# Fundamentals in Atmospheric Modeling

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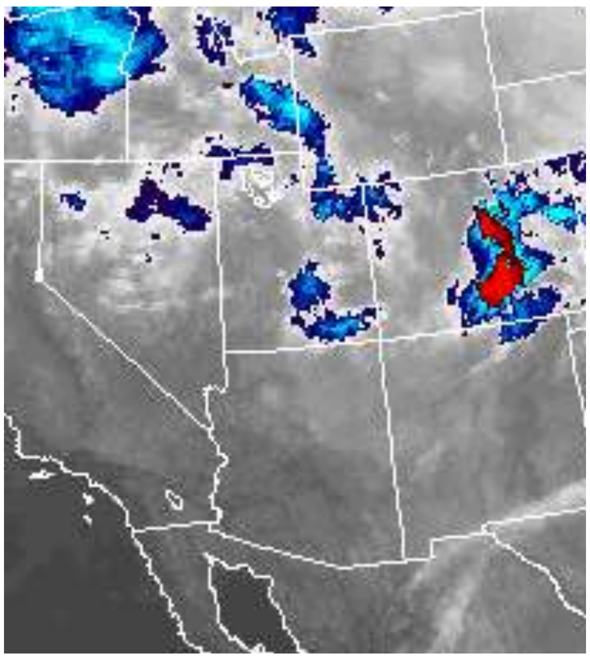
# List of presentations

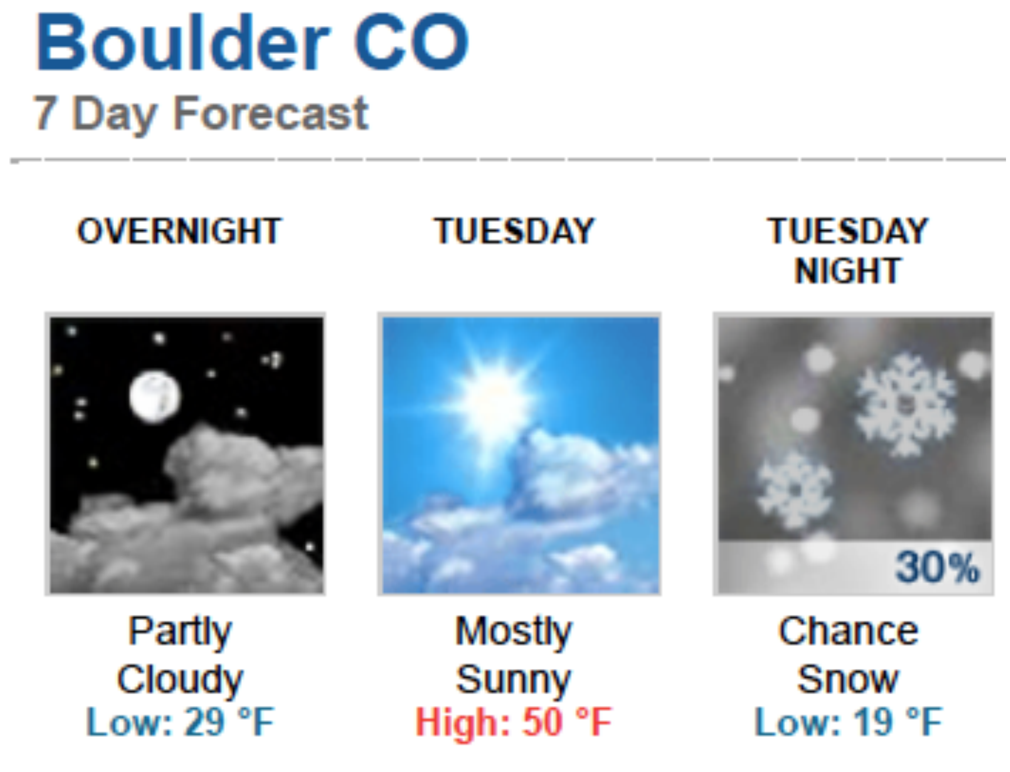
- Concept of modeling
- Structure of models
- Predictability
- Regional modeling

# How were the today's forecasts made ?

Observation → Forecasts

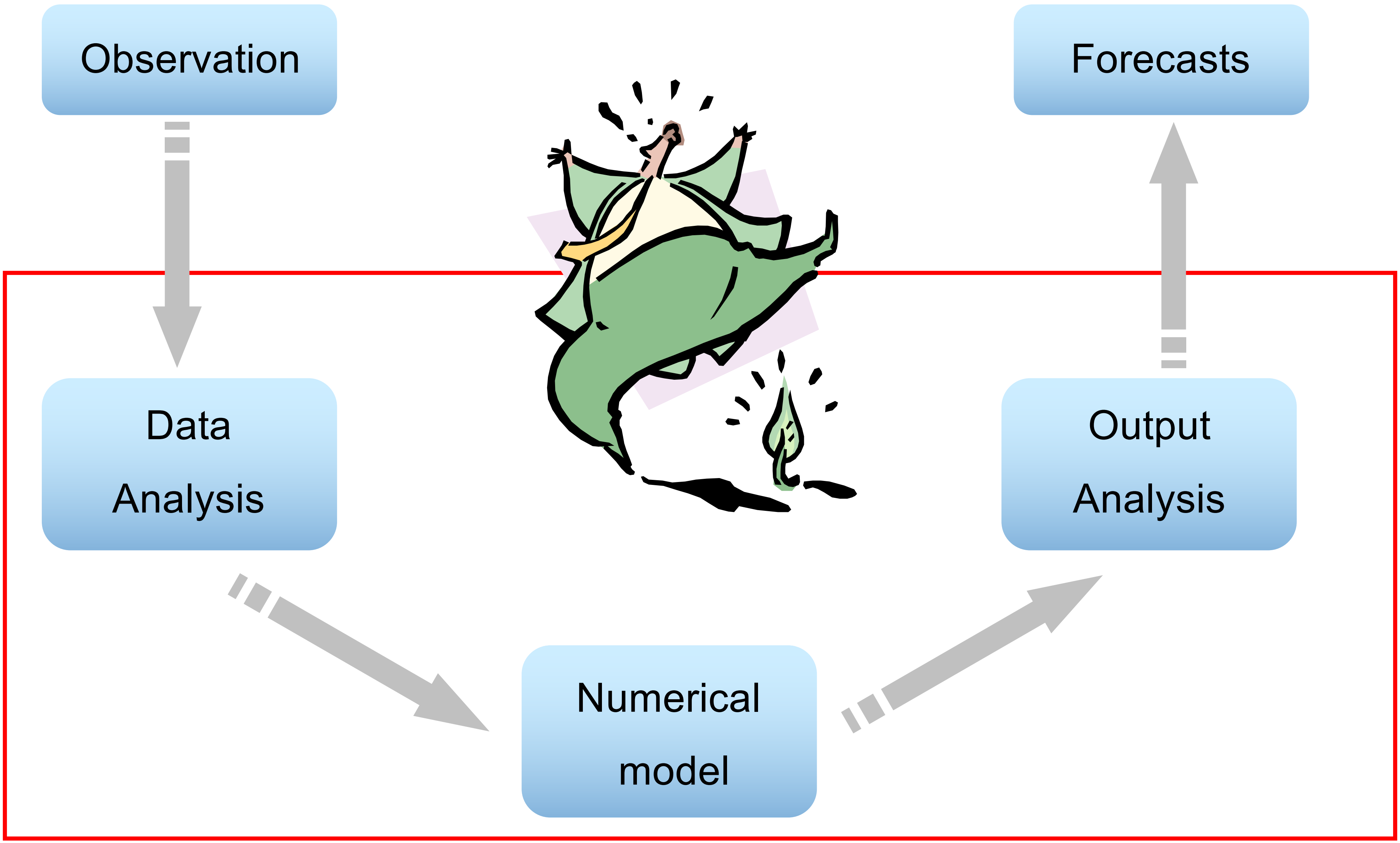
NO!






Then, what ?

# Numerical weather prediction is a crucial component



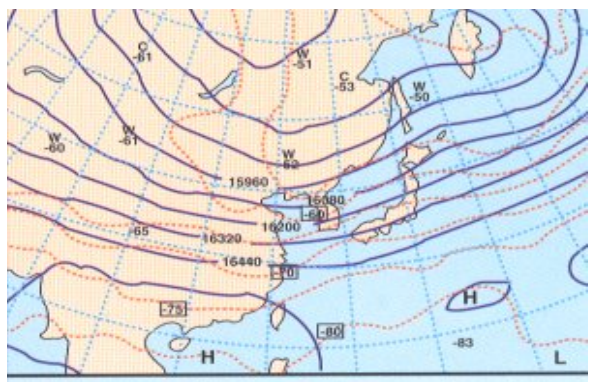
# Then, how ?

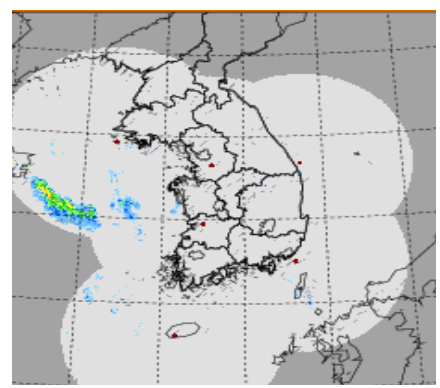
Step1:

Observation

Step2:

Data analysis



Also construct 3-D data of wind, temperature, etc

# Theory of numerical weather prediction (NWP)

## Thermodynamics

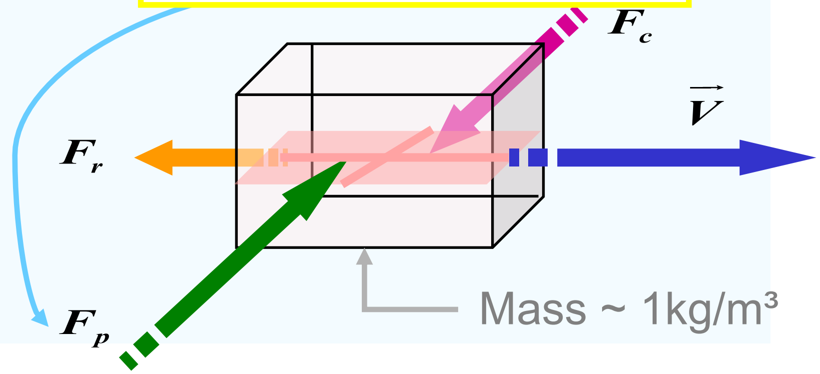
Heat = Energy + Work

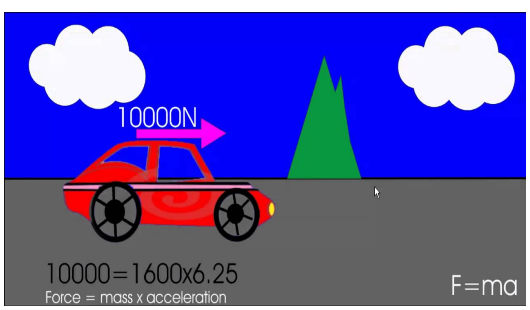
$$\Delta H = c_p \Delta T - \alpha \Delta p = c_v \Delta T + p \Delta \alpha$$

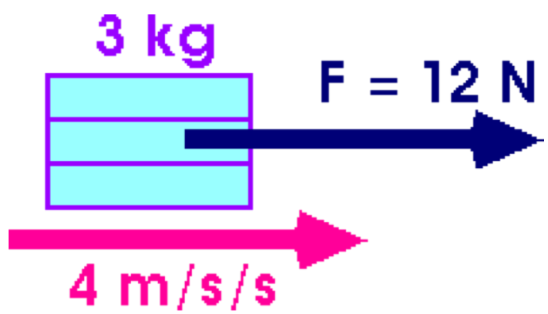
## Dynamics

Force = Mass × Acceleration

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




$$\Rightarrow v = v_0 + at$$

# **Theory of NWP :** Atmosphere is a conserved property

- 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 : mathematical expression

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:

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

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

$$p = \rho R T$$ (5)

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

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

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

solvable

# History of numerical weather prediction

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)

