Constraining MA models by Space-borne Observations: Zonal Mean Flow and Tides

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- *DA of operational data in stratosphere: Biases and consistency of vertical scales*
- *Research satellite data in SMLT: Global view on ZMF and Tides (diurnal cycles).*
- *Optimizing tides and ZMF (tuning parameters of GW-schemes?). Possible inverse schemes.*
- *Transfer existing inverse schemes and sensitivity studies in the statistical estimation framework with appropriate error metrics.*

Make a bridge between NWP DA schemes, bias corrections and MLT model-data analysis studies (UARS-TIMED-Aura).

Persistent data-model and data-data differences

Persistent OmF differences are common in the SMLT model-data analysis

1) ***How to separate data biases from model errors?***

- establish model error metrics => sensitivity and uncertainties
- analyze data-data differences => validation and quality control.

2) ***How to suppress these biases to secure DA foundation e.g. zero-mean errors ?***

NWP-way:

-assimilate data , compute time series of OmF ;
-extract low-frequency (persistent) components from time series;
-associate them with biases ;
-apply Bias-Aware DA (BA-DA) schemes;
- key element of BA-DA is a bias propagator schemes (less attention).

Across the stratopause there are several issues for DA:

- *coverage and quality of data*
- *NWP DA algorithms cannot be simply extended for assimilation of sparse and less frequent data for tracking fast waves (tides);*
- *maturity of models and their high sensitivity to sub-grid physics parameterizations.*

Explorative physically-based DA algorithms and inverse schemes can be considered first to optimize models in the SMLT using current set of research satellite data */UARS-TIMED-Aura.../*

Burrage et al. 1995

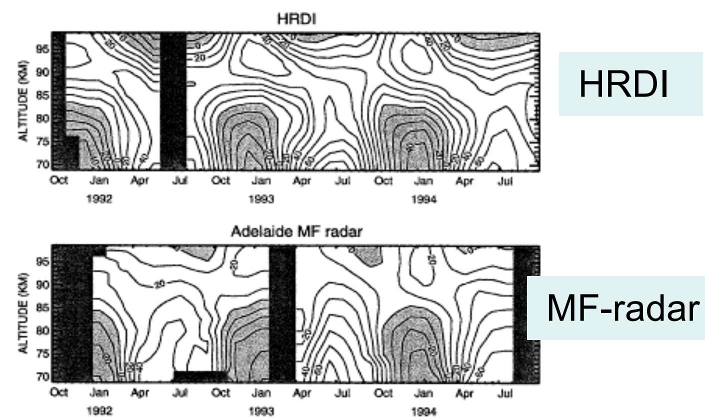


Figure 19. Daytime mean (0600-1800 LST) zonal wind observed by HRDI (32.5°-37.5°S, 0°-360°E) and by the Adelaide MF radar (35°S, 138°E). Both observation sets are presented as monthly means averaged over only daytime local times.

Apr 22, 1993

BURRAGE ET AL.: VALIDATION OF MLT WIN

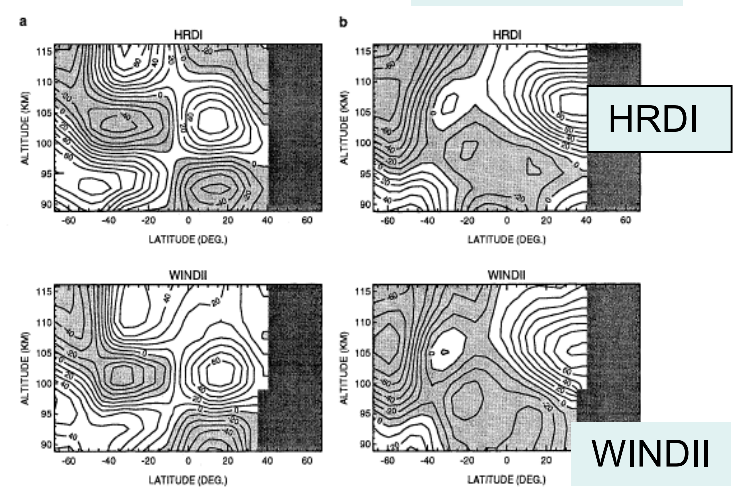


Figure 22. Longitudinal mean winds as a function of altitude and latitude observed by HRDI and by WINDII on April 22, 1993, for (a) the meridional component and (b) the zonal component. The contours are every 20 ms^{-1} and negative winds (southward or westward) are shaded.

Biases in DA and inverse estimation studies of SMLT /example of wavy T-biases in the stratosphere/

DA studies in MA models

(CMAM, GEOS, NRL, ECMWF, METO)

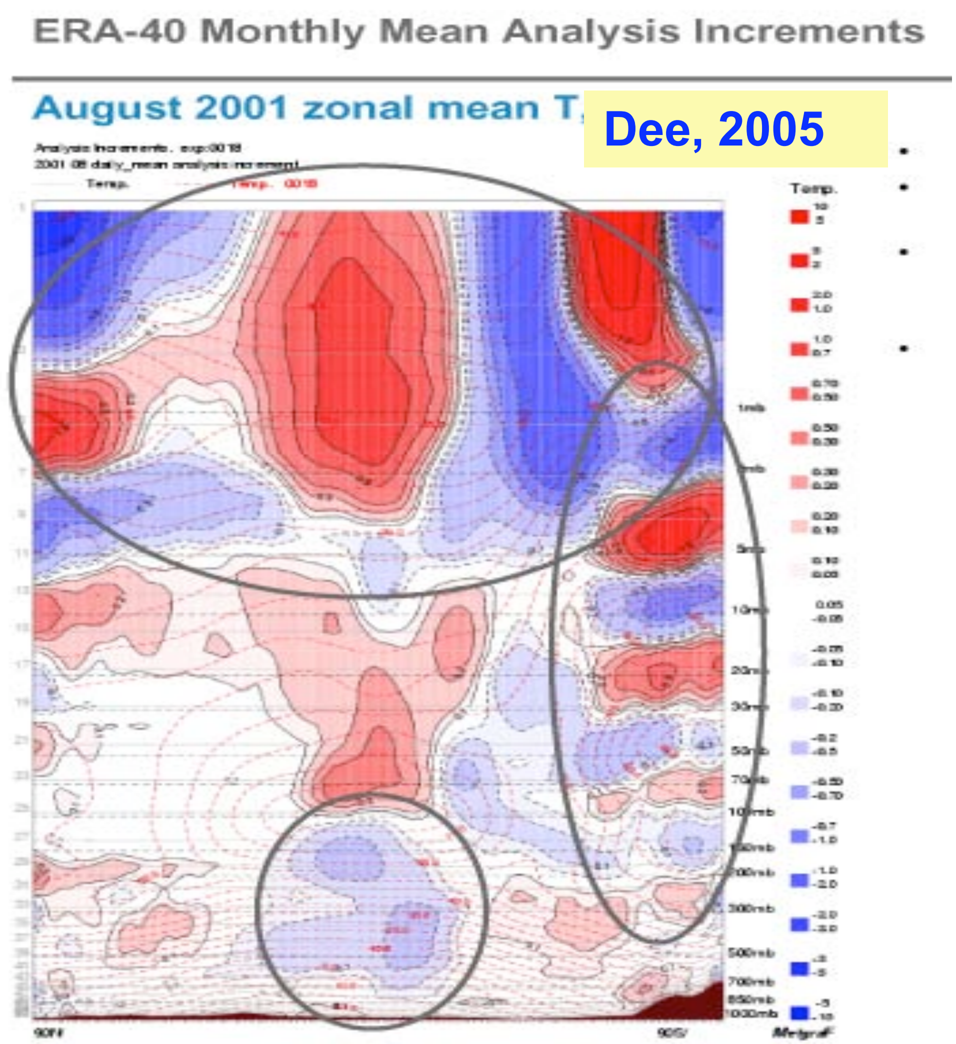
- **Polavarapu et al, 2005, Dee 2005**

Inverse & Diagnostic studies in the SMLT

- **Ortland and Alexander [2006]**
- **Ortland et al. [2004-2006]**
- **Pulido and Thuburn [2006ab]**
- **Alexander and Rosenlof [2003]**
- **Khattatov et al. [1997], Yudin et al. [2000, 1998, 1997].**

Main motivation of these studies is to use data to optimize momentum &heat sources, diffusion initiated by stochastic eddies and sub-grid waves (GWP).

Attractive feature of this motivation for DA: Before assimilation of data they diagnose and attempt to suppress the large model biases operating with model physics and persistent OmF differences.



NP

STRAT: AMSU-A rad-es

SP

Challenges in the MA data assimilation

- DA of radiances from deep-layer sensitive channels (AMSU-10:14) in SMLT /Dee, **Polavarapu et al., 2005**/.
- Two scales of inverse solution: vertical width of Jacobians **(D_w)** and vertical correlation lengths (L_c): **D_w/L_c** >>1.
- In rank-deficient schemes(**D_w/L_c** >>1) initiates "wavy" T-increments that are not bounded by **W,** AMSU Jacobians;
- In areas of high-density data insertion, analysis can be damaged by persistent errors related to scale-inconsistent projections of radiance misfits onto model levels (polar DA waves).
- **With optimal schemes dT-analysis** increments adjust layer averaged values rather than T-profiles.
- **dT-anal** spreads between model levels due to wide width of **W-Jacobian** and should be insensitive to short-scale **T-corr**elations and variances.

CHALLENGES OF MIDDLE ATMOSPHERE DATA ASSIMILATION 3517

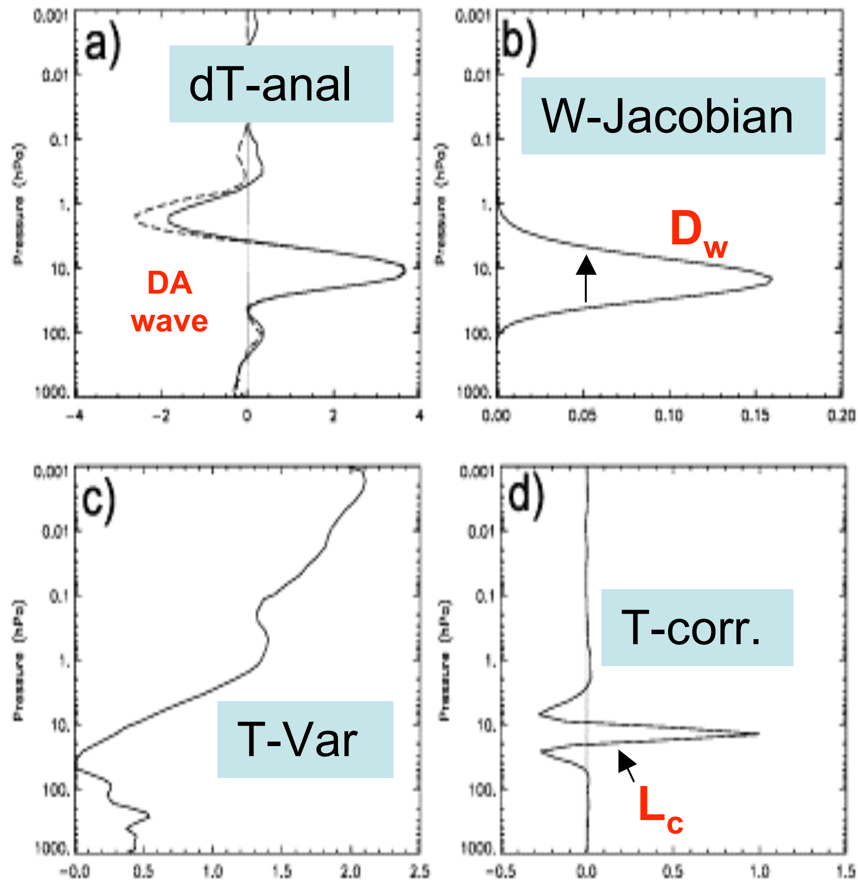


Figure 2. Results of a 1D-Var assimilation with a single observation of brightness temperature: (a) analysis increment (K) using the vertical correlation function shown in (d) (solid), and on setting small correlations to zero (dashed), (b) weighting function (K K^{-1}) corresponding to AMSU-A channel 11, (c) $\log_{10}$ of background-error variances in K^2, and (d) one sample vertical correlation function with a peak near 10 hPa.

D_w/L_c >>1 <=> DFS << N-levels

Math summary for scale-consistent and rank-deficient computations of analysis increments for $D_w/L_c >> 1$

- ***Scale-consistent analysis***

$$dT_b = WdT$$

$$W = USV^T \text{ look at SVD of}$$

$$U^T dT_b = S(V^T dT)$$

$$dX = V^T dT \quad \& \quad dY = U^T dT$$

$$dY = SdX \text{ e.g. Y-point } <=>$$

$$< dX >= K_{svd} dY, \quad < dT >= V$$

- **For deep layer sensitive channels D_w/L_c >>1 V-shapes ∫ W-shapes, e.g. Gaussian shapes. <dT>-increment is not affected by “wavy” vertical correlations.**

- ***Rank-deficient analysis schemes are close to direct use of linear filters that ignore consistency of scales***

$K = WC_{ff}'[WC_{ff}W' + C_{bb}]^{-1}$

$<dT> = K<dT_b>$, DFS = tr(KW) ~.5-2

For DFS~[0.5-2]. **K-gain is** modulated by the forecast errors on scales invisible to the instrument.

Adjustment of fine-scale structures and errors by deep-layer sensitive channels is a signature of the ill-posed inverse projection from data space => forecast.

Wavy structure of analysis **<dT>** initiates spurious “DA” temperature waves

- In addition scale-inconsistent Error Analysis:

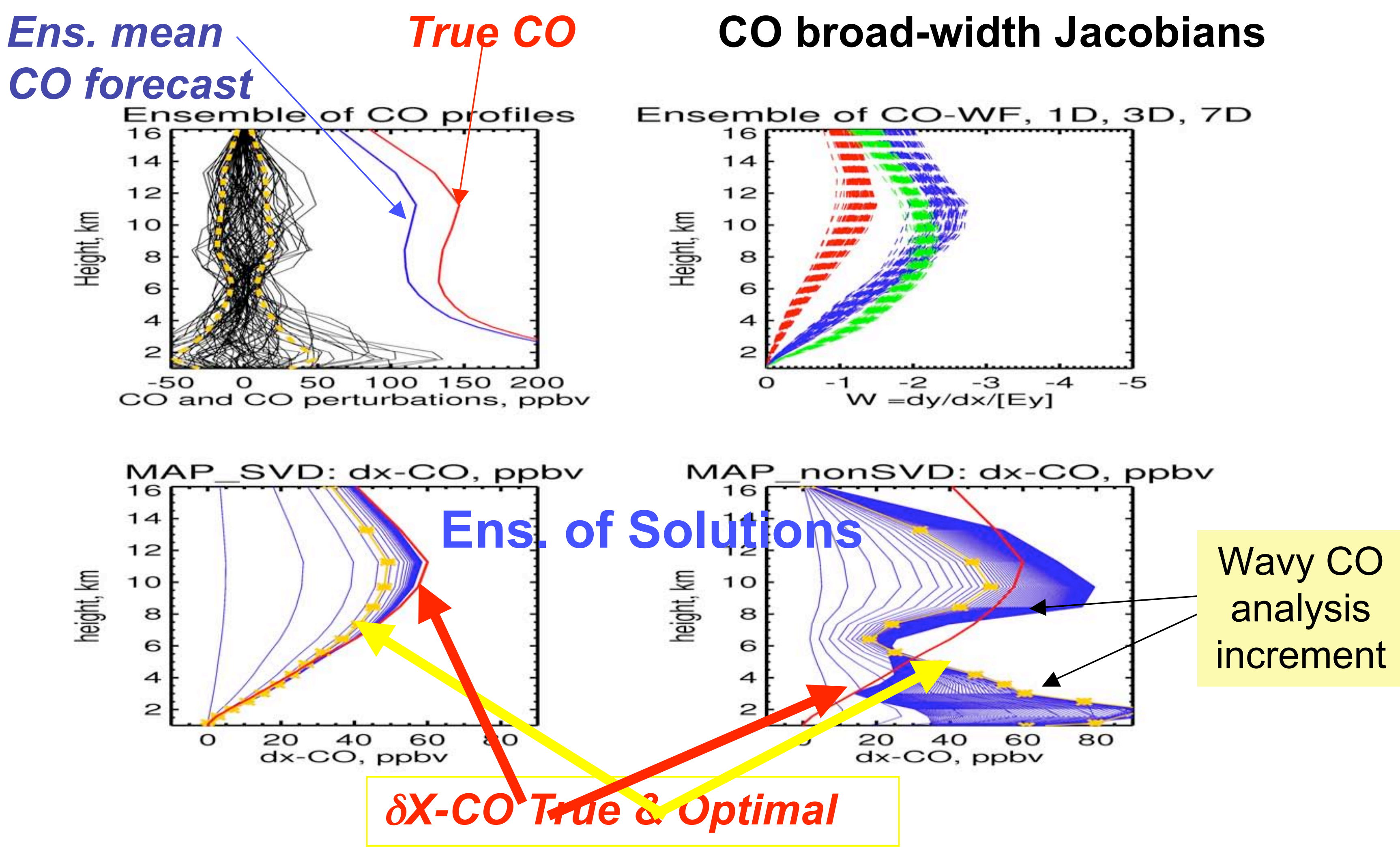
$$[C_{an}]^{-1} = [C_{ff}]^{-1} + W[C_{bb}]^{-1}W^T$$

Mixture of scales	*2km Cor. Length*	*10 km Width of W*

- **SVD of W provides natural tapering of vertical correlations and fine structures in T-variances invisible for AMSU radiances.**

