區域波譜模式(RSM)的動力框架與改進—應用高解析度地形資料及非疊代分維半拉格朗日法(NDSL)

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Central Weather Bureau

RSM: Regional Spectral Model (hydrostatic version)

MSM: Mesoscale Spectral Model (non-hydrostatic version)

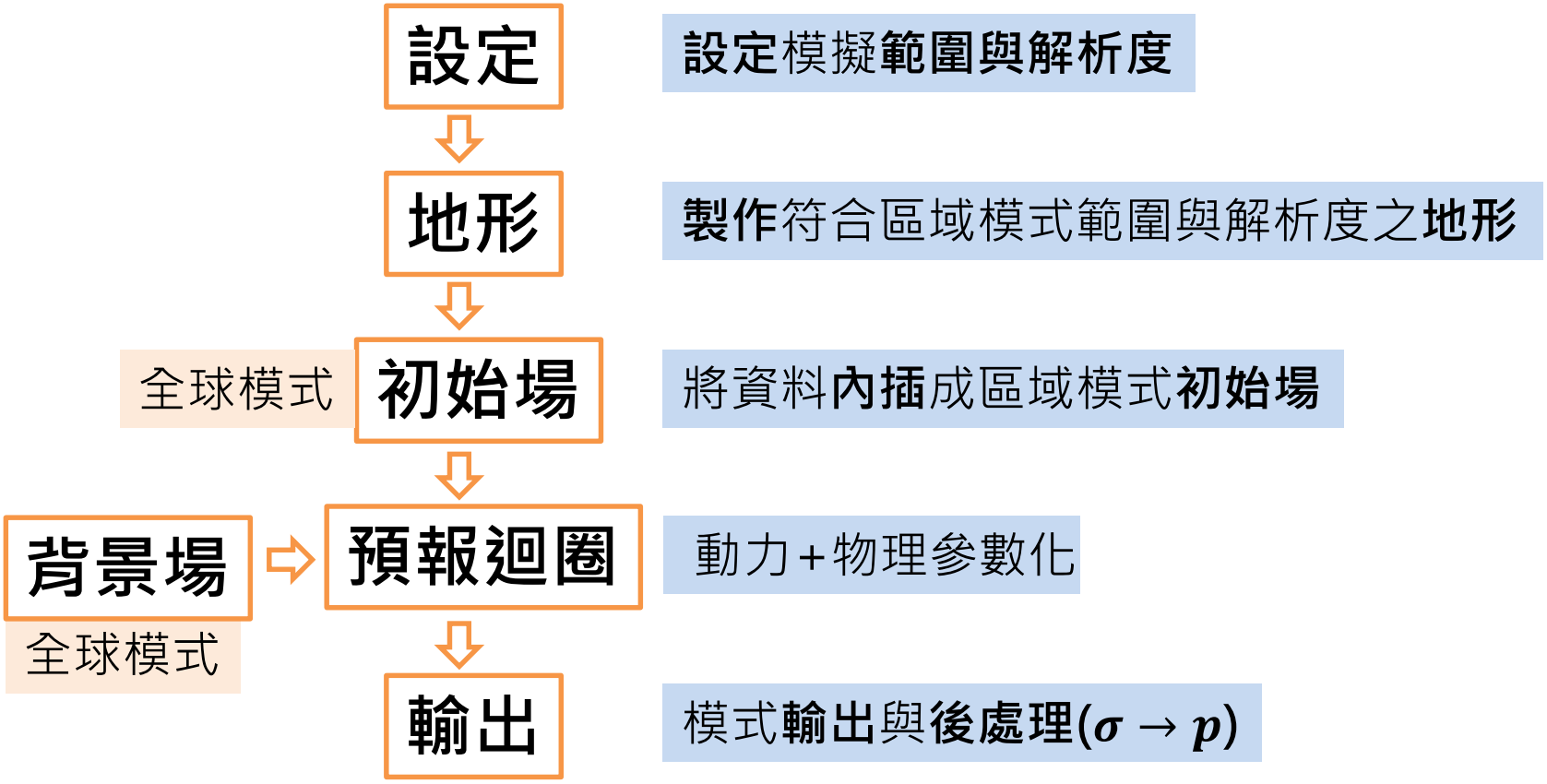
區域波譜模式(RSM/MSM)簡介

RSM/MSM

- Double Fourier Series
- Perturbation Method (perturbation filtering model)
  - satisfy zero boundary condition
  - better B.C. for semi-implicit scheme
  - keep large scale (over domain size) properties from global model
  - 4-th order horizontal diffusion
  - time filter
  - implicit lateral boundary relaxation

(Juang and Kanamitsu, 1994)

RSM/MSM架構


設定
設定模擬範圍與解析度
地形
製作符合區域模式範圍與解析度之地形
全球模式
初始場
將資料內插成區域模式初始場
背景場
全球模式
預報迴圈
動力+物理參數化
輸出
模式輸出與後處理(σ → p)

應用

高解析度地形資料

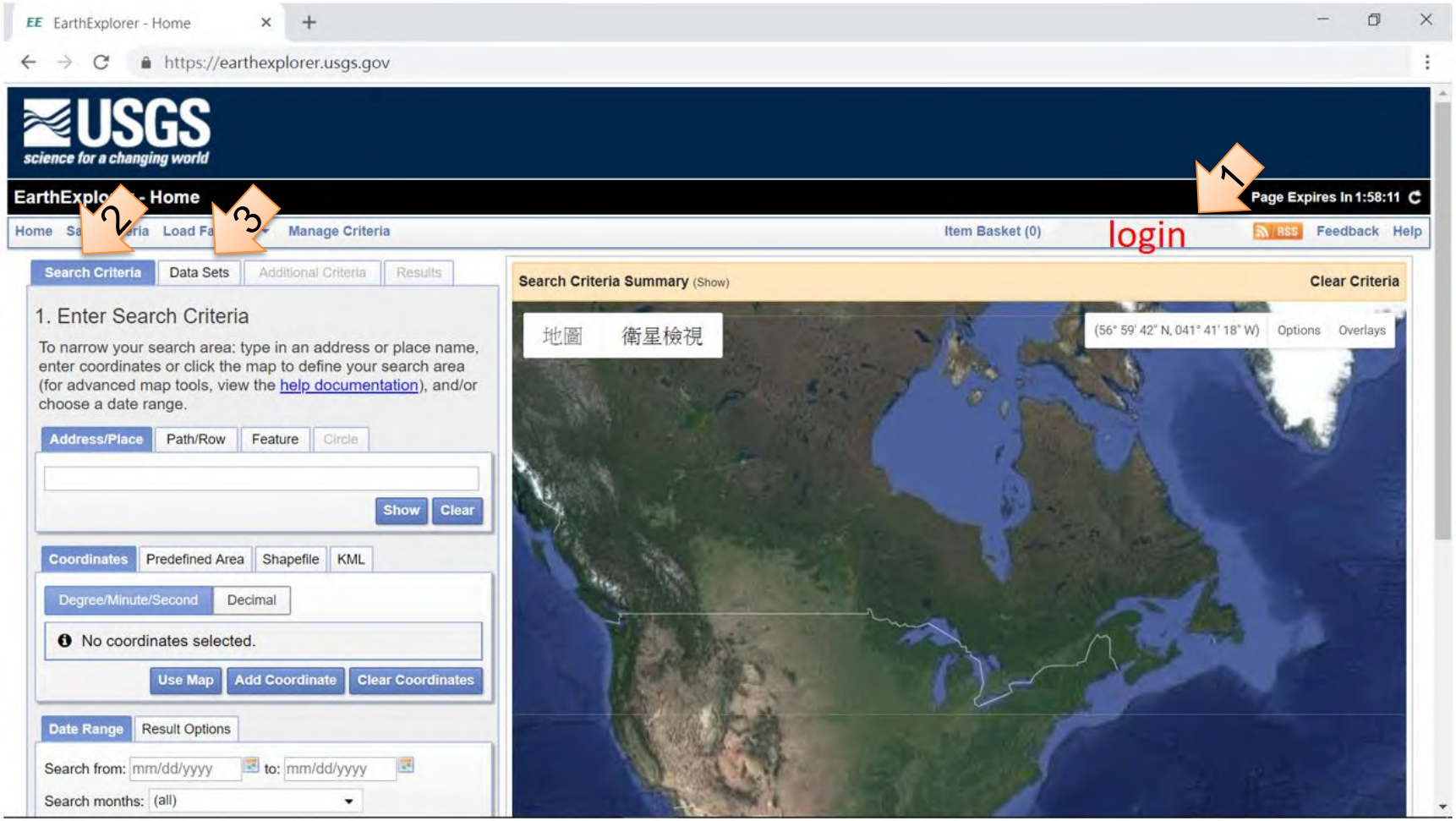
SRTM (SHUTTLE RADAR TOPOGRAPHY MISSION)

SRTM (Shuttle Radar Topography Mission)

- **SRTM 1 Arc-Second Global elevation data** offer worldwide coverage of void filled data at a resolution of **1 arc-second (30 meters)** and provide open distribution of this high-resolution global data set. Some tiles may still contain voids. Users should check the coverage map in EarthExplorer to verify if their area of interest is available. Please note that tiles above 50° north and below 50° south latitude are sampled at a resolution of 2 arc-second by 1 arc-second.

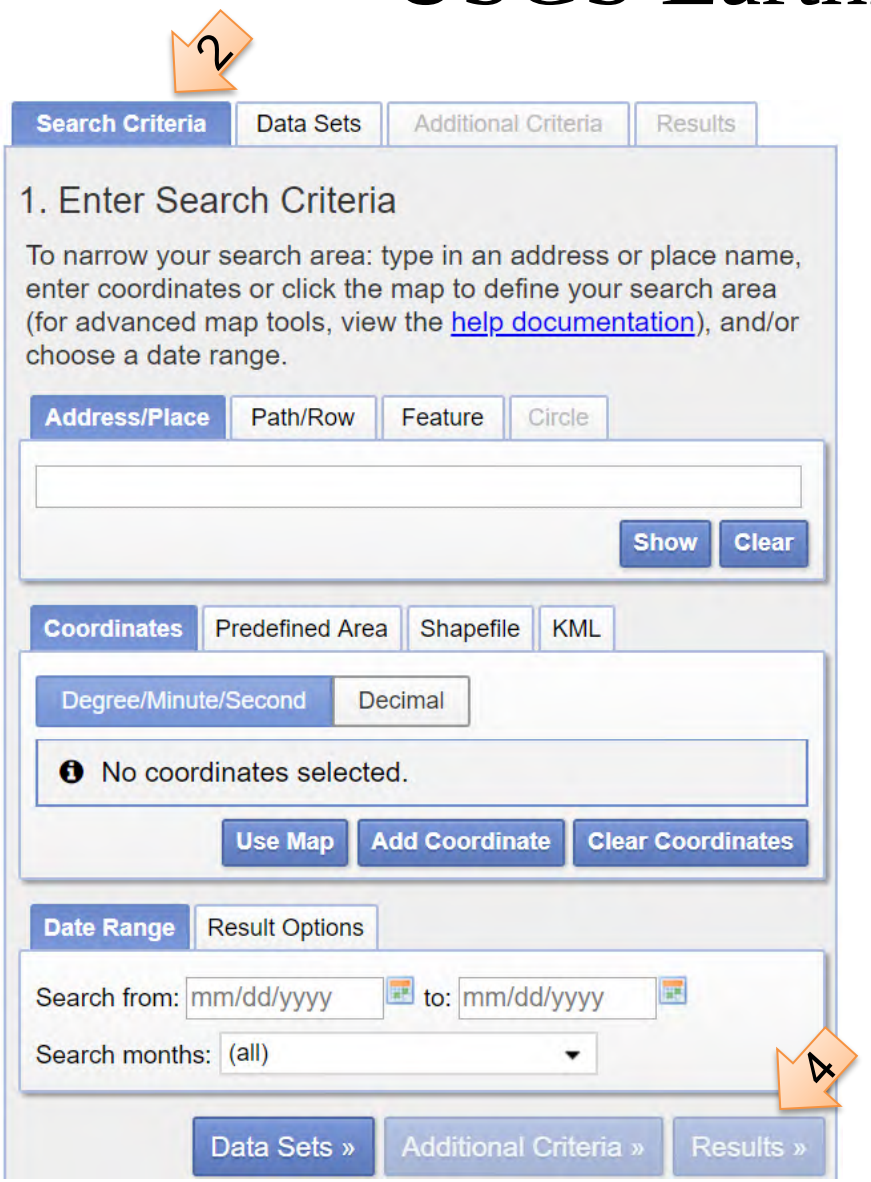
- source: https://lta.cr.usgs.gov/SRTM1Arc
- data accessible at: https://earthexplorer.usgs.gov/

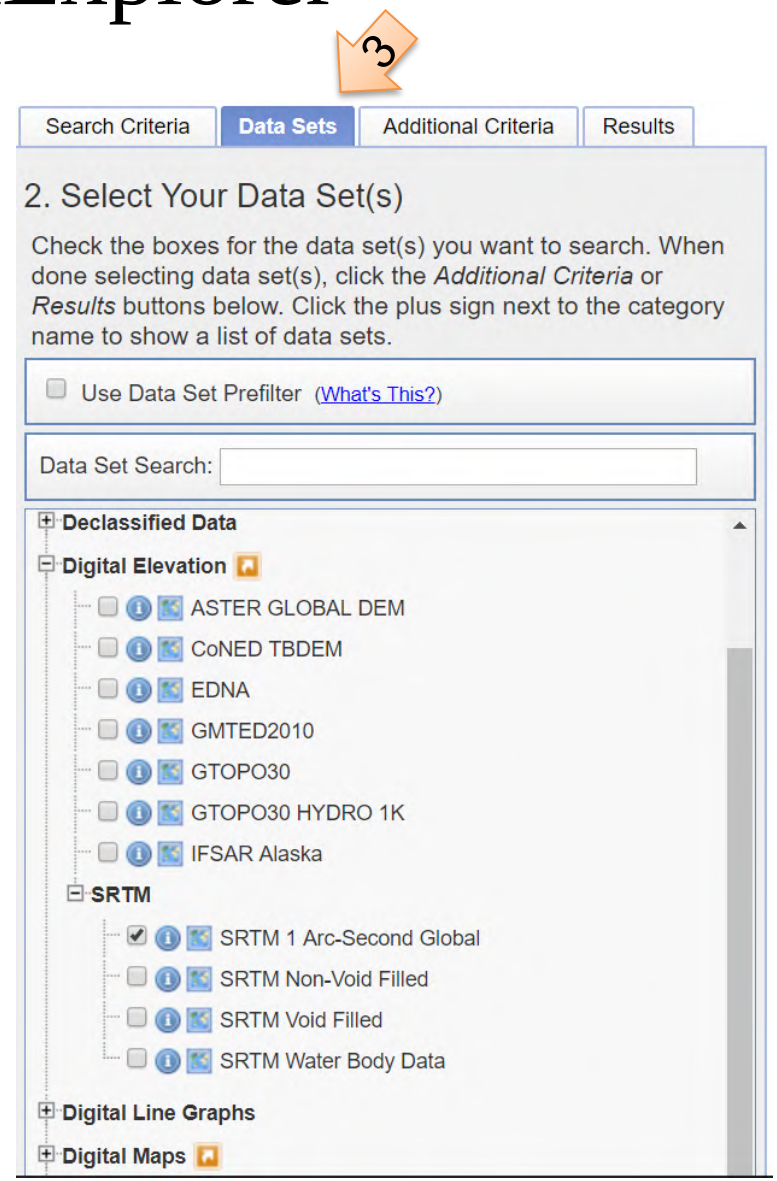
USGS EarthExplorer



link: https://earthexplorer.usgs.gov/

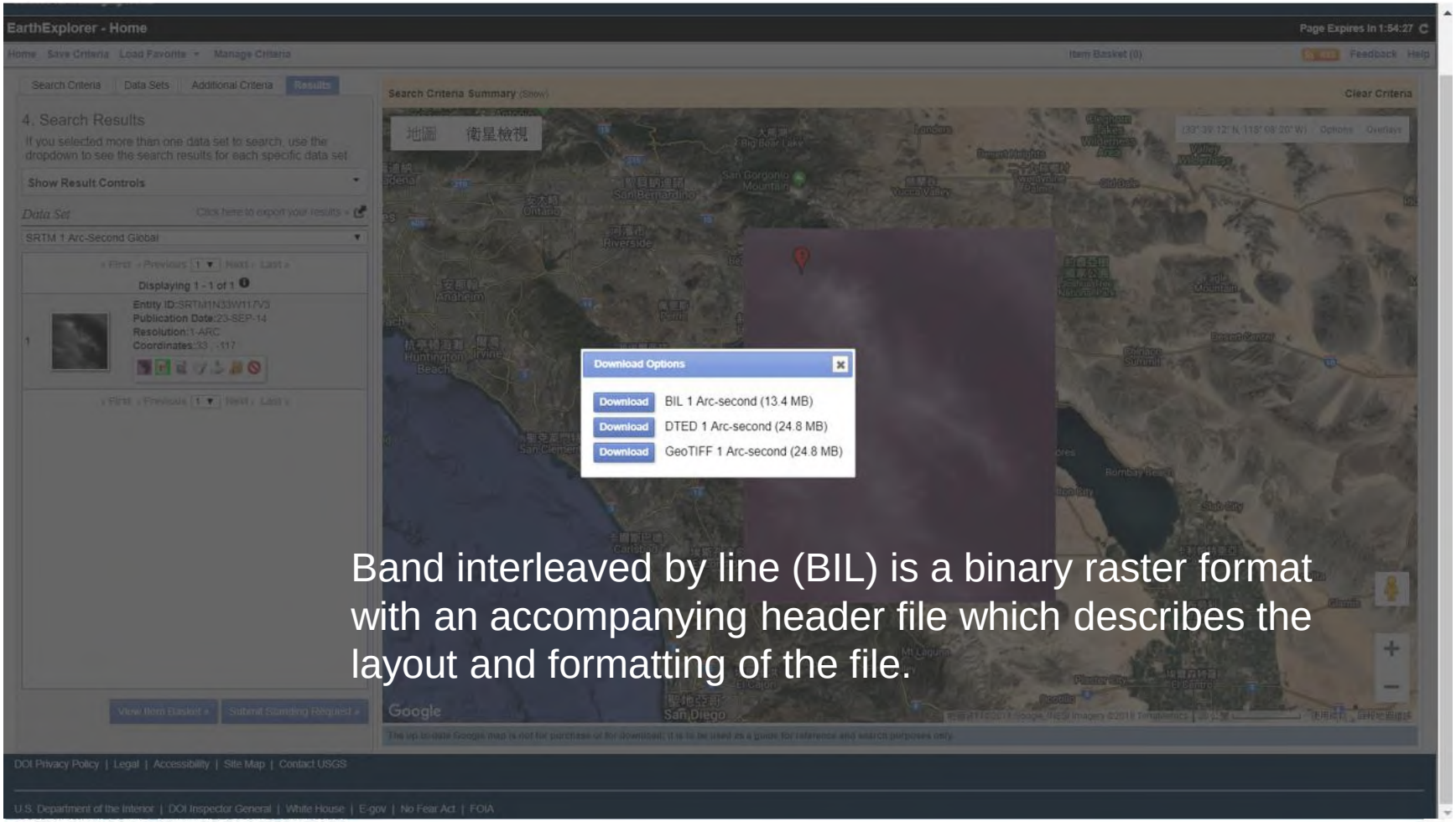
USGS EarthExplorer





link: https://earthexplorer.usgs.gov/

USGS EarthExplorer

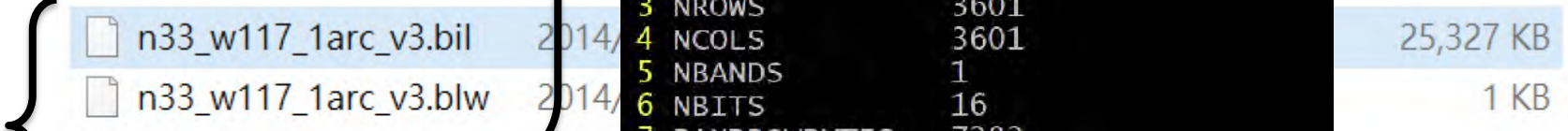


Band interleaved by line (BIL) is a binary raster format with an accompanying header file which describes the layout and formatting of the file.