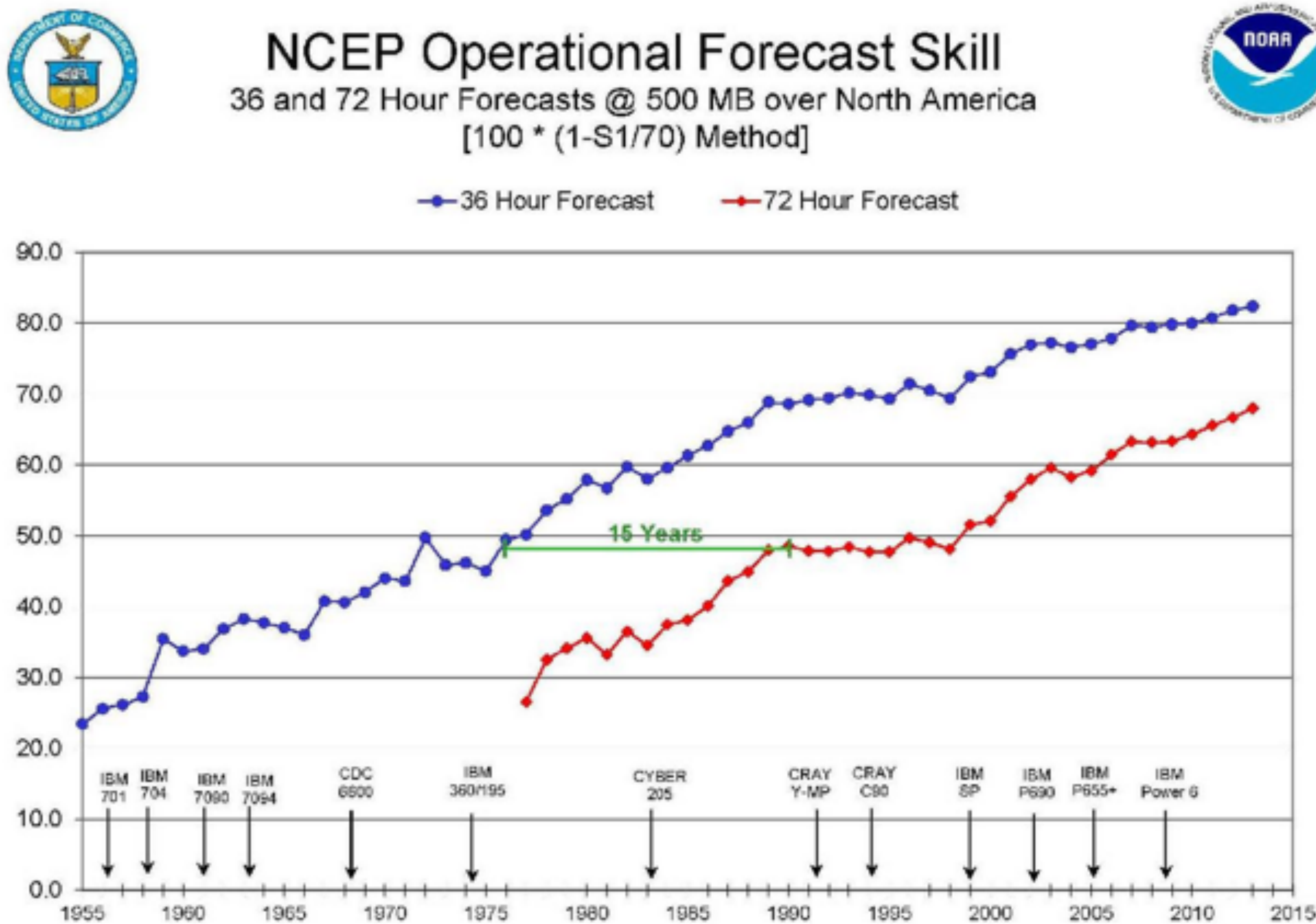
1950 : Princeton Group
(Charney, Fjortoft,
von Newman)
ENIAC
(Electrical Numerical
Integrator and Computer)
→ first success

**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 (global forecast system)




1day / 10year

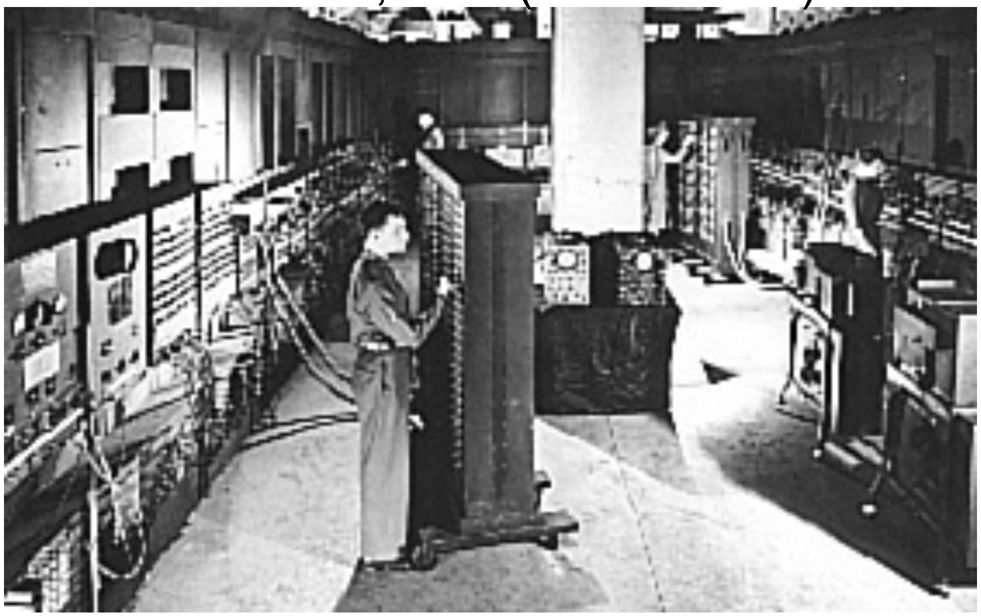
1990: 48 hr fcst skill= 2020: 120 hr fcst skill

# Factors for the improvement (Kalnay 2002)

- Supercomputers
- Physical processes
- Initial conditions

# Super-computer for weather models

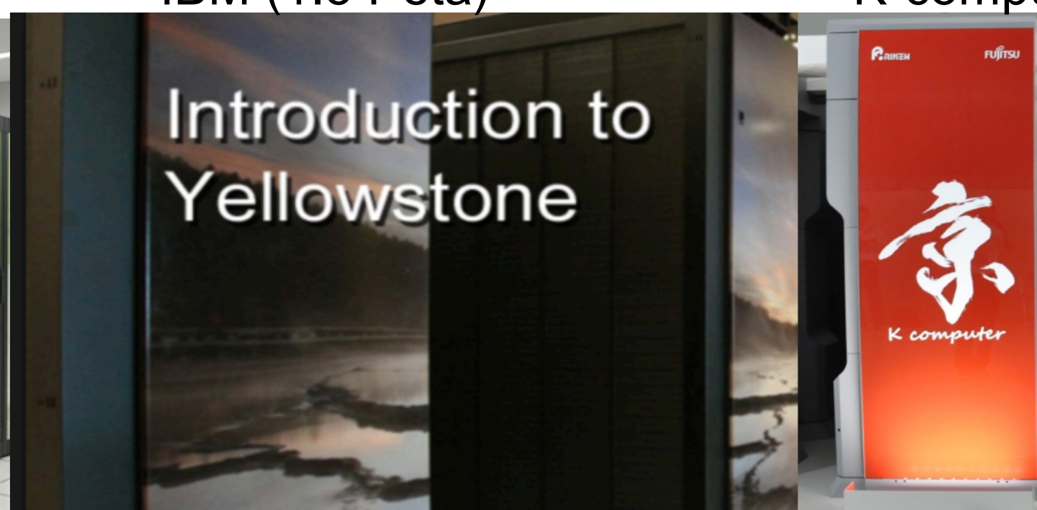
ENIAC,1946 (500 FLOPS)



Sunway (125 Peta=10**15FLOPS)


XC40 (2.9 Peta)

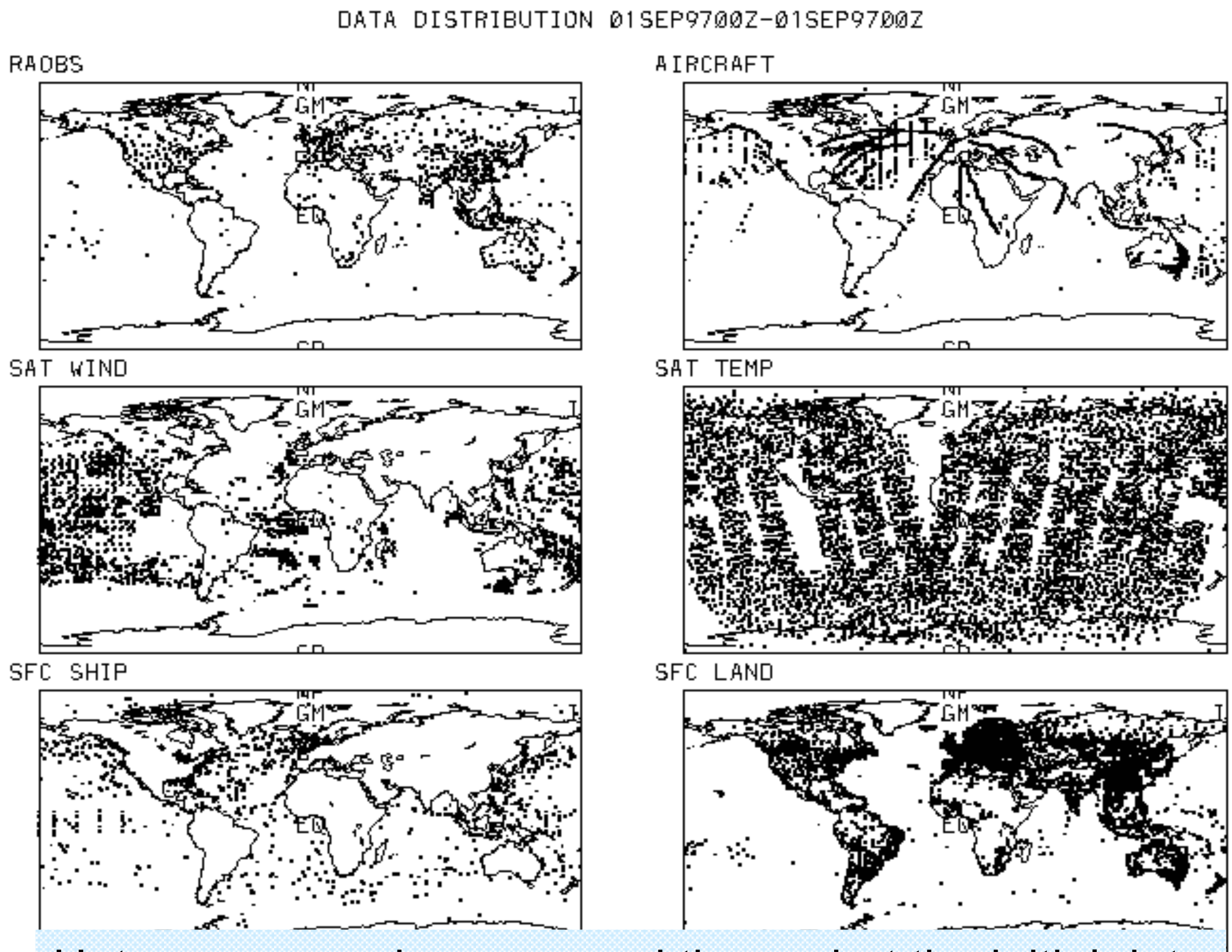

IBM (1.5 Peta)




K-computer  (11.2 Peta)

