Balance issues from the climate perspective

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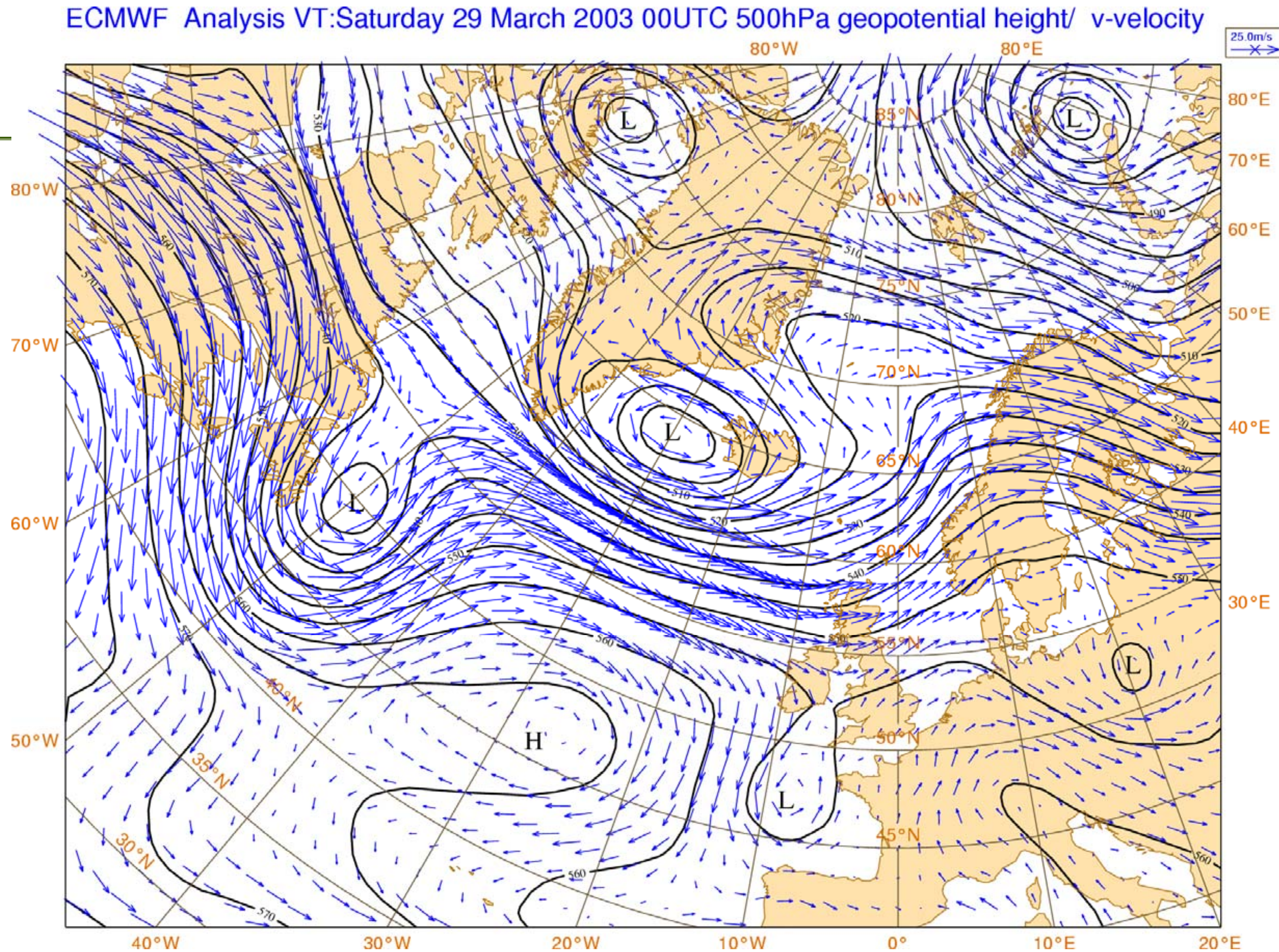
Topics

- Balance in the tropospheric midlatitudes
- The stratosphere and mesosphere
- Balance issues from the climate perspective
  - Gravity waves are part of the signal in the middle atmosphere (How to separate spurious and real GWs?)
  - Initialization of GWs in troposphere impacts mesopause temperatures and tides
  - Noisy wind analyses impact tracer transport
  - Can we use DA to estimate GW drag?