link: https://earthexplorer.usgs.gov/

Data Format and How to Read

n33_w117_1arc_v3_bil.zip




```
BYTEORDER       I
LAYOUT          BIL
NROWS           3601
NCOLS           3601
NBANDS          1
NBITS           16
BANDROWBYTES    7202
TOTALROWBYTES   7202
PIXELTYPE       SIGNEDINT
ULXMAP          -117
ULYMAP          34
XDIM            0.00027777777777777778
YDIM            0.00027777777777777778
NODATA          -32767
```

1 arc. second = $1'' = \left(\frac{1}{60\times60}\right)^{o} = 0.00027777777777777778$

Read file by Fortran:

```
      integer*2, allocatable :: ifile(:,:)
      allocate (ifile(3601,3601),stat=ierr)

      open(21,file='n33_w117_1arc_v3_bil',form='unformatted'      &
     &   ,access='direct',convert='LITTLE_ENDIAN',recl=25934402)
      read(21,rec=1) ((ifile(l,m),l=1,3601),m=1,3601)
      close(21)

      deallocate(ifile)
```

$3601 \times 3601 \times 2 = 25934402$

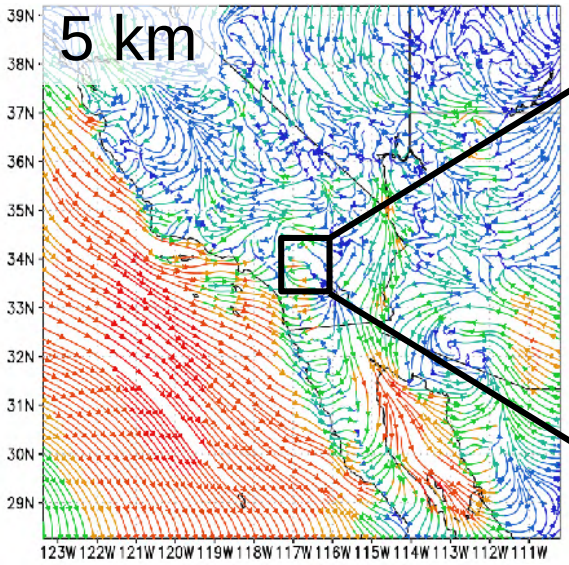
Implement into RSM/MSM

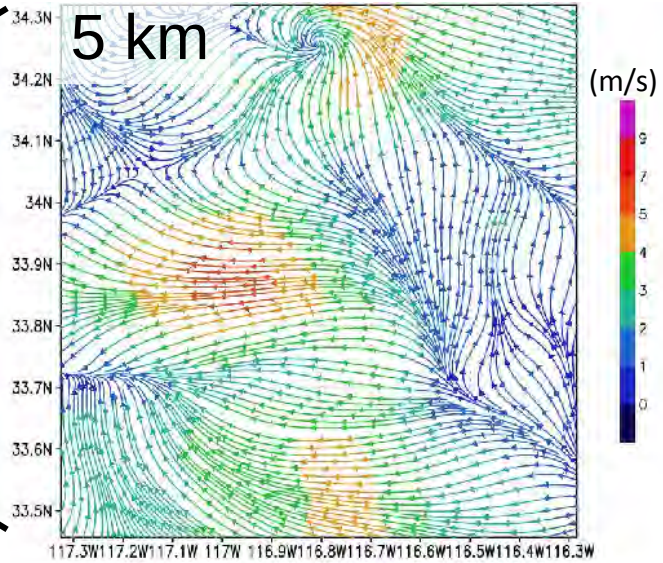
- **Case: Esperanza Fire**
- MSM setting:
  - Initial time:
    2006 Oct. 25_12 UTC
  - Simulation time: 96 hours
    (2006 Oct. 29_12 UTC)
  - Topo. data:
    - 5 km: 2 arc min.
    - 1 km: GTOPO30
      (30 arc second ~ 1 km)
    - 1 km: SRTM1ARC
      (1 arc second ~ 30 m)
    - 650 m: SRTM1ARC
      (1 arc second ~ 30 m)

Credit: NASA image by Jeff Schmaltz, MODIS Rapid Response Team, Goddard Space Flight Center.

10 m wind of +96 hr MSM simulation

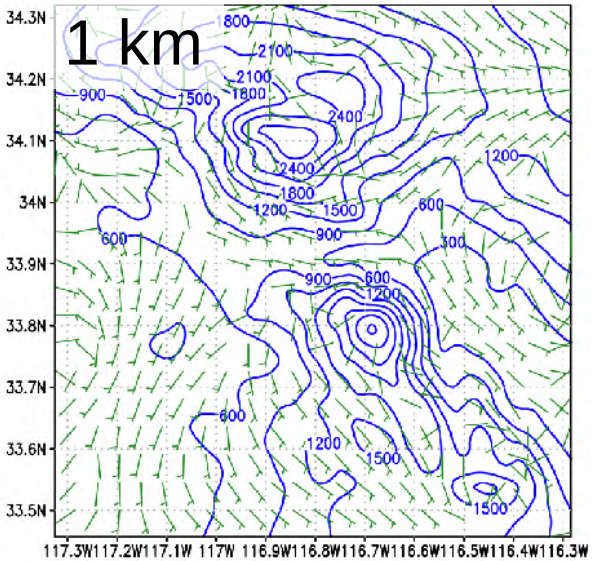
(2006 Oct. 29_12 UTC)

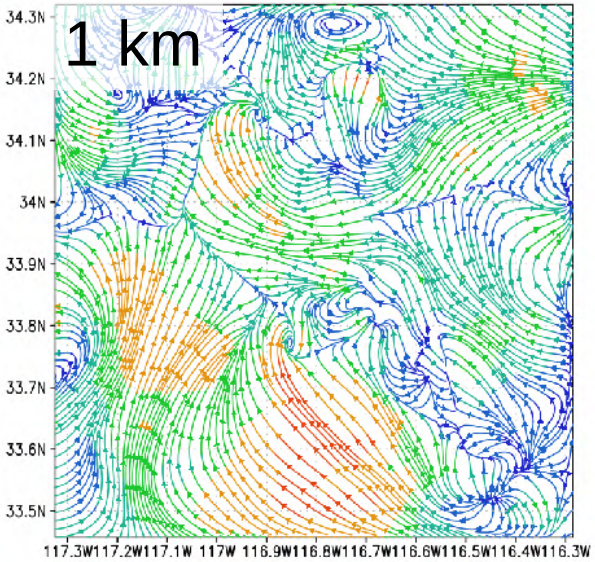




Topo. data:
5km: 2 arc min.
1 km: GTOPO30

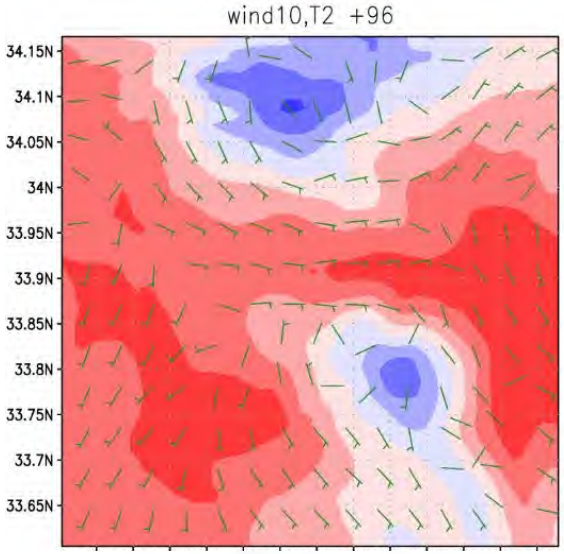
(Google, Maps, 2018)

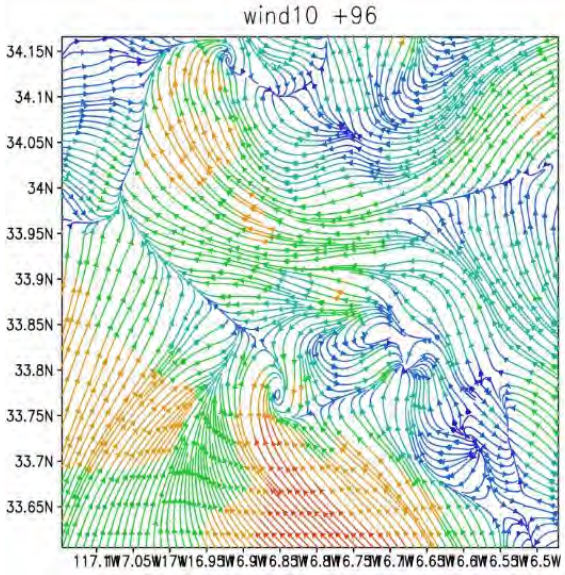




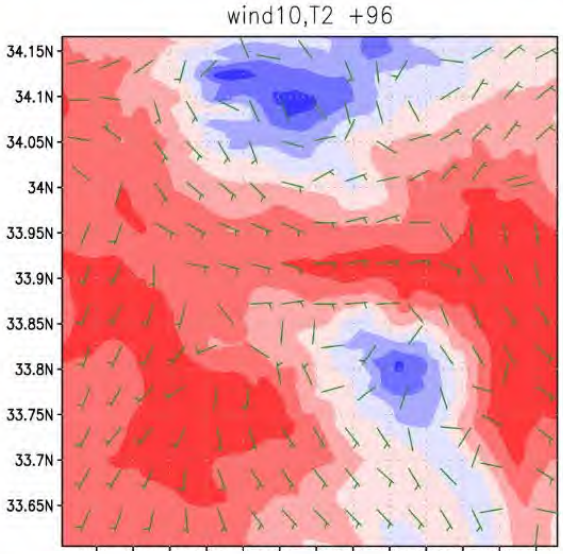
10 m wind & 2 m T of +96 hr MSM simulation

