2019 International Workshop
on Radiative Transfer Models for Satellite Data Assimilation

Assimilation of Doppler Radar Radial Velocity

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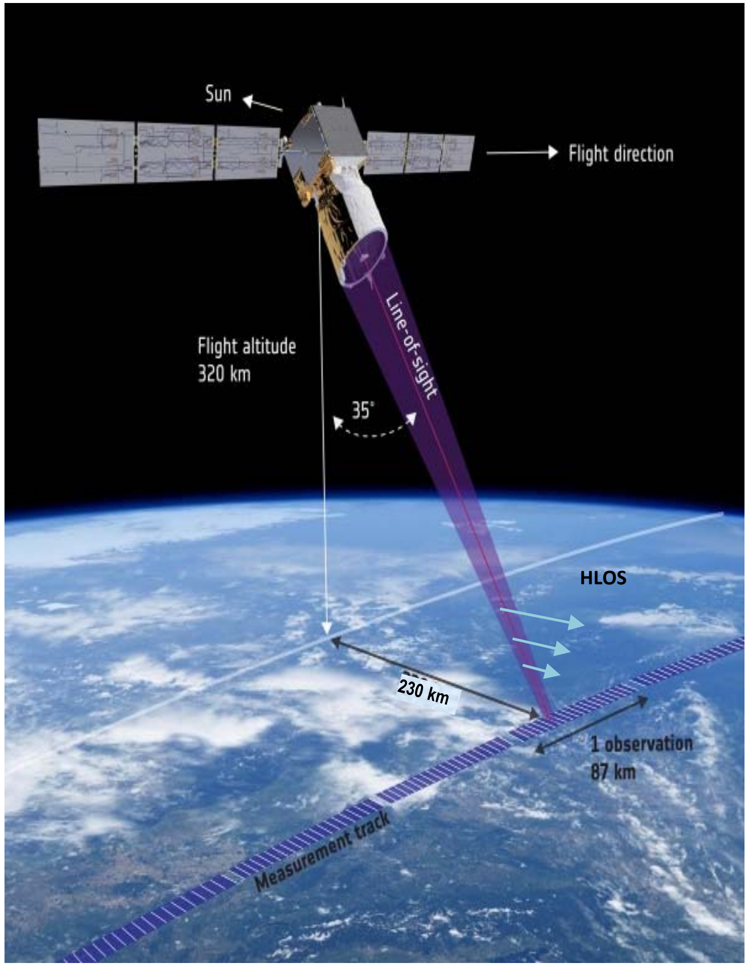
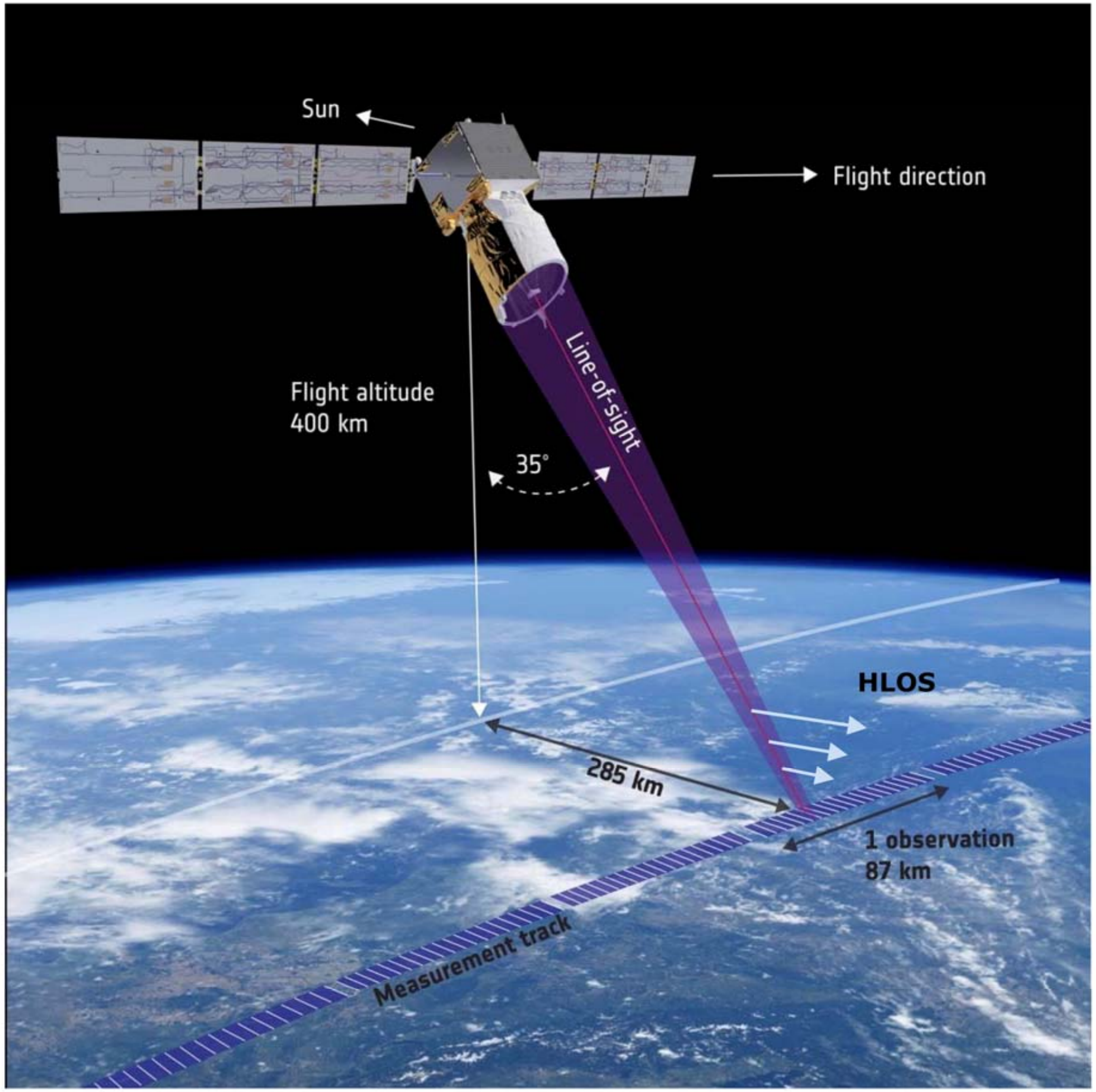
30th April 2019, TianJin



Aeolus: ESA's Wind Lidar Mission

RHEA GROUP


Sun
Flight direction
Line-of-sight
Flight altitude
400 km
35°
HLOS
285 km
1 observation
87 km
Measurement track

Outline

- Introduction
- The idea of IVAP method
- The operator based on IVAP
- Apply the new operator in GSI
- Conclusions & suggestions

Introduction

- Radar data were successfully used in nowcasting (*such as NCAR Auto-Nowcast System*)
- The positive impact of radar reflectivity in short range numerical weather prediction is well known (*Xiao 2007; Sun et al. 1997,2013; Zhao and Xue 2009*)
- Unconventionally observed parameters and mismatched resolutions between model and observation make radar assimilation difficult to implement (*Fabry and Kilambi 2011; Thompson et al. 2012*)
- The impacts of radar velocity in numerical model are uncertain

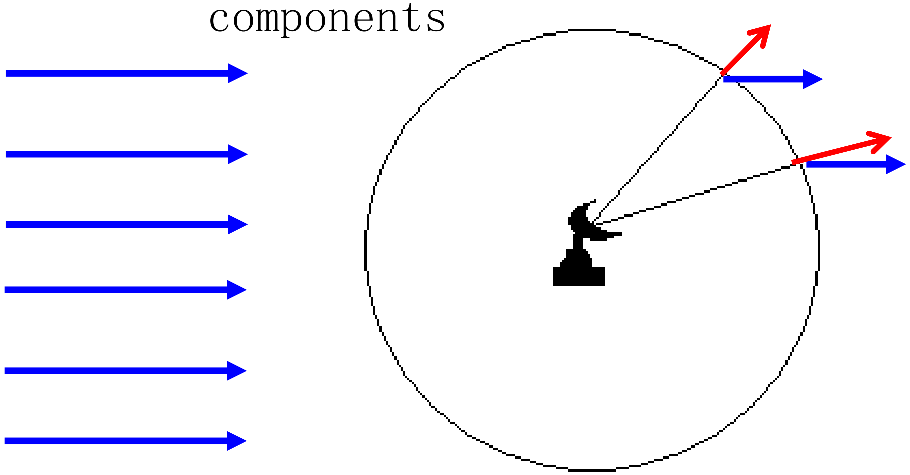
- Radar radial velocity can be directly assimilated using an observation operator (*such as GSI, WRF-DA*)
  (*Wu et al. 2002; Purser et al.2003; Hu et al. 2015; Shao et al. 2016*)

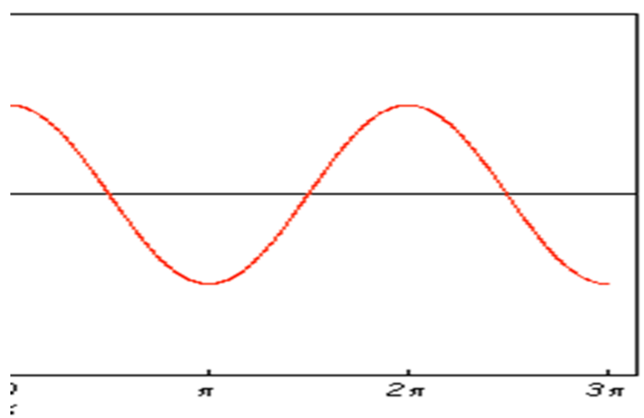
$$V_r = u\cos\theta\cos\alpha + v\sin\theta\cos\alpha + w\cos\alpha$$

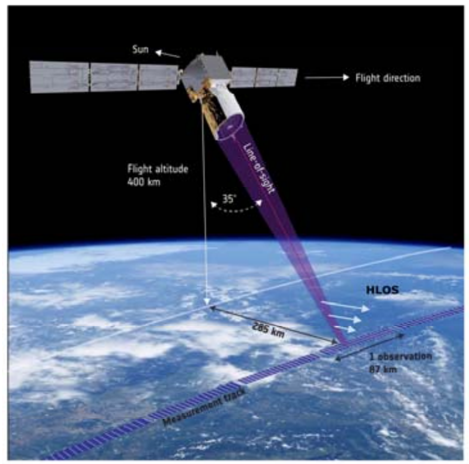
where (*u, v, w*) are model wind components in the Cartesian coordinate of (*x, y*), *u* is the azimuth of the radar, α is the radar elevation angle, and *Vr* is the radar radial velocity with the mass-weighted terminal velocity deducted.