Balance in the tropospheric midlatitudes

Approximate mass-wind balance in mid-troposphere extra-tropics



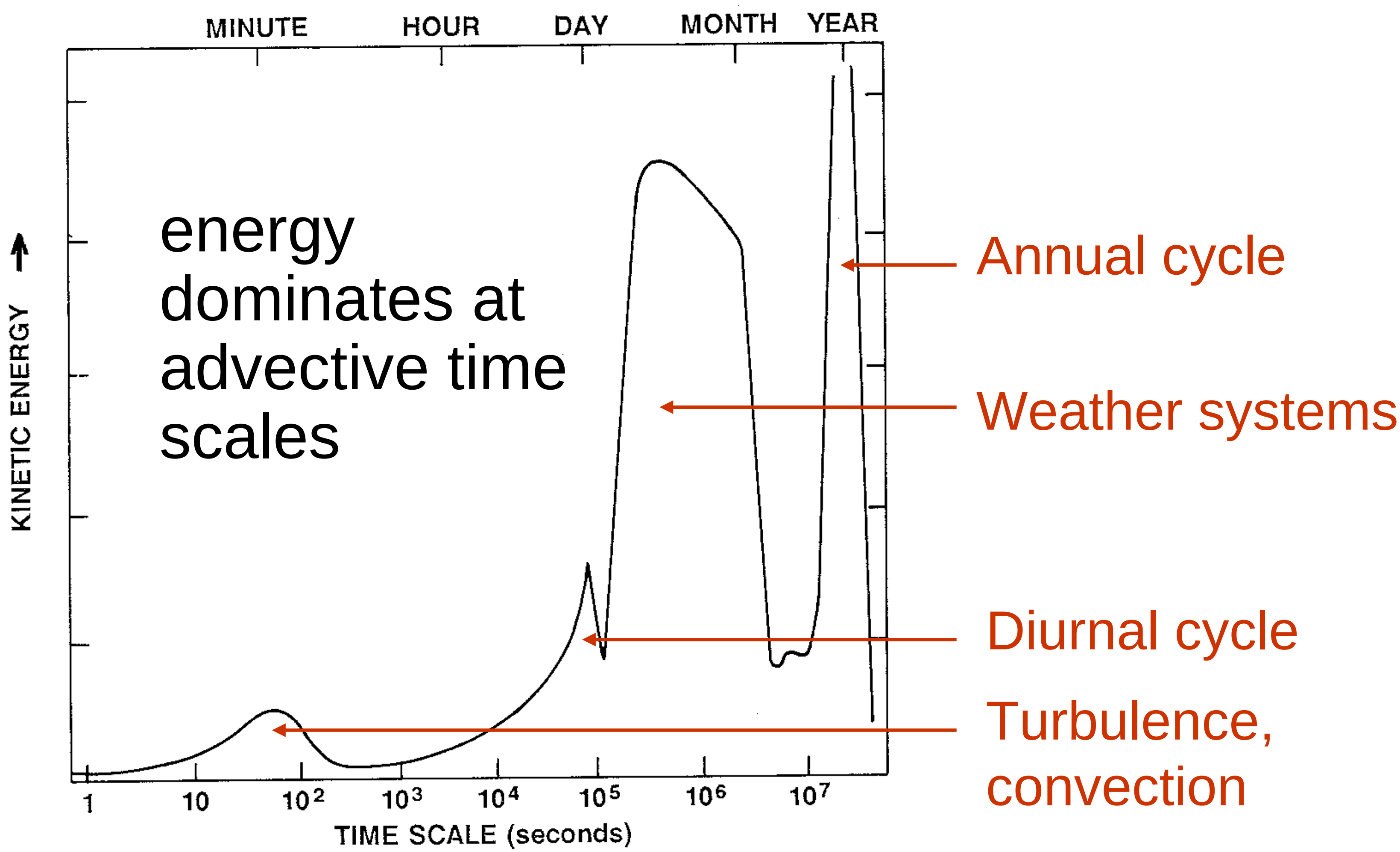
Lars Isaksen (2007)

http://www.ecmwf.int/newsevents/training/meteorological_presentations/MET_DA.html

Why is the midlatitude troposphere largely balanced?

- There are two main timescales: advective and inertial
- Ro = inertial/advective timescale (Rossby number)
- In the midlatitude troposphere, the advective timescale is much longer than inertial timescale (Ro is small)
- Rotational modes governed by advective timescales
- Gravity modes are faster than inertial timescales
- Observations show energy dominates at advective time scales

Temporal spectrum of atmospheric kinetic energy



Vinnichenko (1970) Fig from Daley (1991)

Why is the midlatitude troposphere largely balanced?

