Assimilation of GPS Radio Occultation Data for Global Weather Prediction at CWB

Jen-Cheng J. Chang
CCU/DAS

Outline

- GPS RO observations
- CWB's 3DVAR System
- 2D GPS Ray-tracing Operator
- Some testing results
- Summary
- Things to do

What to assimilate?

<u>GPS Radio Occultation measurements</u>:

1. **Excess phase:** caused by the bending of the radio signal at two frequencies: *1227.6 MHz, 1575.4 MHz*.
2. **Excess Doppler frequency shift:** estimated by the time derivative of excess phase.
3. **<u>Bending angle</u> and impact parameter:** derived from Doppler frequency shift based on satellite geometry (impact parameter is assumed constant at GPS and LEO).
4. ***<u>Refractivity:</u>*** calculated from bending angle through the Abel inversion (the refractivity is assumed spherically symmetric).
5. **Temperature and pressure:** retrieved from refractivity using the hydrostatic equation and neglecting water vapor content.

Why bending angle? *Accuracy*

- The total effect of atmospheric refractivity along the ray path can be included.
- The effect of the ionosphere can be largely removed.
- Problems that are unique to GPS refractivity retrieval from bending angle can be avoided (e.g., the upper boundary condition for the Abel inversion and the ill-poseness of the Abel inversion under super-refraction).
- Providing a benchmark for developing a fast and accurate GPS refractivity assimilation method.
- Computational cost may be significantly reduced by running ray-tracing on multiple processors.

Why not bending angle? *Efficiency*

Why Refractivity

1. The computational cost is low to assimilate N.
2. A priori separation of temperature and moisture information is not required.
3. A weighted average (or a so-called ***linearized non-local operator***) might be sufficient to account
   for the integrated effect of the atmosphere to GPS measurements.

3DVAR System at CWB

CWB's 3DVAR System

- Based on NCEP's SSI (version 1999)
- Operational since May 2003
- Official version: T179/L30 (i.e., 540 x 270 x 30), running with 3PE (on Fujitsu 5000)
- Testing version: T79/L30 (i.e., 240 x 120 x 30), running with 1PE
- Incremental approach: only 1 outer loop, with 100 inner loops (*currently testing 2 outer updates with 70/30 iterations, respectively*)
- No 3- and 9-hr forecasts for temporal interpolation to observational time.

CWB 3DVAR (Contd.)

- Analysis variables:
  vorticity (ζ), unbalanced divergence(D'),
  unbalanced virtual temperature (T_v'),
  unbalanced log of surface pressure ($ln\ p_s$'),
  specific humidity (q)
- Implicitly including a linear balance constraint
- Additional constraint: divergence tendency
- Background term at spectral space, observational terms at physical space

Formula of CWB/3DVAR (i.e. NCEP/SSI)

(Parrish and Derber, 1992)

Cost-function to be minimized:

$$J(\mathbf{w}) = \frac{1}{2}\mathbf{w}^T\mathbf{w} + \frac{1}{2}\left[\mathbf{y} - H(\mathbf{x}_b + \mathbf{C}\mathbf{w})\right]^T \mathbf{R}^{-1}\left[\mathbf{y} - H(\mathbf{x}_b + \mathbf{C}\mathbf{w})\right] + J_c$$

where

$\mathbf{w} = \mathbf{C}^{-1}(\mathbf{x} - \mathbf{x}_b)$	Coefficients of error weighted analysis increments
$\mathbf{x} = \mathbf{x}_b + \mathbf{C}\mathbf{w}$	Analysis variables
$\mathbf{B} = \mathbf{C}\mathbf{C}^T$	Background error covariance matrix
$\mathbf{x}_b$	6-hr forecast of analysis variables
$\mathbf{R} = \mathbf{F} + \mathbf{O}$	Observational & Representative error covariance matrix
H	(Nonlinear) observational (forward) operator
$\mathbf{y}$	Observations

Formula (Contd.)

Gradient:

$$\frac{\partial J}{\partial \mathbf{w}} = \mathbf{w} - \mathbf{C}^T \mathbf{L}^T \mathbf{R}^{-1} \left[\mathbf{y} - H(\mathbf{x}_b + \mathbf{C}\mathbf{w}) \right] \equiv -\mathbf{f}(\mathbf{x})$$

where

$\mathbf{L} = \dfrac{\partial H}{\partial \mathbf{x}}$ tangent linear operator of H; $\mathbf{L}^T$ adjoint operator of L

Outer Loop: At m-th iteration: $\mathbf{w} = \mathbf{w}_m$ $\mathbf{x} = \mathbf{x}_m$ $\mathbf{w}_0 = 0$

At $(m+1)$-th iteration: $\mathbf{w}_{m+1} = \mathbf{w}_m + \mathbf{d}$

$$-\left.\frac{\partial J}{\partial \mathbf{w}}\right|_{m+1} = \underbrace{\mathbf{C}^T \mathbf{L}_m^T \mathbf{R}^{-1} \mathbf{y}_m - \mathbf{w}_m}_{\mathbf{f}(\mathbf{x}_m)} - \underbrace{(\mathbf{I} + \mathbf{C}^T \mathbf{L}_m^T \mathbf{R}^{-1} \mathbf{L}_m \mathbf{C})}_{\mathbf{A}(\mathbf{x}_m)}\mathbf{d} = 0$$

where,

$\mathbf{y}_m \equiv \mathbf{y} - H(\mathbf{x}_b + \mathbf{C}\mathbf{w}_m)$

$\mathbf{f}(\mathbf{x}_m)$ forcing vector

$\mathbf{A}(\mathbf{x}_m)$ coefficient matrix

Linear Conjugate Gradient Method

Inner Loop:

At the *k*-th update:

$$\mathbf{d}_k = \mathbf{d}_{k-1} + \alpha_k \mathbf{p}_k$$

$$\alpha_k = \frac{\mathbf{p}_k^T \mathbf{f}_{k-1}}{\mathbf{p}_k^T \mathbf{A} \mathbf{p}_k}$$

to minimize: $\mathbf{f}_k^T \mathbf{A}^{-1} \mathbf{f}_k$

or

$$\alpha_k = \frac{-\mathbf{p}_k^T \mathbf{d}_{k-1} + (\mathbf{L}_m \mathbf{C} \mathbf{p}_k)^T \mathbf{R}^{-1} [\mathbf{y}_m - \mathbf{L}_m \mathbf{C} \mathbf{d}_{k-1}] - \mathbf{p}_k^T \mathbf{w}_m}{\mathbf{p}_k^T \mathbf{p}_k + (\mathbf{L}_m \mathbf{C} \mathbf{p}_k)^T \mathbf{R}^{-1} (\mathbf{L}_m \mathbf{C} \mathbf{p}_k)}$$

where,

α_k : step size

$\mathbf{p}_k$: search direction

$$\mathbf{p}_k = \mathbf{f}_{k-1} + \beta_{k-1} \mathbf{p}_{k-1}$$

$$\mathbf{p}_1 = \mathbf{f}_0$$

Therefore,

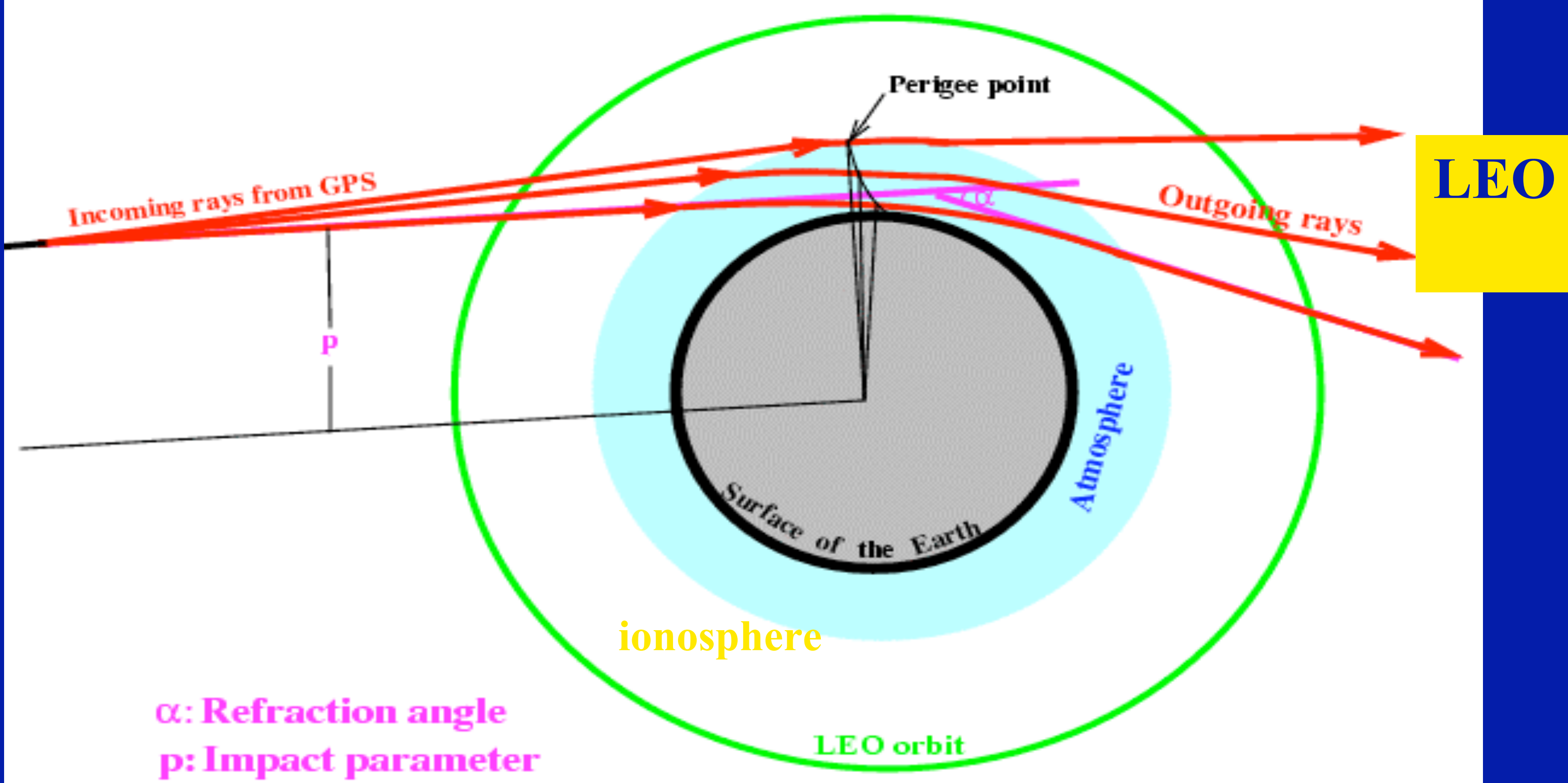
$$\mathbf{f}_k = \mathbf{f}_{k-1} - \alpha_k \mathbf{A} \mathbf{p}_k$$

$$\beta_k = \frac{\mathbf{f}_k^T \mathbf{f}_k}{\mathbf{f}_{k-1}^T \mathbf{f}_{k-1}}$$

(for orthogonality)

