The challenges of middle atmosphere data assimilation

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OUTLINE

1. Vertical Information transfer and the issue of bias
2. Getting the correct Brewer-Dobson circulation
3. Balance in the middle atmosphere
4. Coupling chemical-dynamical variables

1. Vertical information transfer and the issue of bias

- DA can spread the info of obs to data gaps
  - 3D-Var, OI: static background error covariances spread influence of obs
  - 4D-Var: tangent linear model and adjoint implicitly spread error covariances downstream and upstream
  - Kalman Filter: error covariances propagated according to tangent linear (EKF) or nonlinear model dynamics (EnsKF)
- Model can advect information downstream, or through wave propagation during the forecast
- How should tropospheric info (data rich region) be spread to middle atmosphere (data sparse region)?

Canadian Middle Atmosphere Model = CMAM

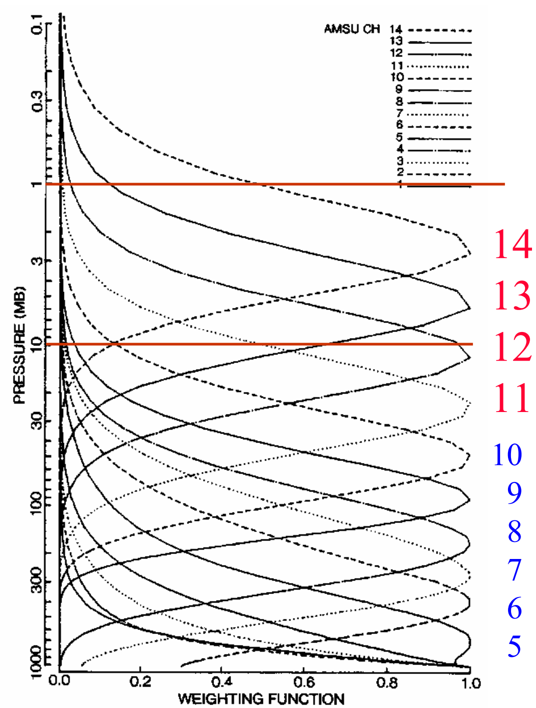
CMAM is a GCM with interactive chemistry, radiation and dynamics

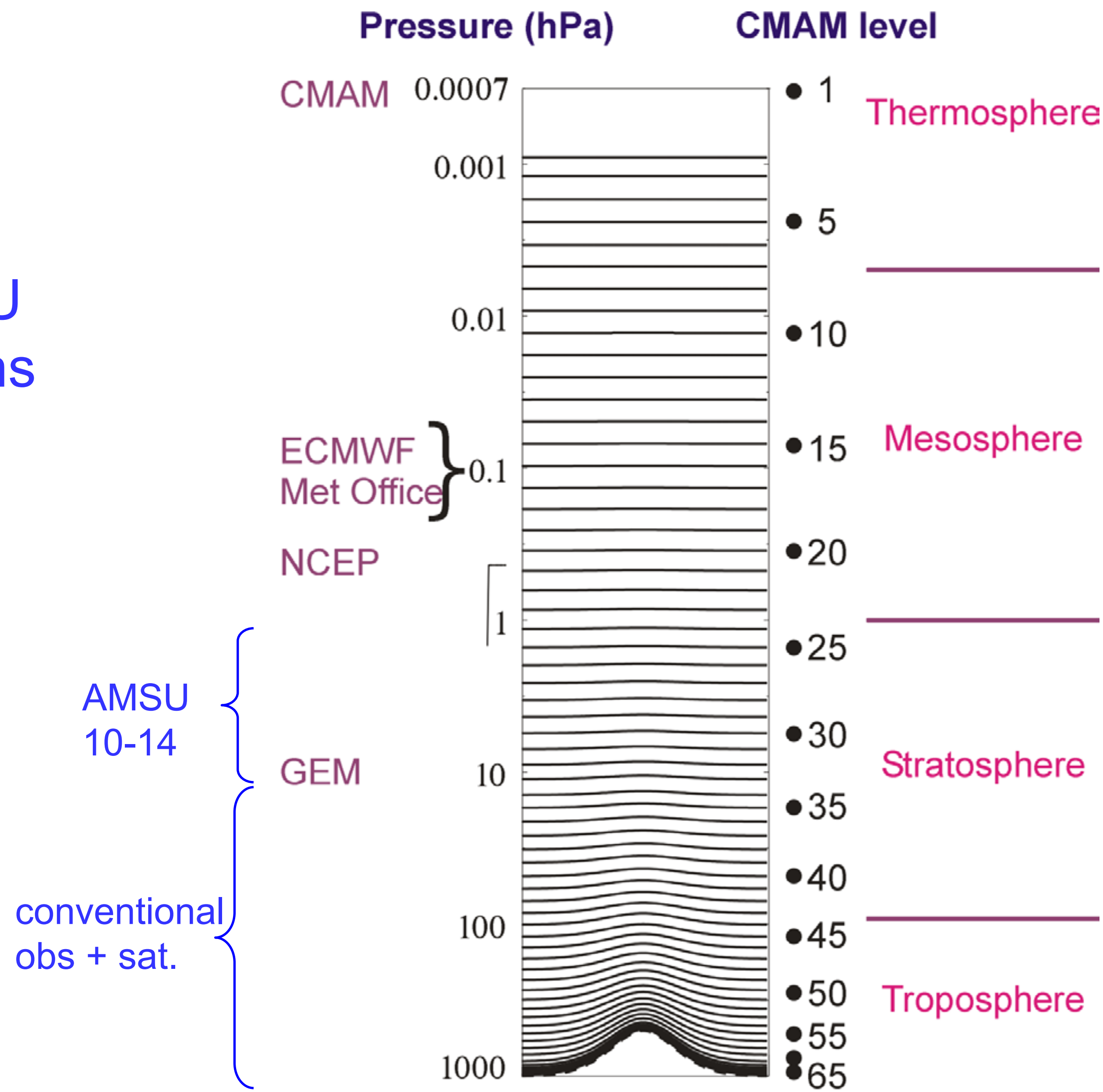
- T47, 65 levels from 0-95 km
- 127 gas-phase chemical reactions
- heterogeneous chemistry
- Hines GWD scheme

CMAM Data Assimilation

- CMC's 3D-Var scheme
- dynamic variables only
- obs: conventional, AMSU-A 4-14
- start up from climate state: Dec. 15, 2001