- Forcing of weather systems (rotational modes) largely driven by differential solar heating. The solar forcing is on much longer timescales than inertial timescale so forcing of gravity waves is weak.
- Atmosphere is also mainly unstable to slow rotational motions than to fast gravity wave type motions.
- Rotational modes relatively stable to gravity waves (Errico 1981)
- There is enough dissipation to keep small amount of imbalance from growing

However

- Below synoptic scales (mesoscale), gravity waves become more important as advective timescale gets shorter
- In the mesosphere, energy in gravity waves becomes large since vertically propagating waves increase in amplitude as density decreases (and rotational waves reach critical levels at lower heights)
- In the tropics, inertial timescale gets long. No unified theory of balance. Diabatic forcing is important.

Balance in data assimilation

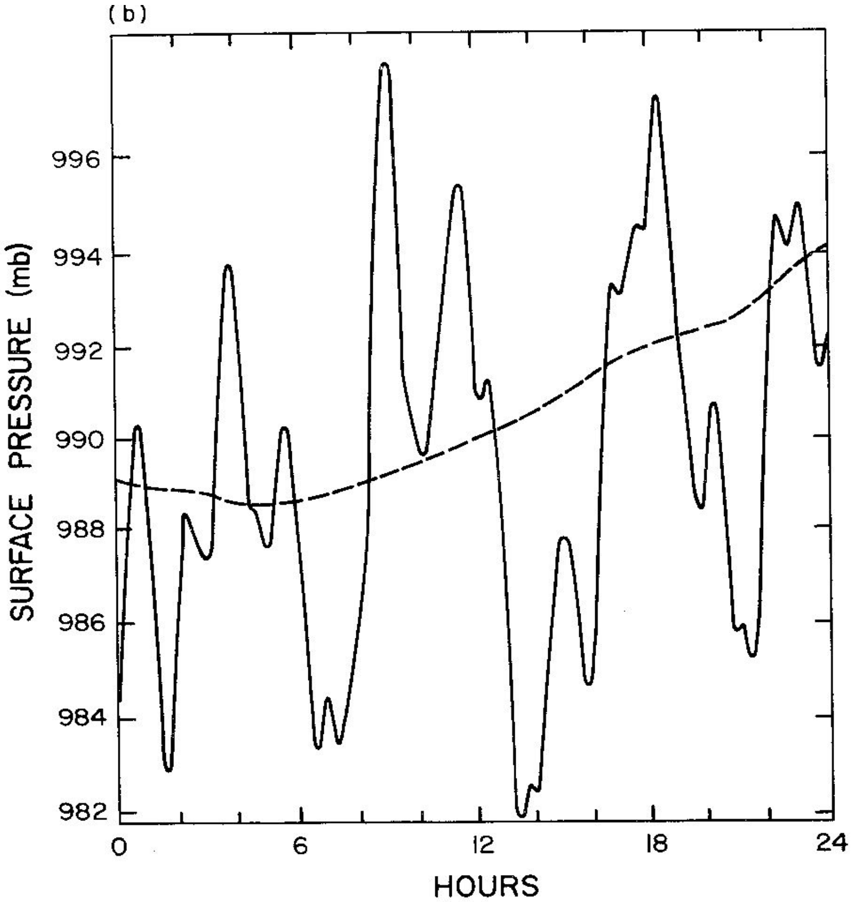


Figure 10.1 Time evolution of surface pressure during a 24 hour model integration for (a) linear and (b) nonlinear normal mode initialization. Solid curves, uninitialized; dashed curves, initialized. (After Williamson and Temperton, *Mon. Wea. Rev.* **109**: 745, 1981. The American Meteorological Society.)

Integrating a model from an analysis can lead to high frequency oscillations

Daley 1991

Why are analyses unbalanced?