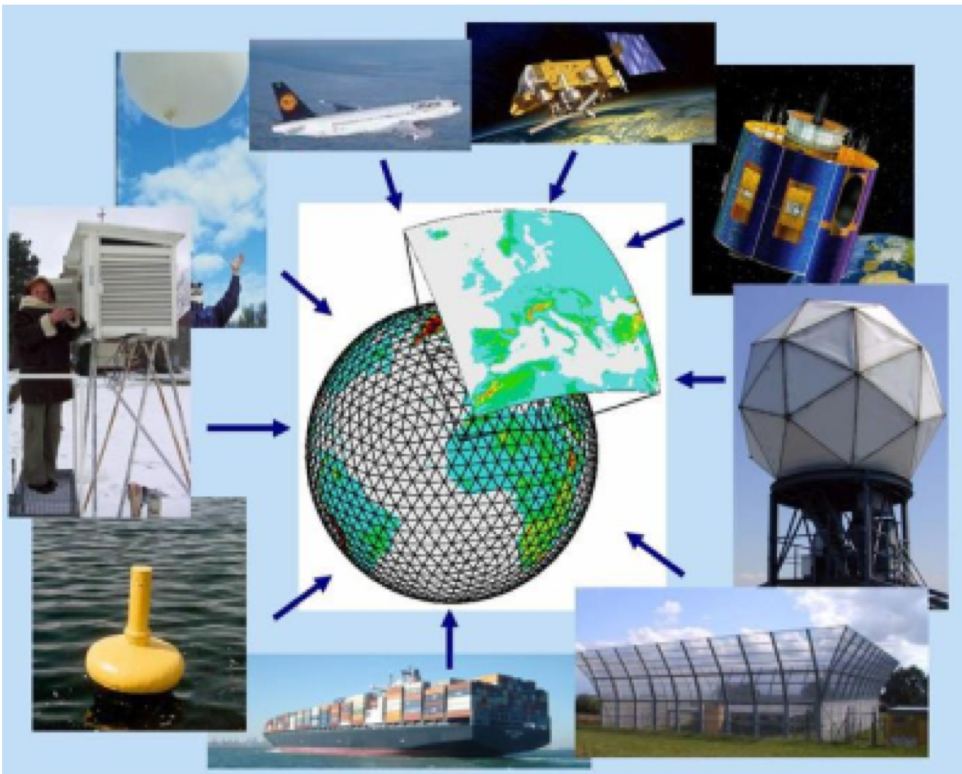
# Initial condition
# (data assimilation)

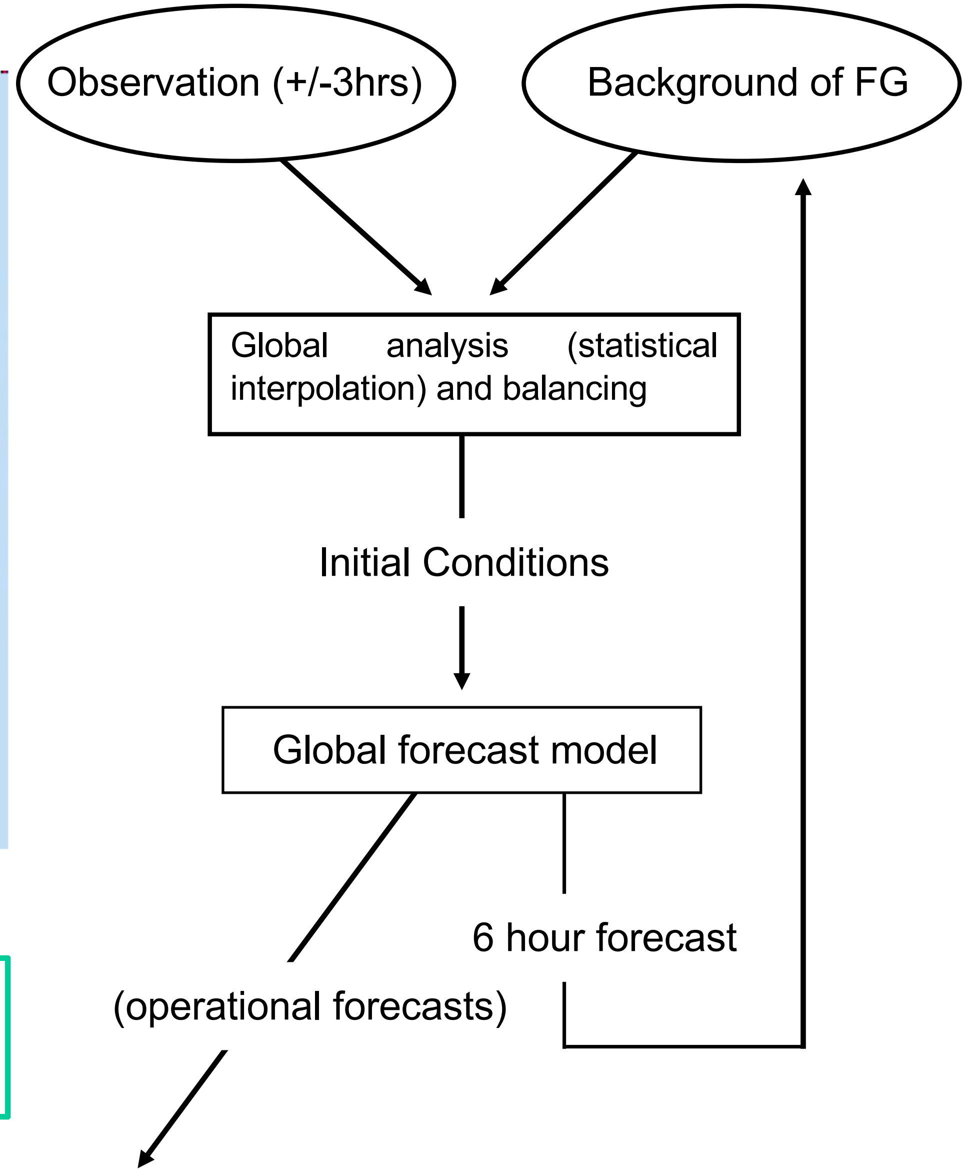
# Various observations




Heterogeneous in space and time….but the initial data should be on a model grid at a specific time ….!

# Data Assimilation





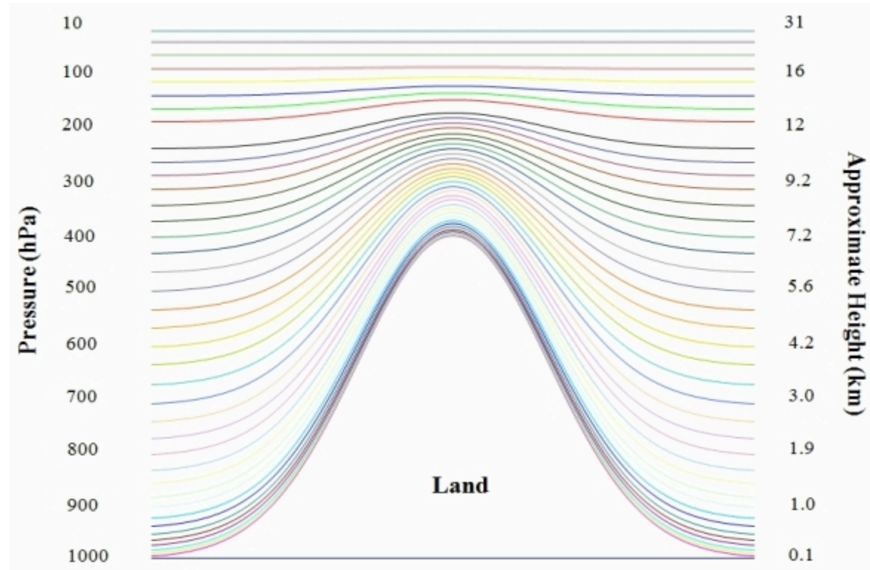

Data assimilation best combines observations and a model

# Model

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

Step3: Integration

# Dynamics : Grid system




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

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

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

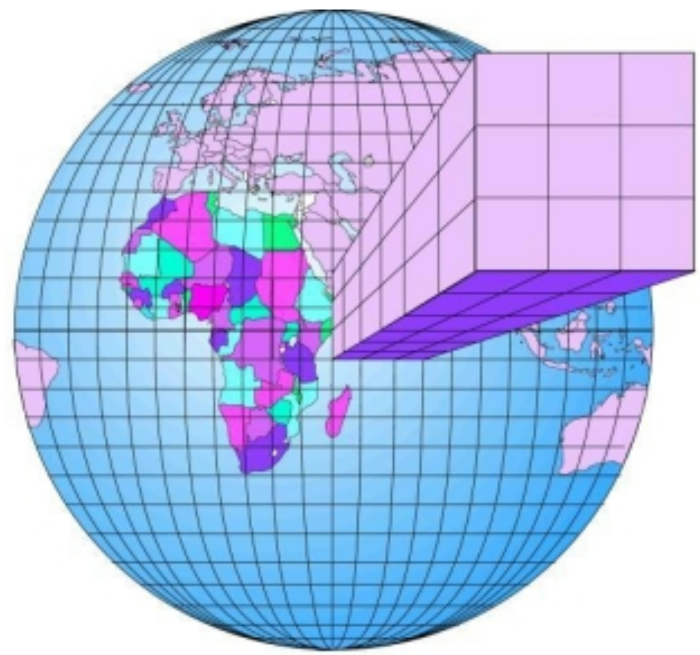
$$\rho_t + u\rho_x + v\rho_y + w\rho_z = -\rho\left( u_x + v_y + w_z \right)$$

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

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

$$p = \rho RT$$

PHYSICS



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)

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

Finite difference method (FDM) :

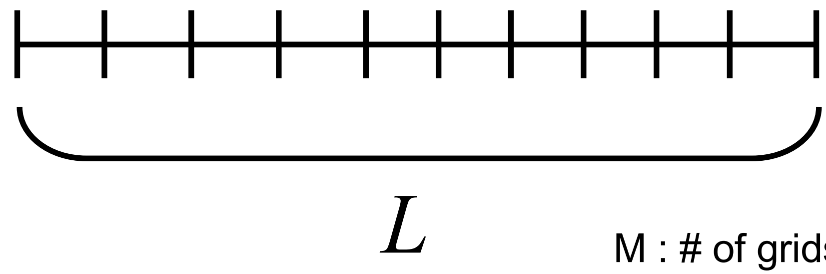
Spectral method (SPM) :

Finite element method (FEM) :

1) Finite difference (FD) method

- Specify the value at physical grids

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



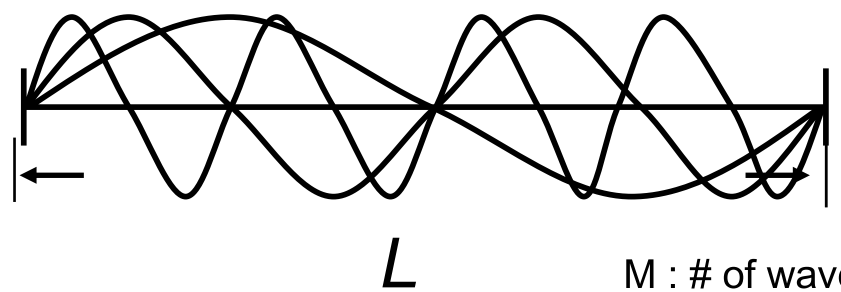

M : # of grids

2) Spectral Method

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

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

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




M : # of waves

* Resolution Increases $\left( \begin{array}{l} \Delta x \rightarrow decreases \\ (\Delta x = L / M) \\ M \rightarrow increases \end{array} \right.$

# **Dynamics :** Numerical method (temporal)

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)