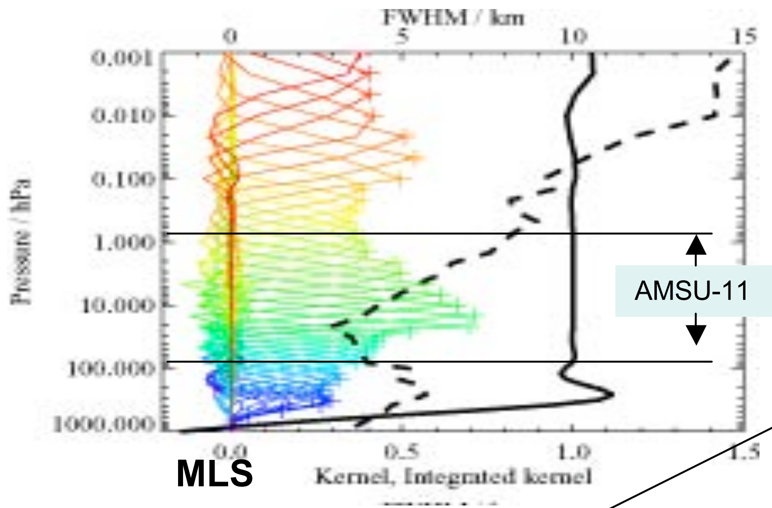
CO estimation by scale-consistent and rank-deficient formulations (Benchmark for MOPITT IR Channels, DFS ~ 1)

[*Tropical Biomass Burning Scene*]



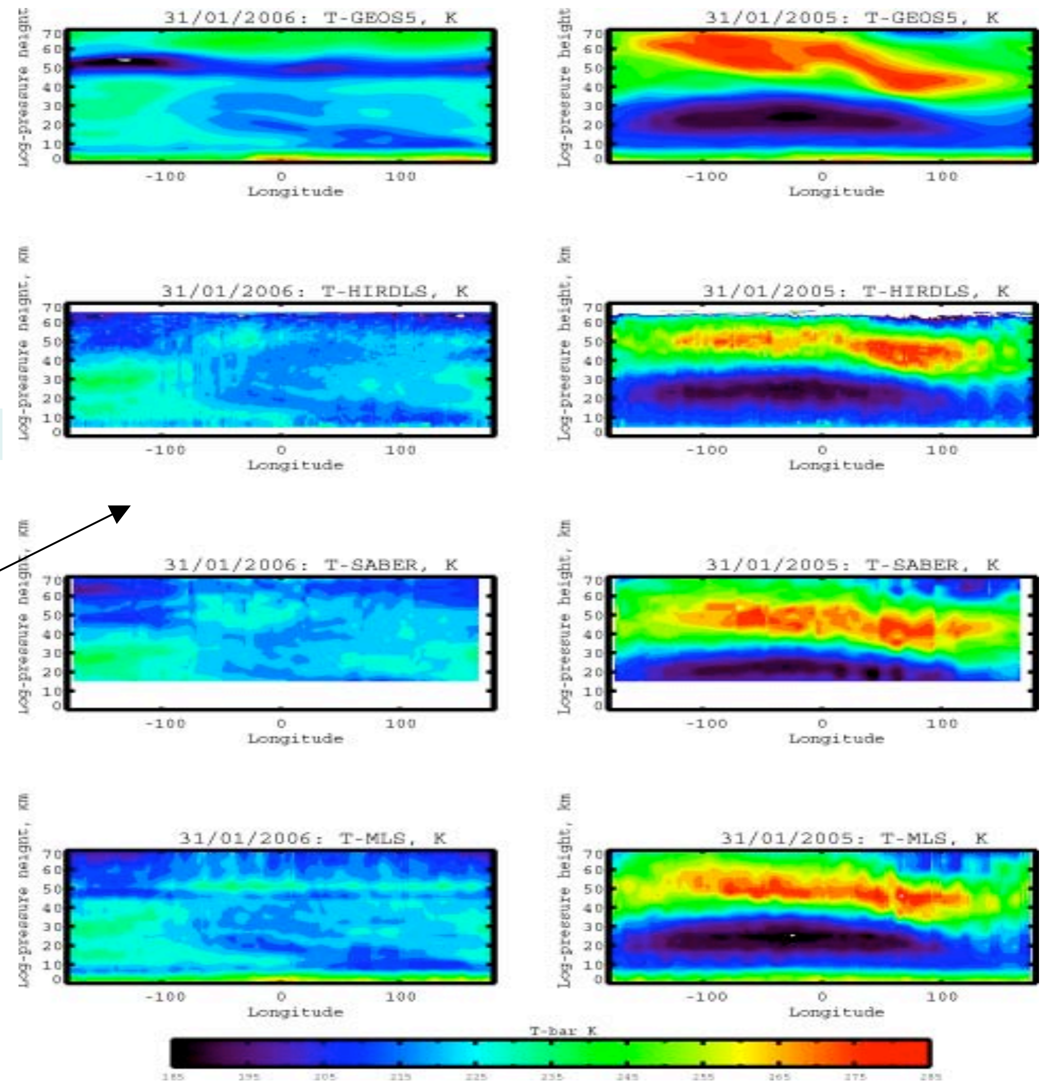
Multi-Instrument Satellite Limb Viewing Observations (LVO: UARS/TIMED/Aura) : with D_w/L_c~1, accurate probing of vertical oscillations

- Jacobians => vertical probing (1-3 km) of wave structures (Tidal modes, PW, even GW). Horizontal FOV of LVO are comparable to model grids.



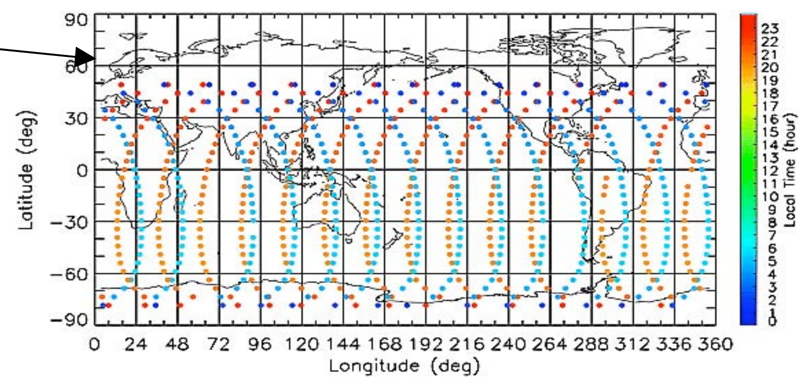
- Remarkable consistency of polar T-retrievals in the stratosphere and lower mesosphere gives opportunity to evaluate and identify model errors. Example: GEOS5-warming at the top lid in the NH polar latitudes.

- Disadvantage of current LVO: Limited sampling without horizontal scans. Localized waves are not fully resolved for DA studies and supported by models.



Extracting Forced Diurnal Modes from Space Data: data decomposition

With data coverage of ~ 14 orbits per day and strong diurnal oscillations in MLT data it is difficult to extract zonal mean and PW structures from asynoptic data.



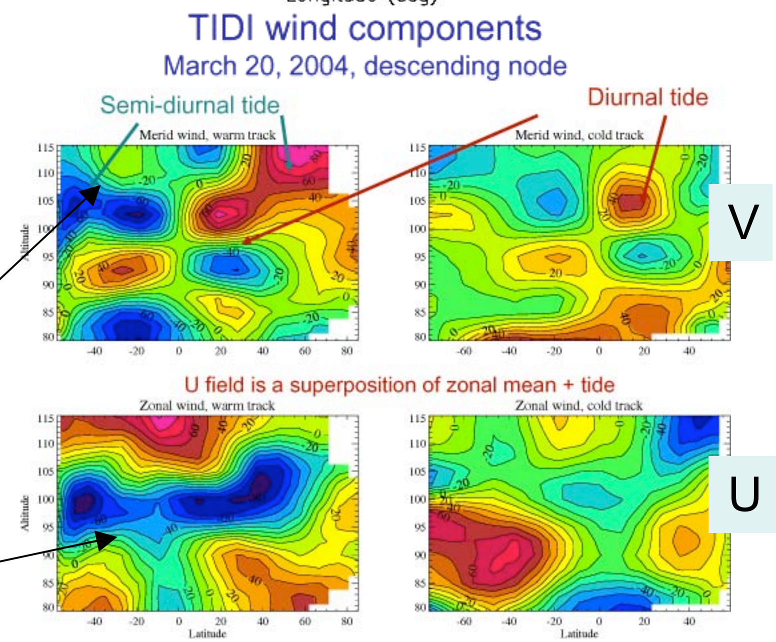
ϖ Trial applications of NWP schemes for assimilation of tidal and vertically propagated waves demonstrated some challenges due to model biases, representation of forecast errors for coupled vertical layers, presence of stochastic GW. New types of NMI to filter partially observed IGWs in presence of tides can be envisioned to attack this problem.

ϖ Data composites (30-60 days) with complete LST sampling can be used to identify systematic tidal errors in models. Composite errors: aliasing of time-varying MF & low-frequency waves, tidal variability.

ϖ Daily separation of ageostrophic fast propagating modes from slow quasi-geostrophic modes is difficult but ....

if models provide guidance for representation of coherent global structure of diurnal variations then.... at least amplitudes of tidal modes can be recovered (V-tidal signals are dominant in meridional winds).

After extraction of fast tides => Slow-varying modes Zonal Mean Wind and SPW can be analyzed (with asynoptic mapping, PV-inversion schemes for errors, etc).



Schemes for extraction and estimation of tidal modes

- **Spatial LSF with daily wind-temperature composites** /HRDI, TIDI, SABER/ to optimize amplitudes of Classical or Generalized Hough modes /*Burrage et al. 1994; Ortland (2004-ongoing)/.*

- **Temporal LSF with complete LST coverage composites**. SABER T-tidal signatures from seasonal composites /*Zhu et al., 2005 (51-day window); Zhang et al., 2006 (120-d window) /* .

- **Both spatial and temporal LSF with HRDI-WINDII meridional winds**, and use of tidal equations to deduce consistently all tidal variables employing TMTM concepts /*SUNYSB-1993-2000*/.

- **First scheme shows consistency between HRDI & TIDI diurnal tide separated by 11 years.**

- **SUNYSB-scheme demonstrates MF-radars and TMTM-HRDI discrepancy for 1992 diurnal tide (90 km, 35 S and 21 N);**

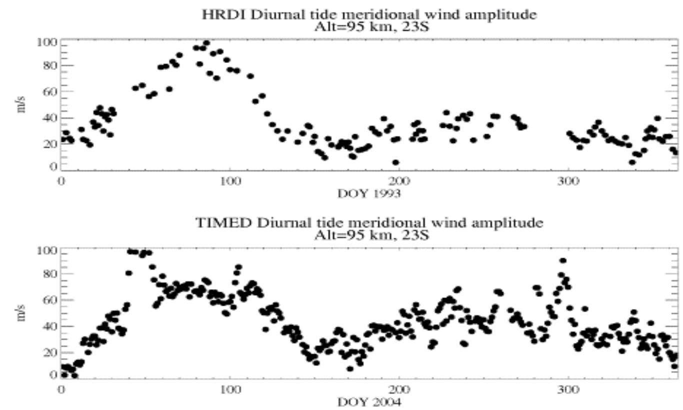
Why optimization models with decomposed data:

Replace raw observations by filtered data in which resolved coherent waves are present while stochastic localized oscillations are removed (climate models do not support them).

HRDI and TIMED diurnal tide amplitude

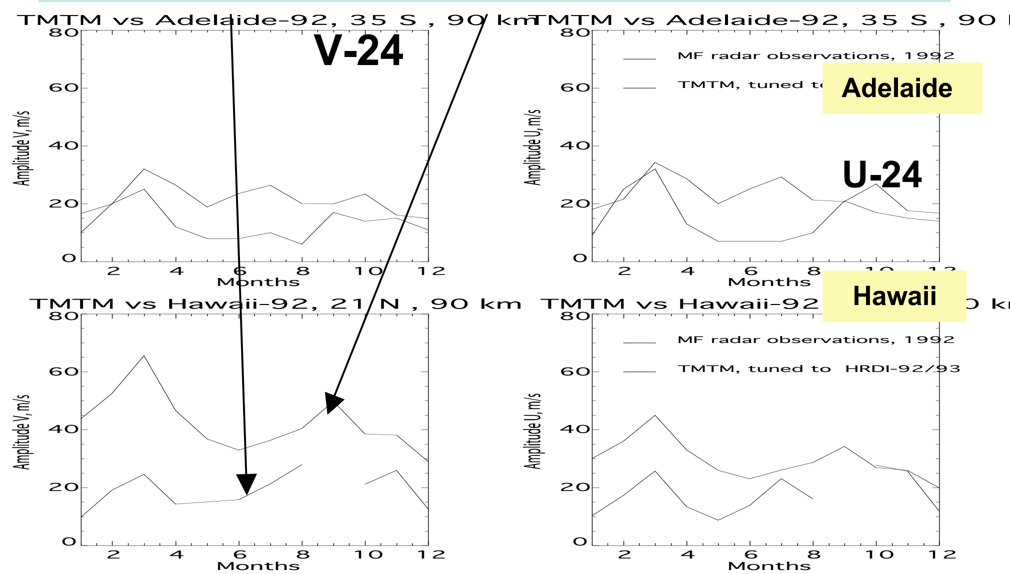
meridional wind at 95 km and 23S

1993 and 2004 have a similar annual cycle



Monthly 24-h tidal wind amplitudes

MF-radars vs TMTM-HRDI simulations (~90 km)



SUNYSB Diurnal Tide Inversion-Extraction Scheme with HRDI and WINDII data /80-110 km/

COMBINED DATA-MODEL ANALYSIS

Yudin et al. (1997,1998) have demonstrated a capability to use combination of tidal model results and UARS winds to tune the dissipation in the models for reproducing observed diurnal tide.

This technique is based on:
(1) the dominant diurnal tidal signatures in the UARS meridional winds ($V_s \sim V_s'$) and
(2) the high level of the model sensitivity to the variation of dissipation K_d at 80-110 km.

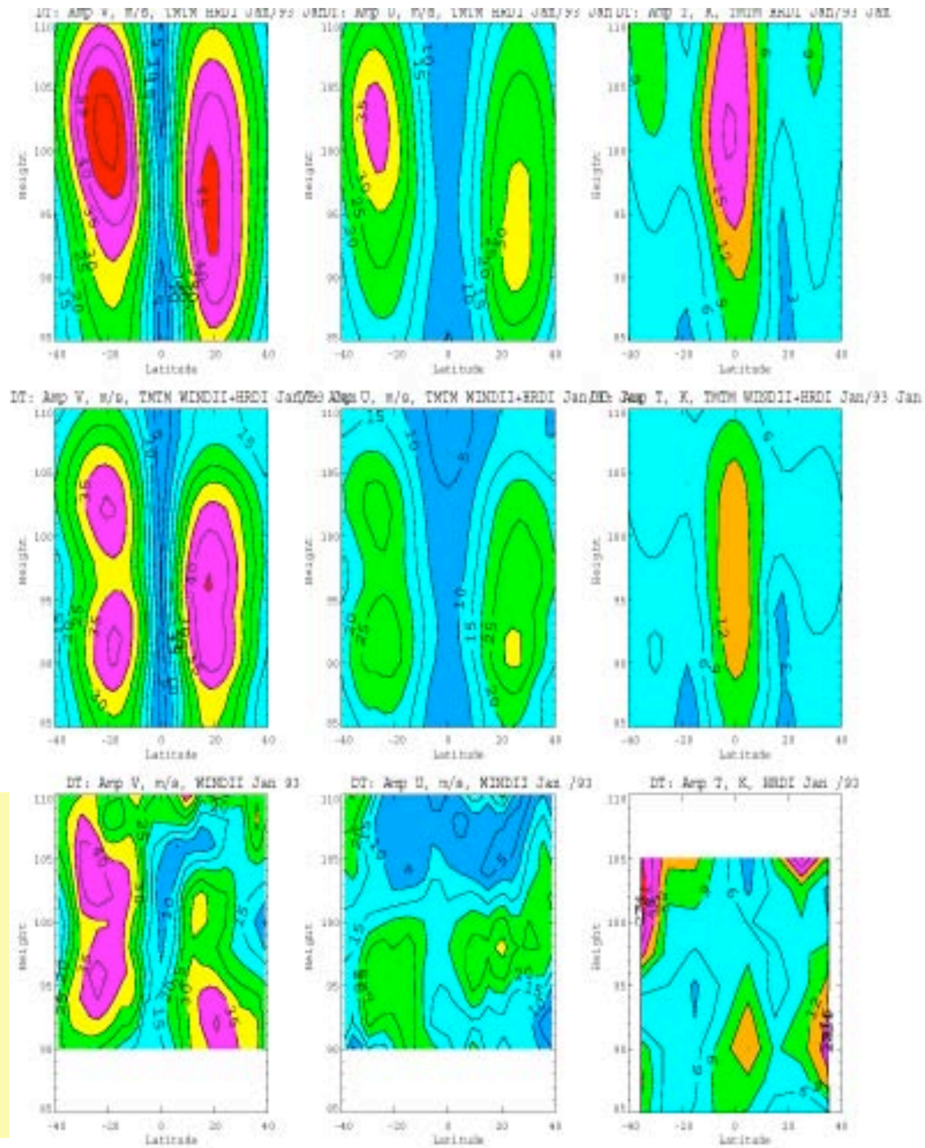
Tuned Mechanistic Tidal Model

Parameters -> Direct Model -> Prediction
(U_o, T_o, K_d, J_o) (Tidal model) (U', V', T')