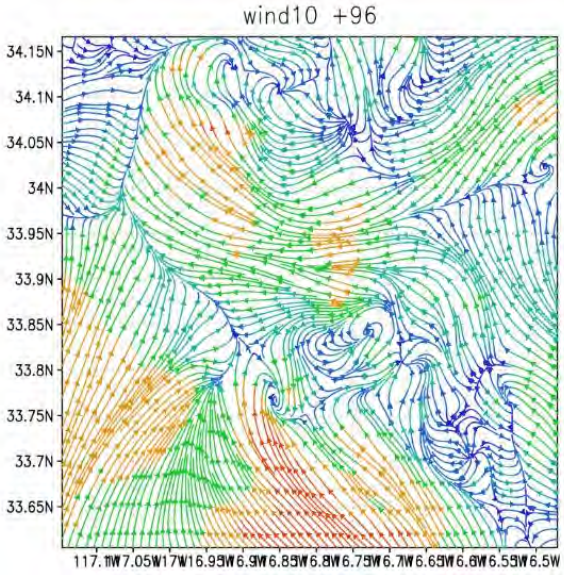
1km GTOPO30



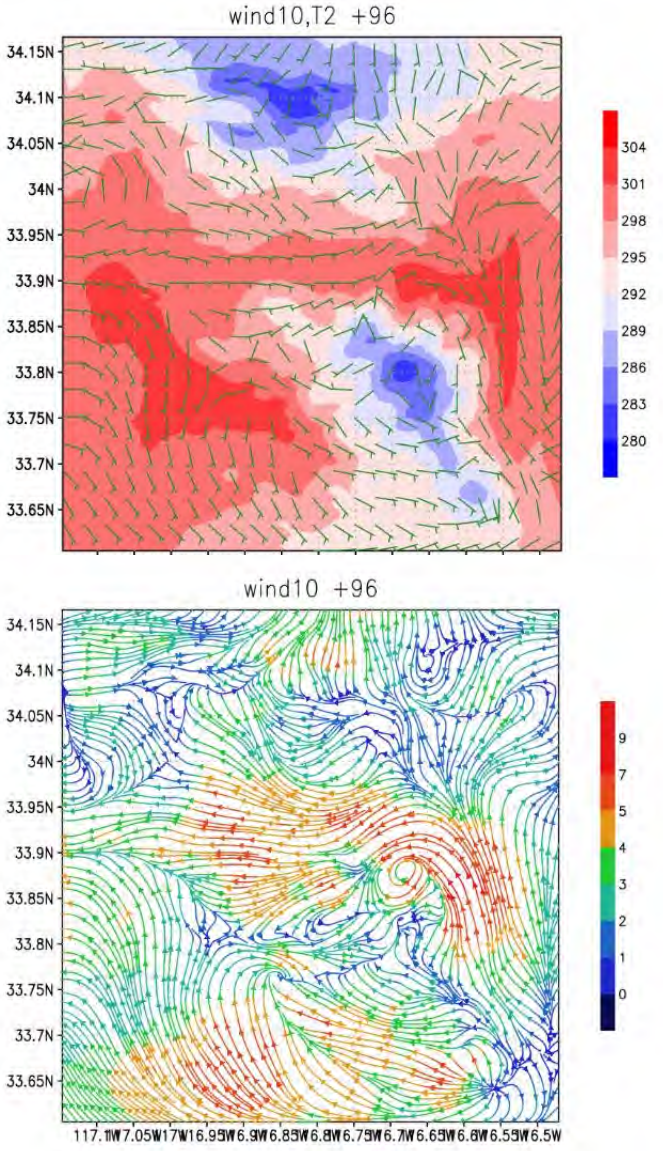


1km SRTM1ARC



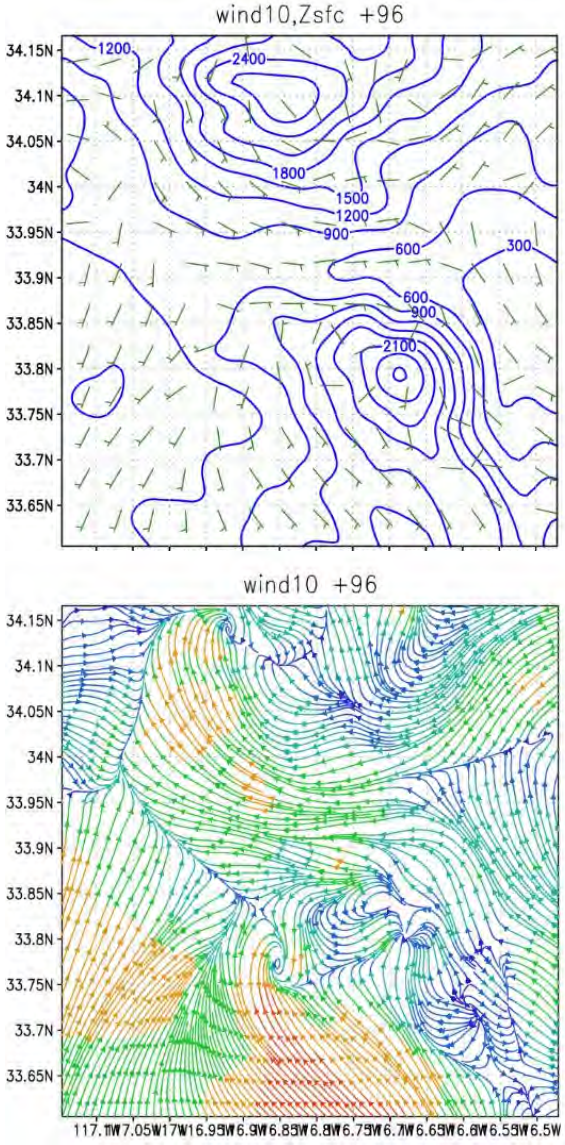


650m SRTM1ARC

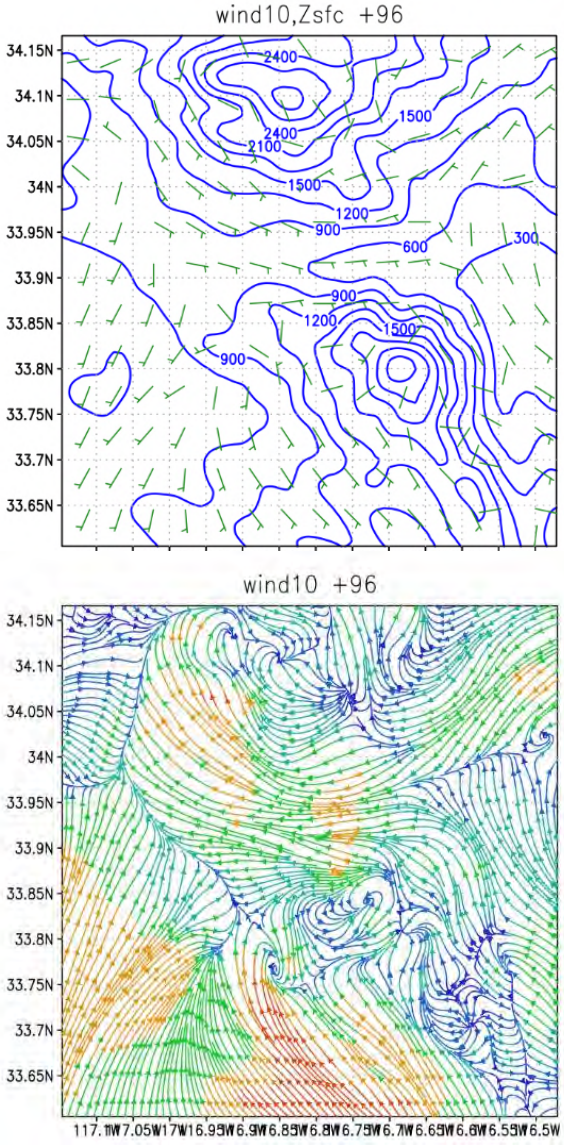


10 m wind & sfc. height of +96 hr MSM simulation

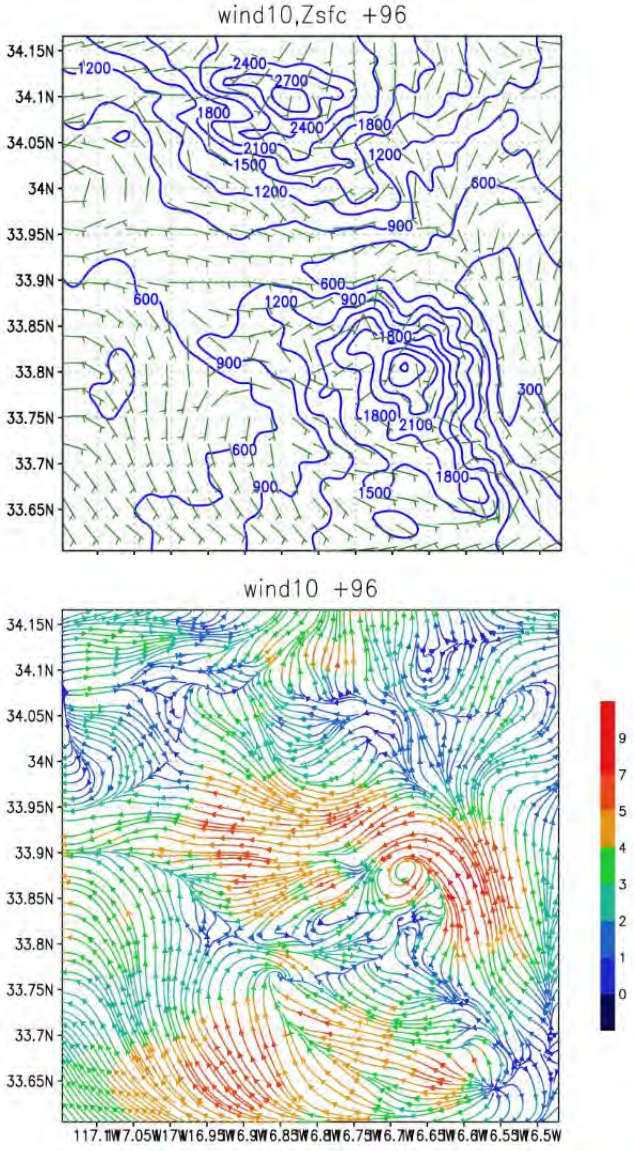
1km GTOPO30



1km SRTM1ARC

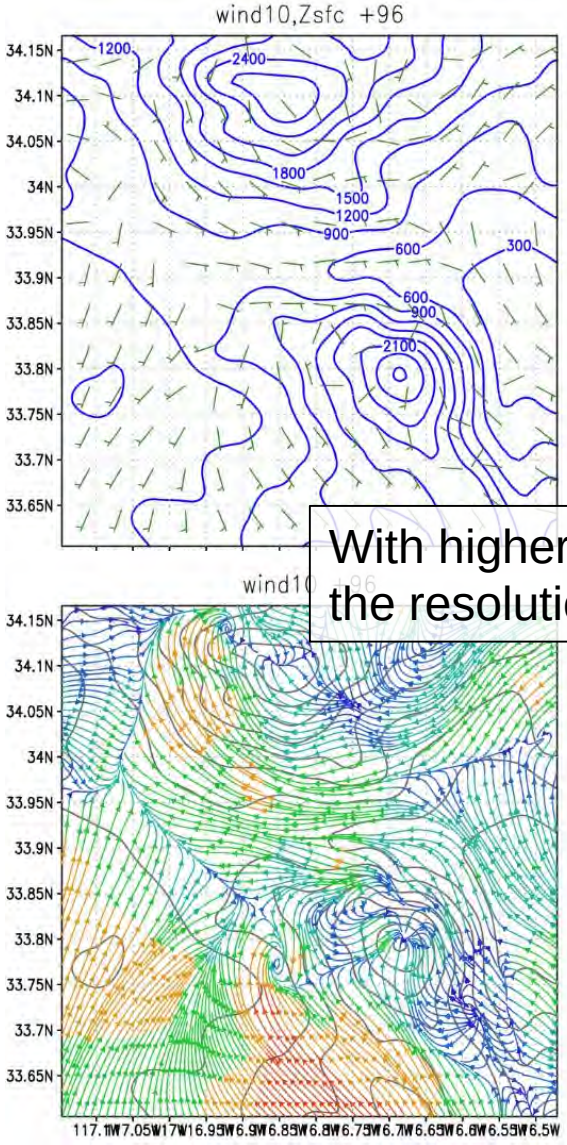


650m SRTM1ARC

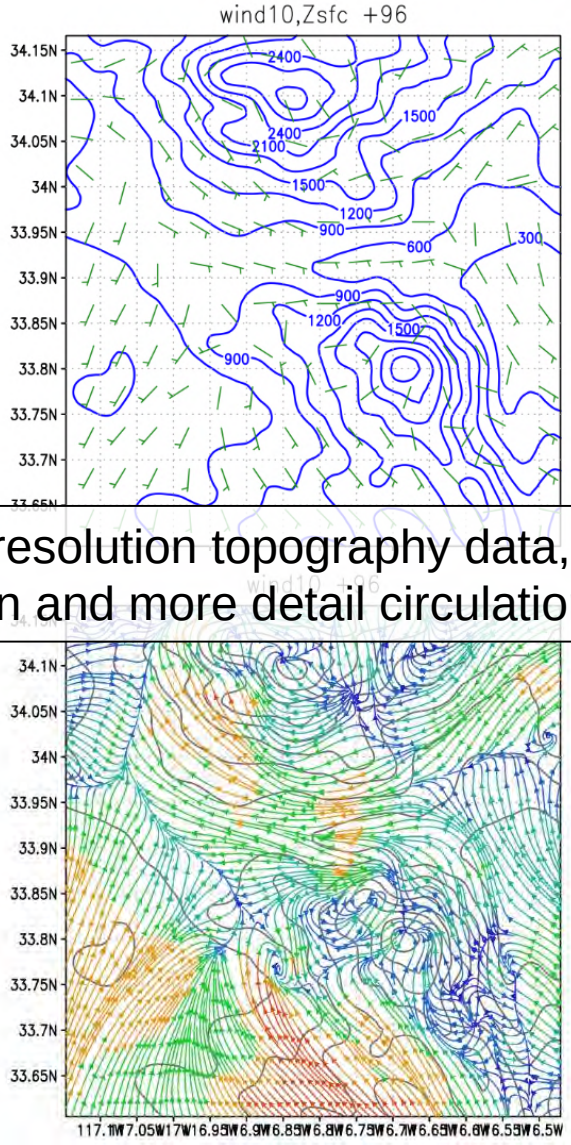


10 m wind & sfc. height of +96 hr MSM simulation

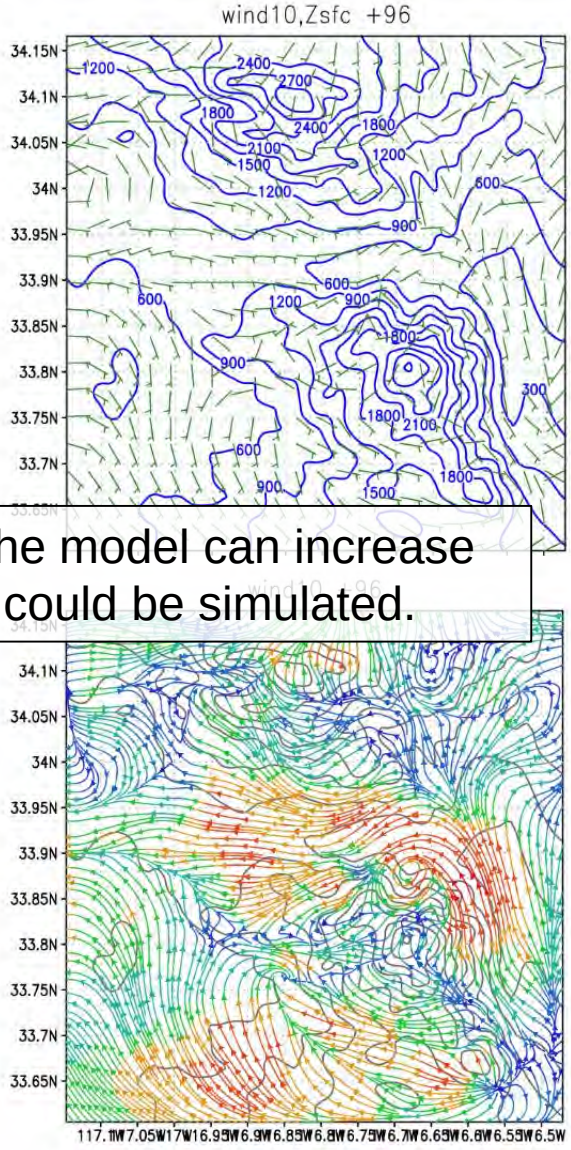
1km GTOPO30



1km SRTM1ARC



650m SRTM1ARC



With higher resolution topography data, the model can increase the resolution and more detail circulation could be simulated.

NDSL: Non-iteration Dimensional-splitting Semi-Lagrangian

應用於追蹤粒子(tracers)場

非疊代分維半拉格朗日法(NDSL)

RSM Governing Equations

perturbation tendency

(full field forcing) – (base field forcing)

$$\frac{\partial u^{*\prime}}{\partial t} = -m^2\left(u^*\frac{\partial u^*}{\partial x} + v^*\frac{\partial u^*}{\partial y}\right) - \dot{\sigma}\frac{\partial u^*}{\partial \sigma} - \frac{1}{2}(u^{*2} + v^{*2})\frac{\partial m^2}{\partial x} + fv^* - \left(\frac{\partial \phi}{\partial x} + RT\frac{\partial Q}{\partial x}\right) + F_u - \frac{\partial u_g^*}{\partial t}, \quad (1.1)$$

$$\frac{\partial v^{*\prime}}{\partial t} = -m^2\left(u^*\frac{\partial v^*}{\partial x} + v^*\frac{\partial v^*}{\partial y}\right) - \dot{\sigma}\frac{\partial v^*}{\partial \sigma} - \frac{1}{2}(u^{*2} + v^{*2})\frac{\partial m^2}{\partial y} - fu^* - \left(\frac{\partial \phi}{\partial y} + RT\frac{\partial Q}{\partial y}\right) + F_v - \frac{\partial v_g^*}{\partial t}, \quad (1.2)$$

$$\frac{\partial T'}{\partial t} = -m^2\left(u^*\frac{\partial T}{\partial x} + v^*\frac{\partial T}{\partial y}\right) - \sigma^{\kappa}\dot{\sigma}\frac{\partial T\sigma^{-\kappa}}{\partial \sigma} + \kappa T\left[\frac{\partial Q}{\partial t} + m^2\left(u^*\frac{\partial Q}{\partial x} + v^*\frac{\partial Q}{\partial y}\right)\right] + F_T - \frac{\partial T_g}{\partial t}, \quad (1.3)$$

$$\frac{\partial Q'}{\partial t} = -\int_0^1 m^2\left(u^*\frac{\partial Q}{\partial x} + v^*\frac{\partial Q}{\partial y}\right)d\sigma - \int_0^1 m^2\left(\frac{\partial u^*}{\partial x} + \frac{\partial v^*}{\partial y}\right)d\sigma - \frac{\partial Q_g}{\partial t}, \quad (1.4)$$

$$\frac{\partial q'}{\partial t} = -m^2\left(u^*\frac{\partial q}{\partial x} + v^*\frac{\partial q}{\partial y}\right) - \dot{\sigma}\frac{\partial q}{\partial \sigma} + F_q - \frac{\partial q_g}{\partial t}, \quad (1.5)$$

$$\frac{\partial \phi}{\partial \sigma} = -\frac{RT}{\sigma}, \quad (1.6)$$

$$\phi = gz_s + \mathbf{AT}_j, \quad (1.7)$$

$$\frac{\partial \dot{\sigma}}{\partial \sigma} = +\int_0^1 m^2\left(u^*\frac{\partial Q}{\partial x} + v^*\frac{\partial Q}{\partial y} + \frac{\partial u^*}{\partial x} + \frac{\partial v^*}{\partial y}\right)d\sigma - m^2\left(u^*\frac{\partial Q}{\partial x} + v^*\frac{\partial Q}{\partial y} + \frac{\partial u^*}{\partial x} + \frac{\partial v^*}{\partial y}\right), \quad (1.8)$$

m: map factor

$u^* = u/m$

$v* = v/m$

$Q = \ln(p_s)$

(Juang and Kanamitsu, 1994)

MSM Governing Equations

perturbation tendency

(full field forcing) – (base field forcing)

$$\frac{\partial u^{*\prime}}{\partial t} = -m^2 u^* \frac{\partial u^*}{\partial x} - m^2 v^* \frac{\partial u^*}{\partial y} - \dot{\sigma}\frac{\partial u^*}{\partial \sigma} - E\frac{\partial m^2}{\partial x} + fv^* - R(\overline{T} + T')\frac{\partial \overline{Q}_s + Q'}{\partial x}$$

$$- \left(1 + \frac{T'}{\overline{T}}\right)\left(1 + \frac{\partial Q'}{\partial \ln\sigma}\right)\frac{\partial \overline{\phi}}{\partial x} + F_{u^*} - \frac{\partial u_b^*}{\partial t}, \tag{3.9}$$

$$\frac{\partial v^{*\prime}}{\partial t} = -m^2 u^* \frac{\partial v^*}{\partial x} - m^2 v^* \frac{\partial v^*}{\partial y} - \dot{\sigma}\frac{\partial v^*}{\partial \sigma} - E\frac{\partial m^2}{\partial y} - fu^* - R(\overline{T} + T')\frac{\partial \overline{Q}_s + Q'}{\partial y}$$

$$- \left(1 + \frac{T'}{\overline{T}}\right)\left(1 + \frac{\partial Q'}{\partial \ln\sigma}\right)\frac{\partial \overline{\phi}}{\partial y} + F_{v^*} - \frac{\partial v_b^*}{\partial t}, \tag{3.10}$$

$$\frac{\partial w'}{\partial t} = -m^2 u^* \frac{\partial w}{\partial x} - m^2 v^* \frac{\partial w}{\partial y} - \dot{\sigma}\frac{\partial w}{\partial \sigma} - g\left[1 - \left(1 + \frac{T'}{\overline{T}}\right)\left(1 + \frac{\partial Q'}{\partial \ln\sigma}\right)\right] + F_w - \frac{\partial w_b}{\partial t}, \tag{3.11}$$

$$\varepsilon_Q\left\{\frac{\partial \overline{Q}_s'}{\partial t} = -m^2 \int_0^1 \left[u^*\frac{\partial \overline{Q}_s}{\partial x} + v^*\frac{\partial \overline{Q}_s}{\partial y} + \left(\frac{\partial u^*}{\partial x} + \frac{\partial v^*}{\partial y}\right)\right] d\sigma - \frac{\partial Q_{s_b}}{\partial t}\right\}, \tag{3.12}$$

$$\varepsilon_T\left[\frac{\partial \overline{T}'}{\partial t} = -m^2 u^* \frac{\partial \overline{T}}{\partial x} - m^2 v^* \frac{\partial \overline{T}}{\partial y} - \dot{\sigma}\sigma^\kappa \frac{\partial \overline{T}\sigma^{-\kappa}}{\partial \sigma} + \kappa\overline{T}\left(\frac{\partial \overline{Q}_s}{\partial t} + m^2 u^*\frac{\partial \overline{Q}_s}{\partial x} + m^2 v^*\frac{\partial \overline{Q}_s}{\partial y}\right) + F_{\overline{T}} - \frac{\partial T_b}{\partial t}\right], \tag{3.13}$$

$$\frac{\partial Q'}{\partial t} = -m^2 u^* \frac{\partial \overline{Q}_s + Q'}{\partial x} - m^2 v^* \frac{\partial \overline{Q}_s + Q'}{\partial y} - \dot{\sigma}\frac{\partial Q'}{\partial \sigma} - \frac{\dot{\sigma}}{\sigma} - \gamma\nabla_3 \cdot \mathbf{V}^* + \gamma\frac{F_T}{T} - \frac{\partial \overline{Q}_s}{\partial t}, \tag{3.14}$$

$$\frac{\partial T'}{\partial t} = -m^2 u^* \frac{\partial \overline{T} + T'}{\partial x} - m^2 v^* \frac{\partial \overline{T} + T'}{\partial y} - \dot{\sigma}\sigma^\kappa \frac{\partial(\overline{T} + T')\sigma^{-\kappa}}{\partial \sigma}$$

$$+ \kappa(\overline{T} + T')\left[\frac{\partial(\overline{Q}_s + Q')}{\partial t} + m^2 u^*\frac{\partial \overline{Q}_s + Q'}{\partial x} + m^2 v^*\frac{\partial \overline{Q}_s + Q'}{\partial y} + \dot{\sigma}\frac{\partial Q'}{\partial \sigma}\right] + F_T - \frac{\partial \overline{T}}{\partial t}, \quad \text{and} \tag{3.15}$$

$$\frac{\partial q'}{\partial t} = -m^2 u^* \frac{\partial q}{\partial x} - m^2 v^* \frac{\partial q}{\partial y} - \dot{\sigma}\frac{\partial q}{\partial \sigma} + F_q - \frac{\partial q_b}{\partial t}, \tag{3.16}$$

(Juang, 2000)