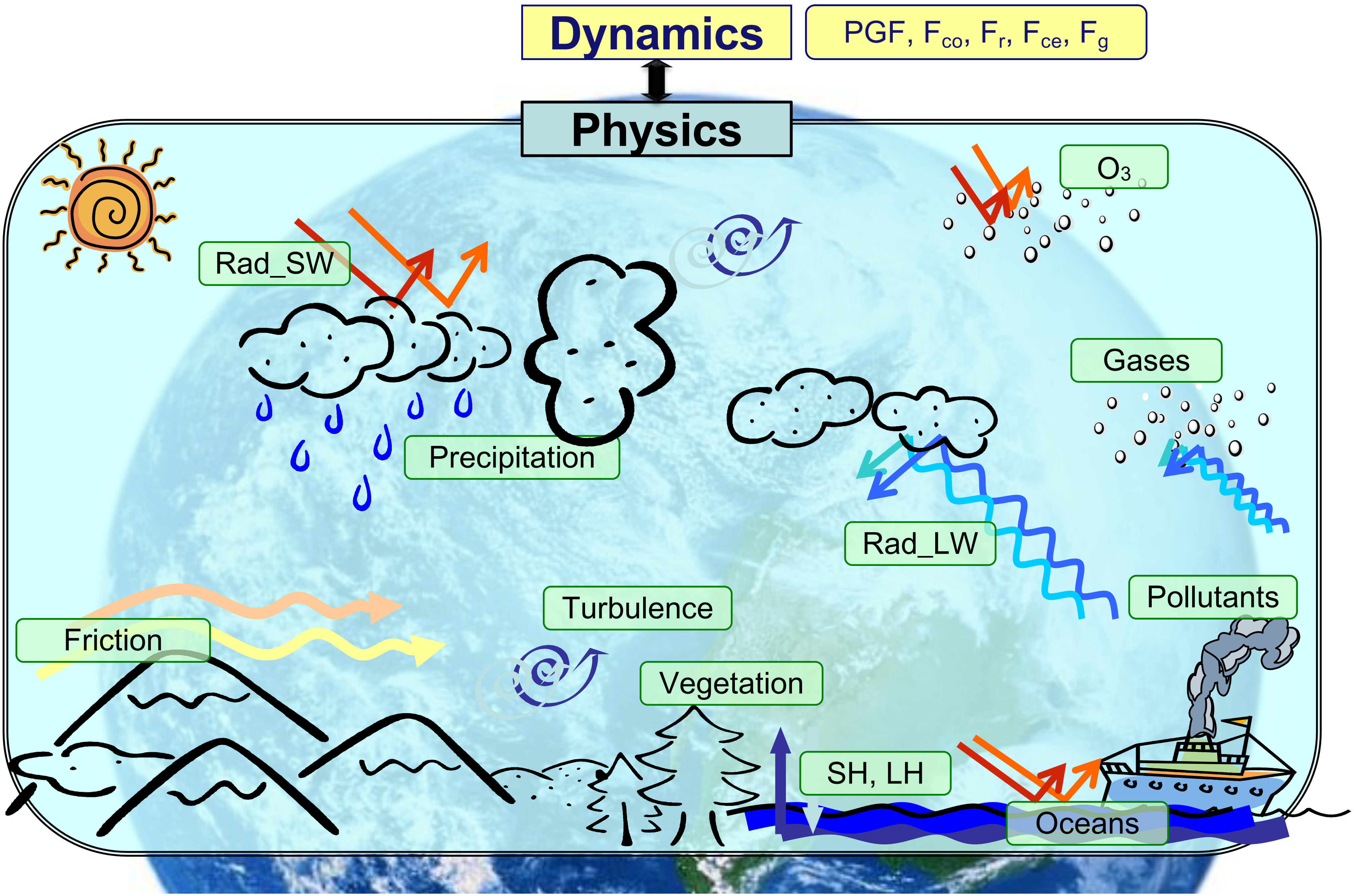
f) $$\frac{u^{n+\frac{1}{2}*}-u^{n}}{\Delta t/2}=F\left(u^{n}\right) \quad : \quad \frac{u^{n+1*}-u^{n}}{\Delta t}=F\left(u^{n+\frac{1}{2}*}\right)$$

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

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

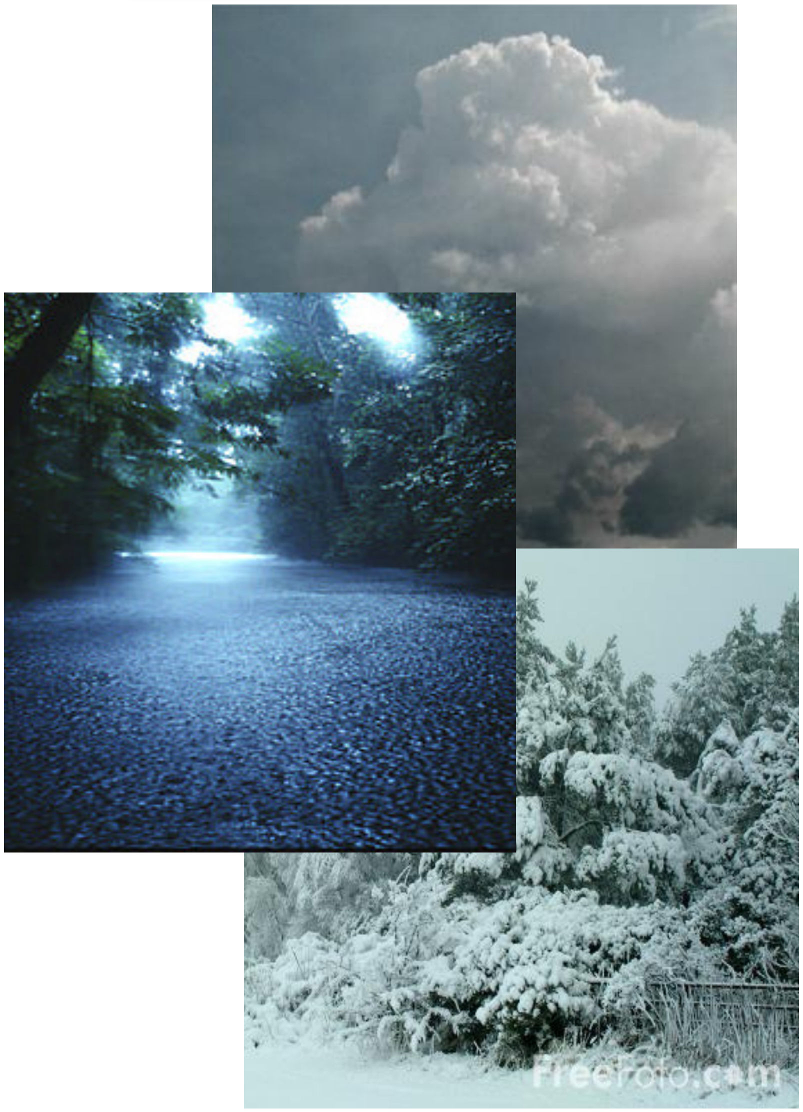
h) $$\frac{u^{*}-u^{n}}{\Delta t}=F_{1}\left(u^{n}\right); \qquad \frac{u^{n+1}-u^{*}}{\Delta t}=F_{2}\left(u^{*}\right)$$ : Fractional steps

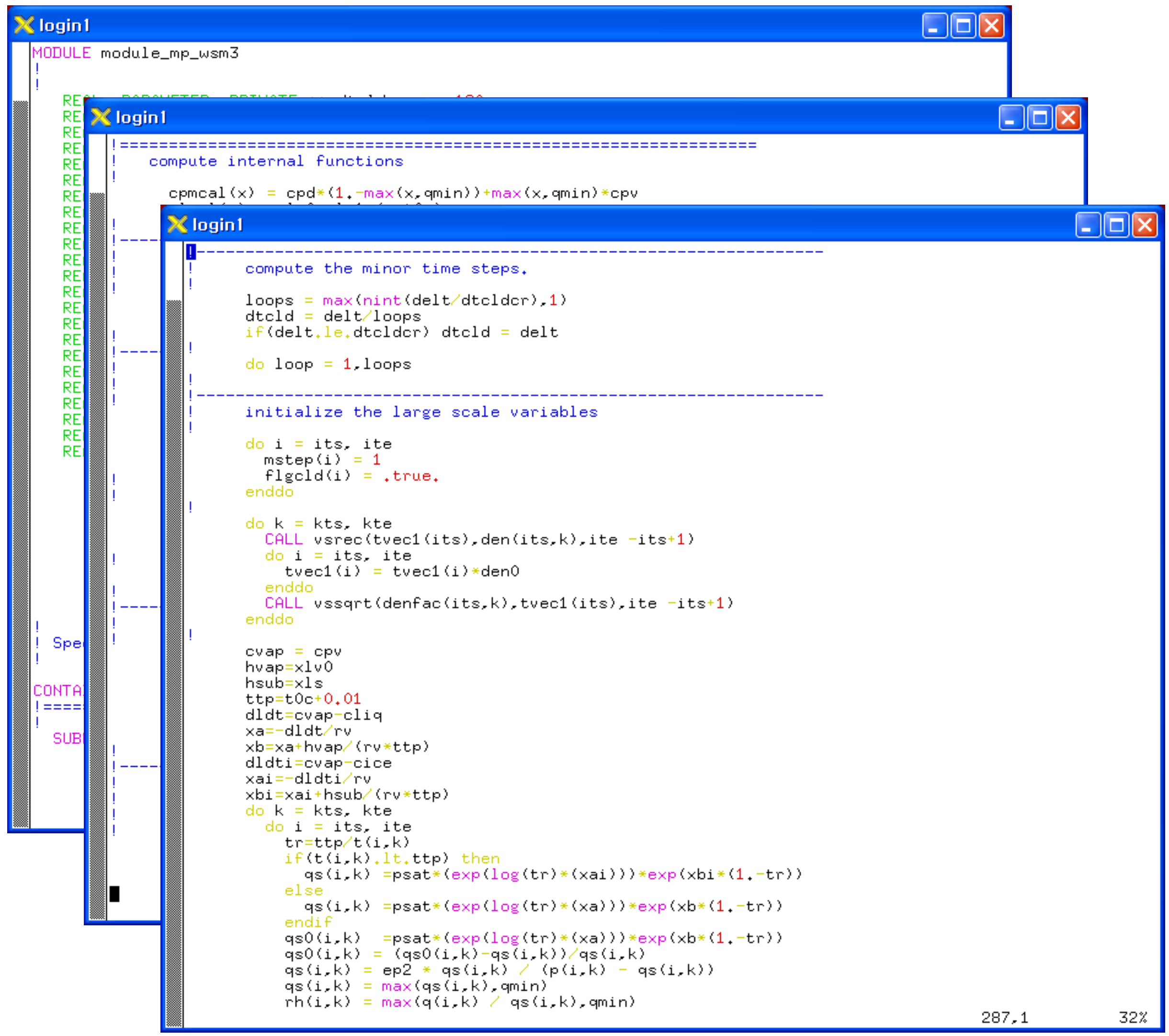
# **Physics modules :** Branches of atmospheric sciences



# Physics module (example): Cloud and precipitation

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



# Physics module (example): 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

Autoconversion

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

Accretion

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

Evaporation

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

# Car and model

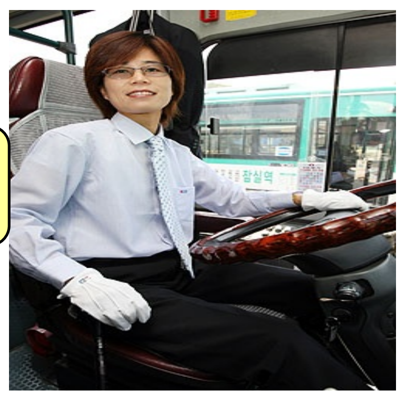
Software

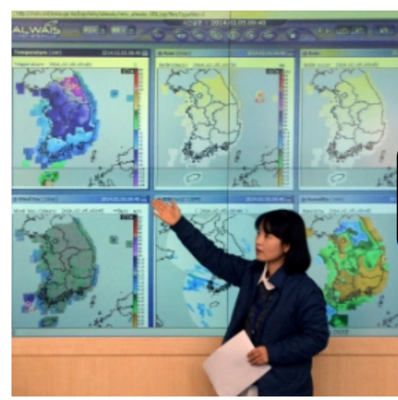
Dynamics

Physics

Data assimilation

Driver





Forecaster

# Classification of models

- Dynamic core

| Hydrostatic | Non-hydrostatic |
| --- | --- |
| Large-scale | Small-scale<br>(heavy rainfall, complex mountain) |

- Scale

| Global | Regional |
| --- | --- |
| 10 km – 100 km<br>(NWP – Climate) | 1 km - 10 km<br>(NWP-Climate) |

