

Fundamentals in Atmospheric Modeling

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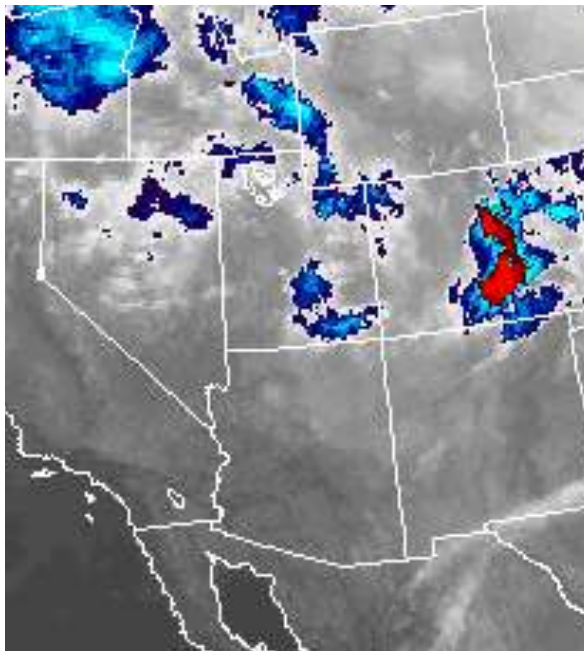
(Also NCAR affiliate scientist)

List of presentations

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

How were the today's forecasts made ?

Observation



NO!

Forecasts

Boulder CO 7 Day Forecast

OVERNIGHT



Partly
Cloudy
Low: 29 °F

TUESDAY



Mostly
Sunny
High: 50 °F

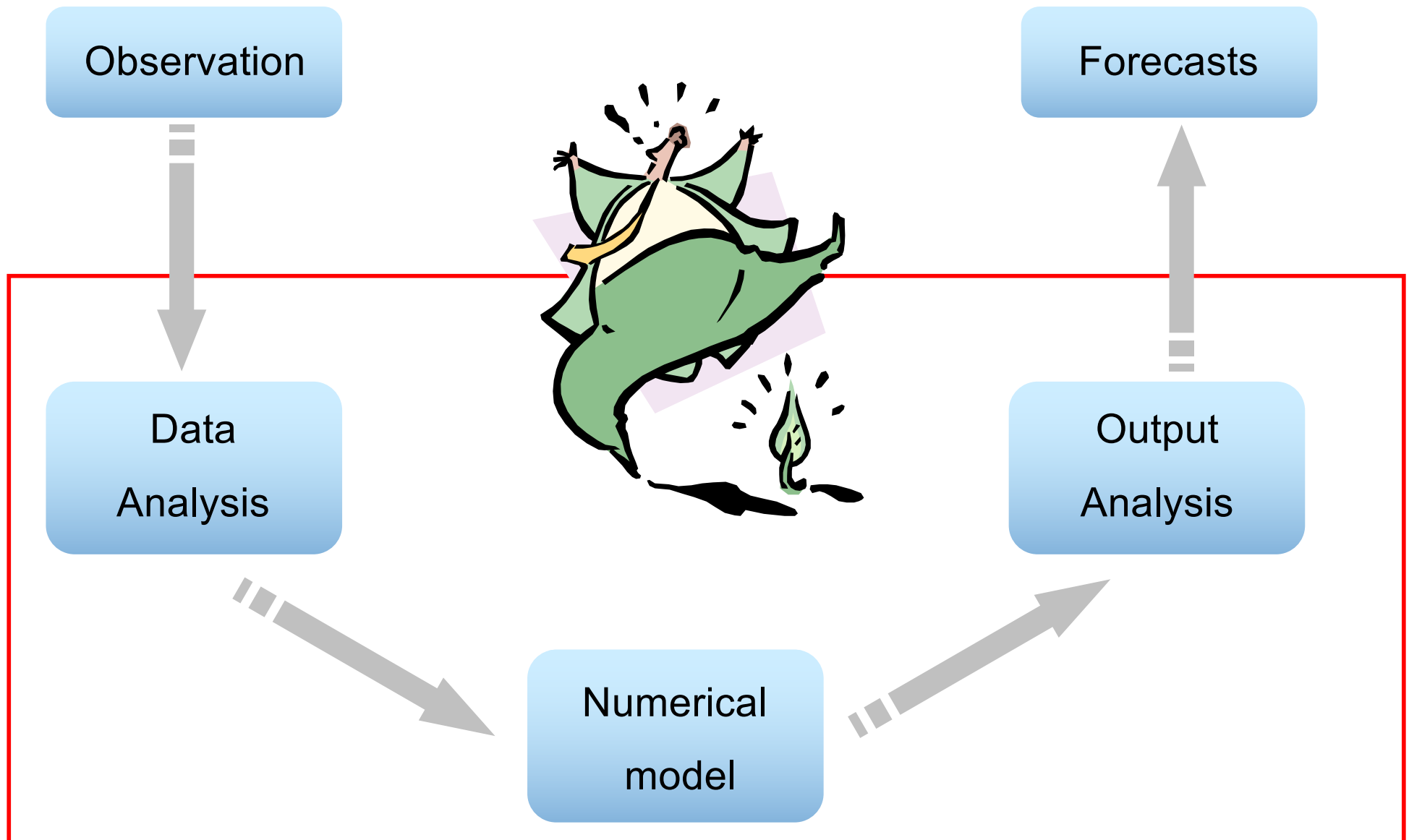
TUESDAY
NIGHT



Chance
Snow
Low: 19 °F

Then, what ?

Numerical weather prediction is a crucial component



Then, how ?

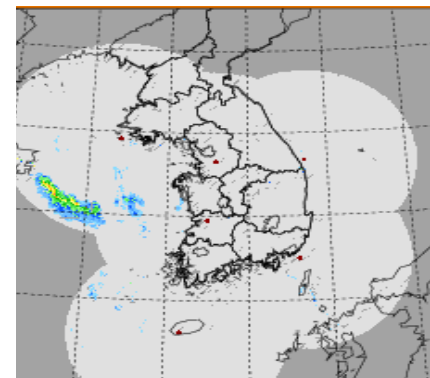
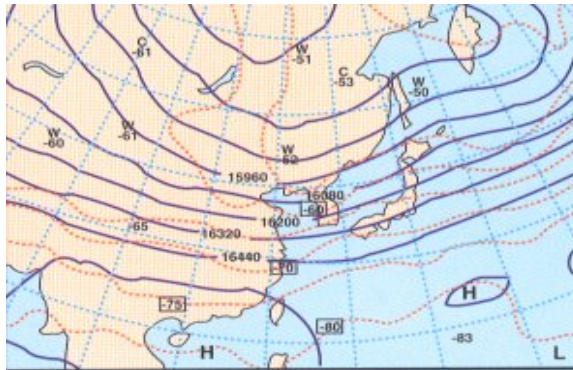
Step1:

Observation



Step2:

Data analysis



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

Theory of numerical weather prediction (NWP)

Thermodynamics

Heat = Energy + Work

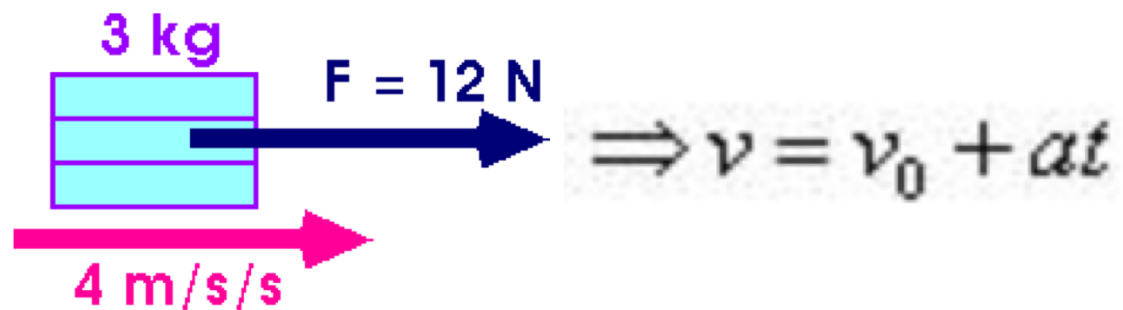
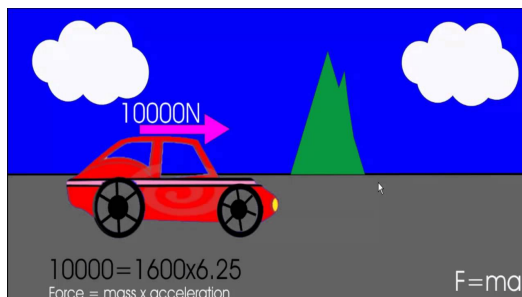
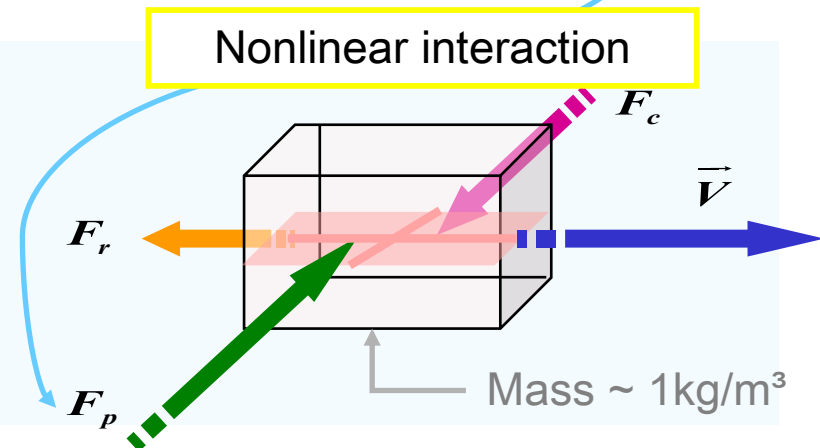


$$\begin{aligned}\Delta H &= c_p \Delta T - \alpha \Delta p \\ &= c_v \Delta T + p \Delta \alpha\end{aligned}$$

Dynamics

Force = Mass $\times$ Acceleration

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



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:

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

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

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

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

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

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

solvable

History of numerical weather 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~)