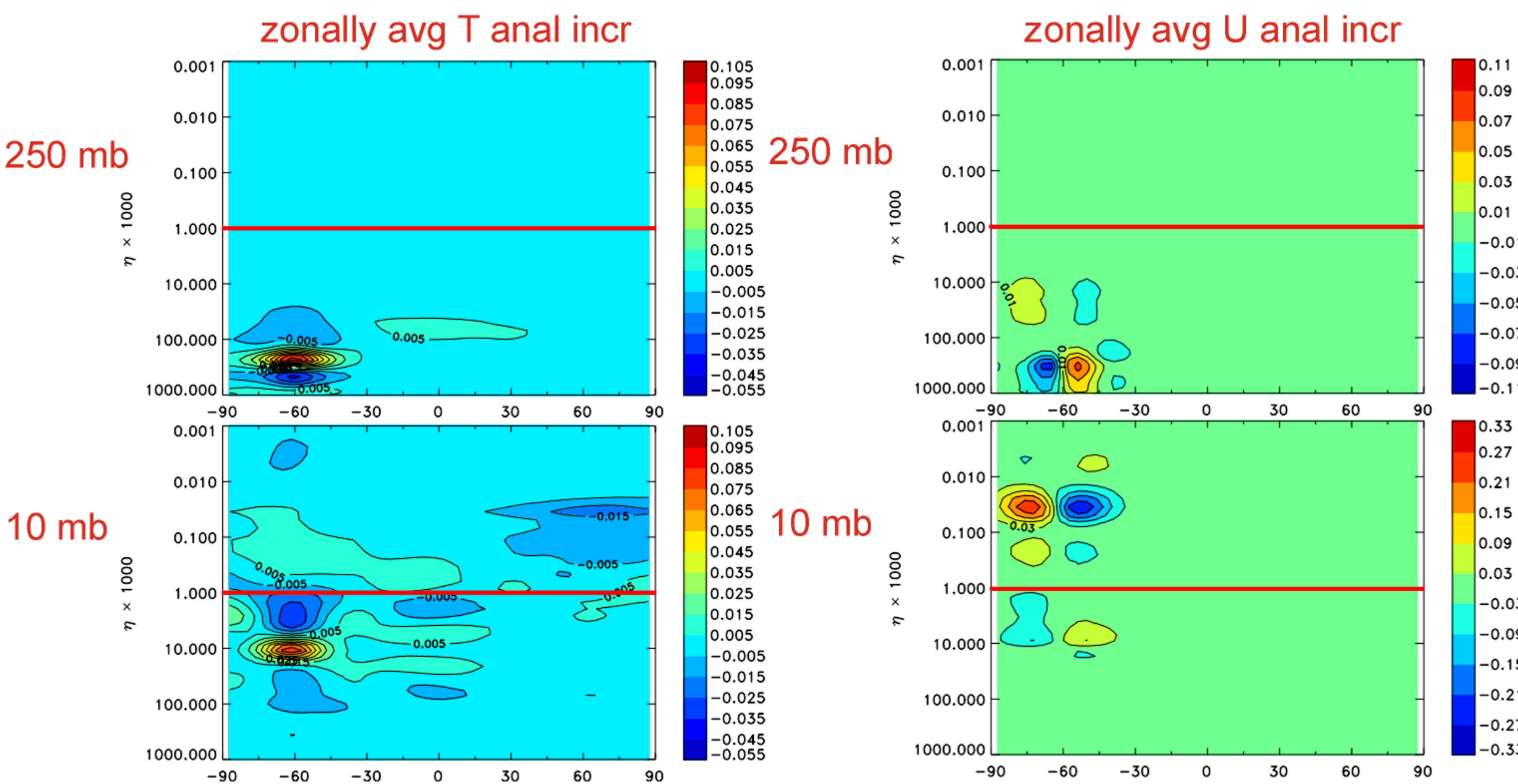
Normalized AMSU Weighting functions



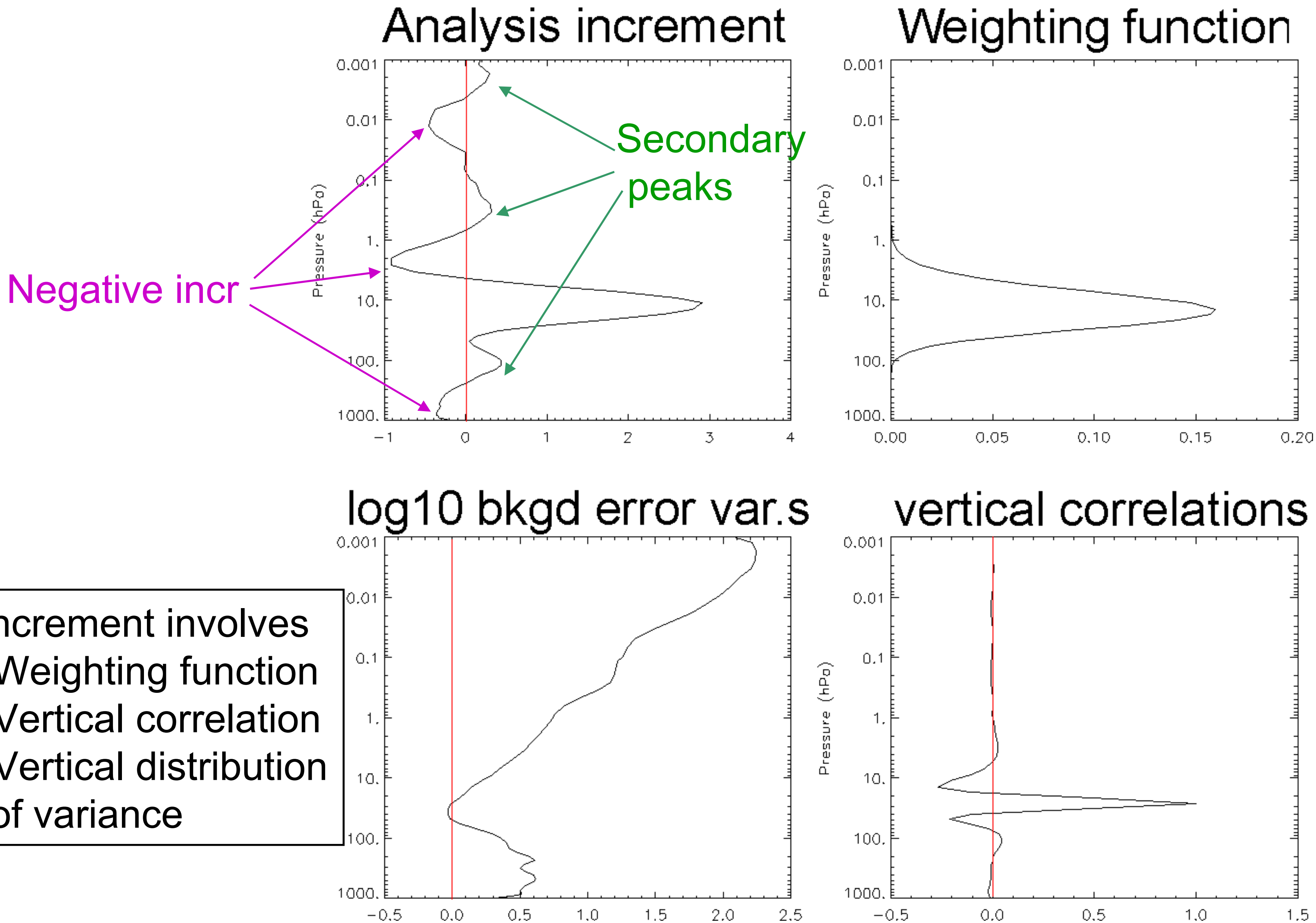


Impact of observations on the mesosphere

One T obs incr of 1 K

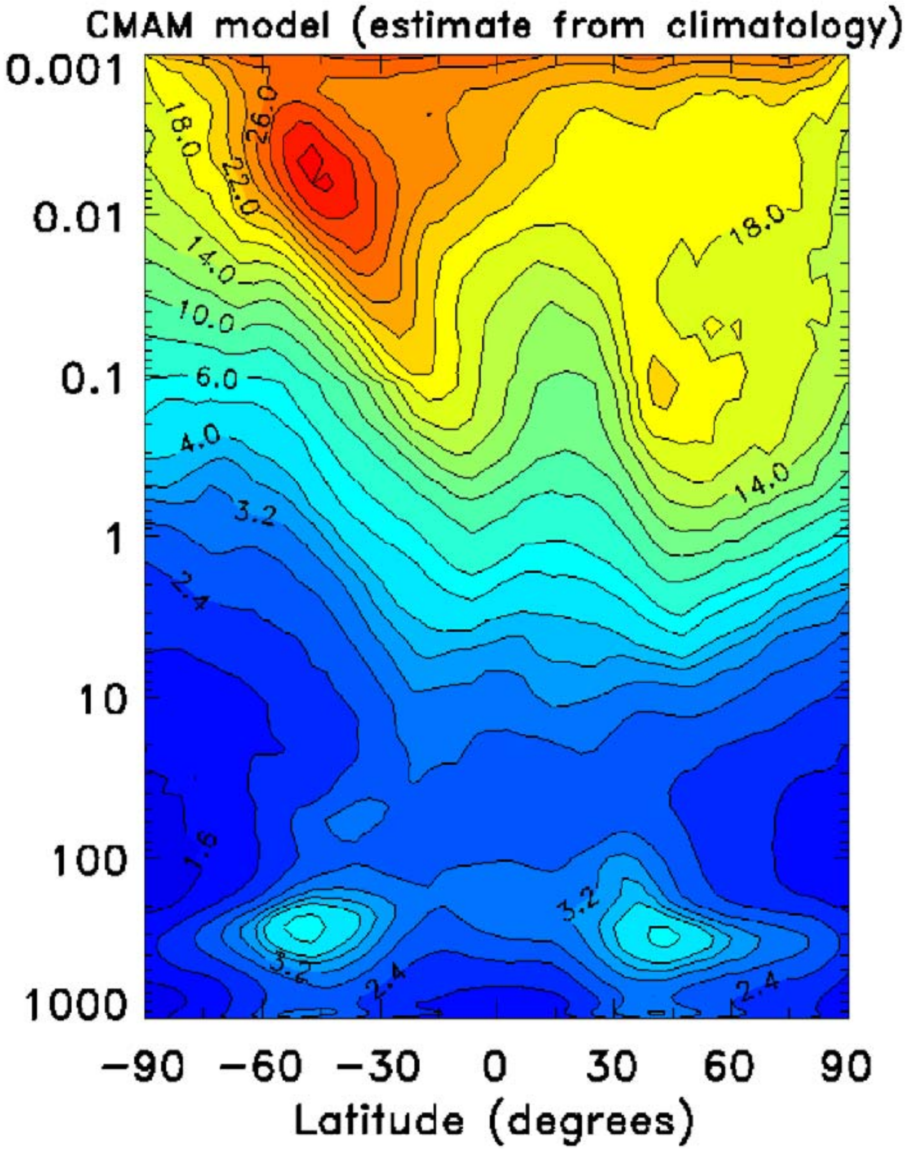


AMSU ch. 11



Increment involves
- Weighting function
- Vertical correlation
- Vertical distribution of variance

CMAM background error std. dev. for U

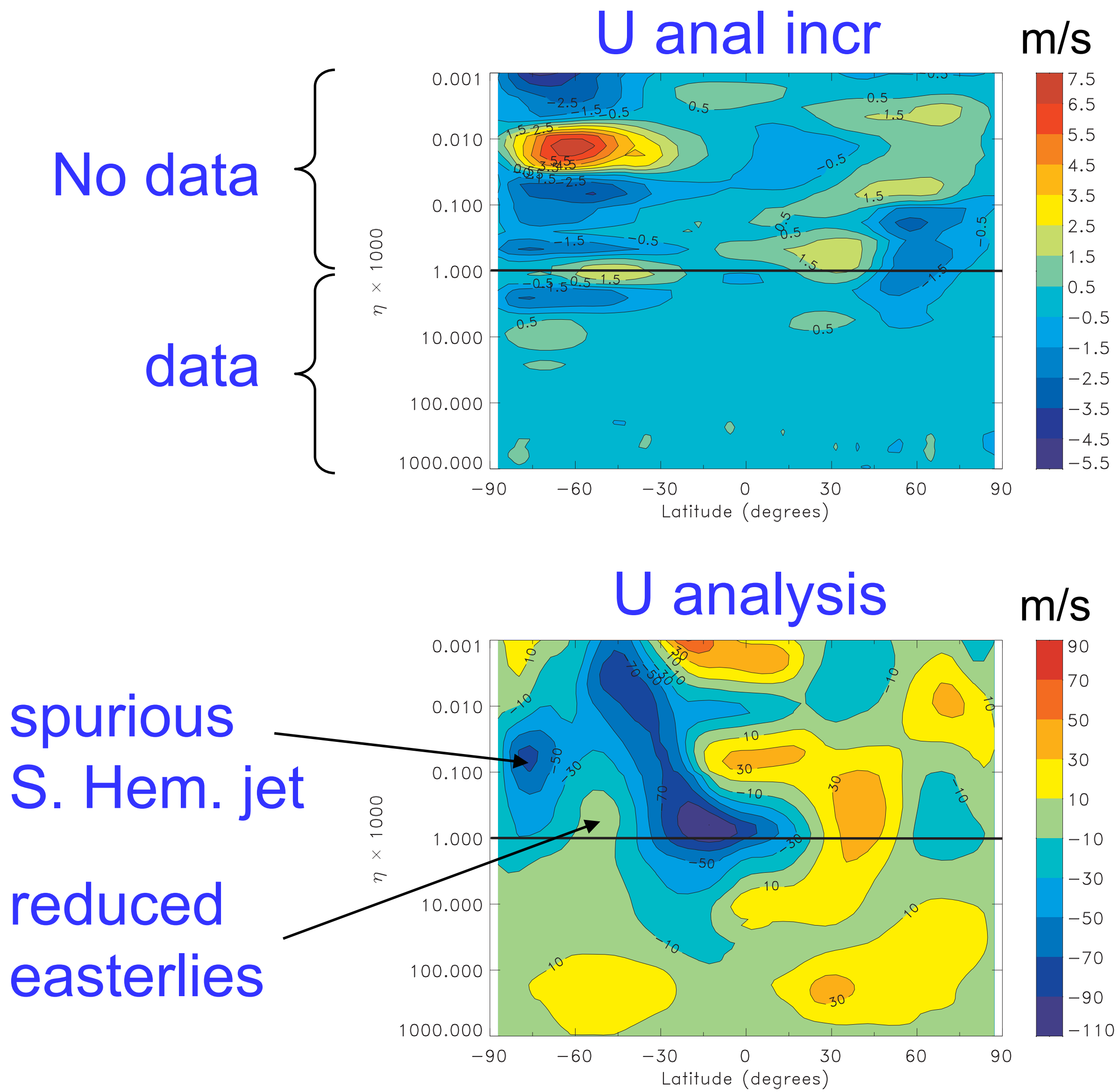


Impact of obs in mesosphere is due to:

- Use of linear balances to derive wind impact from T obs
- nonzero vertical correlations
- large variances in mesosphere (because of gravity waves; see Koshyk *et al.* JGR 1999)