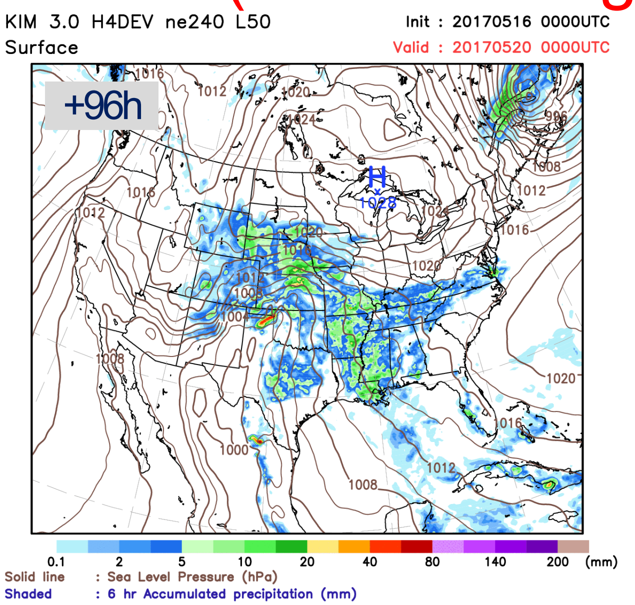
- Purpose

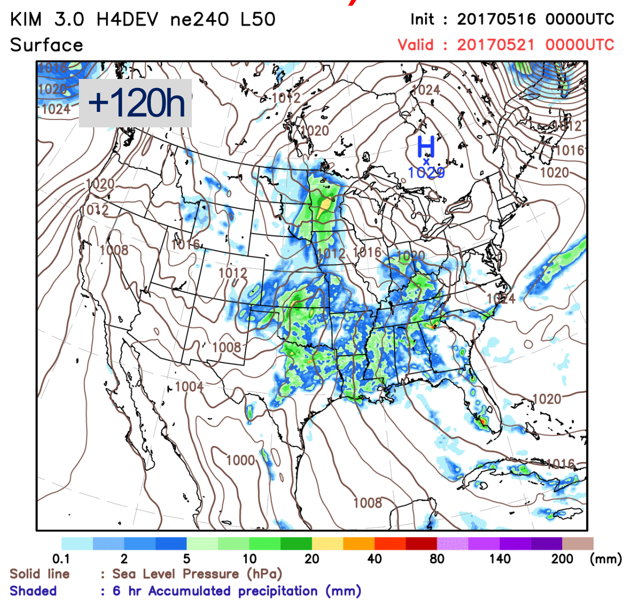
| Initial data-> FORECAST | Forcing → RESPONSE |
| --- | --- |
| NWP : upto 2 weeks | GCM (General circulation model) |

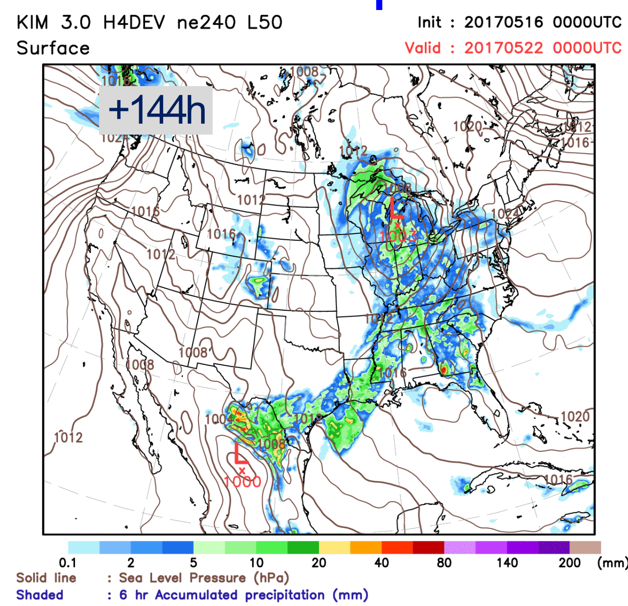
# KIAPS real time forecasts (INIT 2017051600) : 12 km global NWP

