Data Assimilation

Bri
Ge
Ch
Ala
Ga

- Two GAIM Teams funded by the U.S. DOD under a Multidisplinary University Research Initiative (MURI) grant.

- Two Principal Investigators:
  - Dr. Bob Schunk, Utah State University (USU)
  - Dr. Chunming Wang, University of Southern California (USC)

- GAIM = Global Assimilative Ionospheric Model
- Forward Model
- Band-limited Kalman filter (sparse covariance matrix)

- Assim. Runs: input ground GPS TEC only
  - •3 days: May 22-24, 2002
  - •May 23 is a storm day (Ap: 78)

- Validation:
  - • GIM vertical TEC maps
  - • TOPEX vertical TEC measurements
  - • Ionosonde peak density (NmF2) measurements
  - •Slant TEC obs. from independent GPS sites
  - •Density profile retrievals from CHAMP GPS occultations

USC/JPL GAIM

- **New Global Data Sources, Available in Near Real-Time**
  - Global ionosonde network
  - DMSP: in situ electron density, etc.
  - Ground GPS Network (used in GIM TEC maps)
  - CHAMP, SAC-C, & COSMIC: GPS occultation data
  - ARGOS, DMSP & NPOESS: UV airglow & limb scan
  - C/NOFS
- **Combine models & measurements optimally**
  - Use 4DVAR & Approx. Kalman filter techniques
  - Improve on GIM 2D TEC maps (add dynamics)

USC/JPL GAIM

Mapping State
To Measurements

4DVAR

Kalman Filter

USC/JPL GAIM

Current Version

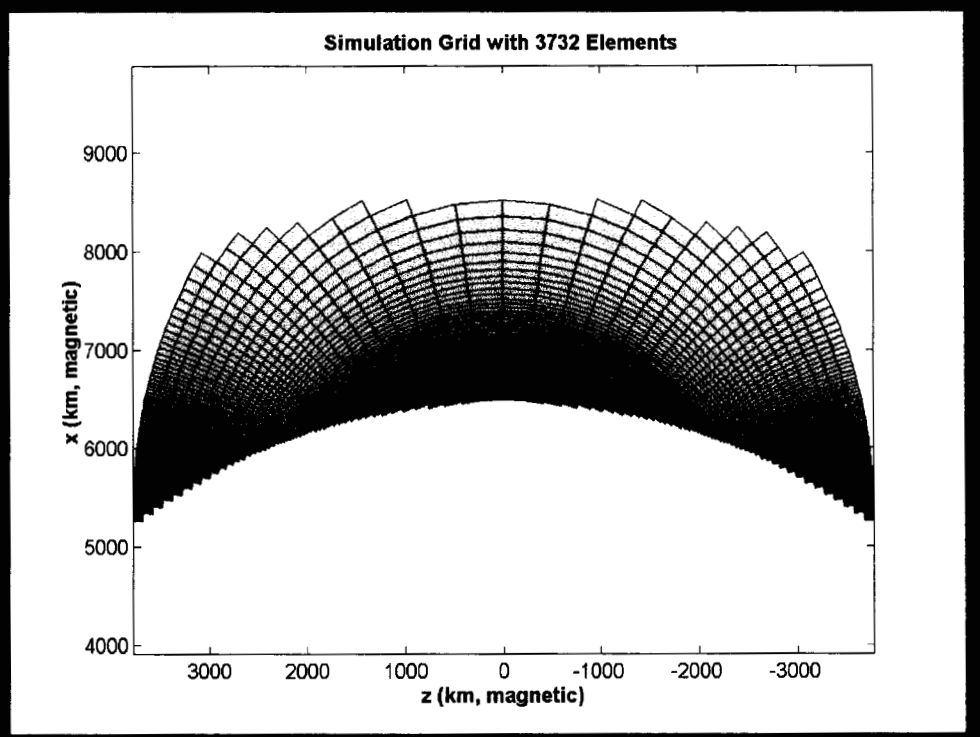
- Eccentric tilted dipole p-q coordinates (varying spacing).
- Finite volume; Eulerian scheme.
- Fully 3-D.
- Single ion (O^+).

- MSIS90 (Empirical N_n)
- HWM93 (Empirical Wind)
- Empirical EUV
- Empirical ExB drift

With a Linux Pentium Workstation:
~120,000 cells with following resolutions

20 km altitude resolution

- 2° latitude resolution
- 7.5° longitude resolution
- ± 30° magnetic latitudes
- 120 - 2000 km altitude



- Elements in p-q Magnetic Coordinates
- Variable Element Size
- Off-Line Computation of Observation Operator
- Solve for ion density using Finite Volume Method
- Efficient Forward Propagation of the State
- Unconditionally Stable Time Integration

USC/JPL GAIM

State Model

$$x_{k+1}^{t} = \Psi_k x_k^t + \varepsilon_k^q$$

Measurement Model

$$m_k^o = H_k x_k^t + \varepsilon_k^o$$

Noise Model

$$\varepsilon_k^o = \varepsilon_k^m + \varepsilon_k^r$$

$$E\left(\varepsilon_k^m, \varepsilon_k^{mT}\right) = M_k$$

$$E\left(\varepsilon_k^r, \varepsilon_k^{rT}\right) = R_k$$

$$E\left(\varepsilon_k^q, \varepsilon_k^{qT}\right) = Q_k$$

- Kalman Filter
- Optimal Interpolation
- Band Limited Kalman Filter

$$x_k^a = x_k^f + K_k\left(m_k^o - H_k x_k^f\right)$$

$$K_k = P_k^f H_k^T \left(H_k P_k^f H_k^T + R_k + Q_k\right)^{-1}$$

$$\cancel{P_k^a = P_k^f - K_k H_k P_k^f}$$

$$x_{k+1}^f = \Psi_k x_k^a$$

$$\cancel{P_{k+1}^f = \Psi_k P_k^a \Psi_k^T + Q_k}$$

$$\sigma_{ij} = \sigma_i \times \sigma_j \times \exp - \left\{ \left(\frac{r_i - r_j}{R} \right)^2 + \left(\frac{\theta_i - \theta_j}{\Theta} \right)^2 + \left(\frac{\phi_i - \phi_j}{\Phi} \right)^2 \right\}$$

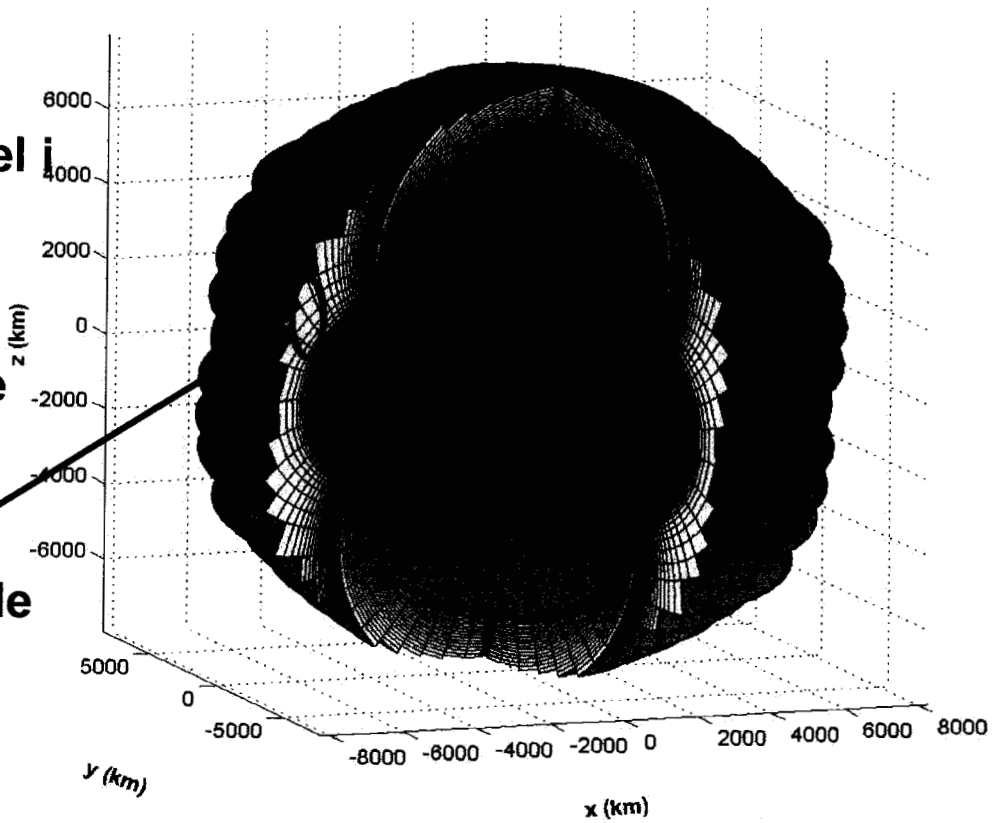
σ_{ij} = Corr. between voxel i and j

σ_i = Uncertainty in density in voxel i

R = Correlation length in altitude

Θ = Correlation length in latitude

Φ = Correlation length in longitude



Correlation Scale

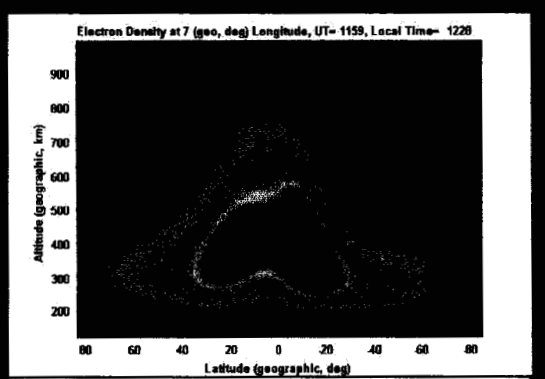
M = No. of measurements
N = No. of Voxels
A = No. of neighbor elements with non-zero covariance

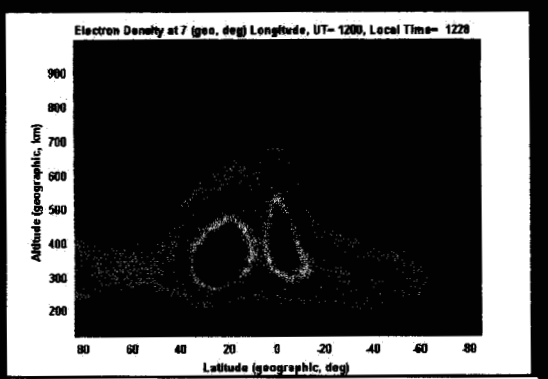
USC/JPL GAIM

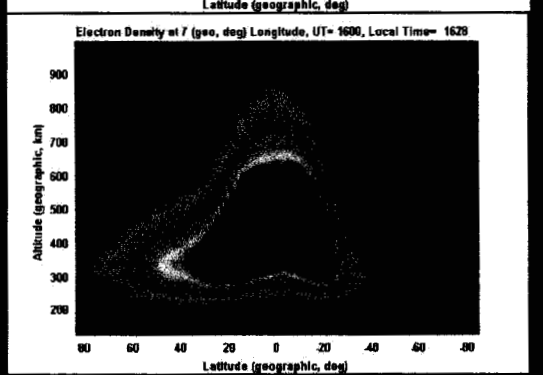
Approach	2D	Mid&Low-lat. 3D	Globa
Full Kalman	X		
Band-limited Kalman	X	X	X
Optimal Interpolation	X	X	X