Observations ->Tuning procedures -> Parameters
U_s, V_s' $V_s' \to (U_s', T_s')$ $U_{os} = U_s - U_s'$

Conservation of tidal energy -> new $(K_d)_s$

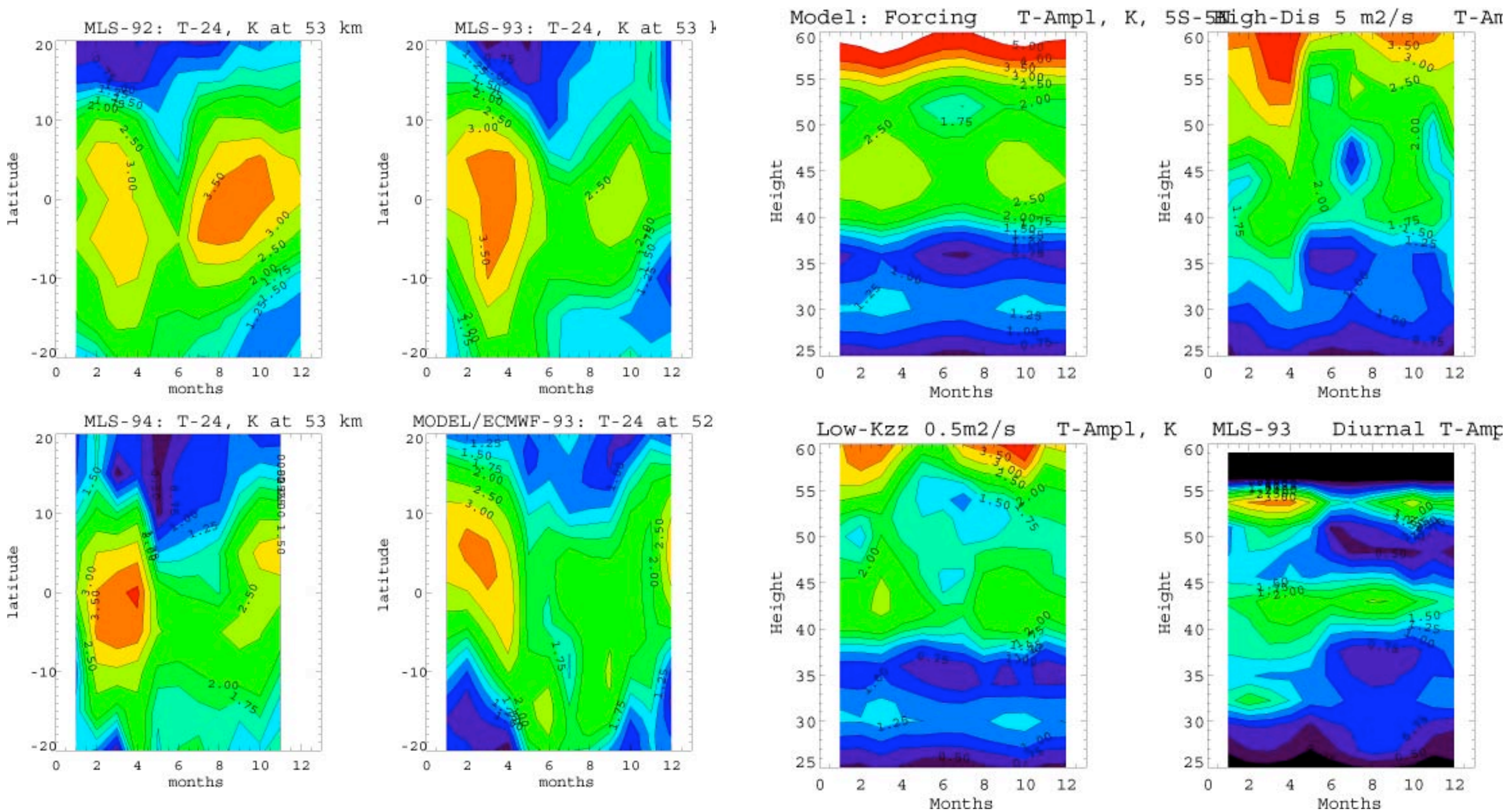
Using sequence of iterative steps we link V_s', $(K_d)_s$ and U_{os} and simulate the new set of tidal variables (with prescribed mean T and forcing) which match the UARS tides.



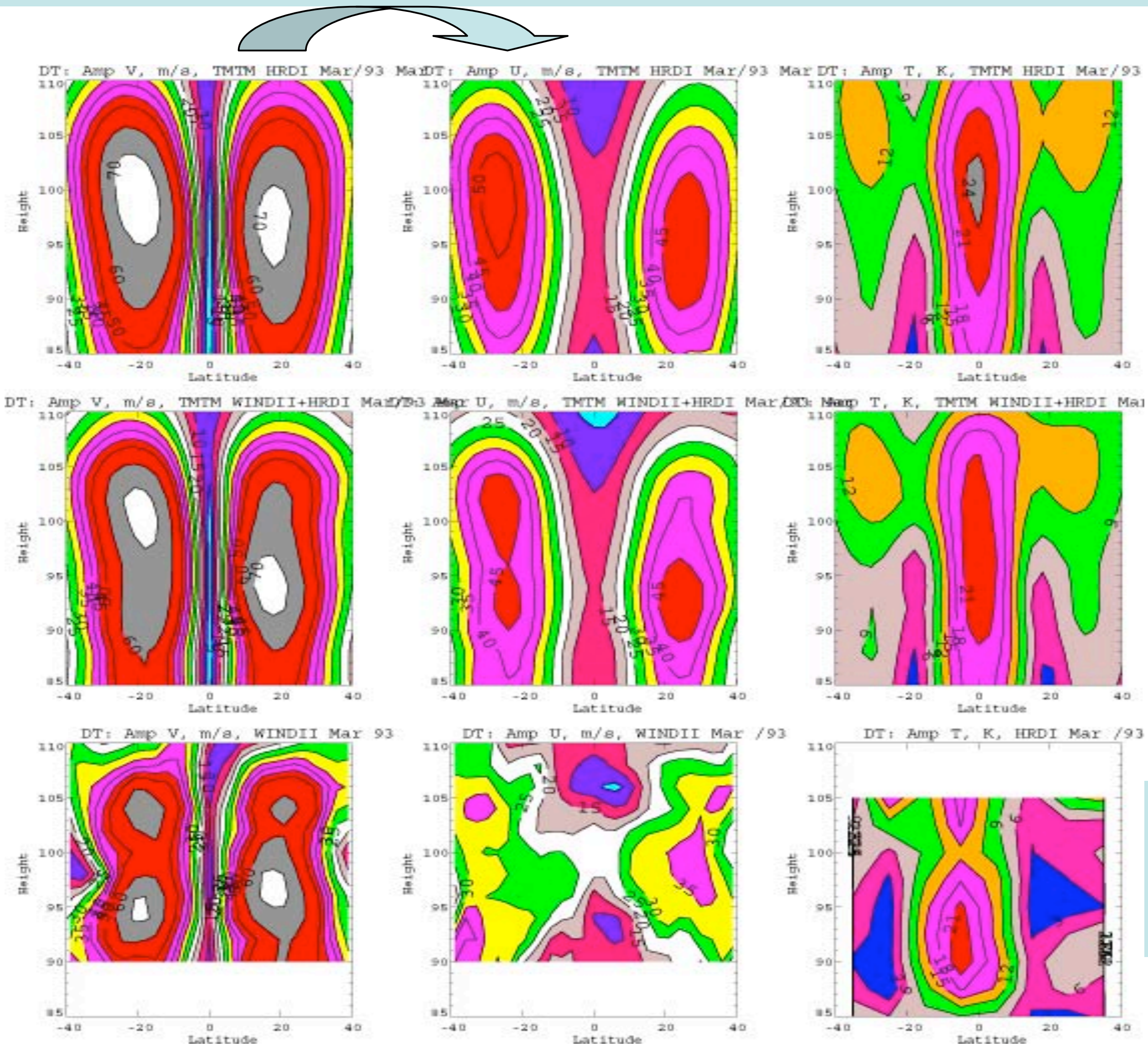
With TIDI winds and SABER temperatures the inverse scheme can be employed to estimate **both T-bar and U-bar**. It can be extended to link eddy dissipation and GW momentum deposition for GWP.

Ortland and Alexander [2006] performed sensitivity study with mechanistic model for diurnal mode and GWP AD-99. Adjustment of model tidal phases to observed has been proposed by tuning GW-effects on tide in the model.

Annual and year-to-year variations of diurnal tide T-oscillations in the stratosphere from MLS/UARS and model simulations (migrating tidal sources are ~ reliable)



Constraining simulated diurnal amplitudes towards March 1993 UARS retrievals: Sensitivity to the data

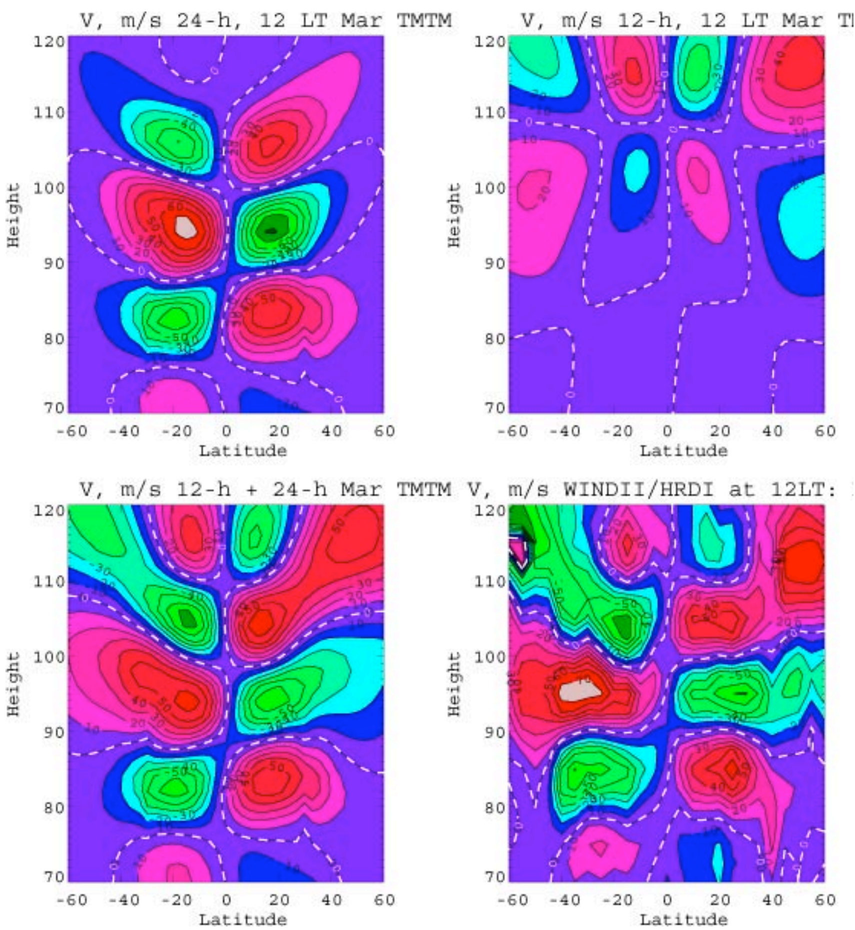


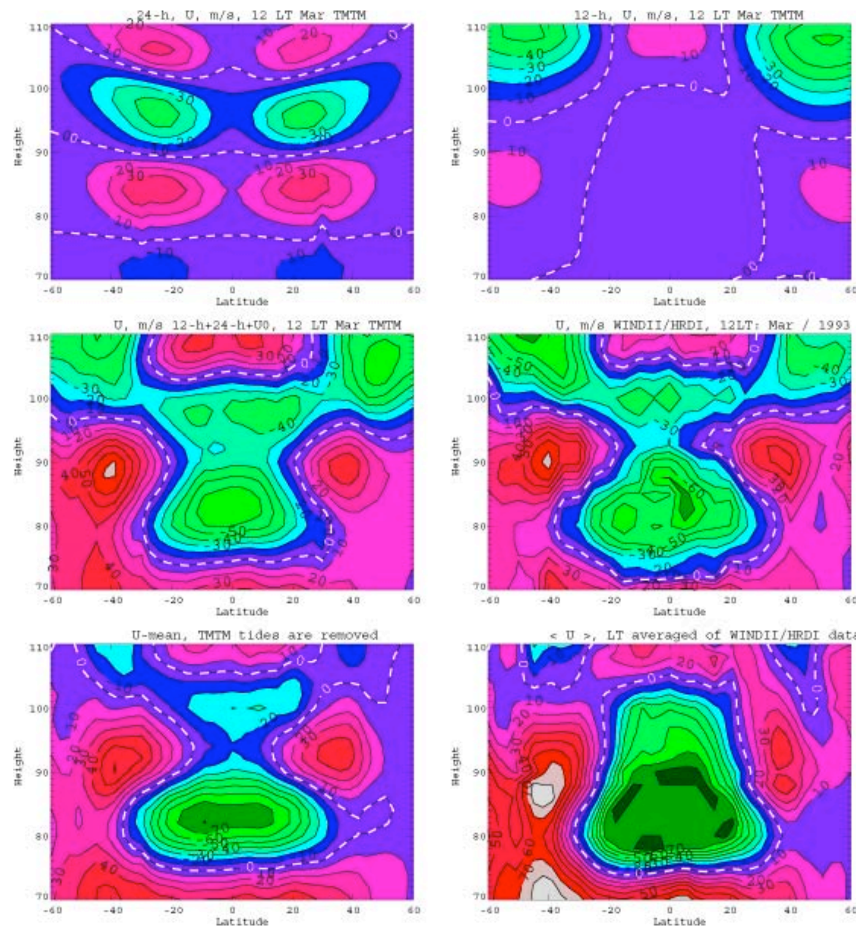
HRDI-V constraint only

HRDI-V+WINDII-V two constraints

LSF Amplitudes from WINDII-wind and HRDI-T data

Evaluation of optimizations: decomposition of meridional and zonal wind components



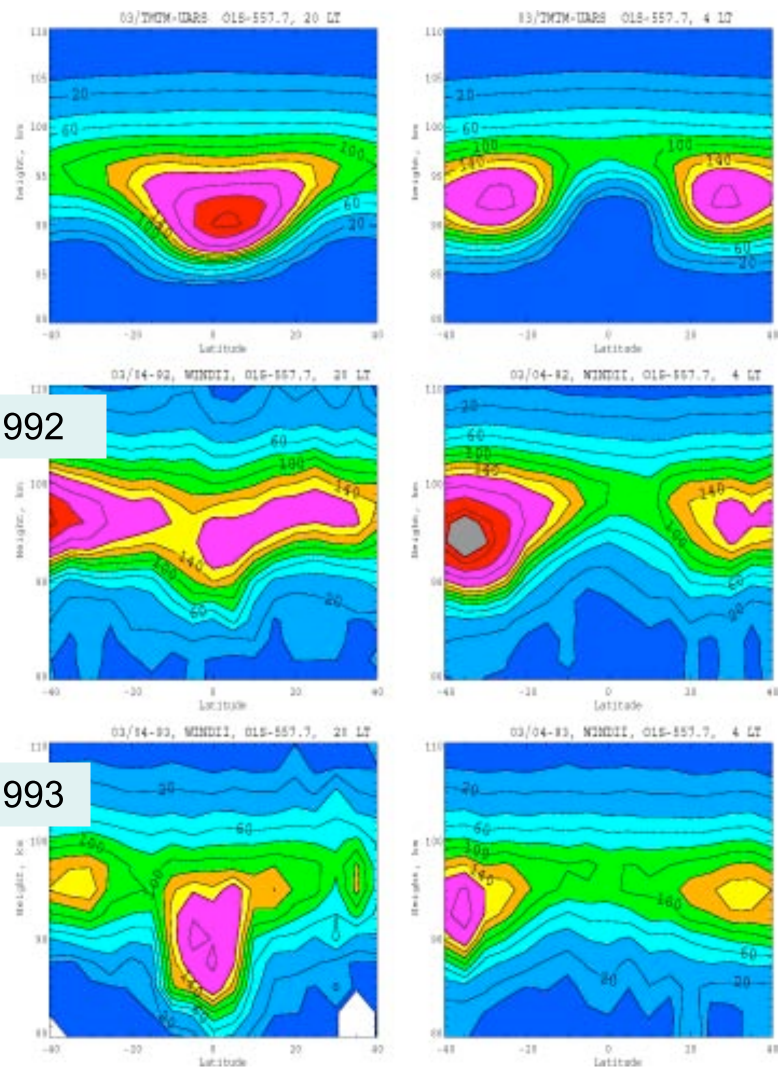


Meridional wind components

Zonal wind components: Tides + ZMF

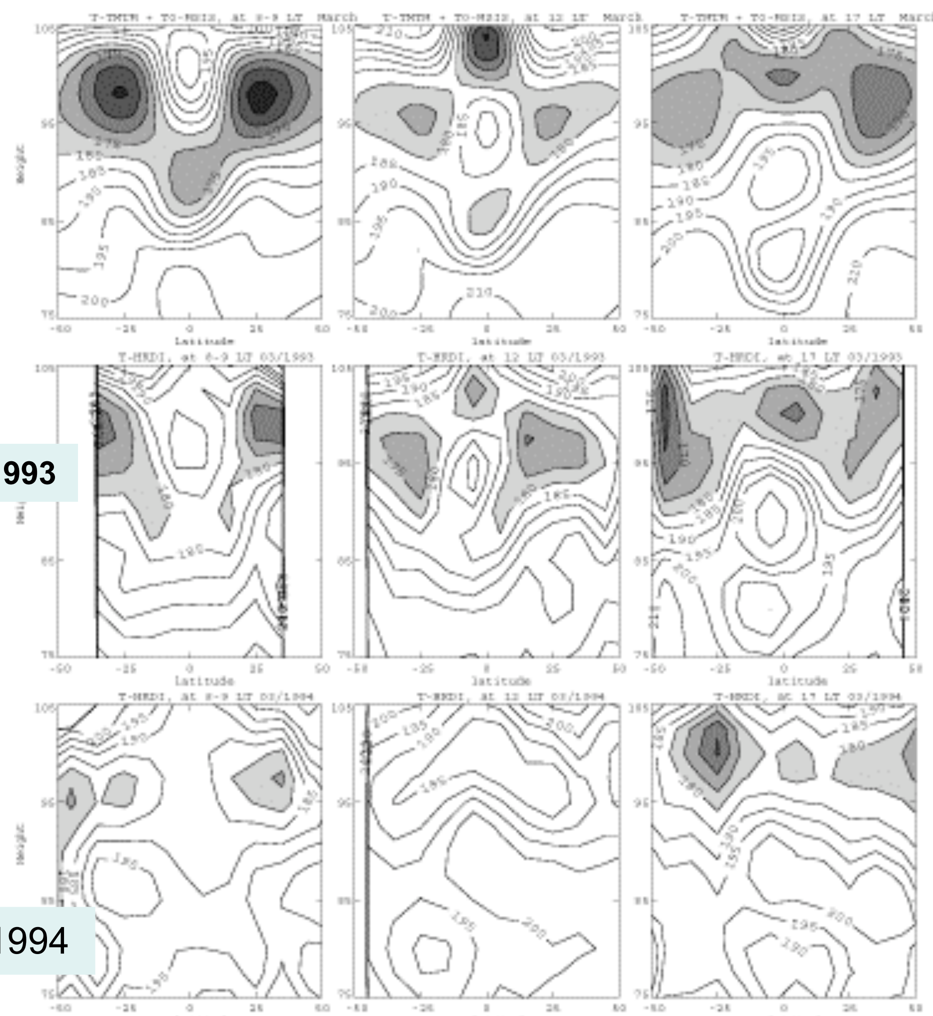
Independent Evaluation of Tidal Inversions for Mar-1993