## KIM (Korean Integrated Model)

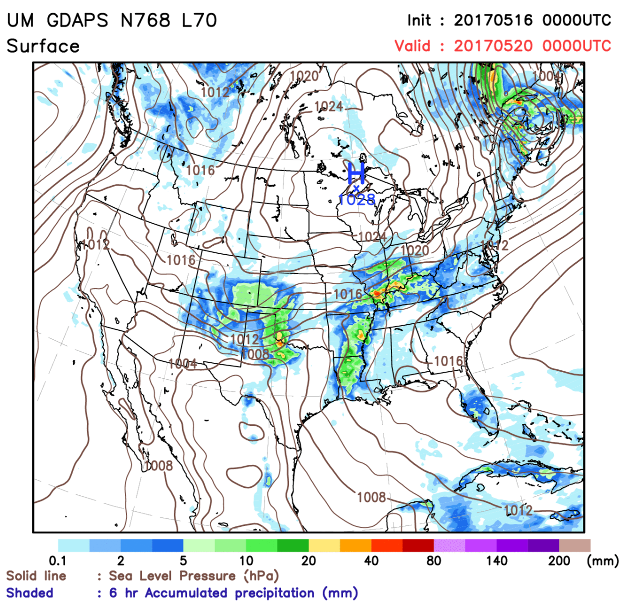
## Snap shots

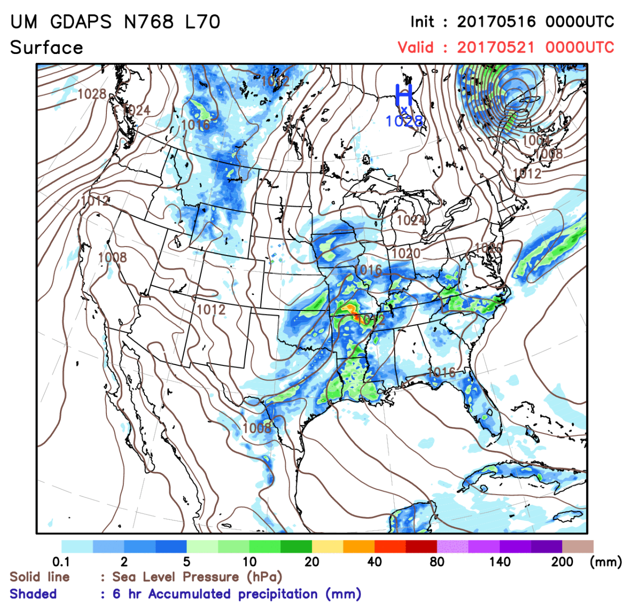


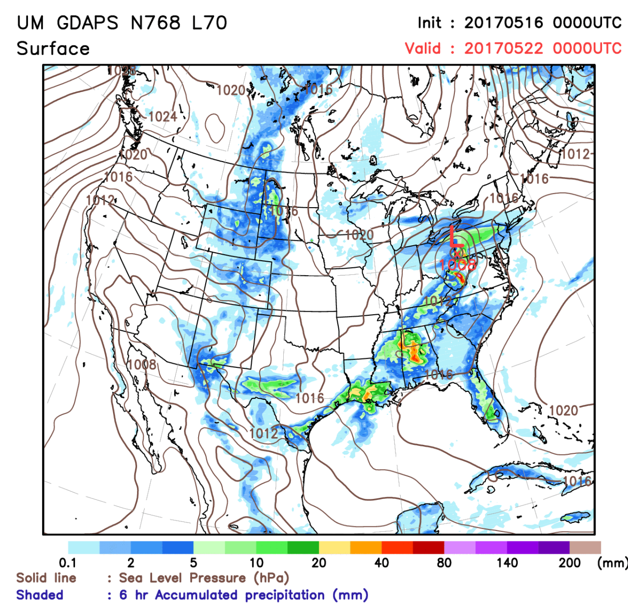




## KMA UM



# 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

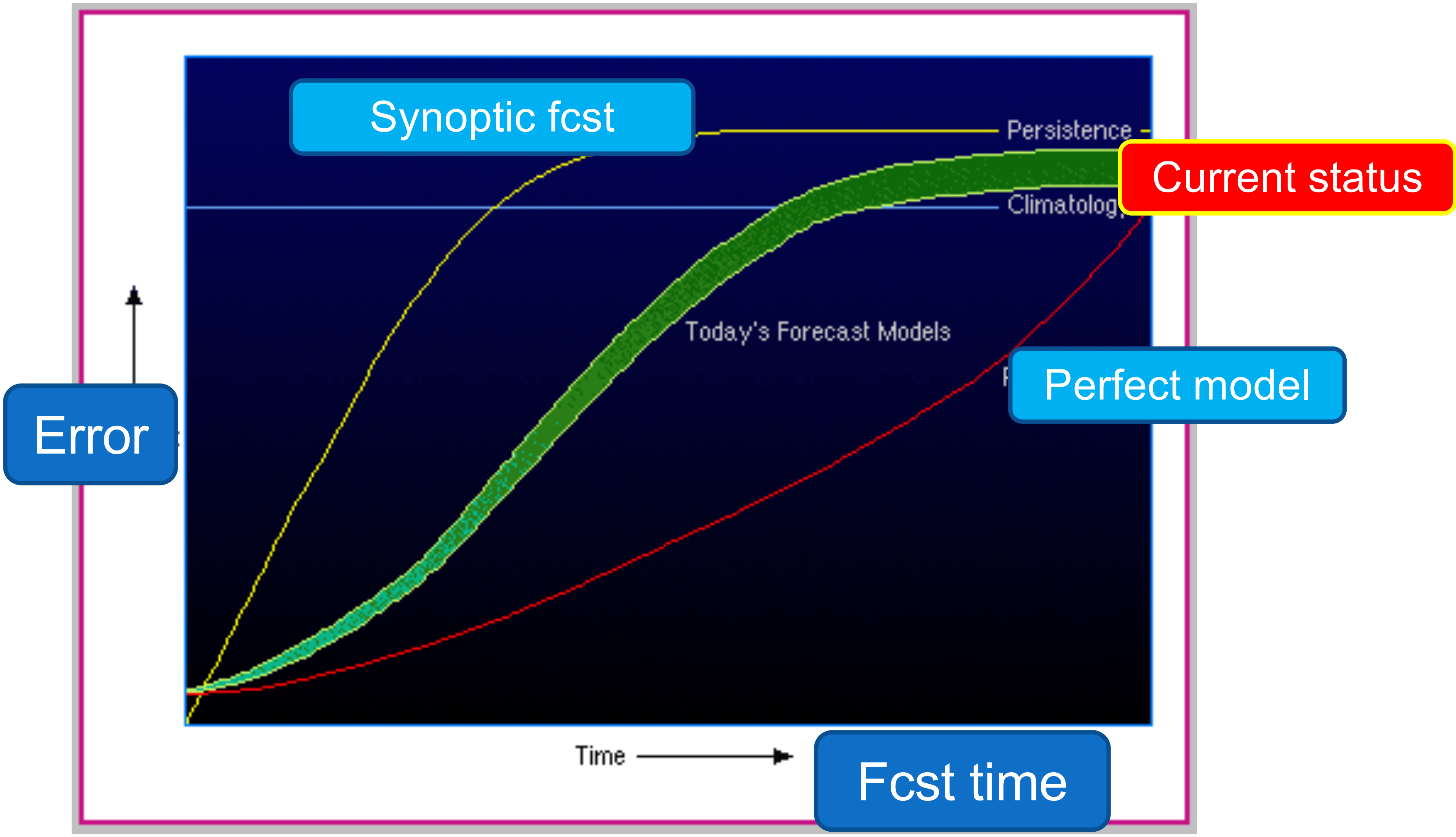
↓

Round-off error -> cause of non-periodcity

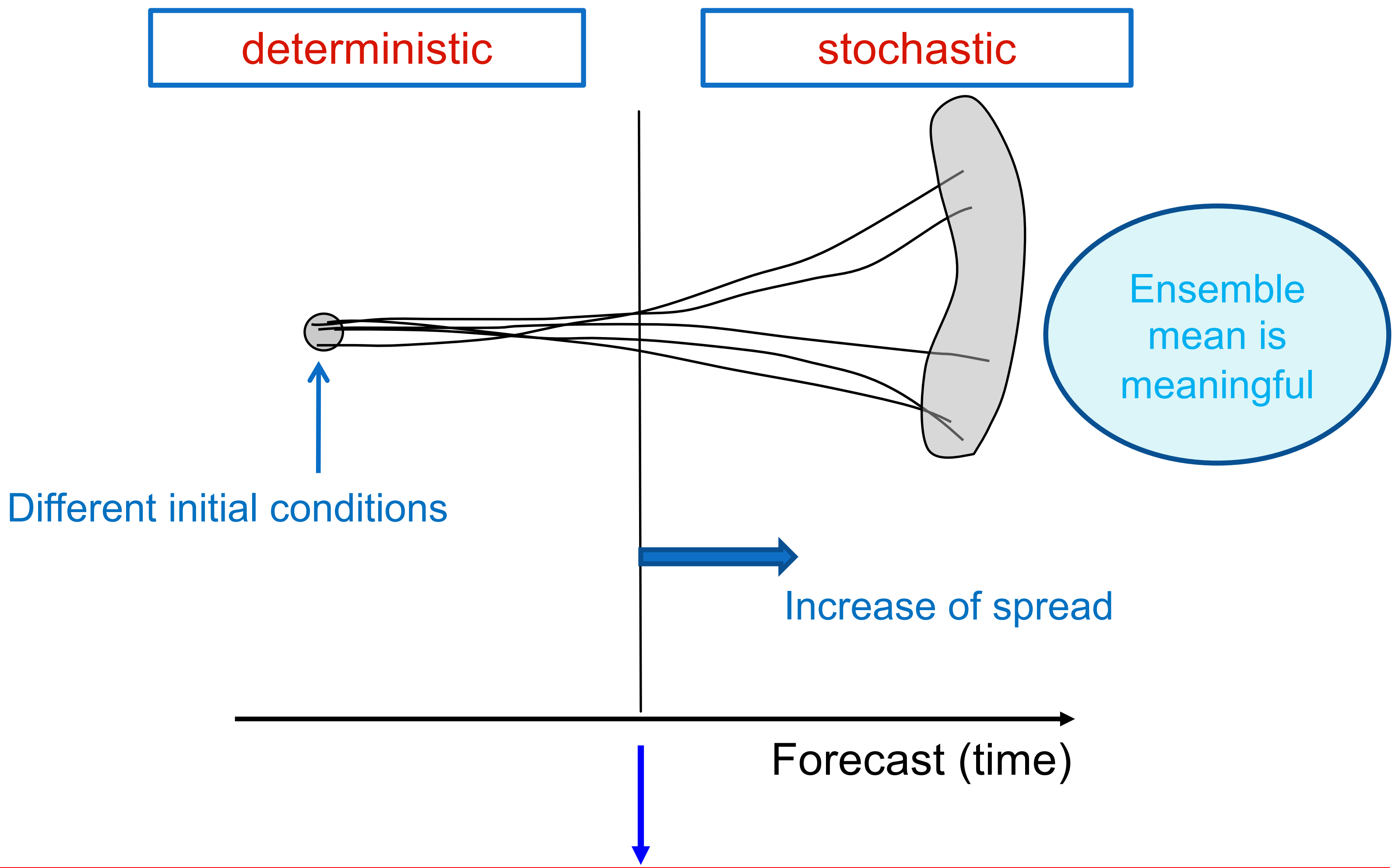
↓

Chaos theory– two weeks for NWP

# **Predictability :** Atmosphere is chaotic



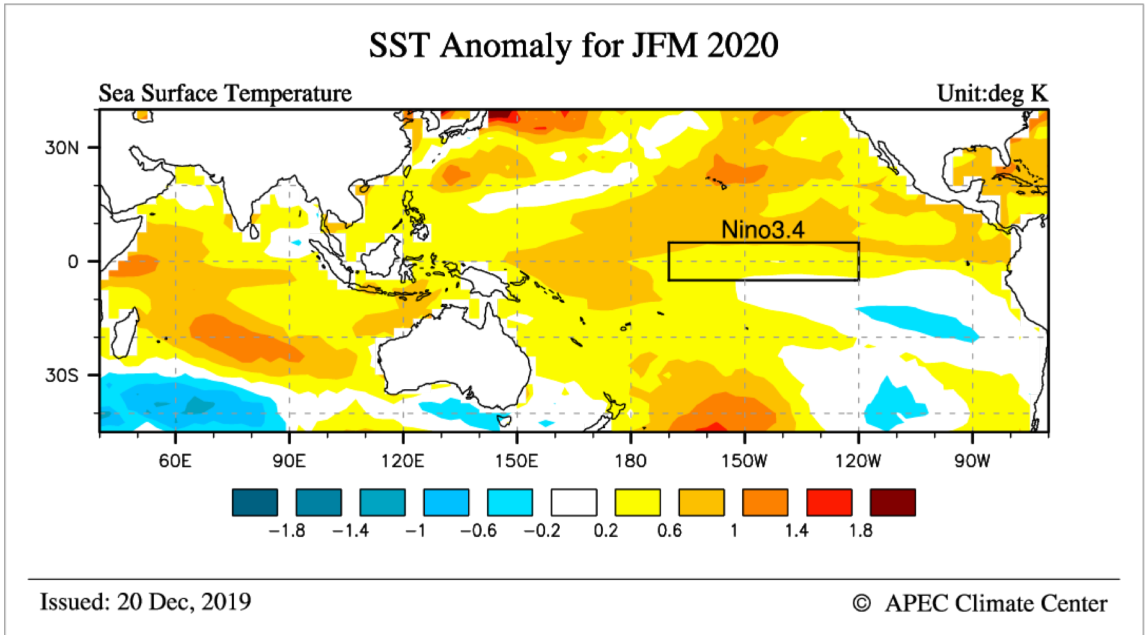
# **Ensemble forecasts** : Seasonal and beyond



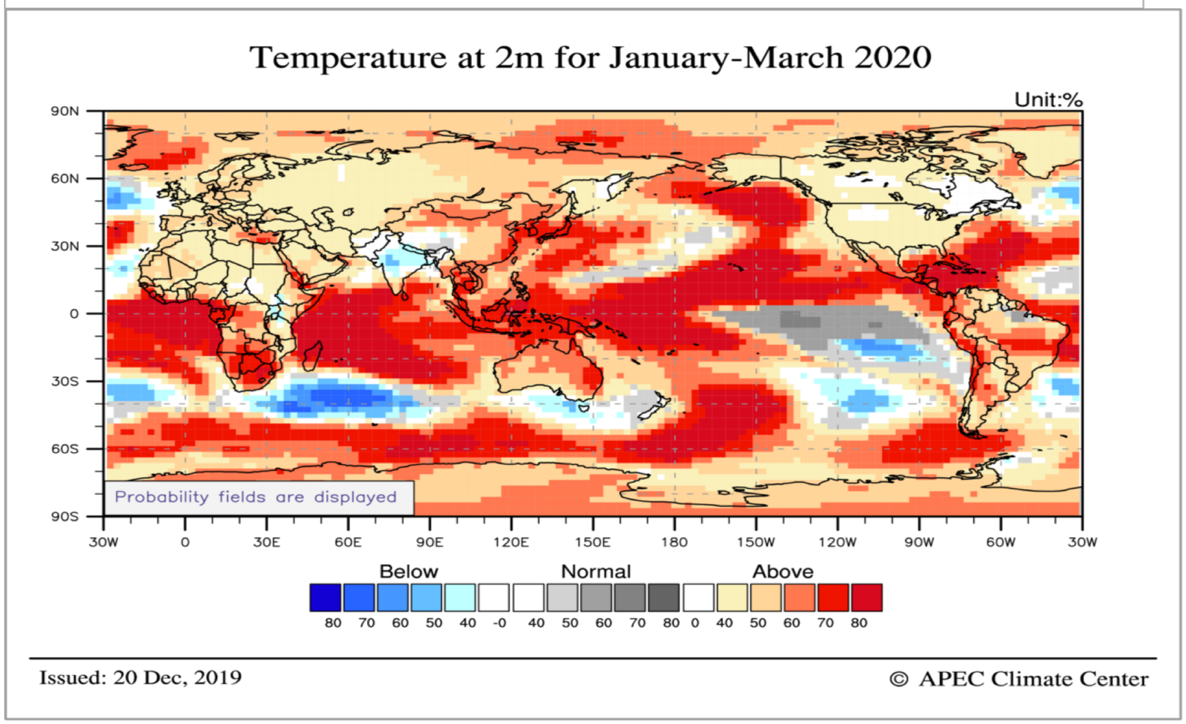

NWP (Initial value)

Seasonal forecasts (External forcing such as SST)