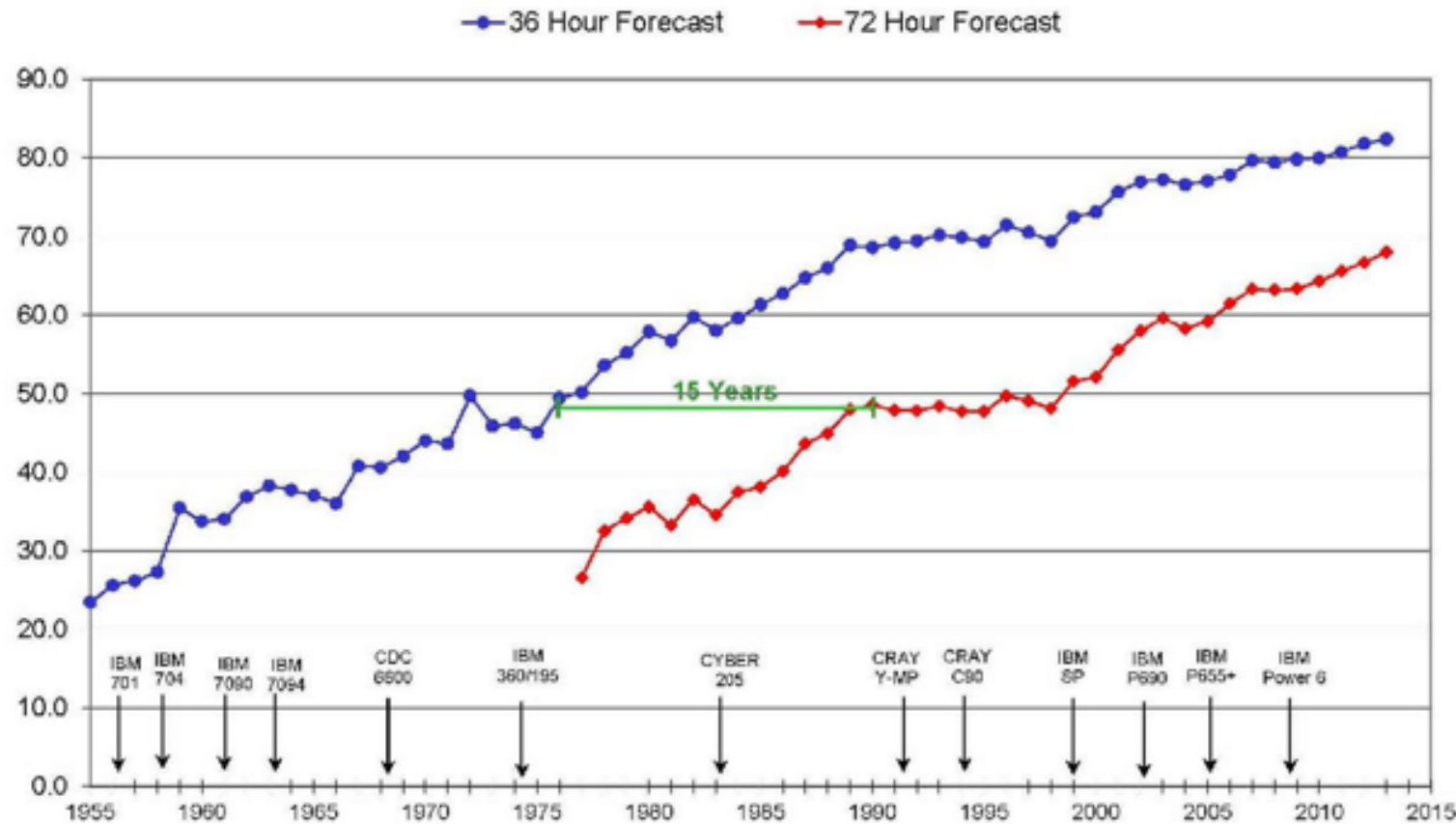
- von Neumann and Charney
 - Applied ENIAC to weather prediction
- Carl-Gustaf Rossby
 - The Swedish Institute of Meteorology
 - First routine real-time numerical weather forecasting. (1954)
(US in 1958, Japan in 1959)



History of NWP skill : NCEP GFS (global forecast system)



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



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)

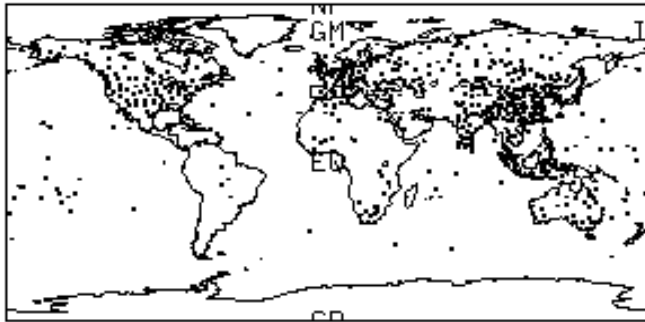


Initial condition
(data assimilation)