Airglow and Temperature patterns */1994 T-patterns are in bottom row, for 1994 we need new MF and eddy effects/*



1992

1993

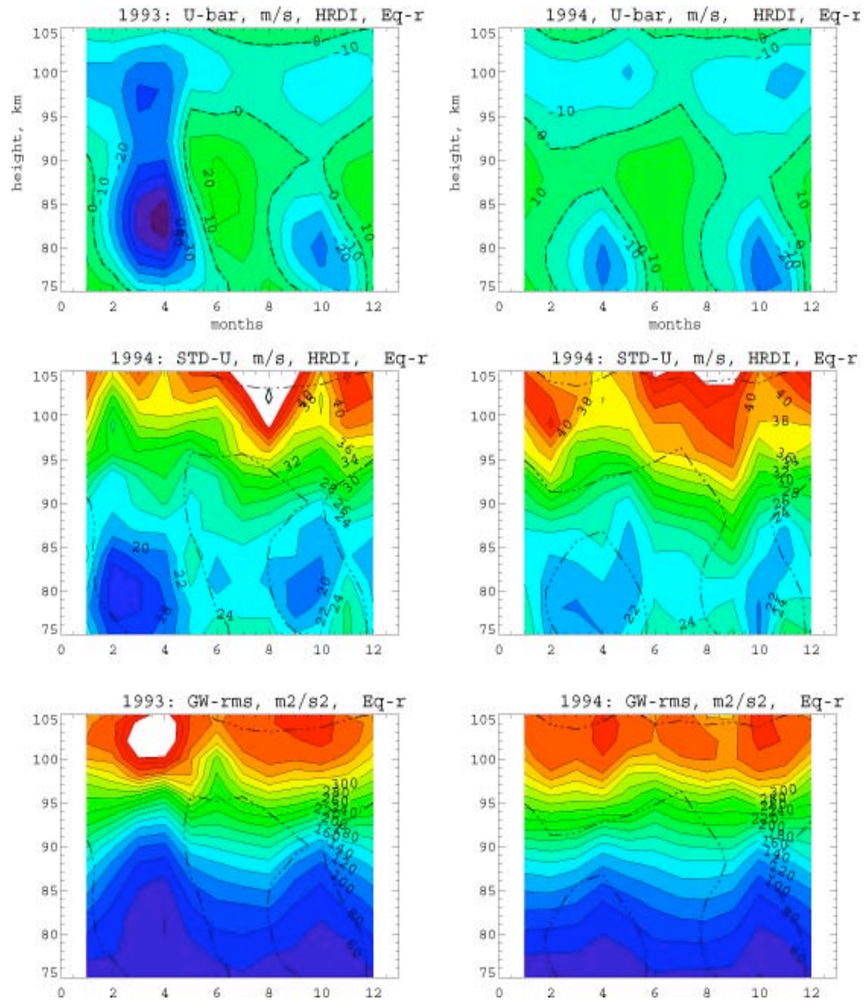


1993

1994

Bringing back observed (filtered) GW-rms terms in MLT data analysis

- Vertical momentum fluxes <u’w’> of GW ~ $\langle T'^2\rangle$, $\langle u'^2\rangle$ /GW-rms/
- In model simulations additional diagnostics can compute GW propagation on the model background with sub-grid modes of GWP;
- Observational filters (H-operator) can be applied to compare simulated and space-borne GW-rms.
- Next: Optimization of GW parameters at the launch level: position of source level and its variation (ensemble); GW-rms; bounds of allowed waves; spectral form (indices).
- Calibration of MLT GW-rms by radar/lidar data.
- Example: Annual cycles of HRDI-U vs GW-rns simulated by GROGRAT/NRL GW model with HRDI background winds.



1993

1994

Example: Constraining interannual (1995 & 1996) tidal amplitudes by effective eddy dissipation predicted by GROGRAT GW model with UARS U-winds

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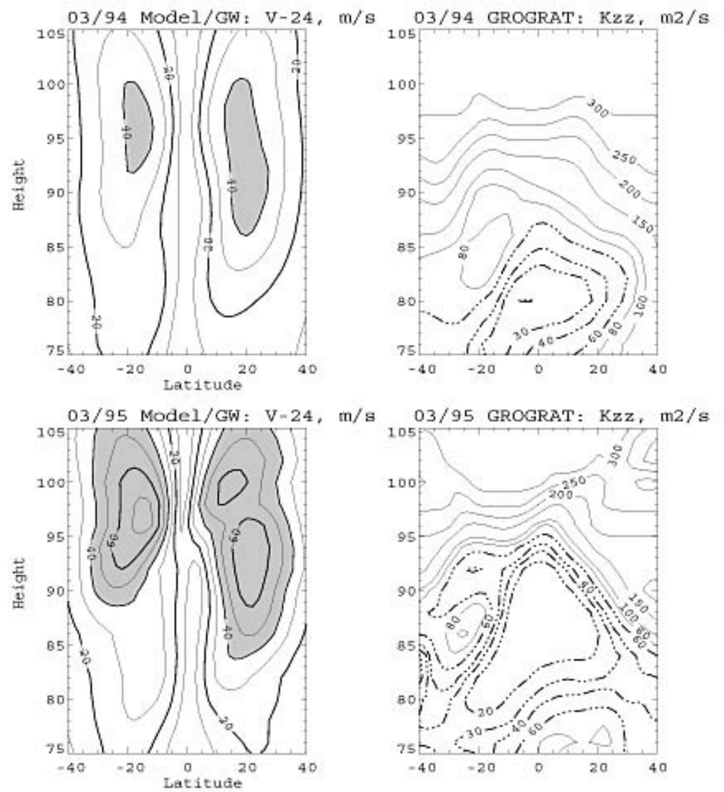

Figure 6. The diurnal tide meridional wind amplitudes (right) predicted by model constrained by the eddy dissipation (left) estimated after GROGRAT GW simulations with the 1994 (top), and 1995 (bottom) mean zonal winds. The amplitude contours higher than 40 ms^{-1} are shaded.

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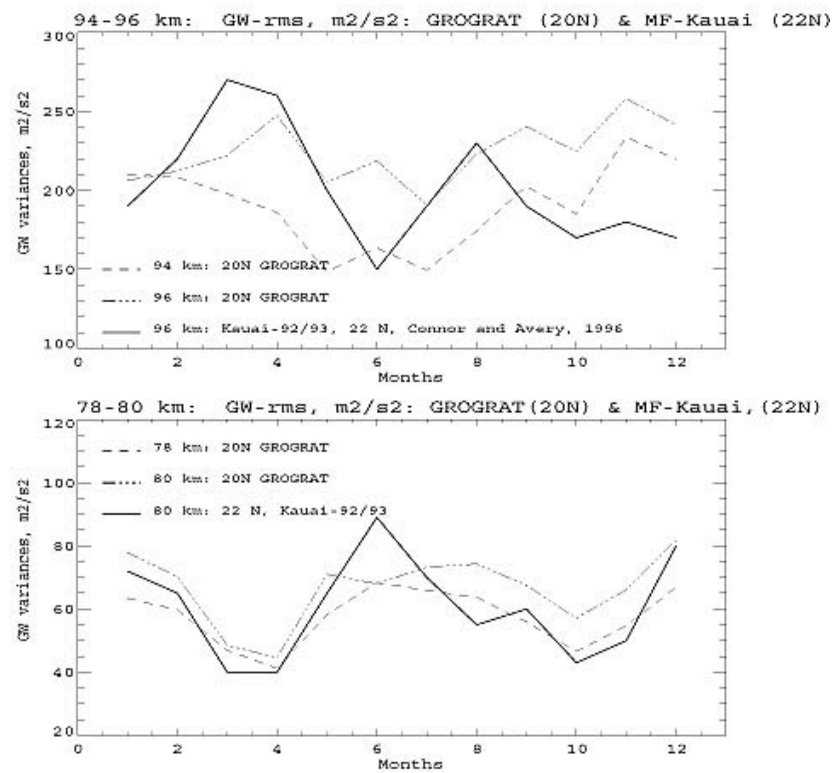
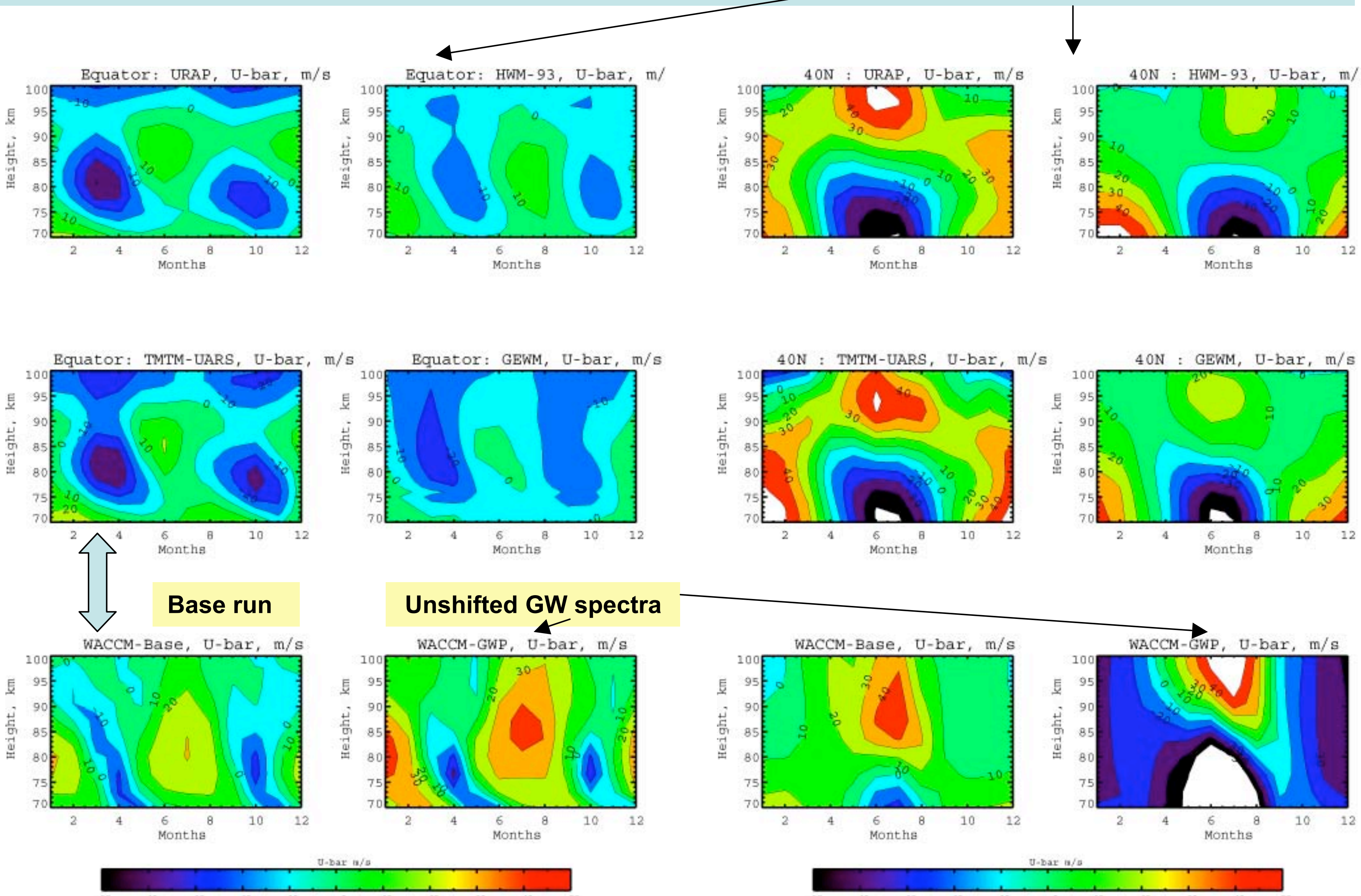


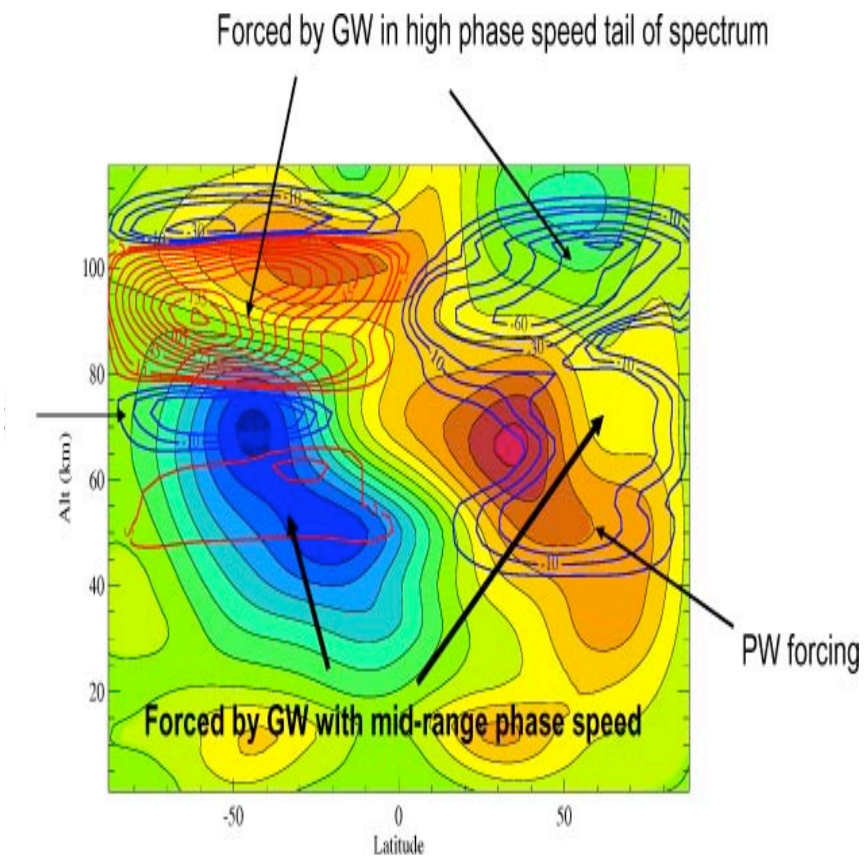
Figure 5. The annual cycle of the monthly averaged gravity variances in m^2s^{-2} predicted by the GROGRAT model results and observed by the Kauai MF radar in 1992-93 at about 95 km (top), and 80 km (bottom).