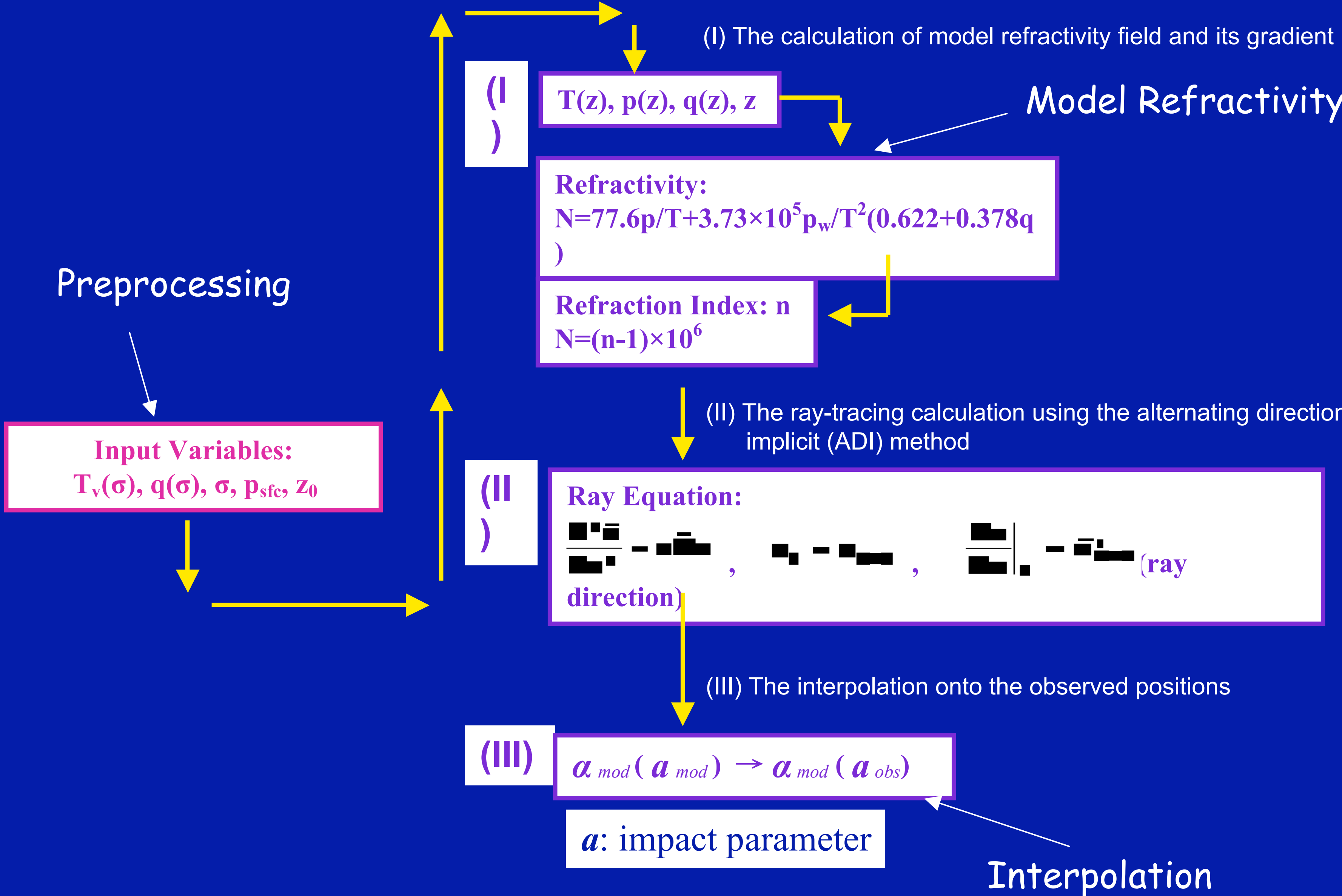
2D GPS Ray-tracing Operator

GPS RO concept



Courtesy of X. Zou

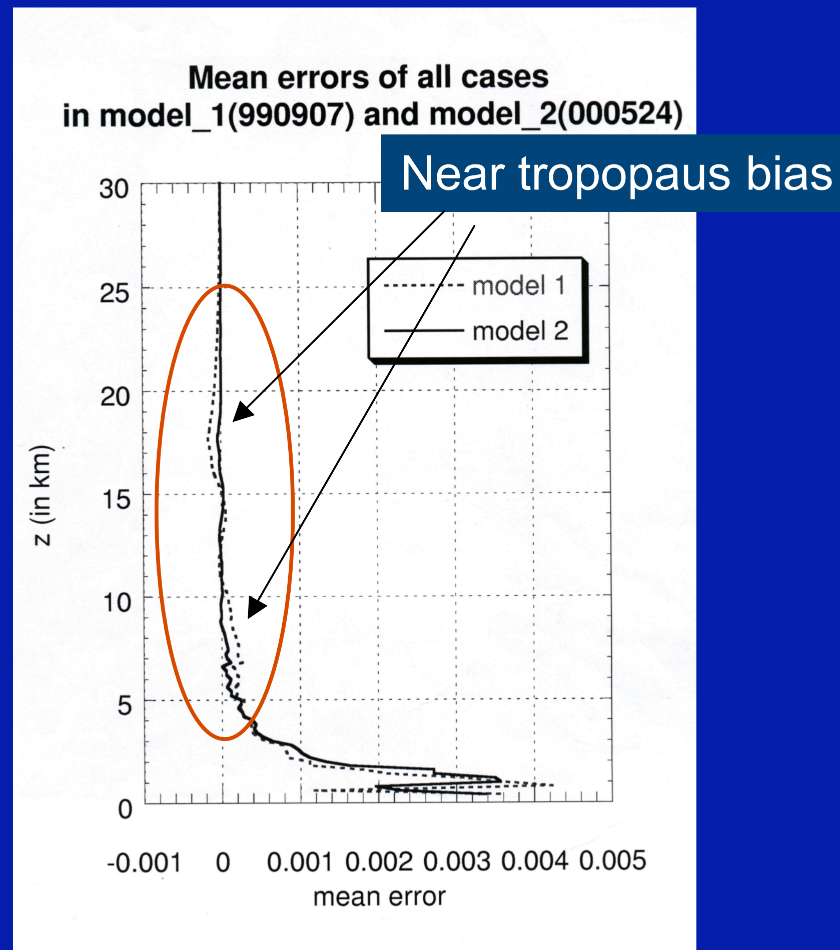
GPS Ray-tracing Operator



A slightly modified version of the 2D GPS ray-tracing operator from Zou et al. (1999) is implemented

Original Operator

- Calculating *N* on the vertical velocity (half) level, but using variables (*T* and *q*) at the following model layer (full level) except *p*
- Calculating the geometric heights of vertical grids on the half-level, but treating *T* as given at the half-level in the hypsometric equation
- Results: a lower tropopause bias



T21/L18

Revised Operator

- Calculating *N* on the model (full) layers, *NOT* the vertical velocity (half) level
- Calculating the geometric heights of vertical grids on the *full-layer,* and treating *T* back to where it belong

CWB Model's Vertical Grids

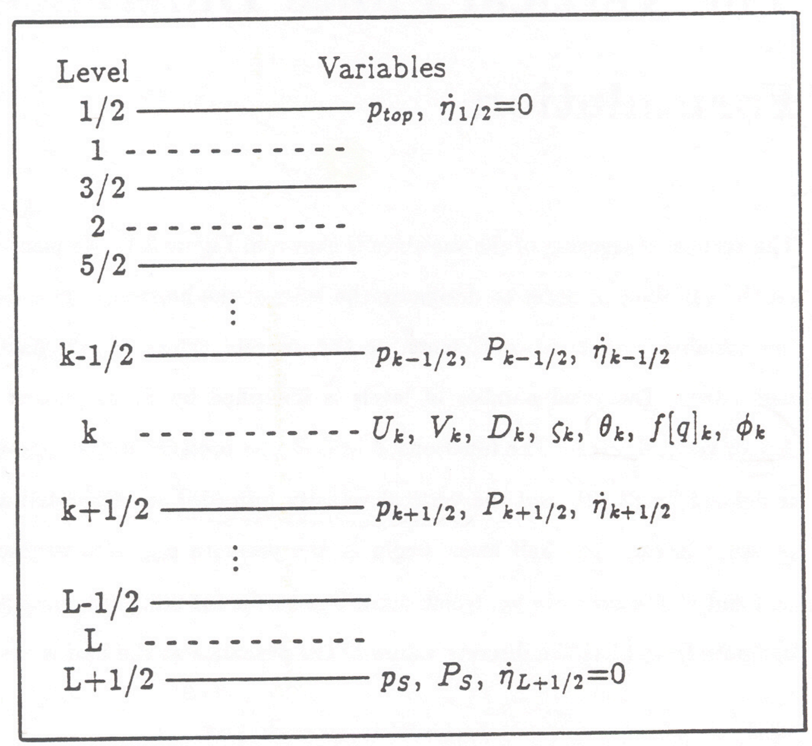
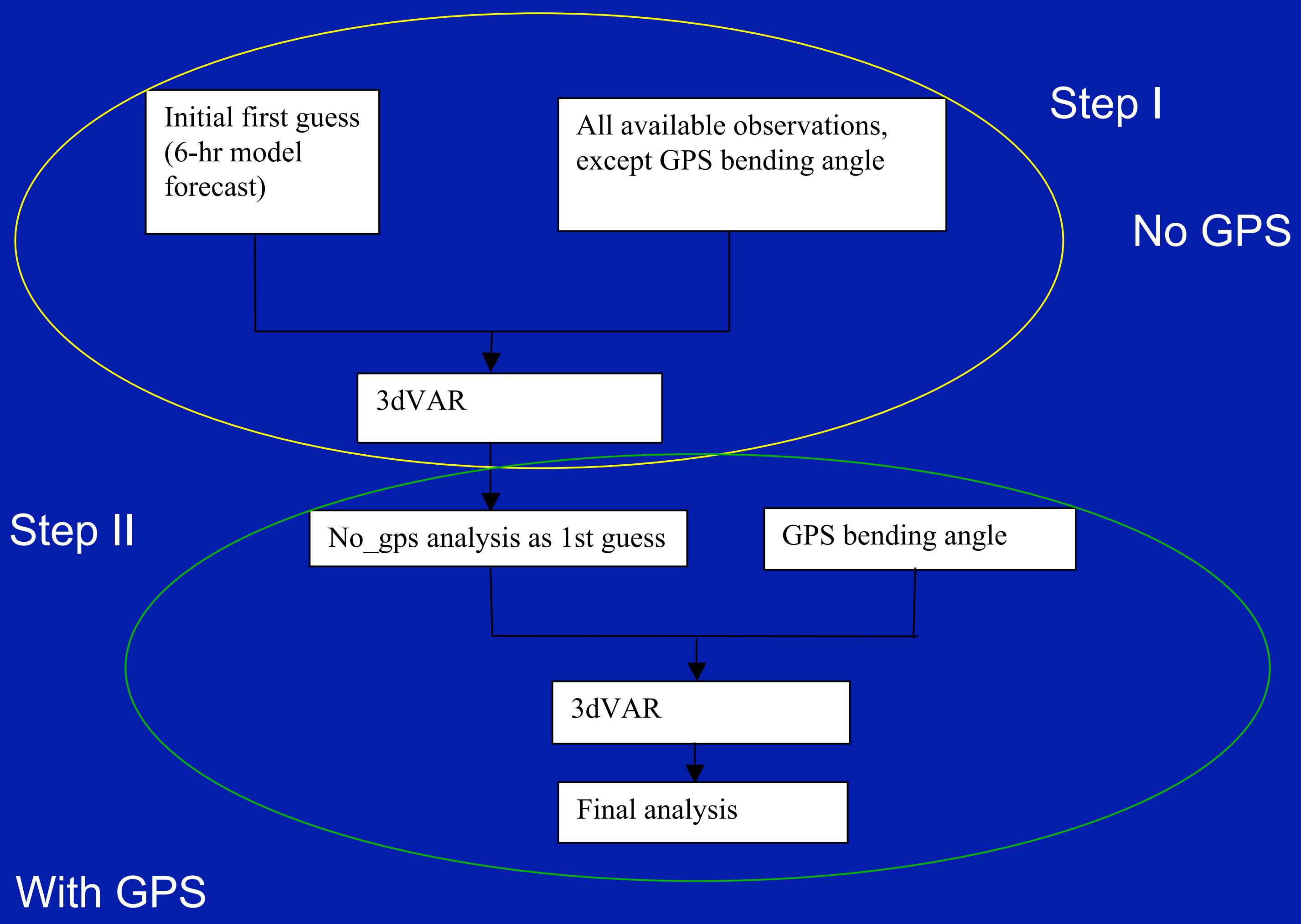


Figure 3.1: The finite difference vertical structure of the forecast model.