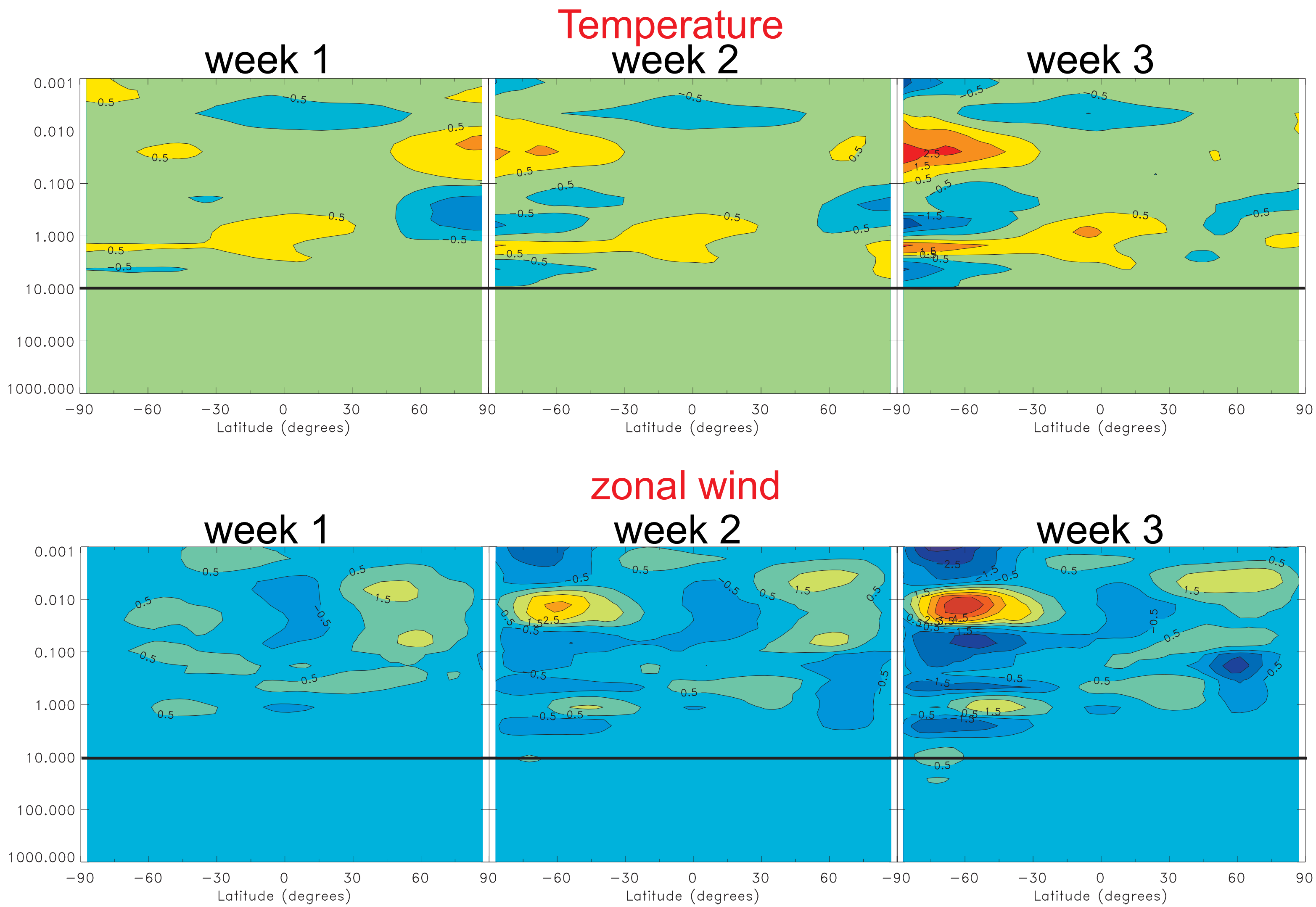
- should reflect 6h fcast error
- NWP centres often uses fcast differences (NMC method)
- here based on 6h differences from climate run
- relation between these different approaches is not well understood

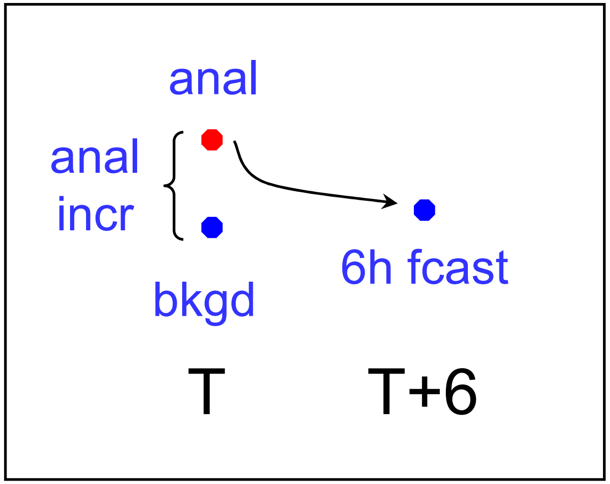
Feb. 22, 2002 18Z zonally avg. fields



Obs and/or model forecast is biased

Zonal mean and time mean anal. incr.



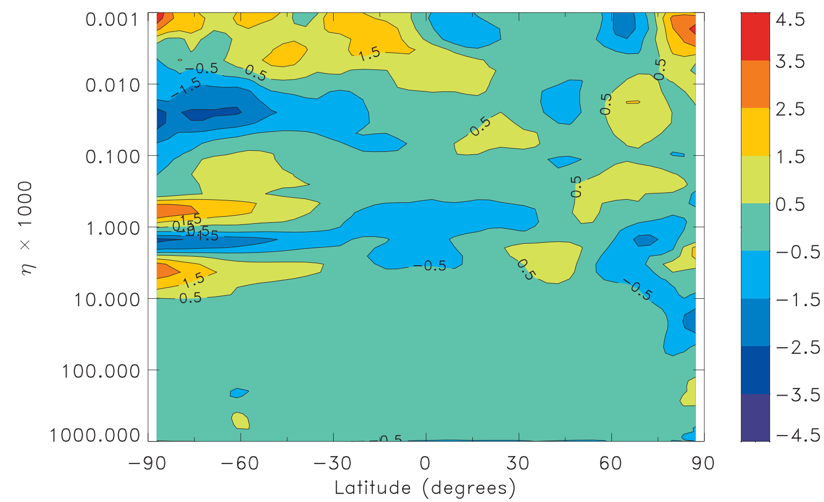


- model response opposes analysis increments
- true for 3D fields
- true for wind fields

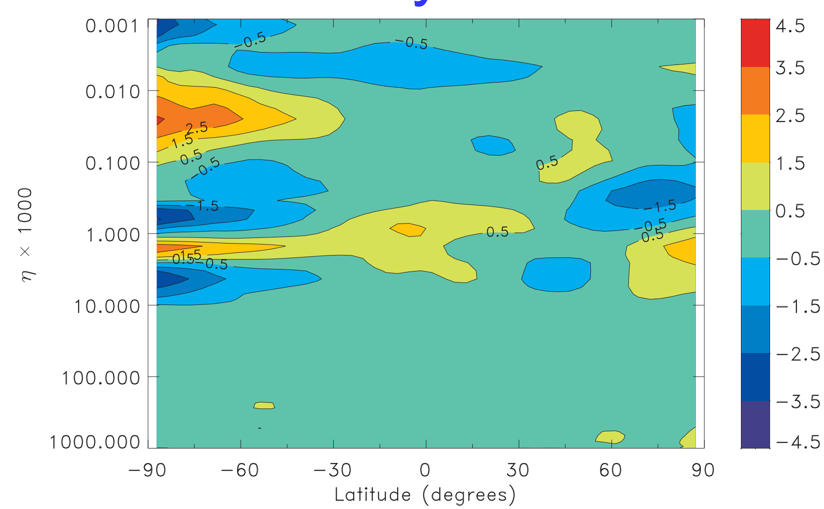
WHY?

Feb. 22, 2002 18Z
zonally avg fields

6-h fcast - anal

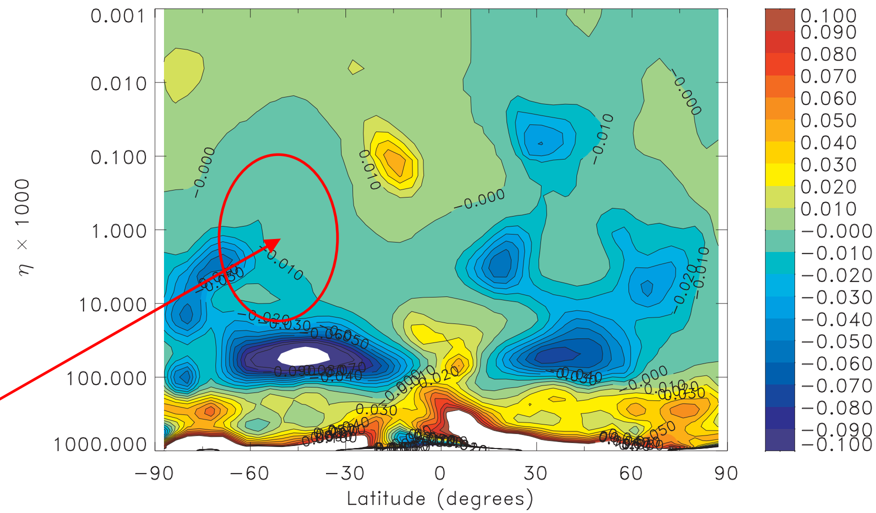


T analysis incr



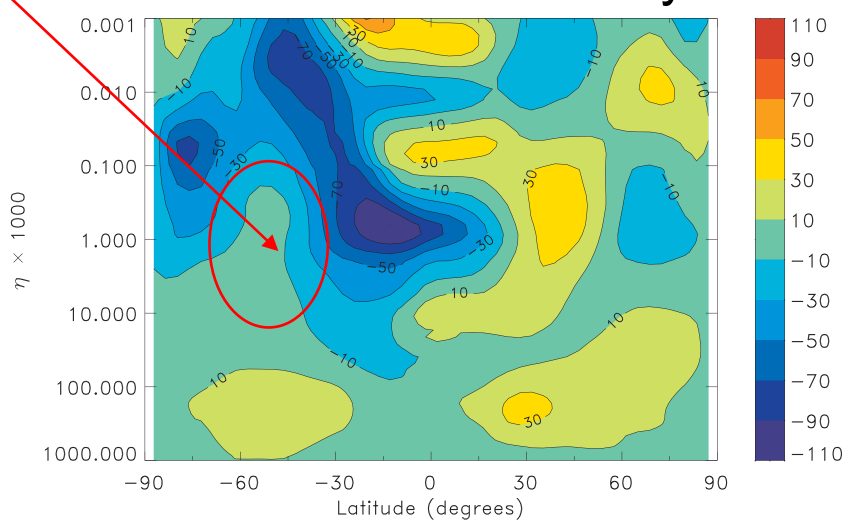
Feb. 22, 2002 18Z
zonal mean fields

U mom. flux divergence x 1E6



GWD scheme wants to damp westerly wind anomaly

zonal mean of U analysis



Spurious mesospheric jet

- Unphysical features develop slowly over time
- Obs-fcast is biased so T incr are too large
- Covariances spread T incr and bias to winds
- Model uses GWD to try to damp increments
- Bias remains or grows in time
- No data in mesosphere to damp incorrect increments

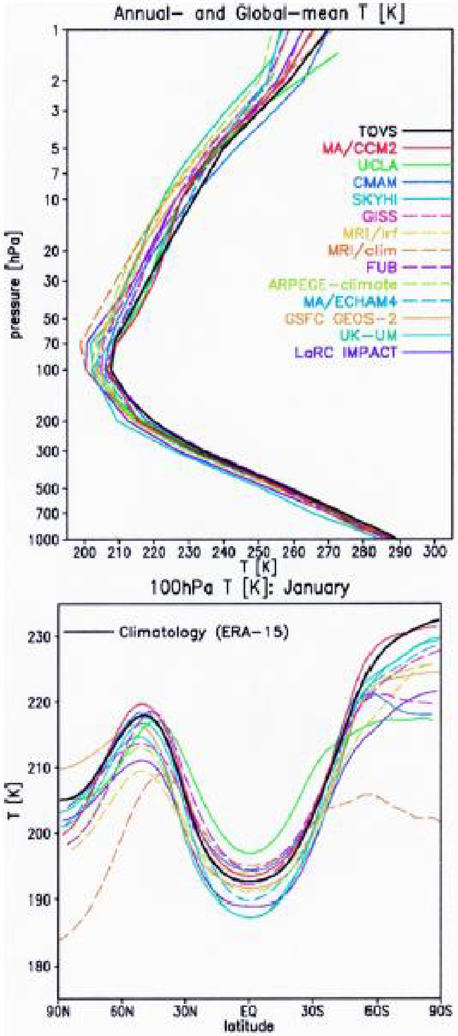


FIG. 1. The top panel shows the vertical structure of the long-term, annual global-mean temperature (K) from observations (thick black line) and the 13 models (thin colored lines). Observations are a 17-yr mean, updated from Randel (1992). The lower panel shows the latitudinal structure of the multiyear monthly mean temperature (K) at 100 hPa in Jan. The observational estimate (thick black line) is specified from ERA-15 data (Gibson et al 1997). The models are represented by the same style and color as in the upper panel.

