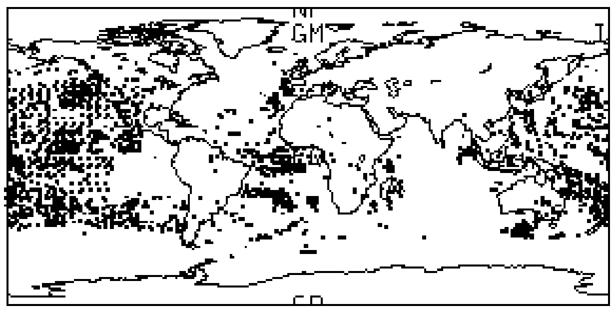
RAOBS



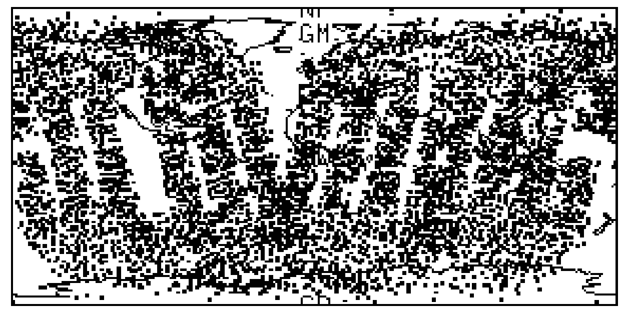
AIRCRAFT



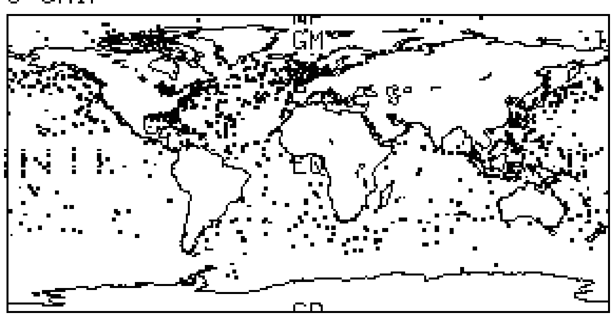
SAT WIND



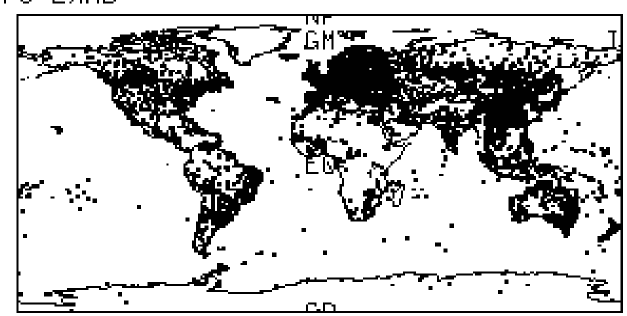
SAT TEMP



SFC SHIP



SFC LAND



Data Assimilation

- Model 1°X 1° resolution, 20 levels

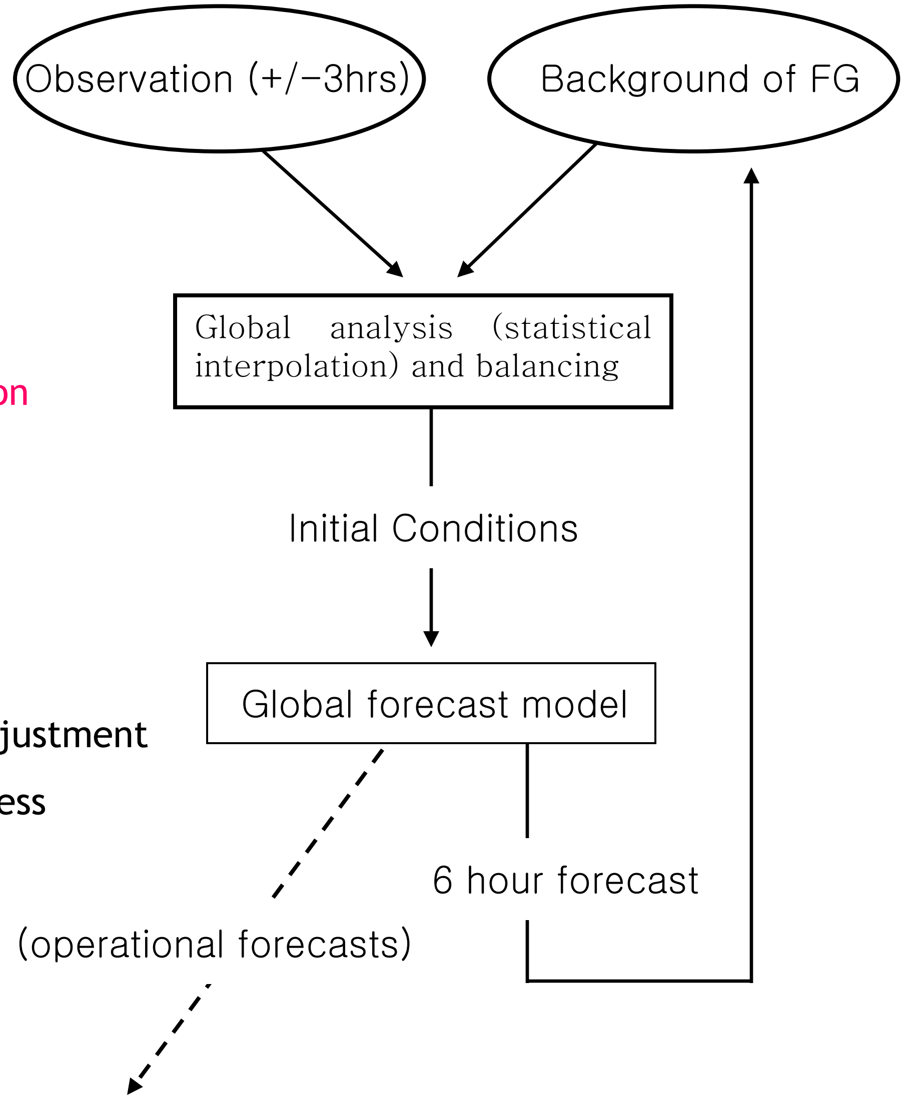
  u, v, T, q, Ps, Tg

  $$360 \times 180 \times 20 = 1.3 \times 10^6 \times 4\ \mathrm{var}\,iabl\ = 5 \times 10^6$$

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

  $\pm 3\ hour\ window$

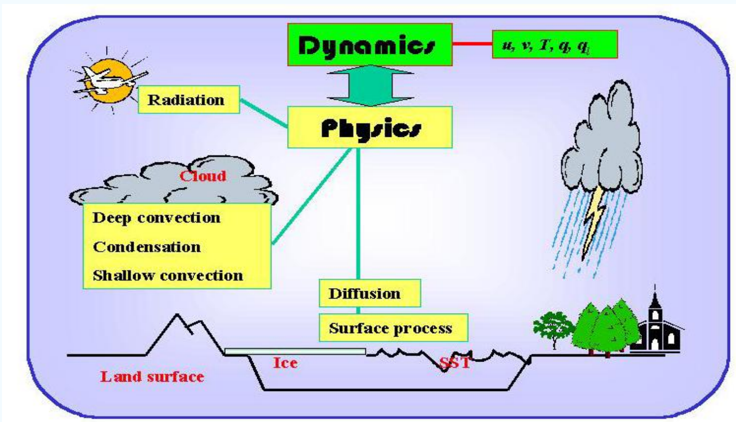
- Data assimilation cycle 1) data checking
  2) objective analysis
  3) Initialization: dynamical adjustment
  4) short-range fcst for first guess



Model

- Dynamics : Speed
- Physics : Predictability

Step3: Integration



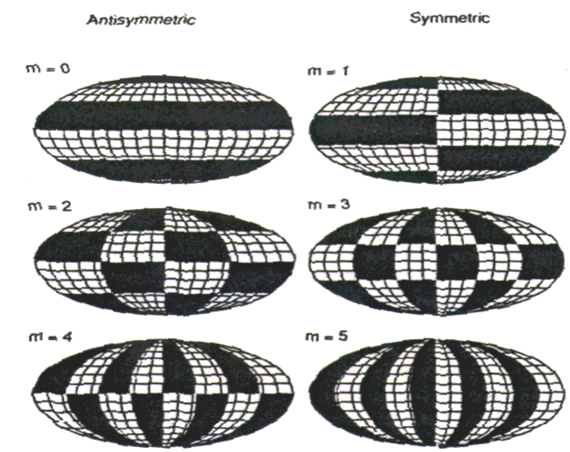
$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - \omega\frac{\partial u}{\partial p} - \frac{\partial \Phi}{\partial x} + fv + F_x$$