L18 → L30

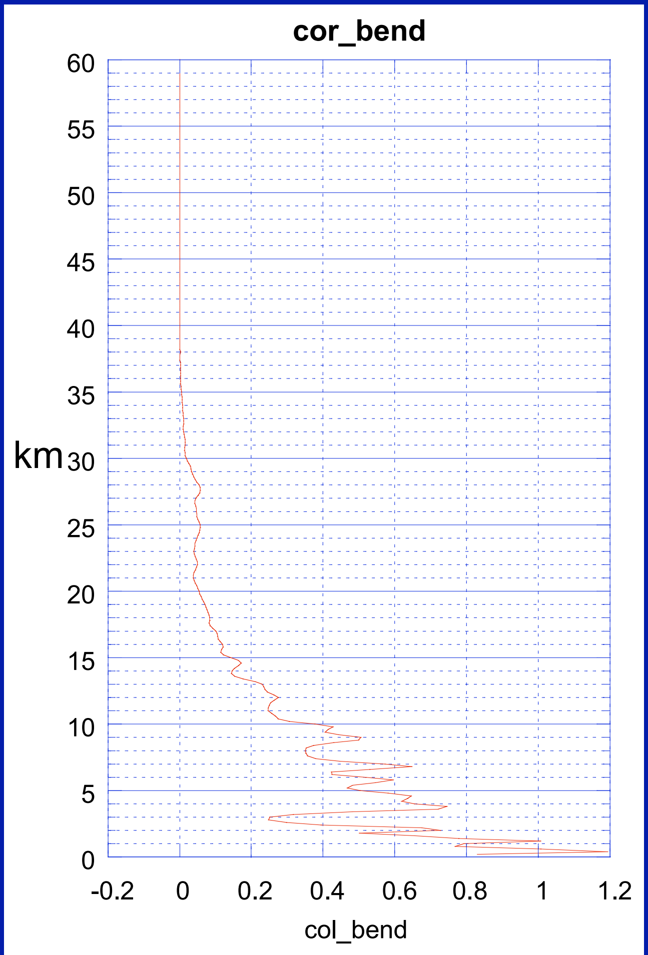
Data Assimilation Procedure of GPS RO Observation



Experiments

Name	Remarks
nogps	All other available data, except GPS (Step I only)
gpswt5	Including GPS observation, but with 10^5 O-weighting
gpswt6	Including GPS observation, but with 10^6 O-weighting

Observational Weighting Profile Used



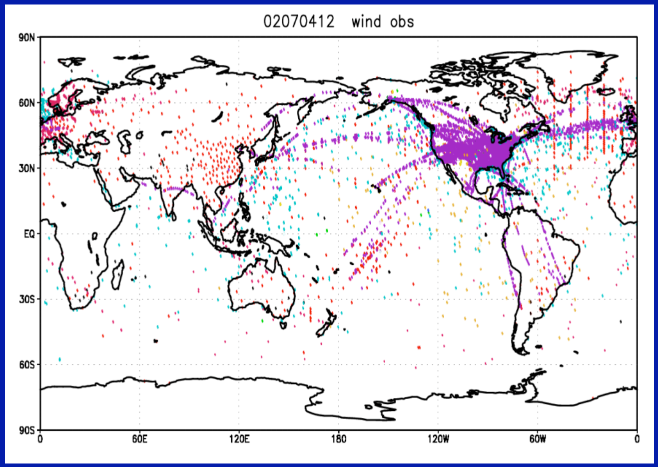
Case Study

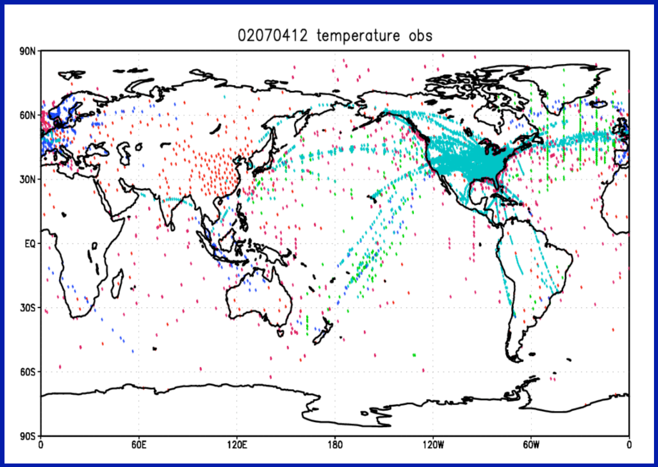
- July 4, 2002, 1200UTC
- From GFZ (GeoForschungs Zentrum) Potsdam CHAMP-ISDC（http://isdc.gfz-potsdam.de/champ/）
- 41 soundings during 09-15UTC

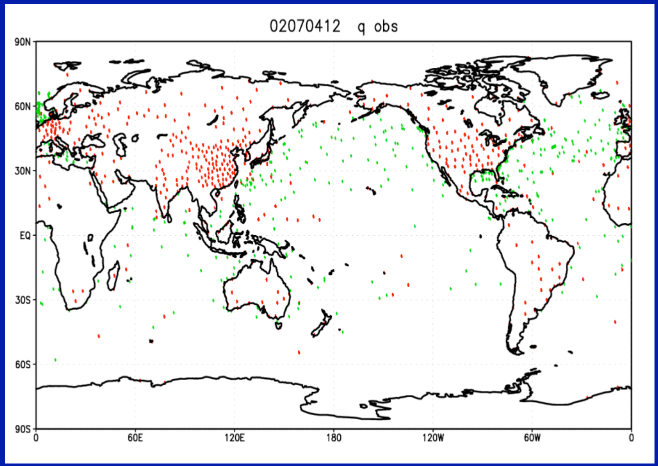
Observations Used

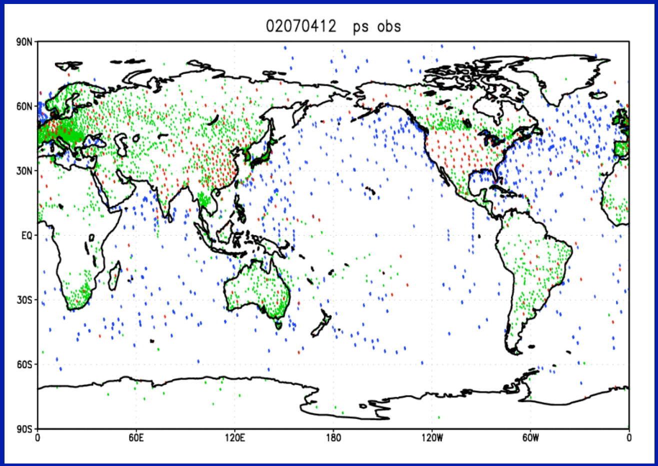
Variables	Types	Amounts
Winds	rawinsonde、pibal、wind profile、NEXRAD、AIREP、ACARS、SATOB、SHIP、BUOY、surface SSM/I wind speed	111192
Temperature	rawinsonde、AIREP、SHIP	43088
Water Vapor	rawinsonde、SHIP	10567
Surface Pressure	rawinsonde、surface land、SHIP	13770
Bending Angle	GPS/RO	6586(41 soundings with vertical resolution 200m)