Pawson et al. (2000)

Separating model and observation biases

- Model is biased– can't use forecast to remove obs bias
- cross-validation of different obs– more obs
- Bias correction schemes: won't separate model and obs bias
  - Dee and DaSilva (1998), Dee and Todling (2000)
  - Ménard et al. (2003)

2. Getting the correct Brewer-Dobson circulation

If the transport is well represented, then modeled species can be compared with observations to assess photochemical processes.

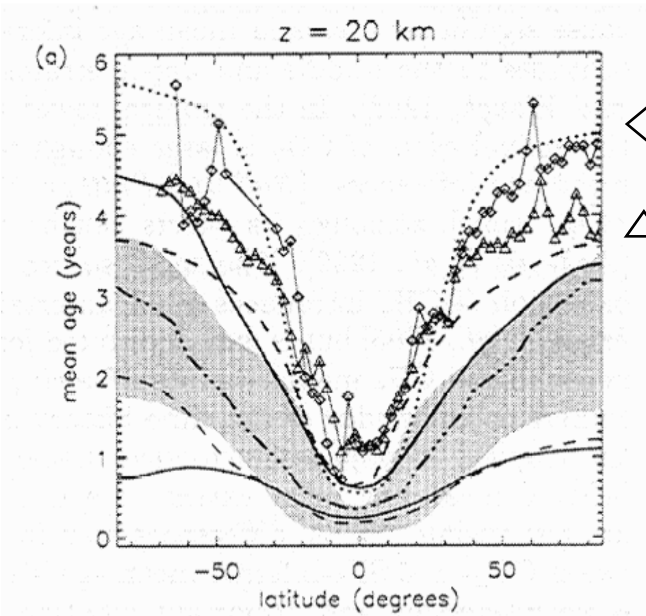
Age of air

- Models:

1. Release a tracer at the equator near the surface for a short duration.
2. Follow evolution of tracer in time over years.

- Measurements:
  - Use long-lived tracers with linear trends e.g. SF_6 or annual mean CO_2.

Most models are too young in the stratosphere



◇ SF_6

△ CO_2

models

1. The age of air is too low in GCMs, esp. at mid and high latitudes.
2. The spread of model mean ages is large compared to obs uncertainty.
3. Most models do not reproduce sharp latitudinal gradients at 10-30° latitude.

Fig. 5. The shaded region indicates the range of mean ages of models, with the exceptions of HARVARD (dotted line), MONASH1 (heavy solid line) and UIUC (light solid line). Obs are from aircraft measurements from SPADE, ASHOE/MAESA, STRAT and POLARIS for CO2 and from ASHOE/MAESA, STRAT and POLARIS for SF6. Data are avg in 2.5° latitude bins.

Hall et al. (1999)

Assimilated winds produce much younger ages than GCM winds when used to drive CTMs

Note the weak latitudinal gradients

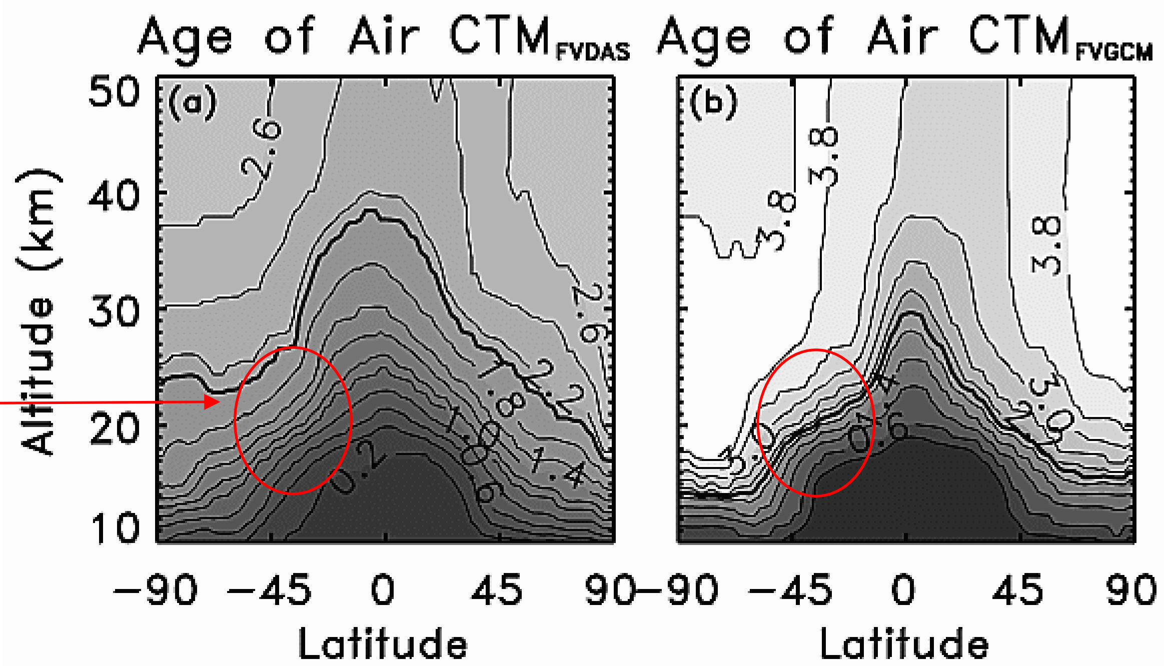
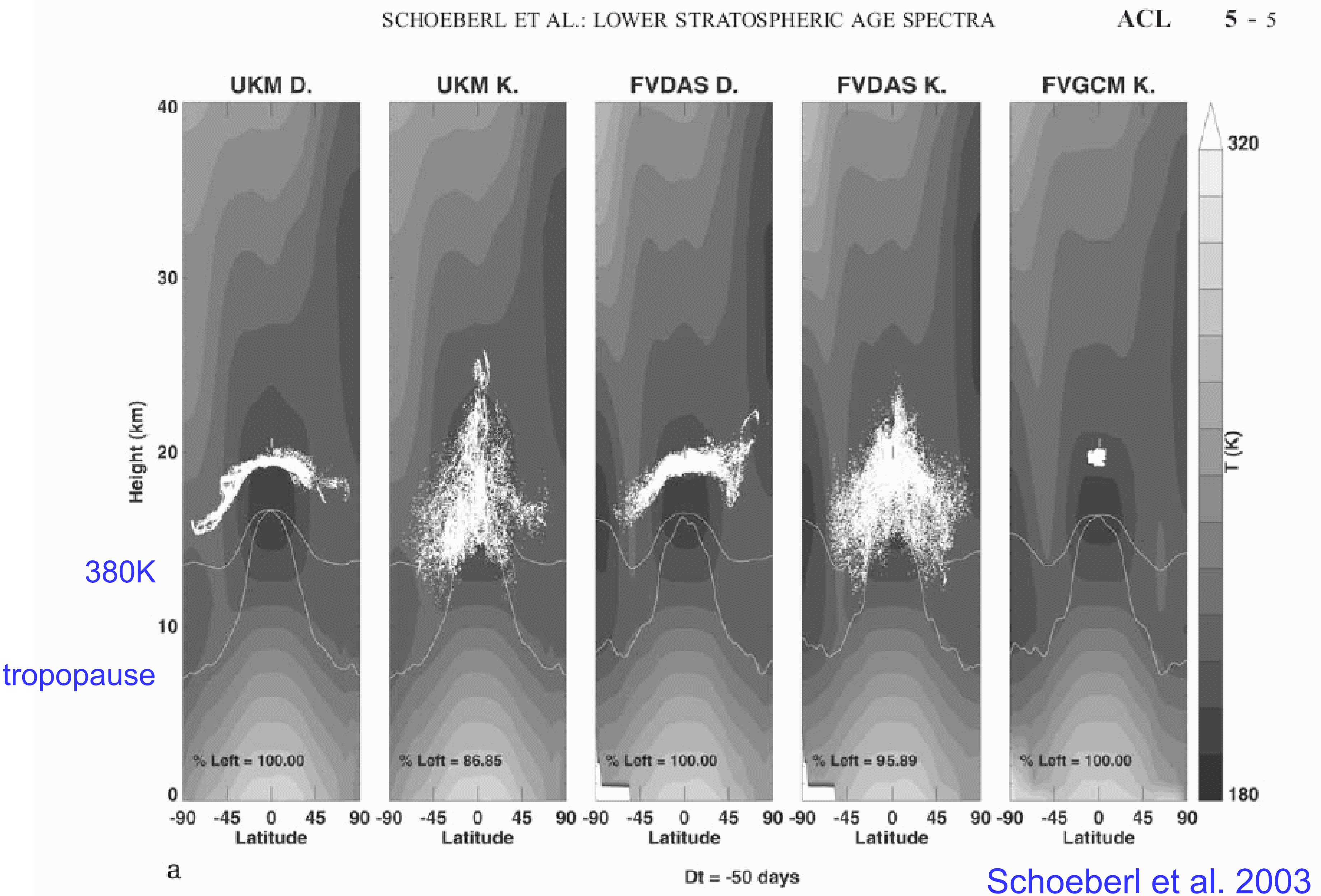


Figure 6. (a) Age of air (years) calculated from an SF-6 simulation using CTM_{FVDAS}. The age calculation converges after 5 years integration. (b) Same as Figure 6a but using CTM_{FVGCM}. The age calculation converges after 9 years integration. The contour interval is 0.2 years; the 2-year contour is bold for both panels.