Calibration of GW-rms of GROGRAT/NRL model by Kuai MF-radar GW-variances

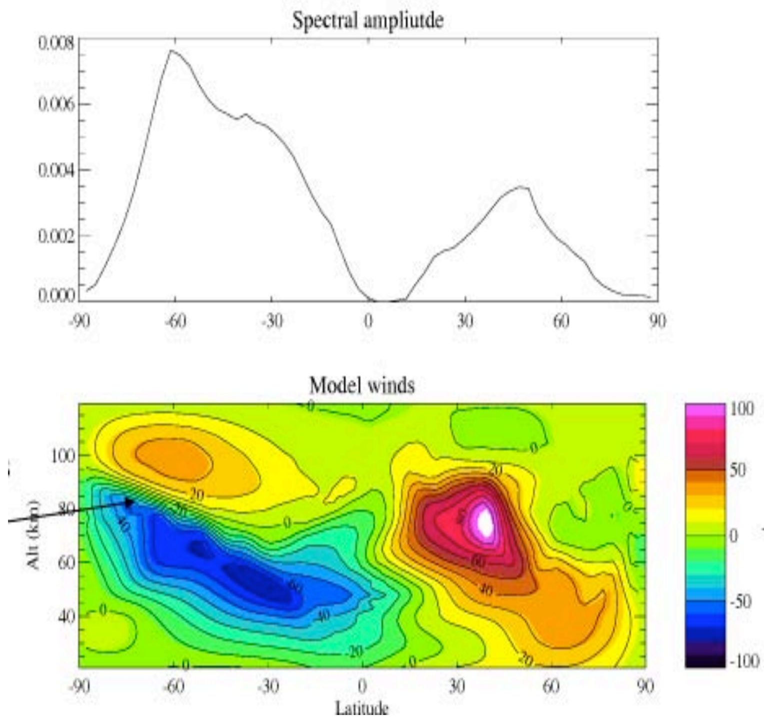
Annual cycles of zonal winds from four empirical models and two WACCM runs with diff. GWP (Equator & 40oN)



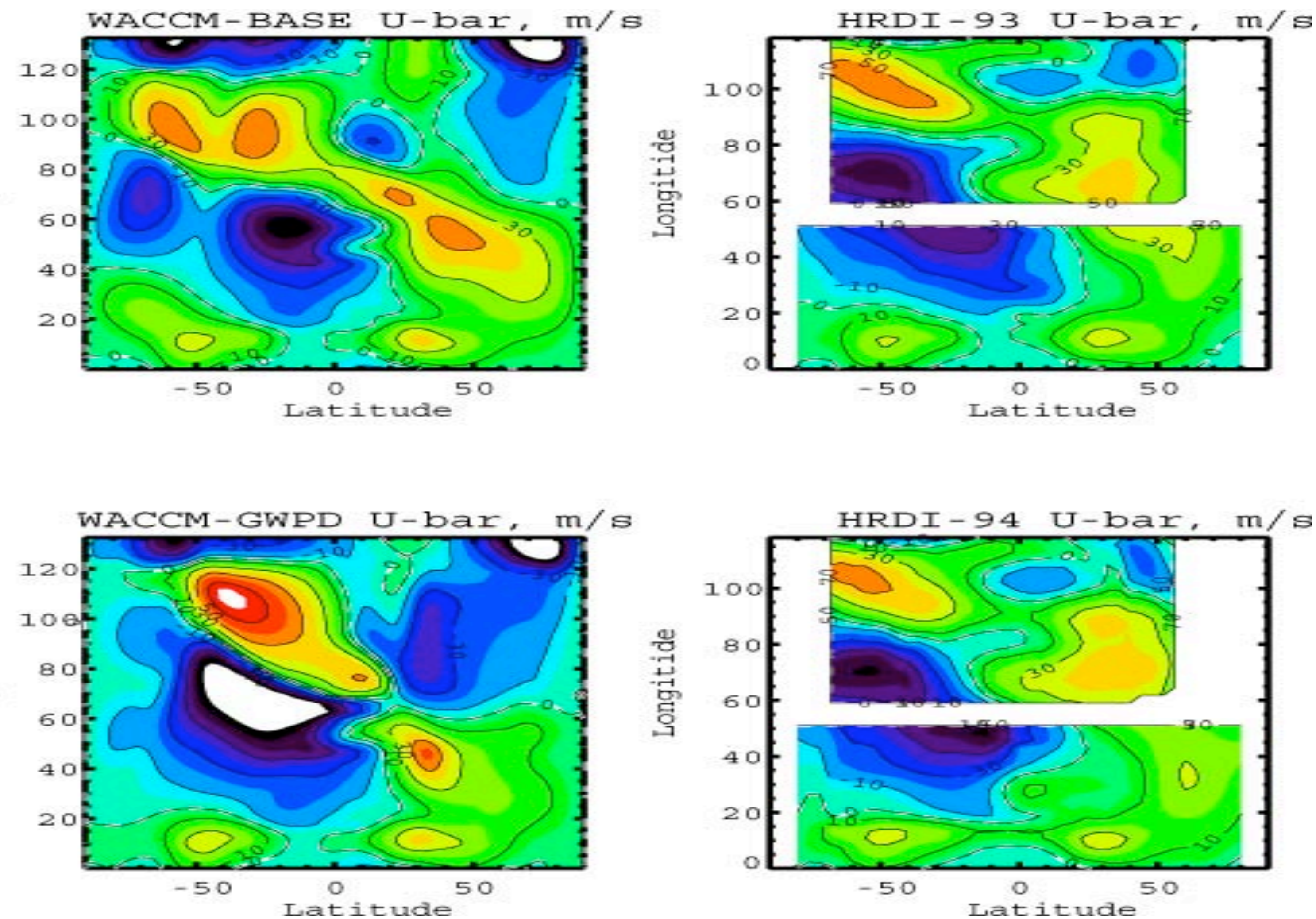
Schematic distributions of Jan zonal wind forcing by GW/PW momentum deposition and Dave Ortland's trial example to inverse GW-spectra at the launch level with AD-99 GWP scheme



- Impose analytic form for the GW spectrum: $F(c) = A / (c - u(z_0))^2$
- Latitude dependent amplitude A is derived from the inverted spectrum
- Use additional GW spectra for low lat S Hem and high lat N Hem

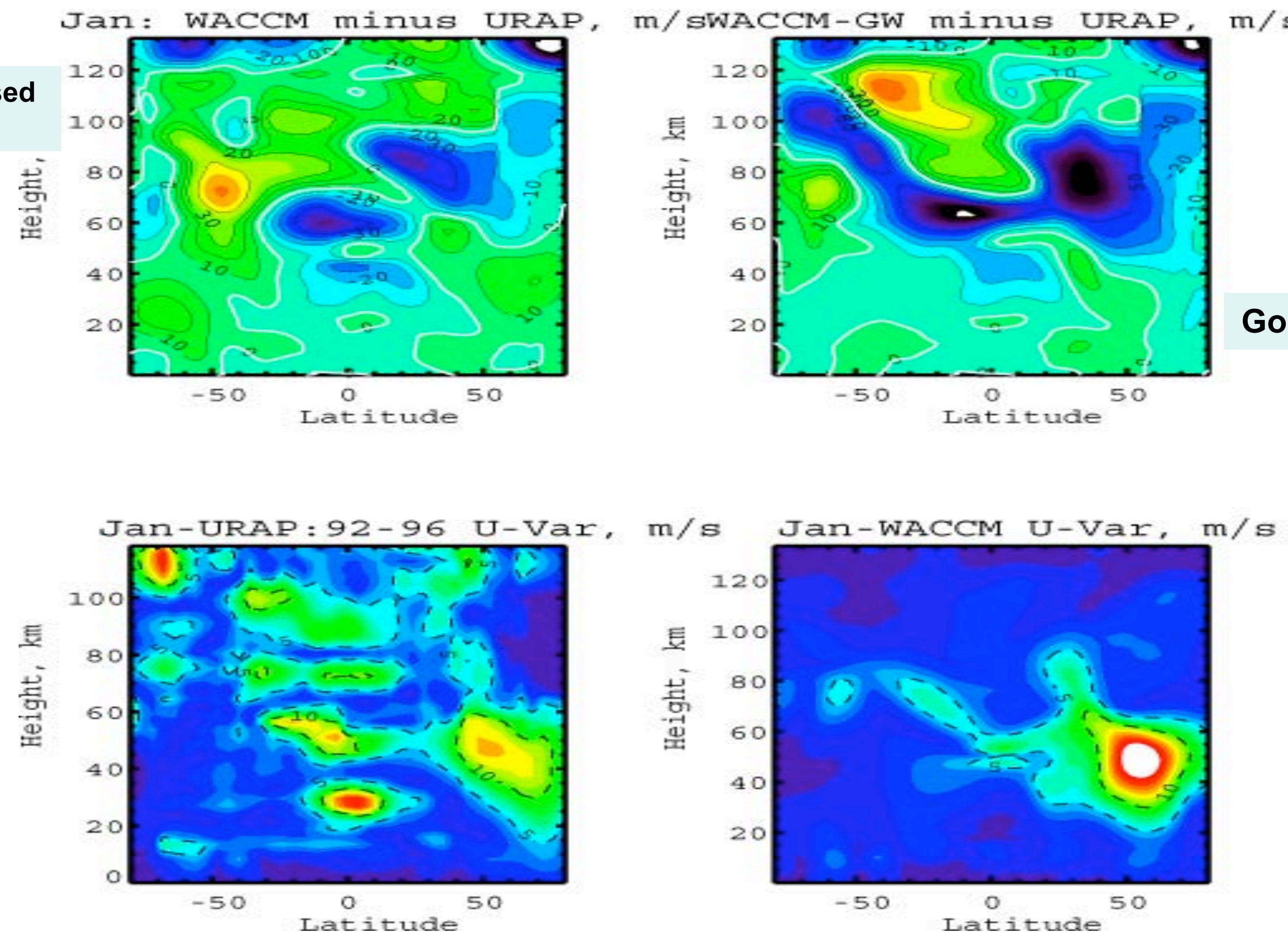


Jan WACCM (Base & GWPD) simulations and HRDI/UARS + UKMO (93 & 94) wind data



U-differences /top/ WACCM minus URAP, U-variances /bottom, URAP (5yr) & WACCM (50 yr)/

Less biased MLT



Good UTLS

Possible inversion (balanced bias propagator) schemes for ZMF with global temperature-data

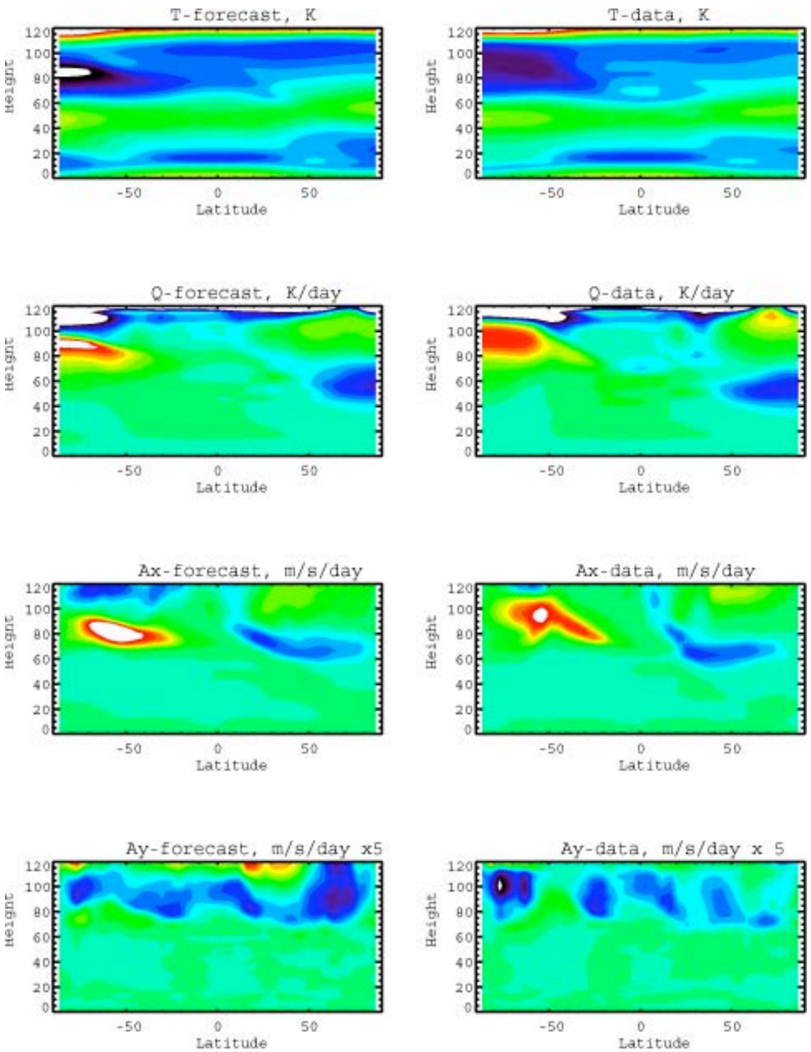
- **Scheme 1 /*extratropical balance,* *HSEq-scheme* /:** Temperature OmF => geopotential increment, restoring *dU-increment* and *dAx-guess* /parameterization dependent/. Spectral iterative solutions of zonal mean vorticity-divergence equations with updated GW momentum deposition without explicit vertical layer coupling.

- **Scheme 2 /***HSEq +XiEq-scheme***/** adds vertical layer coupling through explicit adjustment of meridional streamfunction (Xi) and "time-dependent" U-T iterations with inluence of meridional advection terms (layer coupling => elliptical equation for Xi, iterations => time integrations of U and T equations with observed composition).

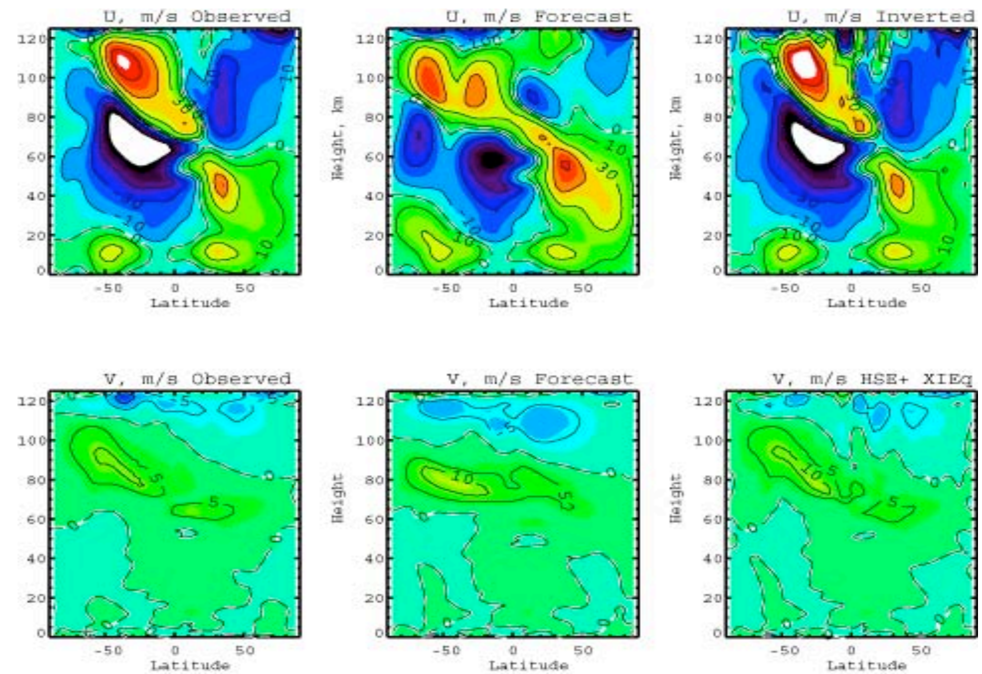
- **Statistical estimation schemes /in progress/.** Inverse schemes (1 and 2) are formulated in the statistical estimation framework by assigning data error metrics (variability of observed climate) and forecast uncertainties (through ensemble forecast of model states).