Data Distributions



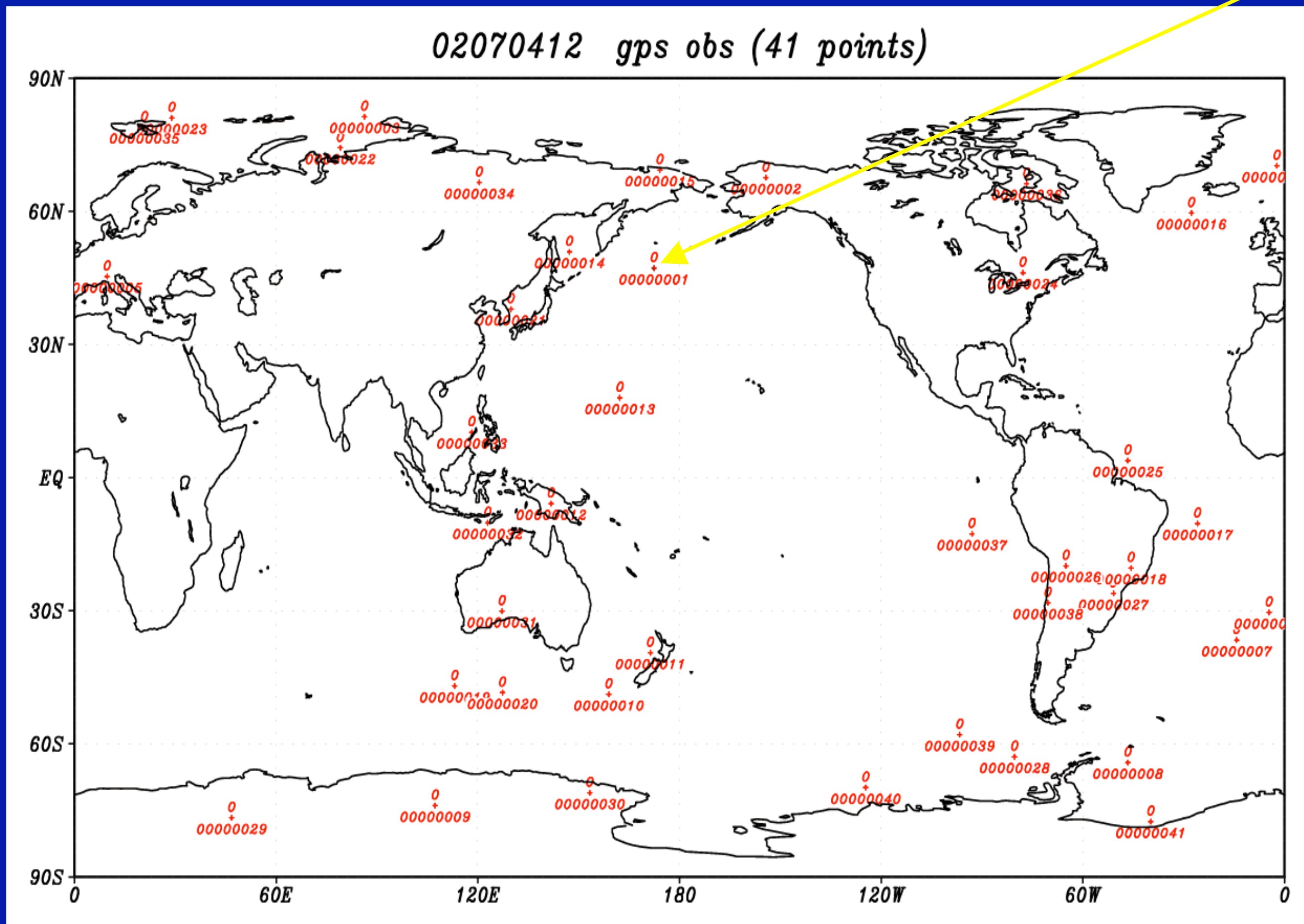




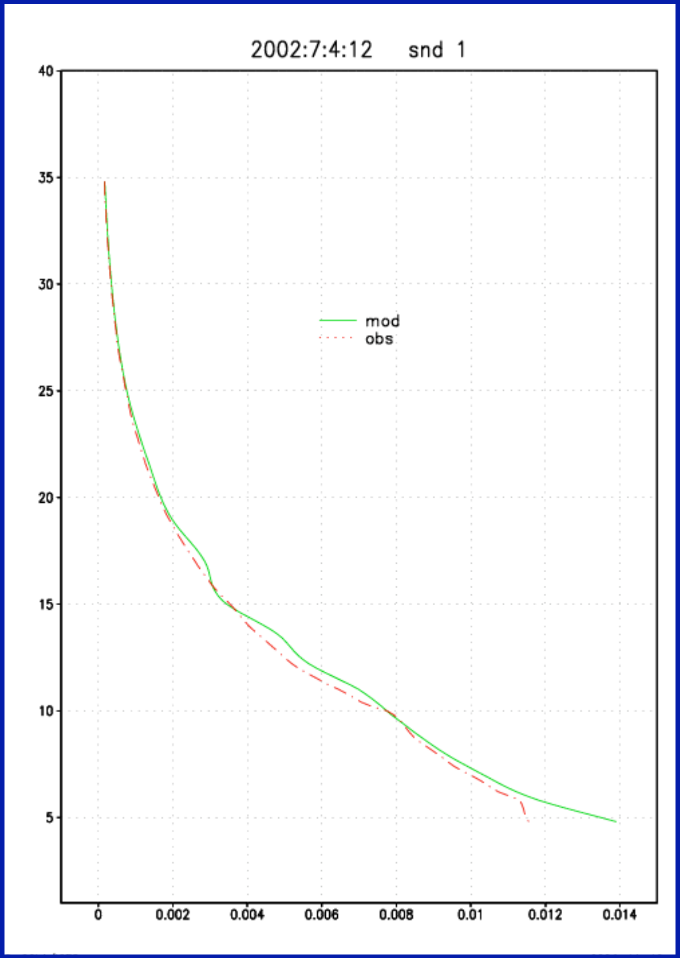


GPS Soundings

GPS1 for 1 sounding test



GPS_only Exp
(1 sounding)

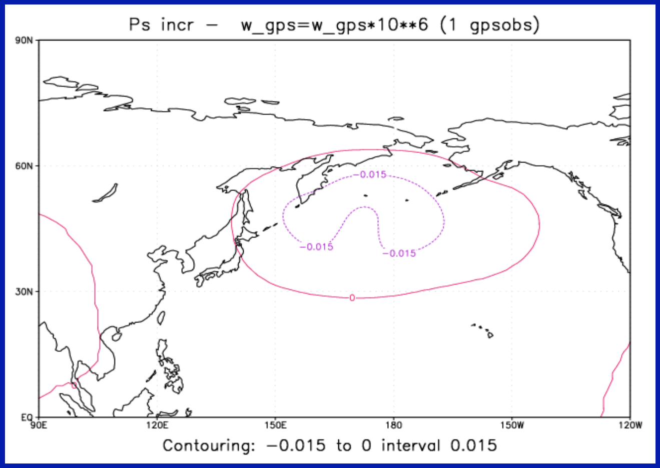


- Systematically larger model bending angles:

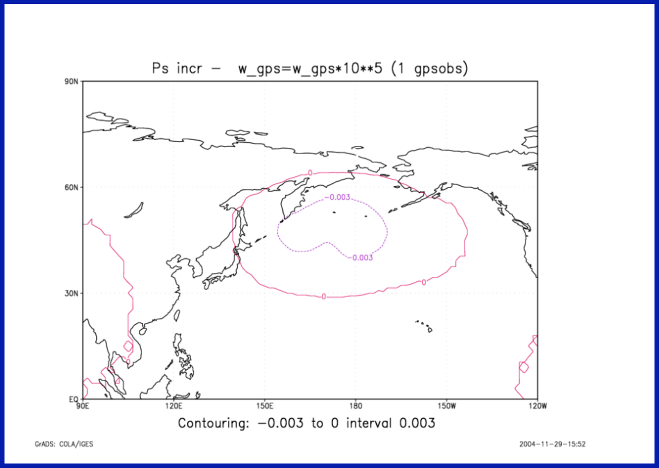
  ➔

  - lower p_{sfc},
  - dryer q
  - warmer T_v

Analysis increments: p_{sfc}



wgt6

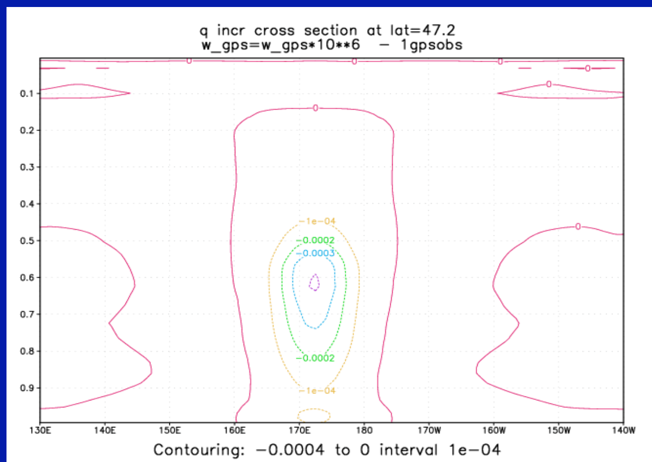


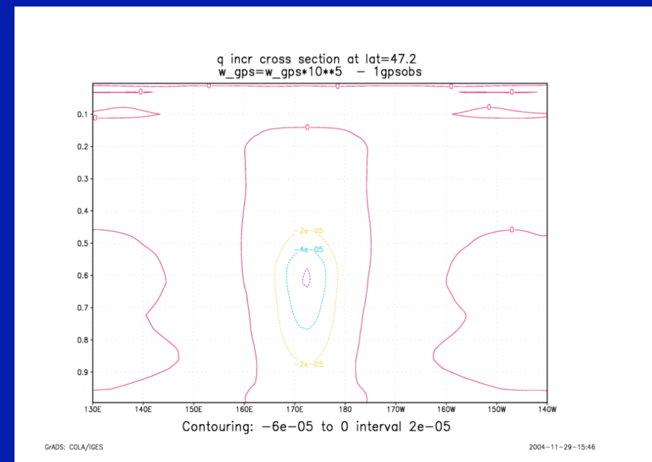
wgt5

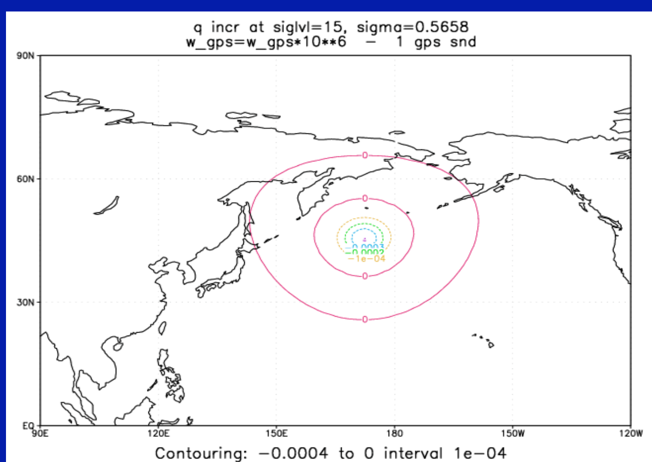
- lower adjustment indeed.
- wgt6 : wgt5 ~ 5 : 1