Some problems in radar radial velocity assimilation

Radar radial velocity is projection of three wind components





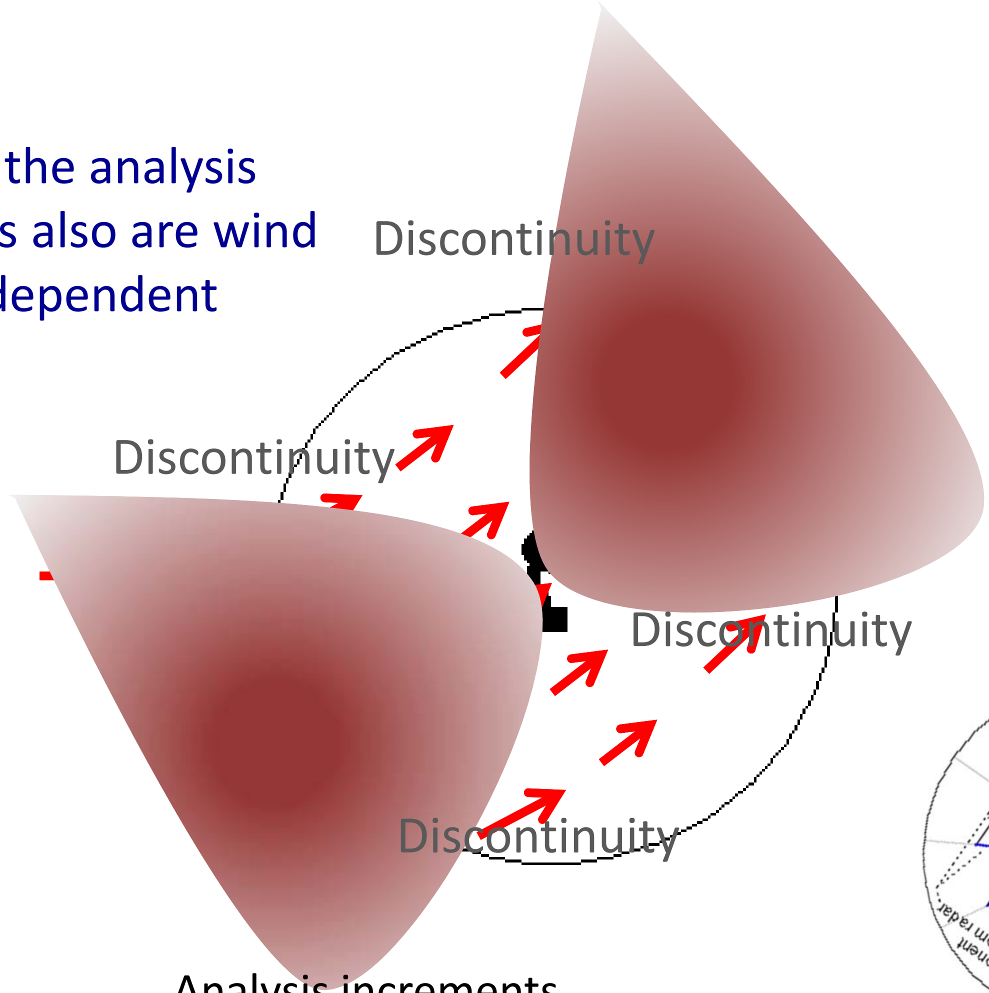


Observation operator

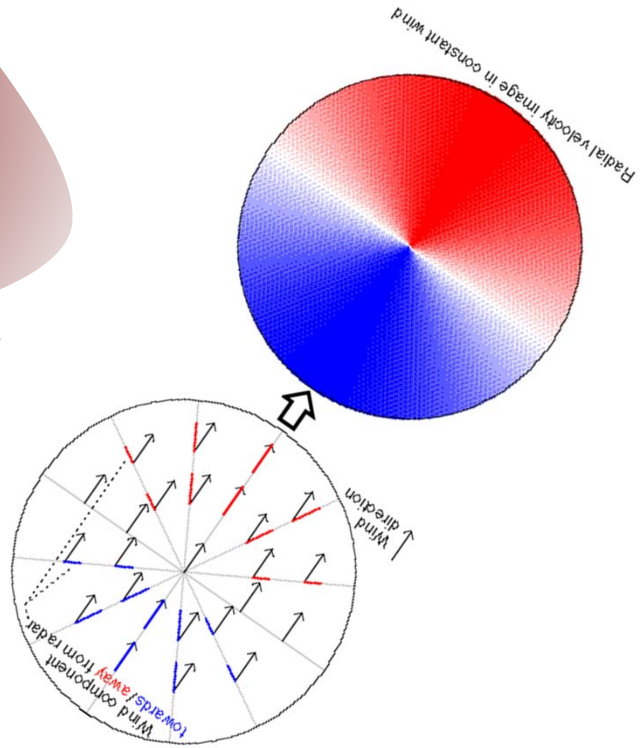
$$V_r = u\cos\theta\cos\alpha + v\sin\theta\cos\alpha + w\cos\alpha$$

1. Underdetermined problem

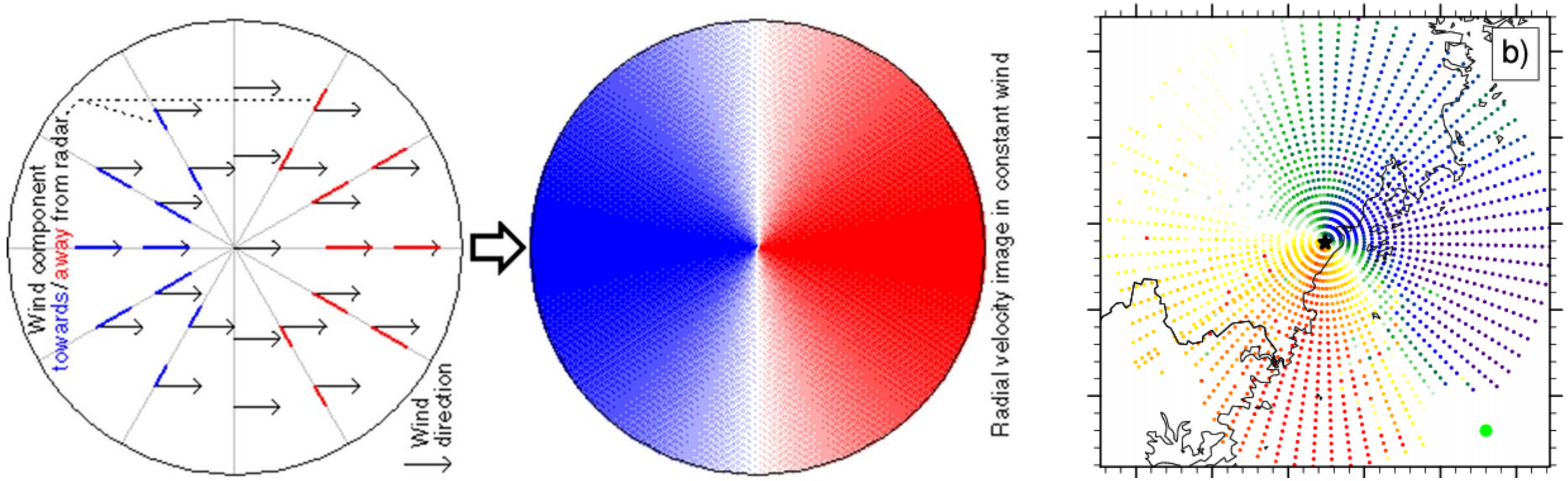
Generally, the analysis increments also are wind direction dependent



Analysis increments



2. Discontinuity caused by wind direction dependent



3. Higher and variant spatial resolution

$$V_r = u\cos\theta\cos\alpha + v\sin\theta\cos\alpha + w\cos\alpha$$

Problem	Outcome & resolution
1. Underdetermined problem	The impacts are uncertain (case dependent)
2. Discontinuity caused by wind direction dependent	Decrease the impacts (data thinning)
3. Higher and variant spatial resolution	Decrease the resolution (super-ob)