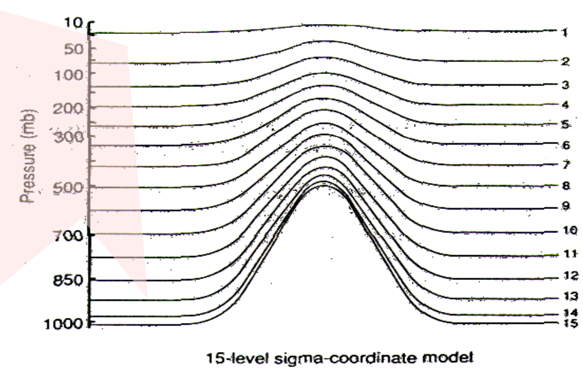
$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - \omega\frac{\partial v}{\partial p} - \frac{\partial \Phi}{\partial y} - fu + F_y$$

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

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

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





Dynamics : model frame

Finite difference method (FDM) :

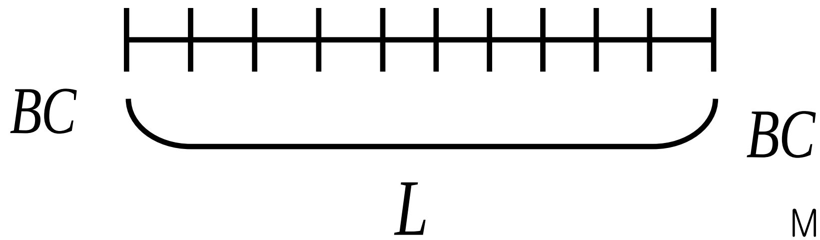
Spectral method (SPM) :

Finite element method (FEM) :

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

1) FDM (유한 차분법)

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



M 개의 grids

No variation between grid points

2) Spectral Method (분광법)

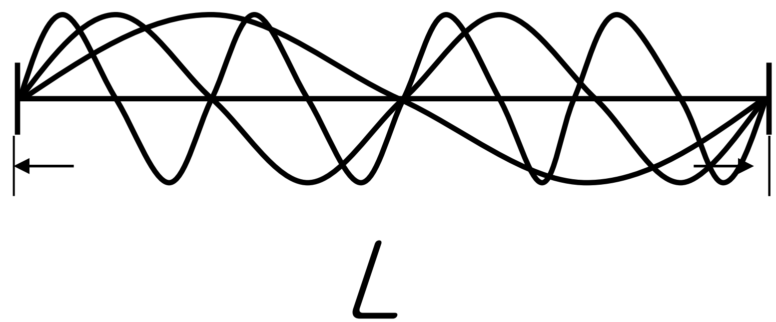
M 개의 function

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

- Expand ϕ in terms of a time series

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

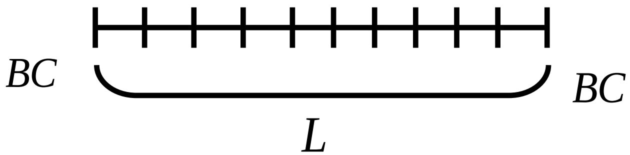
$$\Rightarrow \phi(x,t) = \sum_{m=m_1}^{m_2} \phi_m(t) e_m(x)$$



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

Dynamics : model frame (continued)

Ex) $\dfrac{\partial u}{\partial t} = -cu_x$; advection eq.



M 개의 grids

No variation between grid points

Integration scheme

Explicit : $\dfrac{u^{n+1} - u^n}{\Delta t} = F\left(u^n\right)$: forward

$\dfrac{u^{n+1} - u^{n-1}}{\Delta t} = F\left(u^n\right)$: leap−frog ⇒ conditionally stable

Implicit : $\dfrac{u^{n+1} - u^n}{\Delta t} = F\left(u^{n+1}\right)$: fully implicit

$\dfrac{u^{n+1} - u^n}{\Delta t} = F\left(\dfrac{u^n + u^{n+1}}{2}\right)$: Crank−Nicholson absolutely stable

* Summary

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)**

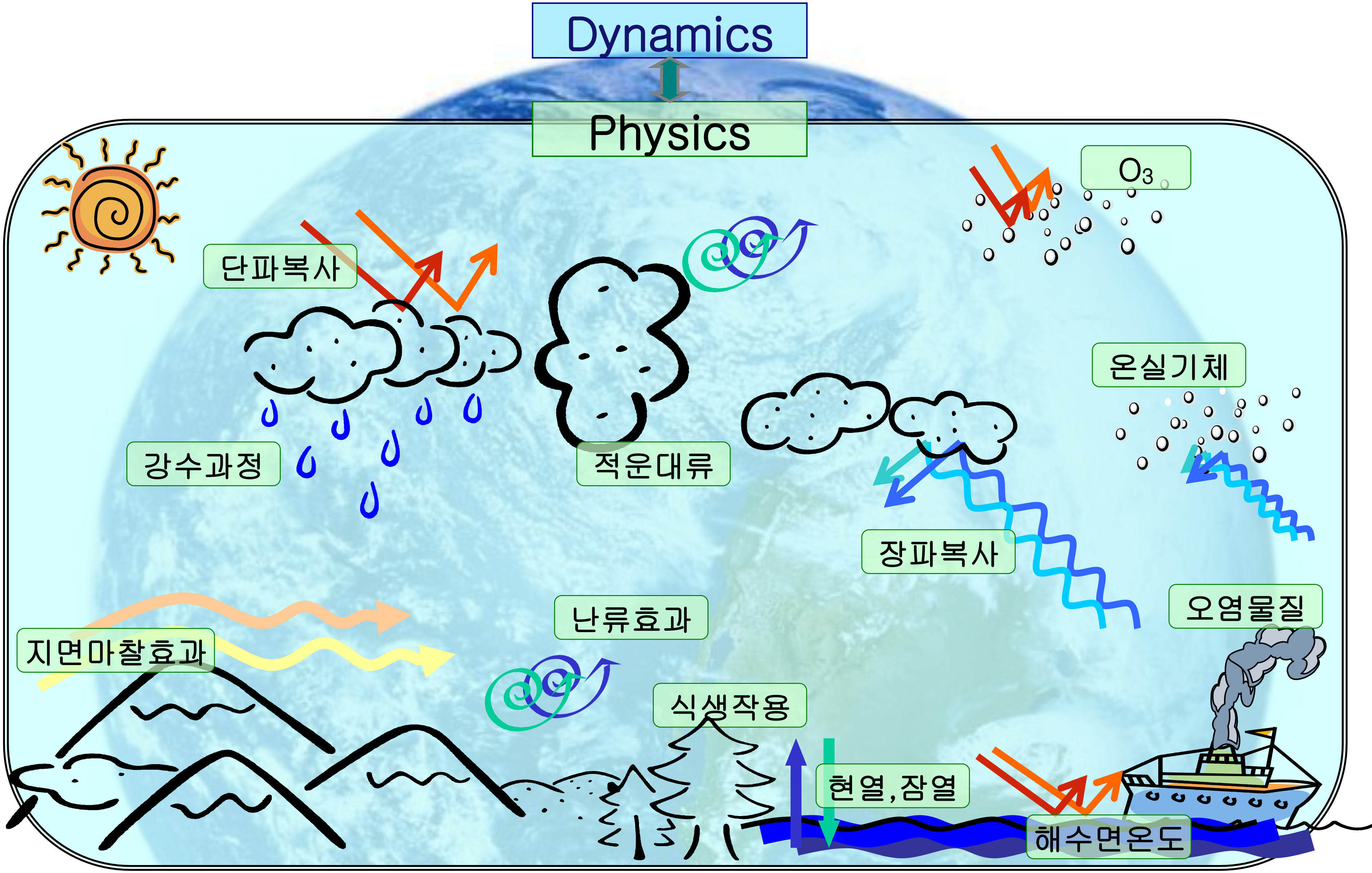
f) $$\frac{u^{n+\frac{1}{2}*}-u^{n}}{\Delta t/2}=F\left(u^{n}\right) \quad : \quad \frac{u^{n+\frac{1}{2}**}-u^{n}}{\Delta t/2}=F\left(u^{n+\frac{1}{2}*}\right)$$

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

Numerical modeling



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

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

Weather Research and Forecasting (WRF) Model

ADMINISTRATION

CALENDAR

GROUP HOME PAGES

DIRECTORY OF DEVELOPERS

USERS

DOCUMENTATION/ PRESENTATIONS

FORUM

REAL-TIME WRF FORECASTS

ANNOUNCEMENTS/ UP COMING EVENTS

NEW! **Announcing WRF V2.0 Release** (May 18, 2004)

What is in WRF V2.0?

- Advanced Research WRF (ARW) dynamical core: Eulerian mass coordinate
- One-way and two-way nesting
- A few new physics options, including Noah LSM, RUC LSM, YSU PBL, and Grell-Devenyi ensemble cumulus scheme
- ESMF time manager
- Enhanced I/O options
- New SI V2.0
- WRF 3DVAR V2.0

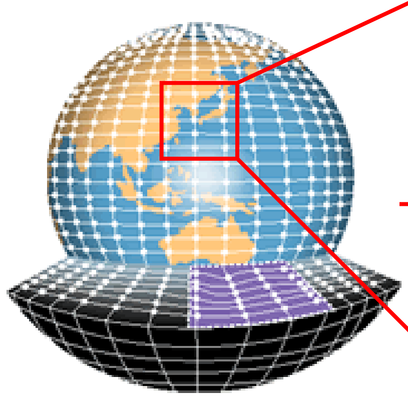
How do you get WRF V2.0?