# Ensemble forecasts : Seasonal and beyond



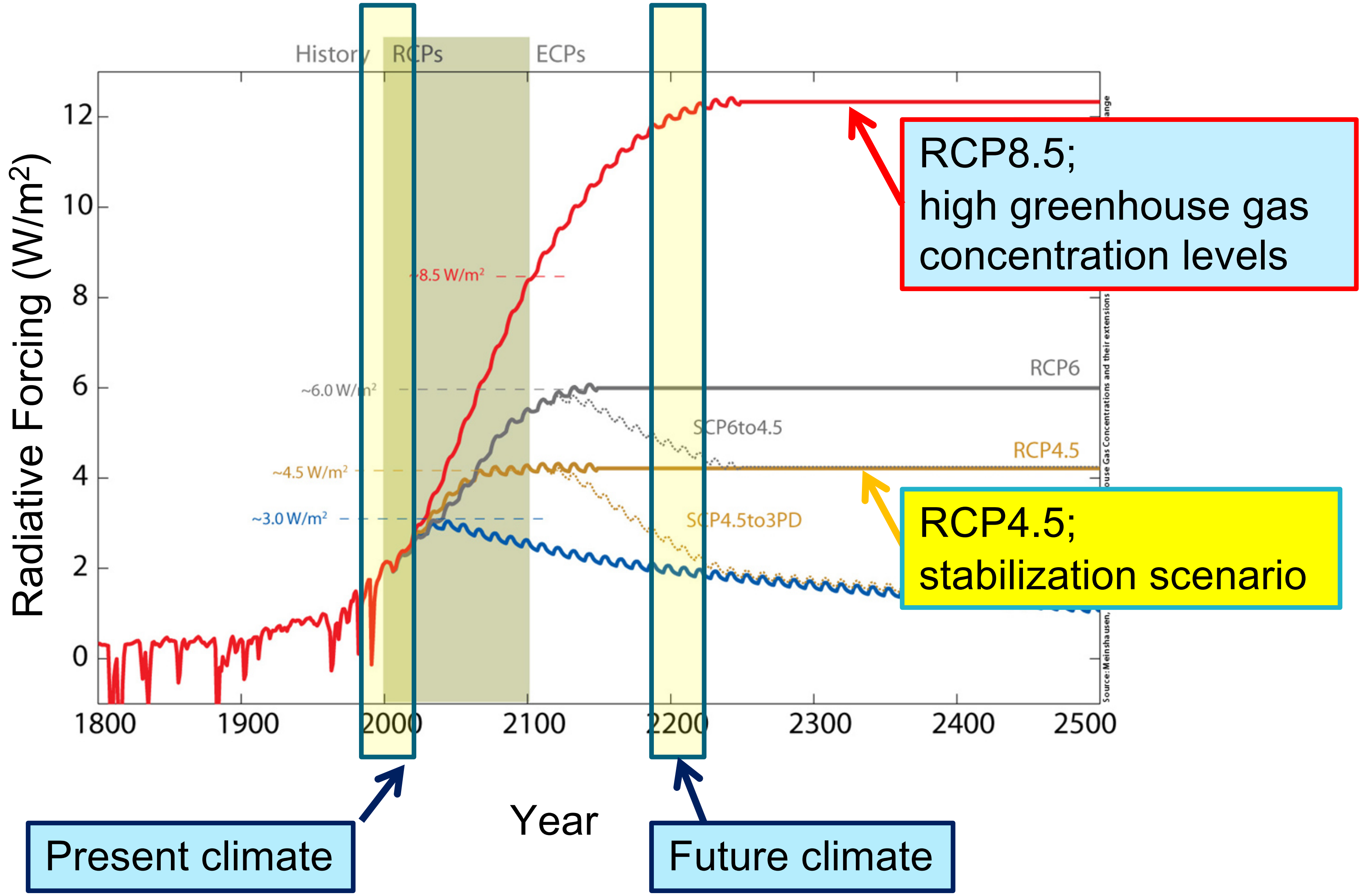

SST anomaly in JFM 2020



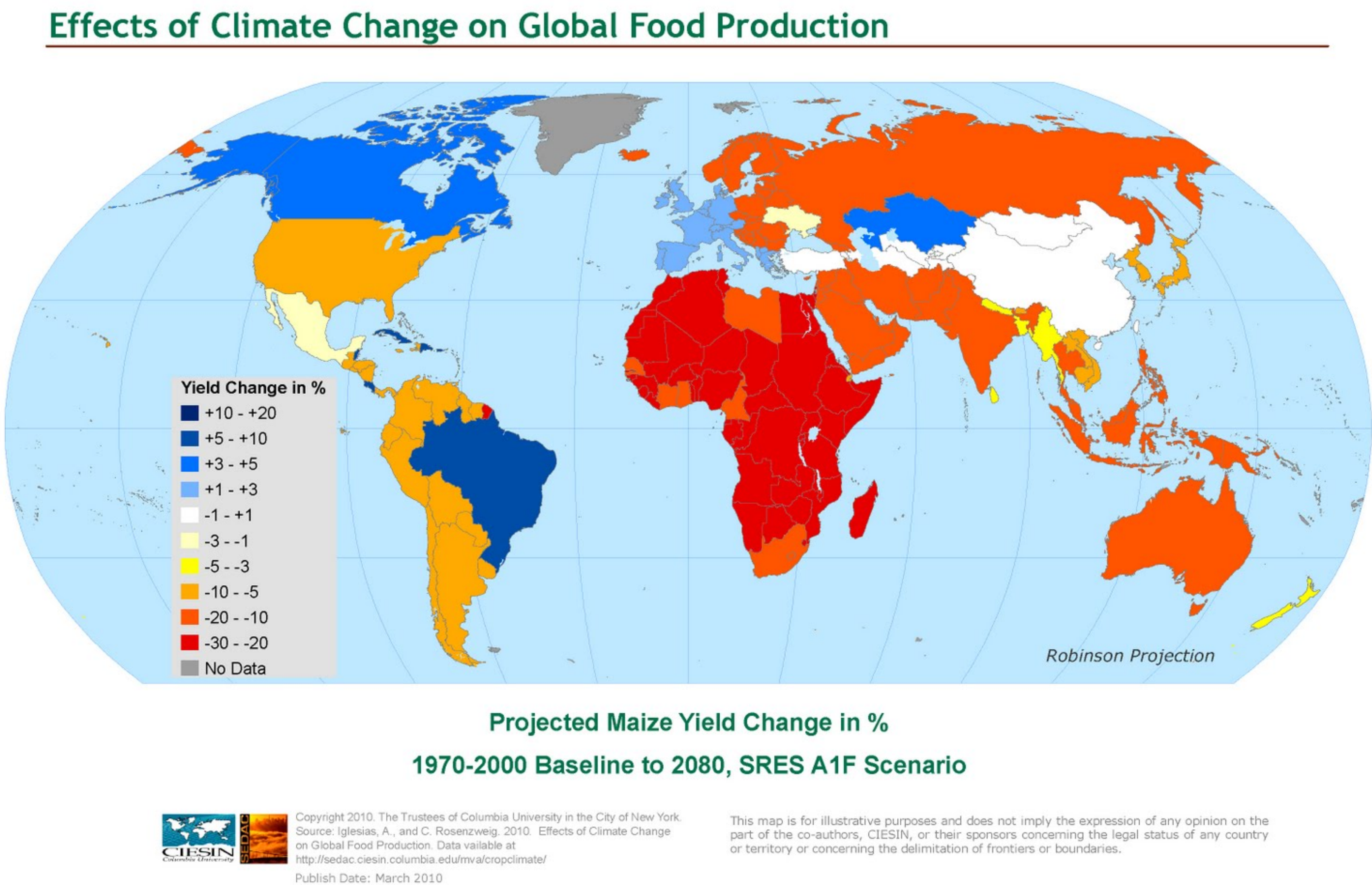

Temperature anomaly in JFM 2020

# Climate prediction : For given representative change pathway (RCP) scenarios,

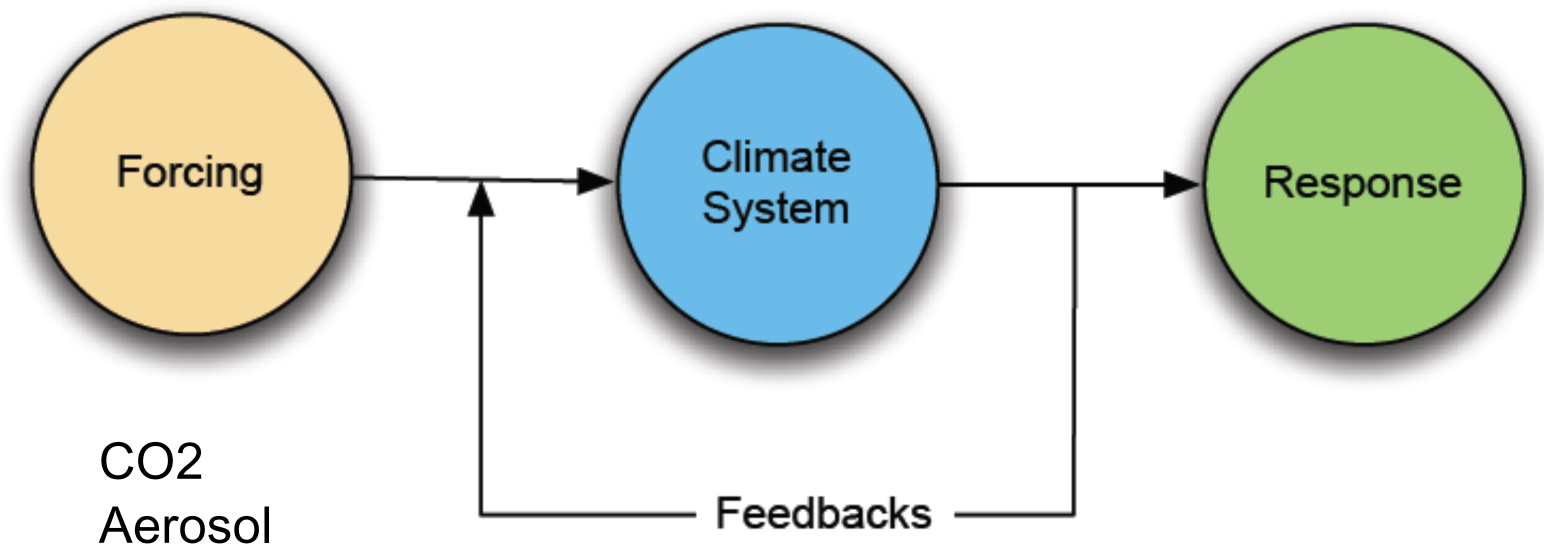
## Climate changes = future minus present



# Climate prediction : For given RCP scenarios



# Climate prediction : Climate system sensitivity



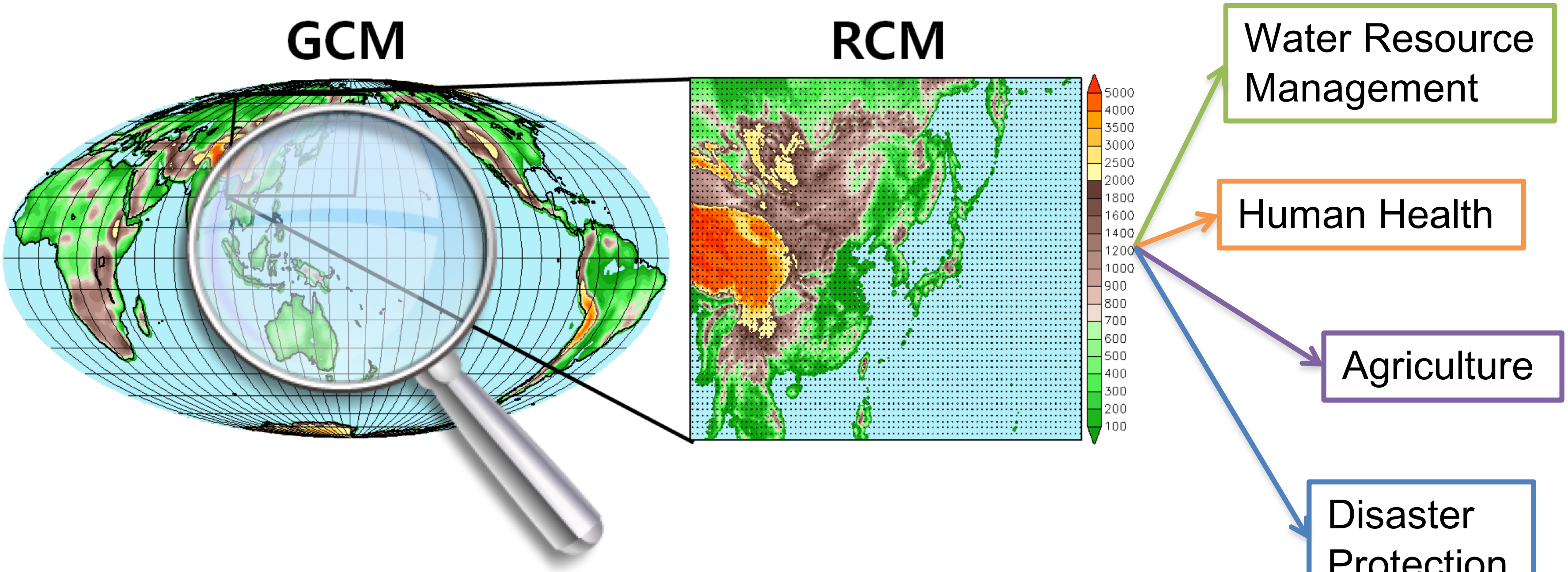

CO2
Aerosol
Volcanic

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

NWP / GCM : models could be unified.

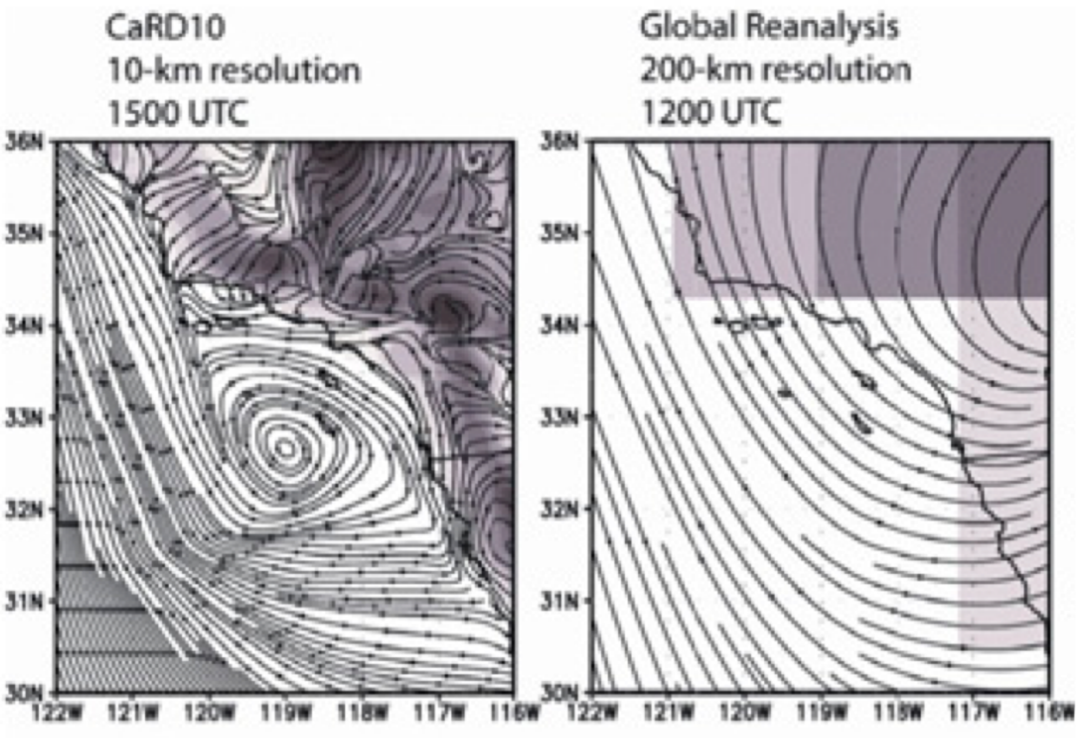
# Global vs Regional

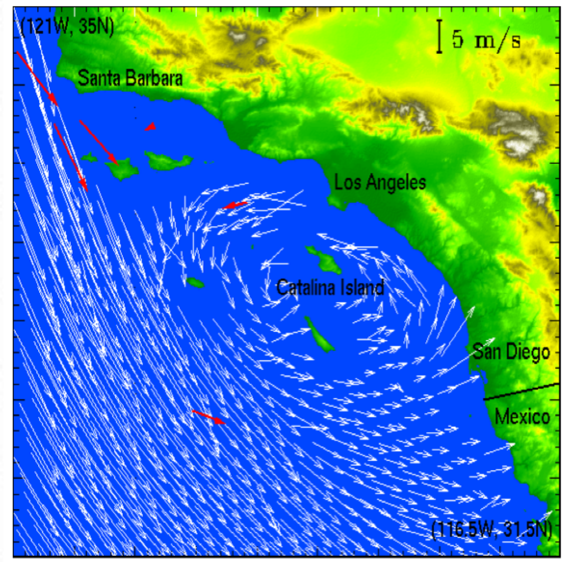
# Regional modeling : need for applications