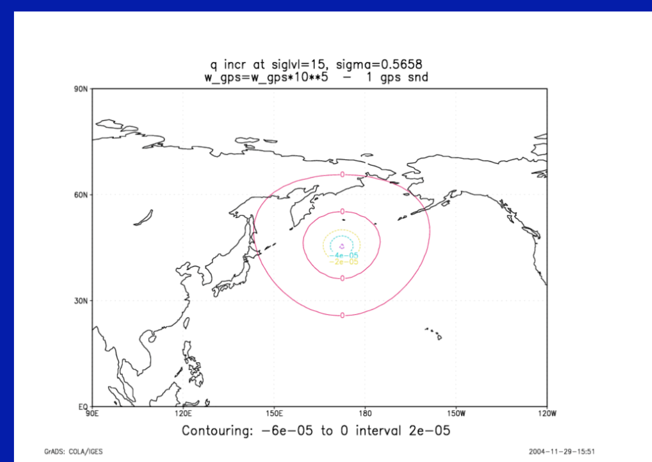
Analysis increments: q

E-W cross section at lat = 47.2˚N & at σ= 0.5658









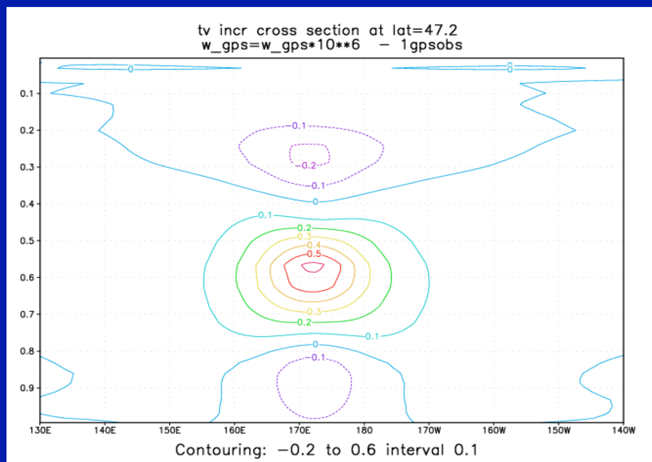
- dryer
- localized
- ~7 : 1

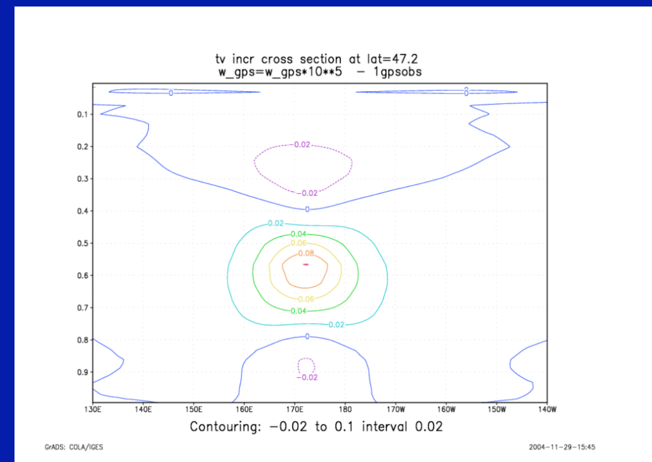
wgt6

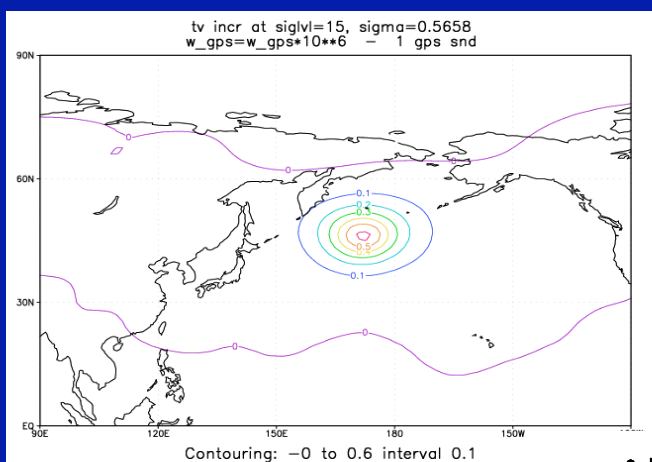
wgt5

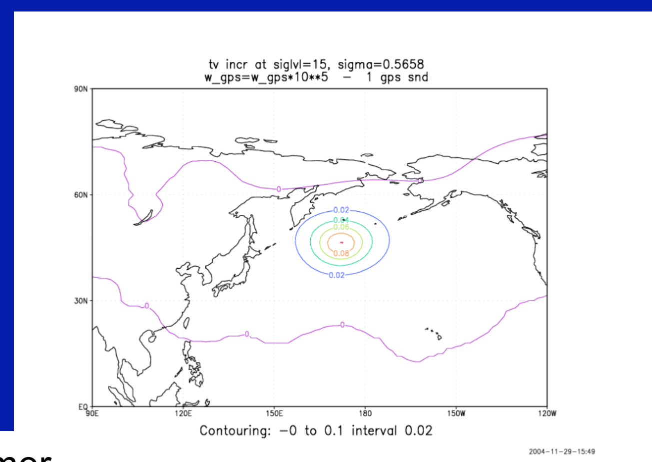
Analysis increments: T_v

E-W cross section at lat = 47.2 & at σ= 0.5658









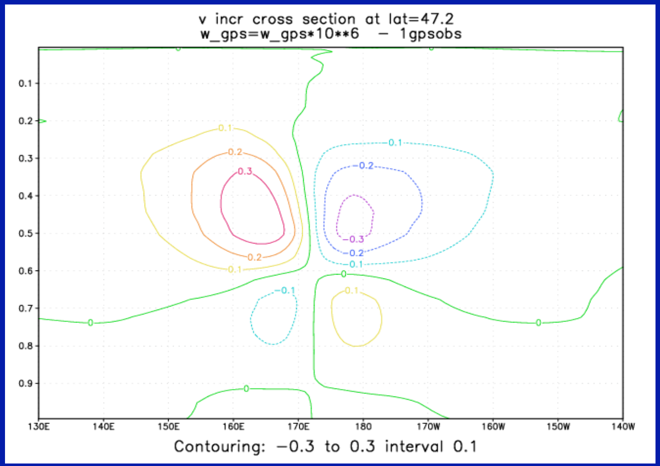
wgt6

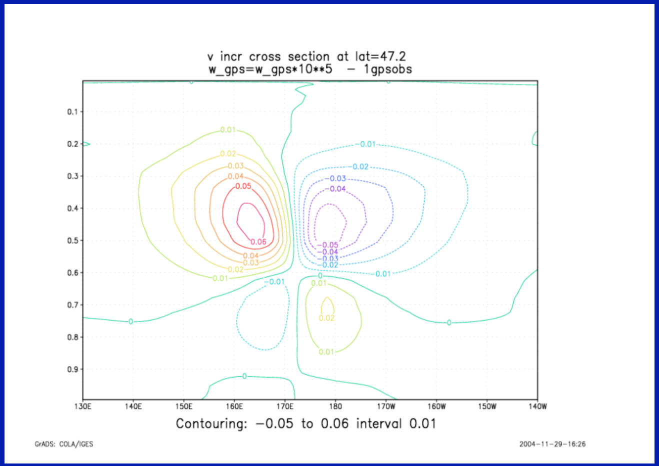
- primarily warmer
- vertical structure from **B**
- not as localized as q
- ~6 : 1

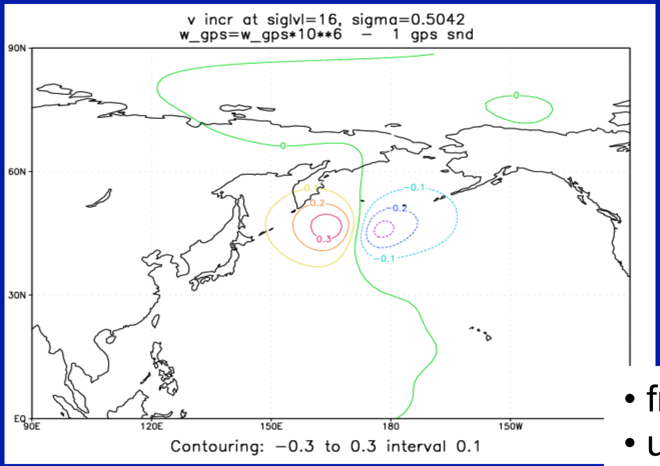
wgt5

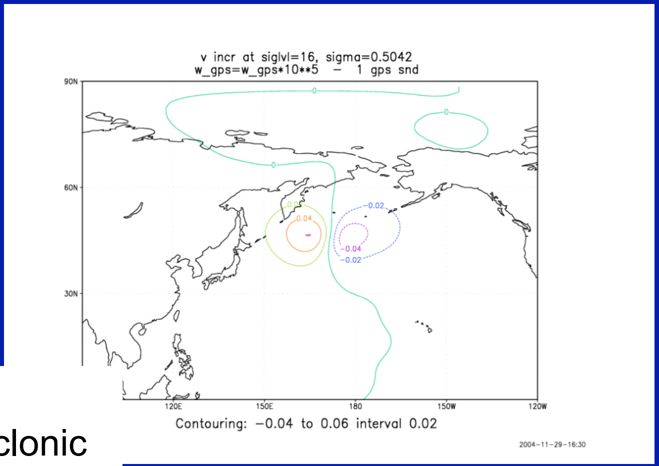
Analysis increments: v

E-W cross section at lat = 47.2 & at σ= 0.5042









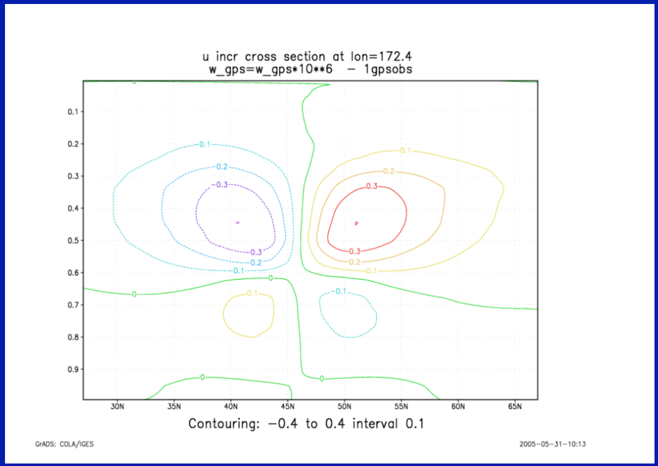
- from **B**
- upper: anti-cyclonic
- lower: cyclonic
- not as localized as q
- ~6 : 1

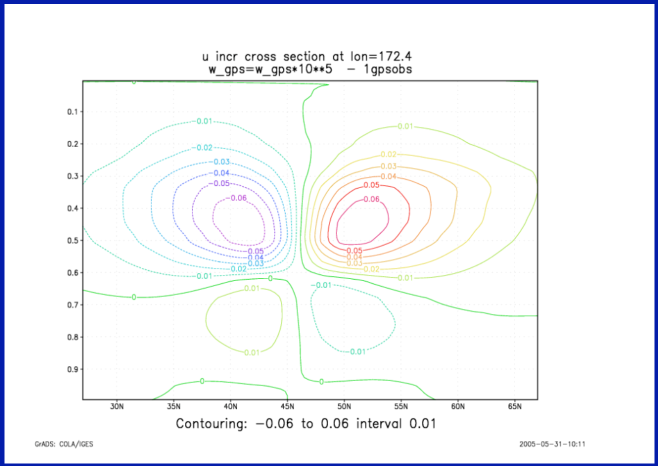
wgt6

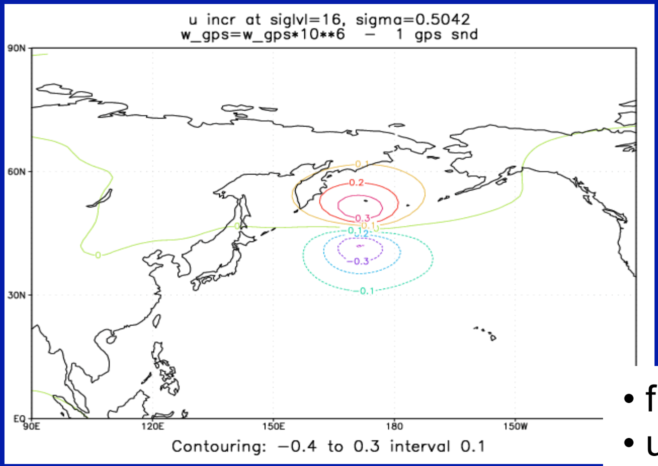
wgt5

Analysis increments: u

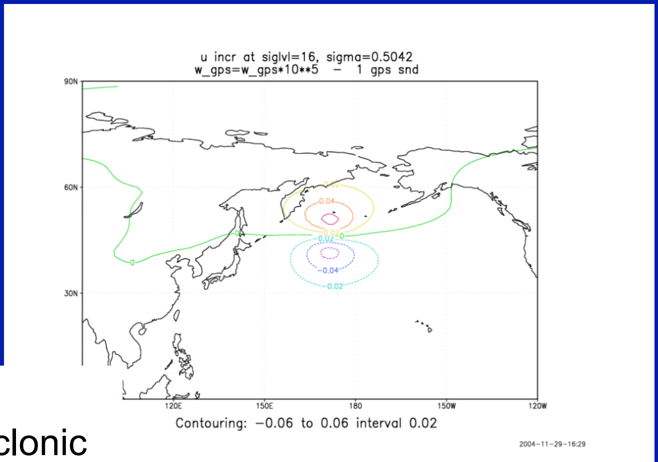
N-S cross section at lon = 172.4E & at σ= 0.5042