WACCM twins: HSEq, HSEq+XIEq wind inversions through mass-wind balances

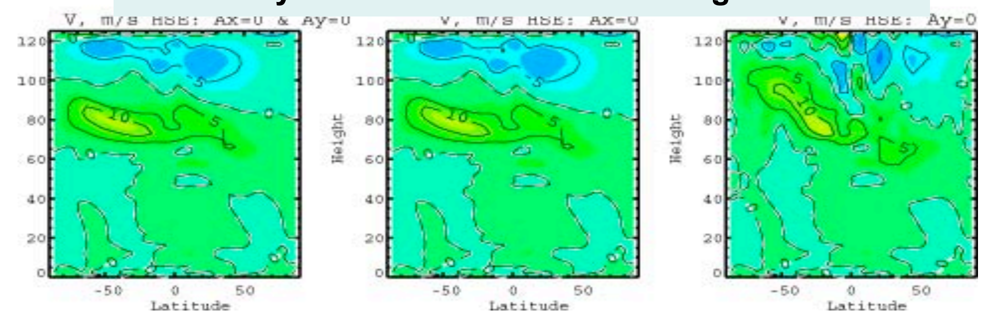
Setup: 2 WACCM runs



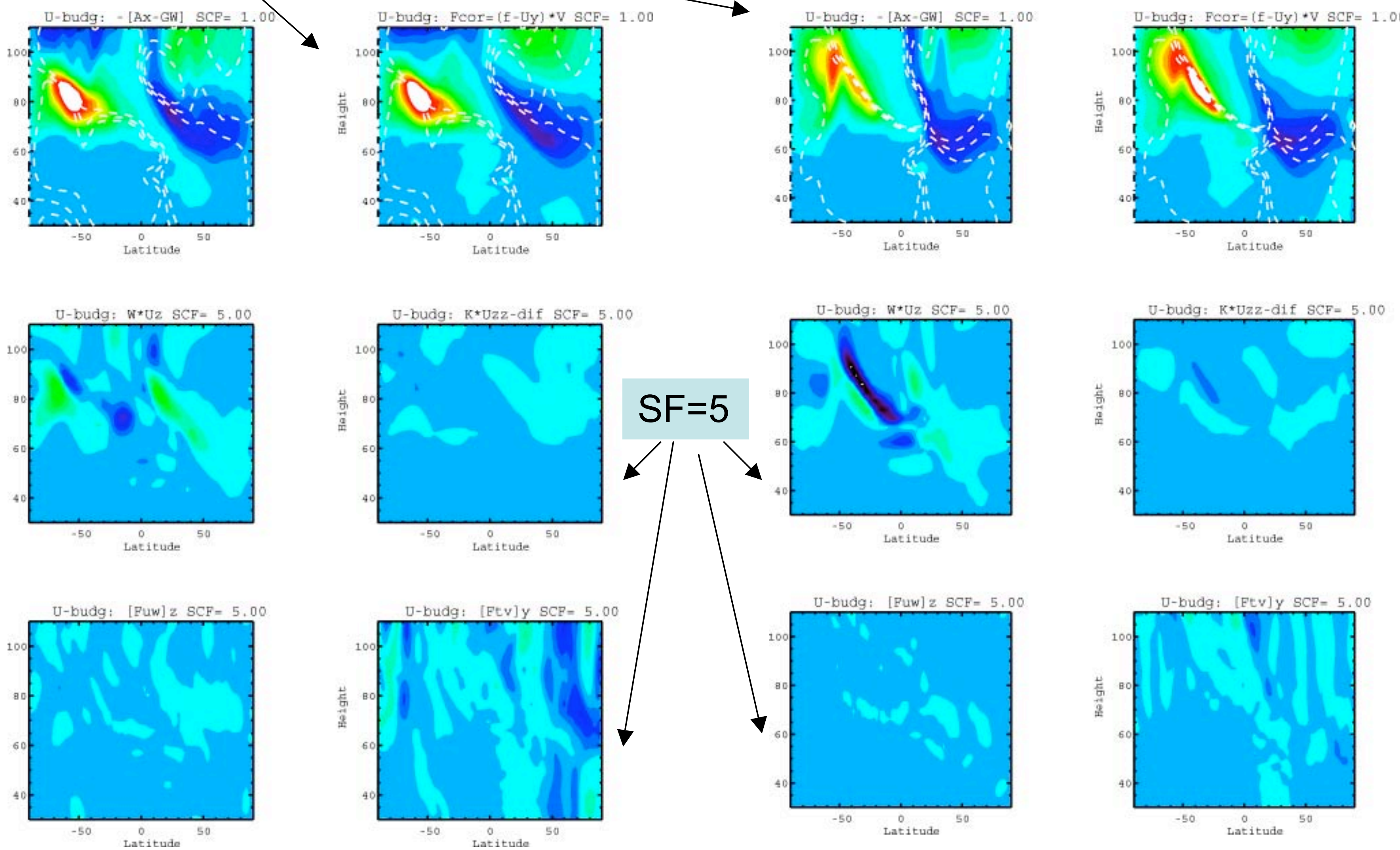
Results: Compare 1 & 3 colums



Sensitivity V-bar to momentum forcing terms



U-balances in WACCM simulations (Base & GWPD) /fV* ~ A_x, leading MLT terms are forced/

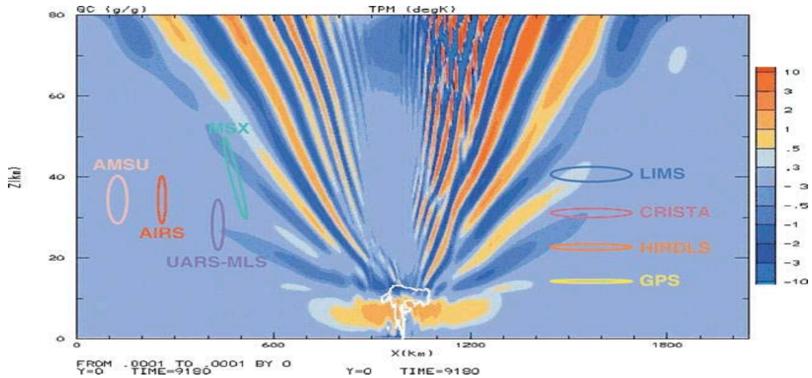


Monitoring short-scale wave activity from the space: AMSU/AIRS/MLS/SABER/CRISTA/HIRDLS/GPS [studies of Hyunah Lee, Joan Alexander, Dong Wu, Steve Eckermann]

Extraction of short-scale portion of GW-rms from T-retrievals and measured radiances.

How can be useful these GW data in DA and optimization of model predictions:

1) GW – heat and momentum fluxes => constrain parameterizations (most exciting adventure).
2) Vertical correlations for forecast errors.
3) Flow-dependent stochastic T-variance.
4) Proxies for geo-locations and variations of GW activities/sources (day-to-day, seasonal, interannual).



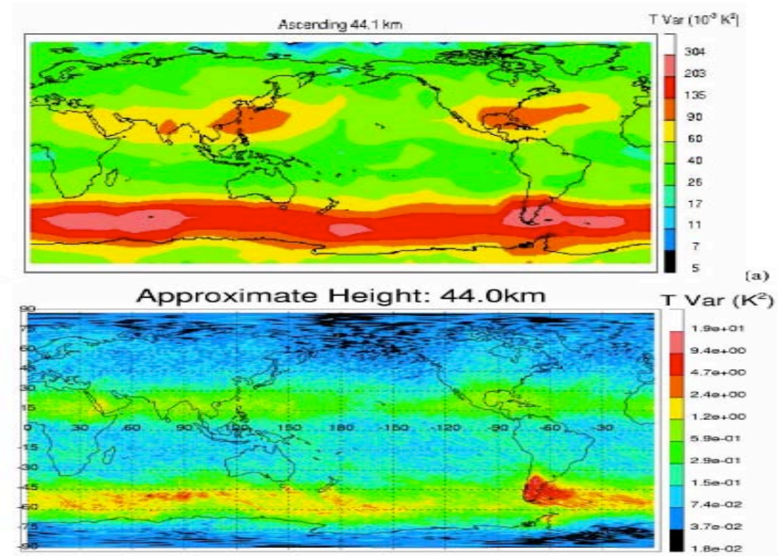
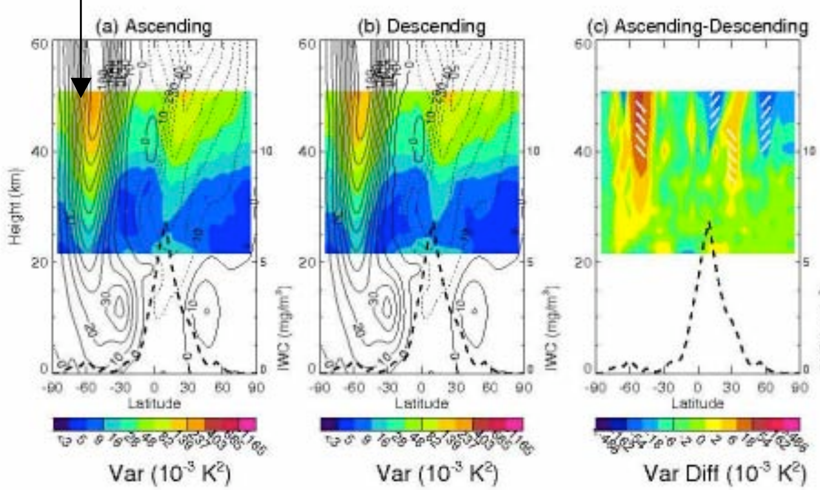
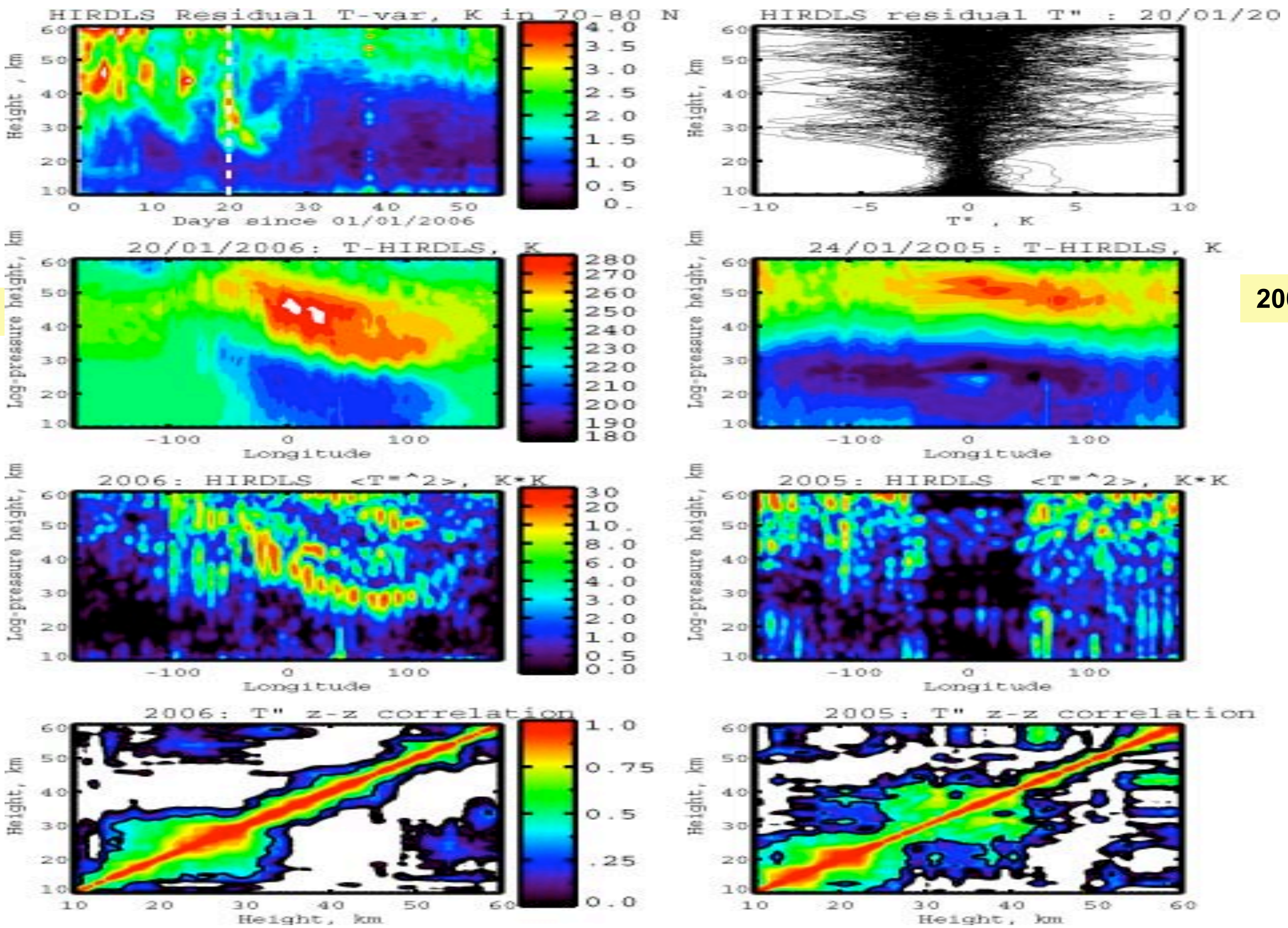


Figure 11. Monthly mean map of GW temperature variance at ~44 km pressure altitude from (a) Aura MLS 40-pt variance in Channels 11/15, and (b) ECMWF IFS T_L799L91 analyses for every day of August 2006. As in Figs. 9-10, temperature perturbations in the ECMWF IFS analyses were truncated to exclude horizontal wavelengths > ~300 km before the variance was computed: no vertical filter was applied.



2005 (strong vortex) and 2006 (major warming) HIRDLS short-scale T-oscillations in polar NH latitudes /70N-80N, Jan/

2006



2005

Concluding Remarks

- Consistency of research satellite observations /UARS, TIMED, Aura/ provide opportunity to formulate inverse schemes for optimization of vertically structured waves and MF. These data are critical for global SMLT wave dynamics.

- Talk illustrates possible inverse schemes to constrain models errors by these data. Global systematic model-data differences (biases) are the data for these schemes, while quasi-linear PDE are the non-local bias propagator models.

- Three steps can be envisioned to ensure unbiased conditions for SMLT analysis **1) Identification of biases; 2) Bias correction and tracking physical mechanisms that can suppress identified biases; 3) Update model physics, tuning uncertain model parameters and think about formulation of weak-constrained DA.**

- Recent space-borne data for optimization of GWP schemes are very attractive but we need to understand how to use effectively these data in DA and inverse studies.

- *Future work in the area of GWP-optimization will may include*

  appropriate GW-MF closures, numerics of GWP and representation of Jacobians for key parameters; Inter-comparison of physics and conservation laws in parameterizations; introduction of stochastic elements in GWP (ensemble of launch levels, spectral parameters; breaking criteria); communication between model columns.

Global Estimates of GW momentum flux from HIRDLS T-retrievals, May 2006 /Alexander et al., 2007/

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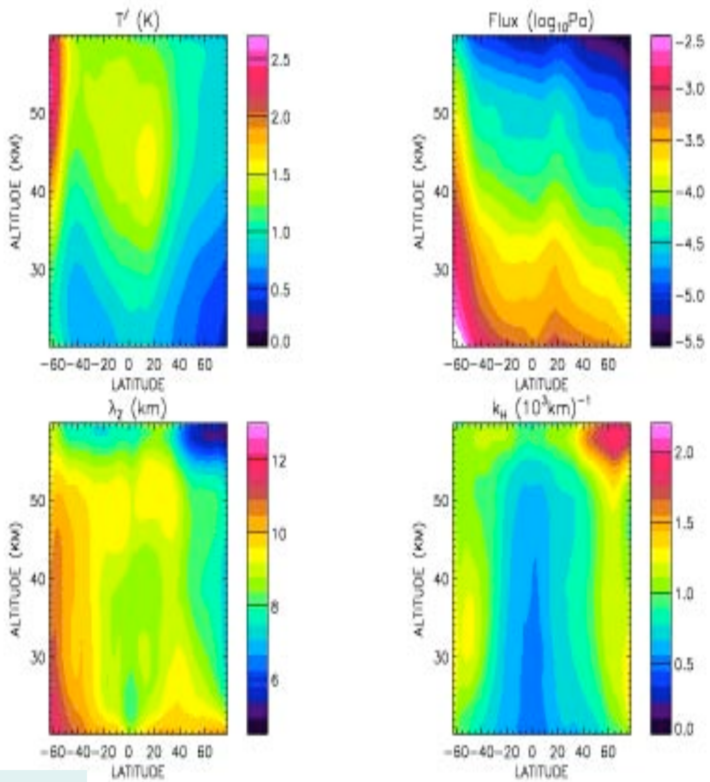
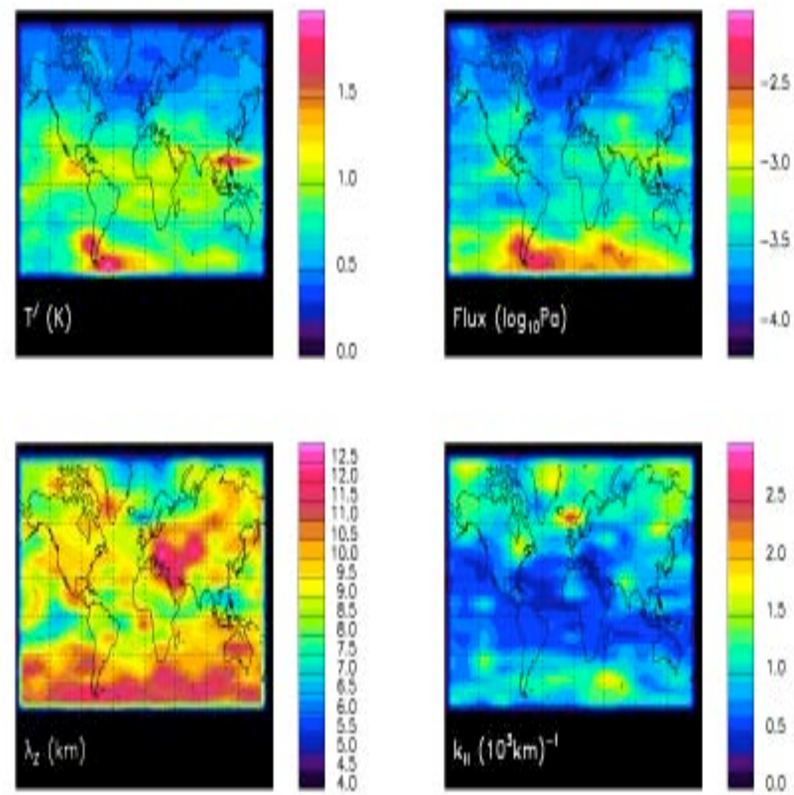


May 2006 Latitude height variations in gravity wave properties. Top left panel is wave temperature amplitude (T'); top right panel is momentum flux (flux); bottom is left vertical wavelength (λ_Z); bottom right is horizontal wavenumber (k_H).



Gravity wave T-var, momentum flux, L_z, and horizontal wavenumber, in height range 20-30 km, May 16 2006.

GWP and Data Assimilation (DA): similarities and differences

- Both procedures => to shift model simulations towards reliable observations to produce well-established empirical climate signatures.

- They overall modify momentum and heat tendencies. GWP makes it directly at every model grid and time step, while DA (or nudging schemes) modifies variables incrementally. Continuous in time (GWP) and localized in time (DA).

- In models both procedures establish non-local response to local adjustment of tendencies through the mass-wind balances.