Regional model is a magnifying glass

# High resolution benefit ?   ---- Very clear !



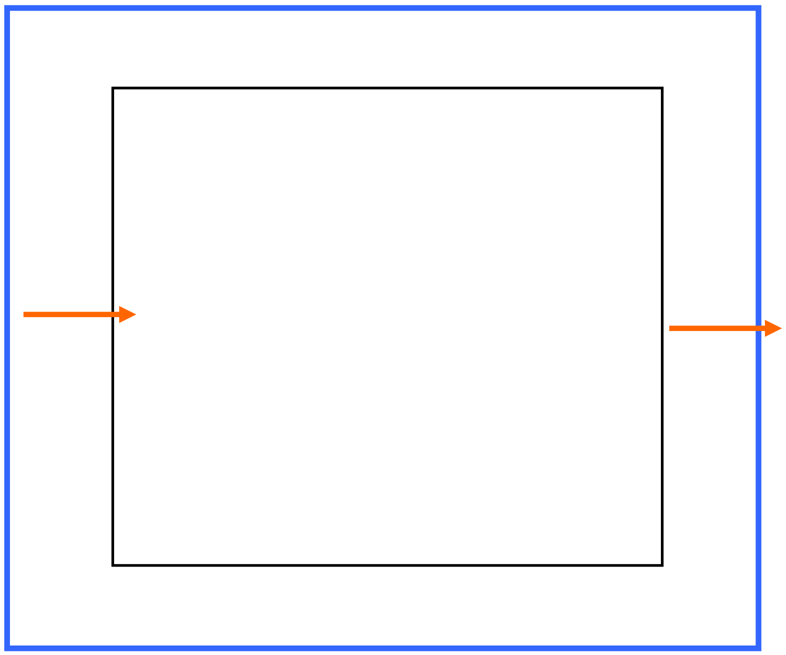

10 km

200 km

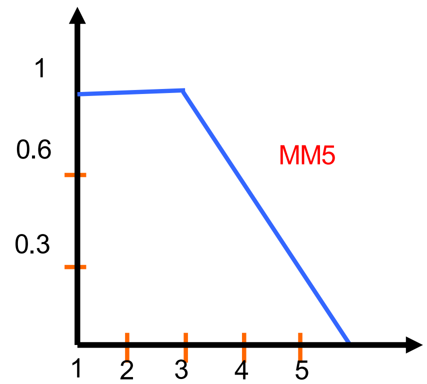
Observed

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

Buffer zone



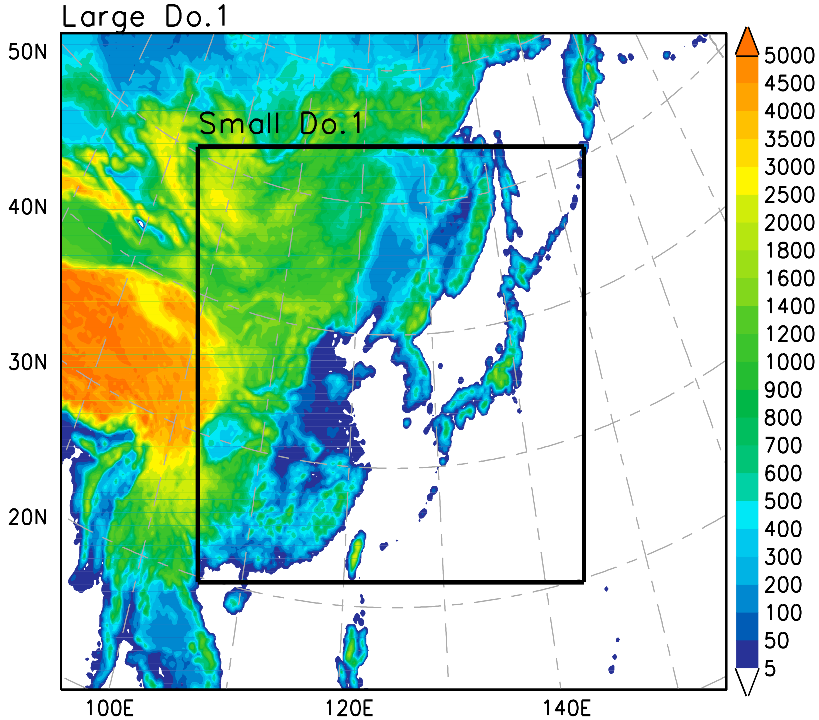
F(n) : weighting of global

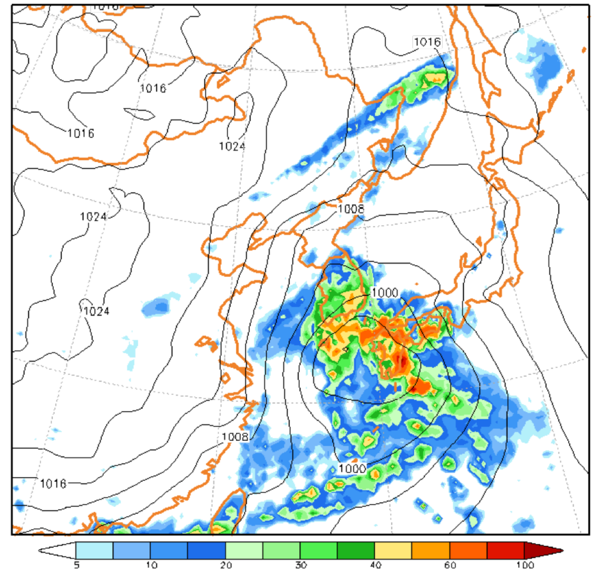



$$\left.\frac{\partial A}{\partial t}\right|_n = F(n)F_1(A_{CM} - A_{FM}) - F(n)F_2\nabla^2(A_{CM} - A_{FM})$$

So, empirical

# Domain size sensitivity : A mid-latitude cyclone

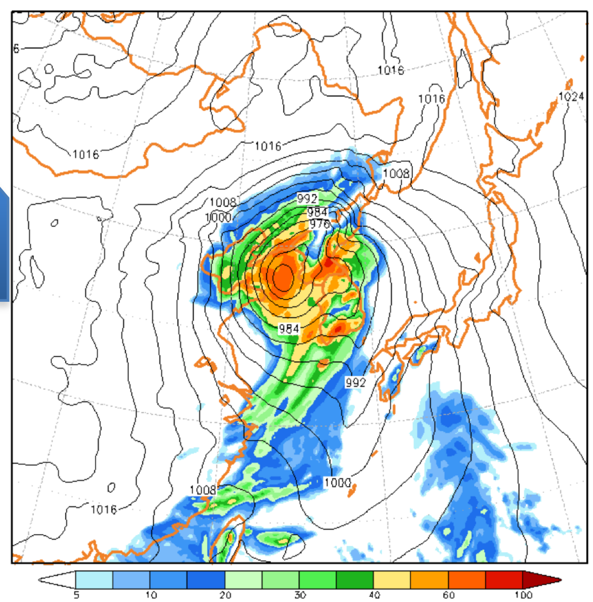


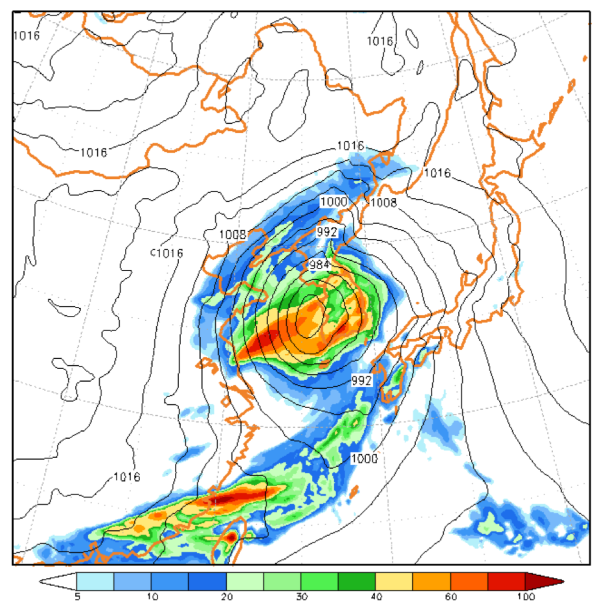



Observed

Large

Away from OBS
But more freedom

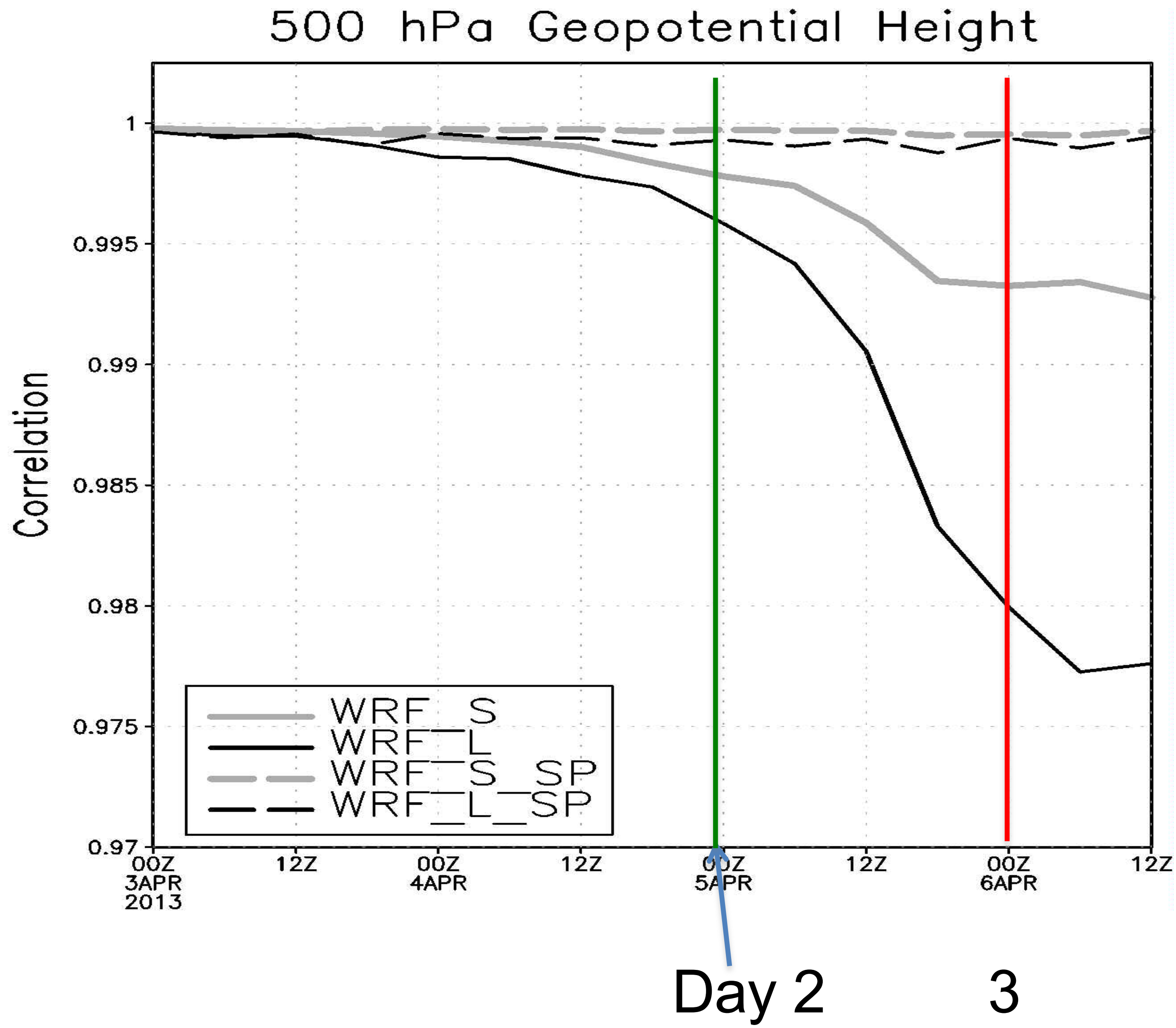




Small

Close to OBS
But less freedom

# 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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