wgt6

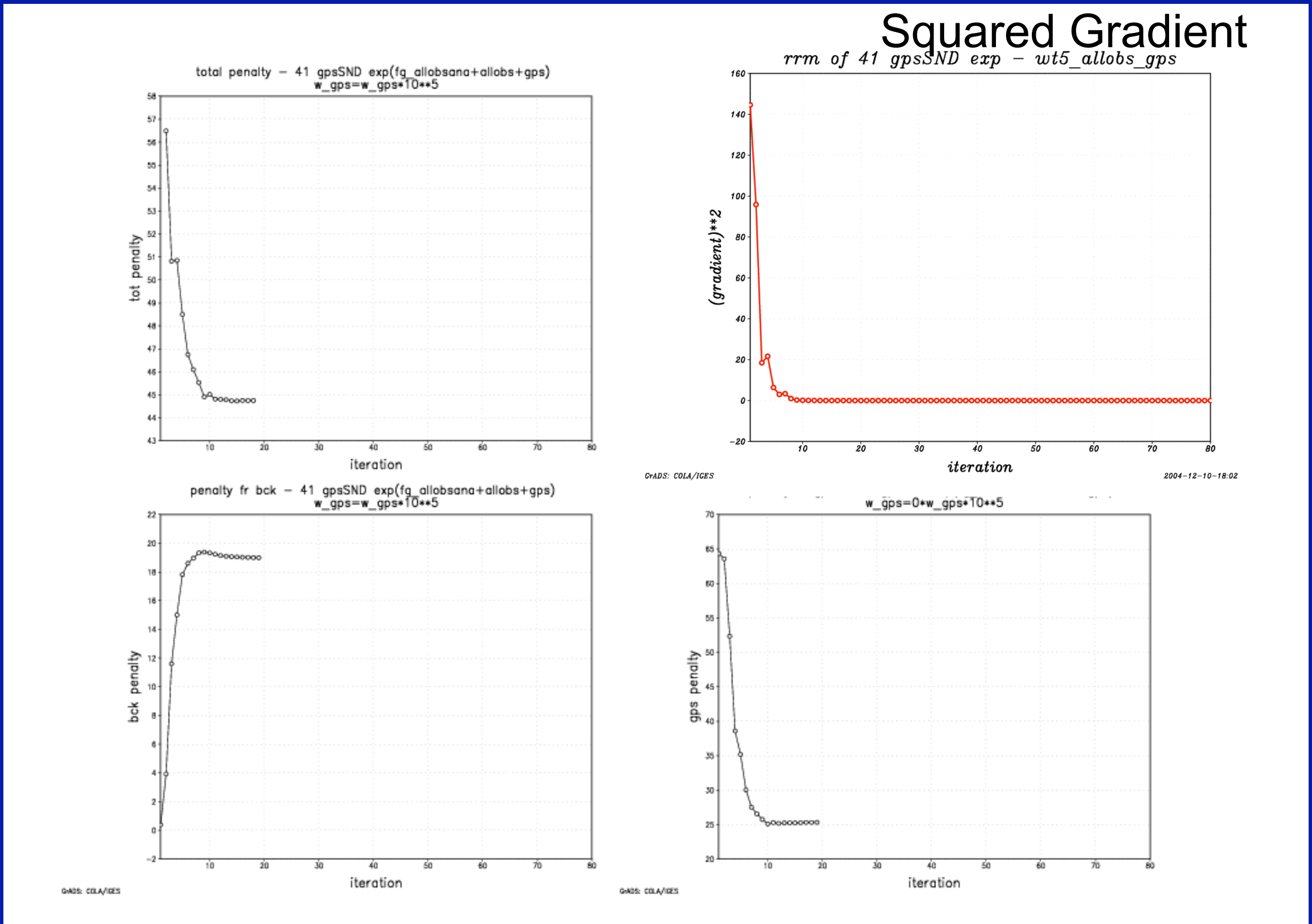


wgt5

- from **B**
- upper: anti-cyclonic
- lower: cyclonic
- not as localized as q
- ~6 : 1

Multi-sounding Results

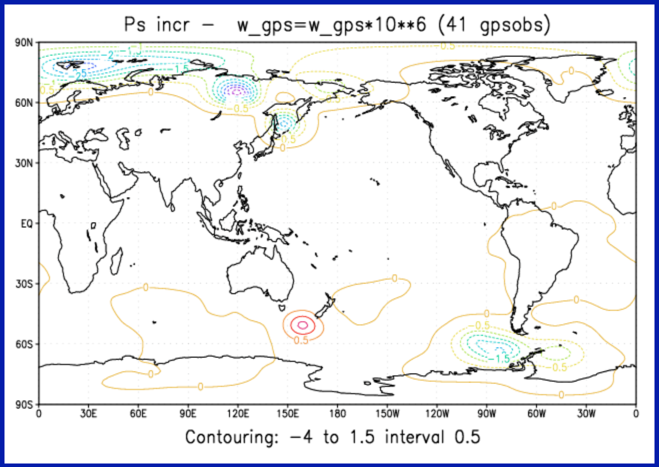
Cost-Function

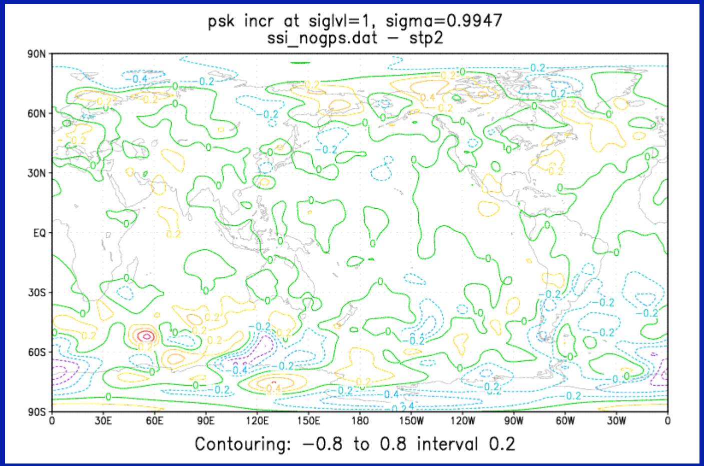


gpswt5

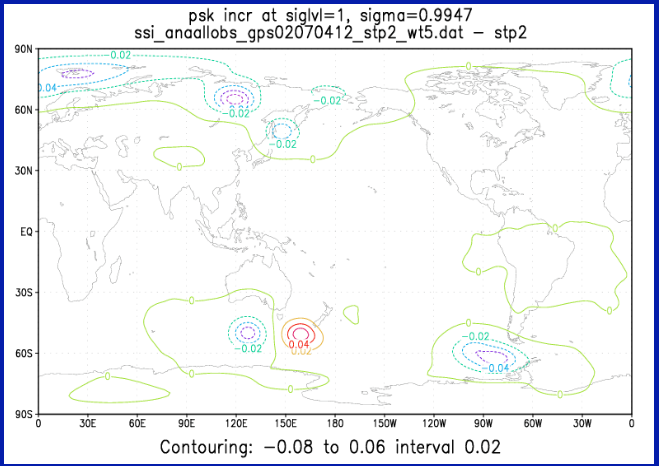
Analysis Increments (P_{sfc})

gps_only (wt6)





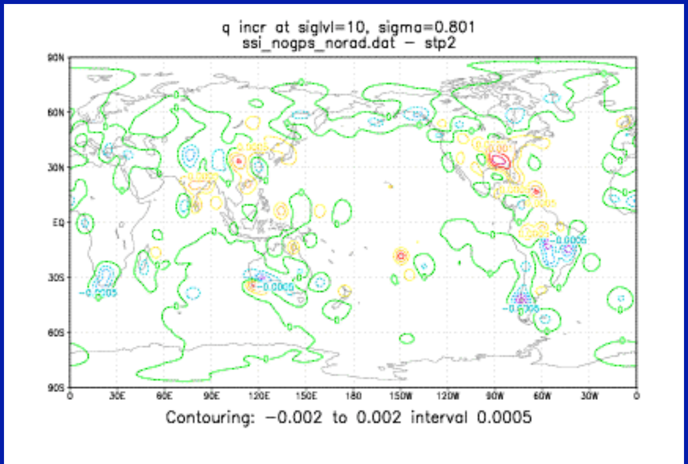
nogps



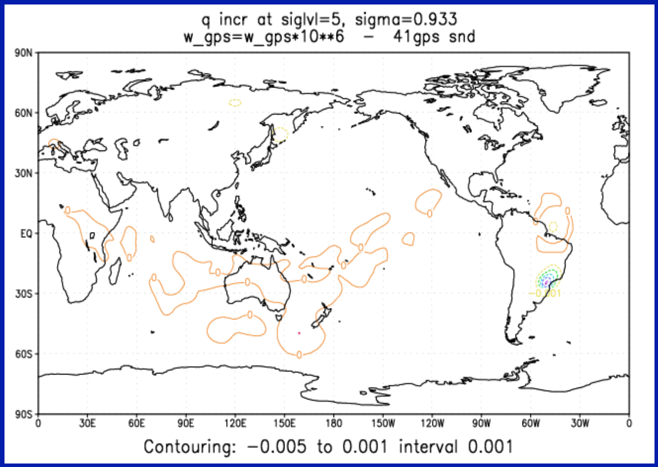
gpswt5

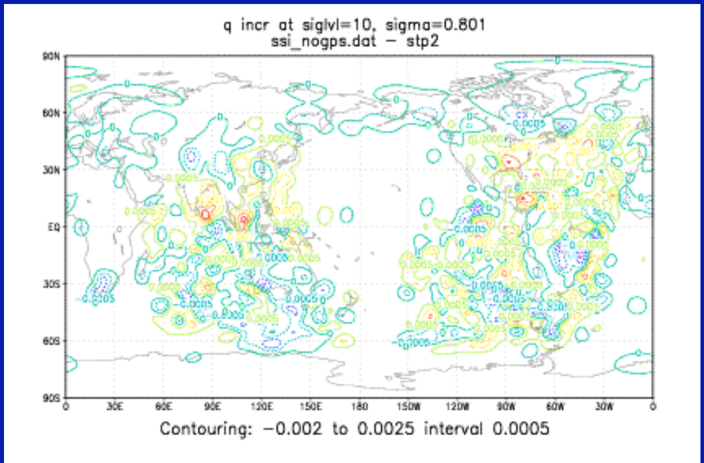
Analysis Increments (q)

norad

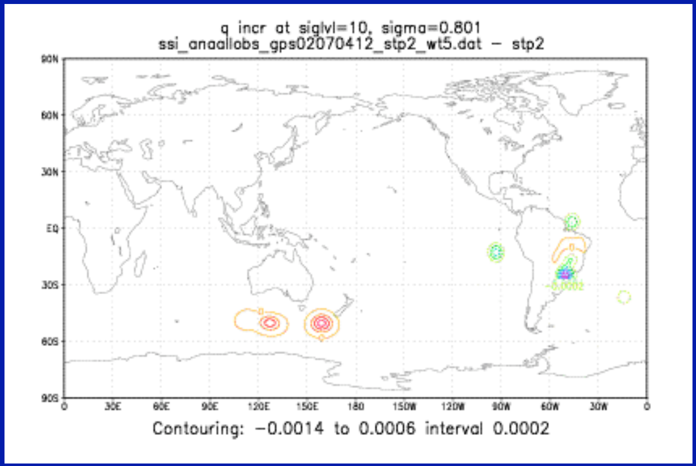


gps_only (wt6)





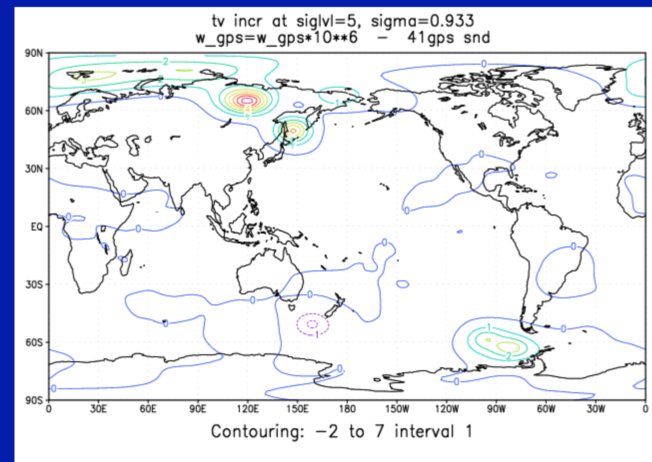
nogps

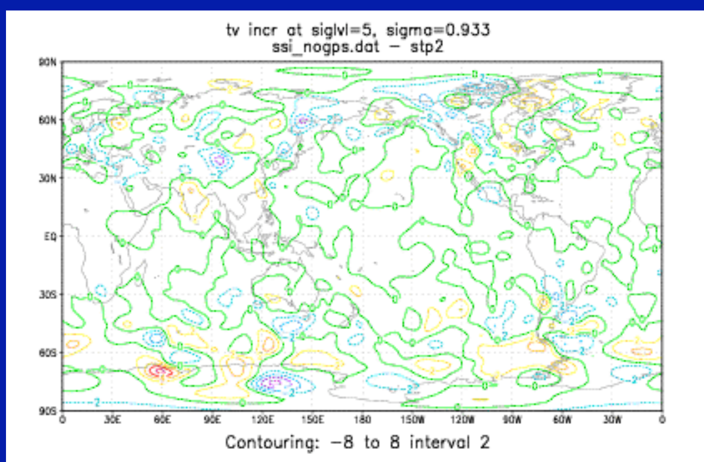


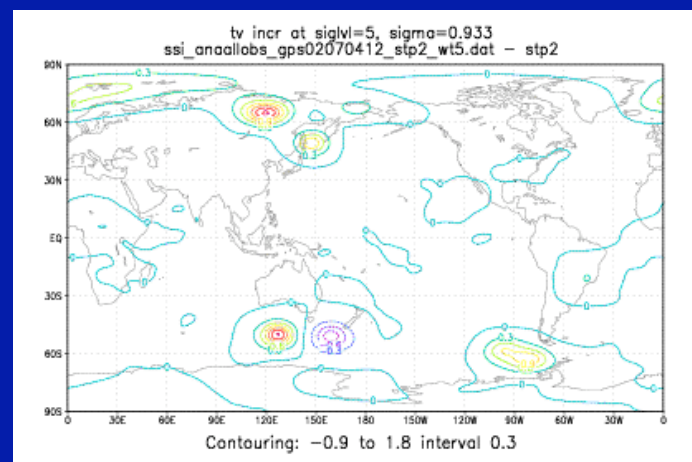
gpswt5

Analysis Increments (T_v)

gps_only (wt6)