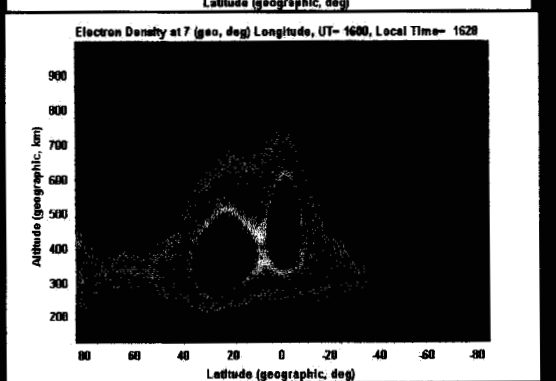
State Dimension

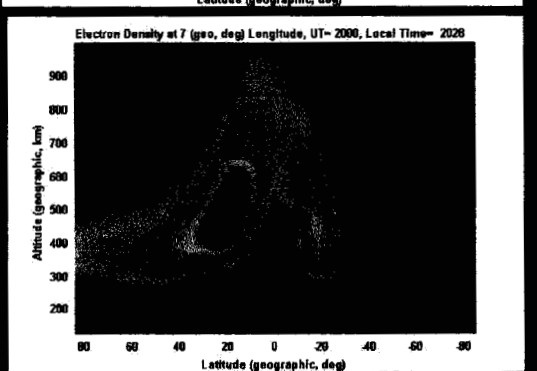
USC/

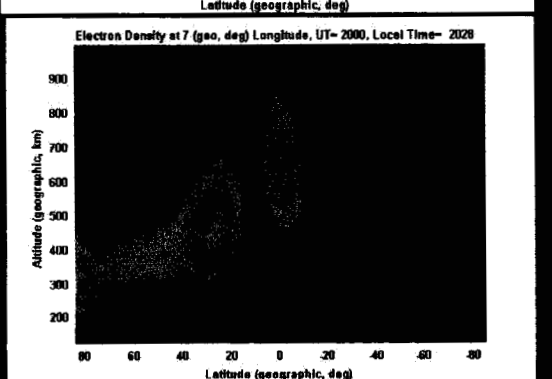

Electron Density at 7 (geo, deg) Longitude, UT= 1159, Local Time= 1228
Altitude (geographic, km)
900
800
700
600
500
400
300
200
80 60 40 20 0 -20 -40 -60 -80
Latitude (geographic, deg)


Electron Density at 7 (geo, deg) Longitude, UT= 1200, Local Time= 1228
Altitude (geographic, km)
900
800
700
600
500
400
300
200
80 60 40 20 0 -20 -40 -60 -80
Latitude (geographic, deg)


Electron Density at 7 (geo, deg) Longitude, UT= 1600, Local Time= 1628
Altitude (geographic, km)
900
800
700
600
500
400
300
200
80 60 40 20 0 -20 -40 -60 -80
Latitude (geographic, deg)


Electron Density at 7 (geo, deg) Longitude, UT= 1600, Local Time= 1628
Altitude (geographic, km)
900
800
700
600
500
400
300
200
80 60 40 20 0 -20 -40 -60 -80
Latitude (geographic, deg)


Electron Density at 7 (geo, deg) Longitude, UT= 2000, Local Time= 2028
Altitude (geographic, km)
900
800
700
600
500
400
300
200
80 60 40 20 0 -20 -40 -60 -80
Latitude (geographic, deg)


Electron Density at 7 (geo, deg) Longitude, UT= 2000, Local Time= 2028
Altitude (geographic, km)
900
800
700
600
500
400
300
200
80 60 40 20 0 -20 -40 -60 -80
Latitude (geographic, deg)

USC/JPL GAIM

~100 Global GPS Ground Stations

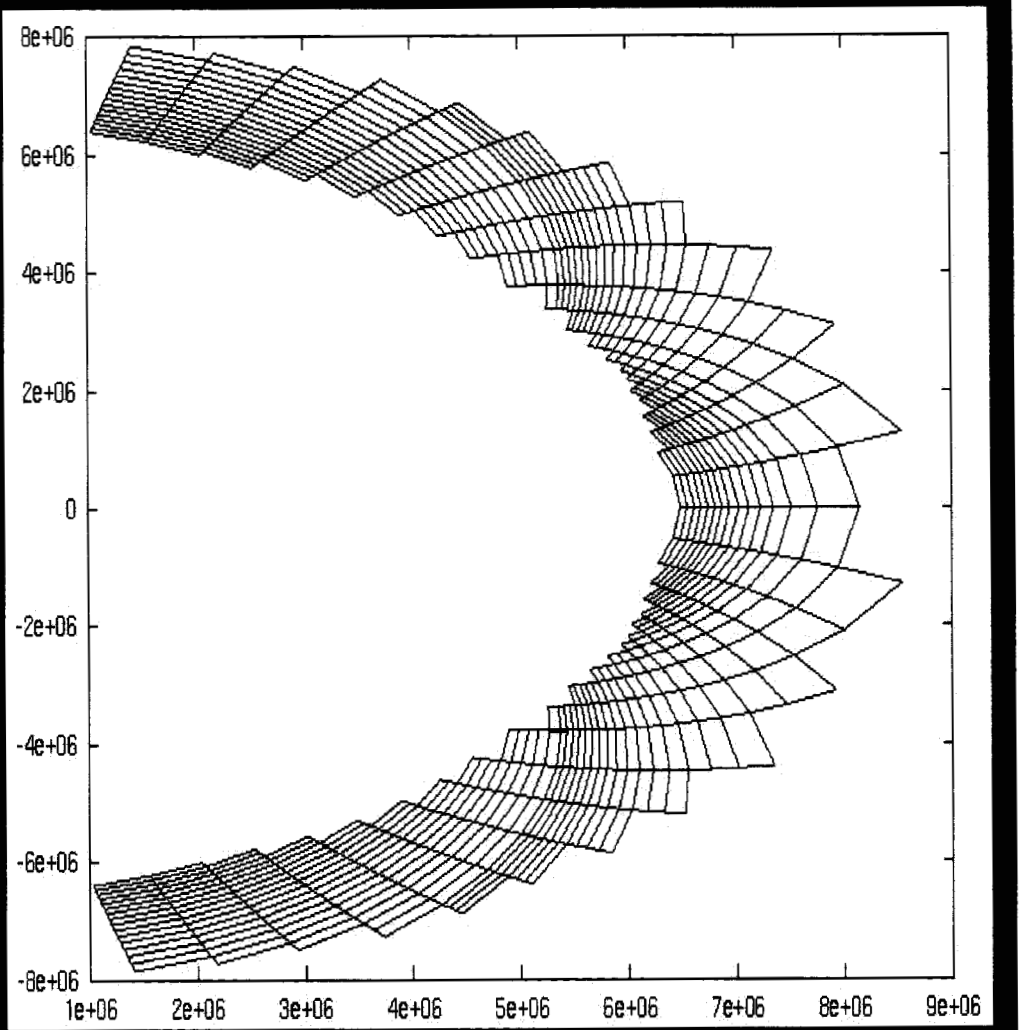
GAIM assimilates ~200,000 TEC links (@ 5 min rate) per day

CHAMP (@ 440 km)
SAC-C (@ 700 km)
IOX (@ 800 km)
GRACE (@ 350 km)
Topex/Poseidon (@1330 km) (Upward looking only)
Jason 1 (@1330 km) (Upward looking only)
C/NOFS

LORAAS on ARGOS
GUVI on TIMED
SSUSI & SSULI on DMSP (F15)

TEC from TOPEX Altimeter
Ionosonde
DMSP in situ
CHAMP in situ
GRACE Cross links
ISR

USC/JPL GAIM

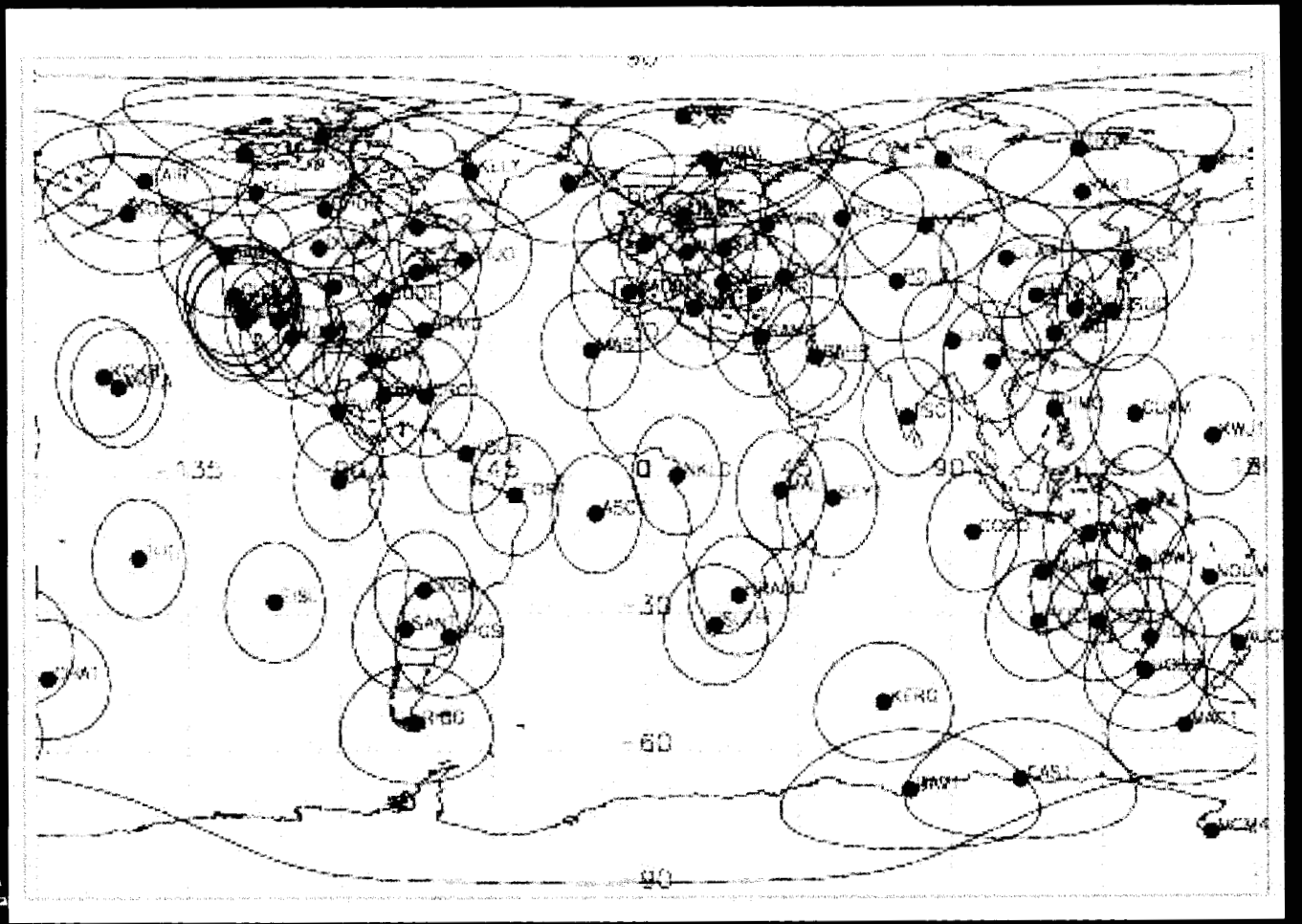

8e+06
6e+06
4e+06
2e+06
0
-2e+06
-4e+06
-6e+06
-8e+06
1e+06
2e+06
3e+06
4e+06
5e+06
6e+06
7e+06
8e+06
9e+06