Holton (1992)

Table 2.1 *Scale Analysis of the Horizontal Momentum Equations*

	A	B	C	D	E	F	G
x-Eq.	$\frac{Du}{Dt}$	$-2\Omega v \sin\phi$	$+2\Omega w \cos\phi$	$+\frac{uw}{a}$	$-\frac{uv\tan\phi}{a}$	$= -\frac{1}{\rho}\frac{\partial p}{\partial x}$	$+F_{rx}$
y-Eq.	$\frac{Dv}{Dt}$	$+2\Omega u \sin\phi$		$+\frac{vw}{a}$	$+\frac{u^2\tan\phi}{a}$	$= -\frac{1}{\rho}\frac{\partial p}{\partial y}$	$+F_{ry}$
Scales	U^2/L	$f_0 U$	$f_0 W$	$\frac{UW}{a}$	$\frac{U^2}{a}$	$\frac{\delta P}{\rho L}$	$\frac{\nu U}{H^2}$
$(\mathrm{m\,s^{-2}})$	10^{-4}	10^{-3}	10^{-6}	10^{-8}	10^{-5}	10^{-3}	10^{-12}

A 10% error in wind obs gives a 100% error in acceleration

U ~ 10 m/s
W ~ 1 cm/s
L ~ 10^6 m
H ~ 10^4 m
$\delta P/\rho \sim 10^3\ \mathrm{m^2/s^{-2}}$
L/U ~ 10^5 s

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Geostrophic Adjustment - 1

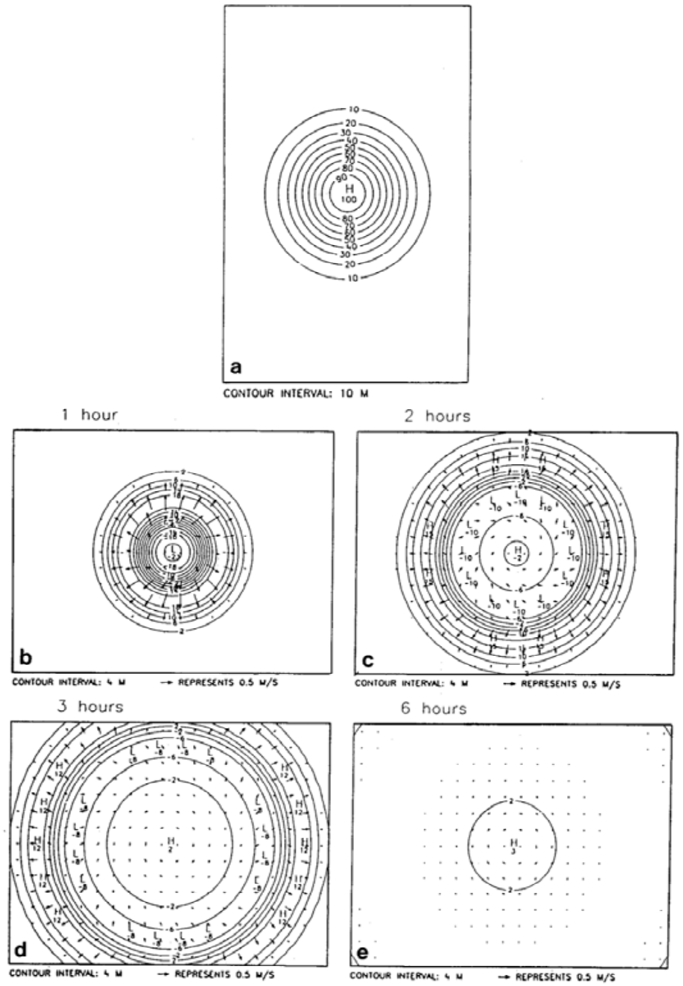
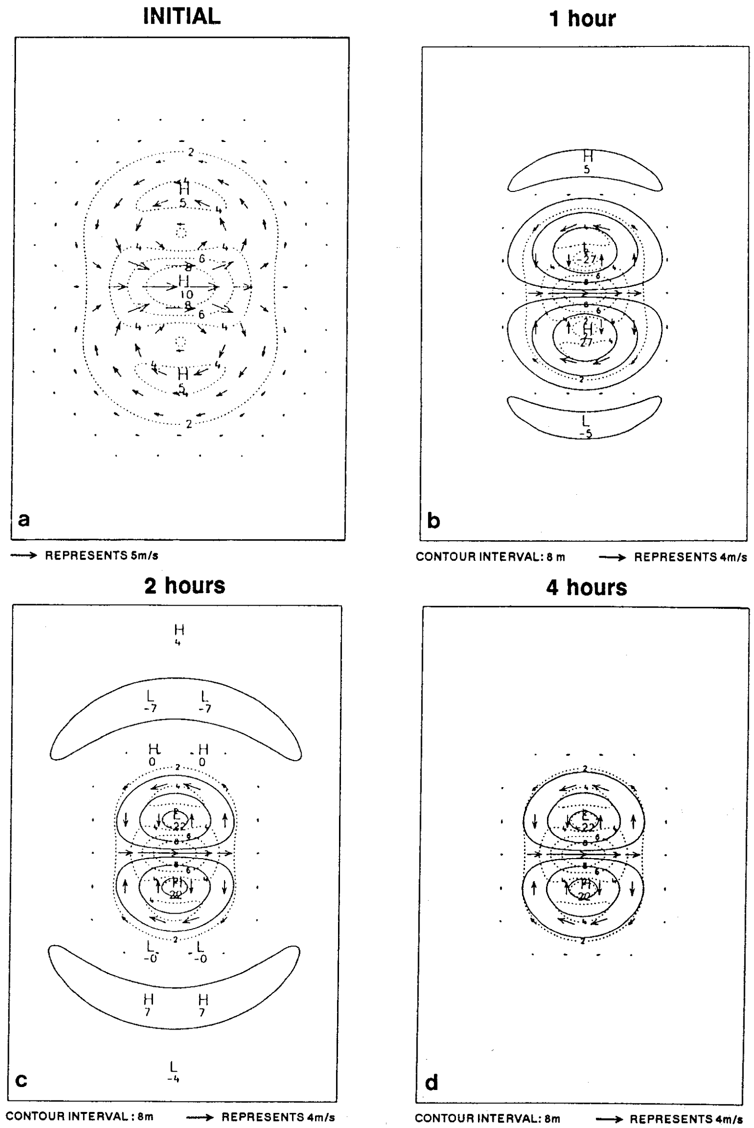