Less and less radar velocity are used

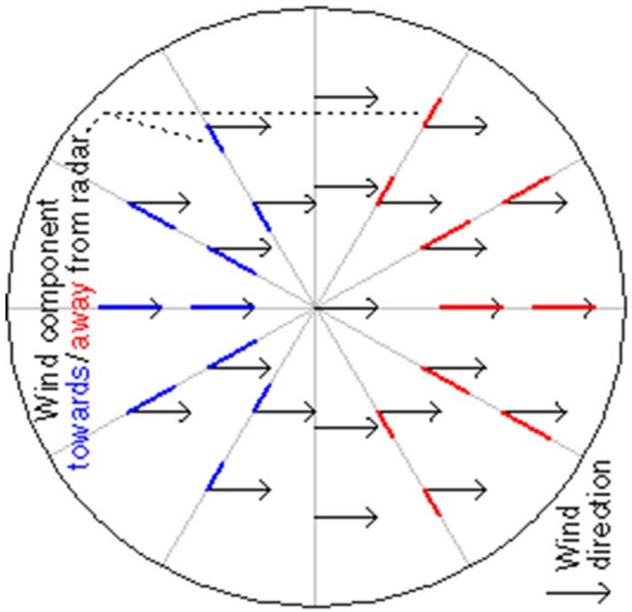
- To solve a underdetermined problem
  - Need more constraints (equations)
  - Need more samples for one equation(data)

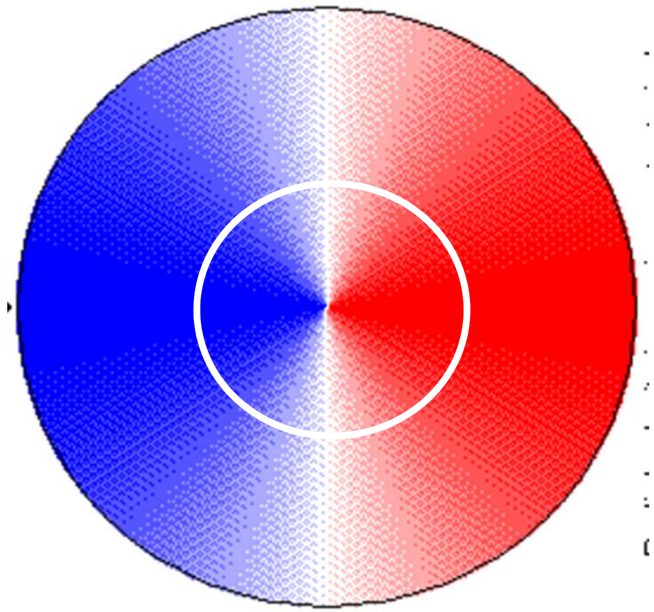
VDRAS (Four-Dimensional Variational Doppler Radar Analysis System) is a example (*Sun and Crook 1997*) for using more constraints and data.

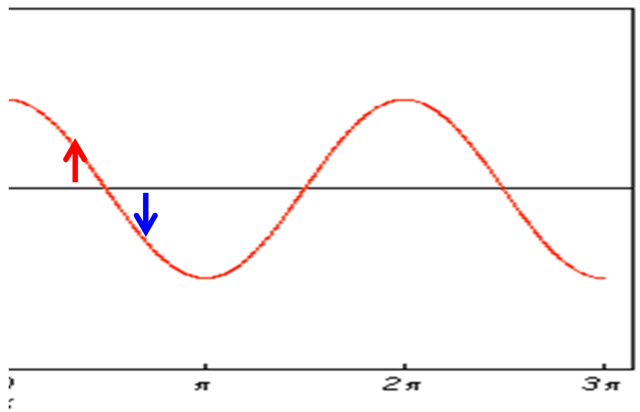
- Using a cloud-resolving model as a forward forecast model
- Assimilating radar observation within a time window

How to use more information of radar velocity observation ?

The idea of IVAP method



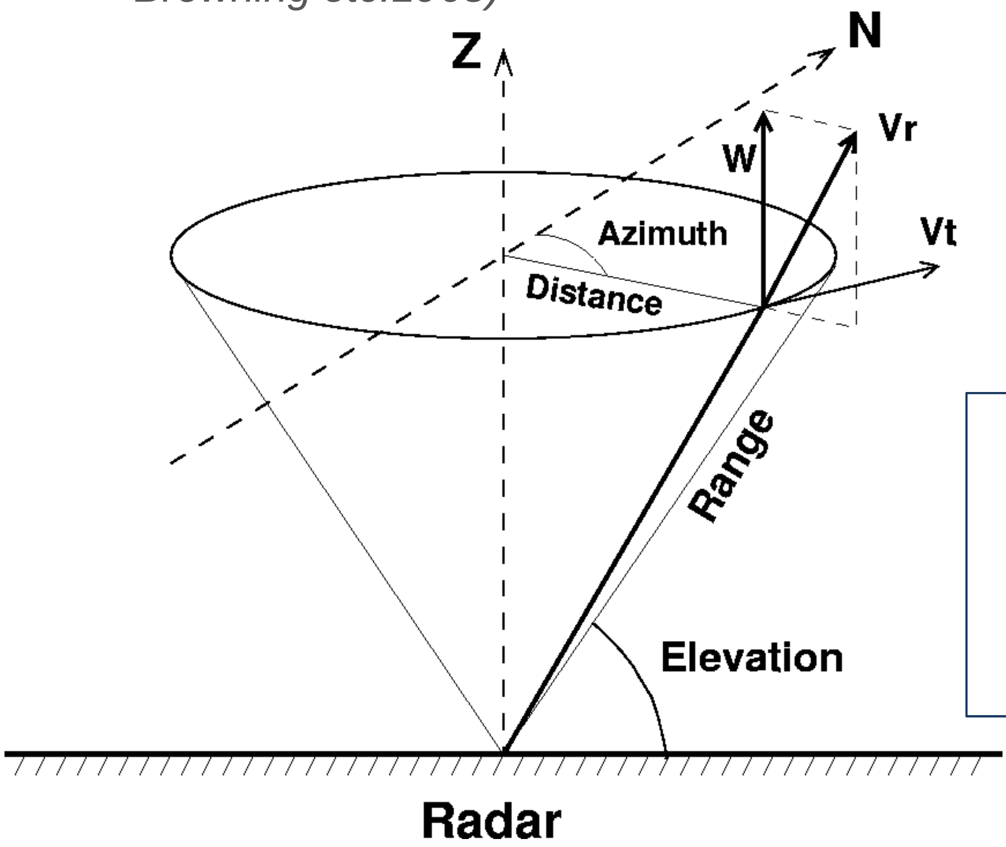




The variation of the velocity along the azimuth are useful

VAD method——Circle averaged wind

Velocity Azimuth Display, VAD (Caton 1963，Browning etc.1968)

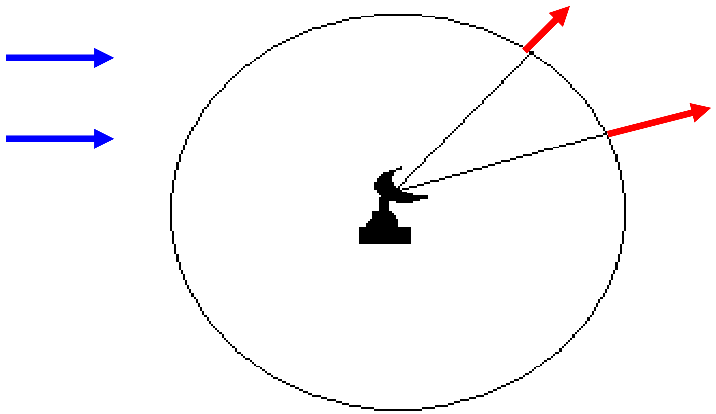


$$
\begin{aligned}
V_R &= \cos\theta\cos\phi u_0' + \sin\theta\cos\phi v_0' + \sin\phi w_0 \\
&+ [r\cos\theta\sin\theta\cos^2\phi - (\frac{x_0\cos\theta + y_0\sin\theta}{2})](v_x' + u_y') \\
&+ (r\cos^2\theta\sin^2\phi - x_0\sin\theta)u_x' \\
&+ (r\cos^2\theta\cos^2\phi - y_0\cos\theta)v_y' \\
&+ (r\sin\theta\sin\phi\cos\phi - z_0\sin\theta\cos\phi)u_z' \\
&+ (r\cos\theta\sin\phi\cos\phi - z_0\cos\theta\cos\phi)v_z' \\
&+ (r\sin^2\phi - z_0\sin\phi)w_z' \\
&+ (r\sin\theta\sin\phi\cos\phi - x_0\sin\phi)w_x' \\
&+ (r\cos\theta\sin\phi\cos\phi - y_0\sin\phi)w_y'
\end{aligned}
$$

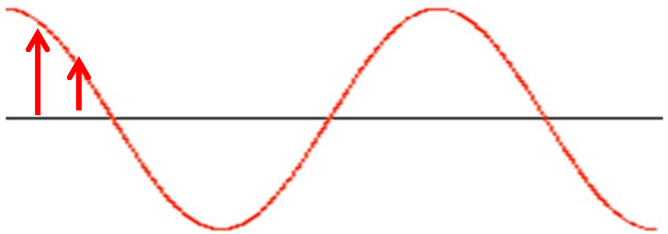
$$
u = \frac{-\int_0^{2\pi} V_\theta\cos\theta d\theta}{\int_0^{2\pi}\cos^2\theta d\theta} \qquad v = \frac{-\int_0^{2\pi} V_\theta\sin\theta d\theta}{\int_0^{2\pi}\sin^2\theta d\theta}
$$

VAP、UW technique－－small area averaged wind

Uniform Wind, UW (Persson etc. 1987)
Velocity Azimuth Process, VAP(Tao 1992)