- Stochastic GW-rms of wind and T can represent uncertainties of forecast (error covariance in DA).

$$dX = X_a - X_f = K_G(X_d - X$$

$$K_G = C_{ff}A^T(AC_{ff}A^T + C_{dd})^-$$

$$A_{XDA} = dX/\tau; \quad A_{XGW} = -\partial F_z$$

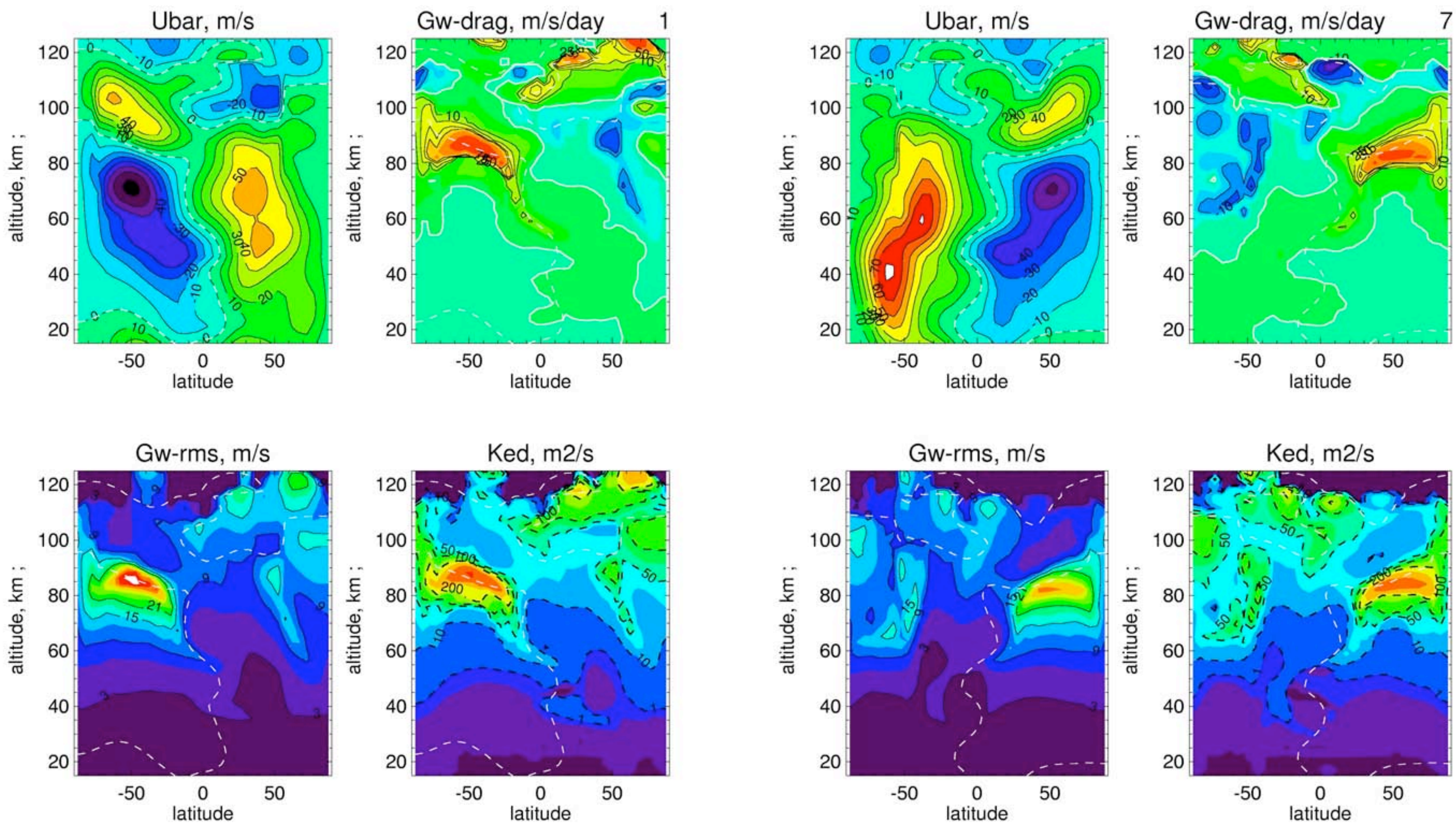
- Current GWP schemes are formulated in “vertical column physics” framework, while DA employs horizontal correlations to spread out analysis increments.

- GWPs are mainly solicited in the adjustment of momentum sources, while operational DA systems work with nadir-viewing temperature data and provides the wind adjustment through calculated temperature analysis increments;

- GWP closures for heat and momentum is not well established in models and relatively large abrupt and unbalanced wind changes are permitted. DA schemes works under unbiased assumptions, allowing moderate T-increments.

- Foundation of DA is error metrics of data and forecast uncertainties; Current GWPs are relatively deterministic although uncertainties of GW sources are large and waves are stochastic. Probabilistic ensemble-based computations of GW effects on the mean flow may be fruitful to acknowledge stochastic nature of GWs.

GWP: H-97 with the HRDI 92-96 zonal mean flow; L_{ze} = 12 km, S_{grow} = 3/2; January – left, July – right.



On DA language, Generalized Inverse related to effects of GWs and possible cost functions

$$X = X(X_i, , S, A_{GW}, V_{GW}) \qquad J = J_{dres} + J_{fres} + J$$

X_d V_d ~ large-scale (resolved by models) and short-sc

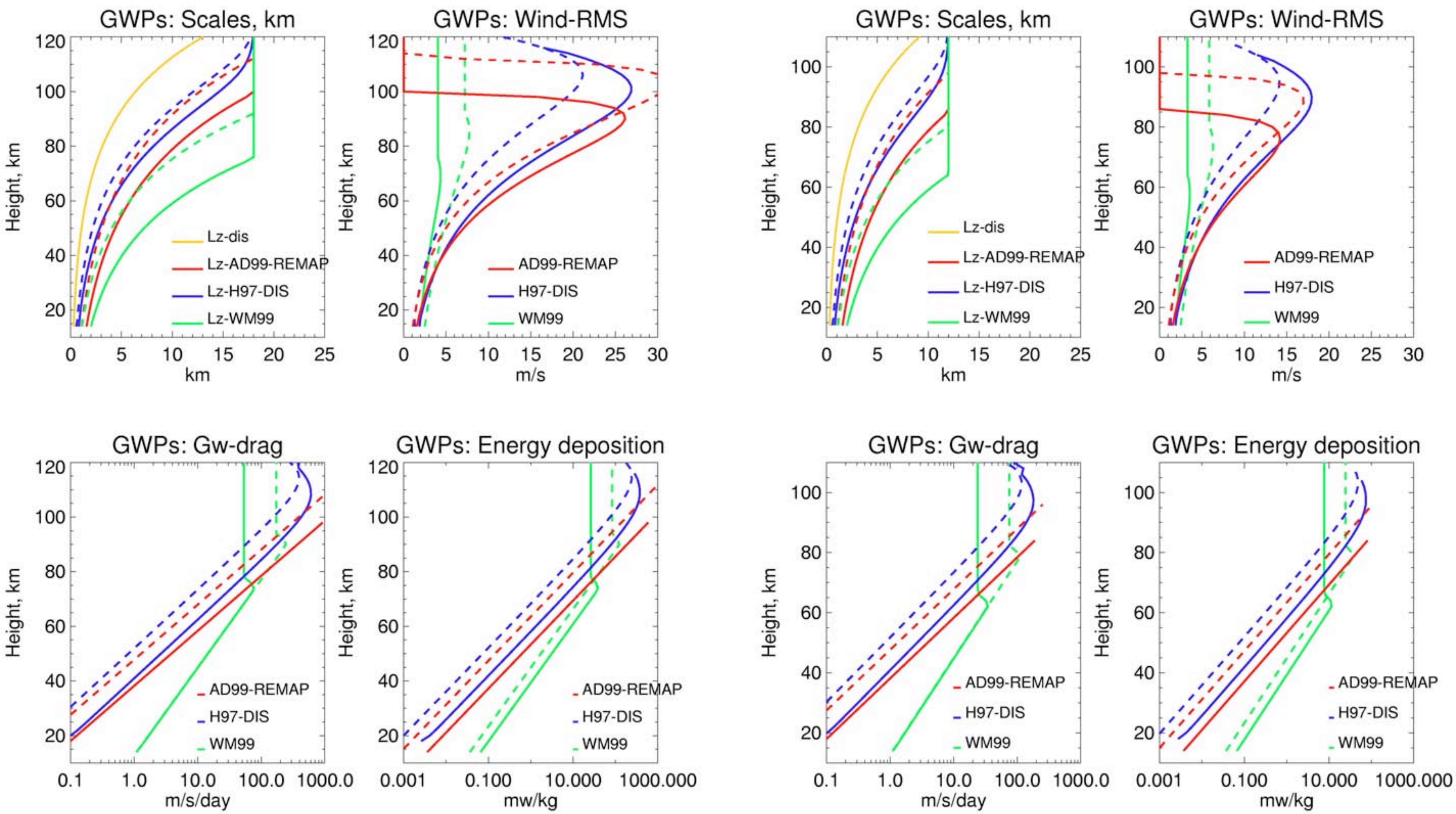
$$J_{dres} = (X_d - H[X])^T C_d^{-1} (X_d - H[X])$$

$$J_{fres} = (X - X_f)^T C_f^{-1} (X - X_f)$$

$$J_{sext} = (S - S_f)^T C_S^{-1} (S - S_f) \qquad J_{GWP} = (A - A_f)^T$$

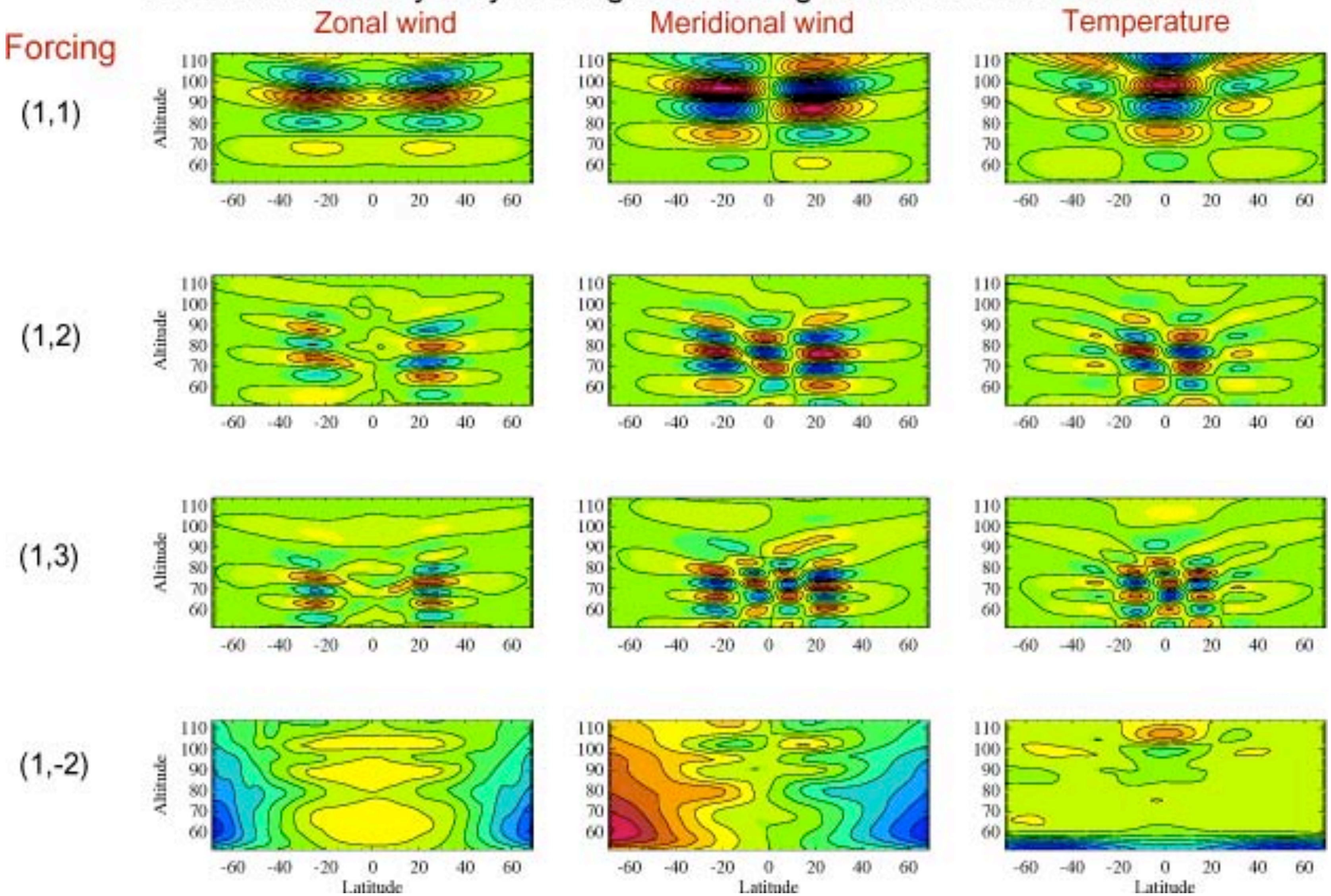
$$J_{dGW} = (V_d - V)^T C_{Vd}^{-1} (V_d - V)^T$$

H-97 (blue), WM-99 (green), and AD-99 with remapping (red) with two cut-offs: $L_z = 18$ km; $L_z = 12$ km. $S_{grow} = 1$

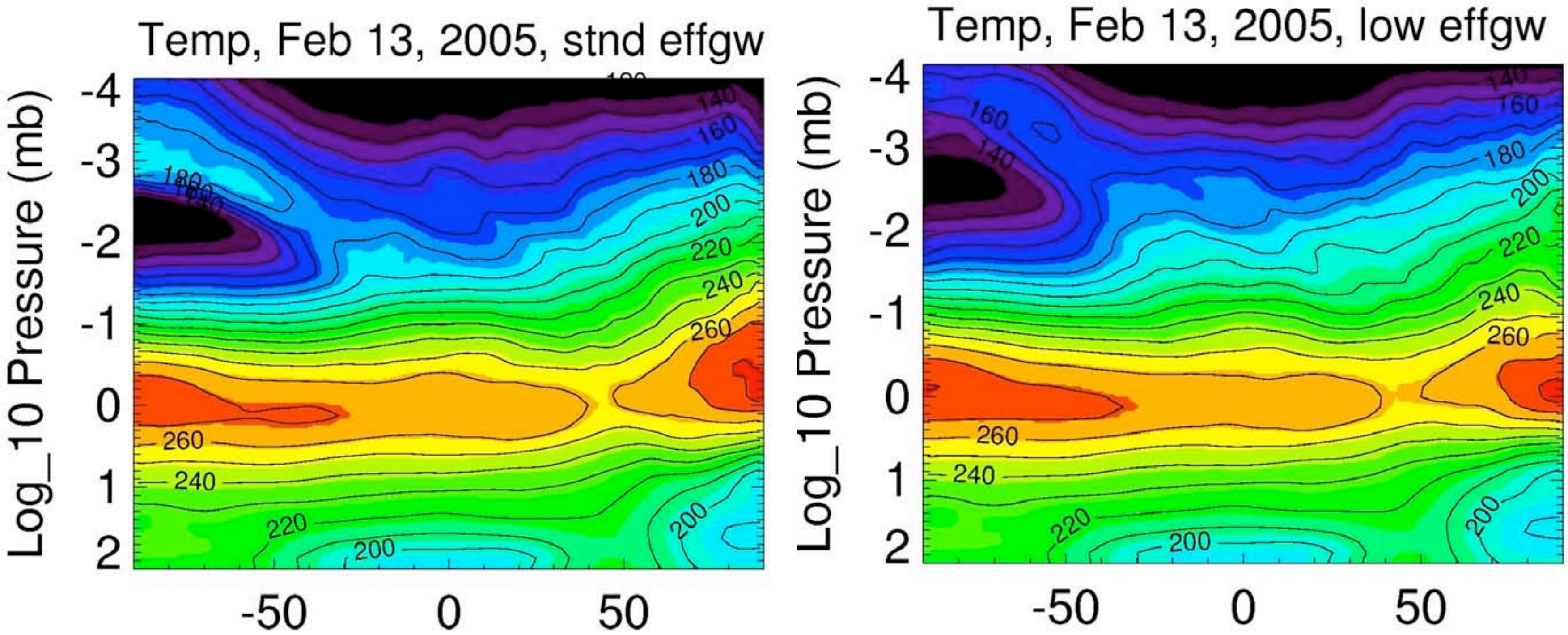


Diurnal tide basis functions

Generated with a linear tidal model, GW forcing, eddy, molecular diffusion;
URAP March wind/temperature background;
Forced in a thin layer by heating with a Hough function horizontal structure



NOGAPS/NRL 2005 T-simulations, with two sets of GW-efficiency [WACCM-GWP], after Sisskind [2007]