USC/JPL GAIM

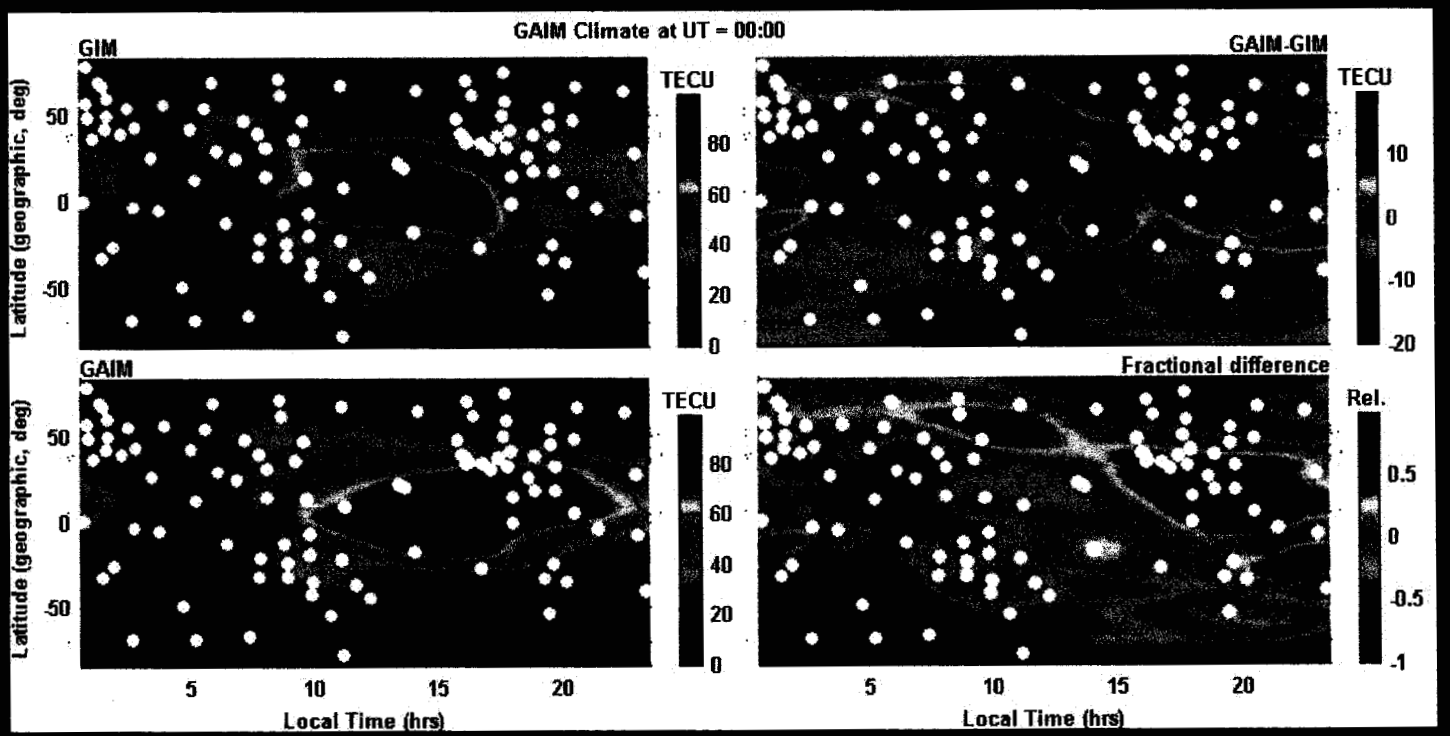
- Geophysical Parameters
  - May 22: F10.7=185.6, Ap=8
  - May 23: F10.7=184.8, Ap=78
  - May 24: F10.7=193.9, Ap=2
- Ground GPS Data
  - May 22: 192,000 links, 98 sites
  - May 23: 190,500 links, 98 sites
  - May 24: 198,000 links, 98 sites
- Empirical drivers same over 3 runs
  - ExB drift pattern: June, Solar max.

USC/JPL GAIM

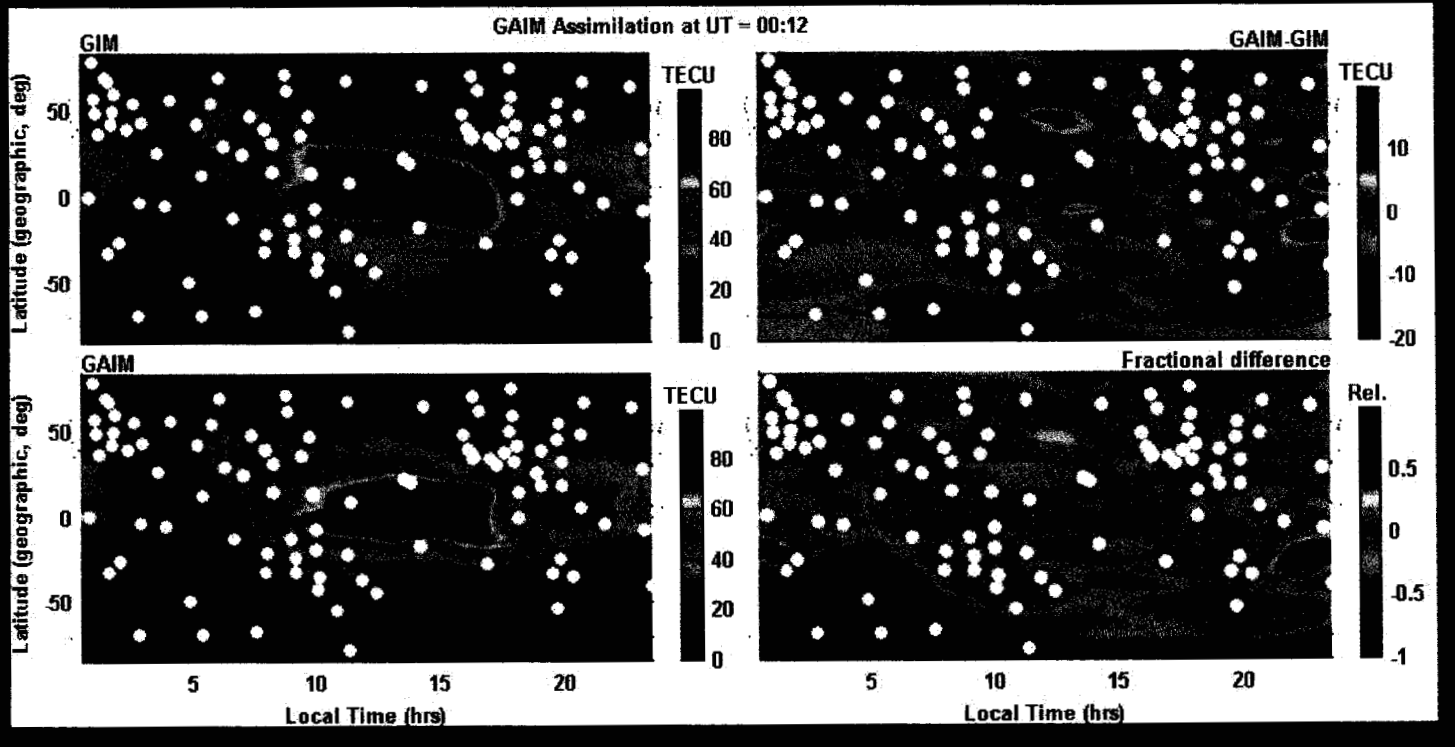
(10 degree elevation mask; 450 km shell height)



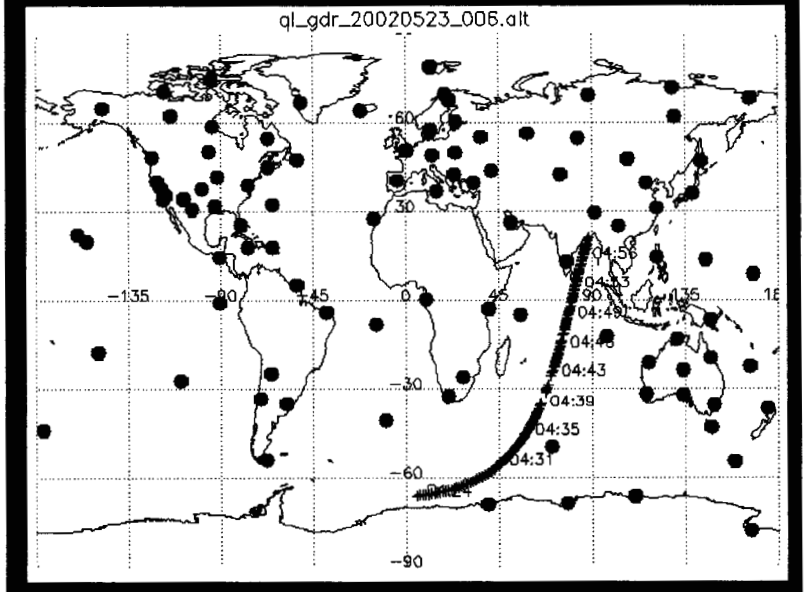
USC/JPL GAIM


GAIM Climate at UT = 00:00
GIM
GAIM-GIM
GAIM
Fractional difference
TECU
Rel.
Latitude (geographic, deg)
Local Time (hrs)
50
0
-50
5
10
15
20
80
60
40
20
0
10
-10
-20
0.5
-0.5
-1

USC/JPL GAIM


GAIM Assimilation at UT = 00:12
GIM
GAIM-GIM
GAIM
Fractional difference
TECU
Rel.
Latitude (geographic, deg)
Local Time (hrs)
50
0
-50
5
10
15
20
80
60
40
20
0
10
-10
-20
0.5
-0.5
-1