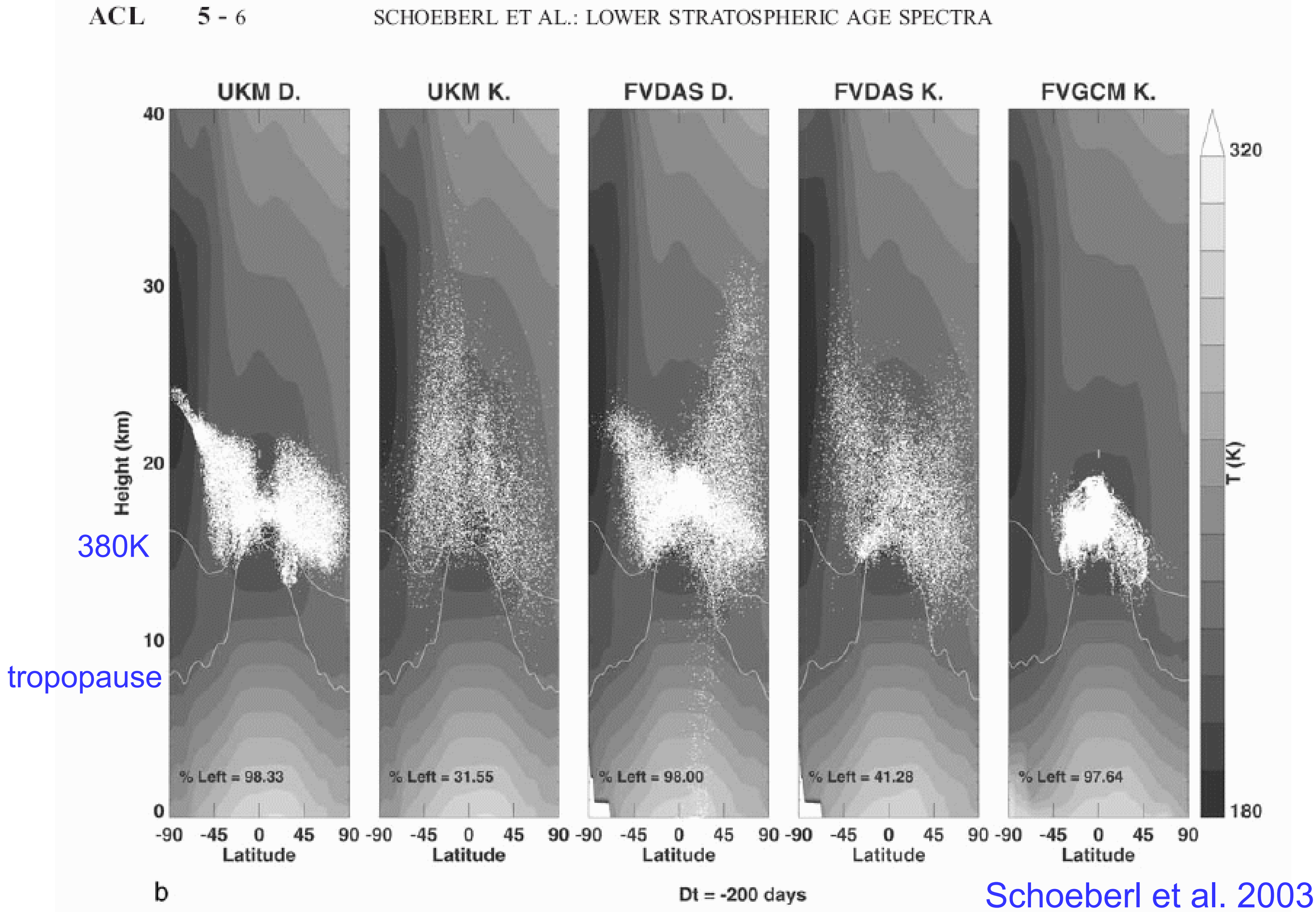
Douglass et al. (2003)

Distribution of parcels 50 days after start of back trajectories



Schoeberl et al. 2003

Distribution of parcels 200 days after start of back trajectories



Schoeberl et al. 2003

The Brewer-Dobson circulation is too fast for CTMs driven by analyses

This results in biases in ozone: too low values at tropics, too high elsewhere

"…current DAS products will not give realistic trace gas distributions for long integrations" – Schoeberl et al. (2003)

Problems with analysed winds:

- Too much vertical motion in tropics
- Vertical motion is noisy
- Horizontal motion is noisy in tropics
- Tropical ascent: obs: 24 mo., GCM: 12 mo., ECMWF: 6 mo.

Differences in wind analyses affect ozone transport

Why do assimilated winds lead to poor transport on long time scales?

- Imbalance due to insertion of data excite spurious gravity waves which creates excessive vertical motion. Weaver et al. (1993)
- Impact of data insertion important when model and obs biases exist. Douglass et al. (2003)
- Assimilation of tropical data leads to spurious PV anomalies (wave activity) and excessive ventilation of tropics. Schoeberl et al. (2003)

3. Balance

Kinetic Energy spectra

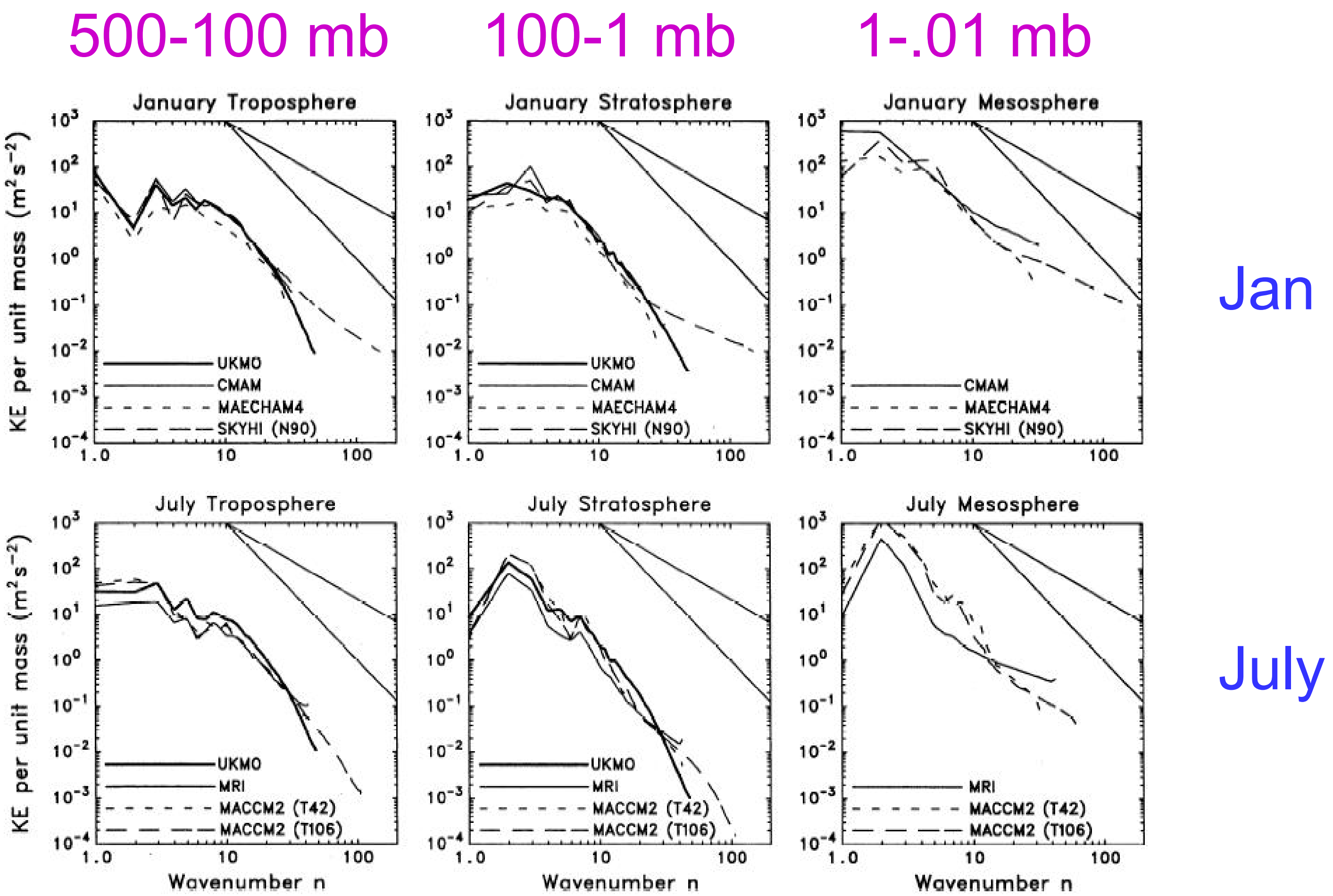


Figure 1. Monthly and vertically averaged kinetic energy (KE) per unit mass versus total horizontal wavenumber for six different middle-atmosphere general circulation models and for U.K. Meteorological Office (UKMO) assimilated data. The horizontal resolution of each model is given in Table 1. The vertical averages are taken over the following levels: troposphere, 500-100 mbar; stratosphere, 100-1 mbar; mesosphere, 1-.01 mbar. Straight lines in the top right-hand corner of each panel have slopes of -3 and -5/3. Models for which January/July data are available are represented in the top/bottom rows.

Koshyk et al. (1999)