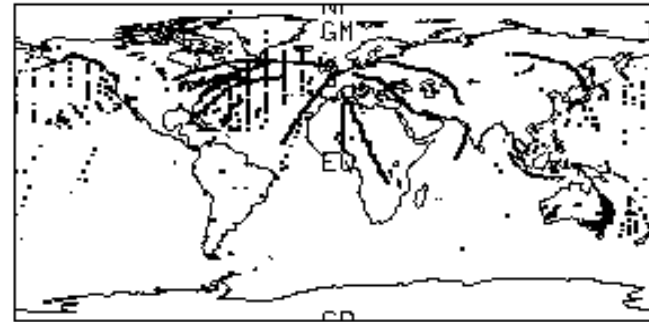
Various observations

DATA DISTRIBUTION 01SEP9700Z-01SEP9700Z

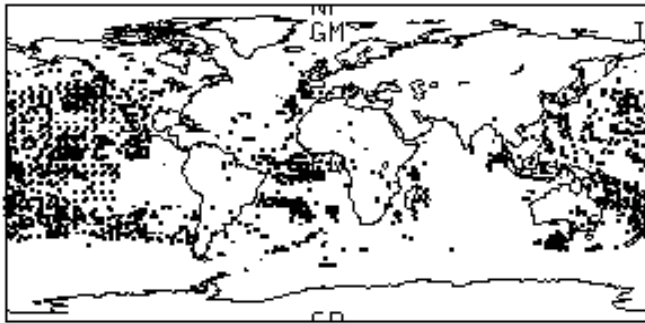
RAOBS



AIRCRAFT



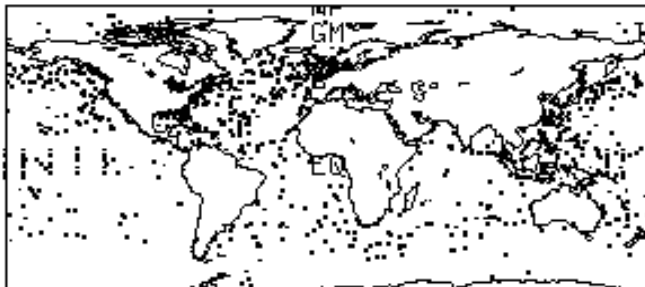
SAT WIND



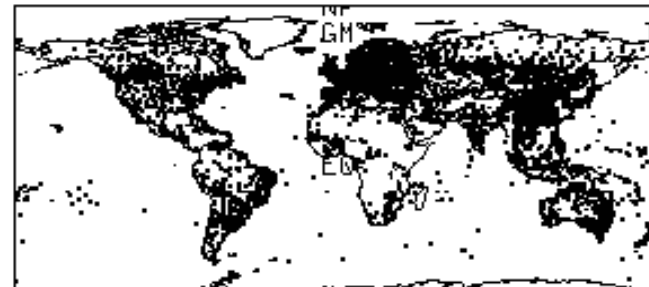
SAT TEMP



SFC SHIP

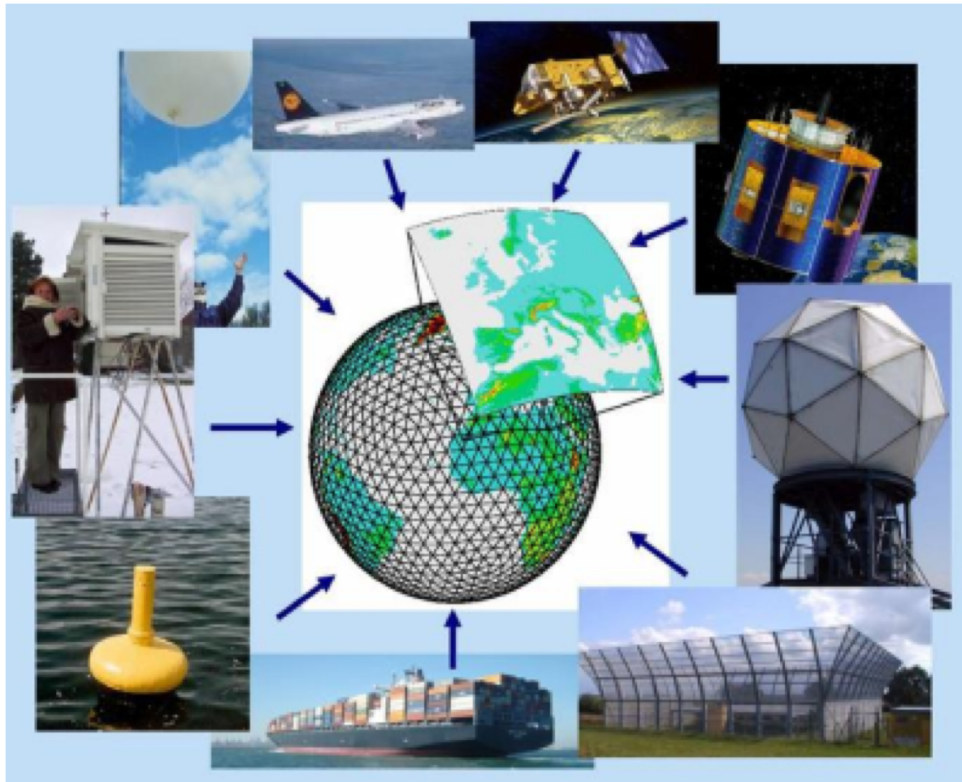


SFC LAND

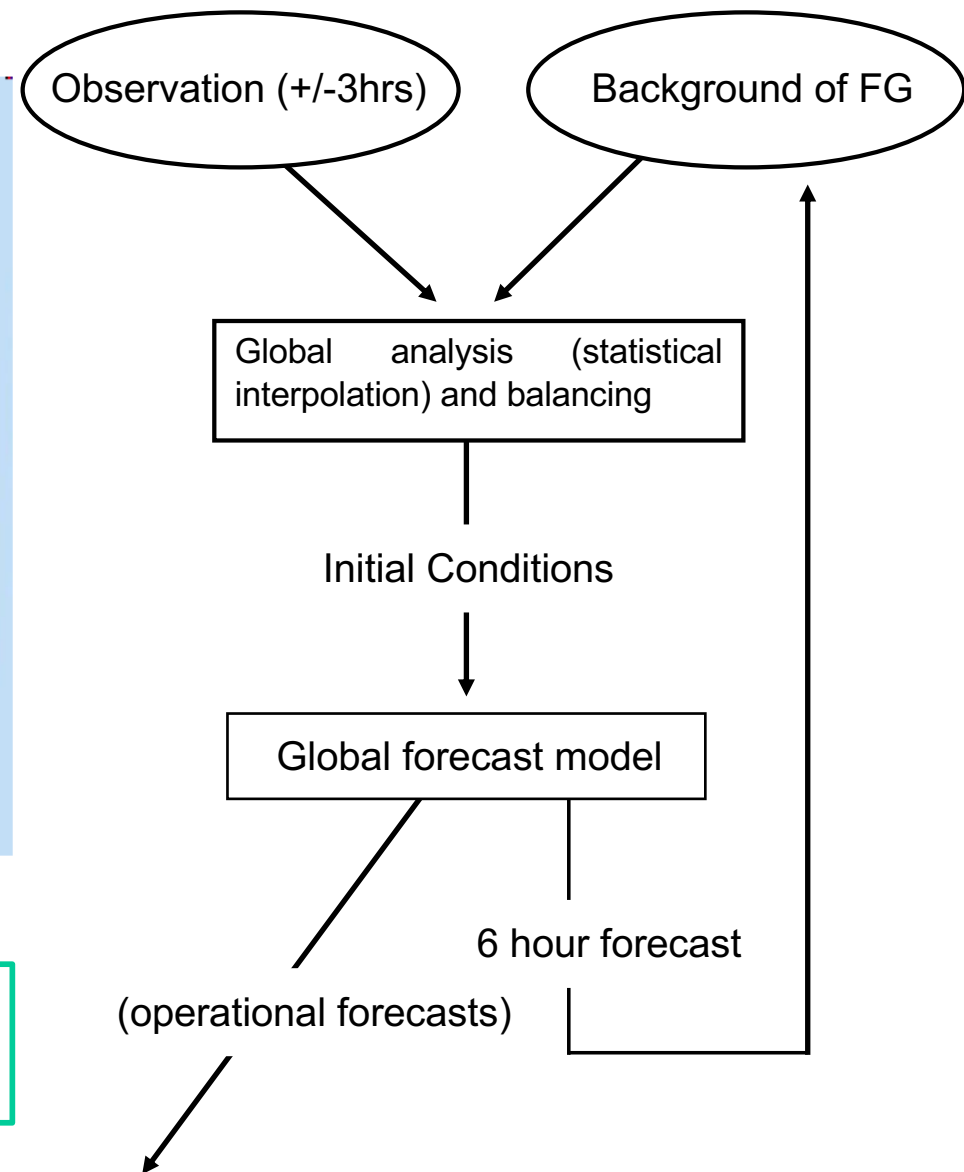


Heterogeneous in space and time....but the initial data should be on a model grid at a specific time!

Data Assimilation



Data assimilation best combines observations and a model



Model

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

Step3: Integration

Dynamics : Grid system

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

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

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

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

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

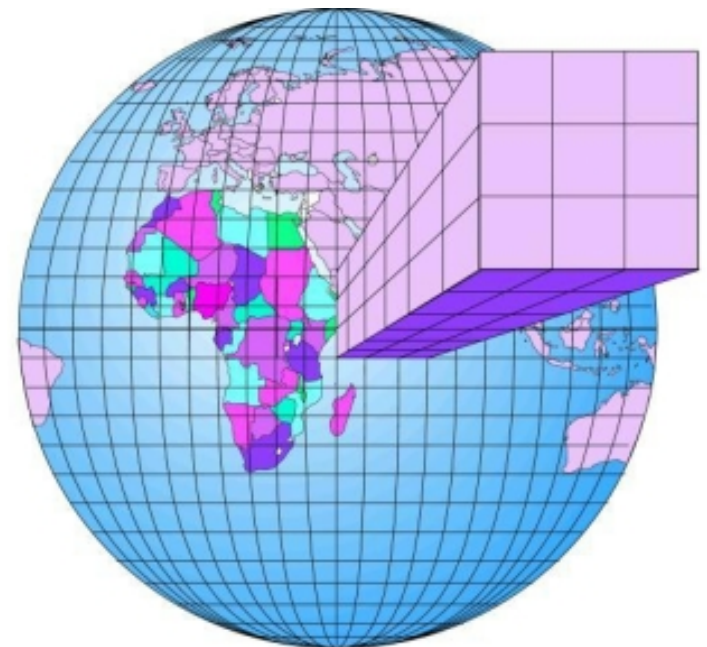
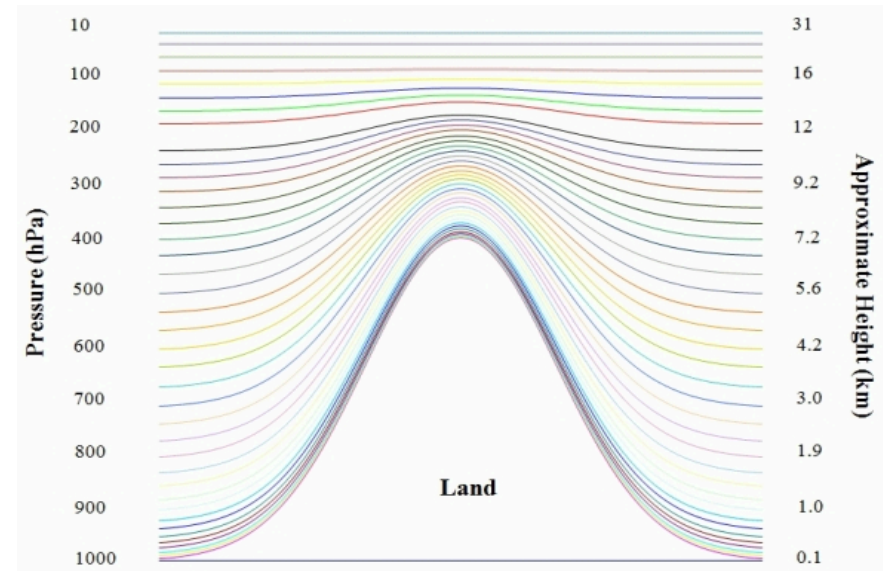
$$q_t + uq_x + vq_y + wq_z = M$$

$$p = \rho RT$$

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)

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

Finite difference method (FDM) :

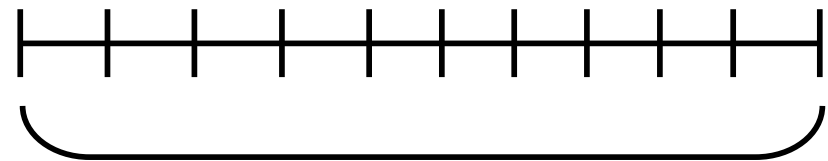
Spectral method (SPM) :

Finite element method (FEM) :

1) Finite difference (FD) method

- Specify the value at physical grids

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



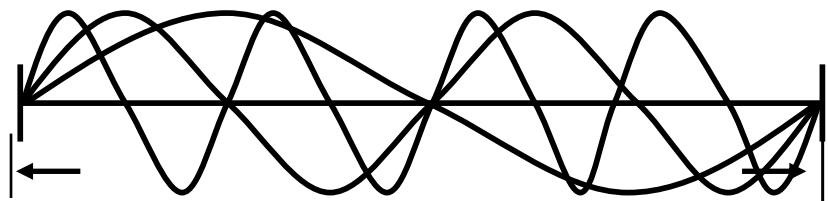
M : # of grids

2) Spectral Method

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

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

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



L

M : # of waves

* Resolution Increases

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

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

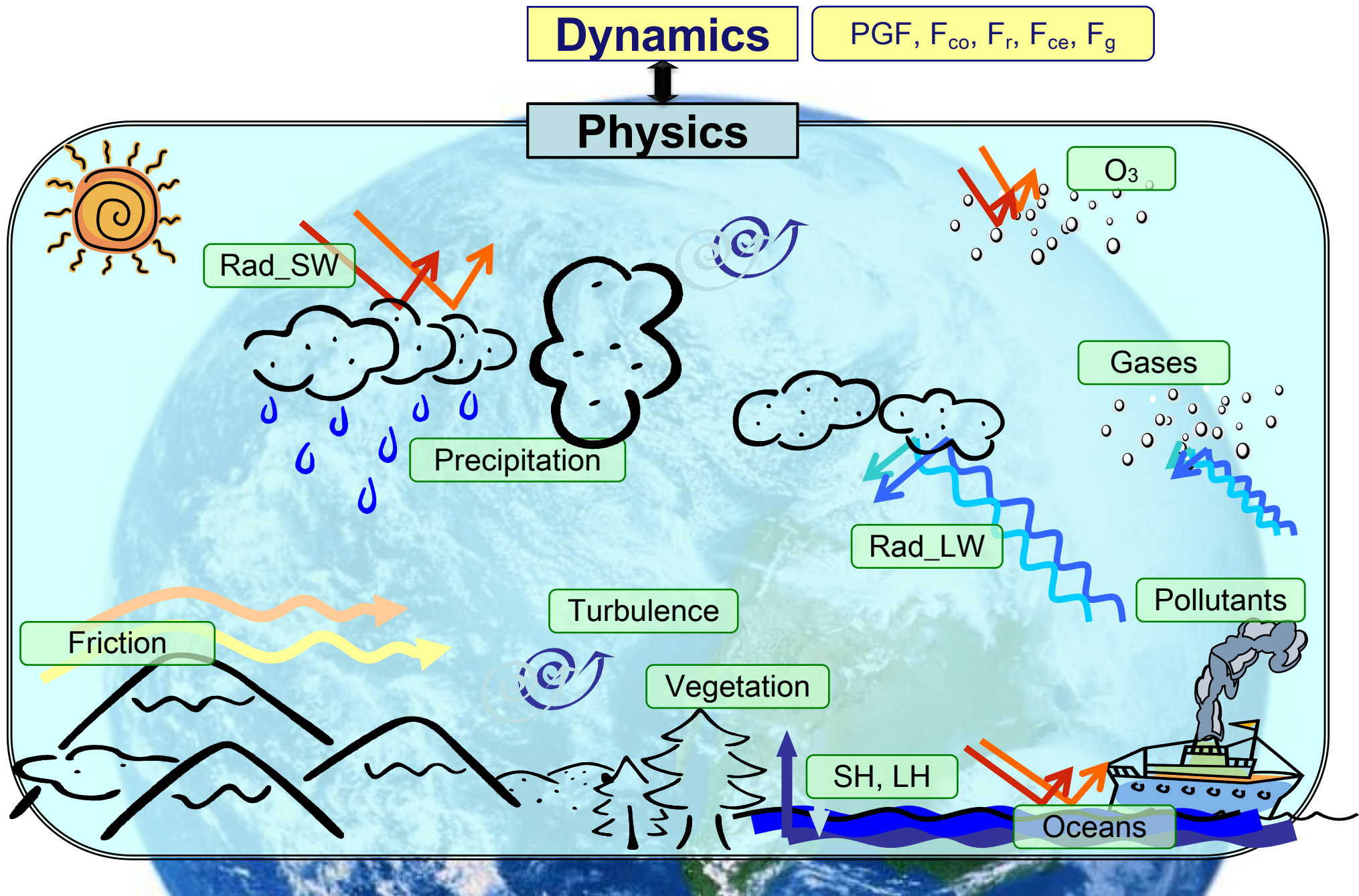
e) $\frac{u^* - u^n}{\Delta t} = F(u^n)$: $\frac{u^{n+1} - u^n}{\Delta t} = F(u^*)$: Euler-backward (Matzuno)

f) $\frac{u^{n+\frac{1}{2}*} - u^n}{\Delta t/2} = F(u^n)$: $\frac{u^{n+1*} - u^n}{\Delta t} = F\left(u^{n+\frac{1}{2}*}\right)$
 $\frac{u^{n+1} - u^n}{\Delta t} = \frac{1}{6} \left[F(u^n) + 4F\left(u^{n+\frac{1}{2}*}\right) + F(u^{n+1*}) \right]$: 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