USC/JPL GAIM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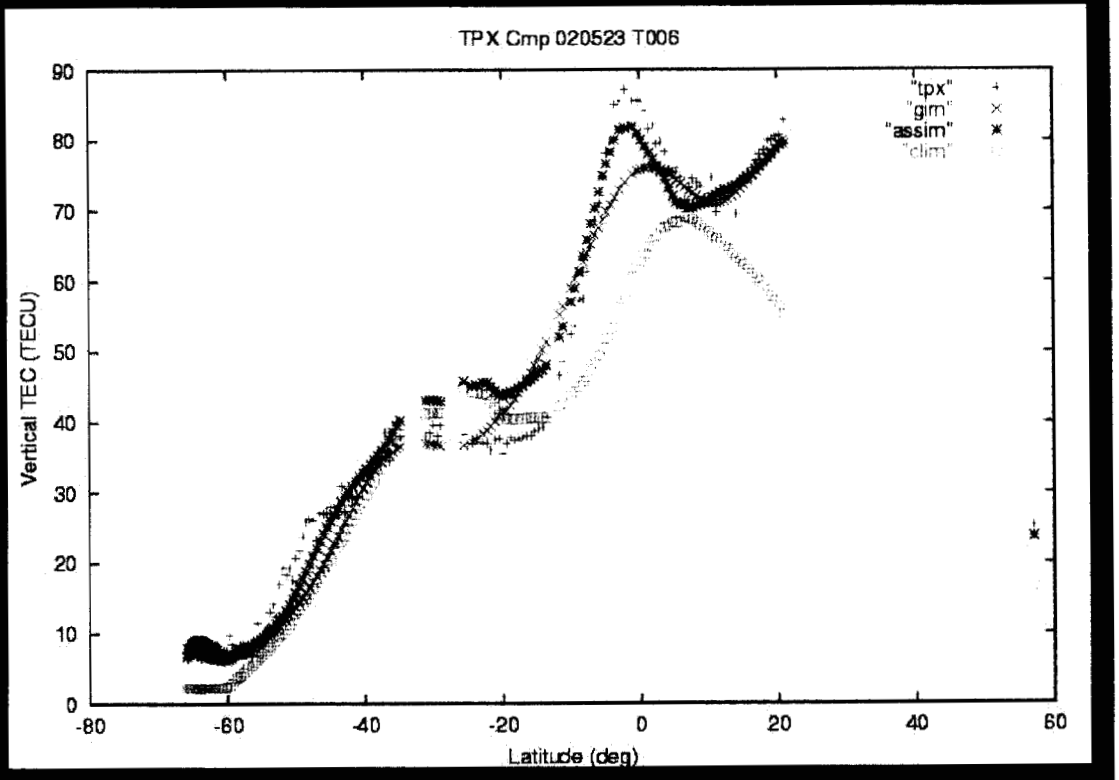
04:55
04:51
04:47
04:43
04:39
04:35
04:31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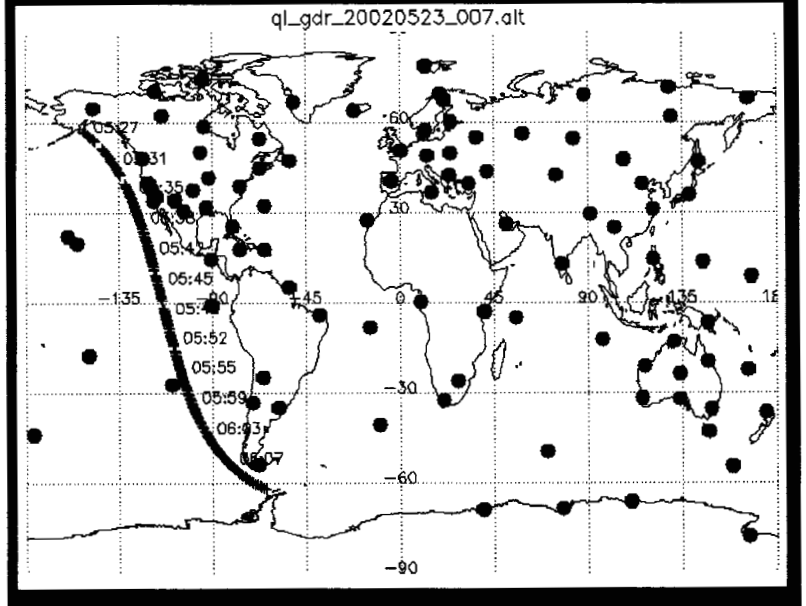
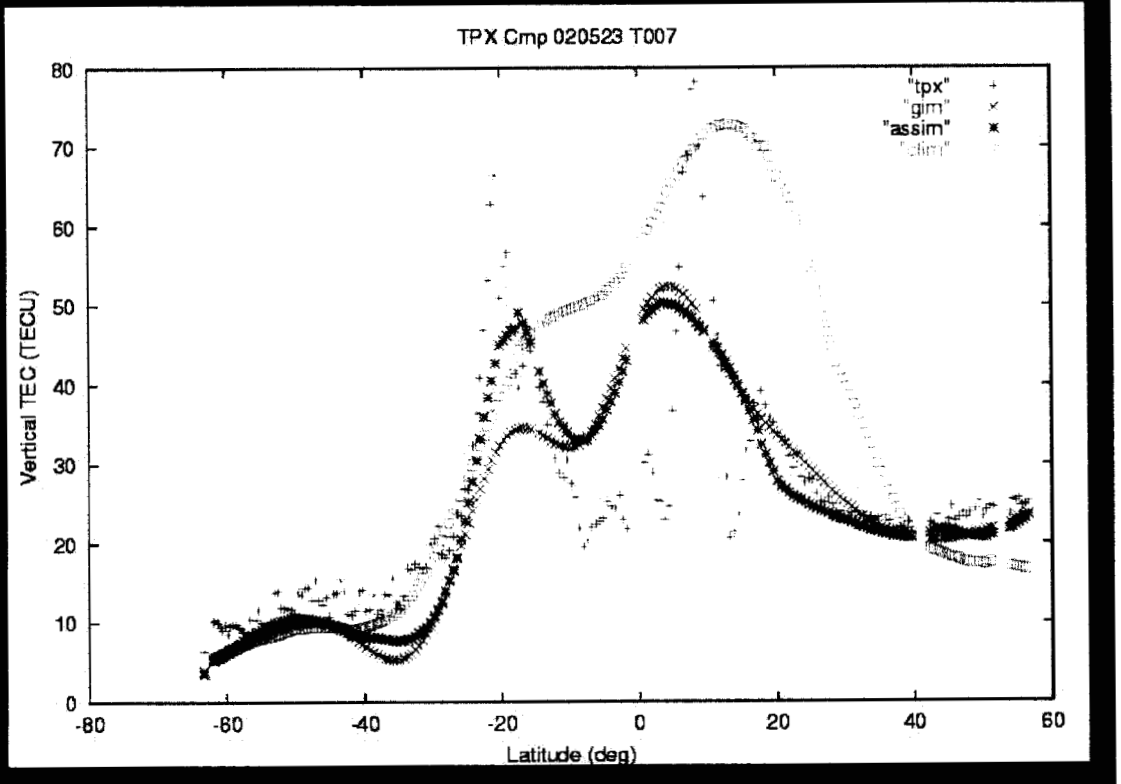
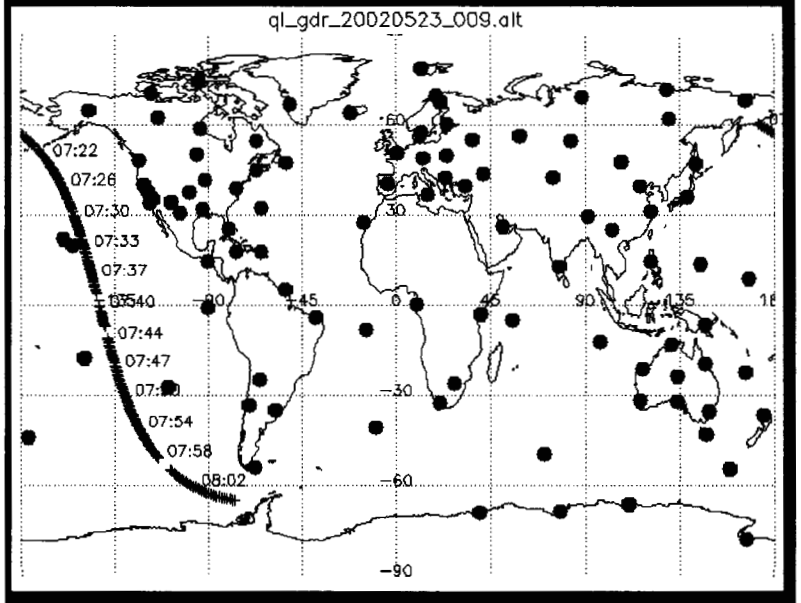
"tpx"
"gim"
"assim"
"clim"
Vertical TEC (TECU)
Latitude (deg)

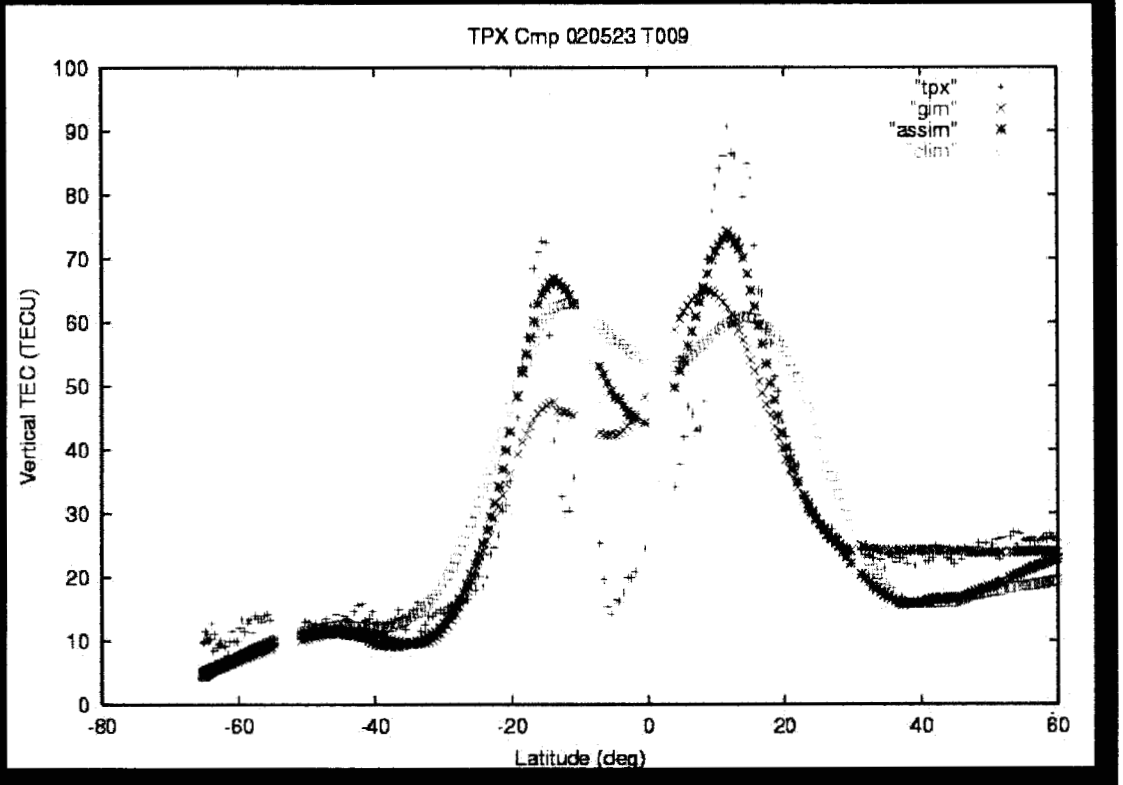
USC/JPL GAIM


ql_gdr_20020523_007.alt
05:27
05:31
05:35
05:42
05:45
05:52
05:55
05:59
06:03
06:07
-135
-90
-45
0
45
90
135
60
30
-30
-60
-90

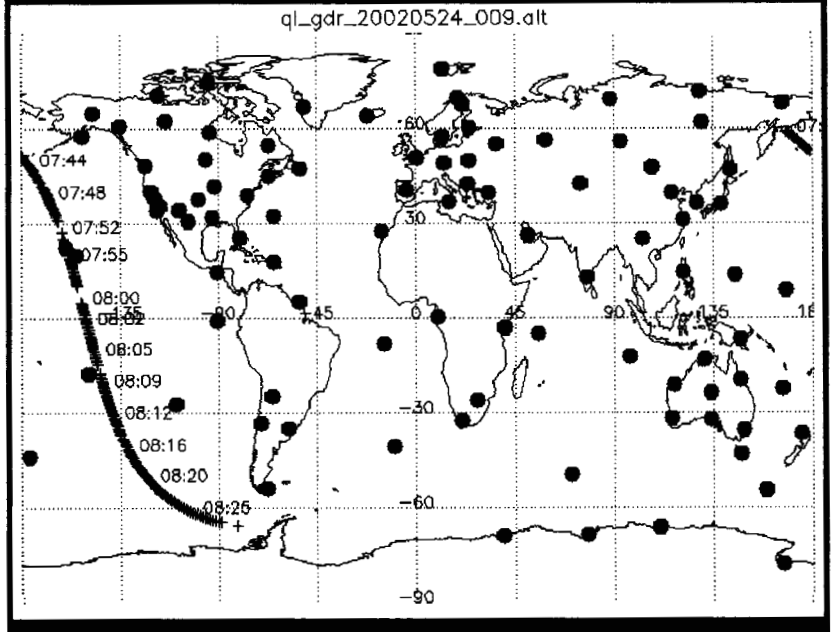

TPX Cmp 020523 T007
"tpx"
"gim"
"assim"
"clim"
Vertical TEC (TECU)
Latitude (deg)
80
70
60
50
40
30
20
10
0
-80
-60
-40
-20
0
20
40
60