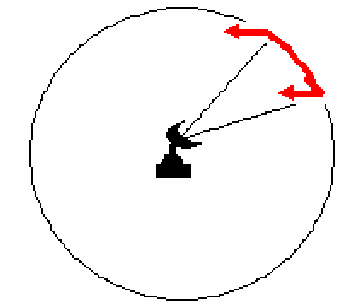
VAP/UW



$$u = \frac{V_{\theta 1} \sin\theta_2 - V_{\theta 2} \sin\theta_1}{\sin\theta_1 \cos\theta_2 - \sin\theta_2 \cos\theta_1}$$

$$v = \frac{-V_{\theta 1} \cos\theta_2 + V_{\theta 2} \cos\theta_1}{\sin\theta_1 \cos\theta_2 - \sin\theta_2 \cos\theta_1}$$

IVAP method (Integrating Velocity-Azimuth Process)



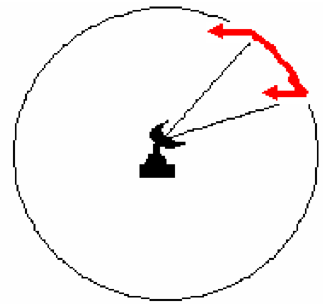
$$V_\theta = u_\theta \cos\theta + v_\theta \sin\theta$$

$$\int_{\theta_1}^{\theta_2} V_\theta \sin\theta\, d\theta = \int_{\theta_1}^{\theta_2} u_\theta \cos\theta \sin\theta\, d\theta + \int_{\theta_1}^{\theta_2} v_\theta \sin^2\theta d\theta$$

$$\int_{\theta_1}^{\theta_2} V_\theta \cos\theta\, d\theta = \int_{\theta_1}^{\theta_2} u_\theta \cos^2\theta\, d\theta + \int_{\theta_1}^{\theta_2} v_\theta \cos\theta \sin\theta d\theta$$

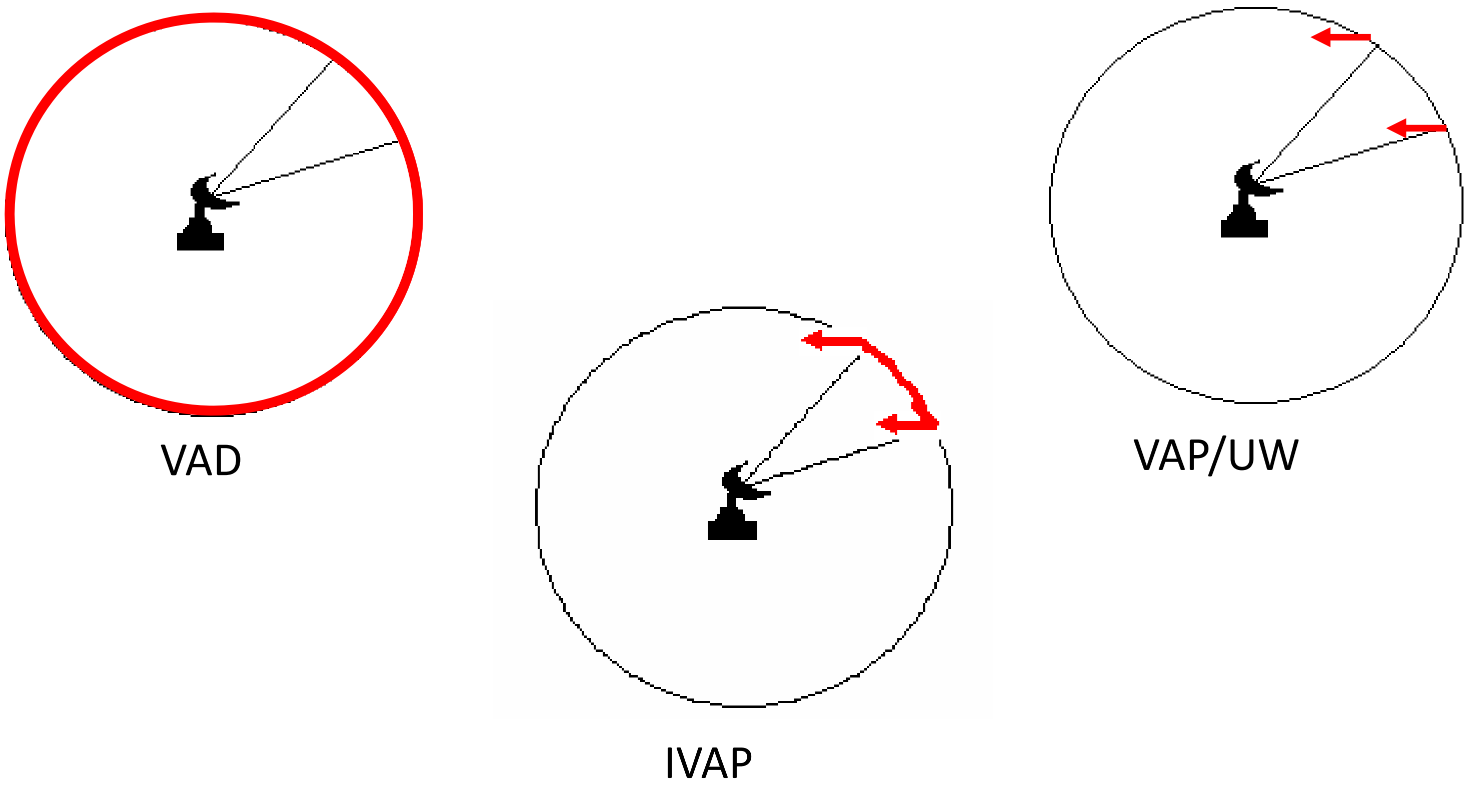
$$u = \frac{\int_{\theta_1}^{\theta_2} V_\theta \cos\theta\, d\theta \int_{\theta_1}^{\theta_2} \sin^2\theta d\theta - \int_{\theta_1}^{\theta_2} V_\theta \sin\theta\, d\theta \int_{\theta_1}^{\theta_2} \cos\theta \sin\theta\, d\theta}{-\int_{\theta_1}^{\theta_2} \sin^2\theta d\theta \int_{\theta_1}^{\theta_2} \cos^2\theta\, d\theta + (\int_{\theta_1}^{\theta_2} \cos\theta \sin\theta\, d\theta)^2}$$

$$v = \frac{\int_{\theta_1}^{\theta_2} V_\theta \sin\theta\, d\theta \int_{\theta_1}^{\theta_2} \cos^2\theta\, d\theta - \int_{\theta_1}^{\theta_2} V_\theta \cos\theta\, d\theta \int_{\theta_1}^{\theta_2} \cos\theta \sin\theta\, d\theta}{-\int_{\theta_1}^{\theta_2} \cos^2\theta\, d\theta \int_{\theta_1}^{\theta_2} \sin^2\theta d\theta + (\int_{\theta_1}^{\theta_2} \cos\theta \sin\theta d\theta)^2}$$



Giving averaged (u, v) within a given sector

Liang X., 2007: An Integrating Velocity-Azimuth Process Single-Doppler Radar Wind Retrieval Method. ***J. Atmos. Oceanic Technol.****, 24, 658-665*



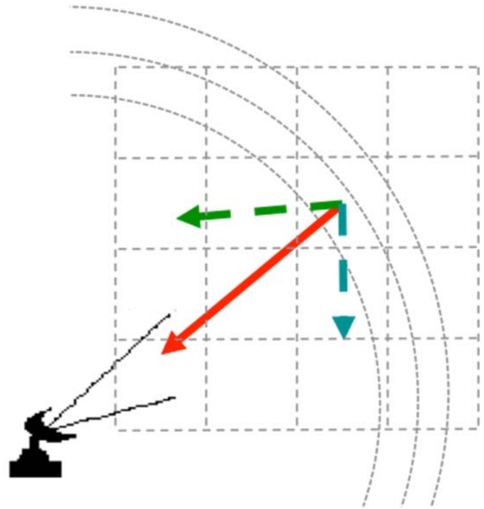
The size of the sector can be chosen as demand

$$v=\frac{\int_{\theta_1}^{\theta_2} V_\theta \sin\theta\, d\theta \int_{\theta_1}^{\theta_2} \cos^2\theta\, d\theta - \int_{\theta_1}^{\theta_2} V_\theta \cos\theta\, d\theta \int_{\theta_1}^{\theta_2} \cos\theta \sin\theta\, d\theta}{-\int_{\theta_1}^{\theta_2} \cos^2\theta\, d\theta \int_{\theta_1}^{\theta_2} \sin^2\theta\, d\theta + \left(\int_{\theta_1}^{\theta_2} \cos\theta \sin\theta\, d\theta\right)^2}$$

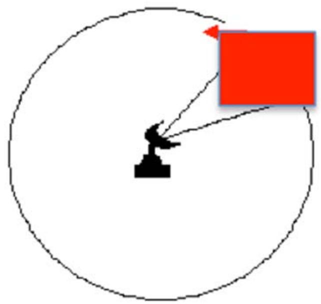
$$u=\frac{\int_{\theta_1}^{\theta_2} V_\theta \cos\theta\, d\theta \int_{\theta_1}^{\theta_2} \sin^2\theta\, d\theta - \int_{\theta_1}^{\theta_2} V_\theta \sin\theta\, d\theta \int_{\theta_1}^{\theta_2} \cos\theta \sin\theta\, d\theta}{-\int_{\theta_1}^{\theta_2} \sin^2\theta\, d\theta \int_{\theta_1}^{\theta_2} \cos^2\theta\, d\theta + \left(\int_{\theta_1}^{\theta_2} \cos\theta \sin\theta\, d\theta\right)^2}$$