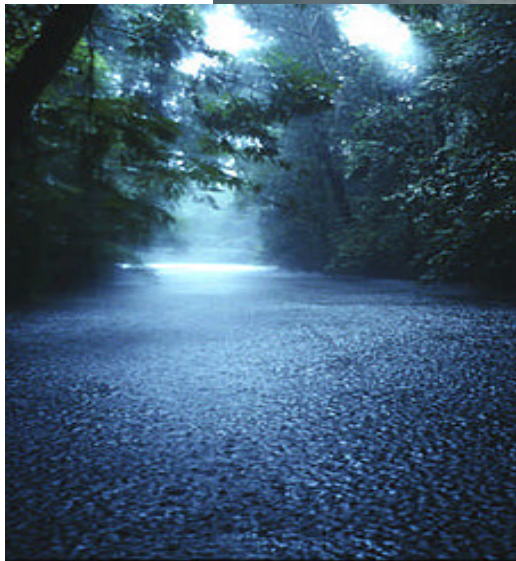
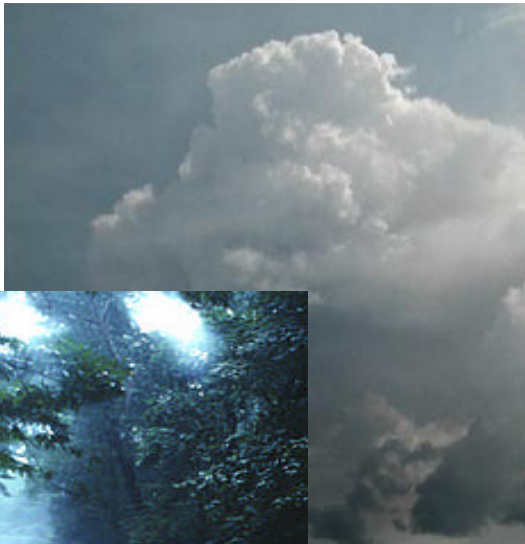


Physics module (example): Cloud and precipitation

Real
atmosphere

Theory
Formulation

Model (computer program)



```
login1
MODULE module_mp_wsm3
!
! REQUIRES: module_mp_wsm1, module_mp_wsm2
!
! compute internal functions
!
cpmcal(x) = cpd*(1.-max(x,qmin))+max(x,qmin)*cpv
!
! compute the minor time steps.
!
loops = max(nint(delt/dtoldcr),1)
dtold = delt/loops
if(delt.le.dtoldcr) dtold = delt
do loop = 1,loops
!
! initialize the large scale variables
!
do i = its, ite
  mstep(i) = 1
  flgcid(i) = .true.
enddo
!
do k = kts, kte
  CALL vsrec(tvec1(its),den(its,k),ite -its+1)
  do i = its, ite
    tvec1(i) = tvec1(i)*den0
  enddo
  CALL vssqrt(denfac(its,k),tvec1(its),ite -its+1)
enddo
!
cvap = cpv
hvap=xlv0
hsub=xls
ttp=t0c+0.01
dldt=cvap-cliq
xa=-dldt/rv
xb=xa+hvap/(rv*ttp)
dldti=cvap-cice
xai=-dldti/rv
xbi=xai+hsub/(rv*ttp)
do k = kts, kte
  do i = its, ite
    tr=ttp/t(i,k)
    if(t(i,k).lt.ttp) then
      qs(i,k) = psat*(exp(log(tr)*(xai)))*exp(xbi*(1.-tr))
    else
      qs(i,k) = psat*(exp(log(tr)*(xa)))*exp(xb*(1.-tr))
    endif
    qs0(i,k) = psat*(exp(log(tr)*(xa)))*exp(xb*(1.-tr))
    qs0(i,k) = (qs0(i,k)-qs(i,k))/qs(i,k)
    qs(i,k) = ep2 * qs(i,k) / (p(i,k) - qs(i,k))
    qs(i,k) = max(qs(i,k),qmin)
    rh(i,k) = max(q(i,k) / qs(i,k),qmin)
  enddo
enddo
!
! Spe
CONTAINS
SUBROUTINE
```

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/dtold
    if(t(i,k).ge.t0c) then

=====
warm rain processes
- follows the processes in RH83 and LFO except for autoconversion
=====