Simply select the USERS button to the left. Information on the User's page is updated for the new release. You may download WRF software and test datasets from the site.

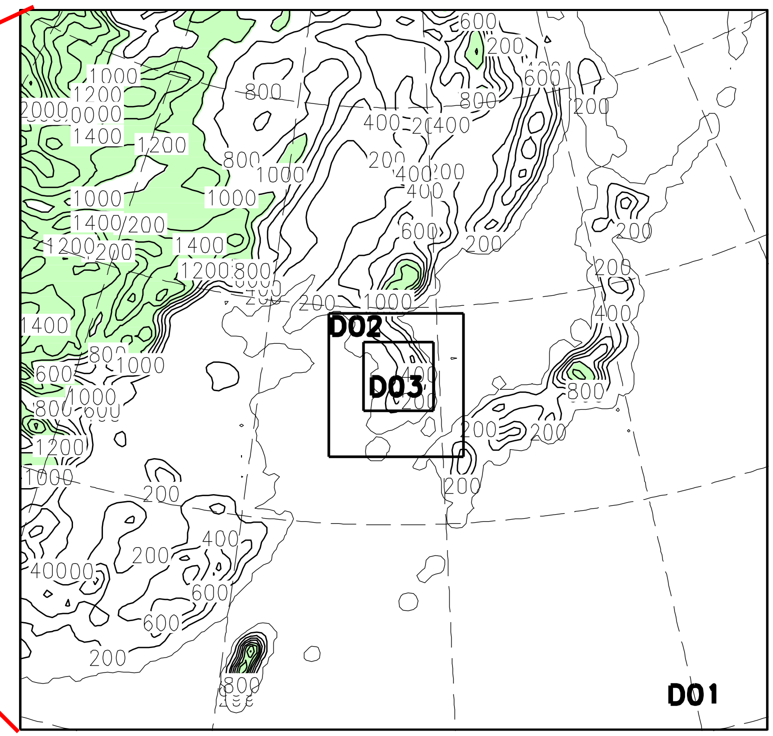
WRF Model

The Weather Research and Forecasting Model (WRF)

- Mesoscale grid model



Global model



Mesoscale model

Dynamics : model frame (continued)

In real NWP model (http://wrf-model.org)

Governing equations in flux form

Vertical coordinate: η-coord. $\eta = (p - p_t)/\mu$ where $\mu = p_s - p_t$

Flux-form variables: $\vec{V} = \mu\vec{v} = (U, V, W),\ \Omega = \mu\dot{\eta},\ \Theta = \mu\theta,$

$$\partial_t U + (\nabla \cdot \vec{V}u) - \partial_x(p\partial_\eta \phi) + \partial_\eta(p\partial_x \phi) = F_U$$

$$\partial_t V + (\nabla \cdot \vec{V}v) - \partial_y(p\partial_\eta \phi) + \partial_\eta(p\partial_y \phi) = F_V$$

$$\partial_t W + (\nabla \cdot \vec{V}w) - g(\partial_\eta p - \mu) = F_W$$

$$\partial_t \Theta + (\nabla \cdot \vec{V}\theta) = 0$$

$$\partial_t \mu + \nabla \cdot \vec{V} = 0$$

$$\partial_t \phi + \mu^{-1}\left[(\vec{V} \cdot \nabla \phi) - gW\right] = 0$$

1) Temporal Discretization

A time-split integration scheme is used.

For low-frequency modes:

Runge-Kutta time integration scheme

$$\Phi^{*} = \Phi^{t} + \frac{\Delta t}{3} RK(\Phi^{t})$$

$$\Phi^{**} = \Phi^{t} + \frac{\Delta t}{2} RK(\Phi^{*})$$

$$\Phi^{t+\Delta t} = \Phi^{t} + \Delta t RK(\Phi^{**})$$

For high-frequency acoustic modes:

Integrated over smaller time steps to maintain numerical instability

Dynamics : model frame (continued)

In real NWP model

Governing equations in flux form

Vertical coordinate: η-coord. $\eta = (p - p_t)/\mu$ where $\mu = p_s - p_t$

Flux-form variables: $\vec{V} = \mu\vec{v} = (U, V, W),\ \Omega = \mu\dot{\eta},\ \Theta = \mu\theta,$

$$\partial_t U + (\nabla \cdot \vec{V} u) - \partial_x (p \partial_\eta \phi) + \partial_\eta (p \partial_x \phi) = F_U$$

$$\partial_t V + (\nabla \cdot \vec{V} v) - \partial_y (p \partial_\eta \phi) + \partial_\eta (p \partial_y \phi) = F_V$$

$$\partial_t W + (\nabla \cdot \vec{V} w) - g(\partial_\eta p - \mu) = F_W$$

$$\partial_t \Theta + (\nabla \cdot \vec{V} \theta) = 0$$

$$\partial_t \mu + \nabla \cdot \vec{V} = 0$$

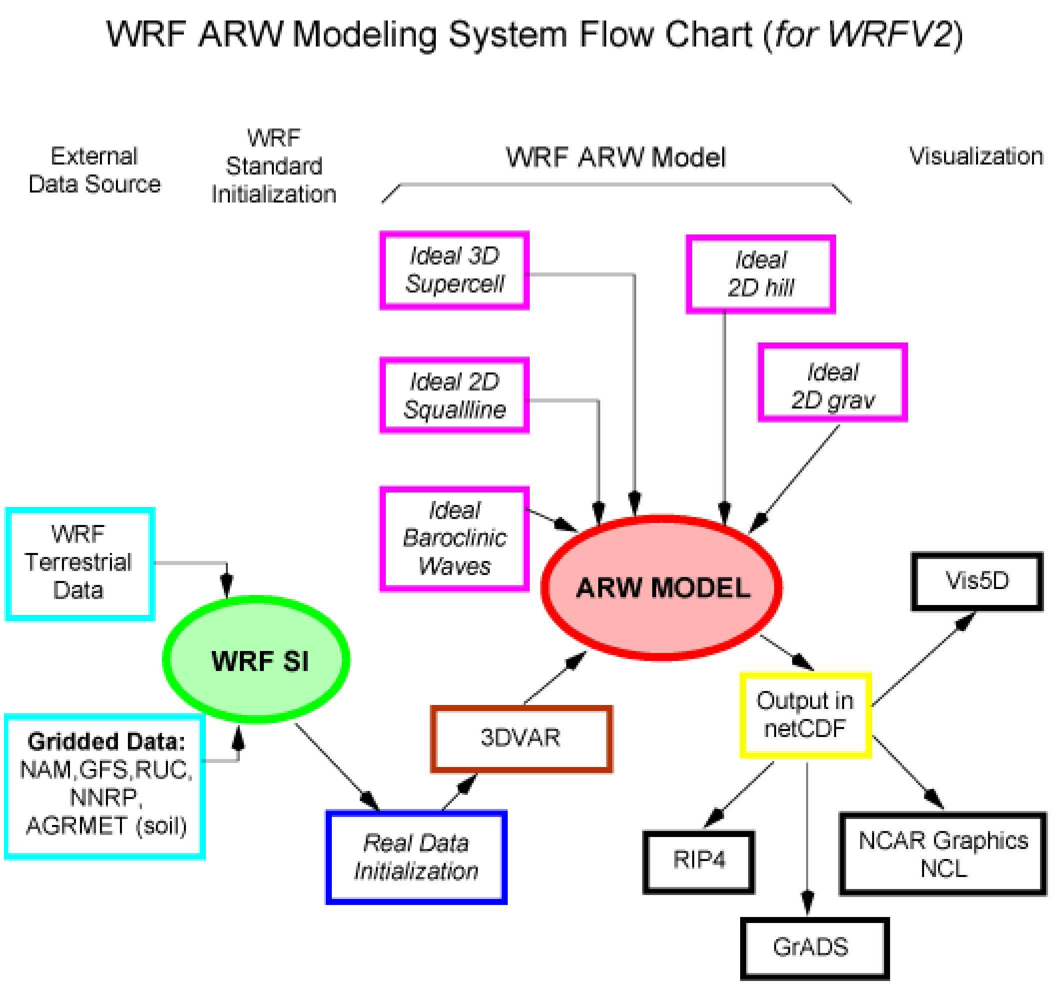
$$\partial_t \phi + \mu^{-1}\left[(\vec{V} \cdot \nabla \phi) - gW\right] = 0$$