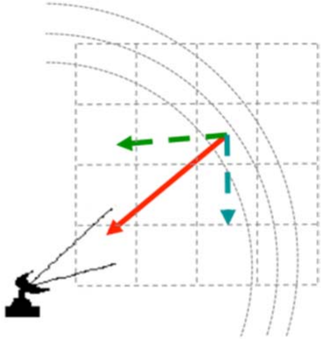
The Operator Based on IVAP

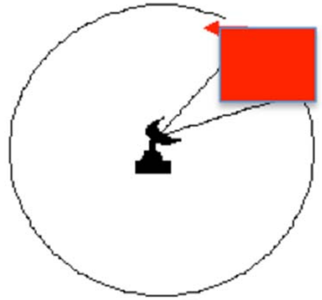
$$V_r = u\cos\theta\cos\alpha + v\sin\theta\cos\alpha + w\cos\alpha$$



$$\begin{cases} \sum_{\Omega} V_r \sin\theta = \bar{u}\sum_{\Omega}\sin\theta\cos\theta\cos\alpha + \bar{v}\sum_{\Omega}\sin^2\theta\cos\alpha + \bar{w}\sum_{\Omega}\sin\theta\sin\alpha \\ \sum_{\Omega} V_r \cos\theta = \bar{u}\sum_{\Omega}\cos^2\theta\cos\alpha + \bar{v}\sum_{\Omega}\sin\theta\cos\theta\cos\alpha + \bar{w}\sum_{\Omega}\cos\theta\sin\alpha \end{cases}$$







$$V_r = u\cos\theta\cos\alpha + v\sin\theta\cos\alpha + w\cos\alpha$$

$$\begin{cases} \sum_{\Omega} V_r \sin\theta = \bar{u}\sum_{\Omega}\sin\theta\cos\theta\cos\alpha + \bar{v}\sum_{\Omega}\sin^2\theta\cos\alpha + \bar{w}\sum_{\Omega}\sin\theta\sin\alpha \\ \sum_{\Omega} V_r \cos\theta = \bar{u}\sum_{\Omega}\cos^2\theta\cos\alpha + \bar{v}\sum_{\Omega}\sin\theta\cos\theta\cos\alpha + \bar{w}\sum_{\Omega}\cos\theta\sin\alpha \end{cases}$$

Underdetermined problem

Discontinuity caused by wind direction dependent

Higher and variant spatial resolution

Less data are used

Two equations

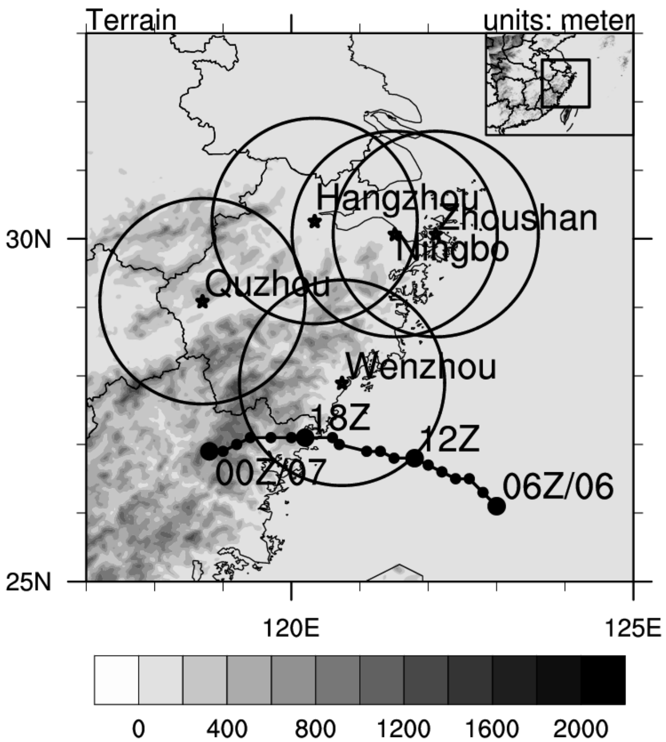
(*with assumption*)

A given sector with same size and shape in both radar and model coordinates

Using all of the data within the sector

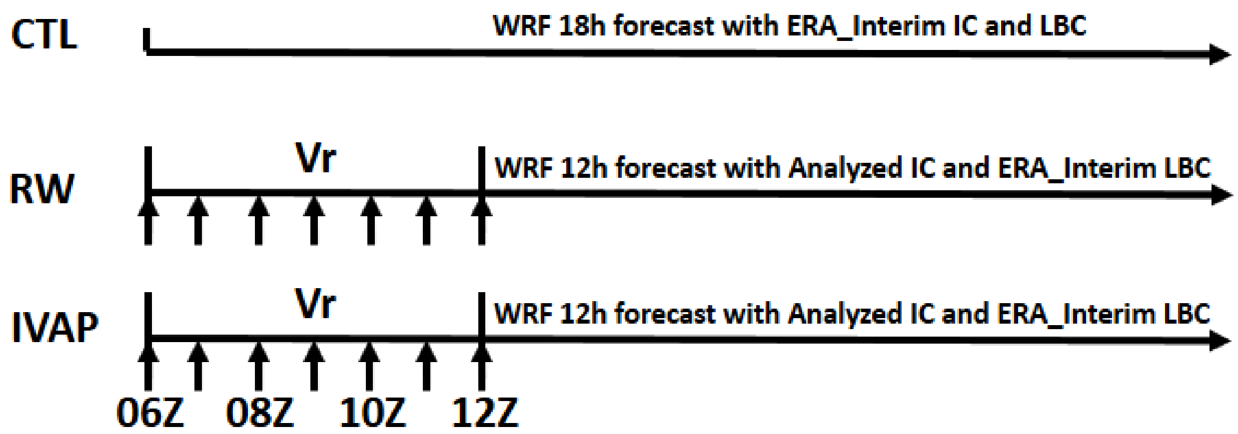
More data are used

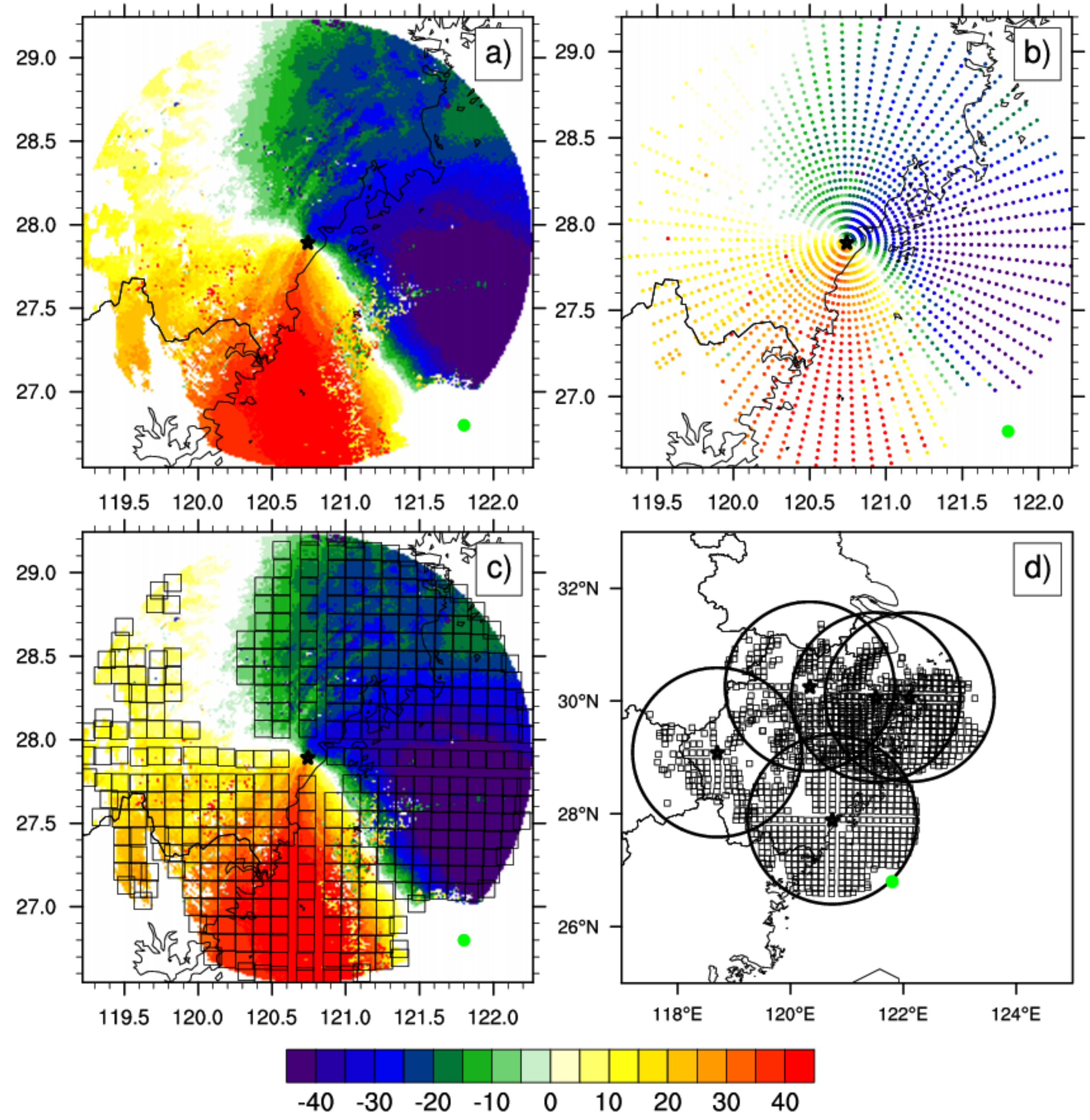
Chen F., X. Liang, 2017: Application of IVAP-based observation operator in radar radial velocity assimilation: the case of Typhoon Fitow, **Mon. Wea. Rev.**, 145, 4187-4203.*