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)/dtold)
    endif

pracr: 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(pacr*rslope3(i,k)*rslopeb(i,k)
        *qci(i,k)*denfac(i,k),qci(i,k)/dtold)
    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)/dtold)
        pres(i,k) = max(pres(i,k),satdt/2)
      else
        pres(i,k) = min(pres(i,k),satdt/2)
      endif
    endif
  endif
else
  endif
endif

```

$T > 0^\circ\text{C}$

Autoconversion

$$P_{aut1} = \min \left(\frac{0.104 g E_C \rho^{\frac{4}{3}}}{\mu (N_c \rho_w)^{\frac{1}{3}}} q_c^{\frac{7}{3}}, \frac{q_c}{dt} \right)$$

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



Dynamics



Physics

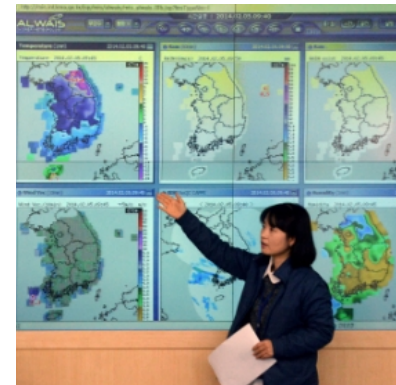
Software



Data assimilation



Driver



Forecaster

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

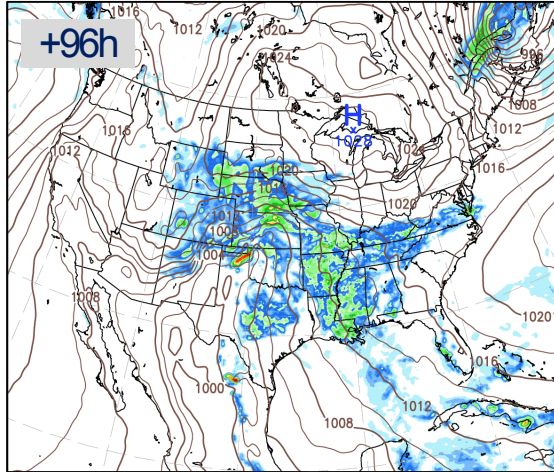
Initial data-> FORECAST	Forcing → RESPONSE
NWP : upto 2 weeks	GCM (General circulation model)

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

KIM (Korean Integrated Model)

KIM 3.0 H4DEV ne240 L50
Surface

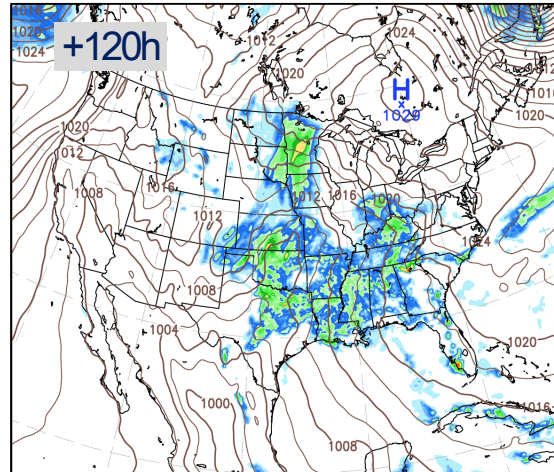
Init : 20170516 0000UTC
Valid : 20170520 0000UTC



0.1 2 5 10 20 40 80 140 200 (mm)
Solid line : Sea Level Pressure (hPa)