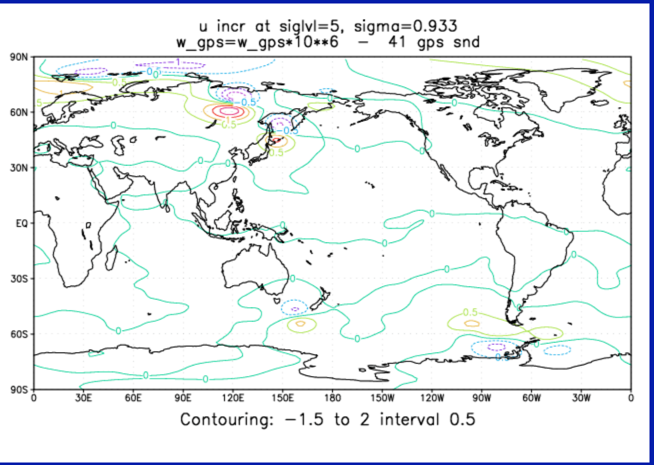


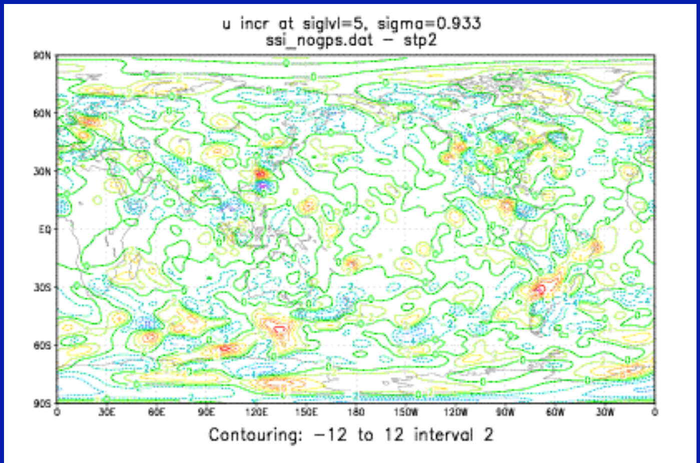
nogps

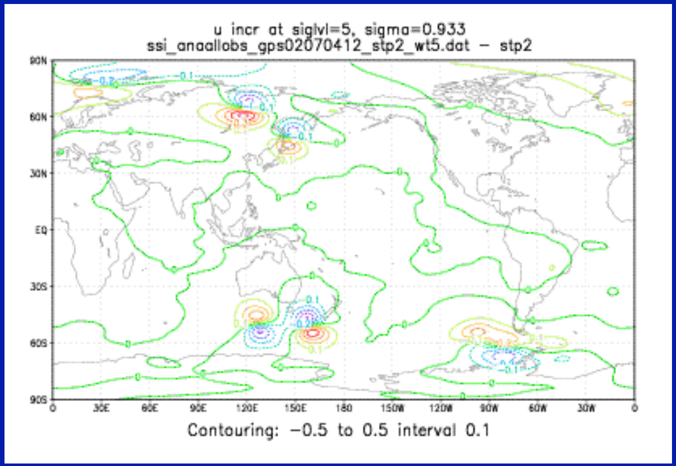
gpswt5

Analysis Increments: u

gps_only (wt6)





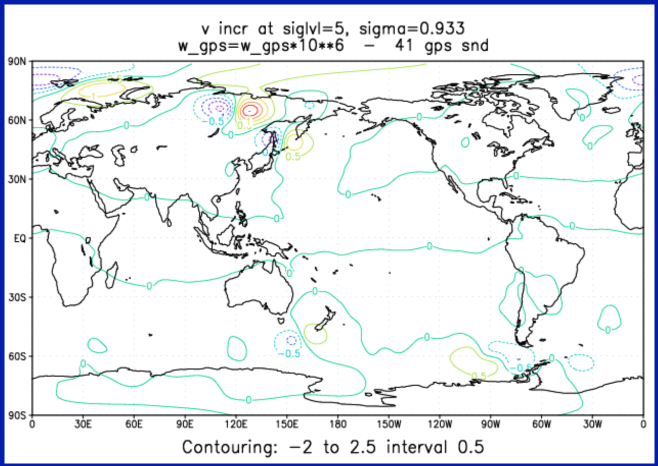


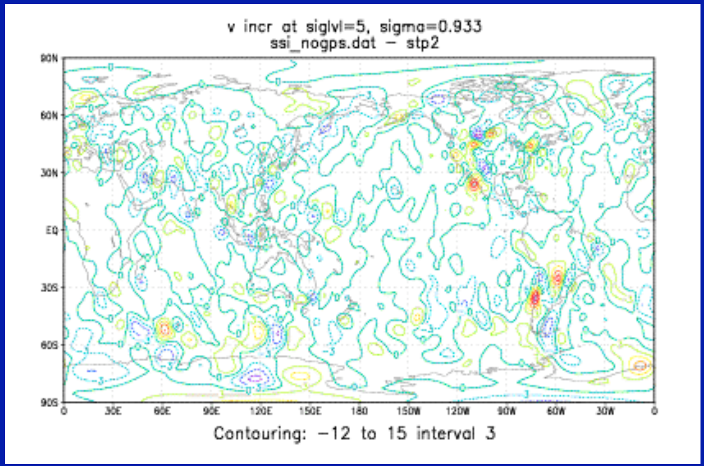
nogps

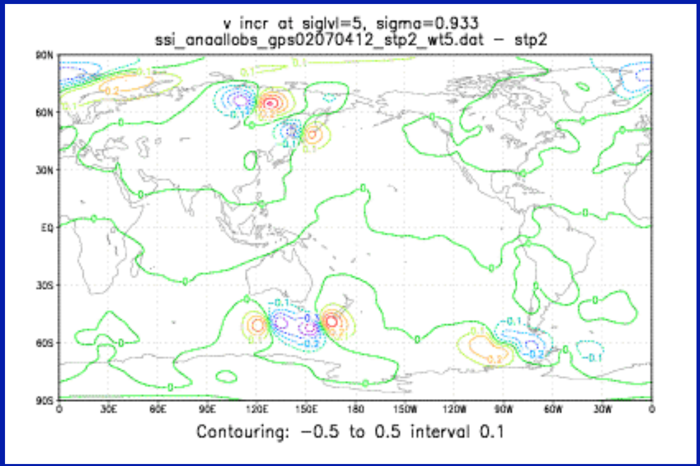
gpswt5

Analysis Increments: v

gps_only (wt6)