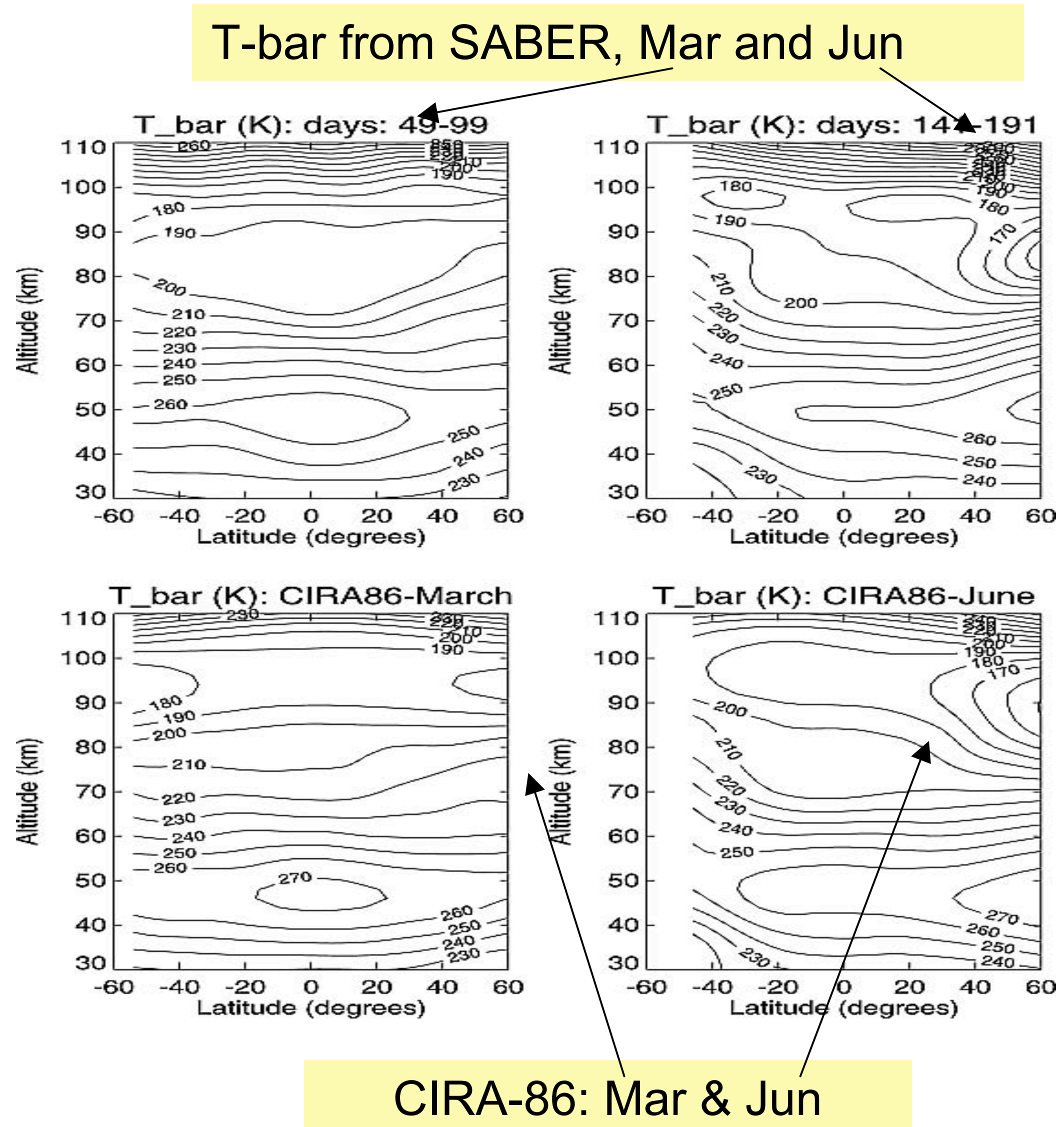
T_{min} at SP = 106K T_{min} at SP = 121K

SABER Zonal Mean Temperatures vs CIRA-86 after extraction of tidal modes, *Zhu et al. [2005]*

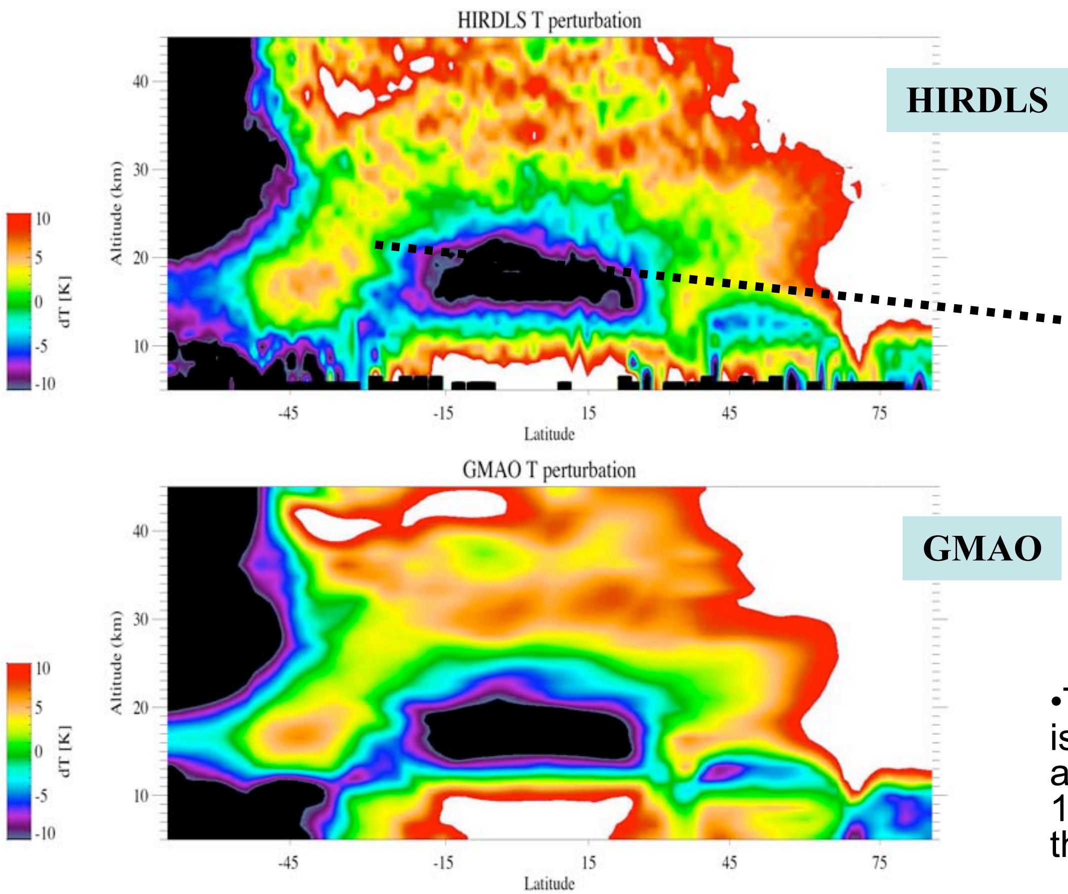
Removal of biases in the zonal mean states /T and U/ is important step to simulate propagation of large- and short-scale waves and propagate OmF by tangent linear models in the SMLT.

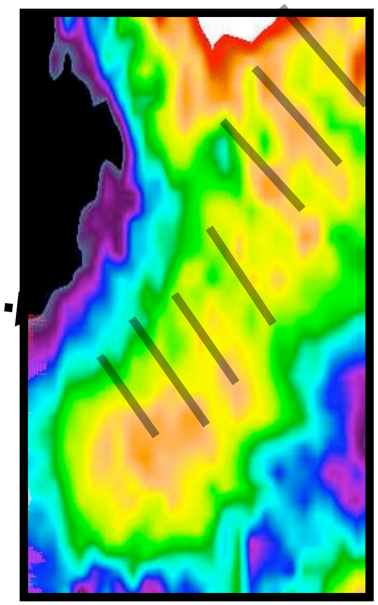
Without revisiting model physics the large biases in ZMF and waves are difficult to remove by BA-DA schemes.

Next several slides illustrate simple tidal inversions that adjust observable modes and variables and propagate clean OmF signal to variables where mixture of modes is expected in the data. Revisit of tidal dissipation can be viewed as simplified description GW influence on tides.



HIRDLS Fine Vertical Scale Wave Activity Observed in HIRDLS Temperature /retrieved by *Dr. Hyunah Lee/*





•This wave event has a vertical wavelength is 3-4 km, horizontal wavelength of 500 km along the scan track, and an amplitude of 1-2K. The GEOS5 analysis doesn't show these wave events.

HIRDLS data on June 19, 2005

Optimization schemes

- Budget studies for zonal means with remote sensing T and constituents retrievals [ZMD in TEF, radiation code, analyzed winds]
- Model-based estimation of “missing” momentum sources under assumption that GW-heating are negligible
- Algebra of “budget” terms or tangent linear/variational estimation of “residual” sources that model needs.
- DA studies in the MLT:
- a) Geophysically-based tuning of model results to “monthly” climatologies;
- b) Adjustment of resolved modes and

References to the GW schemes

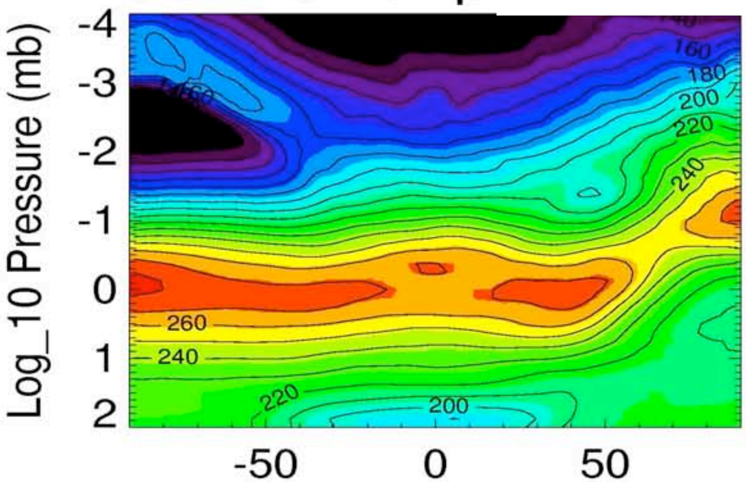
Hodges-68	Wave saturation and Eddy mixing in the windless environment (Prototype of Lindzen-81)
Lindzen-81 *L-81*	Linear wave saturation in the mean flow: Eddy mixing, and momentum deposition, wave drag .
Weinstock-76, -84, -90 (*W-90****)***	Nonlinear saturation and damping, strong wave-wave interaction: Regular wave in the 'wave turbulence field'.
Smith, Fritts, VanZandt :86,93	The 'universal' GW spectra in the atmosphere, observational constraints, linear saturation and wave intermittence.
Hines-91, 93, 97 (*H-97****)***	Critique of the linear saturation theory. Stochastic nonlinear Doppler Spreading Theory (DST). DST as the GWP scheme
Warner, 99-00 and McIntyre (*WM-99****)***	The propagation of the 'universal' GW pseudomomentum spectra and its approximations through realistic atmosphere
Medvedev and Klaassen: *MK-95*	Nonlinear diffusive spectral dumping in the spirit of Weinstock-90 in the parameterization framework.
Alexander and Dunkerton: *AD-99*	Delta-Lindzen scheme for the specific broad spectra in C_x-space without MFA. Spectra intermittance is a substantial part of the scheme.

Optimizing GWP schemes and building Jacobians

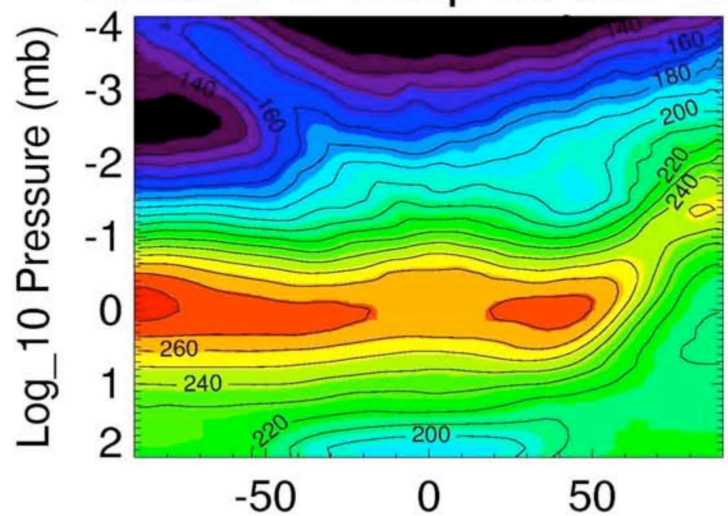
- **GWP => Ax, Et, U-, T- rms, Ked**
- **Main parameters of non-oro GWP: wave spectra characteristics at the launch/source level**
- **Physics of scheme is fixed, numerical implementation and optimization of uncertain parameters: -**
- **Zl position of sources; total U/T-rms; Kx –typical horizontal wavenumber; breaking and instability fudge factors; intermittency or efficiency; window of spectral modes Cx-max (Kz-min).**
- **Jacobians J = dAx/db to write optimization scheme**

dAx = sum(Jb#db) and <b> = b + <db>

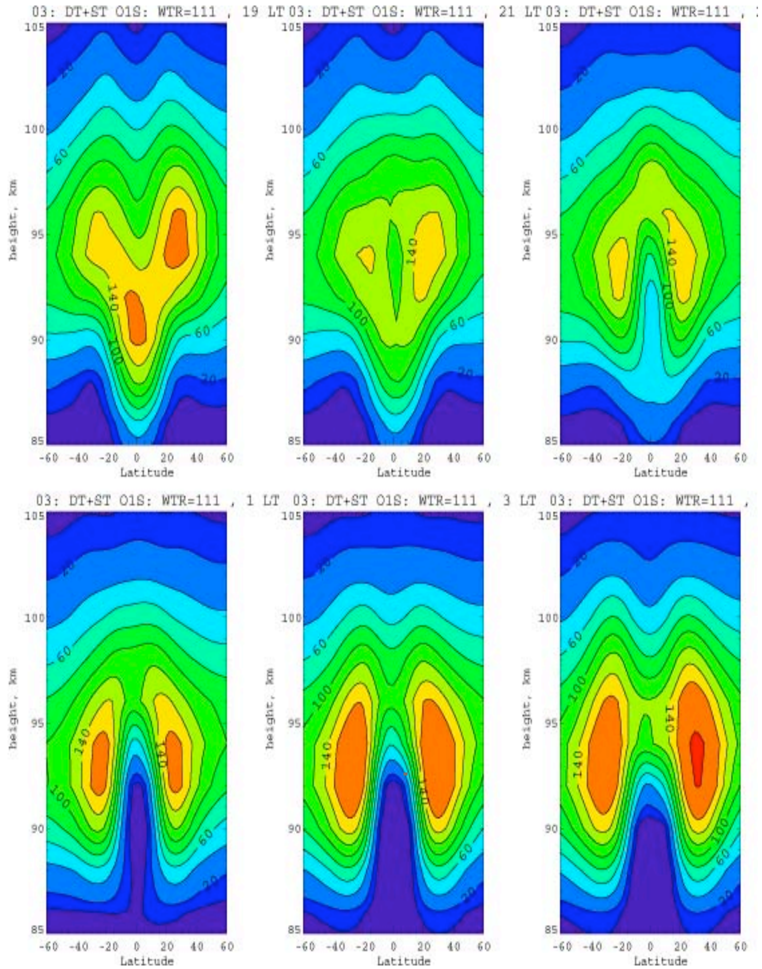
NOGAPS Temp Feb-2006

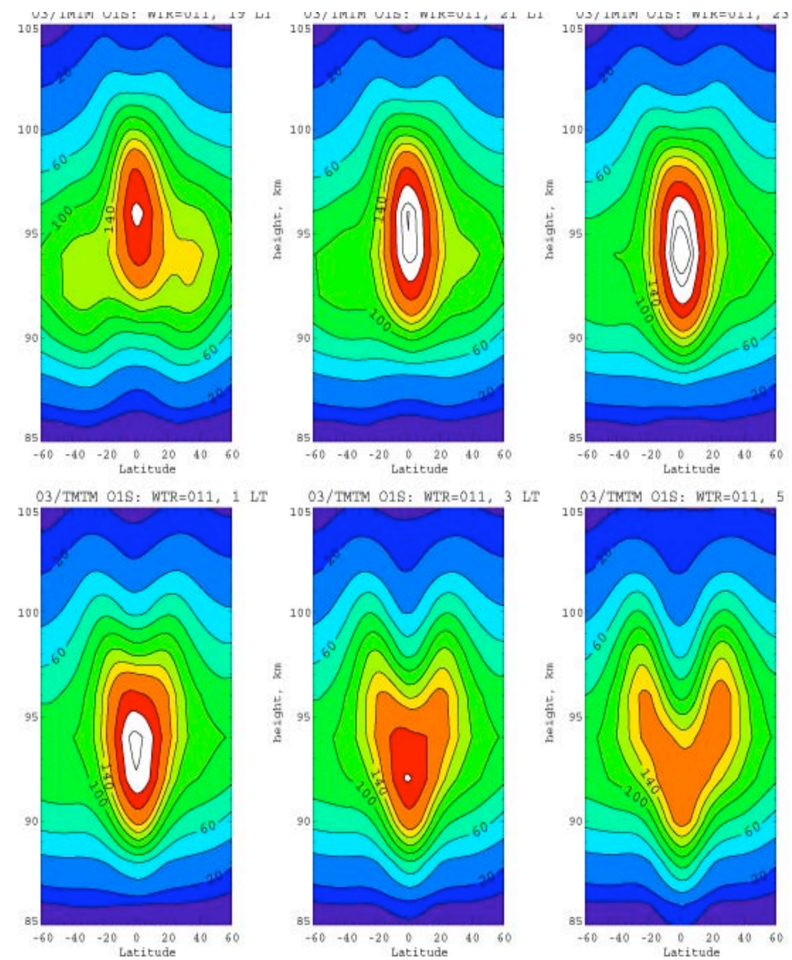


NOGAPS Temp for 336 hrs



Simulated nighttime variations of O1S-airglow: Tidal wind, temperature and density oscillations are from TMTM-2000.





W’(t) =/=0, I’ = sT’ +dR’ +cW’

W’(t) =0, I’ = sT’ +dR’

Zhang et al., 2006