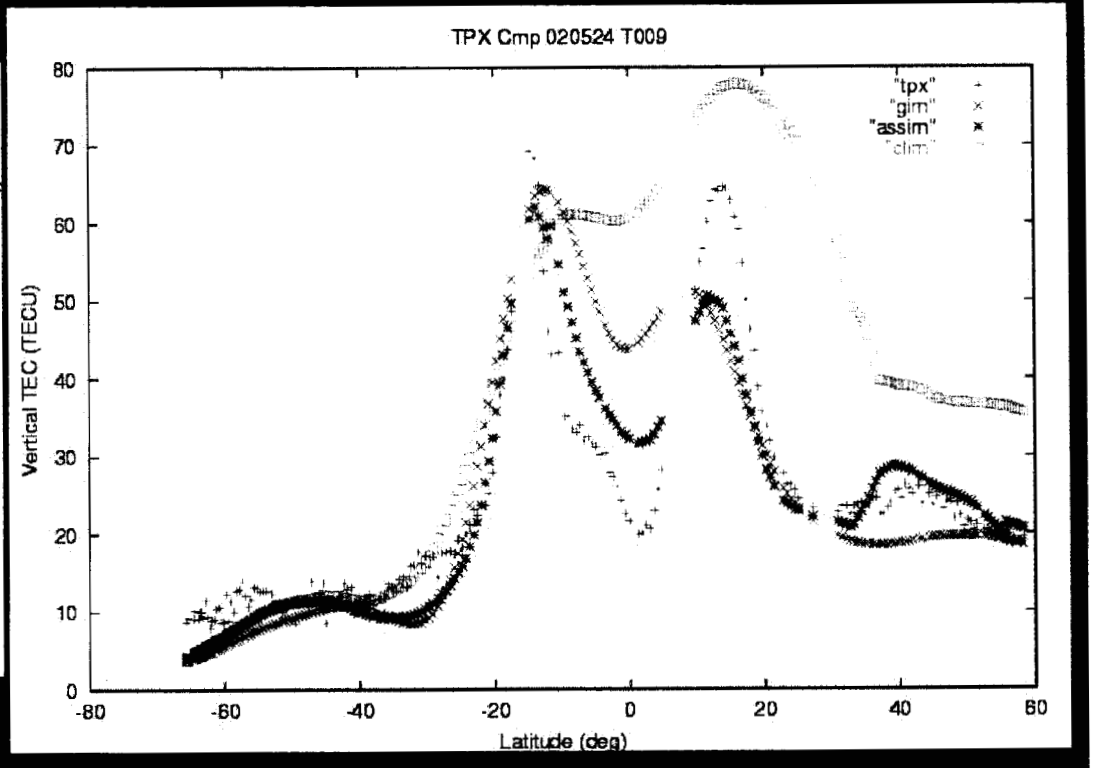
USC/JPL GAIM


ql_gdr_20020523_009.alt
07:22
07:26
07:30
07:33
07:37
07:40
07:44
07:47
07:54
07:58
08:02
60
30
-30
-60
-90
-45
0
45
90
135

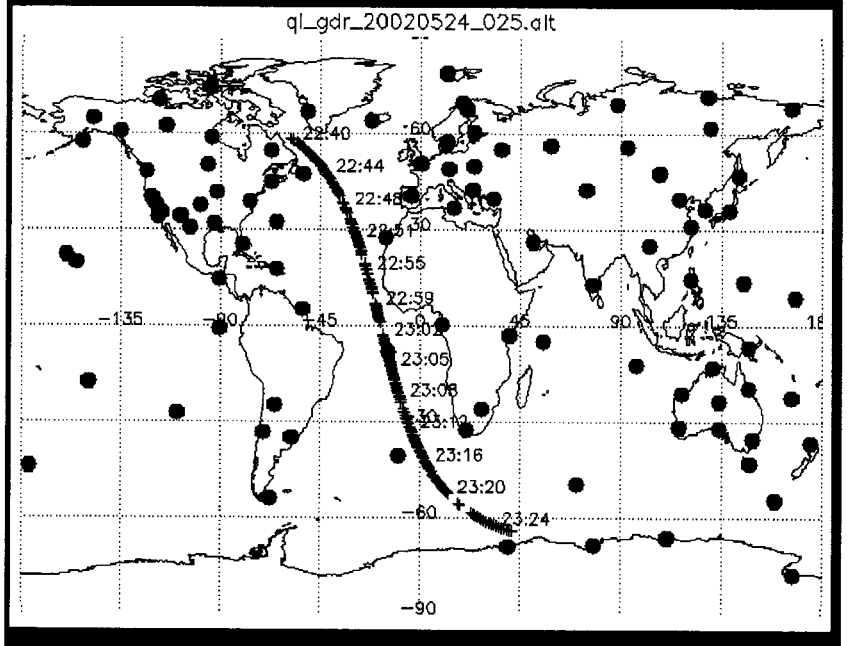

TPX Cmp 020523 T009
"tpx"
"gim"
"assim"
"clim"
Vertical TEC (TECU)
Latitude (deg)
0
10
20
30
40
50
60
70
80
90
100
-80
-60
-40
-20
0
20
40
60

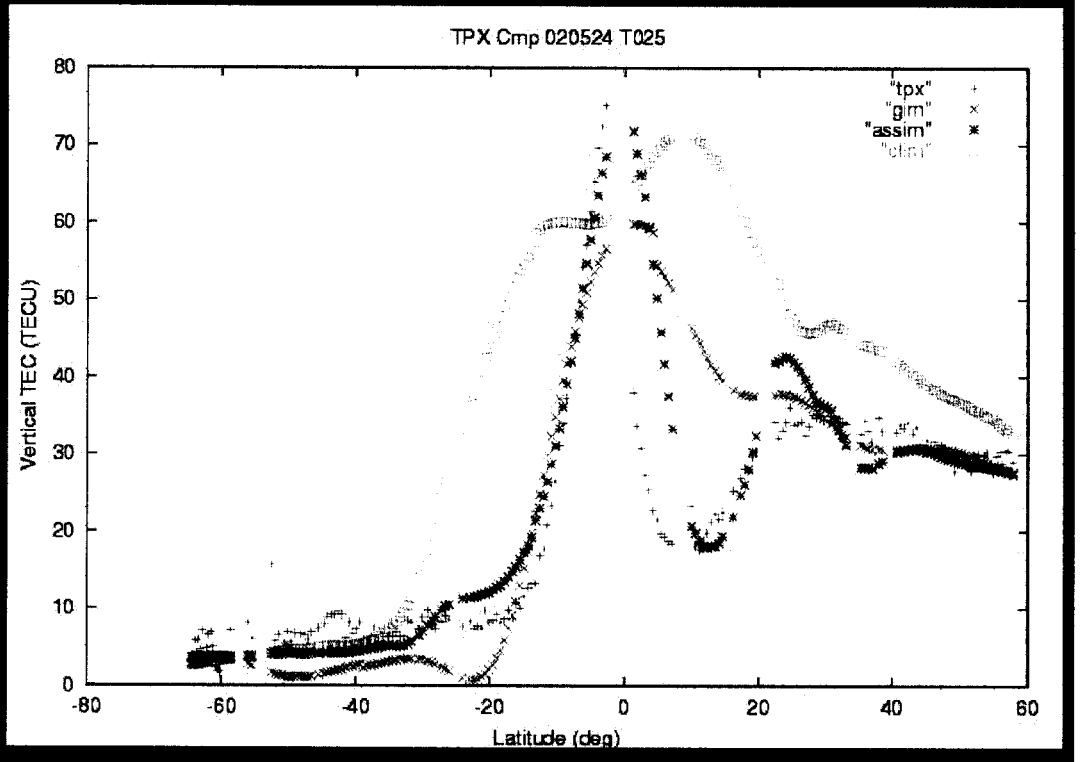
USC/JPL GAIM


ql_gdr_20020524_009.alt
07:44
07:48
07:52
07:55
08:00
08:05
08:09
08:12
08:16
08:20
08:25
60
30
-30
-60
-90
-90
-45
0
45
90
135

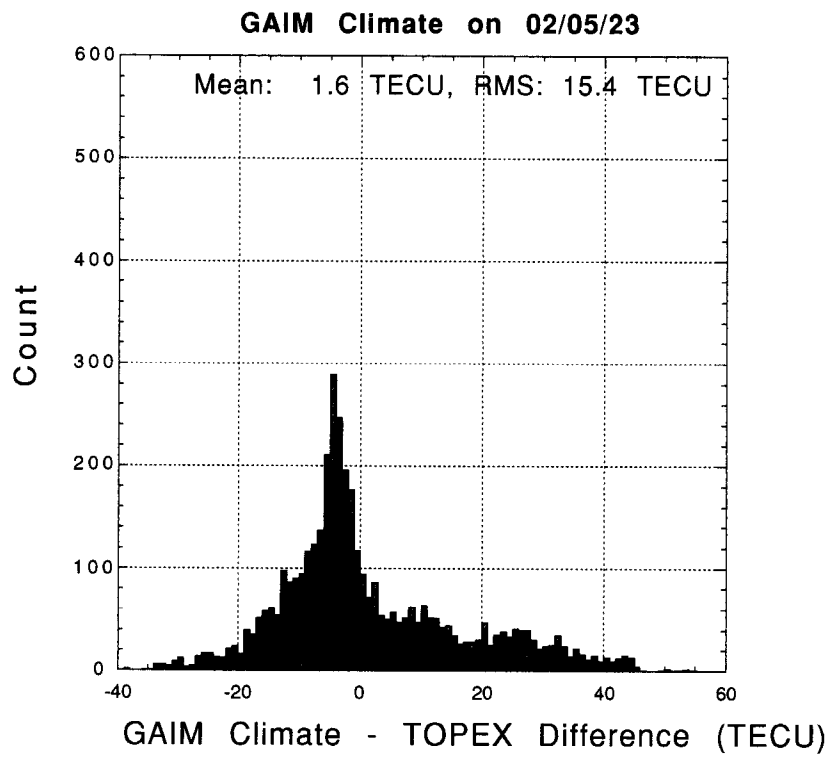

TPX Cmp 020524 T009
"tpx"
"gim"
"assim"
"clim"
Vertical TEC (TECU)
Latitude (deg)
80
70
60
50
40
30
20
10
0
-80
-60
-40
-20
0
20
40
60

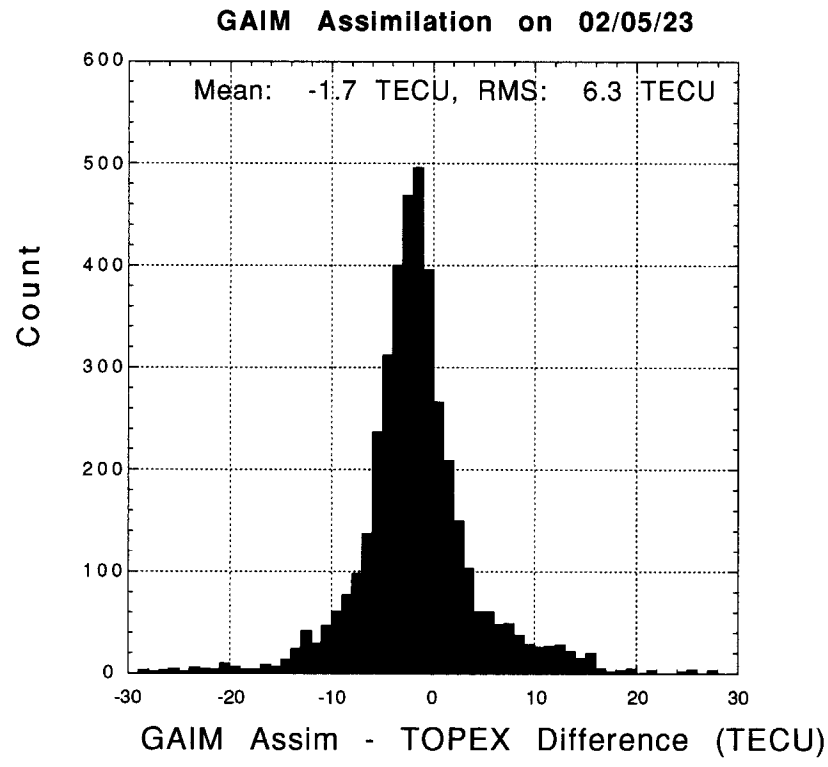
USC/JPL GAIM

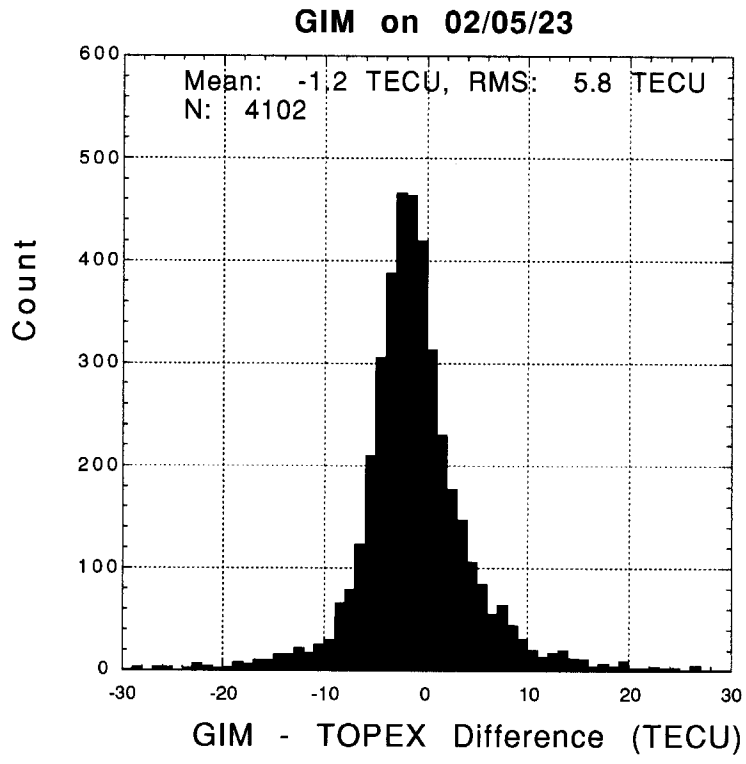

ql_gdr_20020524_025.alt
22:40
22:44
22:48
22:55
22:59
23:05
23:16
23:20
23:24
-135
-90
-45
45
90
135
-60
-90