2) Spatial Discretization

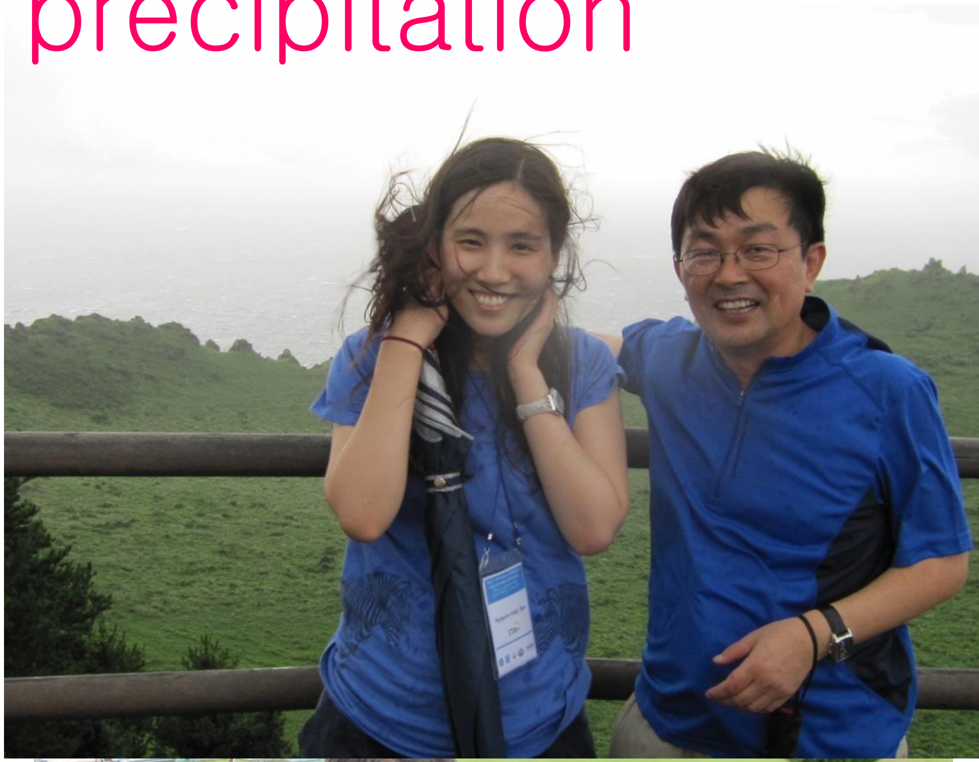
Ex) Horizontal momentum

$$\partial_t U'' + \overline{\mu^{t_*}}^x \overline{\alpha^{t_*}}^x \delta_x p''^t + (\overline{\mu^{t_*}}^x \delta_x \overline{p}) \overline{\alpha''^t}^x + \overline{(\alpha/\alpha_d)}^x \left[\overline{\mu^{t_*}}^x \delta_x \overline{\phi''^t}^\eta + (\delta_x \overline{\phi^{t_*}}^\eta)(\delta_\eta \overline{\overline{p''}^x}^\eta - \overline{\mu''}^x)^t \right] = RK_U^{t_*}$$

WRF Model Process



Cloud and precipitation



WSMMP (WRF-Single-Moment- MicroPhysics)

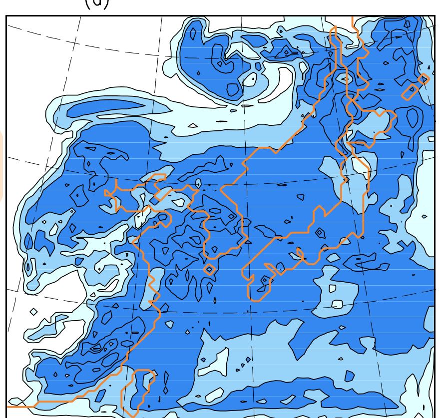
Hong, Dudhia and Chen (2004)

Major modifications suggested by Hong et al. (2004)

	(Rutledge and Hobbs, 1983)	(Hong et al, 2003)
Number concentration of cloud ice	$N_I(m^{-3}) = 10^{-2}\exp[0.6(T_0 - T)]$	$N_I = c(\rho q_I)^d$
Ice nuclei number	$N_I(m^{-3}) = 10^{-2}\exp[0.6(T_0 - T)]$	$N_{I0} = 10^3\exp[0.1(T_0 - T)]$
Intercept parameter for snow	$N_{0S} = 2 \times 10^7\ \mathrm{m}^{-4}$	$N_{0S}(m^{-4}) = 2 \times 10^6\exp\{0.12(T_0 - T)\}$

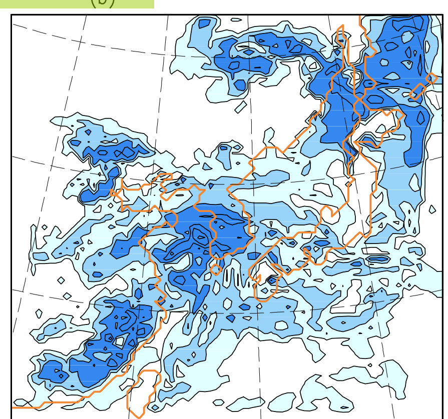
old

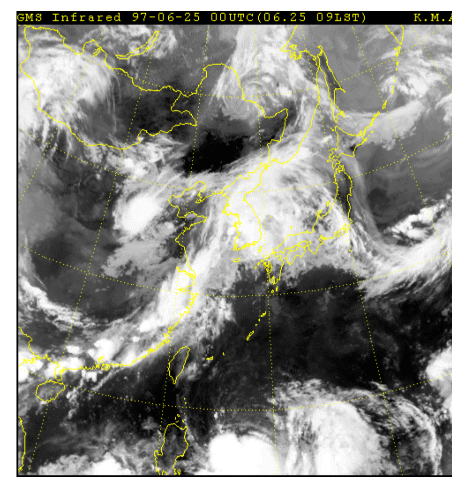
(a)



new

(b)





23 –25 June 1997

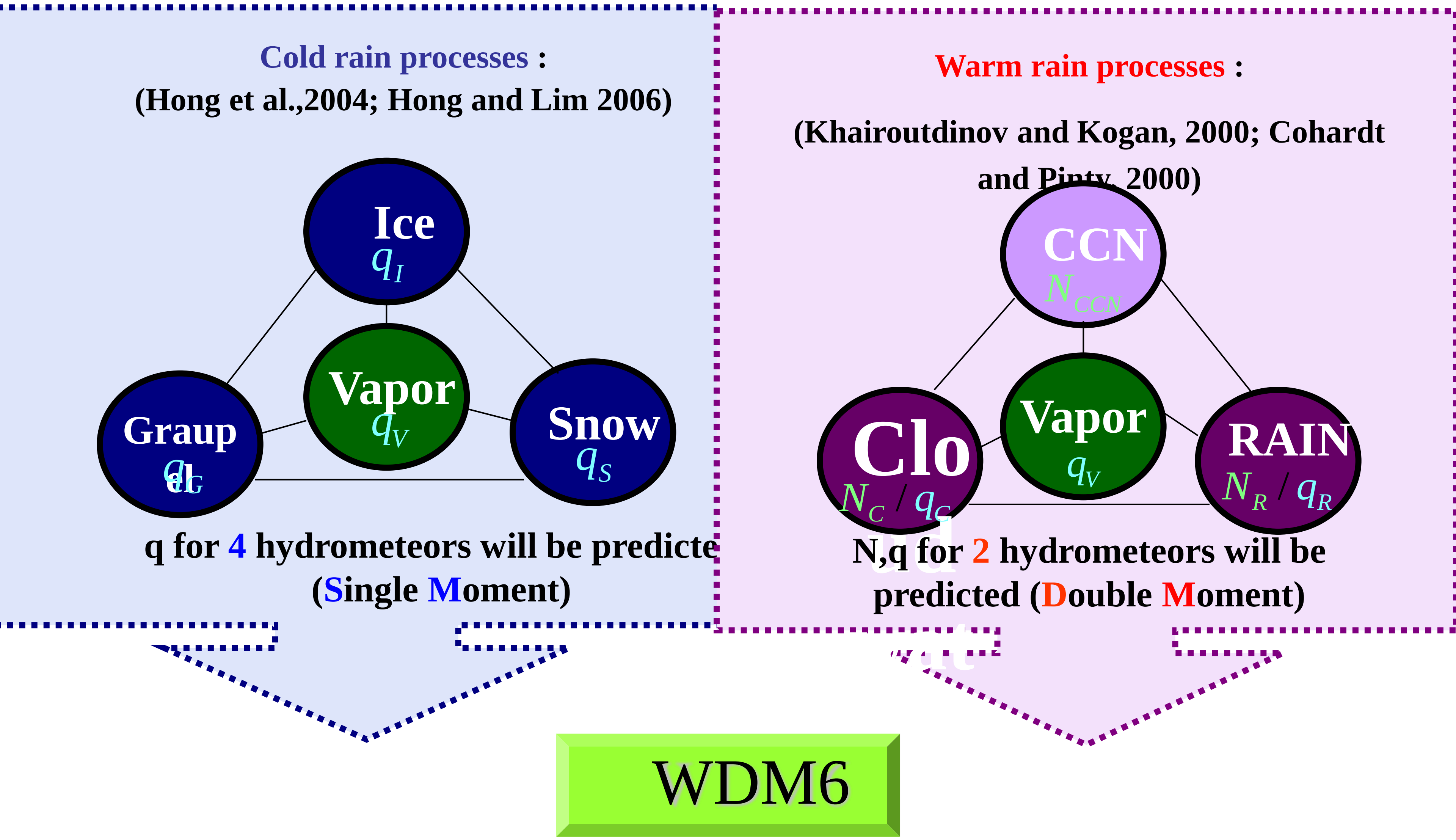
Heavy Rainfall Case

(Vertically integrated cloud ice)