Shaded : 6 hr Accumulated precipitation (mm)

KIM 3.0 H4DEV ne240 L50
Surface

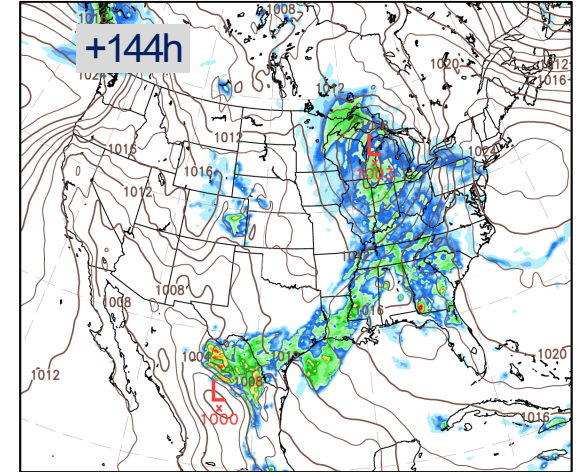
Init : 20170516 0000UTC
Valid : 20170521 0000UTC



0.1 2 5 10 20 40 80 140 200 (mm)
Solid line : Sea Level Pressure (hPa)
Shaded : 6 hr Accumulated precipitation (mm)

KIM 3.0 H4DEV ne240 L50
Surface

Init : 20170516 0000UTC
Valid : 20170522 0000UTC



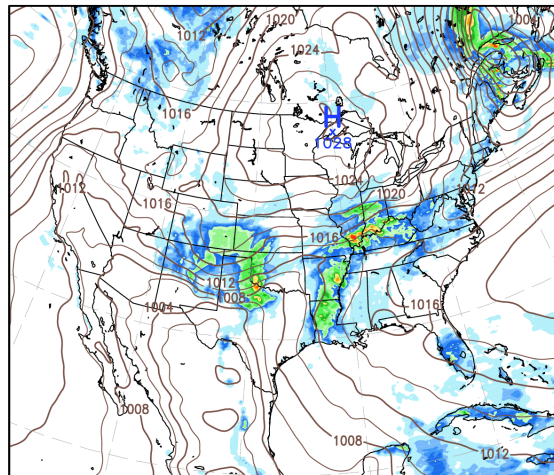
0.1 2 5 10 20 40 80 140 200 (mm)
Solid line : Sea Level Pressure (hPa)
Shaded : 6 hr Accumulated precipitation (mm)

Snap shots

KMA UM

UM GDAPS N768 L70
Surface

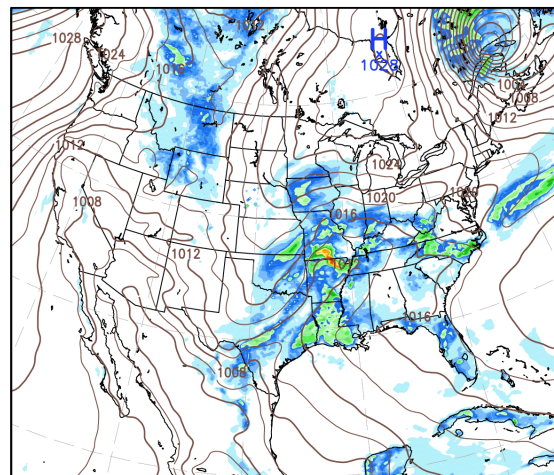
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UM GDAPS N768 L70
Surface

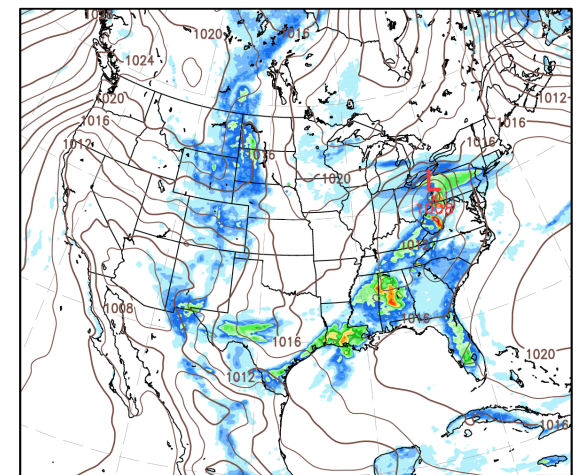
Init : 20170516 0000UTC
Valid : 20170521 0000UTC



0.1 2 5 10 20 40 80 140 200 (mm)
Solid line : Sea Level Pressure (hPa)
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UM GDAPS N768 L70
Surface

Init : 20170516 0000UTC
Valid : 20170522 0000UTC



0.1 2 5 10 20 40 80 140 200 (mm)
Solid line : Sea Level Pressure (hPa)
Shaded : 6 hr Accumulated precipitation (mm)

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

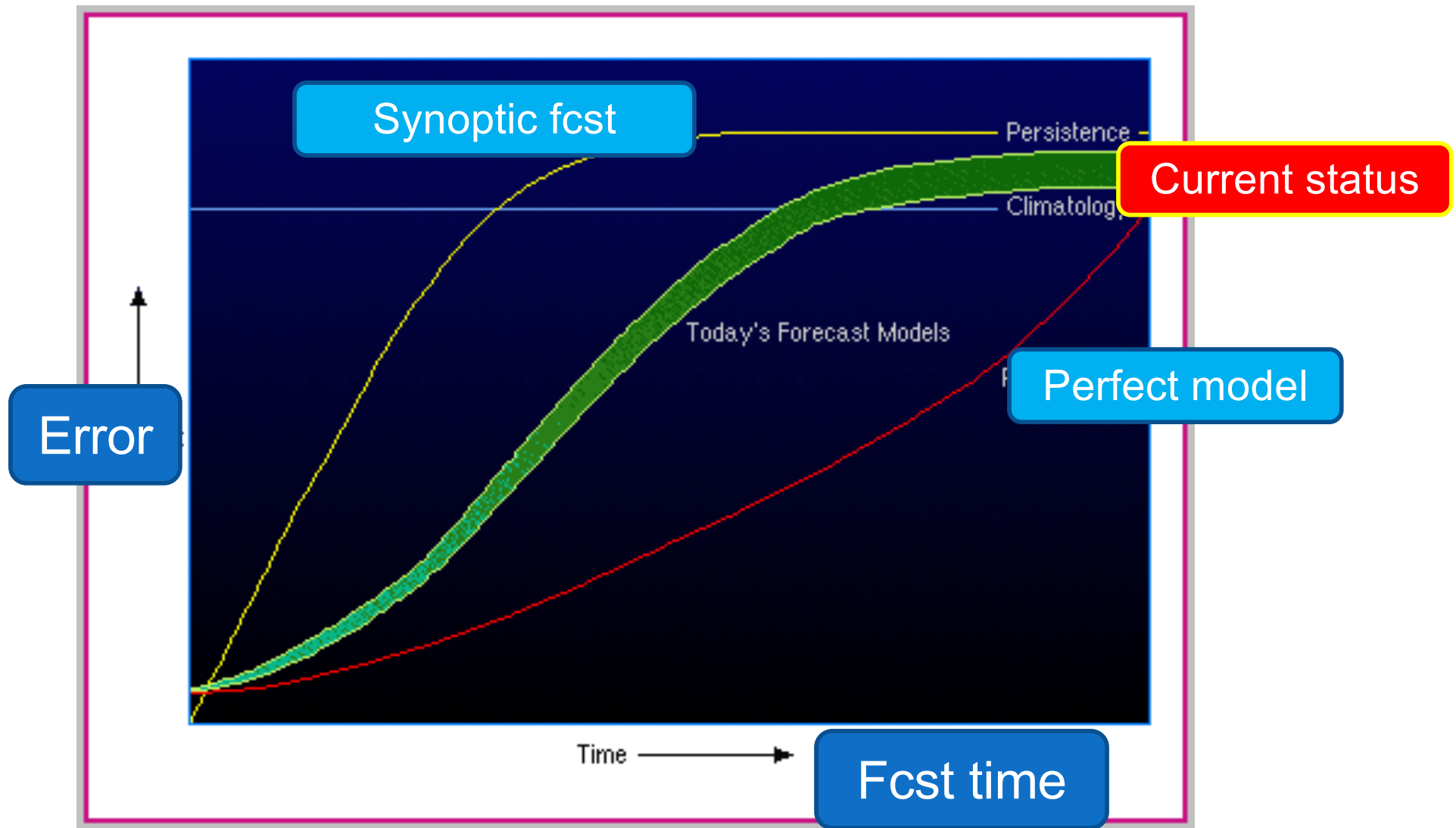


Round-off error -> cause of non-periodicity

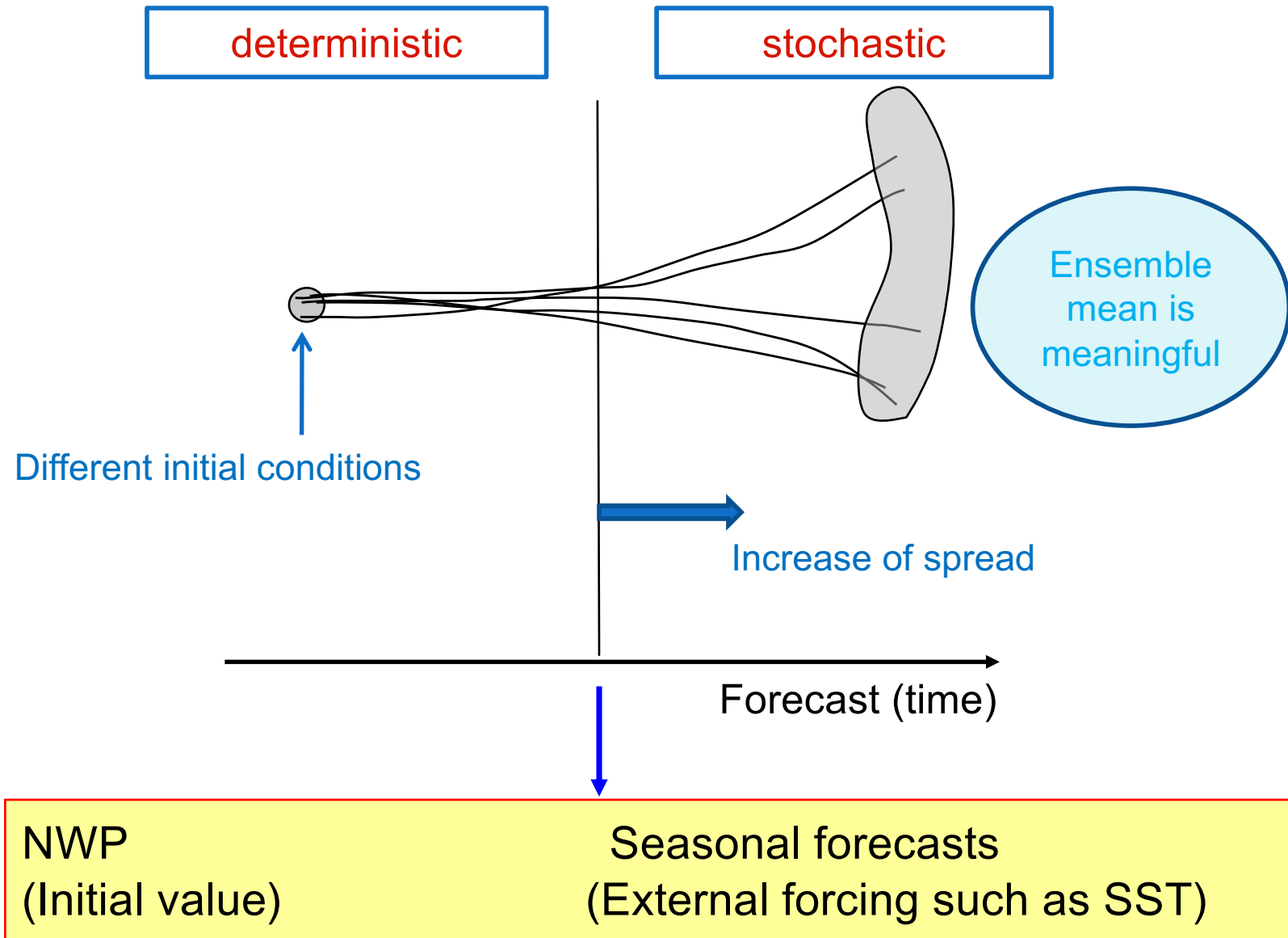