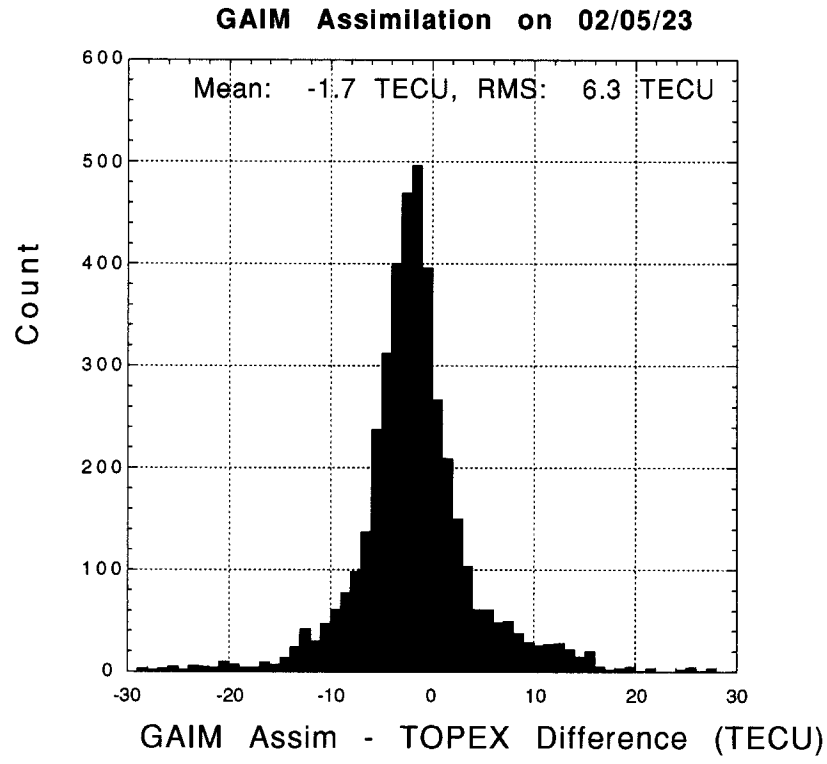

TPX Cmp 020524 T025
"tpx"
"gim"
"assim"
Vertical TEC (TECU)
Latitude (deg)
0
10
20
30
40
50
60
70
80
-80
-60
-40
-20
0
20
40
60

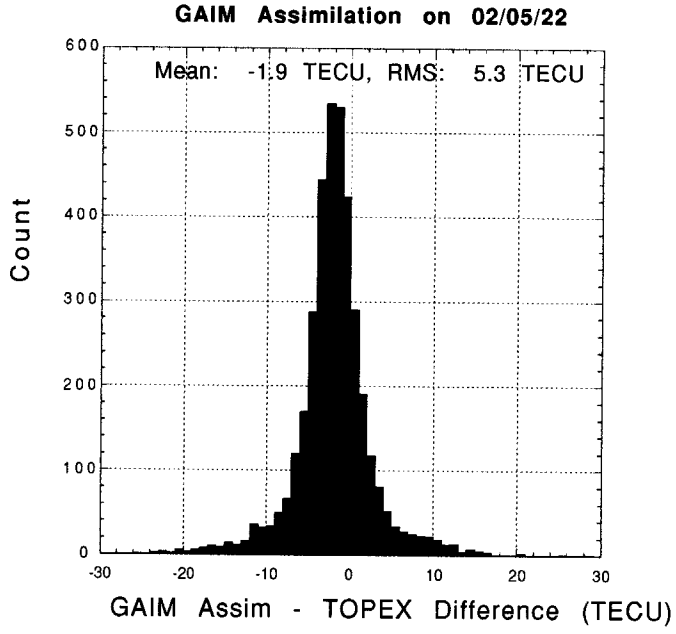
USC/JPL GAIM

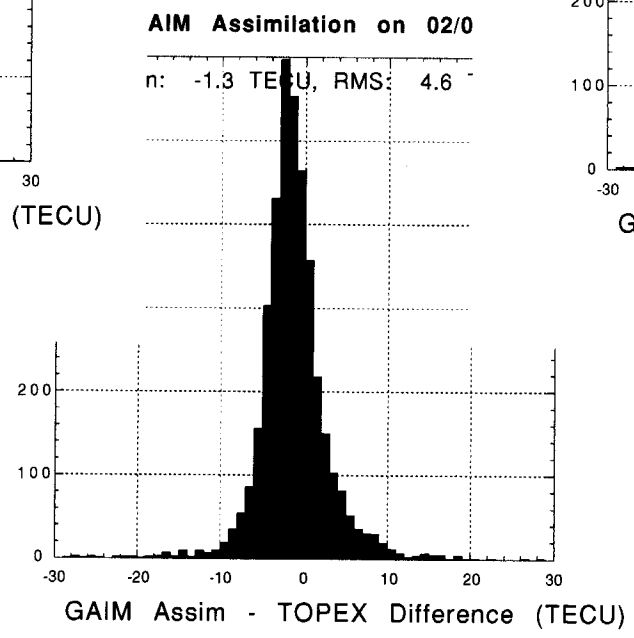

GAIM Climate on 02/05/23
Mean: 1.6 TECU, RMS: 15.4 TECU
Count
600
500
400
300
200
100
0
-40
-20
0
20
40
60
GAIM Climate - TOPEX Difference (TECU)

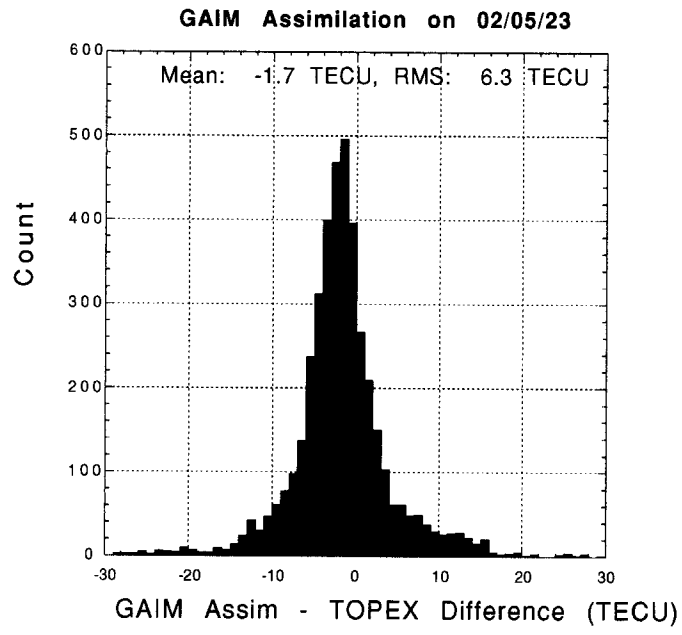

GAIM Assimilation on 02/05/23
Mean: -1.7 TECU, RMS: 6.3 TECU
Count
600
500
400
300
200
100
0
-30
-20
-10
0
10
20
30
GAIM Assim - TOPEX Difference (TECU)


GIM on 02/05/23
Mean: -1.2 TECU, RMS: 5.8 TECU
N: 4102
Count
600
500
400
300
200
100
0
-30
-20
-10
0
10
20
30
GIM - TOPEX Difference (TECU)

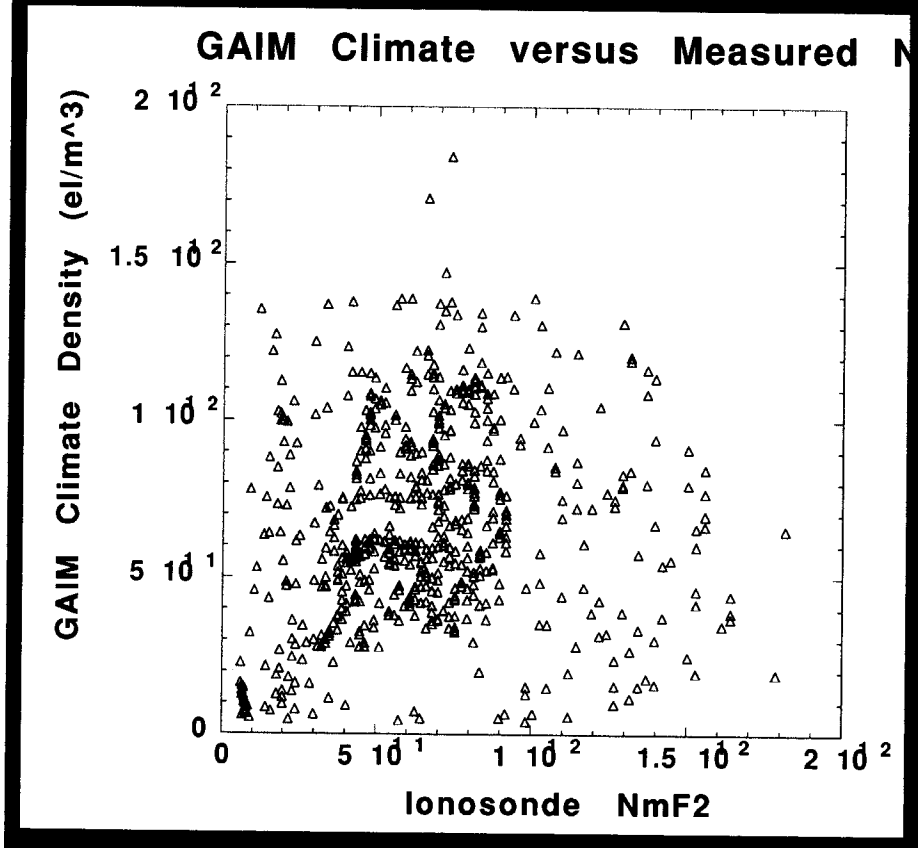

GAIM Assimilation on 02/05/23
Mean: -1.7 TECU, RMS: 6.3 TECU
Count
600
500
400
300
200
100
0
-30
-20
-10
0
10
20
30
GAIM Assim - TOPEX Difference (TECU)