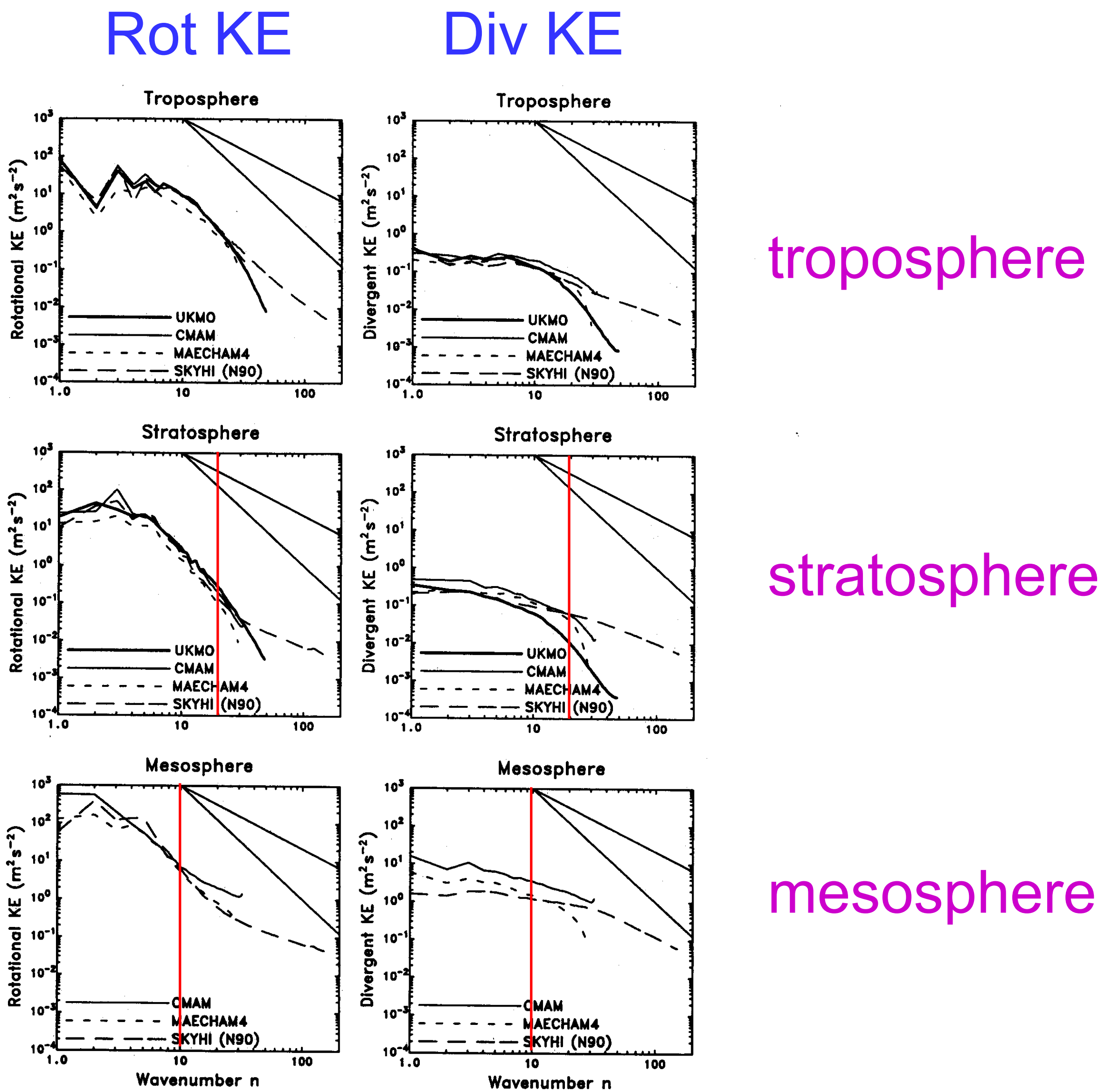


Figure 4. Rotational and divergent parts of the monthly mean kinetic energy per unit mass versus total horizontal wavenumber for January data from the UKMO assimilation, CMAM, MAECHAM4, and SKYHI (N90) models. The curves represent vertically averaged values over the troposphere (top), stratosphere (middle), and mesosphere (bottom), as described in Figure 1.

Koshyk et al. (1999)

Gravity waves are important in the mesosphere

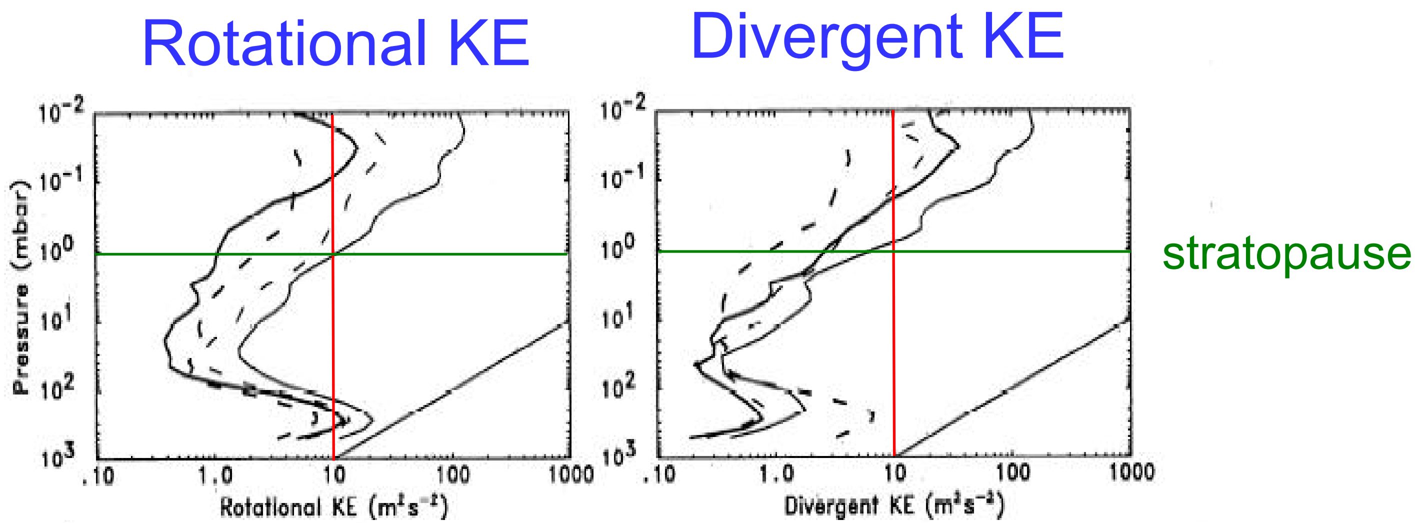


Figure 6. Rotational (left) and divergent (right) parts of the kinetic energy per unit mass as functions of pressure. Values at each pressure level are obtained by summing the spectrum over the wavenumber range $15 \leq n \leq 30$. The curves correspond to the models as follows: CMAM, January (thin solid line); MAECHAM4, January (thin dashed); MRI, July (thick solid line); MACCM2 T42, July (thick dashed). The straight line in the bottom right-hand corner of each panel has a slope of +1.

Koshyk et al. (1999)

Zonal wind

contours:
20 m/s (pos)
10 m/s (neg)

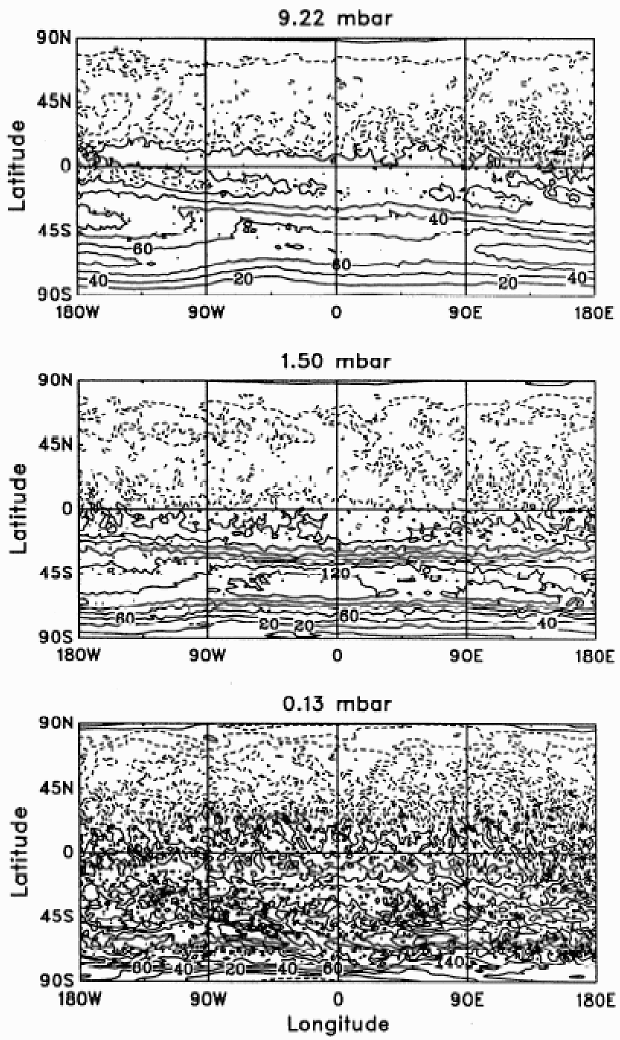


Figure 10. Zonal wind field on three different SKYHI (N90) model levels for a single snapshot in July: 9.22 mbar (top), 1.50 mbar (middle), and 0.13 mbar (bottom). Contour interval = 20 m/s for positive-valued contours and 10 m/s for negative-valued contours.

Lower stratosphere

stratopause

mesosphere

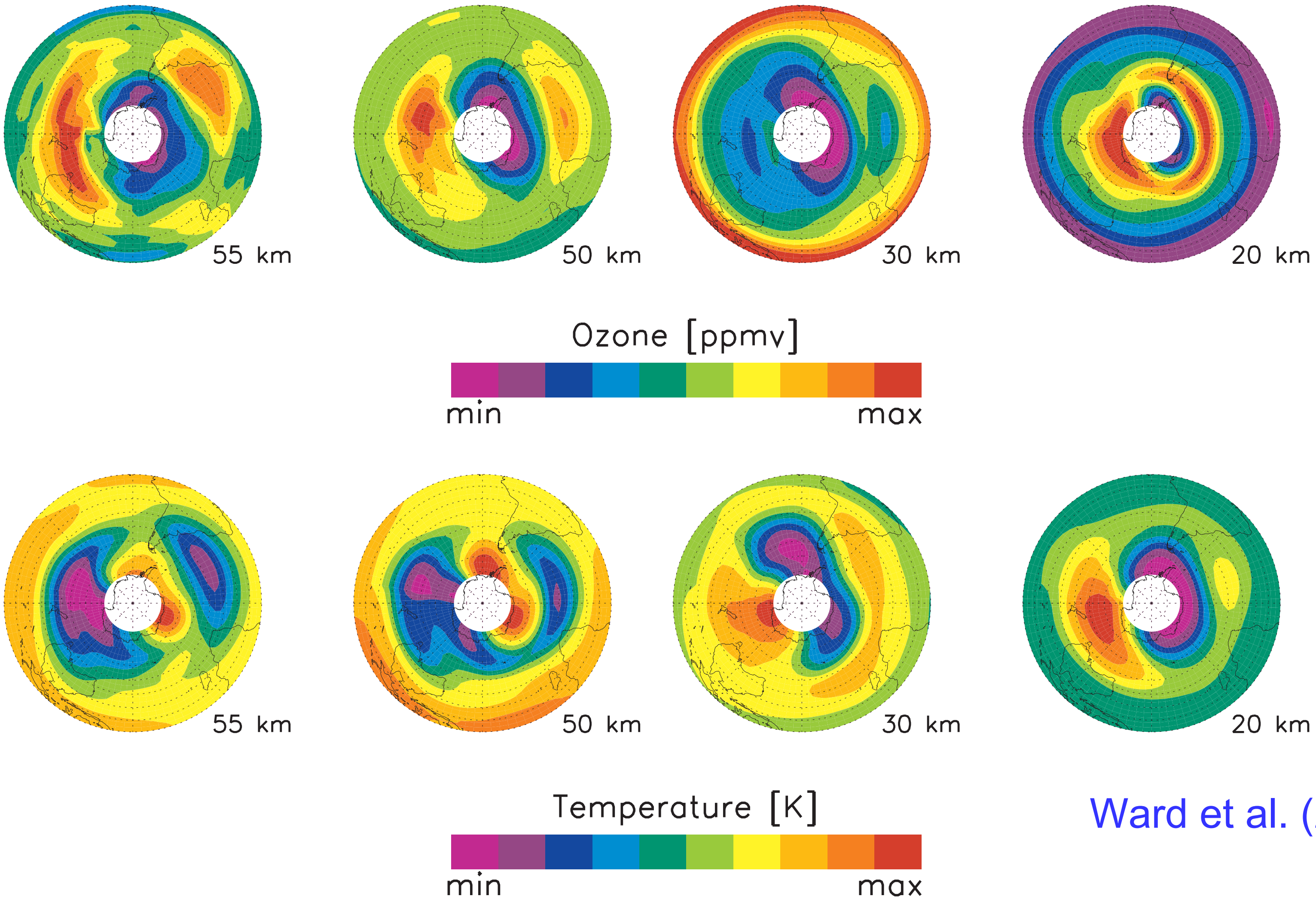
Koshyk et al. (1999)

Balance issues

- Tropics: no wind obs, no balance imposed.
- The stratosphere is dominated by large scales, rotational motion but the mesosphere has a shallow KE spectrum and divergent motions are important. Choice of analysis variables as departures from linear balance helps reduce cross correlations in B matrix. This choice works for the stratosphere. Will it work for the mesosphere?
- enforcing balance in B matrix in presence of bias → spurious wind incr.