Equation for Tracers

perturbation tendency **full field forcing** **– base field forcing**

$$\frac{\partial q'}{\partial t} = \overbrace{-m^2 u^* \frac{\partial q}{\partial x} - m^2 v^* \frac{\partial q}{\partial y} - \dot{\sigma} \frac{\partial q}{\partial \sigma} + F_q}^{\text{dynamic}} - \frac{\partial q_b}{\partial t}$$

physics known

spectrum **NDSL**

Non-iteration Dimensional-splitting
Semi-Lagrangian

NDSL: Non-iteration Dimensional-splitting Semi-Lagrangian

use 1-D equation for example:
Consider mass conservation,

$$\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x} + \rho\frac{\partial u}{\partial x} = 0$$

where ρ is scalar and u is wind. Write the last term $\frac{\partial u}{\partial x}$ as

$$\frac{\partial u}{\partial x} = \frac{1}{\Delta_x}\left(\frac{d\Delta_x}{dt}\right)$$

then the first equation becomes

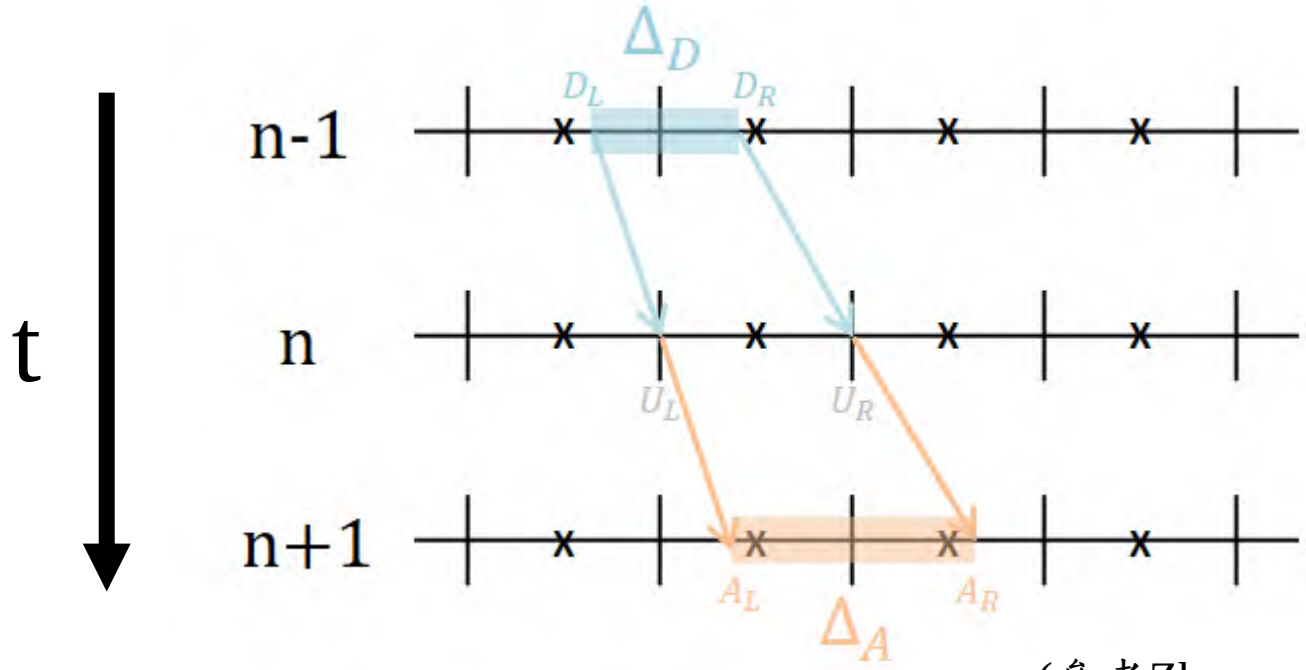
$$\frac{d\rho\Delta_x}{dt} = 0$$

that is

$$(\rho\Delta_x)_D^{n-1} = (\rho\Delta_x)_A^{n+1}$$

(Juang, 2007, 2008)
(Zhang and Juang, 2012)

一維質量保守NDSL示意圖



(參考Zhang and Juang, 2012 圖2)

一維NDSL質量保守平流的計算細節為

1.計算網格邊界的風場。

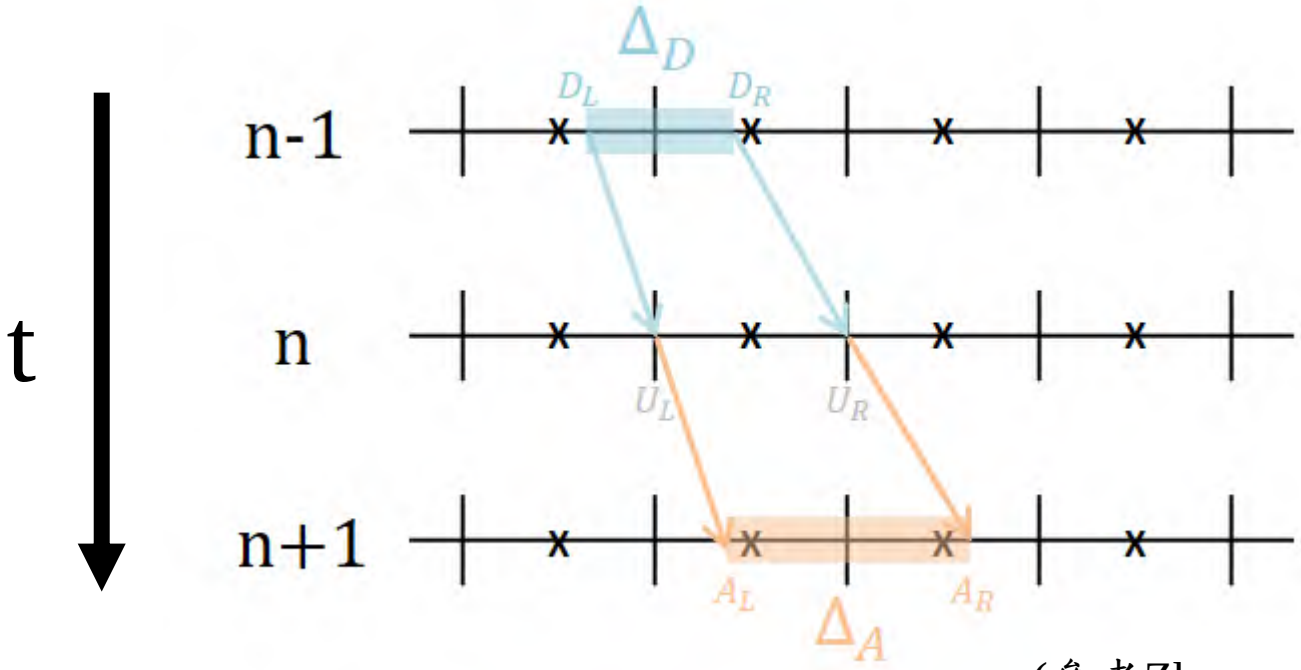
2.計算出發點(n-1)與抵達點(n+1)的位置和網格大小。

3.以PLM將密度由模式網格點內插(interpolation)到n-1時的出發點座標。

4.透過$(\rho\Delta_x)_D^{n-1} = (\rho\Delta_x)_A^{n+1}$，將質量由出發點(n-1)座標移至抵達點(n+1)座標。

5.將密度以PLM由抵達點(n+1)座標再映射(remap)回模式網格點上。

一維質量保守NDSL示意圖



(參考Zhang and Juang, 2012 圖2)

格點值內插得q_{D}^{n-1}
(interpolation)

q_A^{n+1}再映射回格點上
(remap)

Dimensional Splitting

- For 2D:

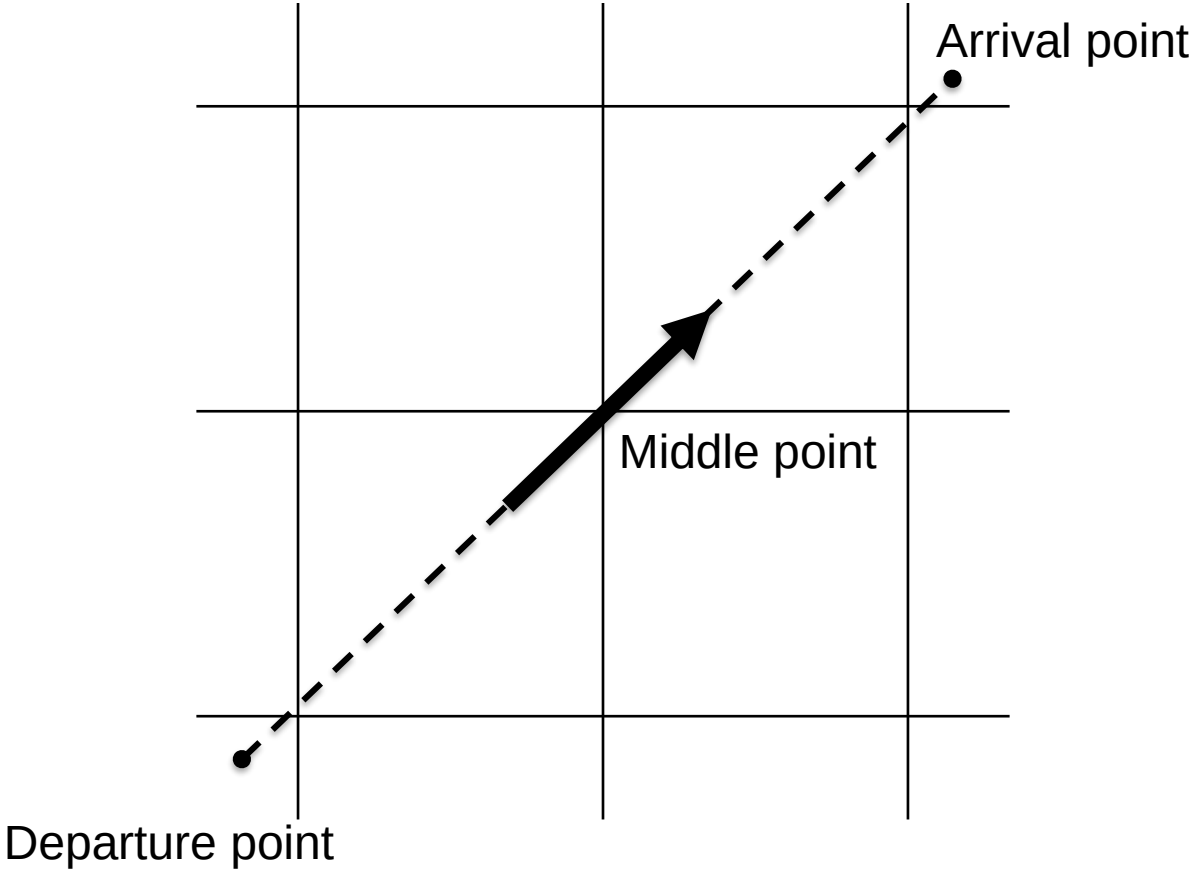
$$\frac{\partial q}{\partial t} + u\frac{\partial q}{\partial x} + v\frac{\partial q}{\partial y} = 0$$

➢ *dimensional splitting into x direction and y direction*

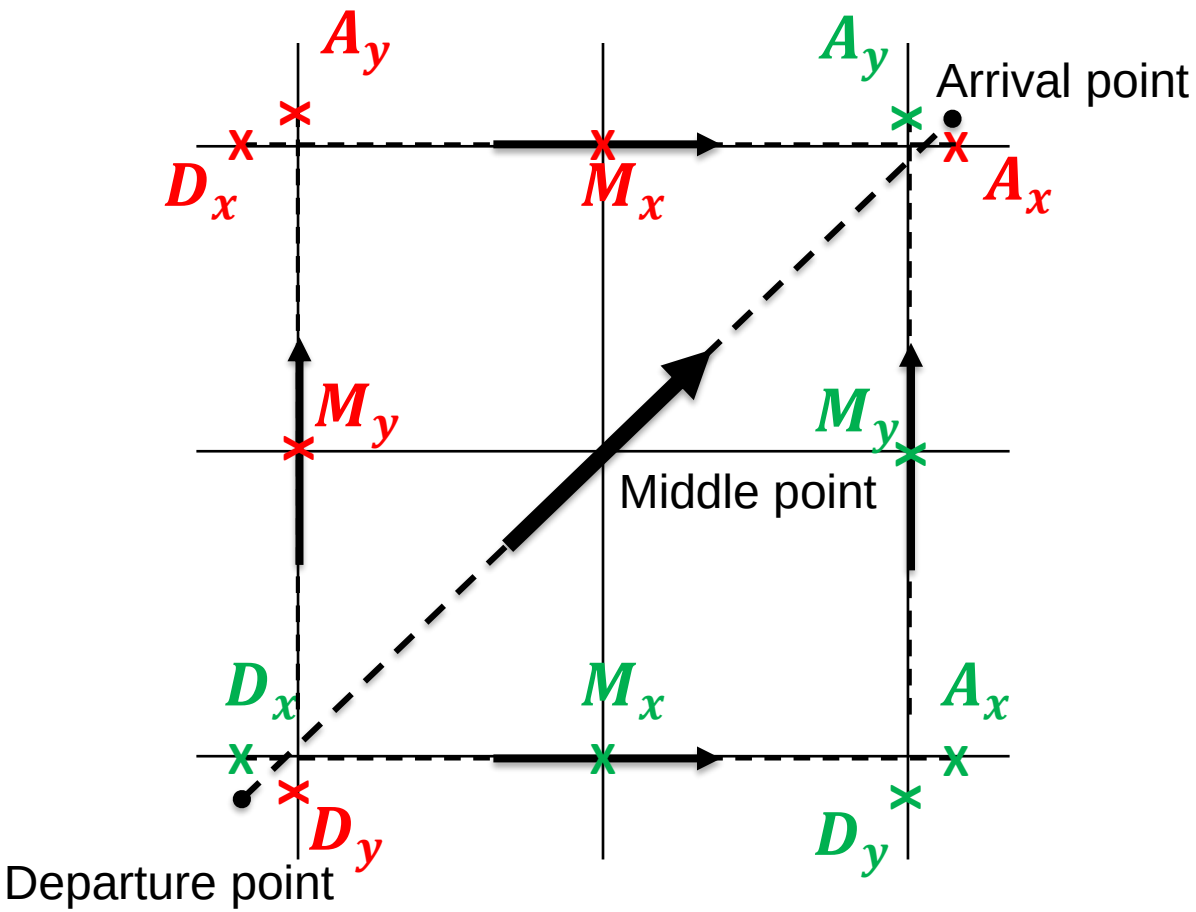
$$\left(\left(\frac{\partial q}{\partial t}\right)_{xdirection} + u\frac{\partial q}{\partial x}\right) + \left(\left(\frac{\partial q}{\partial t}\right)_{ydirection} + v\frac{\partial q}{\partial y}\right) = 0$$

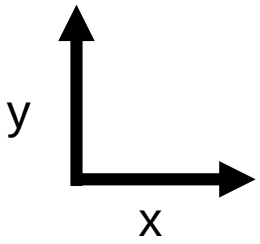
(Zhang and Juang, 2012)

2D NDSL

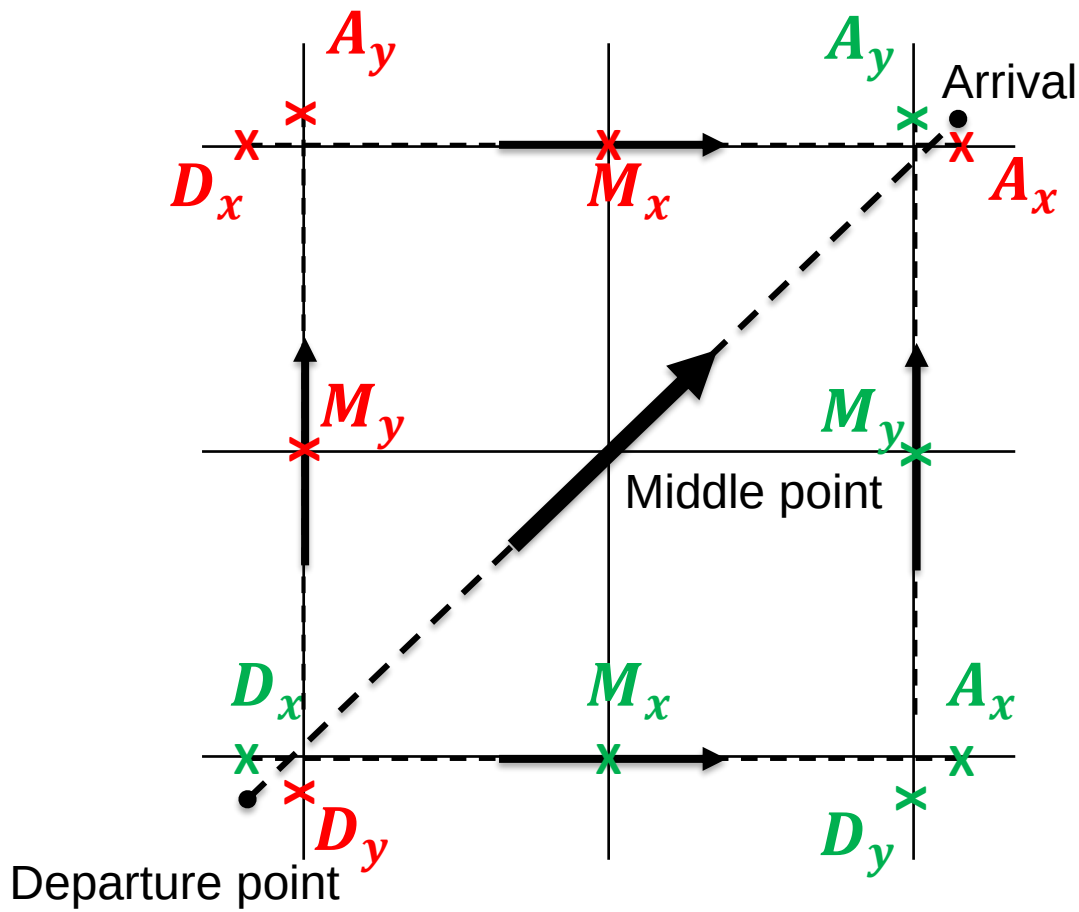


2D NDSL


A_y
A_y
Arrival point
D_x
M_x
A_x
M_y
M_y
Middle point
D_x
M_x
A_x
D_y
D_y
Departure point


y
x

2D NDSL



$$\left(\frac{\partial q}{\partial t}\right)_{adv} = \left(\frac{q^{n+1} - q^{n-1}}{2\Delta t}\right)_{adv}$$

$$= \left(\frac{q^{n+1} - q^{n+1^*}}{2\Delta t} + \frac{q^{n+1^*} - q^{n-1}}{2\Delta t}\right)_{adv}$$

$$\boldsymbol{Y} \qquad \boldsymbol{X}$$

$$\boldsymbol{X} \qquad \boldsymbol{Y}$$

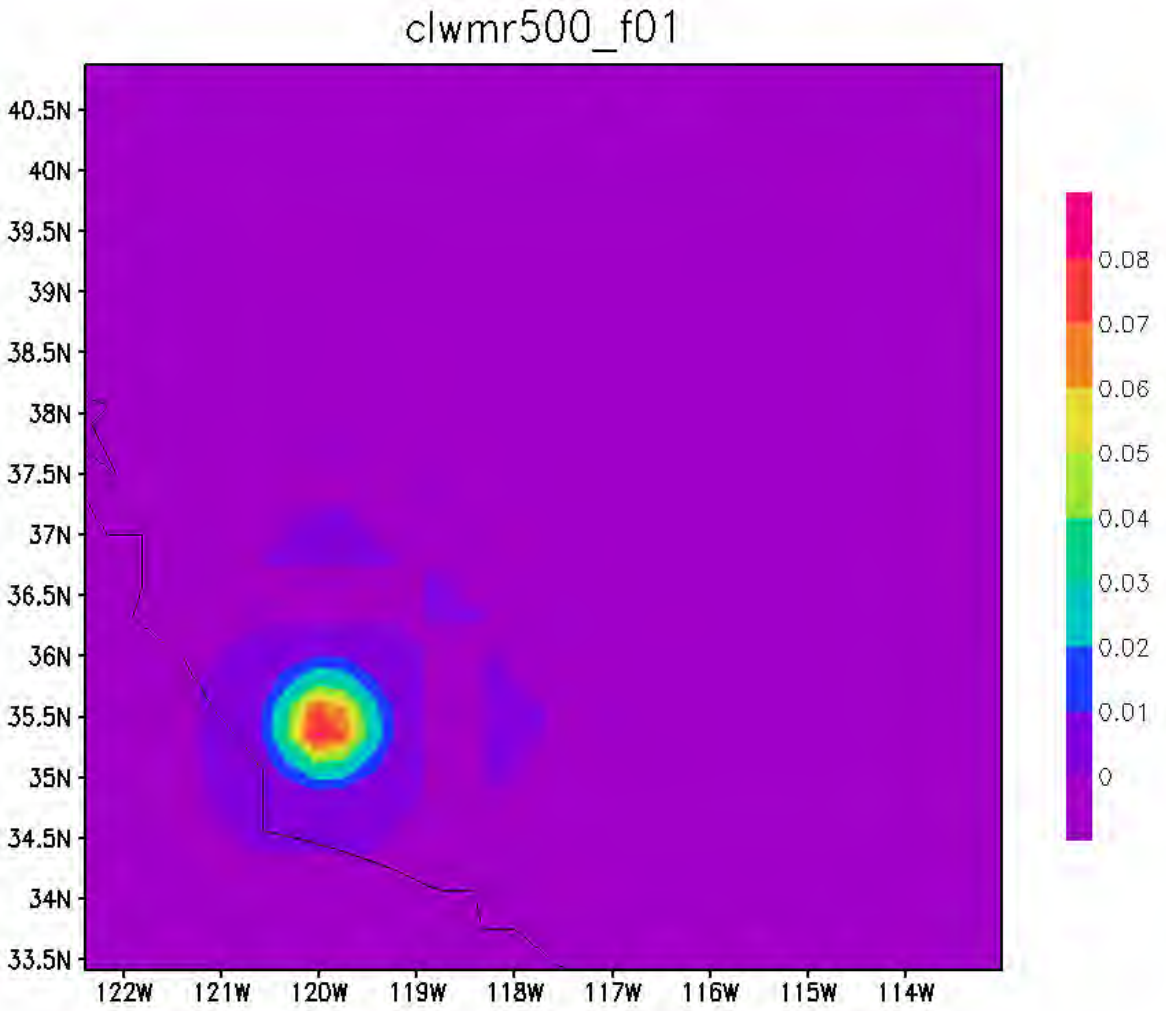
$$= \frac{1}{2}\left[\boldsymbol{X}\left(\boldsymbol{Y}(\boldsymbol{q})\right) + \boldsymbol{Y}\left(\boldsymbol{X}(\boldsymbol{q})\right)\right]$$