Case study
Typhoon Fitow(2013)

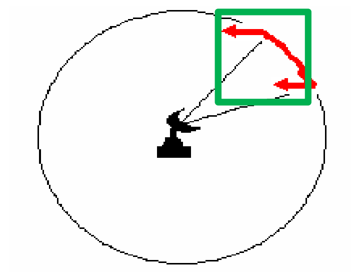
Data assimilation system： GSI
Model： WRF
Horizontal resolution： 3km
Data： : 06UTC 6th—00UTC, 7th Oct. 2013



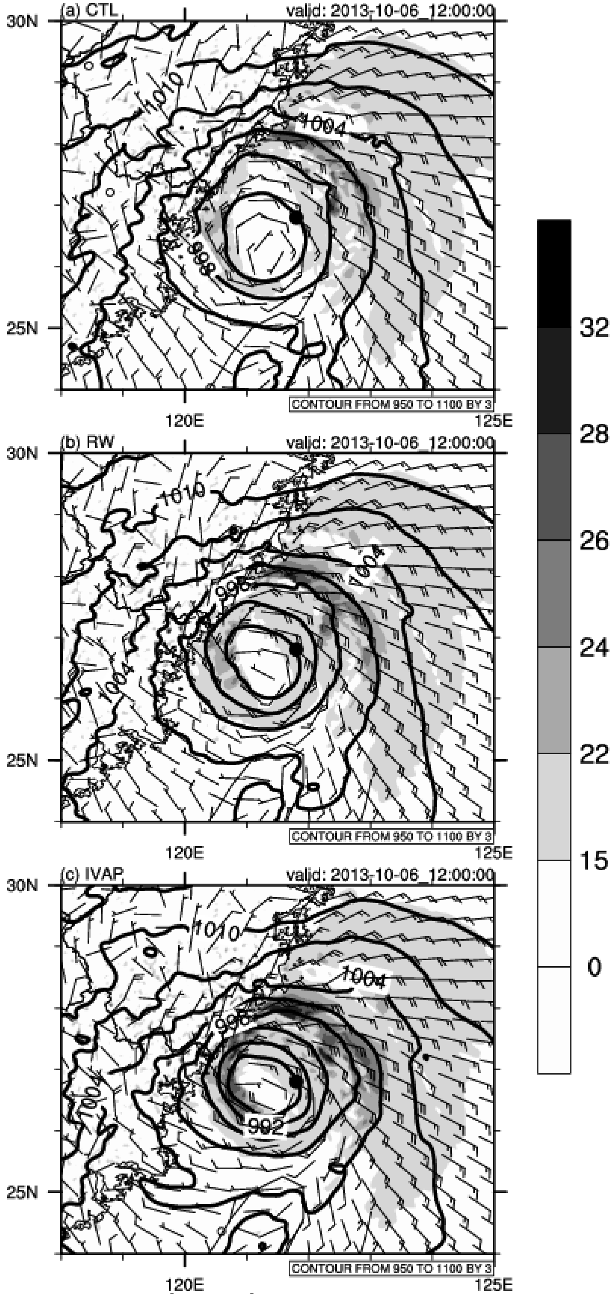


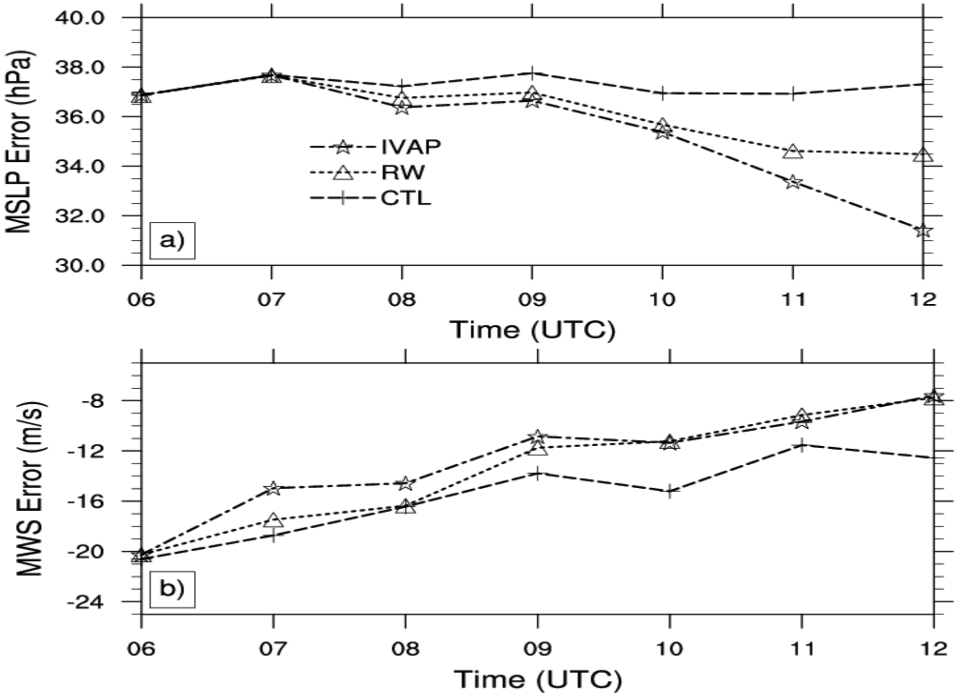
elevation angle 0.5°

(a) Raw data
(b) Super observation in GSI
(c) Data groups in IVAP method(12km*12km)
(d) Radar network