4. Coupling chemical and dynamical variables

Ozone temperature correlations



Ward et al. (2003)

What can be gained using T-O_3 correlations in B matrix?

Issues in Middle Atmosphere Data Assimilation

- Separating model and observation biases
- Getting the correct Brewer-Dobson circulation
- Identifying simple dynamical balance for use in forecast error covariances, or in choosing analysis variables
- Coupling chemical-dynamical variables

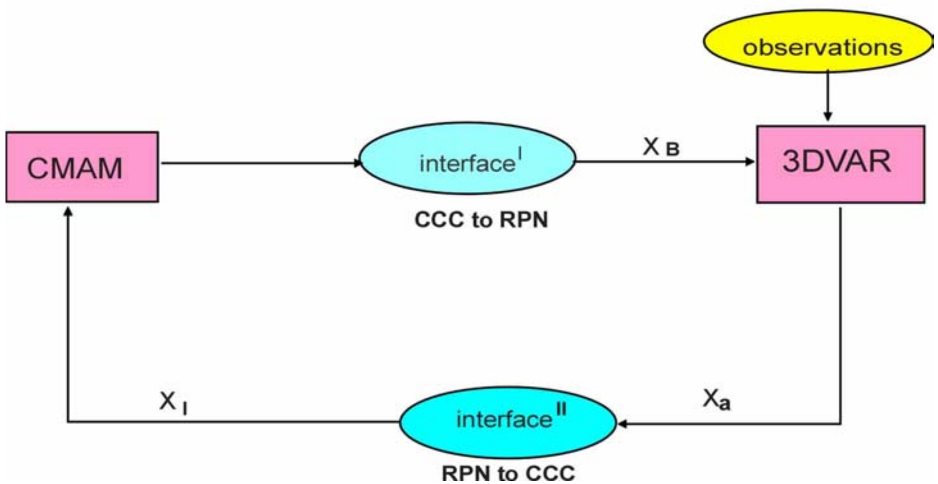
Extra slides

CMAM in data assimilation mode

- added digital filter (Nils Ek). Humidity not filtered.
- changed output of chemistry fields
- no moisture conservation
- changed QHYB def'n: $q_0 = 0.02$ (0.01)

$$QHYB = \begin{cases} q & \text{if } q \geq q_0 \\ \dfrac{q_0}{1 + \ln\left(\dfrac{q_0}{q}\right)} & \text{if } q < q_0 \end{cases}$$

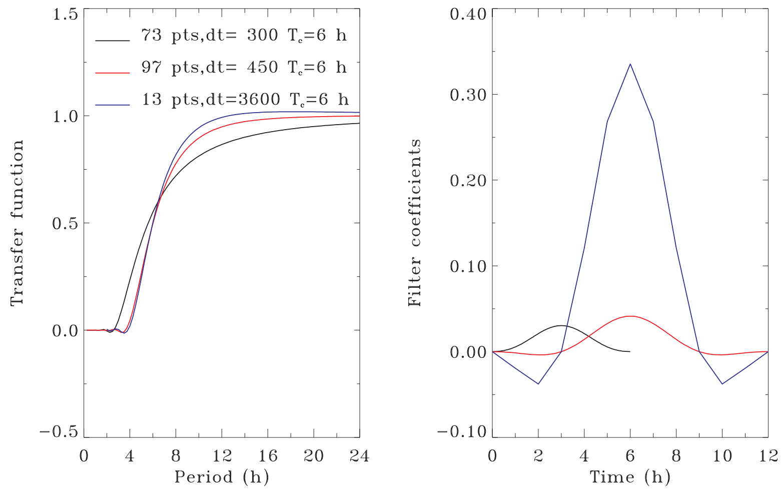
The Structure of the CMAM+3DVAR system



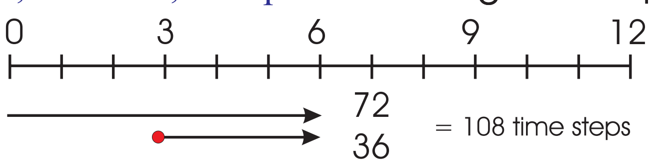
- use absolute compiled in CCC env't copied to RPN env't
- interfaces between RPN and CCC files needed

Digital Filter

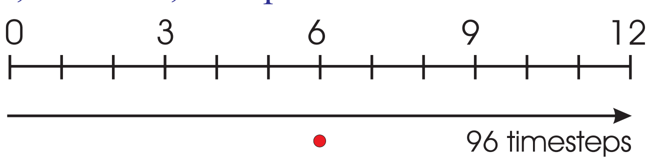
- original 6-h span changed to 12-h
- likely detrimentally to mesospheric dynamics: tides
- intend to replace with IDF, IAU or new idea (SR)



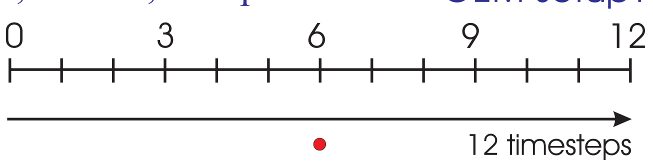
1) N=73, Δt=300 s, DF span = 6 h Original setup



2) N=97, Δt=450 s, DF span = 12 h Current setup



3) N=13, Δt=1 hr, DF span = 12 h GEM setup?



CMAM-DA System
current status

- Assimilation of tropospheric and lower stratospheric dynamic variables. Comparison against sondes, Met Office analyses good. (Polavarapu *et al*. 2004, *submitted to Atm.-Ocean*)

- Upgrades to CMAM8 T47L71 on new IBM, AMSU bias correction, new IAU scheme in progress.

- Plan to run for 2002-3(4?) with dynamic variable assimilation, produce CMAM-DAS species profiles for
  - spring 2002 for Arctic
  - Vanscoy during Aug-Sept 2002 for MANTRA
  - Toronto Atmospheric Observatory in 2002

- Chemical data assimilation (ozone so far) under development (Yang *et al*. poster) with GOME, TOMS, SBUV, OSIRIS. Validation to use Brewers, ozone sondes, ACE, MAESTRO

CMAM-DA research

- Established a theoretical link between IDF and IAU, two methods of initializing fast waves to prevent imbalance in forecasts. (Polavarapu *et al*. 2004, MWR).
- Vertical info transfer through static background error covariances can lead to problems in mesosphere. (Polavarapu SPARC presentation)
- New general method to spread influence of column observations according to physical knowledge. (Rochon *et al*. in preparation)
- New method of initializing fast waves to prevent imbalance in forecast (Ren *et al*.)
- Exploration of tropical balance and how to use it in data assimilation (with Reszka, Shepherd, U of Toronto)
- Comparison with MIMOSA to diagnose model chemistry error (Sankey *et al*.)

CMAM-DA plans

- Run CMAM dynamical assimilation (with full stratospheric chemistry) for 2002-3. (2004-5)
- Validate mesospheric fields with possibly NCAR (TIMED) and ground-based data. (2004-5)
- Develop chemical data assimilation, including OSIRIS (and possibly ACE) satellite instruments. Validate stratospheric analyses with ground-based and satellite data. (2004-7).
- Continue scientific support for Canadian balloon- and space-based measurement programs including MANTRA, OSIRIS, ACE, MAESTRO, SWIFT, GWIM and WaMI. (2004-7)
- Extend CMAM-DA chemistry scheme into the troposphere. (2004-6)
- Extend CMAM dynamical assimilation to the mesosphere. (2005-7)

Background Error Covariance Matrix

$$\mathbf{B}_{\text{climate}} = \left\langle \left(\mathbf{x}_T - \langle \mathbf{x}_T \rangle\right)\left(\mathbf{x}_T - \langle \mathbf{x}_T \rangle\right)^{\mathrm{T}} \right\rangle$$

$$\mathbf{B}_{\text{dif6h}} = \left\langle \left(\mathbf{x}_{T+6} - \mathbf{x}_T - \langle \mathbf{x}_{T+6} - \mathbf{x}_T \rangle\right)\left(\mathbf{x}_{T+6} - \mathbf{x}_T - \langle \mathbf{x}_{T+6} - \mathbf{x}_T \rangle\right)^{\mathrm{T}} \right\rangle$$

- Use climate run results: Output every 6 hours. 1-month of data sufficient for stats of each month.

- 6-hr differences instead of 24-hr lagged forecast differences.

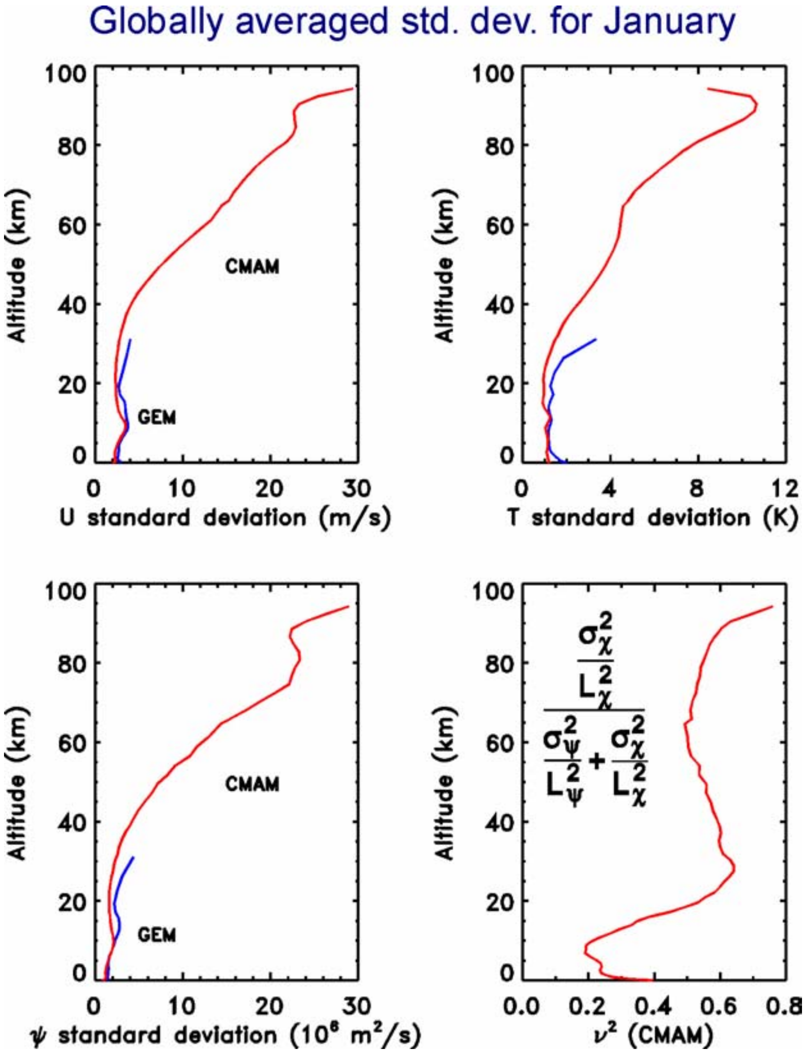
$$x(t+6) - x(t) - \overline{x(t+6) - x(t)}, \quad t=0, 6, 12, 18$$

- Same analysis variables as GEM.