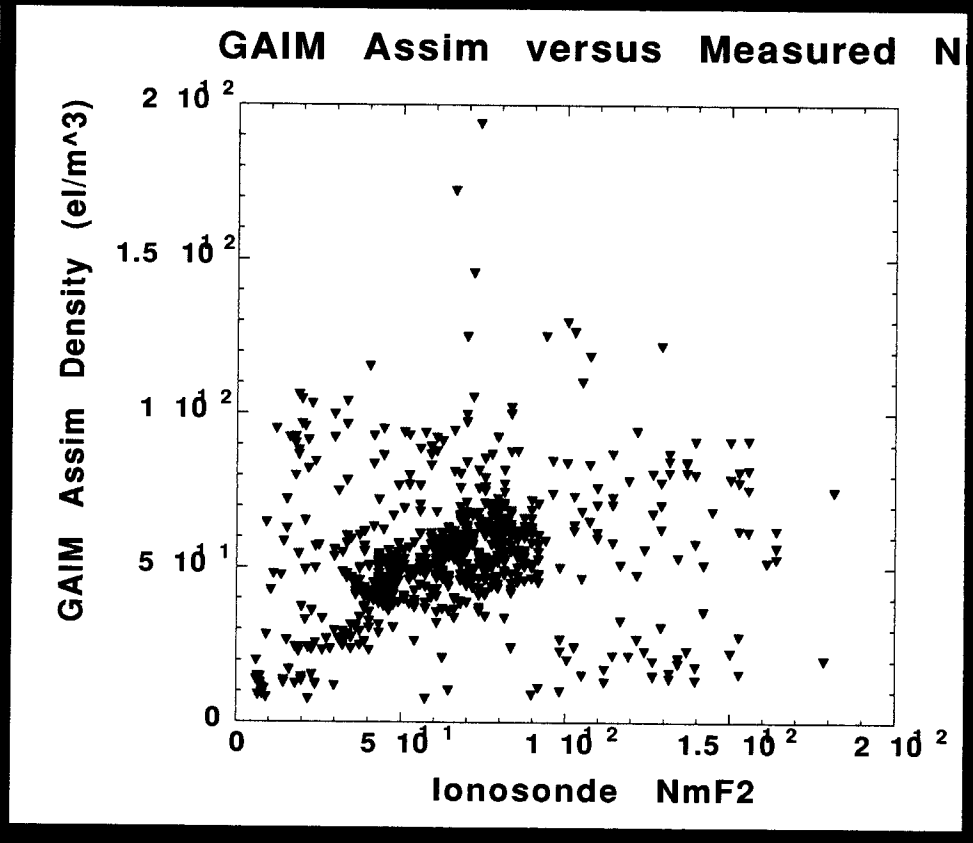

GAIM Assimilation on 02/05/22
Mean: -1.9 TECU, RMS: 5.3 TECU
Count
600
500
400
300
200
100
0
-30
-20
-10
0
10
20
30
GAIM Assim - TOPEX Difference (TECU)


AIM Assimilation on 02/0
n: -1.3 TECU, RMS: 4.6
200
100
0
-30
-20
-10
0
10
20
30
GAIM Assim - TOPEX Difference (TECU)


GAIM Assimilation on 02/05/23
Mean: -1.7 TECU, RMS: 6.3 TECU
Count
600
500
400
300
200
100
0
-30
-20
-10
0
10
20
30
GAIM Assim - TOPEX Difference (TECU)

USC/JPL GAIM





633 NmF2 points from 19 global sites; no quality control

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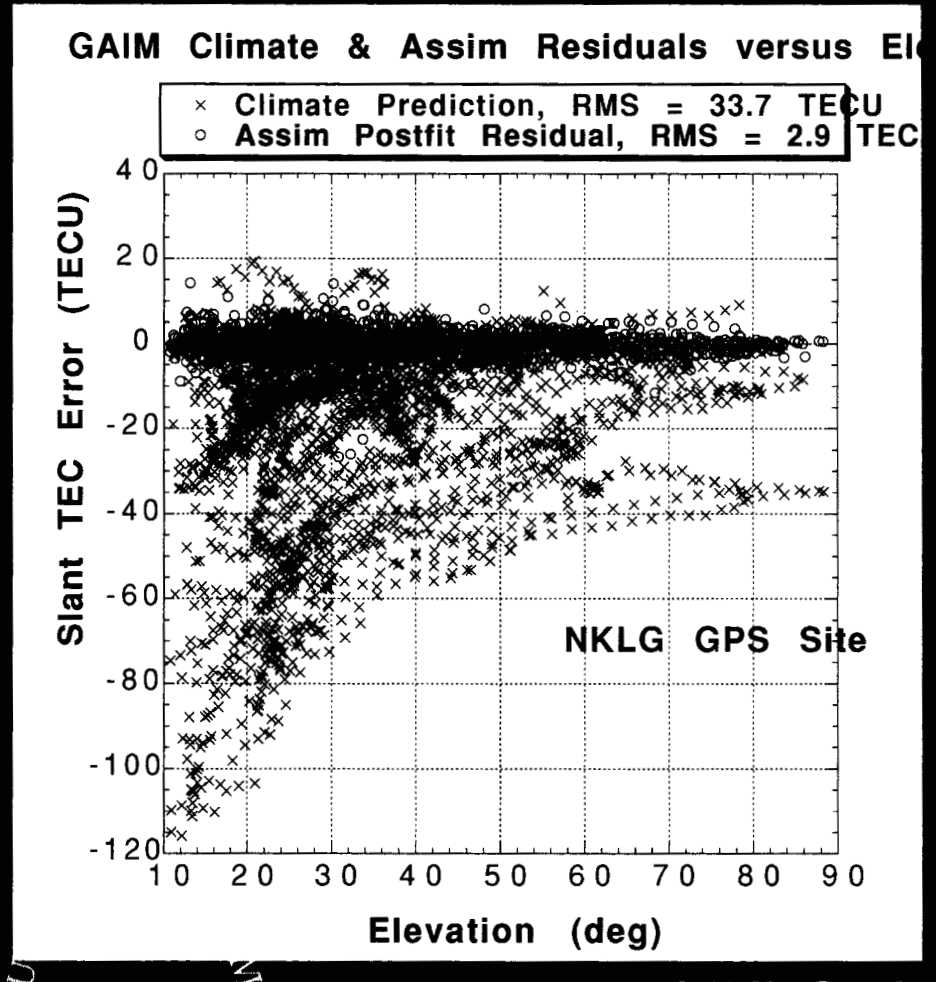
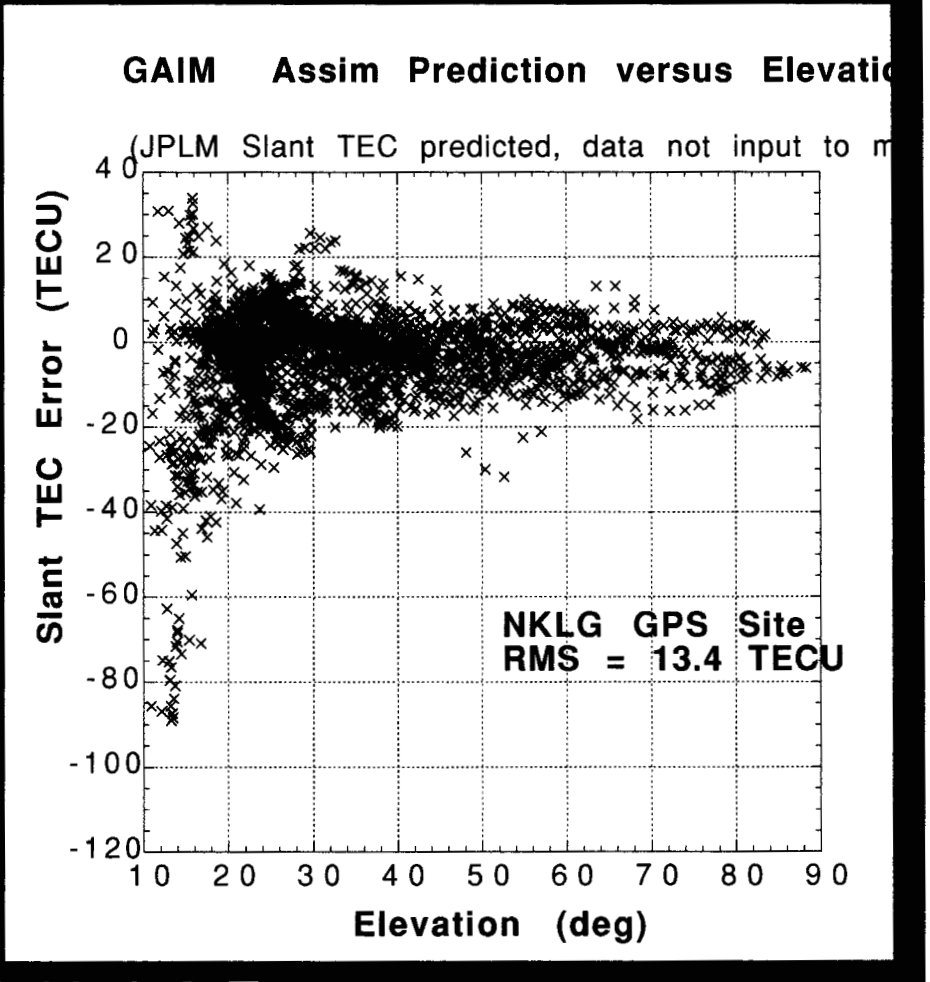
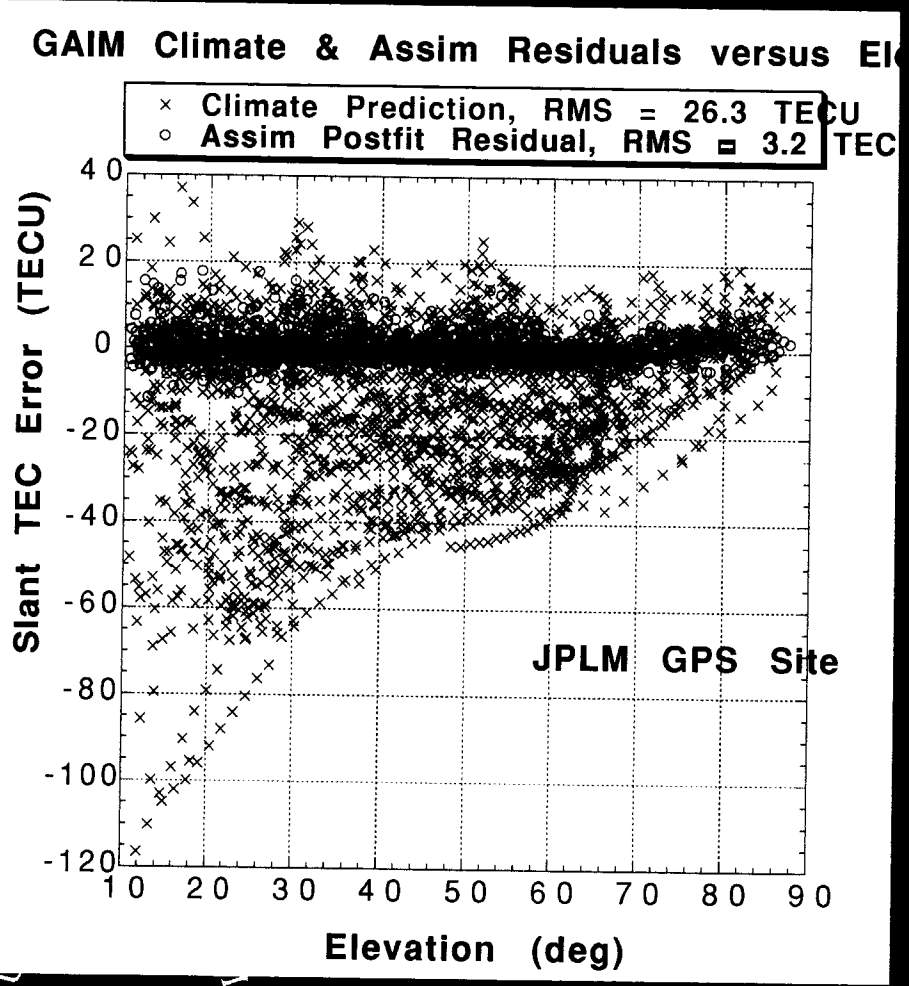
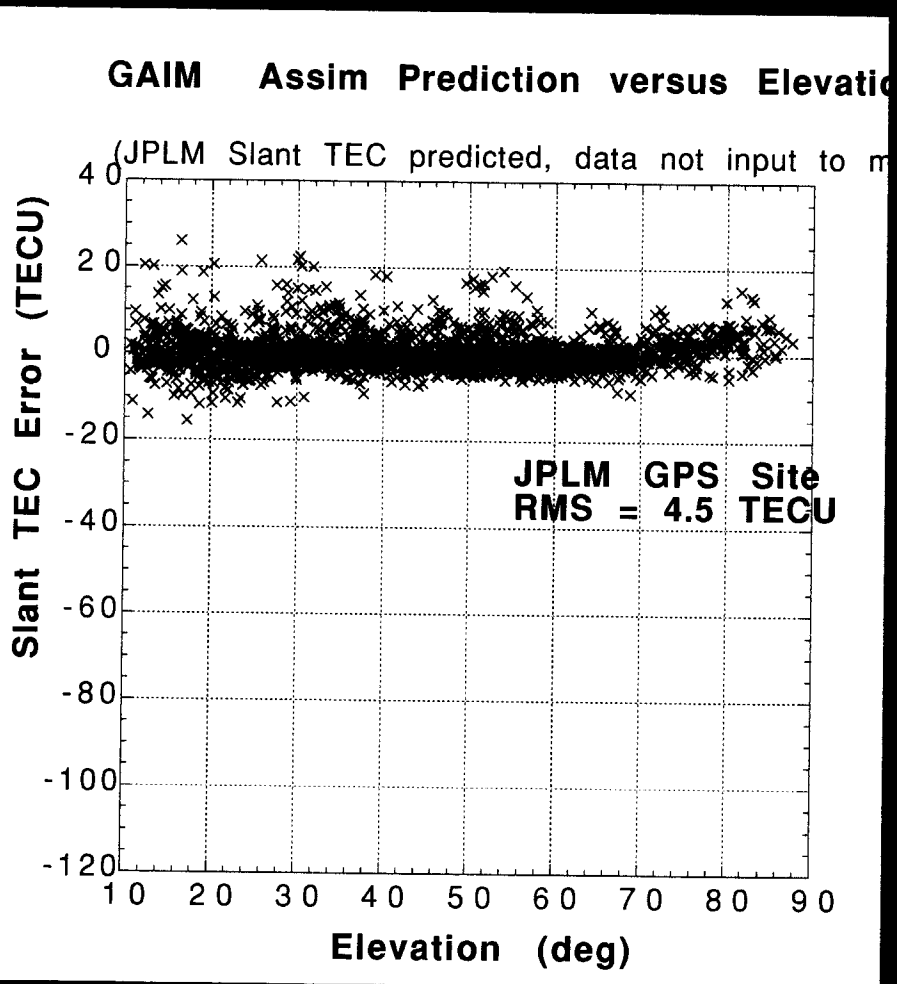
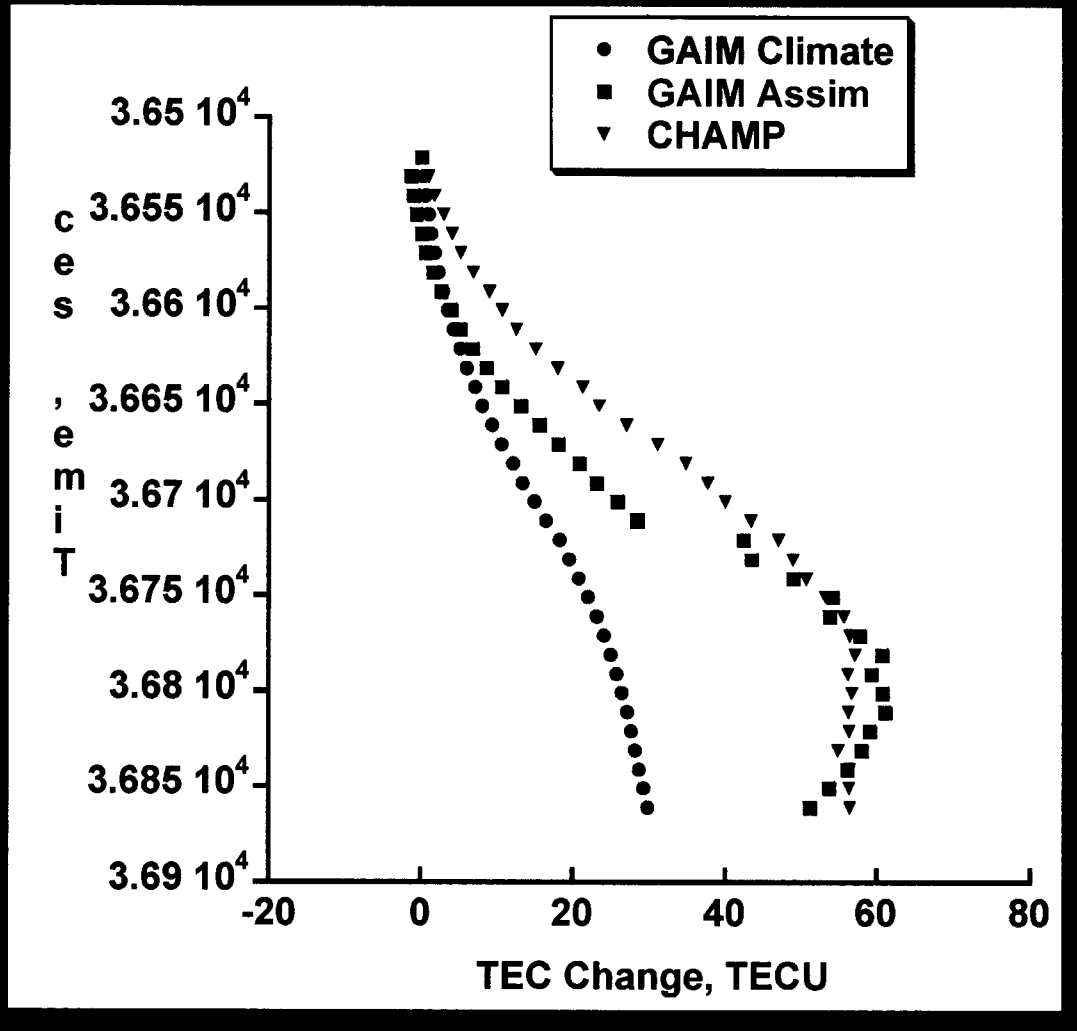