Chaos theory– two weeks for NWP

Predictability : Atmosphere is chaotic

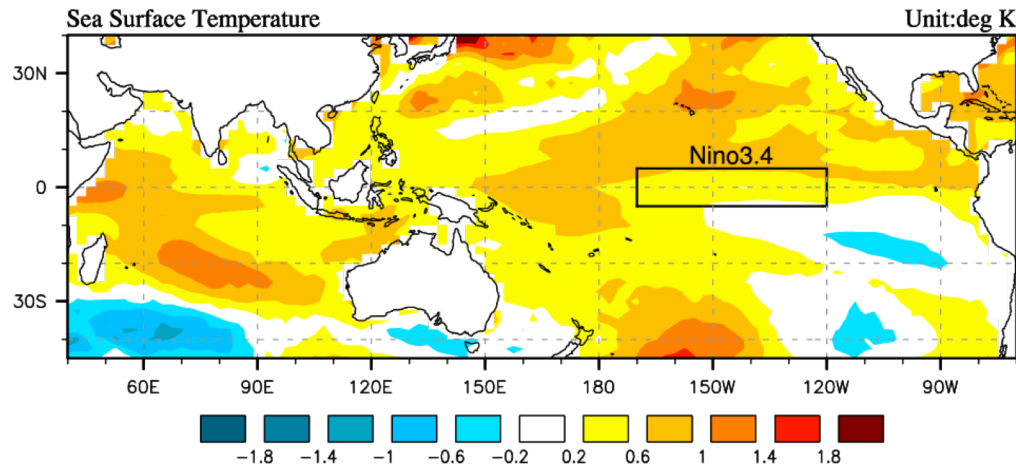


Ensemble forecasts : Seasonal and beyond



Ensemble forecasts : Seasonal and beyond

SST Anomaly for JFM 2020

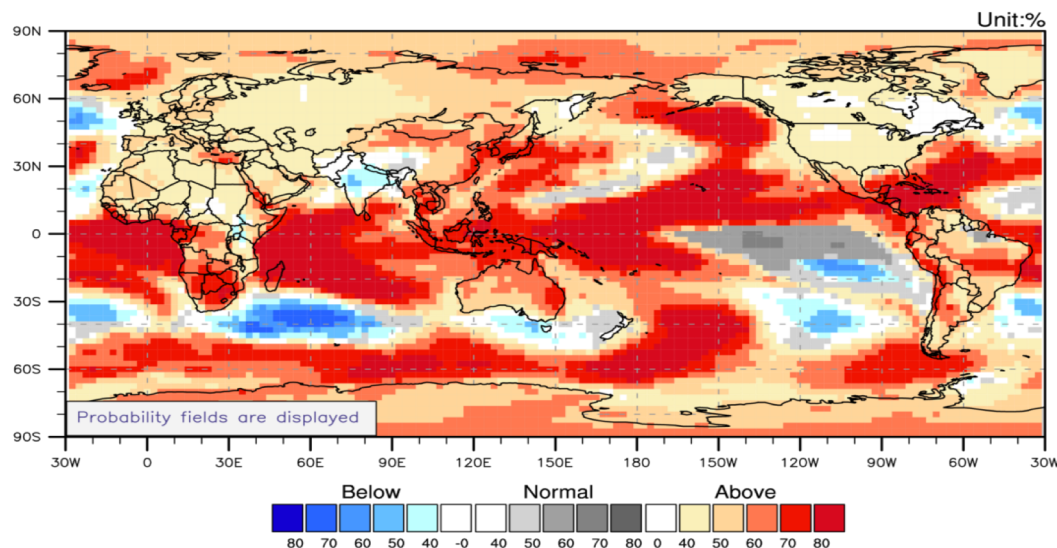


Issued: 20 Dec, 2019

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SST anomaly in
JFM 2020

Temperature at 2m for January-March 2020



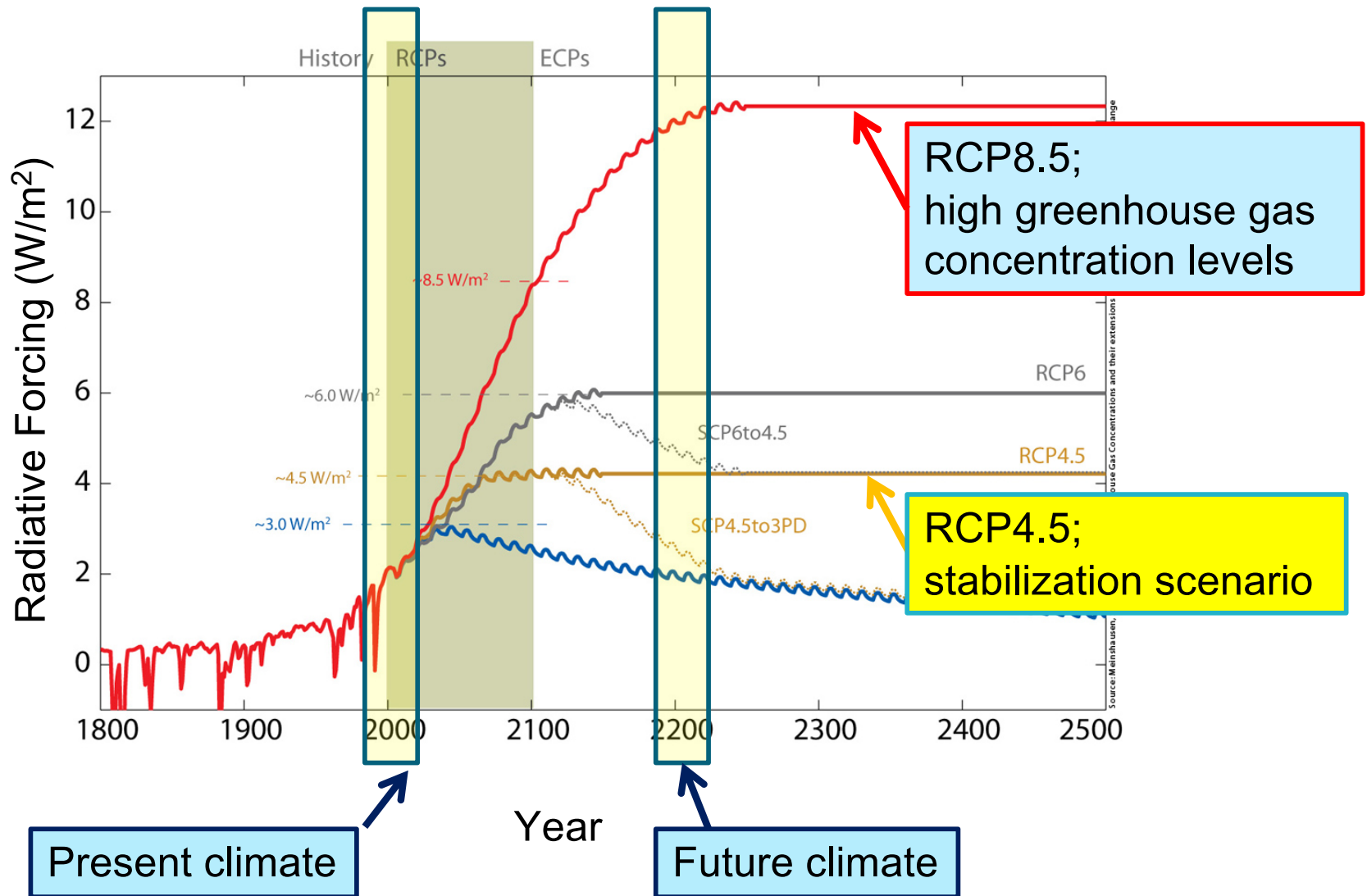
Issued: 20 Dec, 2019

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Temperature anomaly
in JFM 2020

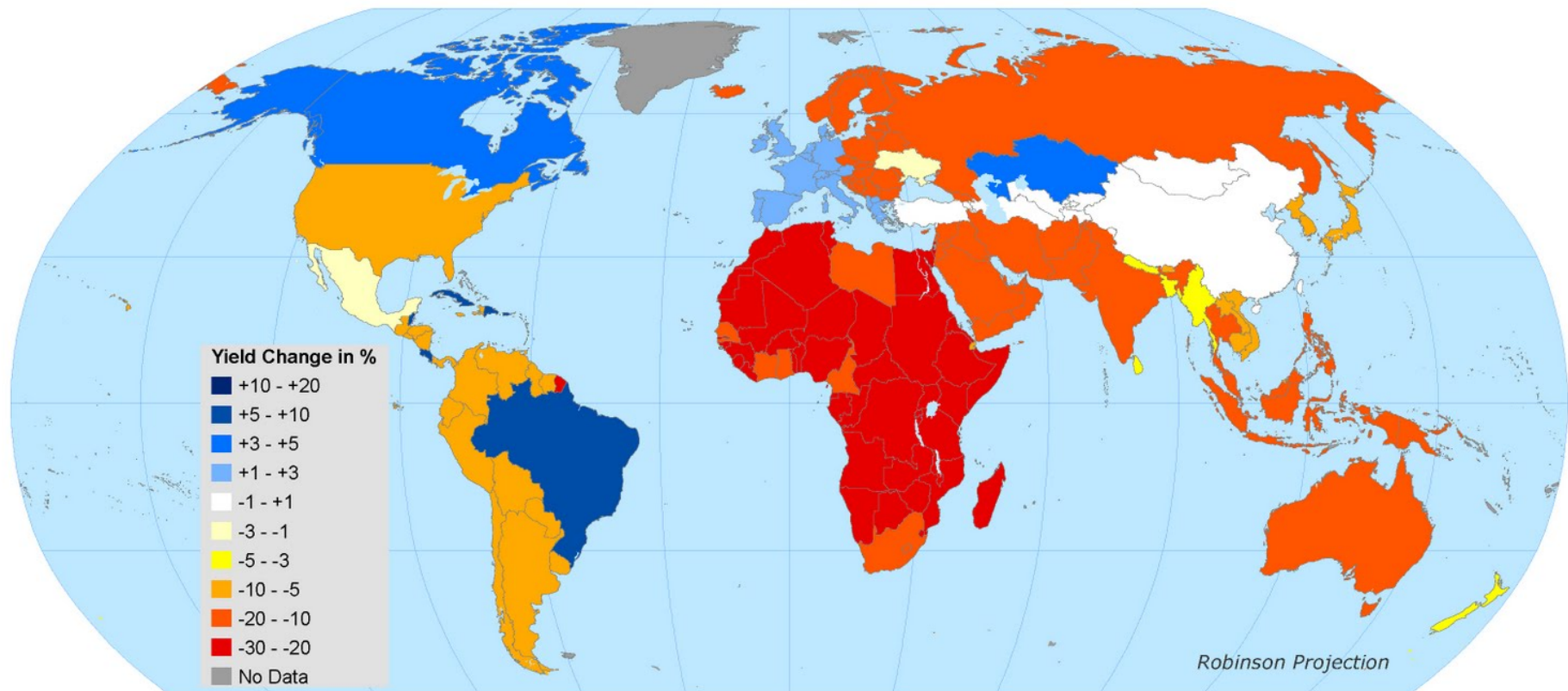
Climate prediction : For given representative change pathway (RCP) scenarios,

Climate changes = future minus present



Climate prediction : For given RCP scenarios

Effects of Climate Change on Global Food Production



Projected Maize Yield Change in %
1970-2000 Baseline to 2080, SRES A1F Scenario



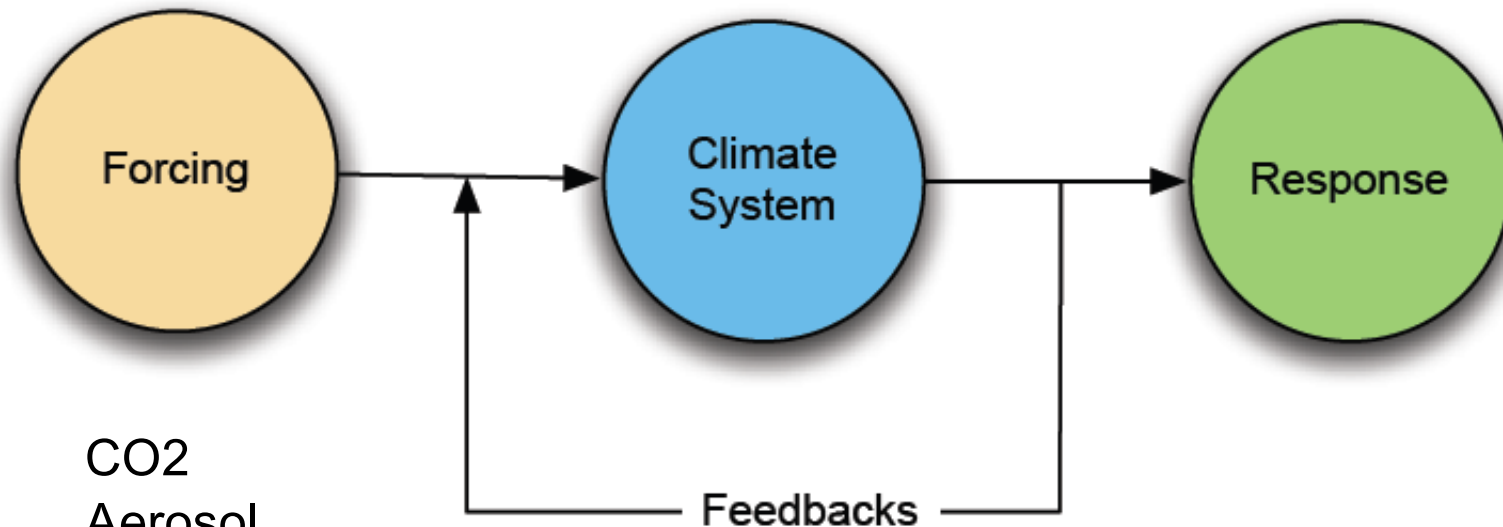
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Source: Iglesias, A., and C. Rosenzweig. 2010. Effects of Climate Change on Global Food Production. Data available at <http://sedac.ciesin.columbia.edu/mva/croplimate/>
Publish Date: March 2010

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Climate prediction : Climate system sensitivity