[Code Description]

Weather Research and Forecasting (WRF) Double-Moment 6-class (WDM6) Microphysics scheme

Lim and Hong (2010)



Cold rain processes :
(Hong et al.,2004; Hong and Lim 2006)
Ice
q_I
Vapor
q_V
Snow
q_S
Graup
q_G
q for 4 hydrometeors will be predicted
(Single Moment)
Warm rain processes :
(Khairoutdinov and Kogan, 2000; Cohardt and Pinty, 2000)
CCN
N_{CCN}
Vapor
q_V
Clo
N_C / q_C
RAIN
N_R / q_R
N,q for 2 hydrometeors will be predicted (Double Moment)
WDM6

```
! warm rain processes
!
! - follows the double-moment processes in Lim and Hong
!
!==================================================================
!
     do k = kts, kte
       do i = its, ite
         supsat = max(q(i,k),qmin)-qs(i,k,1)
         satdt = supsat/dtcld
!-----------------------------------------------------------------
! praut: auto conversion rate from cloud to rain  [CP 17]
!        (C->R)
!-----------------------------------------------------------------
         lencon  = 2.7e-2*den(i,k)*qci(i,k,1)*(1.e20/16.*rslopec2(i,k)      &
                   *rslopec2(i,k)-0.4)
         lenconcr = max(1.2*lencon, qcrmin)
         if(avedia(i,k,1).gt.di15) then
           taucon = 3.7/den(i,k)/qci(i,k,1)/(0.5e6*rslopec(i,k)-7.5)
           praut(i,k) = lencon/taucon
           praut(i,k) = min(max(praut(i,k),0.),qci(i,k,1)/dtcld)
!-----------------------------------------------------------------
! nraut: auto conversion rate from cloud to rain [CP 18 & 19]
!        (NC->NR)
!-----------------------------------------------------------------
           nraut(i,k) = 3.5e9*den(i,k)*praut(i,k)
           if(qrs(i,k,1).gt.lenconcr)                                      &
           nraut(i,k) = ncr(i,k,3)/qrs(i,k,1)*praut(i,k)
           nraut(i,k) = min(nraut(i,k),ncr(i,k,2)/dtcld)
         endif
!-----------------------------------------------------------------
! pracw: accretion of cloud water by rain        [CP 22 & 23]
!        (C->R)
! nracw: accretion of cloud water by rain
!        (NC->)
!-----------------------------------------------------------------
         if(qrs(i,k,1).ge.lenconcr) then
           if(avedia(i,k,2).ge.di100) then
             nracw(i,k) = min(ncrk1*ncr(i,k,2)*ncr(i,k,3)*(rslopec3(i,k)     &
                          + 24.*rslope3(i,k,1)),ncr(i,k,2)/dtcld)
             pracw(i,k) = min(pi/6.*(denr/den(i,k))*ncrk1*ncr(i,k,2)         &
                          *ncr(i,k,3)*rslopec3(i,k)*(2.*rslopec3(i,k)        &
                          + 24.*rslope3(i,k,1)),qci(i,k,1)/dtcld)
           else
             nracw(i,k) = min(ncrk2*ncr(i,k,2)*ncr(i,k,3)*(2.*rslopec3(i,k)  &
                          *rslopec3(i,k)+5040.*rslope3(i,k,1)                &
                          *rslope3(i,k,1)),ncr(i,k,2)/dtcld)
             pracw(i,k) = min(pi/6.*(denr/den(i,k))*ncrk2*ncr(i,k,2)         &
                          *ncr(i,k,3)*rslopec3(i,k)*(6.*rslopec3(i,k)        &
                          *rslopec3(i,k)+5040.*rslope3(i,k,1)*rslope3(i,k,1)) &
                          ,qci(i,k,1)/dtcld)
           endif
         endif
```

** Warm rain processes (Hong and Lim 2010)

*Auto conversion from cloud to rain [C→ R]

$$\text{Praut [kgkg}^{-1}\text{s}^{-1}] = L/\tau \qquad L = 2.7\times10^{-2}\rho_a q_C\left(\frac{10^{20}}{16\lambda_C^4} - 0.4\right)$$

$$\tau = 3.7\frac{1}{\rho_a q_C}\left(\frac{0.5\times10^6}{\lambda_C} - 7.5\right)^{-1}$$

$$\text{Nraut[m}^{-3}\text{s}^{-1}] = 3.5\times10^9\frac{\rho_a L}{\tau}$$

*Accretion of cloud water by rain [C→ R]

$D_R \geq 100$ µm

$$\text{Pracw [kgkg}^{-1}\text{s}^{-1}] = \frac{\pi}{6}\frac{\rho_W}{\rho_a}K_1\frac{N_C N_R}{\lambda_C^3}\left\{\frac{2}{\lambda_C^3} + \frac{24}{\lambda_R^3}\right\}$$

$$\text{Nracw[m}^{-3}\text{s}^{-1}] = -K_1 N_C N_R\left\{\frac{1}{\lambda_C^3} + \frac{24}{\lambda_R^3}\right\}$$

$D_R < 100$ µm

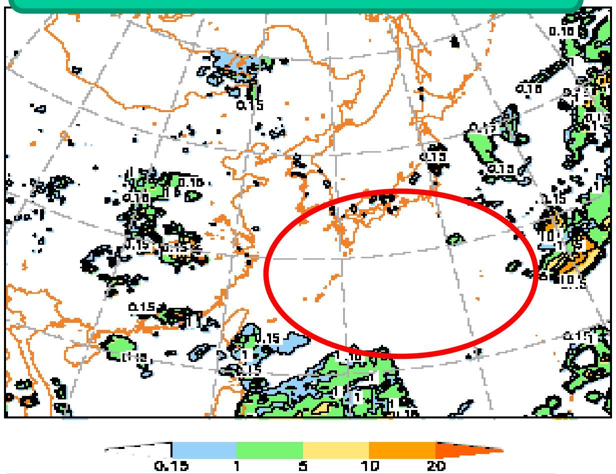
$$\text{Pracw [kgkg}^{-1}\text{s}^{-1}] = \frac{\pi}{6}\frac{\rho_W}{\rho_a}K_2\frac{N_C N_R}{\lambda_C^3}\left\{\frac{6}{\lambda_C^6} + \frac{5040}{\lambda_R^6}\right\}$$

$$\text{Nracw[m}^{-3}\text{s}^{-1}] = -K_2 N_C N_R\left\{\frac{2}{\lambda_C^6} + \frac{5040}{\lambda_R^6}\right\}$$

Precipitation in Spring

-last 6 hour accumulated precipitation

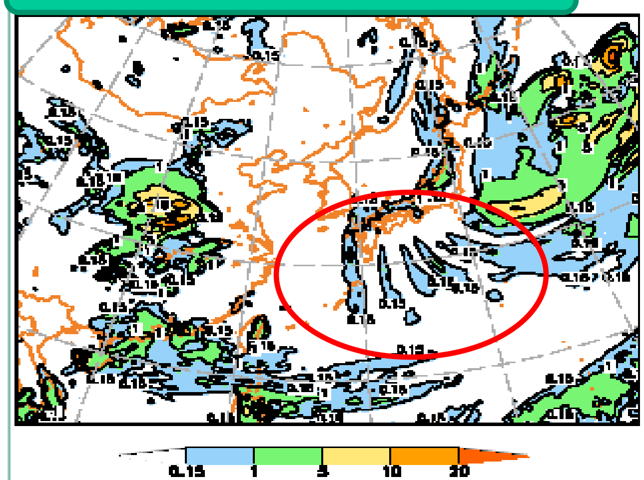
TMPA : rainfall estimates

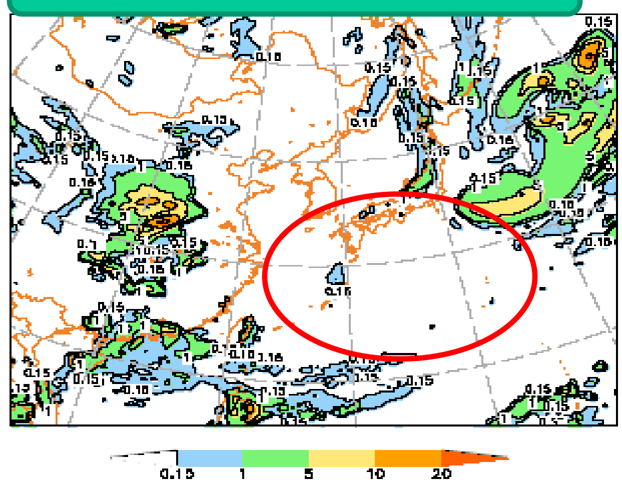


WDM6 (WRF-double-moment 6-class cloud scheme) that predicts CCN, Nc, Nr will be released in WRF in April 2009 (Version 3.1)