GAIM Climate & Assim Residuals versus El
× Climate Prediction, RMS = 33.7 TECU
○ Assim Postfit Residual, RMS = 2.9 TEC
Slant TEC Error (TECU)
40
20
0
-20
-40
-60
-80
-100
-120
10 20 30 40 50 60 70 80 90
Elevation (deg)
NKLG GPS Site


GAIM Assim Prediction versus Elevatio
(JPLM Slant TEC predicted, data not input to m
Slant TEC Error (TECU)
40
20
0
-20
-40
-60
-80
-100
-120
10 20 30 40 50 60 70 80 90
Elevation (deg)
NKLG GPS Site
RMS = 13.4 TECU

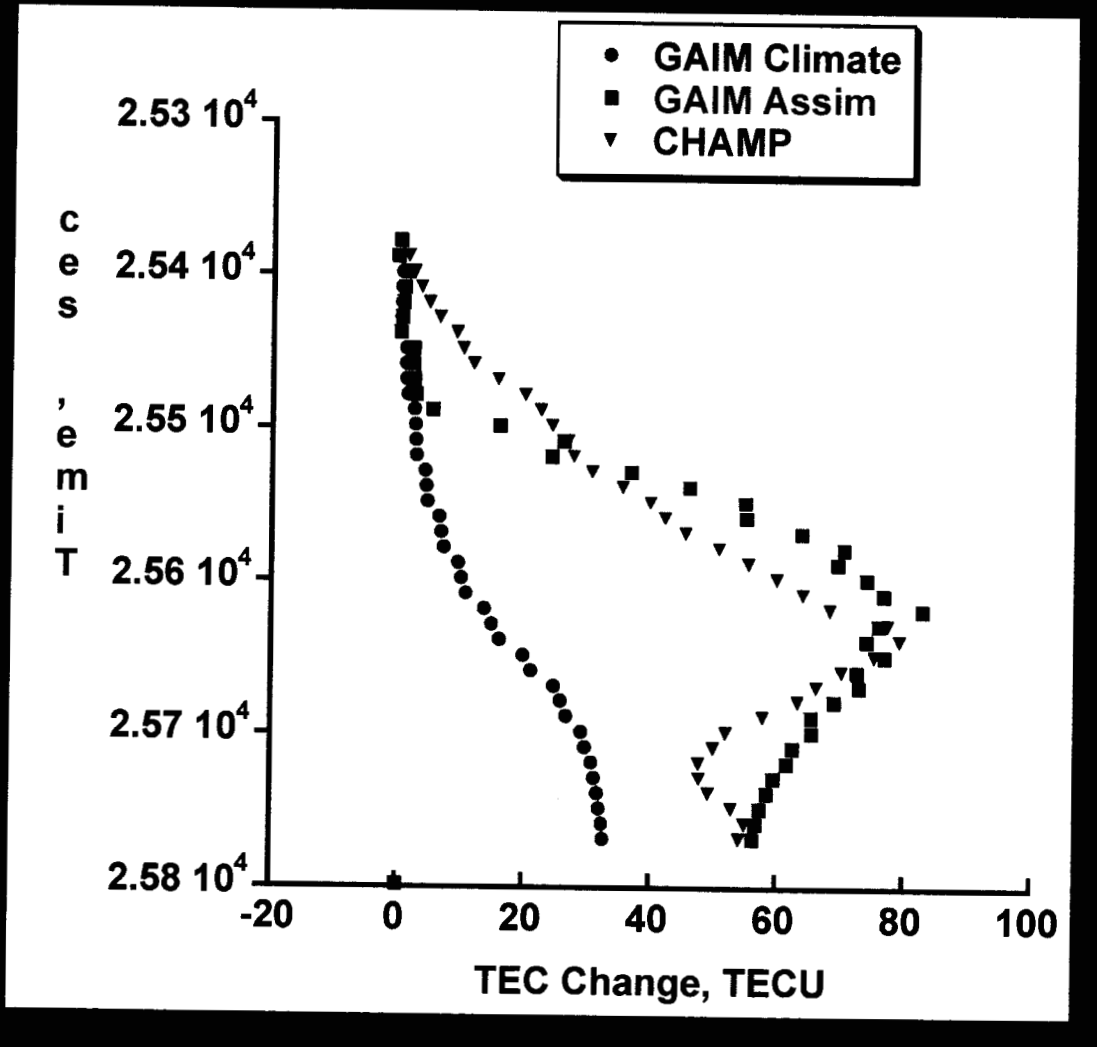
NKLG: 0.3 N, 9.2 E


GAIM Climate & Assim Residuals versus El
× Climate Prediction, RMS = 26.3 TECU
○ Assim Postfit Residual, RMS = 3.2 TEC
Slant TEC Error (TECU)
40
20
0
-20
-40
-60
-80
-100
-120
10 20 30 40 50 60 70 80 90
Elevation (deg)
JPLM GPS Site


GAIM Assim Prediction versus Elevatio
(JPLM Slant TEC predicted, data not input to m
Slant TEC Error (TECU)
40
20
0
-20
-40
-60
-80
-100
-120
10 20 30 40 50 60 70 80 90
Elevation (deg)
JPLM GPS Site
RMS = 4.5 TECU


GAIM Climate
GAIM Assim
CHAMP
3.65 10^4
3.655 10^4
3.66 10^4
3.665 10^4
3.67 10^4
3.675 10^4
3.68 10^4
3.685 10^4
3.69 10^4
Time, sec
-20
0
20
40
60
80
TEC Change, TECU

USC/JPL GAIM


GAIM Climate
GAIM Assim
CHAMP
2.53 10^4
2.54 10^4
2.55 10^4
2.56 10^4
2.57 10^4
2.58 10^4
-20
0
20
40
60
80
100
TEC Change, TECU

USC/JPL GAIM

- GAIM band-limited Kalman now accepts:
  - TEC from ground GPS
  - ΔTEC from GPS occultations
  - UV radiance obs. from nighttime limb scans
  - Ionosonde density profile or foF2, hmF2
  - In situ densities
- Validation so far is encouraging:
  - Using global GPS TEC data effectively
  - GAIM accuracy comparable or superior to GIM TEC maps
  - More Density validation being pursued

USC/JPL GAIM

- Fine tuning of various covariances (state, data noise, process noise)
- Combining 4DVAR and Kalman to solve for the state and drivers simultaneously
- Finish parameterization and testing of various drivers (e.g., Neutral wind, production rate)
- Run many days and assemble a large number of statistics for further validation
- Operational implementation of GAIM