CO₂
Aerosol
Volcanic

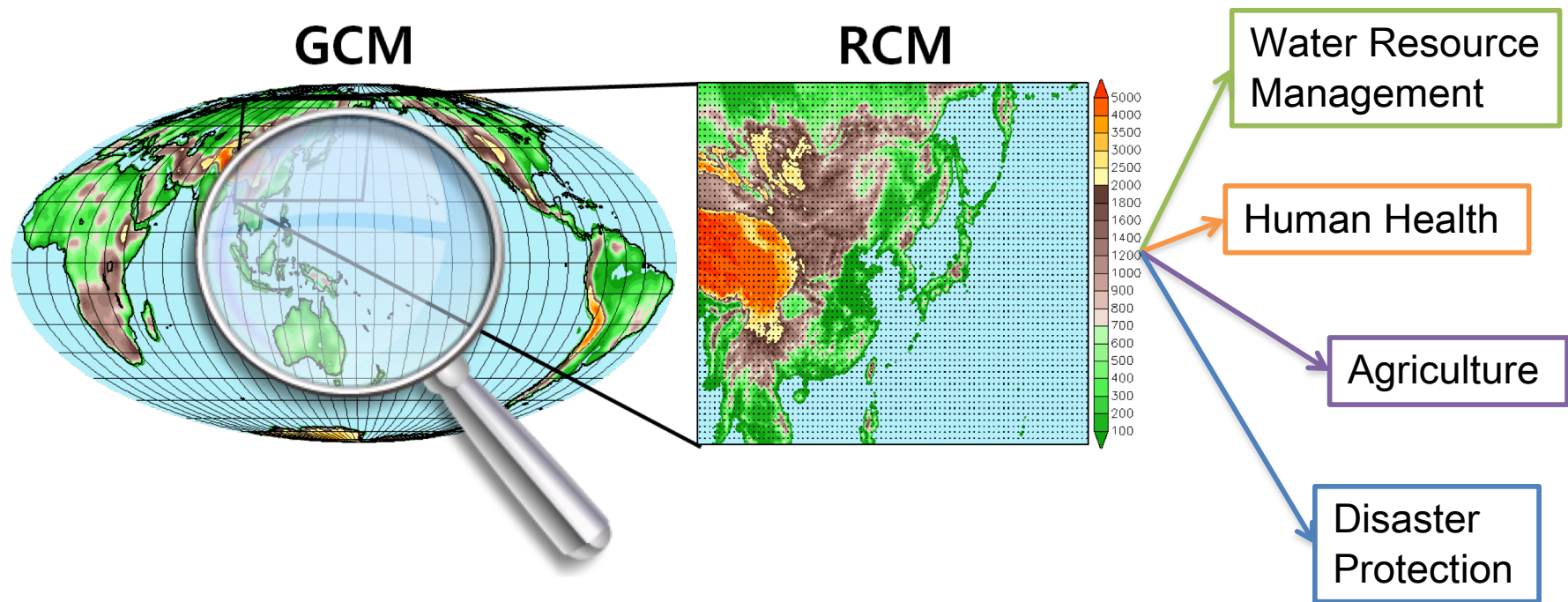
Water vapor feedback
Ice-albedo feedback
Vegetation feedbacks
Cloud (radiative) feedback
(Great debate!, mostly still uncertain)

...

NWP / GCM : models could be unified.

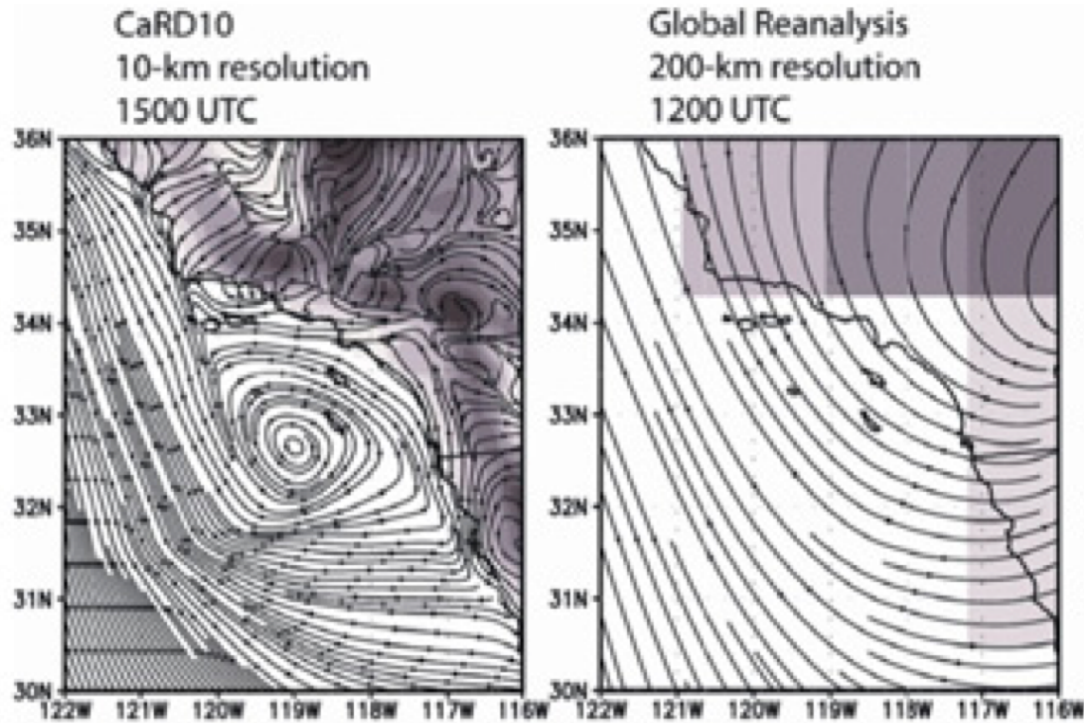
Global vs Regional

Regional modeling : need for applications



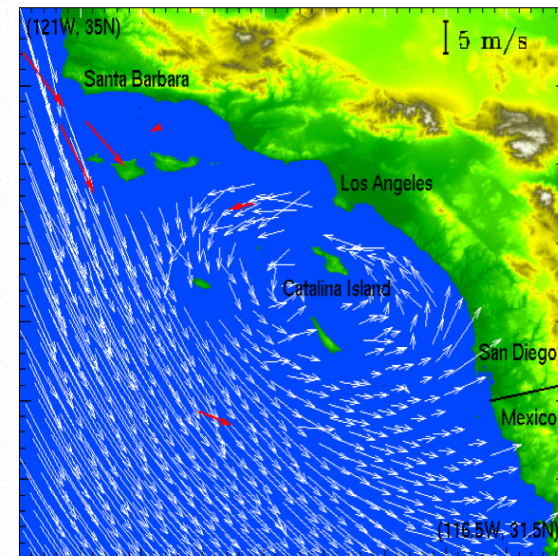
Regional model is a magnifying glass

High resolution benefit ? ---- Very clear !



10 km

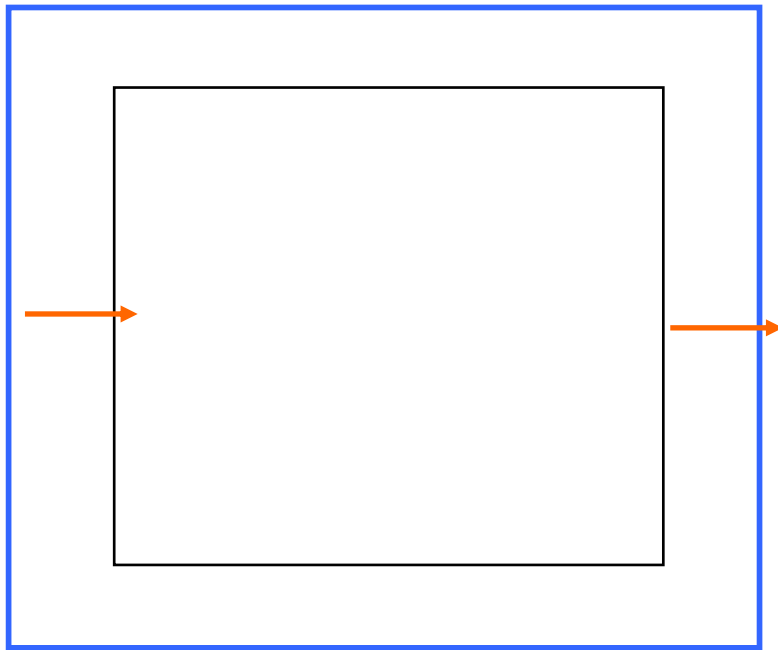
200 km



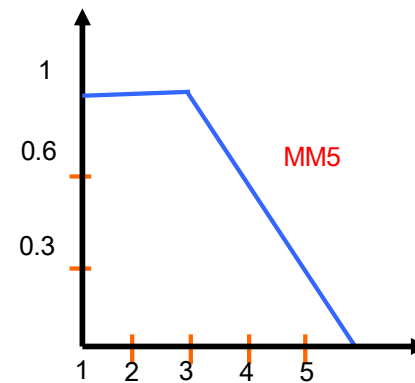
Observed

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

Buffer zone



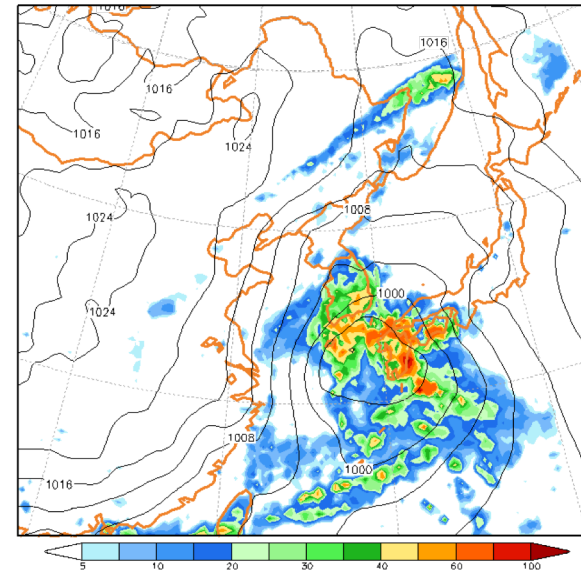
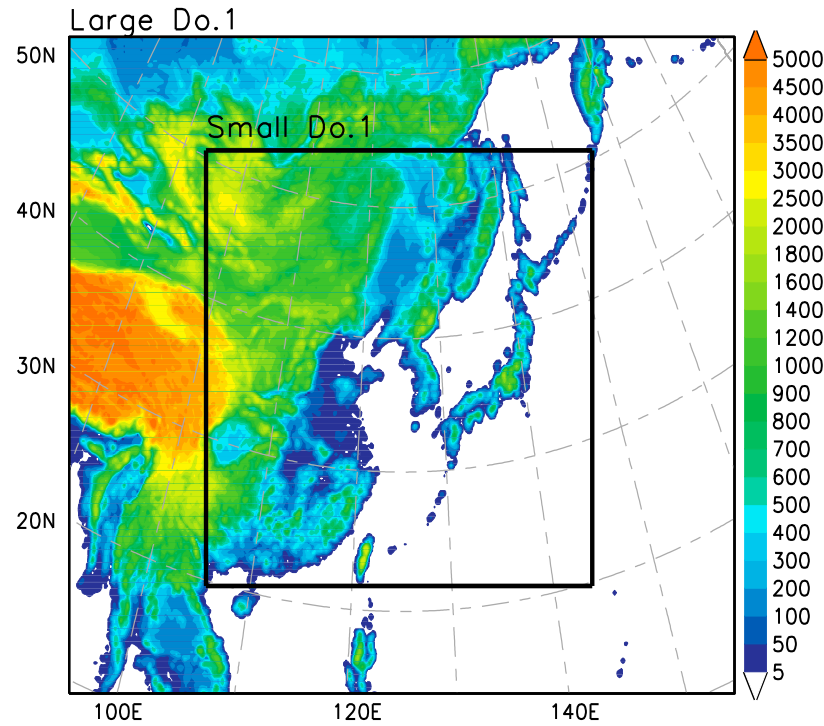
$F(n)$: weighting of global



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

So, empirical

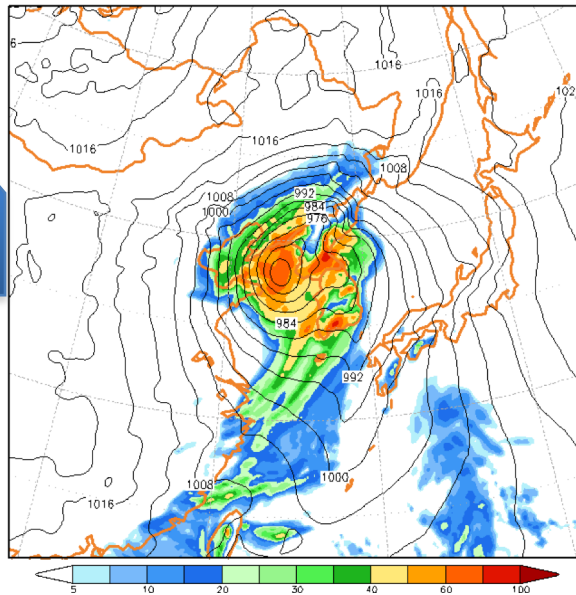
Domain size sensitivity : A mid-latitude cyclone



Observed

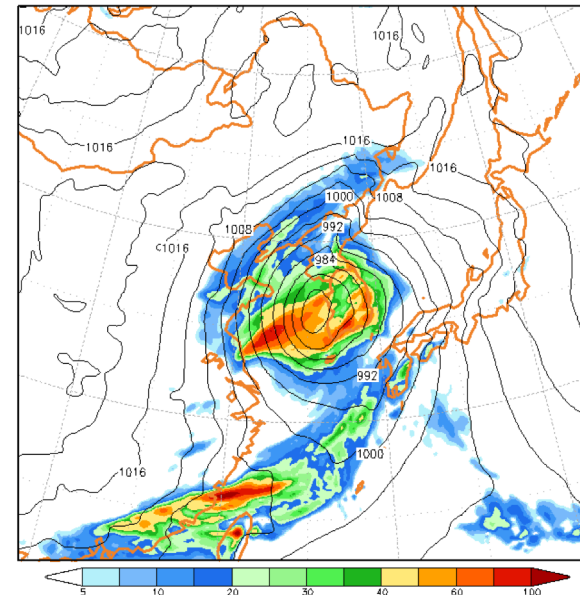
Large

Away from OBS
But more freedom

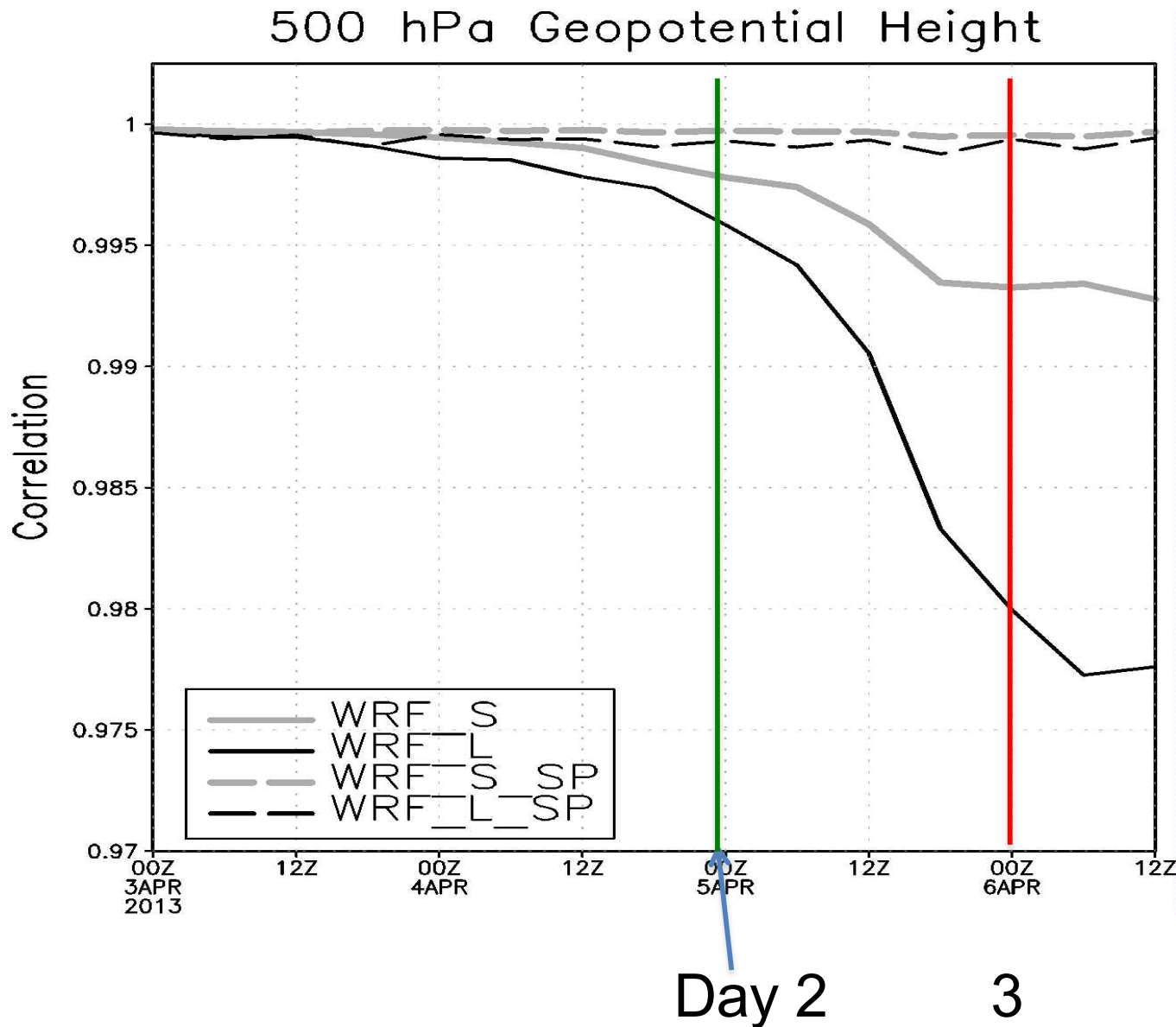


Small

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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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.