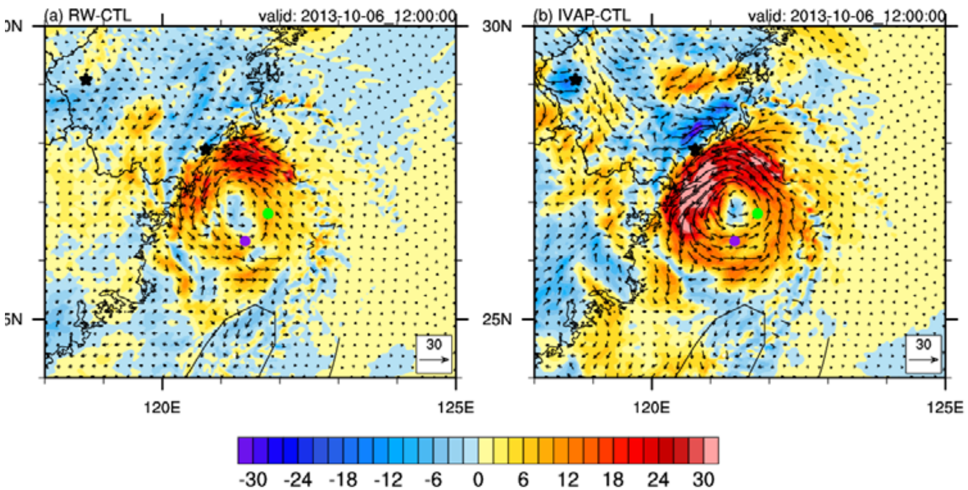


IVAP



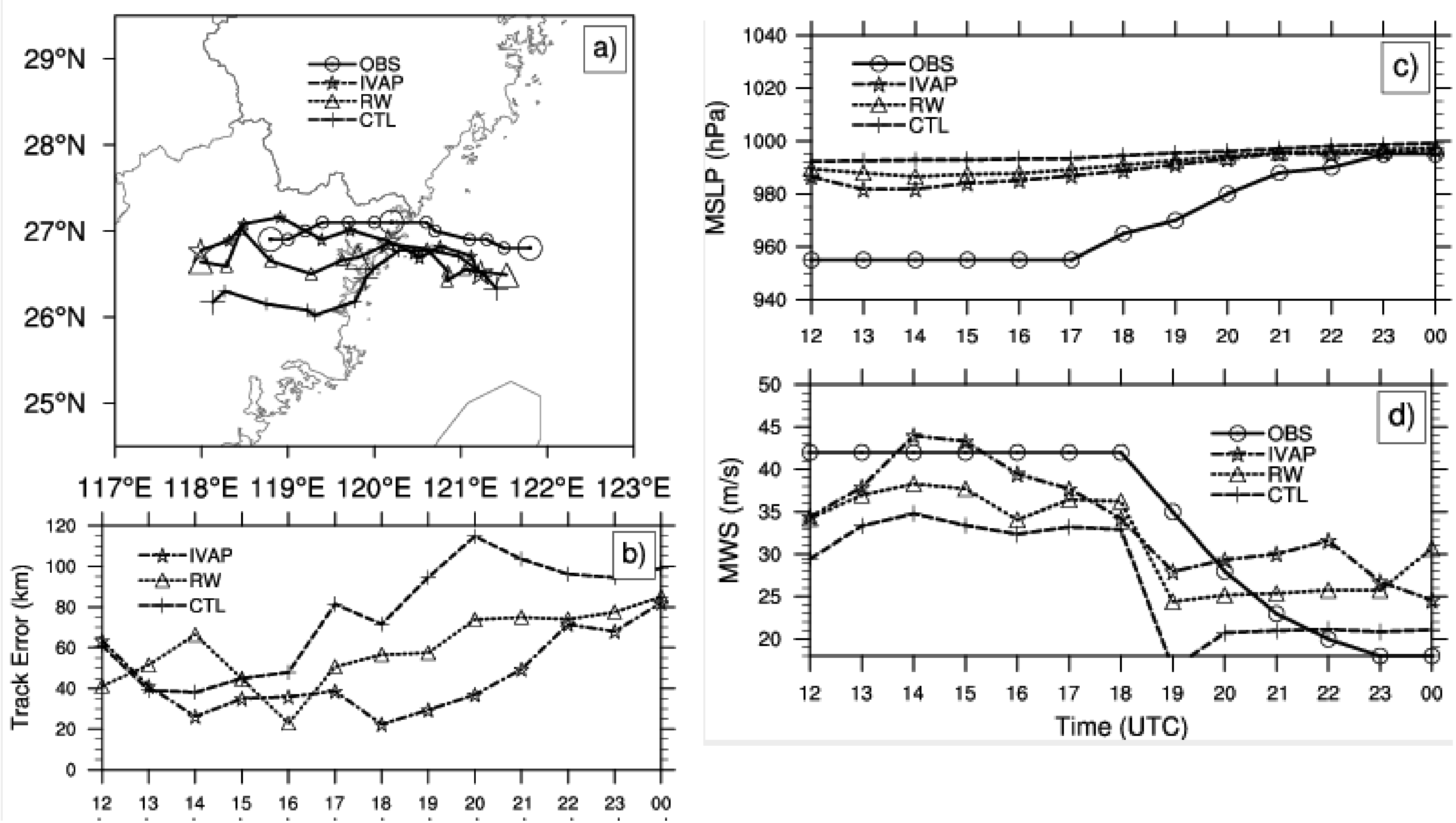


Errors of Intensity during the assimilation cycle



Analyse wind filed (right) vs background (left) on the of 3km height level

Sea level pressure and wind fields



12hr forecast

Apply the New Operator in GSI

"Evaluation of a Newly Developed Observation Operators for Assimilating Radar Radial Velocity Observations in GSI to Improve Storm Forecast Using the HRRR System"

Support for this project was provided by the Developmental Testbed Center (DTC)

$$\begin{cases} \dfrac{\sum\limits_{\Omega} V_r \sin\theta}{\sum\limits_{\Omega} \sin^2\theta\cos\alpha} = \bar{u}\dfrac{\sum\limits_{\Omega} \sin\theta\cos\theta\cos\alpha}{\sum\limits_{\Omega} \sin^2\theta\cos\alpha} + \bar{v} + \bar{w}\dfrac{\sum\limits_{\Omega} \sin\theta\sin\alpha}{\sum\limits_{\Omega} \sin^2\theta\cos\alpha} \\ \dfrac{\sum\limits_{\Omega} V_r \cos\theta}{\sum\limits_{\Omega} \cos^2\theta\cos\alpha} = \bar{u} + \bar{v}\dfrac{\sum\limits_{\Omega} \sin\theta\cos\theta\cos\alpha}{\sum\limits_{\Omega} \cos^2\theta\cos\alpha} + \bar{w}\dfrac{\sum\limits_{\Omega} \cos\theta\sin\alpha}{\sum\limits_{\Omega} \cos^2\theta\cos\alpha} \end{cases}$$

$$\begin{cases} Y_1 = \dfrac{\sum\limits_{\Omega} V_r \sin\theta}{\sum\limits_{\Omega} \sin^2\theta\cos\varphi} \\ Y_2 = \dfrac{\sum\limits_{\Omega} V_r \cos\theta}{\sum\limits_{\Omega} \cos^2\theta\cos\varphi} \end{cases}$$

$$\begin{cases} H_1 = \bar{u}\dfrac{\sum\limits_{\Omega} \sin\theta\cos\theta\cos\alpha}{\sum\limits_{\Omega} \sin^2\theta\cos\alpha} + \bar{v} + \bar{w}\dfrac{\sum\limits_{\Omega} \sin\theta\sin\alpha}{\sum\limits_{\Omega} \sin^2\theta\cos\alpha} \\ H_2 = \bar{u} + \bar{v}\dfrac{\sum\limits_{\Omega} \sin\theta\cos\theta\cos\alpha}{\sum\limits_{\Omega} \cos^2\theta\cos\alpha} + \bar{w}\dfrac{\sum\limits_{\Omega} \cos\theta\sin\alpha}{\sum\limits_{\Omega} \cos^2\theta\cos\alpha} \end{cases}$$

$$J = J_b + J_o$$

$$J_o^r = \frac{1}{2}\left\{\begin{bmatrix} H_1 - Y_1 \\ H_2 - Y_2 \end{bmatrix}^T R^{-1} \begin{bmatrix} H_1 - Y_1 \\ H_2 - Y_2 \end{bmatrix}\right\}$$

Compatibility of the the new operator to the old one

$$V_1 = u_1 \cos\theta_1 + v_1 \sin\theta_1$$
$$V_2 = u_2 \cos\theta_2 + v_2 \sin\theta_2$$
$$V_3 = u_3 \cos\theta_3 + v_3 \sin\theta_3$$

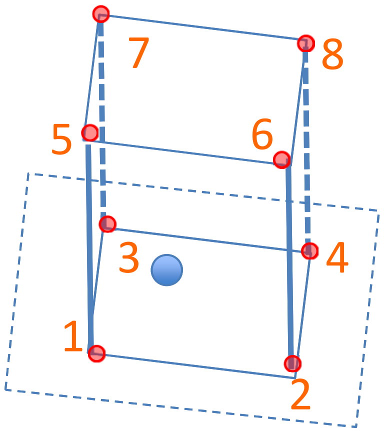
....

$$V_1 = \bar{u} \cos\theta_1 + \bar{v} \sin\theta_1$$
$$V_2 = \bar{u} \cos\theta_2 + \bar{v} \sin\theta_2$$
$$V_3 = \bar{u} \cos\theta_3 + \bar{v} \sin\theta_3$$

....

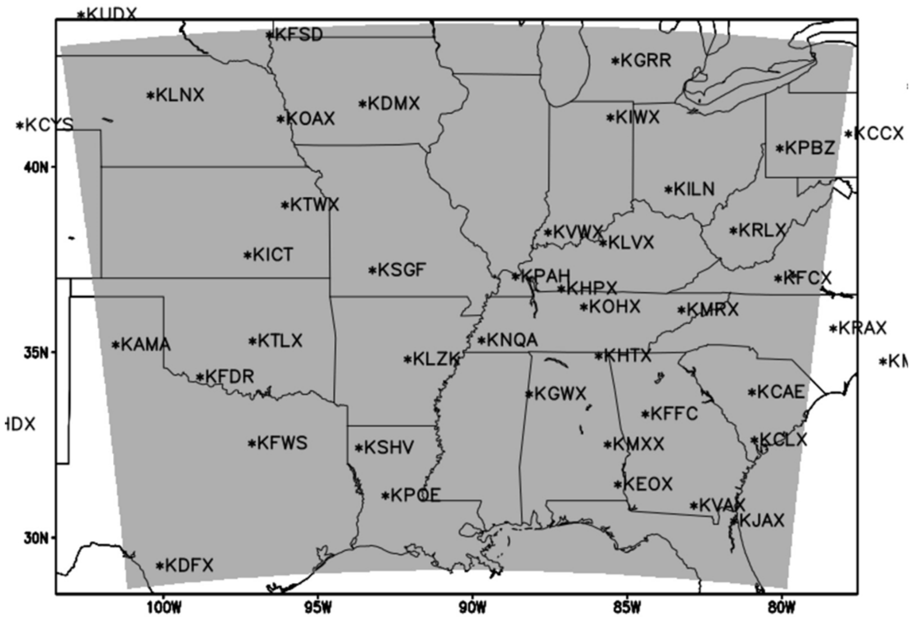
Control the distributions of the data	Super-ob method	read_l2bufr_mod.f90
	Data thinning	read_radar.f90
Operator	Gaussian Smoothing Filter instead of bi-linear interpolation	intsrw.f90 stprw.f90