- Same method of calc as GEM (but done with indep. code)

- O-P adjustment scaled to match GEM values in troposphere. Values in mesosphere reduced as a result.

CMAM Background Error Statistics



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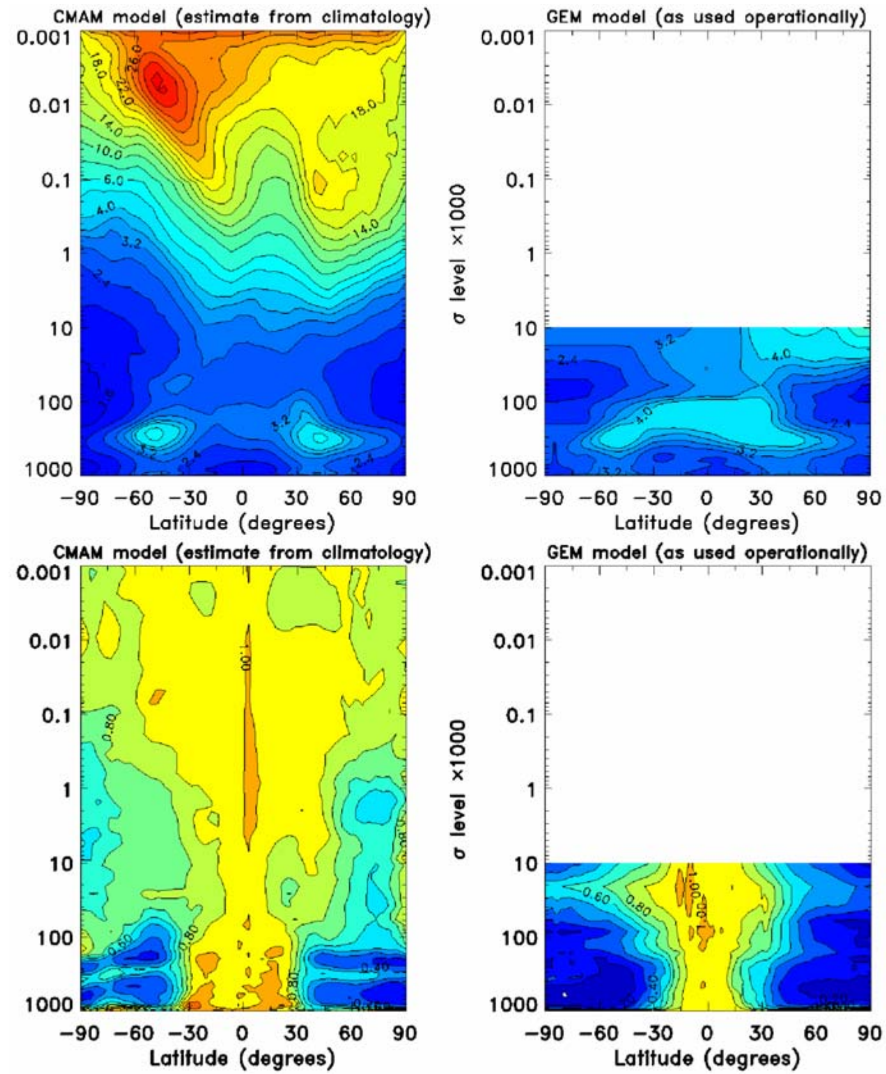
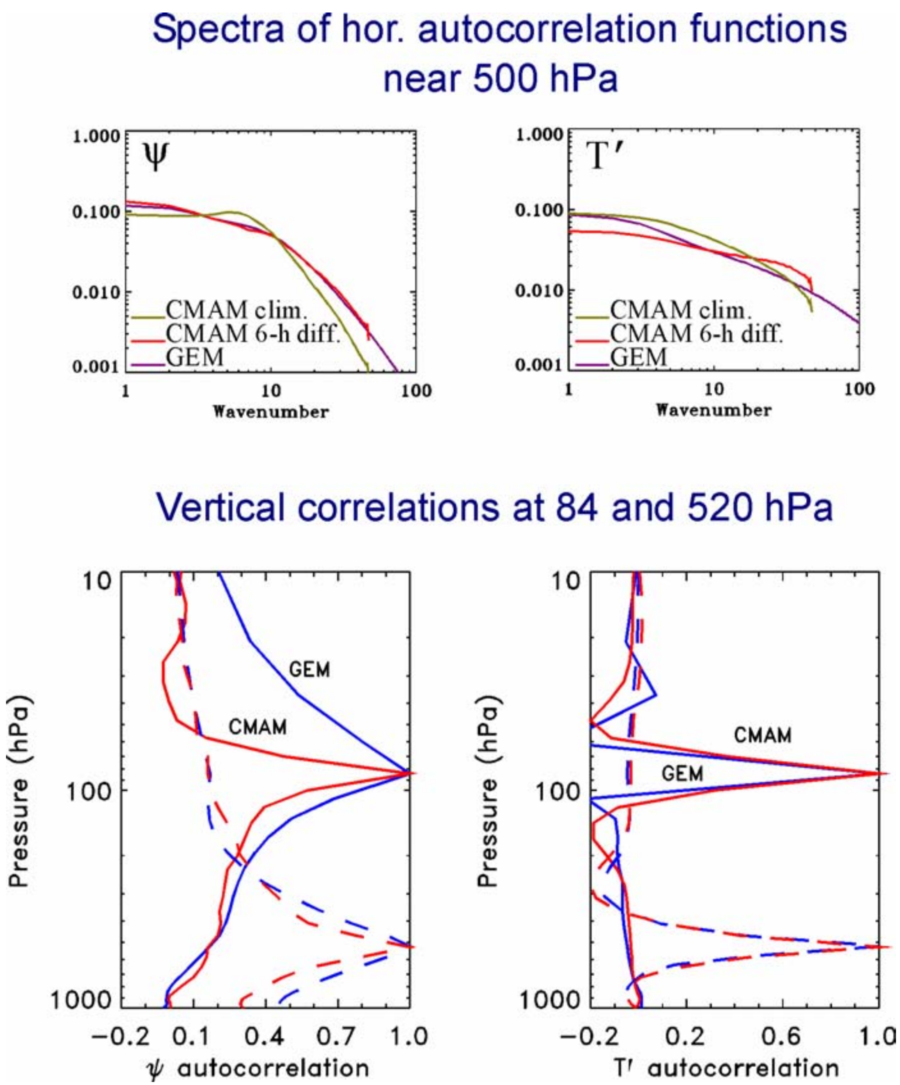
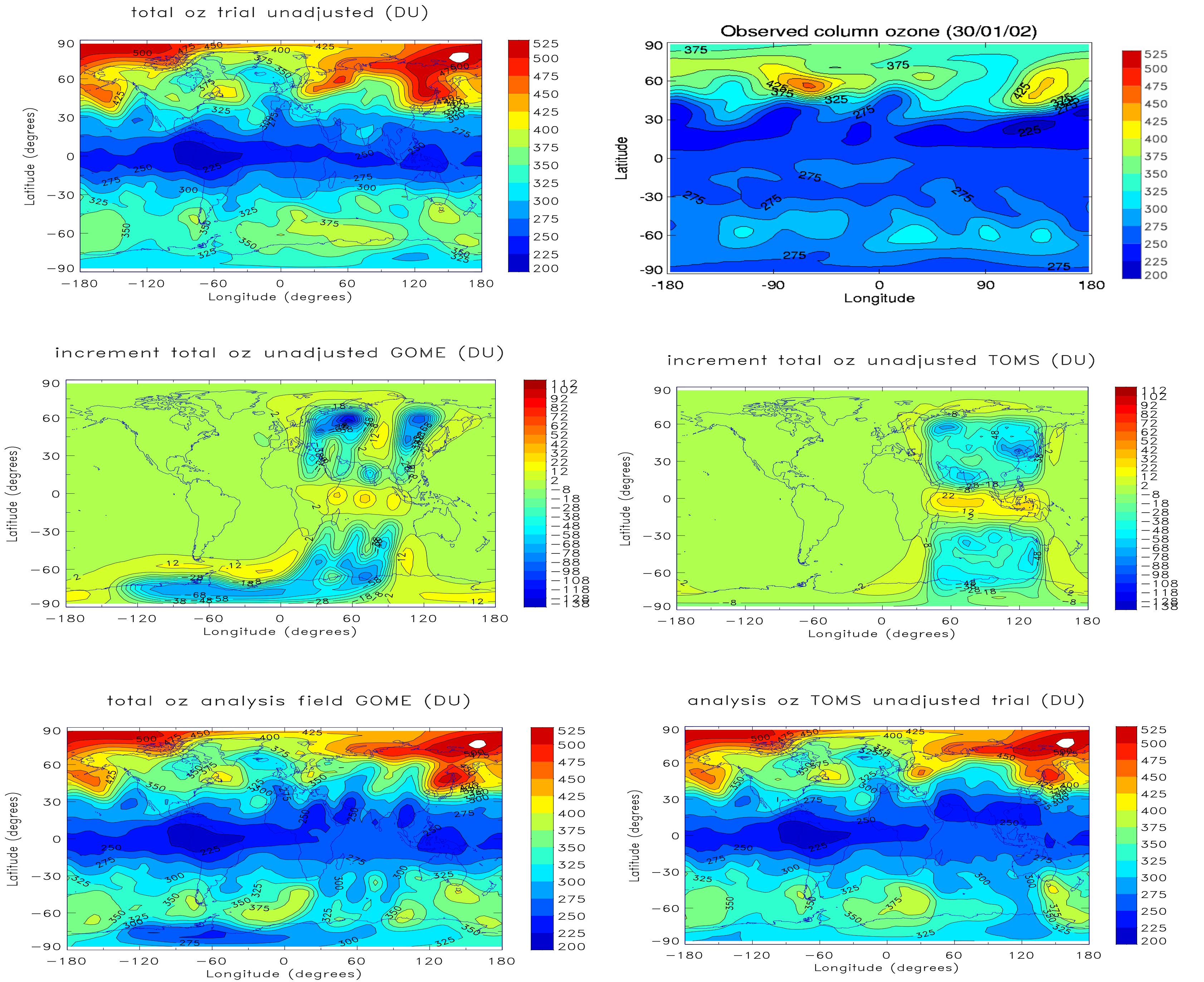


T'/T T'/T

CMAM Background Error Statistics




total oz trial unadjusted (DU)
Latitude (degrees)
Longitude (degrees)
Observed column ozone (30/01/02)
Latitude
Longitude
increment total oz unadjusted GOME (DU)
Latitude (degrees)
Longitude (degrees)
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