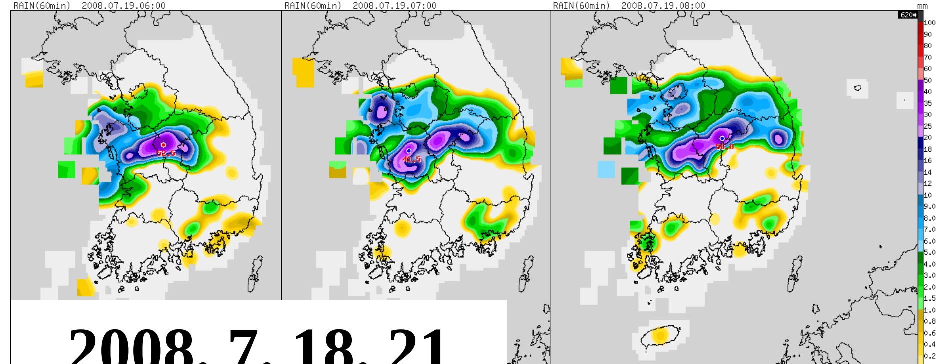
WSM6 : Hong and Lim (2006)

WDM6 : Lim and Hong (2009)



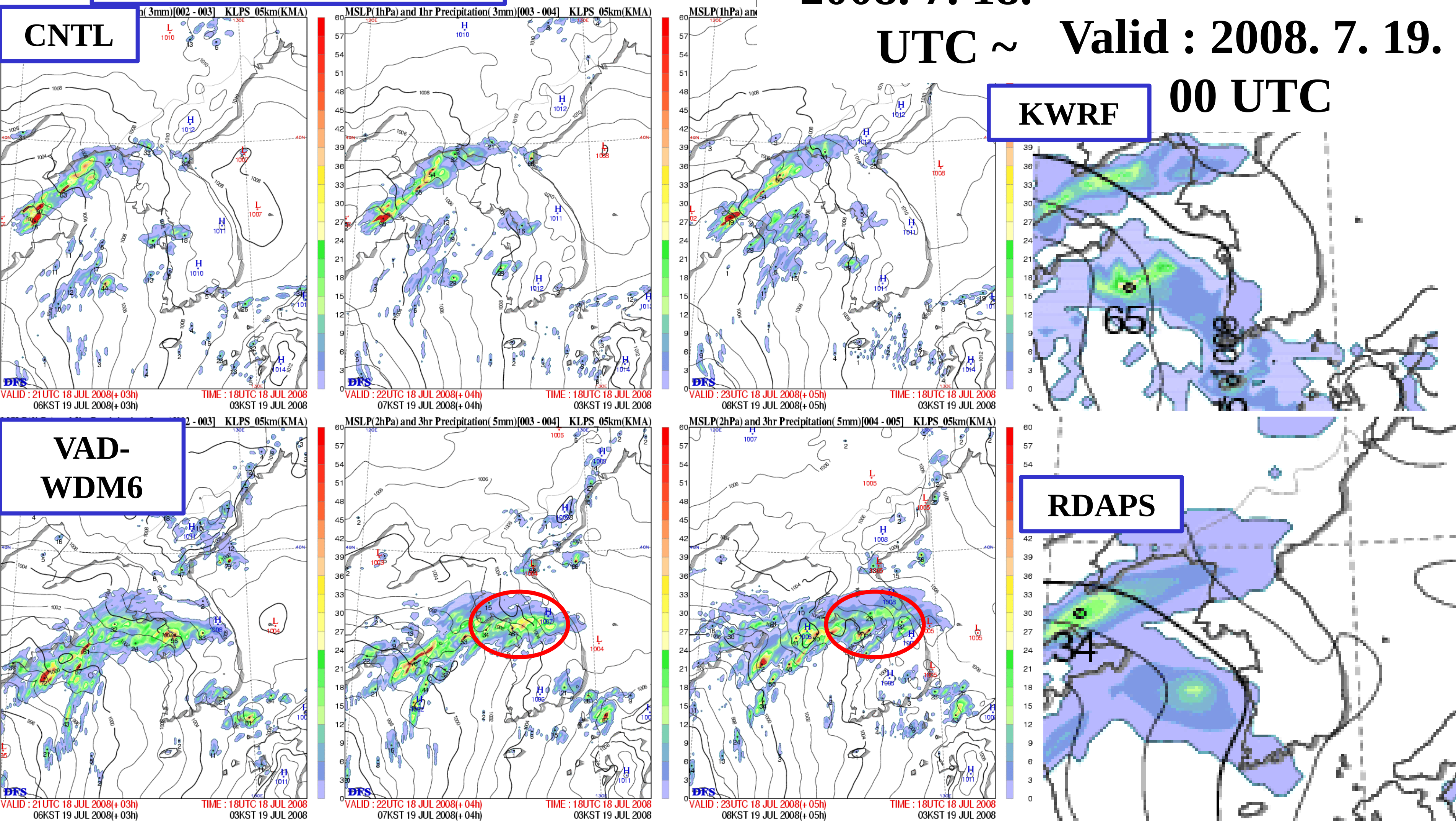


Precipitation (hourly)



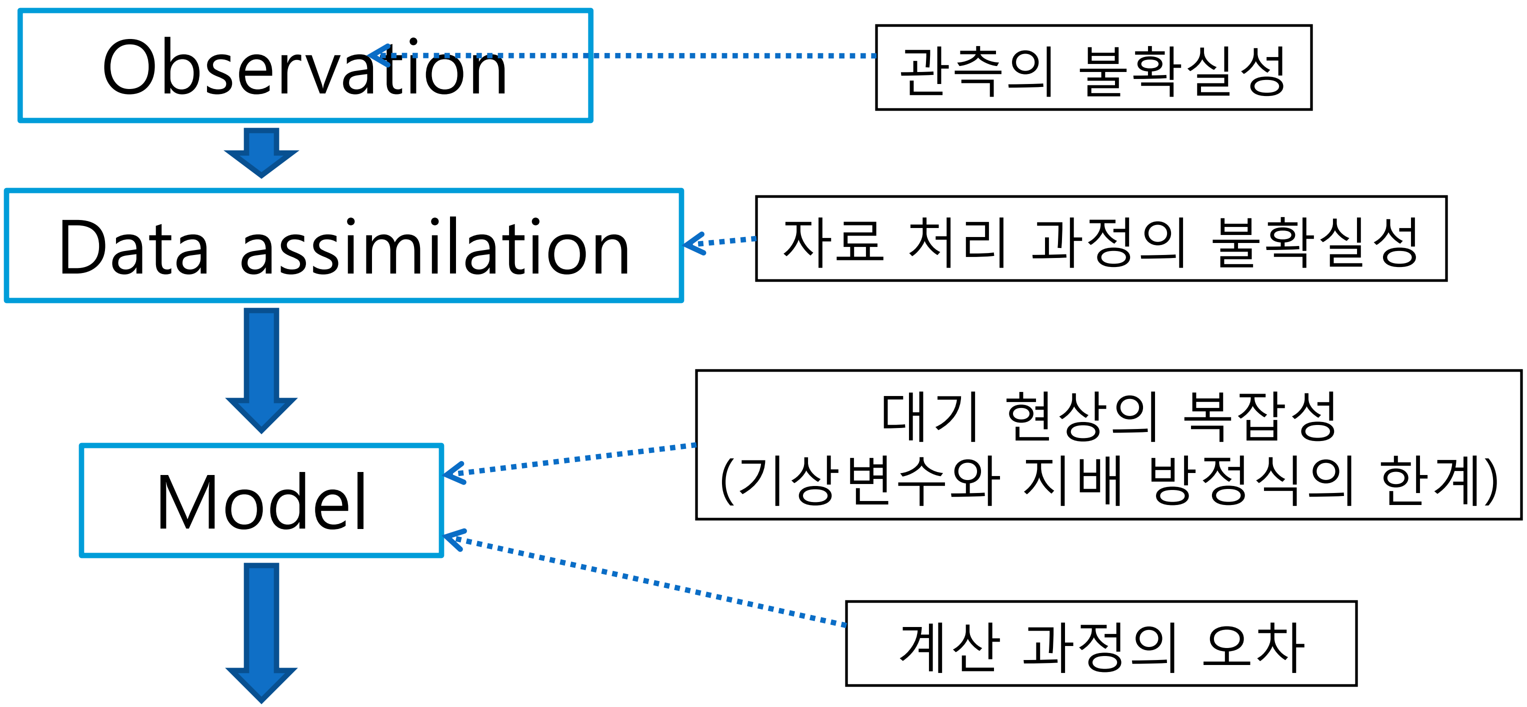
2008. 7. 18. 18 UTC (3-5 fc)