$$\frac{1}{2\pi\sigma^2} \exp\{-\frac{x^2+y^2}{2\sigma^2}\}$$

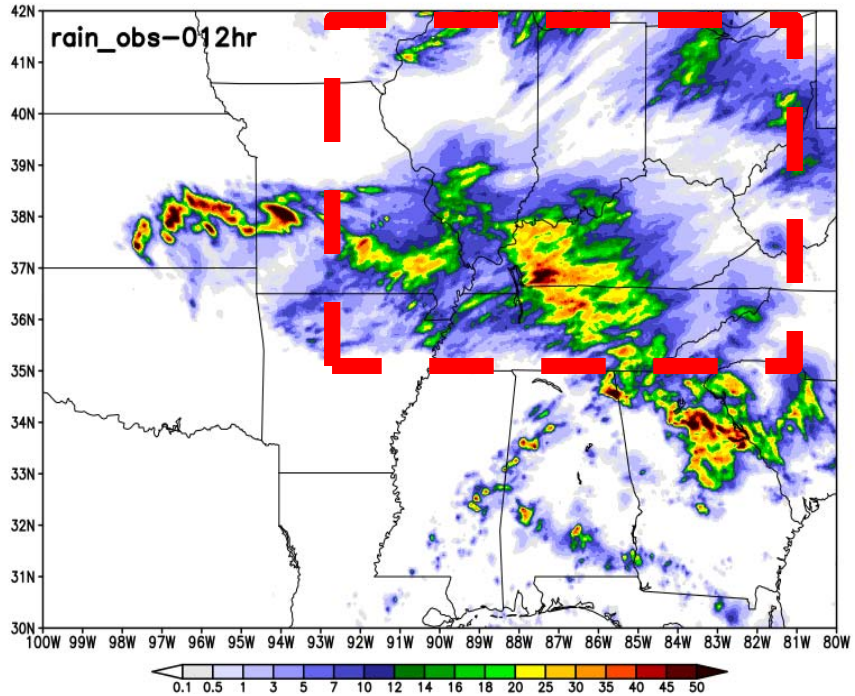


Primary Results of a Case Test

- Initial time 00Z27Jun2018



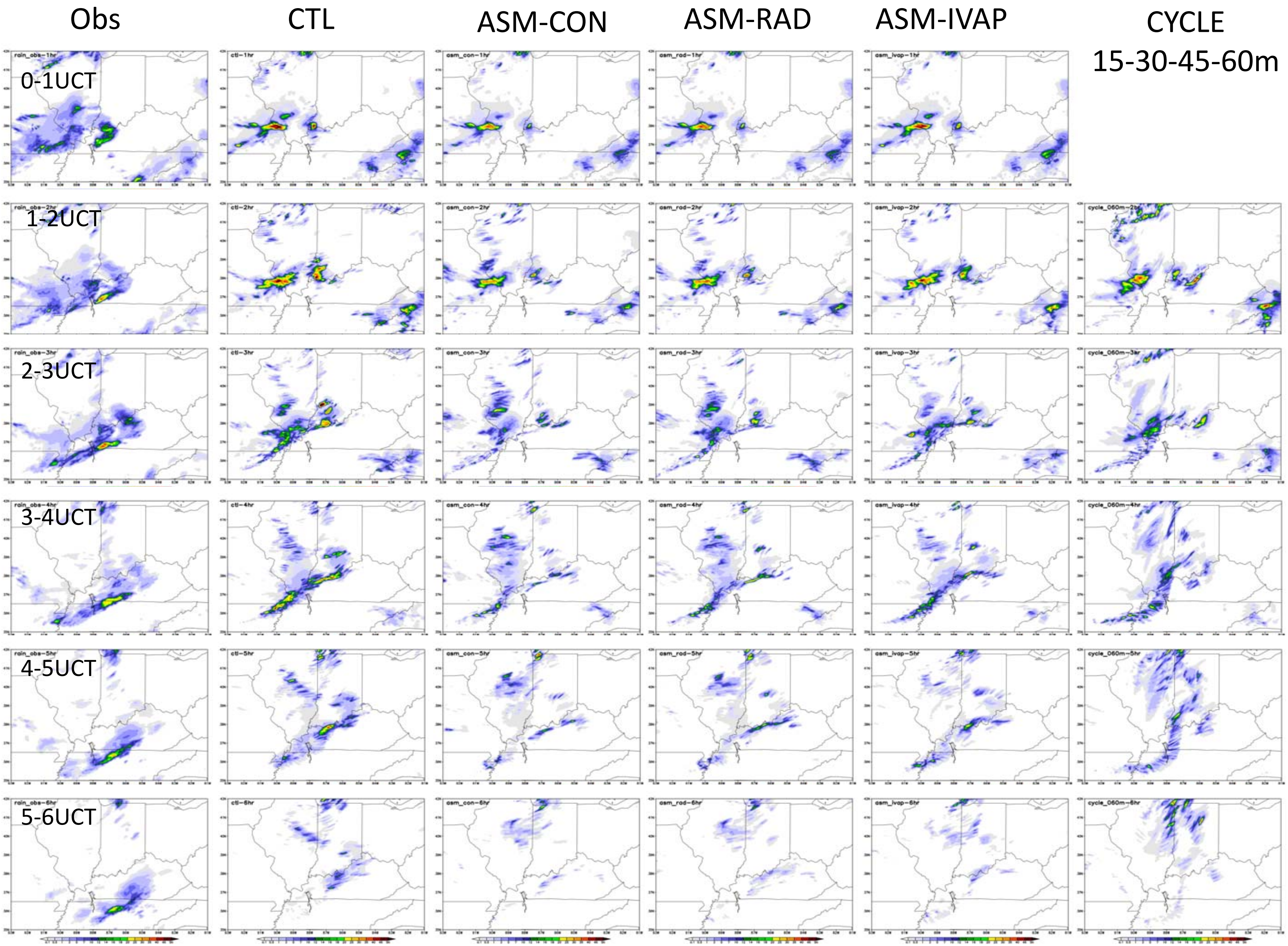
Model domain and radar stations



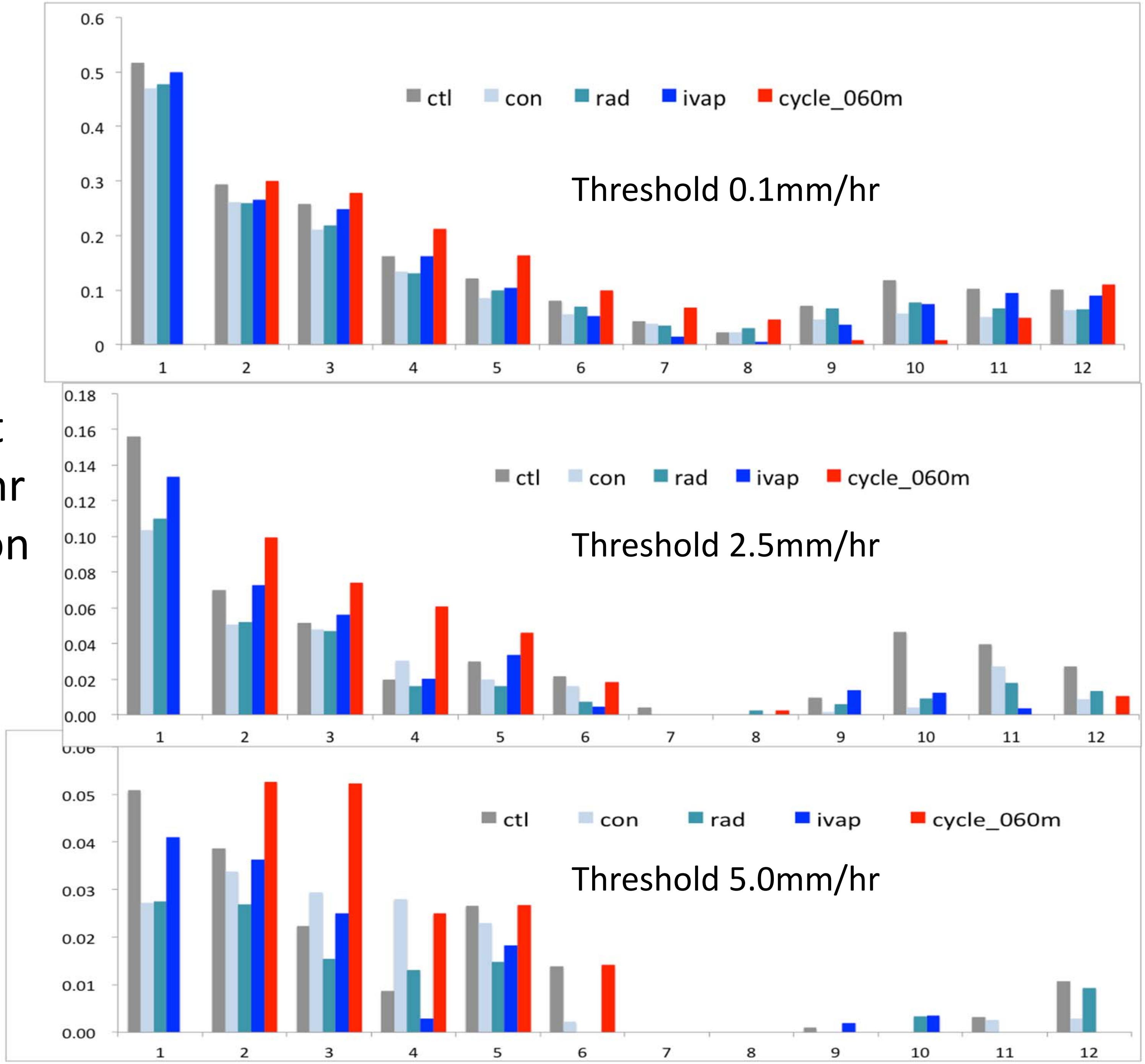
00-12UTC accumulated rainfall

Experiment	Data and method
Ctl	Without data assimilation
asm_con	Data assimilation without radar data
asm_rad	Data assimilation with radar data using traditional operator
asm_ivap	Data assimilation with radar data using IVAP based operator
cycle	Data assimilation with radar data using IVAP based operator in cycle mode

Rain_obs	**1 hour precipitation of Stage IV Data**


Obs
CTL
ASM-CON
ASM-RAD
ASM-IVAP
CYCLE
15-30-45-60m
0-1UCT
1-2UCT
2-3UCT
3-4UCT
4-5UCT
5-6UCT

TS (Threat Score)of 1hr precipitation forecast



Conclusions & suggestions

- A new forward operator for radar radial velocity assimilation was proposed based on IVAP method, which can use more information of radar observation
- The operator was added in the GSI codes
- Primary results of the experiments shown positive impacts
- More works on tuning and testing should be done in the next step, not only for the operator but also for the data pre-processing (*super-ob, thinning*)
- Suggestion: More radar radial velocity observations give more impacts (*positive impacts*) –-*more efforts!!*

Thanks !