理想個案測試

domain size: 32x32

$\Delta t = 60\ s$

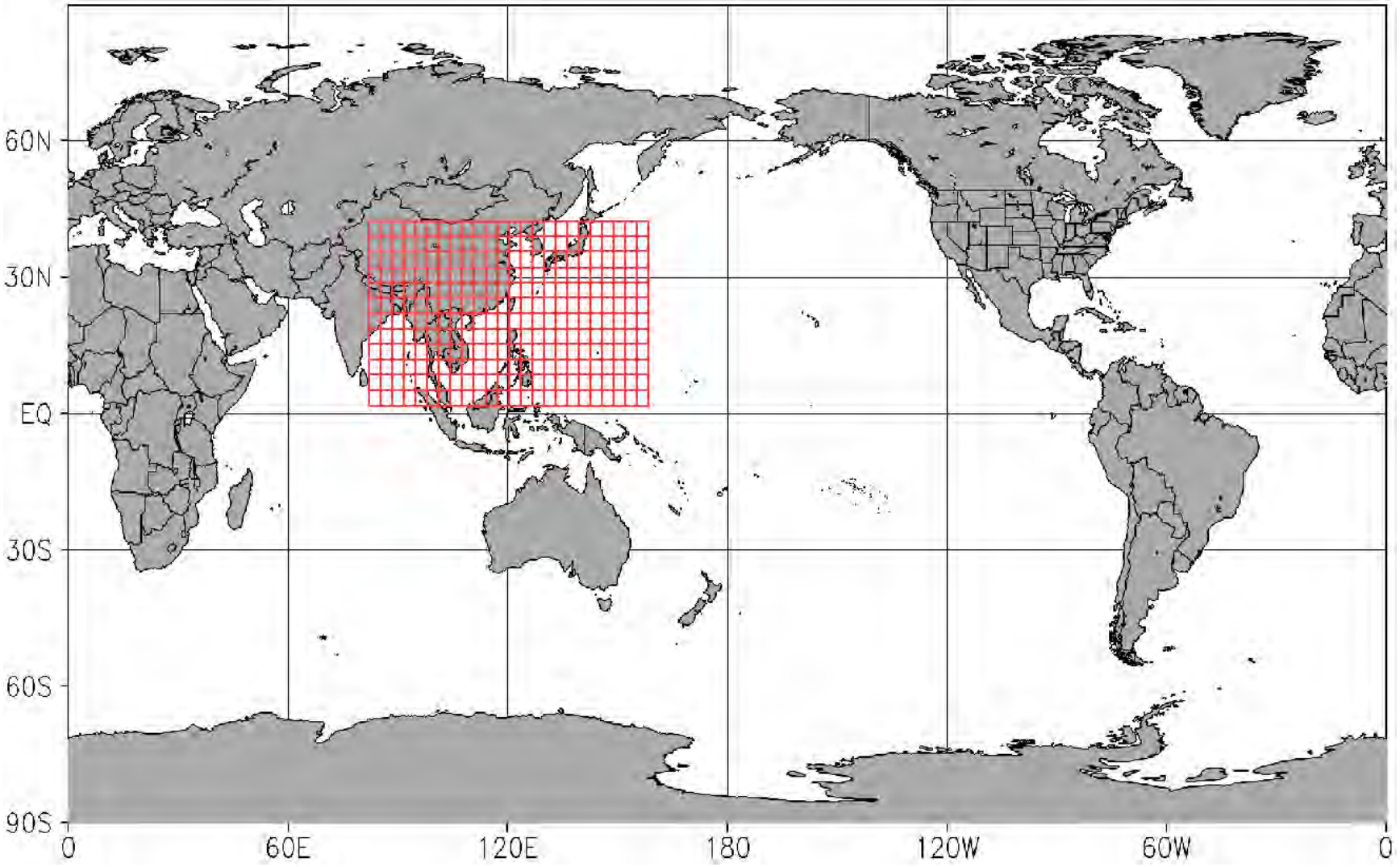
$u = v = 5\ ms^{-1}$



NDSL 實際個案測試

- 個案：泰利颱風(2017年)
- 初始場: 2017/09/11 00 UTC
- 預報時間：5天
- 模式設定：
  - CWBGFS T511 + RSM(靜力) 12 公里

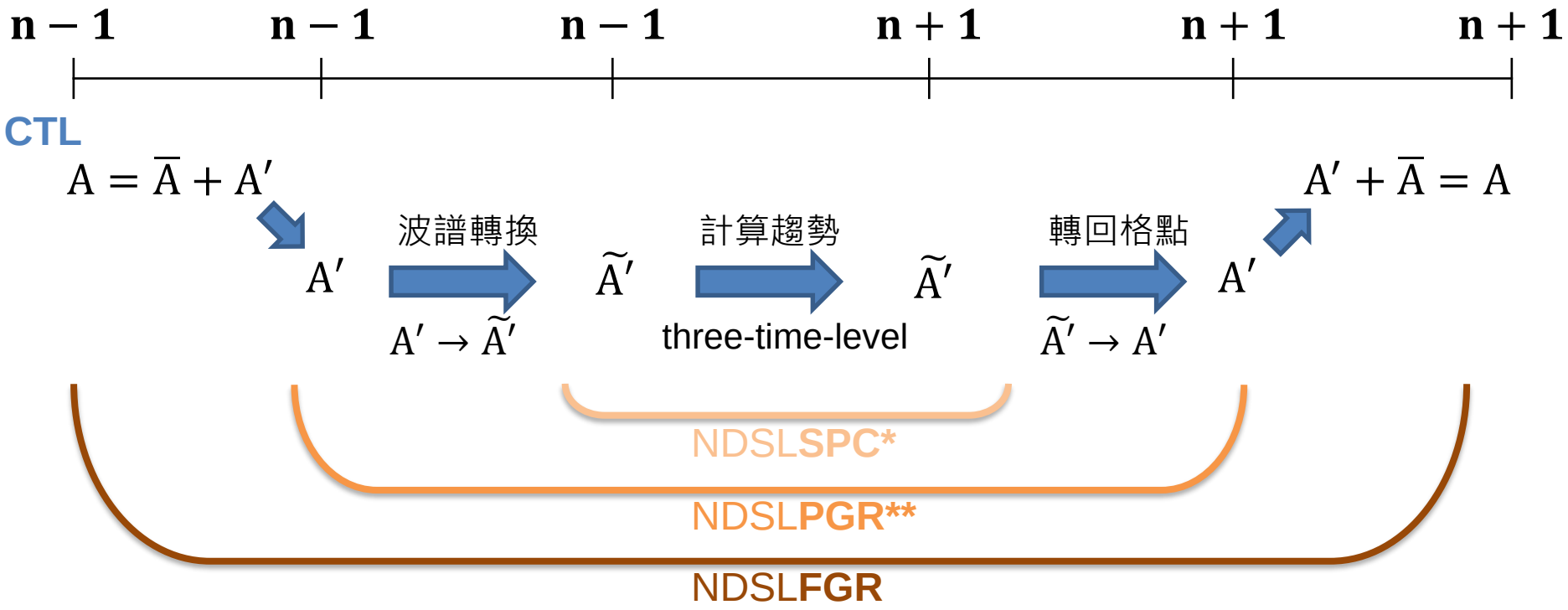
RSM模擬範圍



NDSL 實際個案測試

- 測試四組模擬:
  - CTL: original RSM
  - NDSL**SPC**: NDSL with spectrum transform
  - NDSL**PGR**: NDSL with perturbation relaxation and time filter
  - NDSL**FGR**: NDSL with full grid relaxation and time filter

RSM計算流程(CTL)與三組NDSL改法示意圖



*NDSLSPC: 由波譜轉回格點，加上背景場後，執行NDSL。
**NDSLPGR:由擾動場加上背景場後進行NDSL。

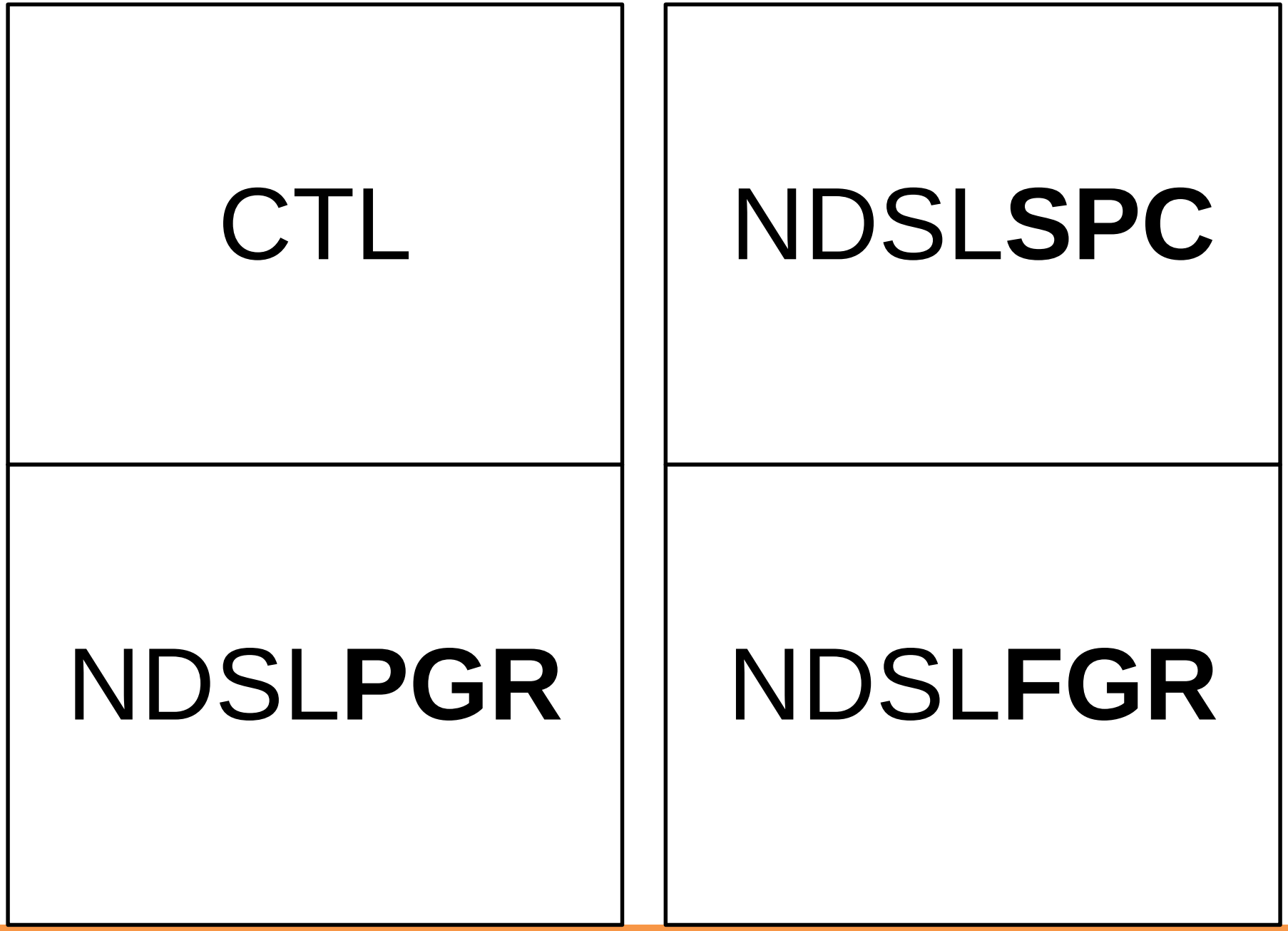
RSM/MSM

- Double Fourier Series
- Perturbation Method (perturbation filtering model)
  - satisfy zero boundary condition
  - better B.C. for semi-implicit scheme
  - keep large scale (over domain size) properties from global model
  - 4-th order **horizontal diffusion**
  - **time filter**
  - implicit lateral boundary **relaxation**

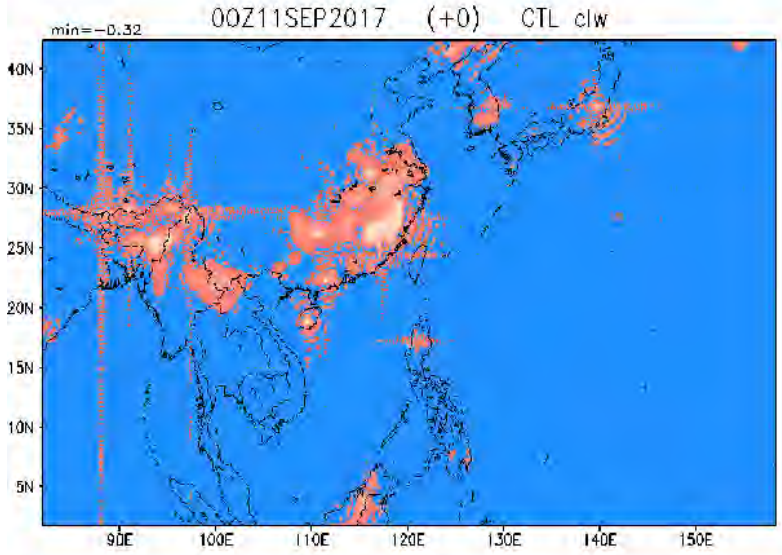
控制組CTL與三組NDSL改法的計算細節

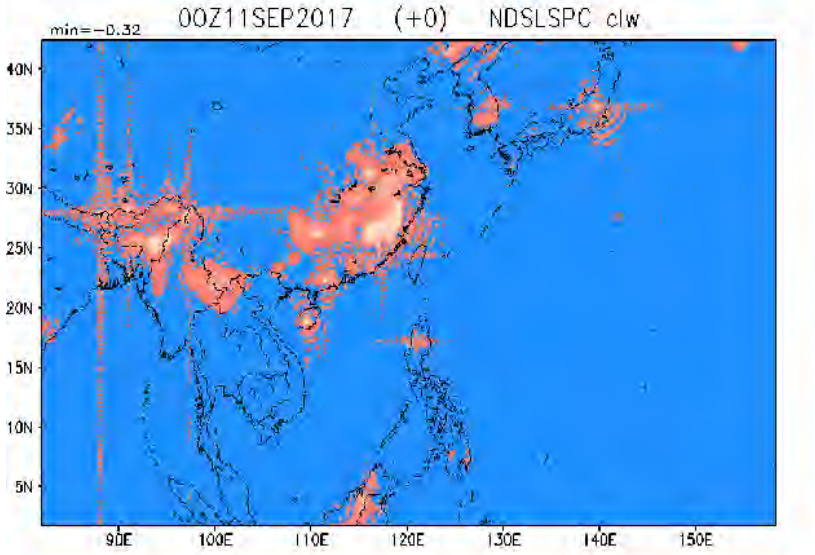
	spectrum truncation	**advection term**	**relaxation**	**horizontal diffusion**	**time filter**
CTL	O	spectrum	perturbation	O	perturbation
NDSL**SPC**	O	NDSL	perturbation	O	perturbation
NDSL**PGR**	X	NDSL	perturbation	X	perturbation
NDSL**FGR**	X	NDSL	full field	X	full field