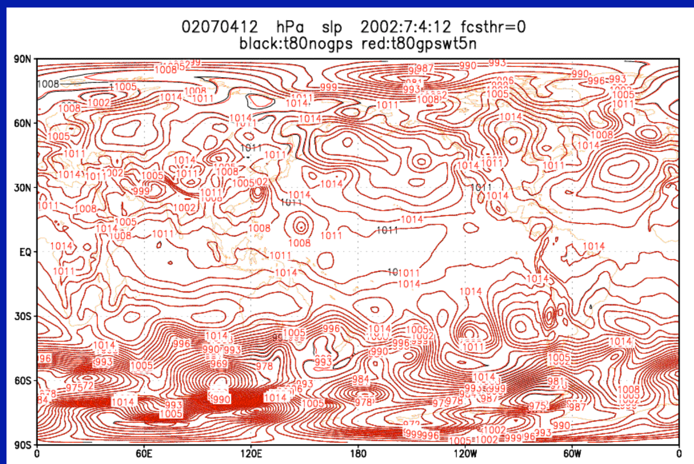


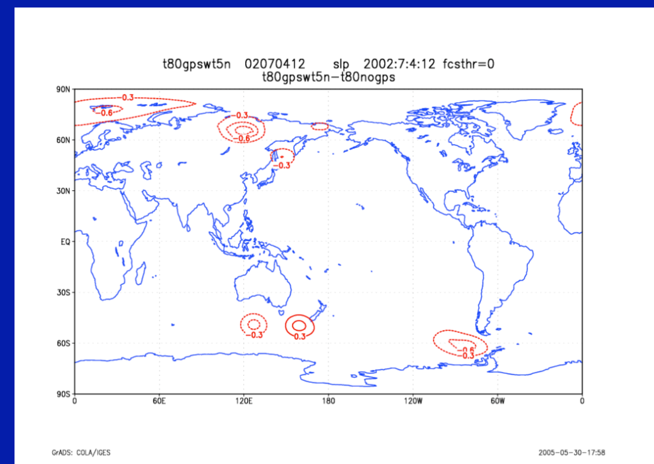
nogps

gpswt5

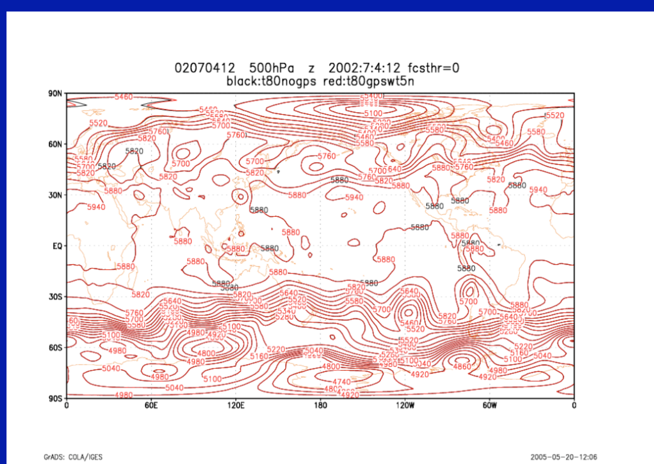
Forecasts

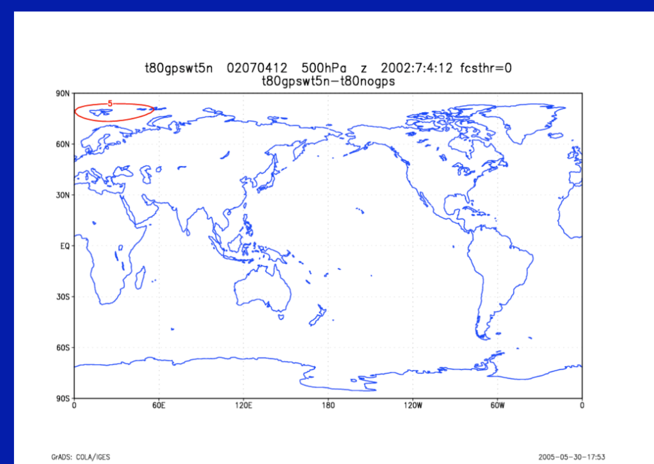
Analysis: Day 0





SLP



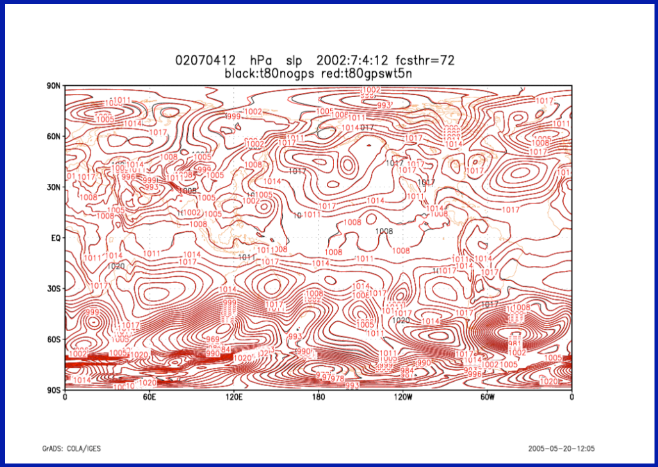


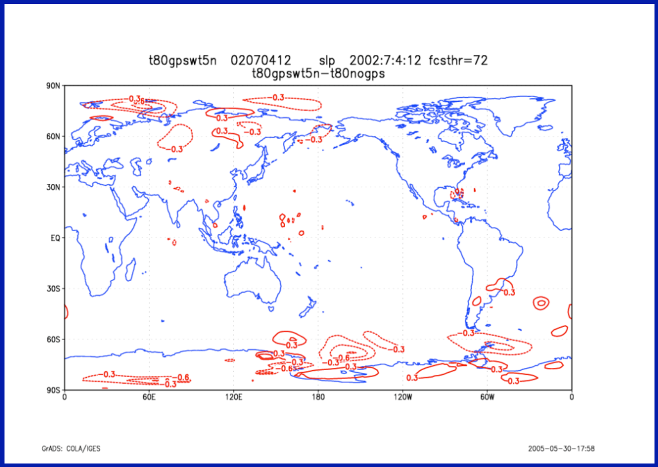
500 H

nogps / gpswt5

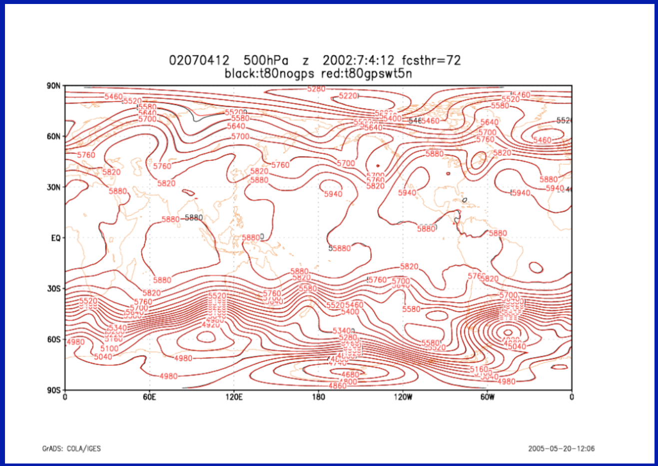
gpswt5 - nogps

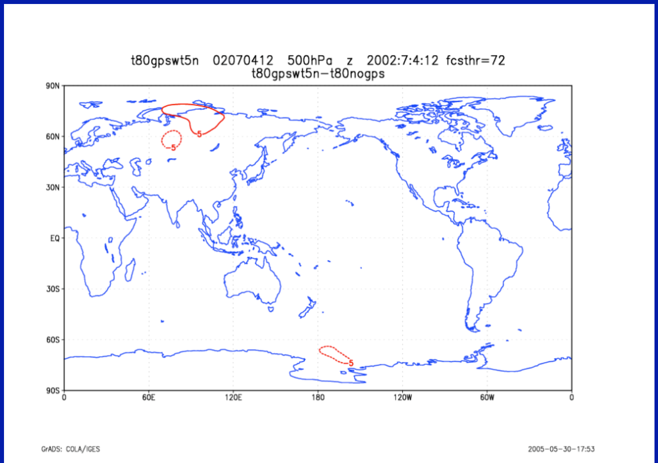
Forecasts: Day 3





SLP



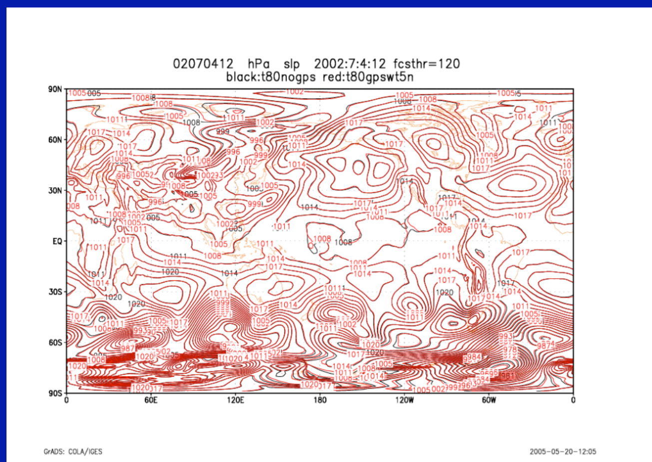


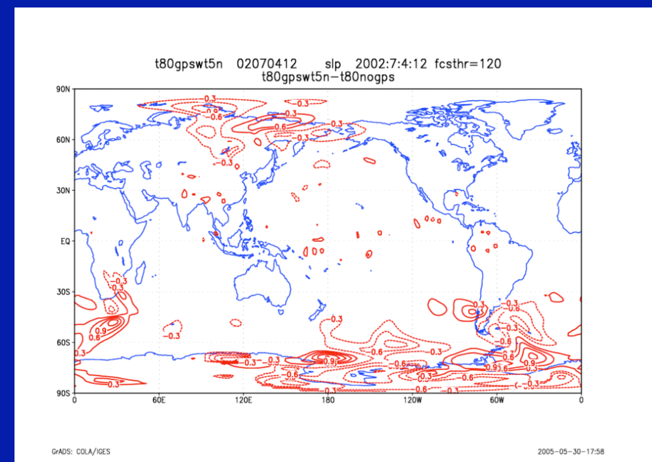
500 H

nogps / gpswt5

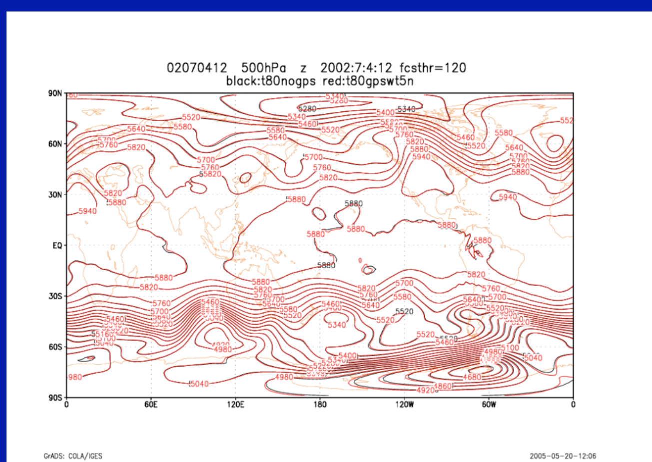
gpswt5 - nogps

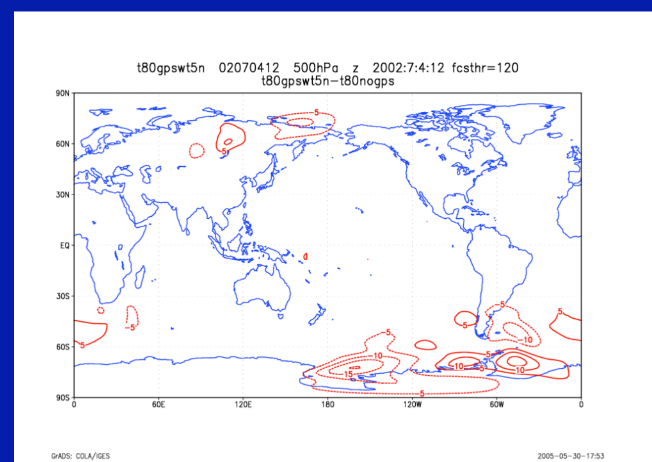
Forecasts: Day 5





SLP





500 H

nogps / gpswt5

gpswt5 - nogps

Anomaly Correlation
(NH: 20˚N-80˚N / SH: 80˚S-20˚S)

	Exp	24-hr	48-hr	72-hr	96-hr	120-hr
SLP	gpswt5	0.8695 / 0.9290	0.8374 / 0.8965	0.7437 / 0.8520	0.6696 / 0.8255	0.6636 / 0.7552
	nogps	**0.8695 / 0.9293**	**0.8380/ 0.8965**	**0.7433 / 0.8524**	**0.6683 / 0.8230**	**0.6630 / 0.7497**
500 H	gpswt5	0.9380 / 0.9486	0.9380 / 0.9315	0.8831 / 0.9600	0.7873 / 0.8520	0.7590 / 0.7492
	nogps	**0.9382 / 0.9487**	**0.9383 / 0.9309**	**0.8829 / 0.9555**	**0.7869 / 0.8495**	**0.7598 / 0.7413**

(Yellow means better!)

Root-Mean-Squared Errors
(NH / SH)

	Exp	24 hr	48 hr	72 hr	96 hr	120 hr
Slp (mb)	gpswt5	3.0394 / 3.8771	3.0718 / 4.7778	3.8642 / 6.0524	4.5628 / 6.7831	4.5594 / 7.9602
	nogps	3.0399 / 3.8722	3.0666 / 4.7803	3.8738 / 6.0488	4.5845 / 6.8404	4.5691 / 8.0626
500 H (m)	gpswt5	26.5011 / 37.9443	24.5412 / 43.8359	31.5442 / 52.9972	42.8493 / 65.8923	43.2711 / 82.1605
	nogps	26.4472 / 37.9236	24.4784 / 44.0226	31.5891 / 53.1366	41.9354 / 66.4673	43.2277 / 83.5716
850 T (C)	gpswt5	1.8392 / 2.7345	2.1729 / 3.0421	2.5124 / 3.5993	2.8975 / 4.0409	3.1161 / 4.3594
	nogps	1.8392 / 2.7281	2.1707 / 3.0409	2.5127 / 3.6115	2.8959 / 4.0756	3.1116 / 4.3951
200 Wind (m/s)	gpswt5	5.0369 / 6.6639	7.4152 / 8.2302	10.1056 / 10.0843	12.3924 / 13.1967	13.2515 / 15.9940
	nogps	5.0392 / 6.6706	7.4168 / 8.2561	10.1036 / 10.1231	12.3933 / 13.1900	13.2855 / 16.0811

Summary

- A *minorly revised* 2D ray-tracing operator and its tangent-linear/adjoint operators (Chang *et al.*, 2003, based on Zou *et al.*, 1999) are currently implemented and tested on CWB/GFS.

- Though marginal, the forecasting impact in this case study is generally positive, which is encouraging!

Summary (II)

- Upper-bound maximal analysis increments (GPS_only_wt6):
  - p_{sfc} ~ 4 hPa
  - T_v ~ 7 K
  - q ~ 5 g/kg
  - u, v ~ 2.5 m/s
- GPS_only 1-sounding tests suggest:
  maximal analysis increments are about 5-7 times smaller for the wt5 experiment.
- CWB's analysis increments without GPS:
  - p_{sfc} ~ 1 hPa
  - T_v ~ 4-7 K
  - q ~ 2-3 g/kg
  - u, v ~ 10-15 m/s

Summary (III)

- Additional increments added by GPS observation are generally *one order smaller*, except moisture (1-2 g/kg) and lower-level temperature (2 K).
- Substantial differences occurred in Day-5 forecasts.

Things To Do

- Impact studies on CWB/GFS analysis and forecasts
- QC
- O matrix
- Speed up
  - Local refractivity operator
  - Data thinning
  - Parallelizing
- Linearized non-local refractivity operator