2008. 7. 18. 21 UTC ~ Valid : 2008. 7. 19. 00 UTC



Predictabilities

Uncertainties



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

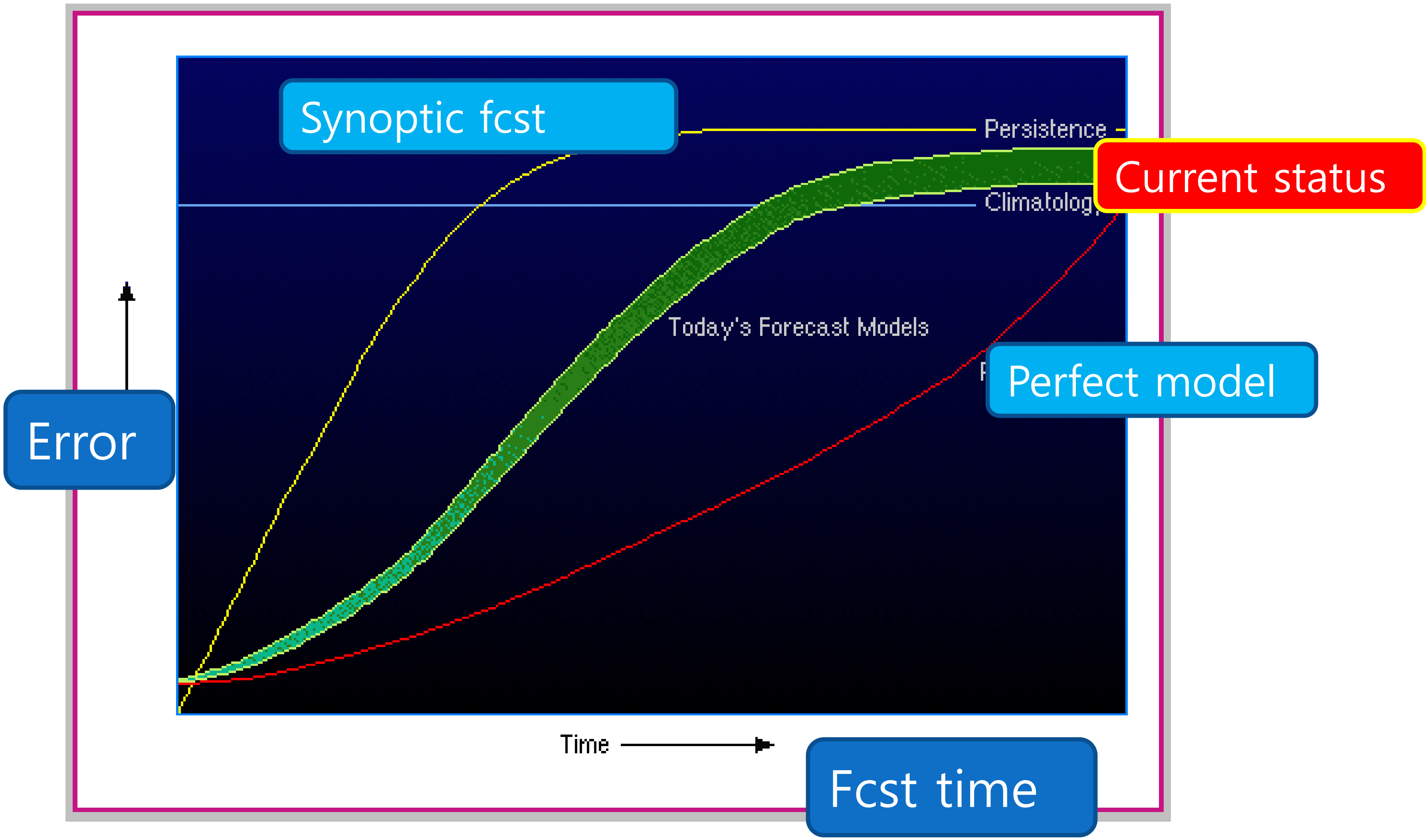
↓

Round-off error -> cause of non-periodcity

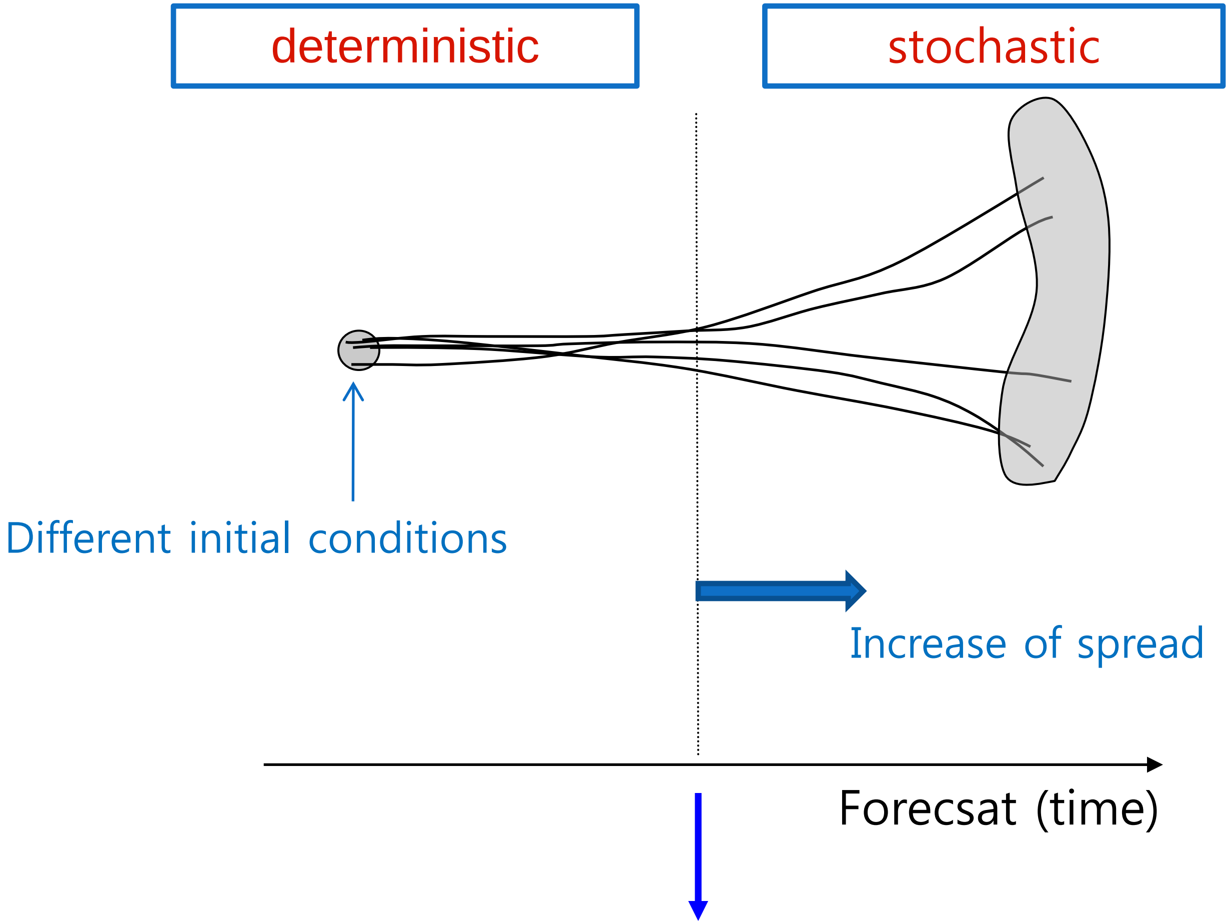
↓

Chaos theory– two weeks

Predictability

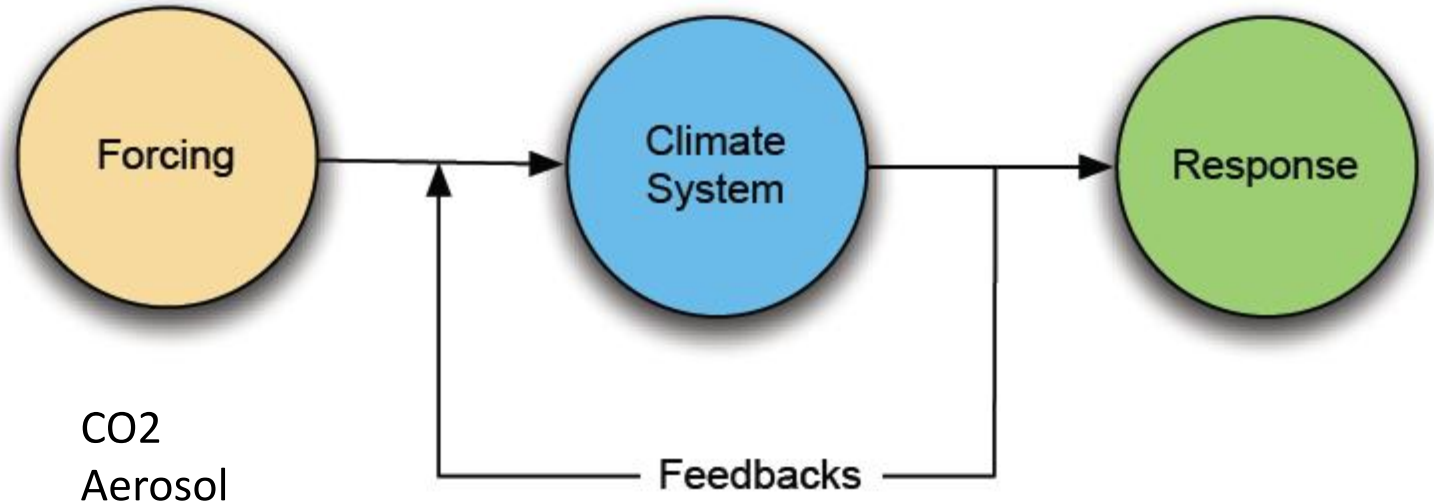


Ensemble forecasts



Large-scale flows : a few days, mesoscale : a few hours