O表示有執行，X表示沒執行。

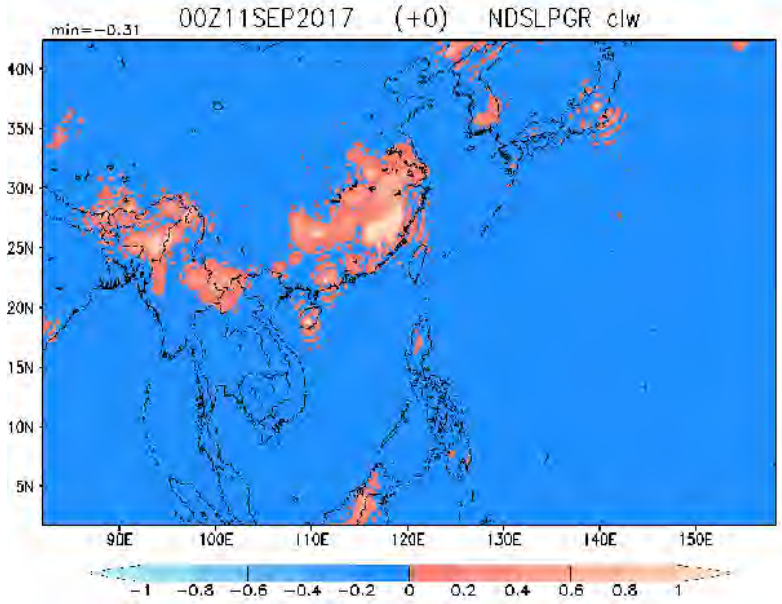

CTL
NDSL**SPC**
NDSL**PGR**
NDSL**FGR**

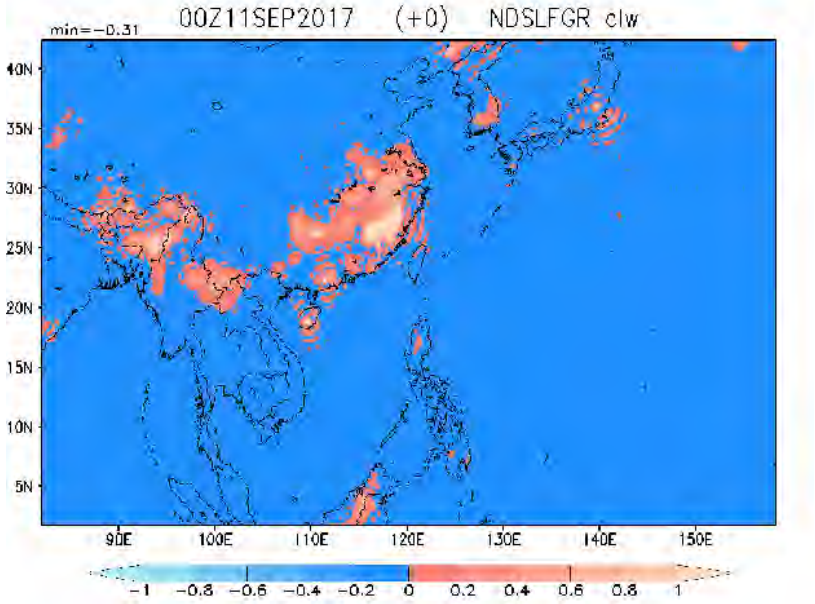
雲水(cloud water)第0小時預報的1000百帕等壓面分布圖



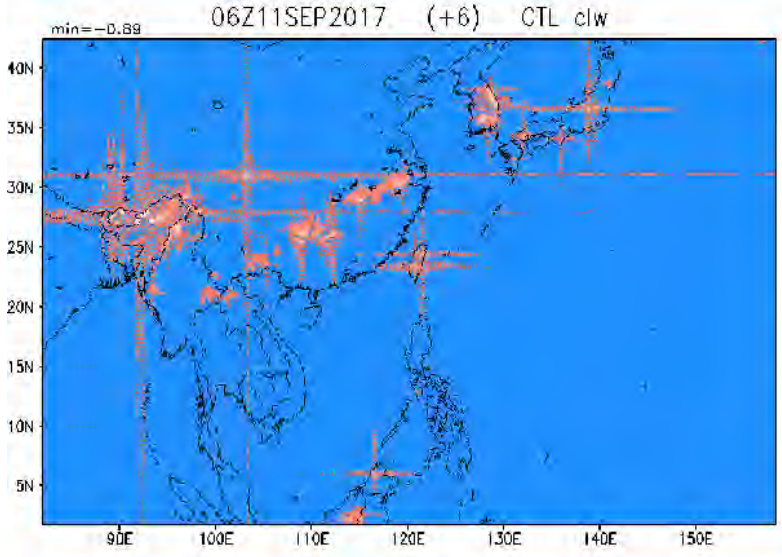


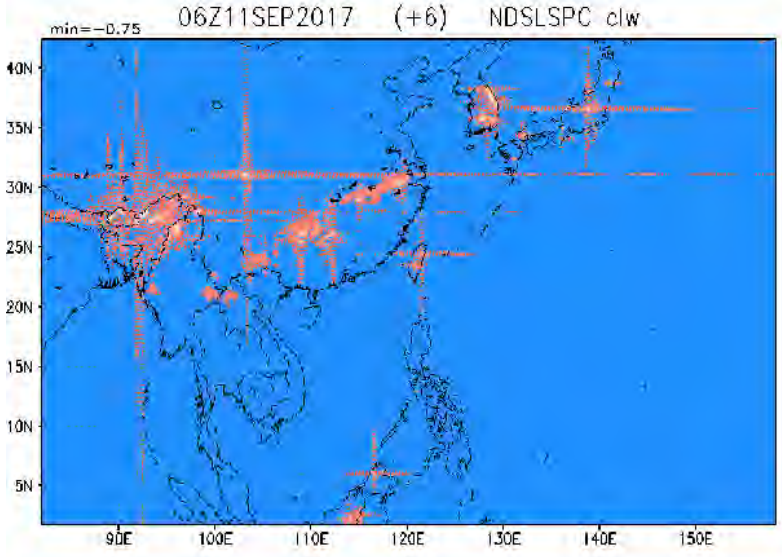
Without spectral transform, the noise caused by Gibbs phenomenon is eliminated.



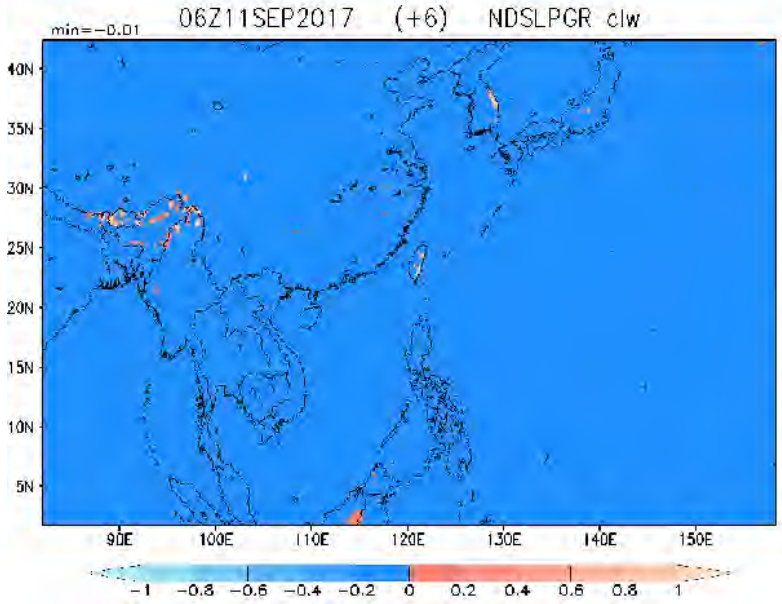


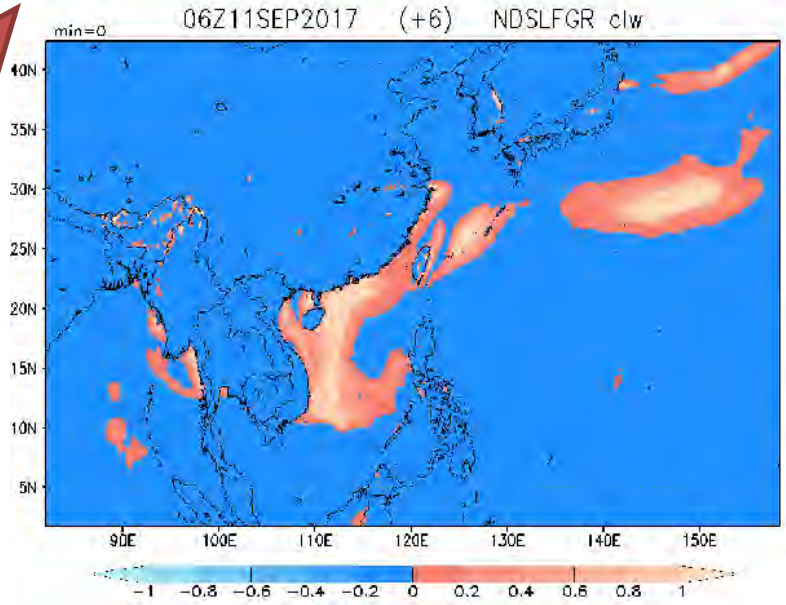
雲水(cloud water)第6小時預報的1000百帕等壓面分布圖



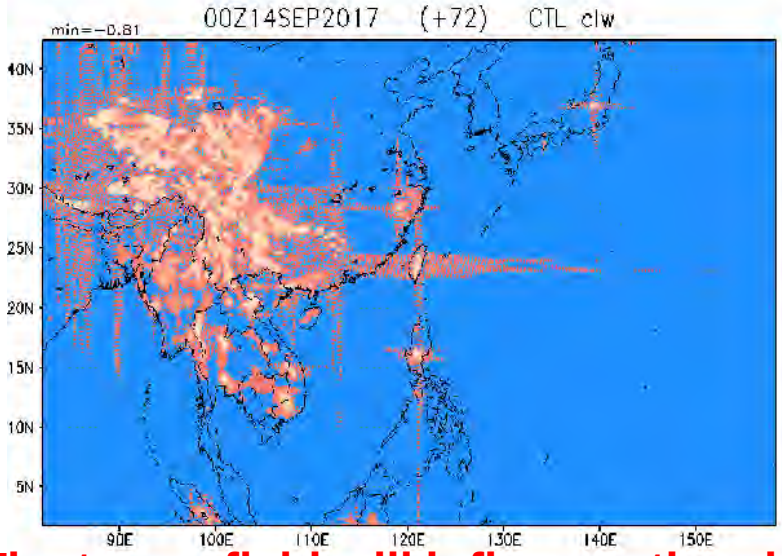


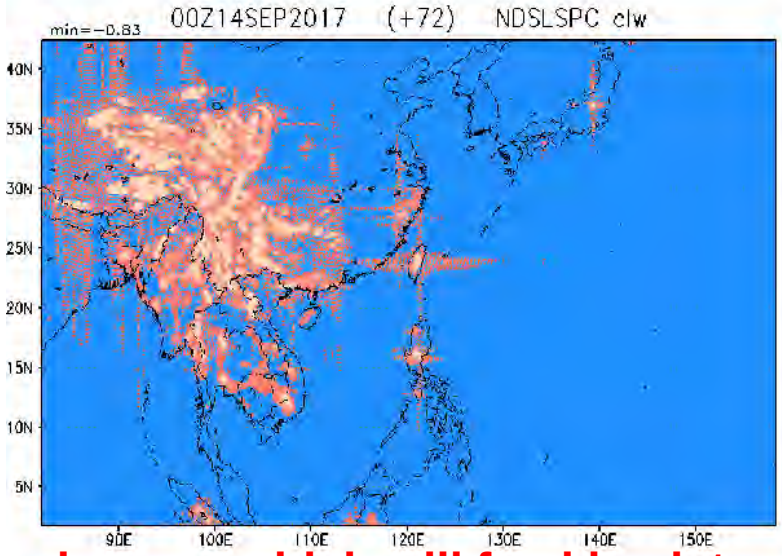
Time filter over full grid value may cause problems.



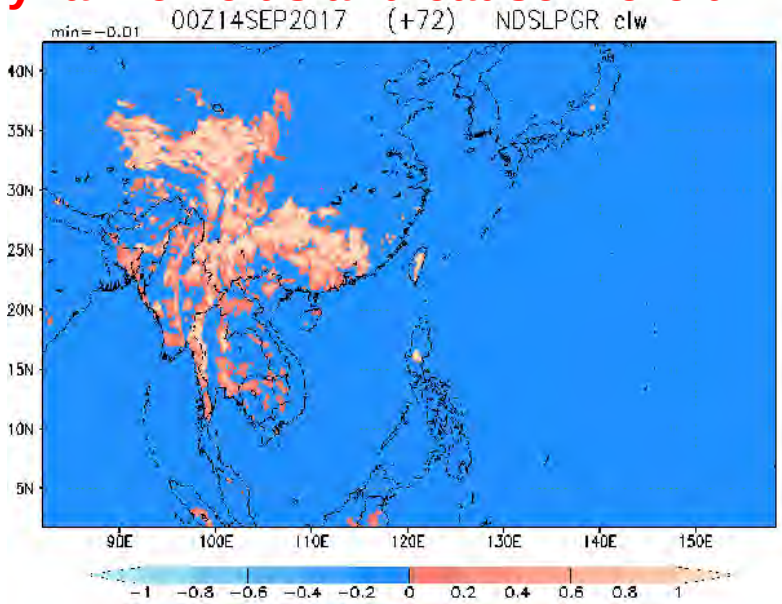


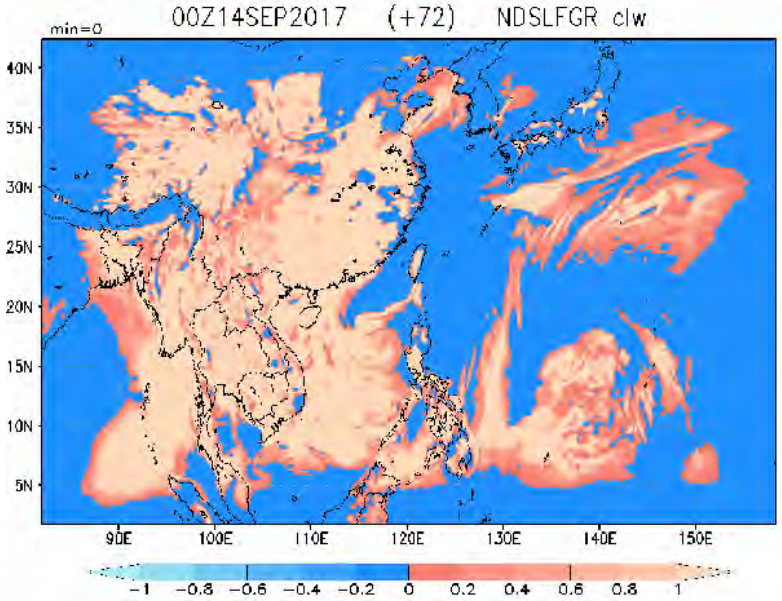
雲水(cloud water)第72小時預報的1000百帕等壓面分布圖





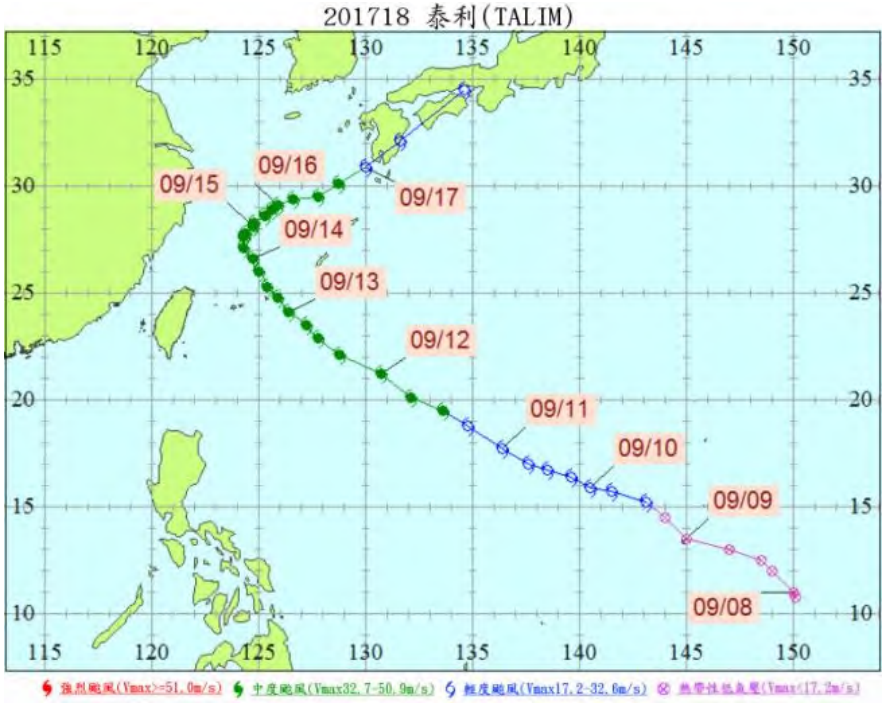
The tracer field will influence the physics schemes, which will feed back to dynamic fields and cause more differences between the scheme.





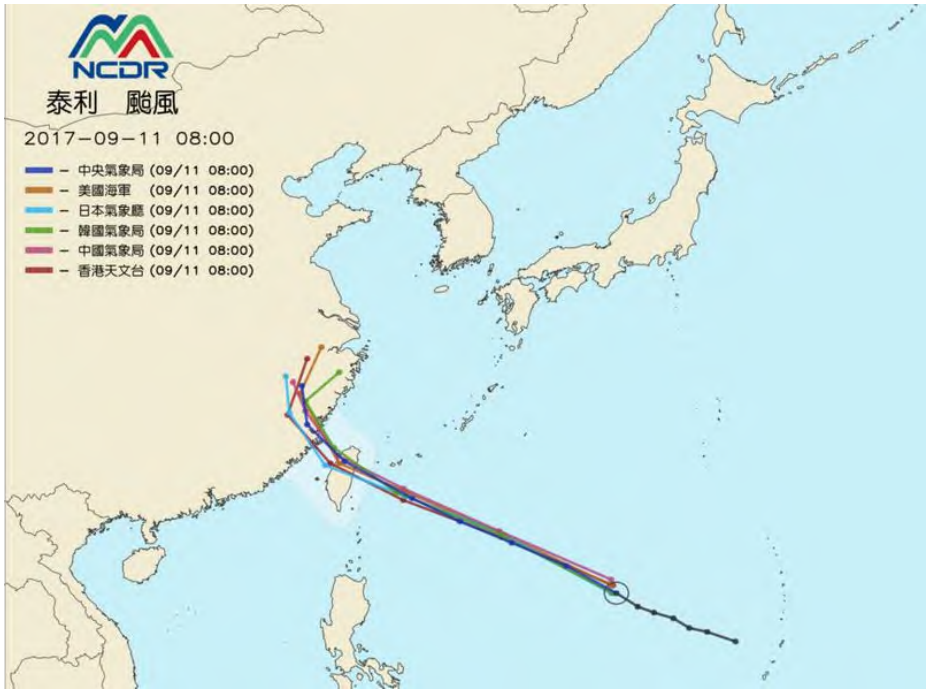
2017年第18號颱風泰利颱風(Talim)