Climate system sensitivity

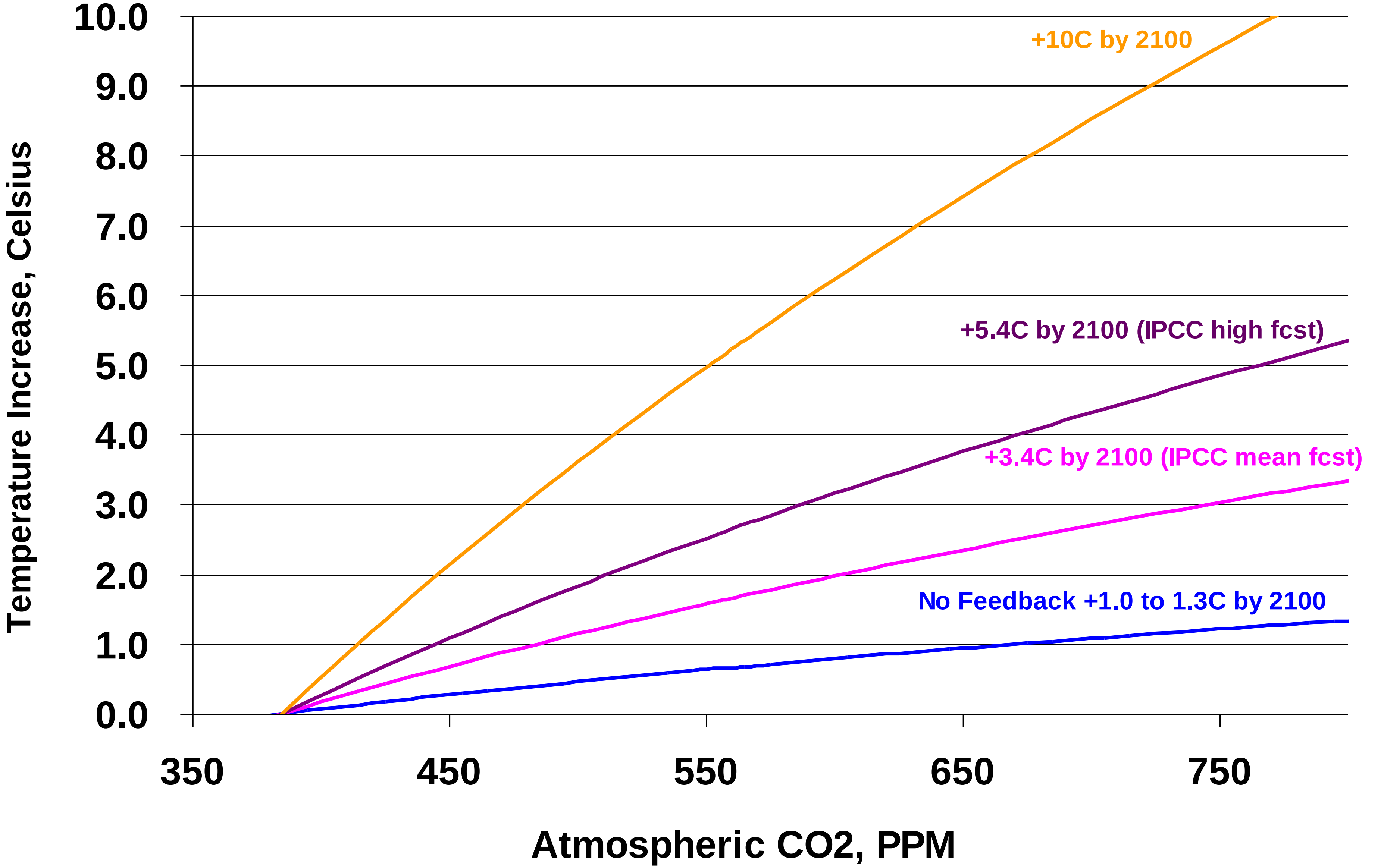


CO2
Aerosol
Volcanic

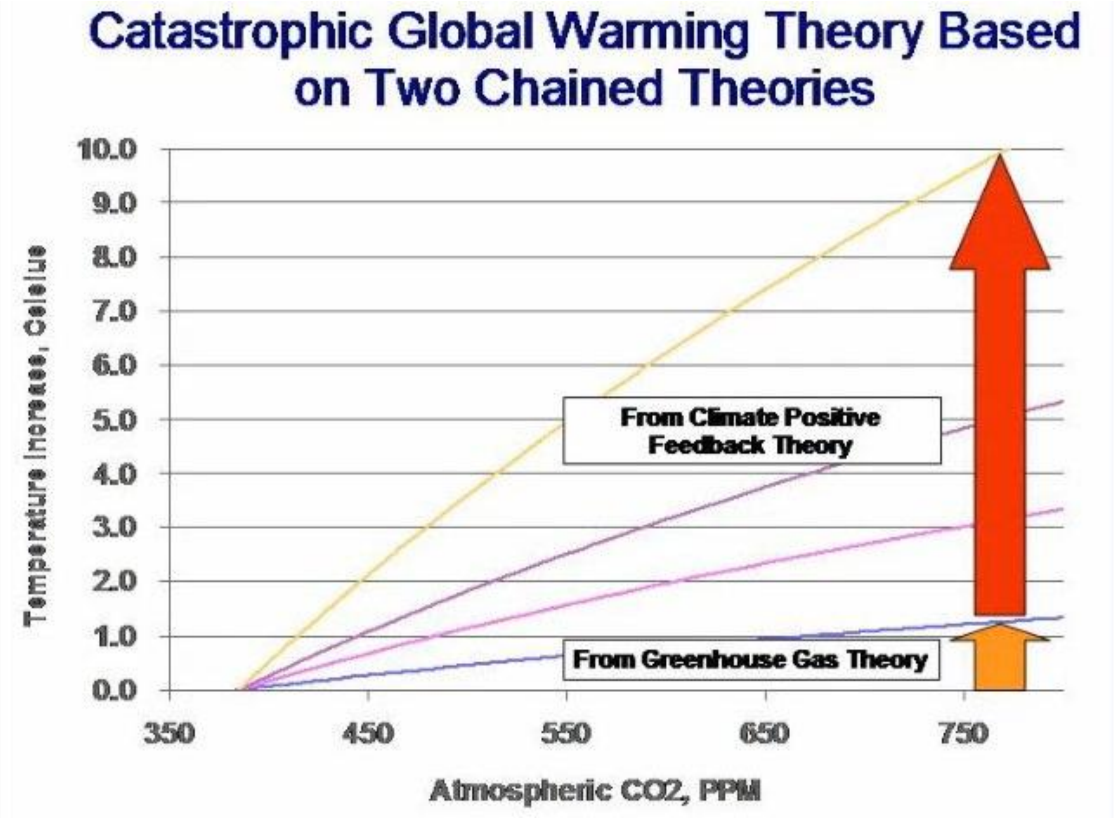
Water vapor feedback
Ice-albedo feedback
Vegetation feedbacks
Cloud (radiative) feedback
(Great debate!, Mostly still uncertain)
…

Temperature Projections From CO2

IPCC A2 (no Abatement) Case



Positive feedback !!!



Also, uncertainties are pronounced ….

END ~~~