泰利（Talim）路徑圖



資料來源：
中央氣象局颱風資料庫

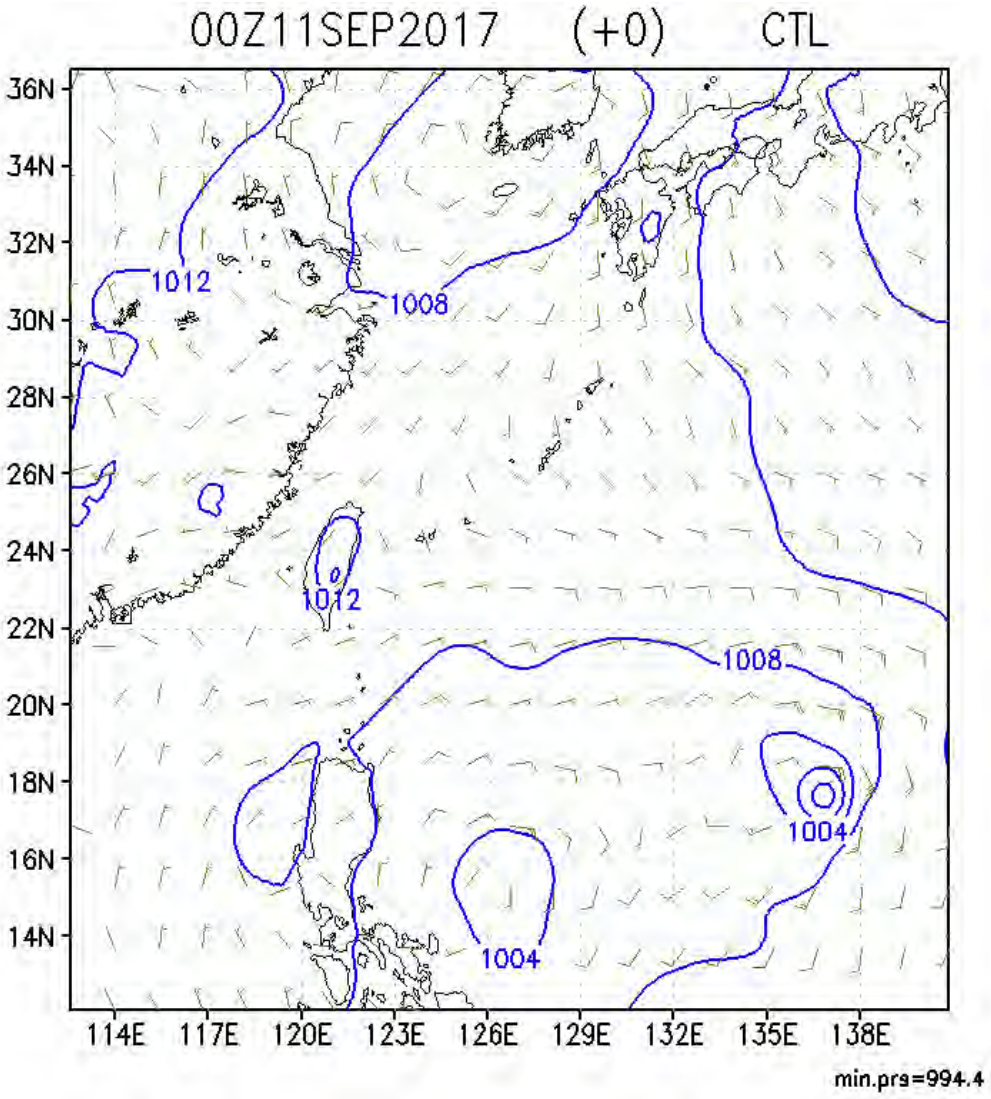
泰利颱風路徑預測圖



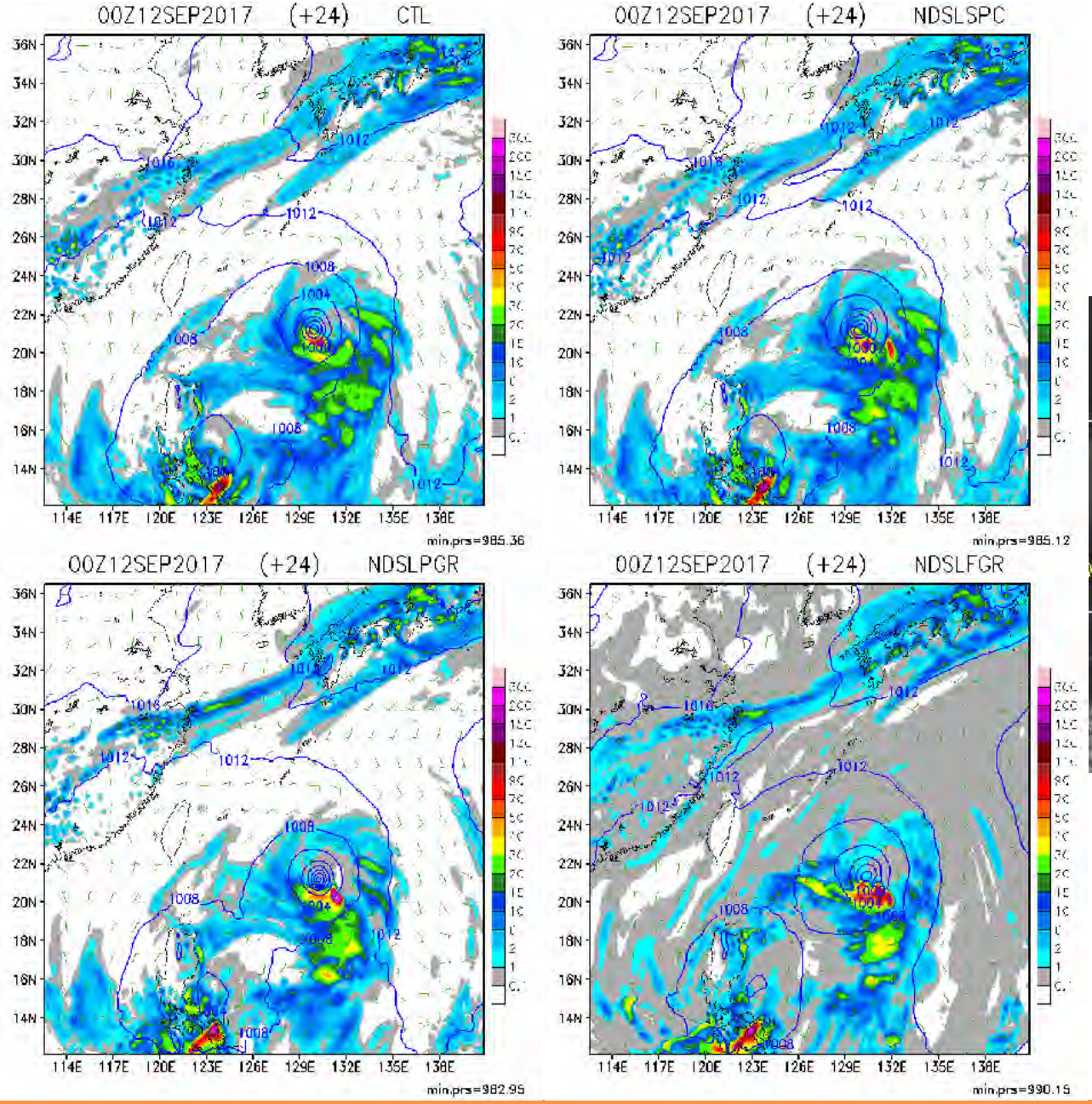
預報初始場為2017年9月11日00 UTC。
資料來源：
國家災害防救中心天氣與氣候監測網

NDSL 實際個案測試-泰利颱風(2017年)

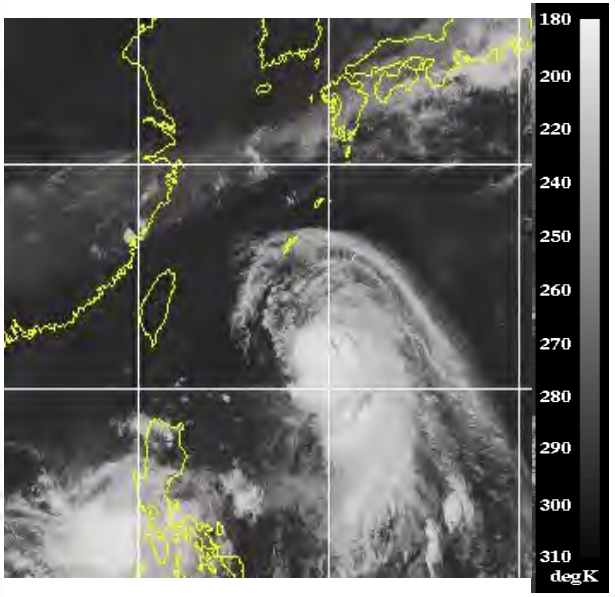
初始場



泰利颱風(2017)-第24小時預報結果



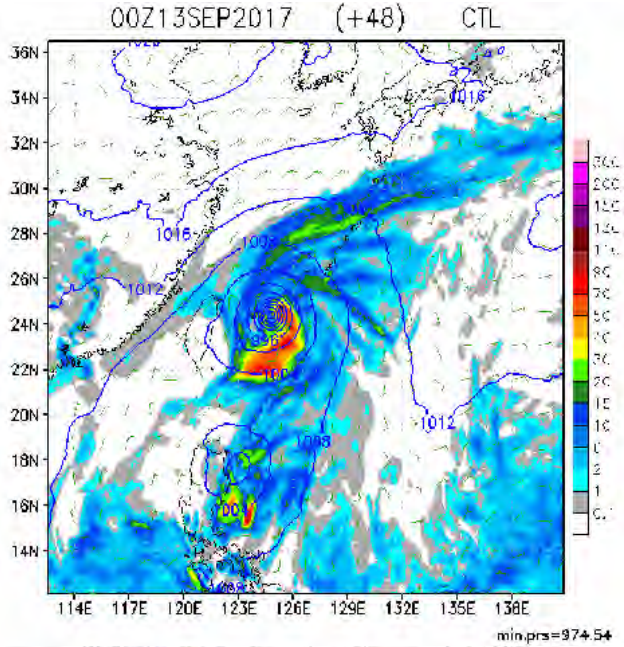
HIMAWARI INFRQRED

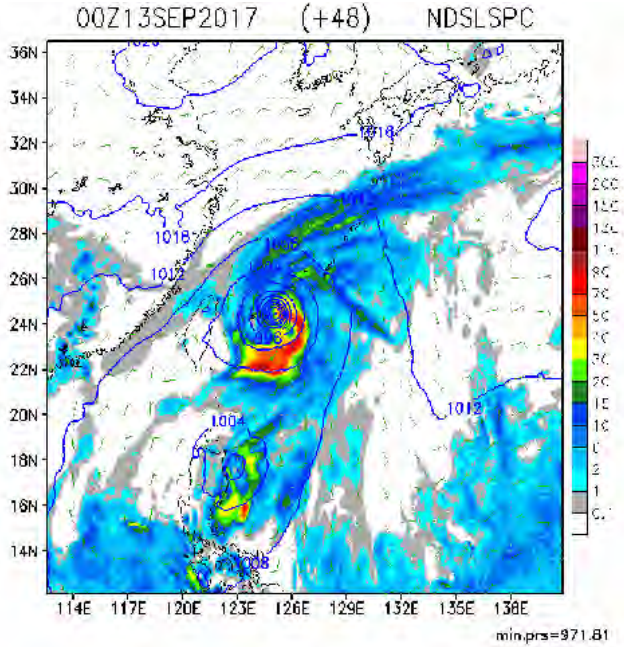


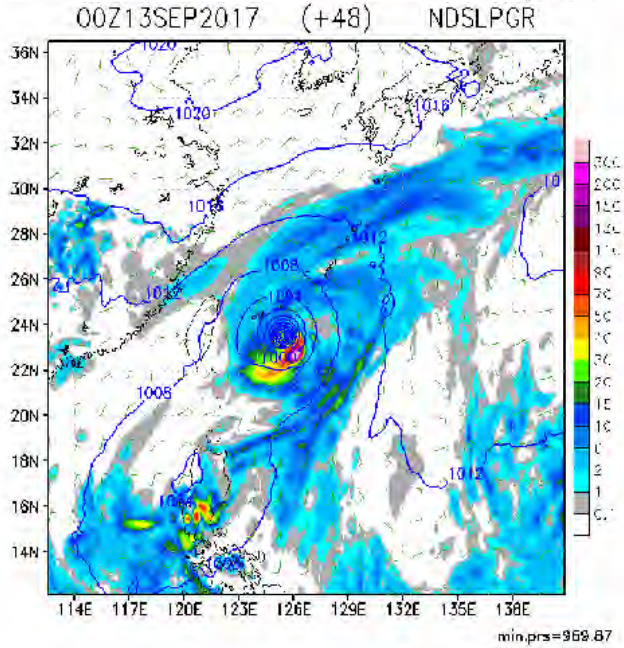
01:30 UTC

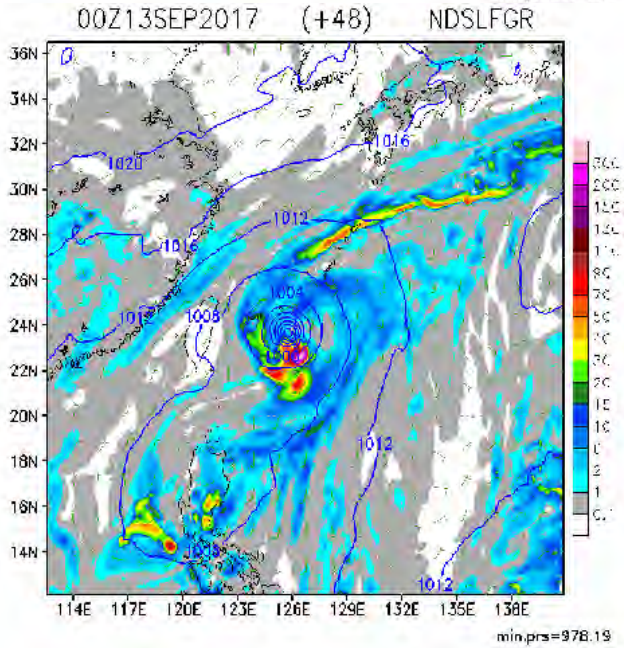
資料來源: CIMSS

泰利颱風(2017)-第48小時預報結果

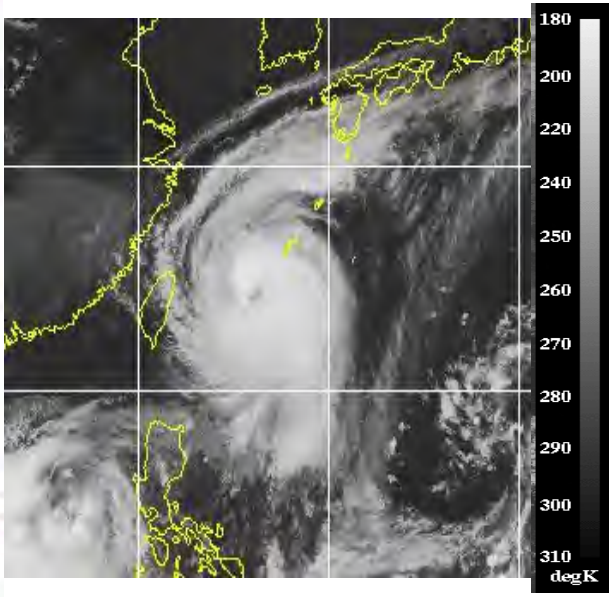








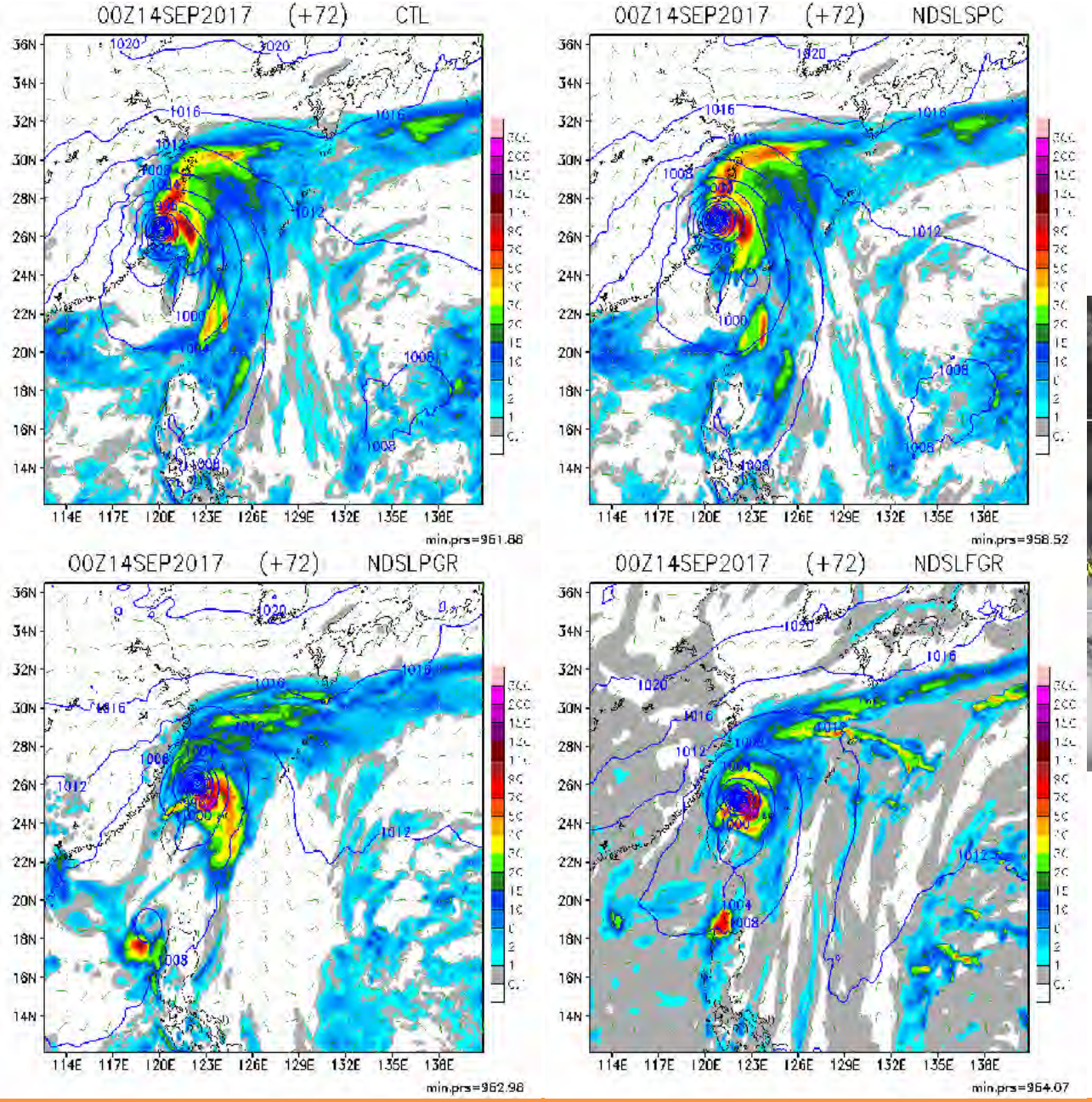
HIMAWARI INFRQRED



01:30 UTC

資料來源: CIMSS

泰利颱風(2017)-第72小時預報結果



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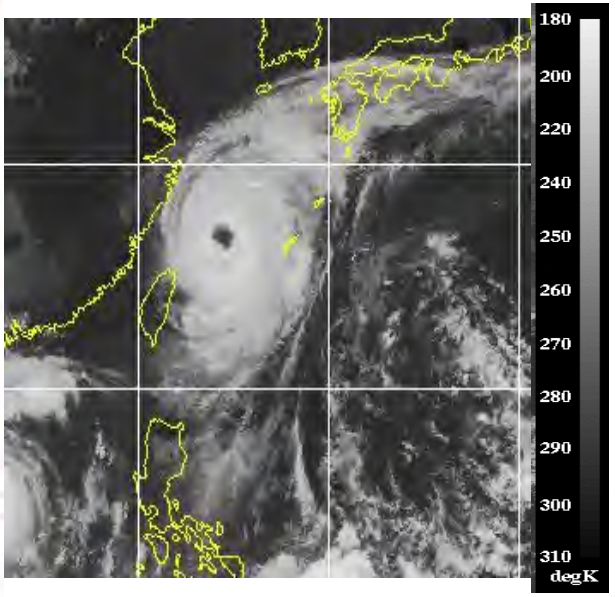
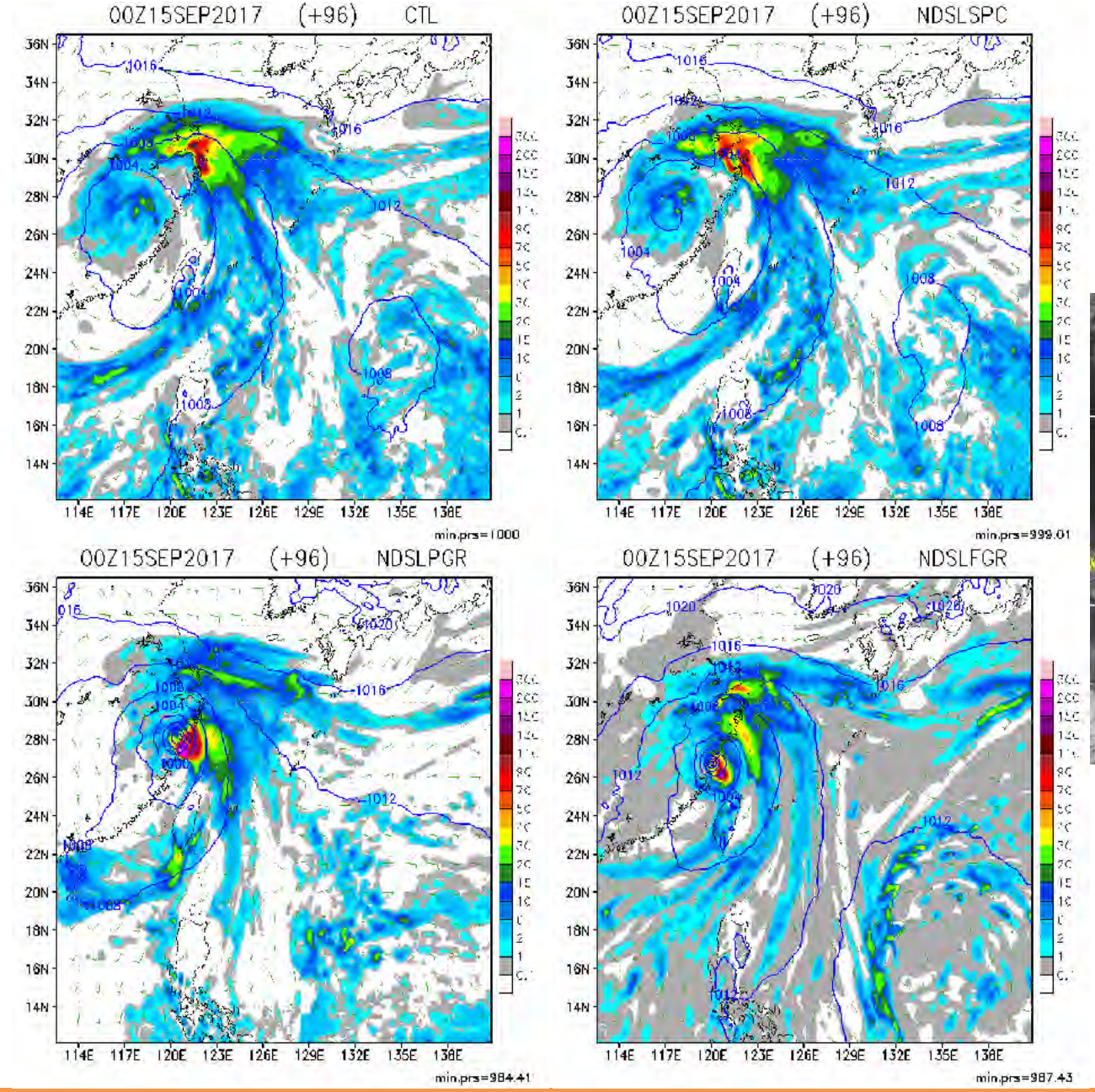


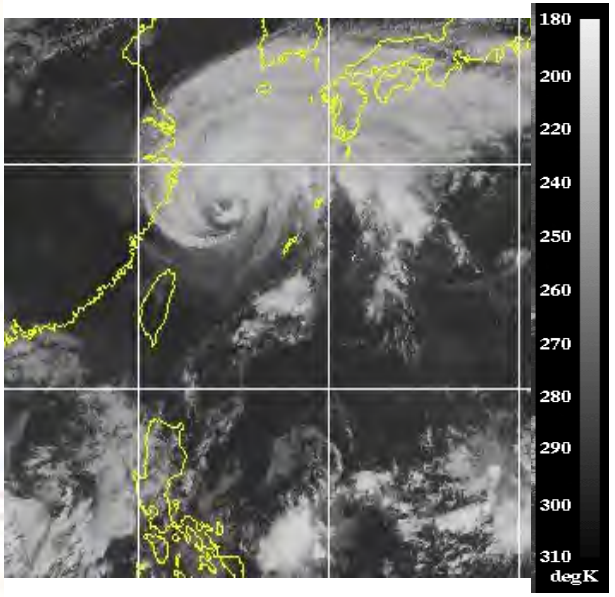
01:30 UTC

資料來源: CIMSS

泰利颱風(2017)-第96小時預報結果



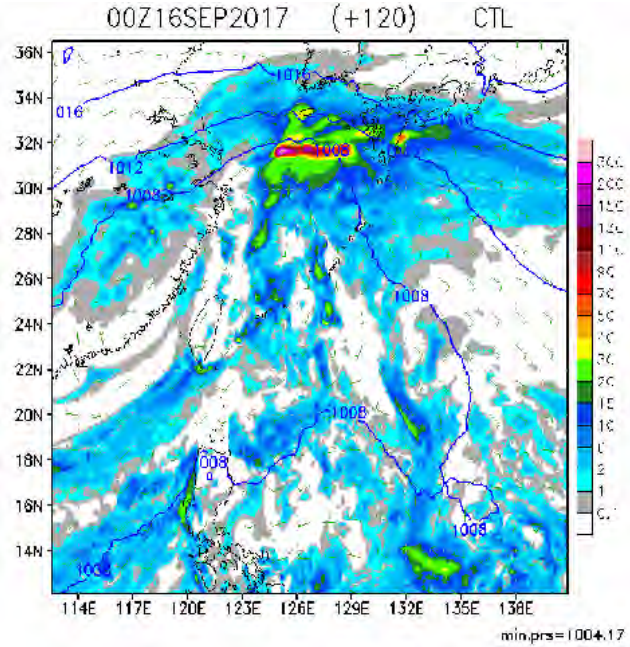
HIMAWARI INFRQRED

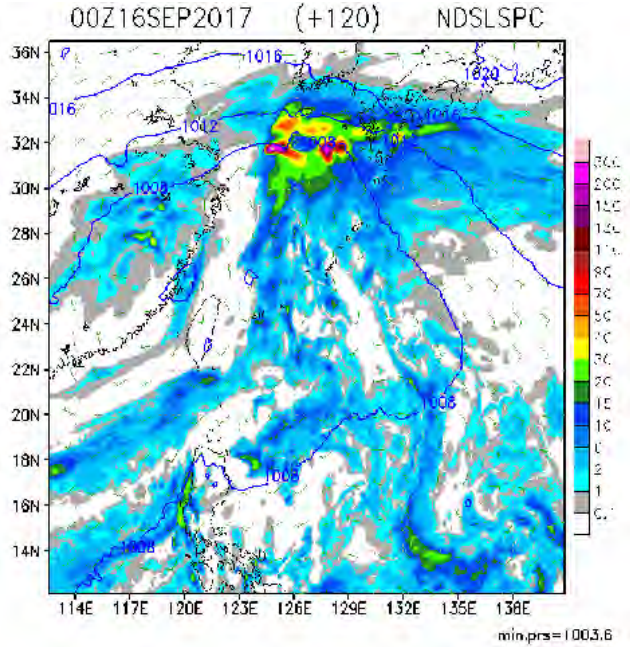


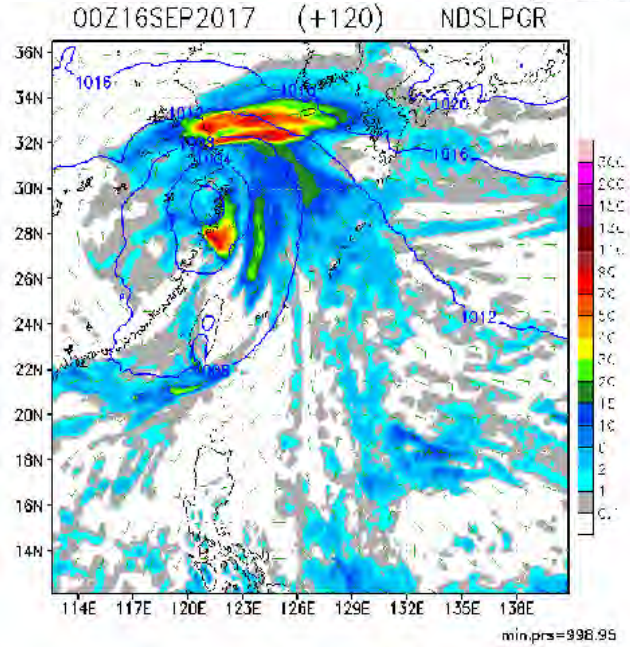
01:30 UTC

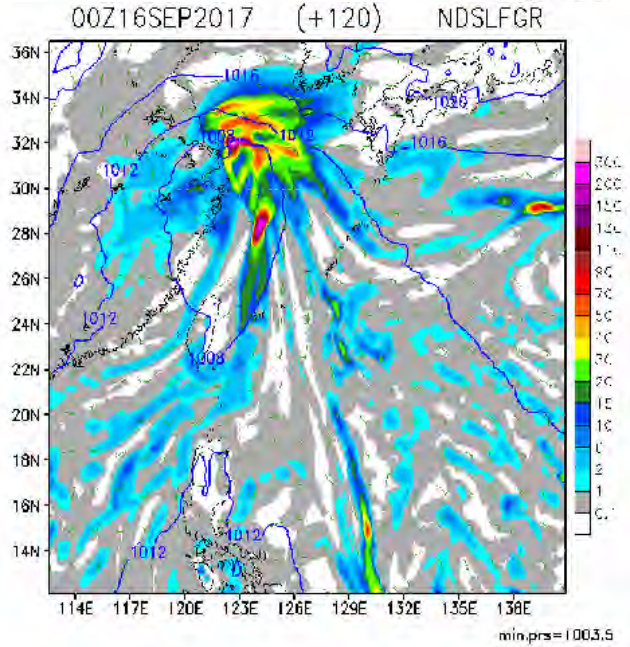
資料來源: CIMSS

泰利颱風(2017)-第120小時預報結果









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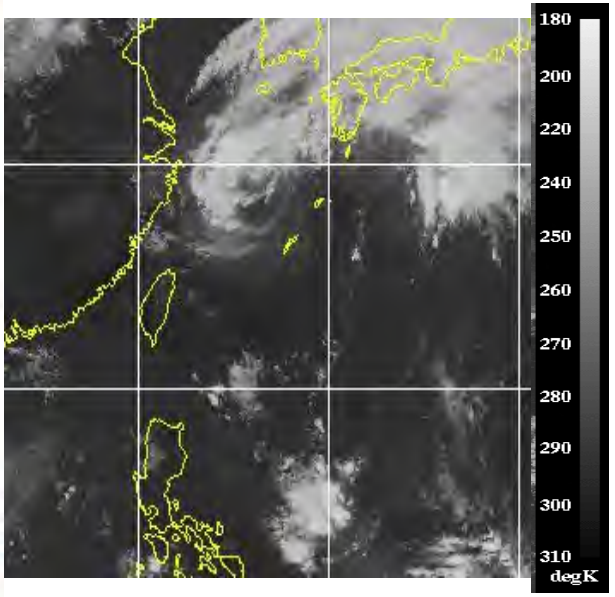
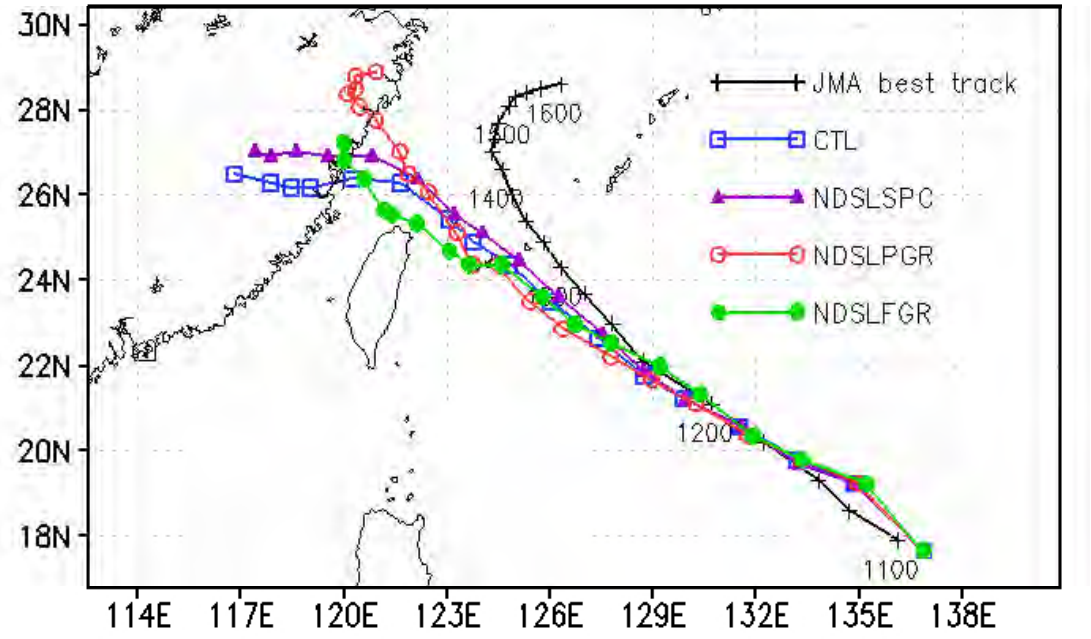


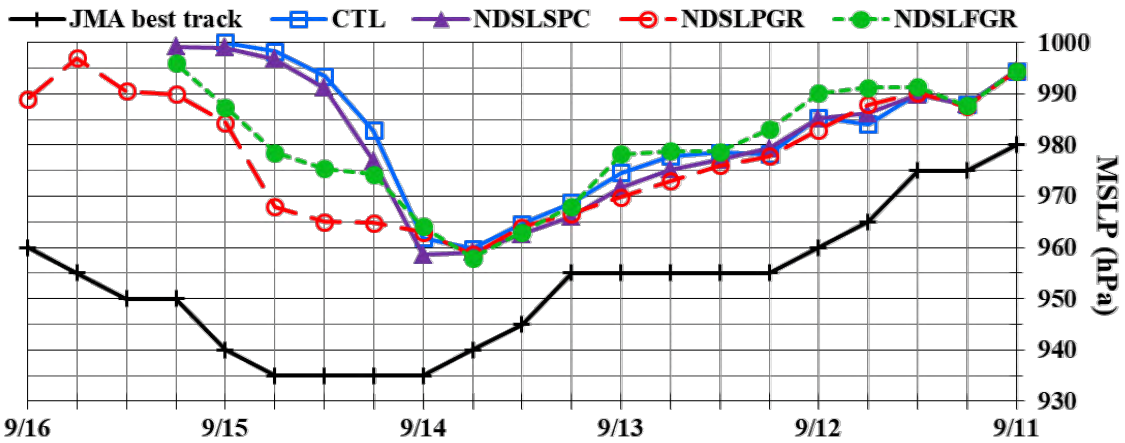
01:30 UTC

資料來源: CIMSS

泰利颱風(2017)路徑與MSLP趨勢圖。

(minimum sea level pressure)





Conclusions

1. By using higher resolution topography data **-SRTM 1 ARC Global**, the model can increase the resolution and more detail circulation could be simulated.

2. NDSL with perturbation lateral boundary relaxation and time filter (NDSL**PGR**) gives the most reasonable result in TY Talim (2017) simulation.
   1) without noises
   2) better track and typhoon intensity

Ongoing Works

1. Increasing model resolution with SRTM 1 Arc Global data
   - problem sizes may increase
   - speeding up the model will be very important

2. implementing NDSL into other dynamic variables (such as u, v, T, …) to increase the timestep

References

- Juang, H.-M. H. and M. Kanamitsu, 1994: The NMC nested regional spectral model, *Mon. Wea. Rev.*, **122**, 3-26.
- Juang, H.-M. H., S.-Y. Hong, and M. Kanamitsu, 1997: The NCEP regional spectral model: An update, *Bull. Amer. Meteor. Soc.* **78,** 2125-2143.
- Juang, H-M. H., 2000: The NCEP mesoscale spectral model: A revised version of the nonhydrostatic regional spectral model. *Mon. Wea. Rev.*, **128,** 2329–2362.
- Juang, H-M. H., 2007: Semi-Lagrangian advection without iteration. *Proc. Conf. on Weather Analysis and Forecasting*, Longtan, Taoyan, Taiwan, Central Weather Bureau, 277.
- Juang, H-M. H., 2008: Mass conserving and positive semi-Lagrangian tracer advection in NCEP GFS.*Proc. Conf. on Weather Analysis and Forecasting*, Taipei, Taiwan, Central Weather Bureau, 225–227.
- Zhang, Y., and H-M. H. Juang, 2012: A mass-conserving non-iteration-dimensional-split semi-Lagrangian advection scheme for limited-area modelling. *Q. J. R. Meteorol. Soc.*, **138**, 2118-2125.

References

- 氣象局颱風資料庫 http://rdc28.cwb.gov.tw/
- 國家災害防救中心天氣與氣候監測網 https://watch.ncdr.nat.gov.tw/watch_tracks.aspx
- CIMSS http://tropic.ssec.wisc.edu/
- Japan Meteorological Agency http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.html
- Google Maps. (2018). *Esperanza Accident*. Retrieved from https://www.google.com/maps/place/33%C2%B052'49.4%22N+116%C2%B048'58.1%22W/@33.8013313,-116.8757035,163410m/data=!3m1!1e3!4m5!3m4!1s0x0:0x0!8m2!3d33.88038!4d-116.81615
- USGS EarthExplorer: https://earthexplorer.usgs.gov/

Thanks for your attention!

- Comments and questions are welcome!

- Thank you!