Figure 6.3 (a) Geostrophic adjustment of initial geopotential perturbation. (b–e) Solutions at 1, 2, 3, and 6 hours. Contoured field is geopotential, and wind arrows indicate speed and direction of windfield. (After Barwell and Bromley, 1988)

- Shallow water equations
- f_o for 38.25 degrees
- Localized perturbation in geopotential, zero wind (panel a)
- Large divergent motion after 1 hour
- Mainly small geostrophic perturbation after 6 hours

Daley (1991)

Geostrophic Adjustment - 2



- Shallow water equations
- f_o for 38.25 degrees
- Localized perturbation has zero geopotential, nondivergent wind (panel a)
- Geopotential perturbation is partly balanced, partly due to gravity waves
- Mainly small geostrophic perturbation after 6 hours

Daley (1991)

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Geostrophic adjustment - 3

- Final state (steady) of the perturbation is balanced. It can be obtained from the initial perturbation and the conservation of potential vorticity

$$\hat{\psi}_s = \frac{\hat{\psi}_0 + (L/L_R)\hat{\phi}_0}{1 + (L/L_R)^2}$$

For linearized shallow water eqs
Daley (1991)

- L_R = horizontal scale over which the height field is adjusted during the approach to steady state (Rossby radius of deformation)

- **Case 1**: $L \ll L_R$ (tropics, large vertical scales, small hor scales), Final state related to initial rotational wind field: $\psi_s = \psi_o$

- **Case 2**: $L \gg L_R$ (mid latitudes, small vertical scales, large hor scales), Final state related to initial geopotential field: $\psi_s = \phi_o$

The “initialization” step

- Integrating a model from an analysis leads to motion on fast scales
- Mostly evident in surface pressure tendency, divergence and can affect precipitation forecasts
- 6-h forecasts are used to quality check obs, so if noisy could lead to rejection of good obs or acceptance of bad obs
- Historically, after the analysis step, a separate “initialization” step was done to remove fast motions
- In the 1980’s a sophisticated “initialization” scheme based on Normal modes of the model equations was developed and used operationally with OI.

Nonlinear Normal Mode Initialization (NNMI)

Consider model $$\frac{d\mathbf{x}}{dt} = i\mathbf{A}\mathbf{x} + N(\mathbf{x})$$

Determine modes $$\mathbf{A} = \mathbf{E}\Lambda\mathbf{E}^{\mathrm{T}}$$

Separate R and G $$\mathbf{E} = \left[\mathbf{E}_R \mid \mathbf{E}_G\right]$$

Project onto G $$\mathbf{c}_G = \mathbf{E}_G^{\mathrm{T}}\mathbf{x}, \quad \mathbf{c}_R = \mathbf{E}_R^{\mathrm{T}}\mathbf{x}$$

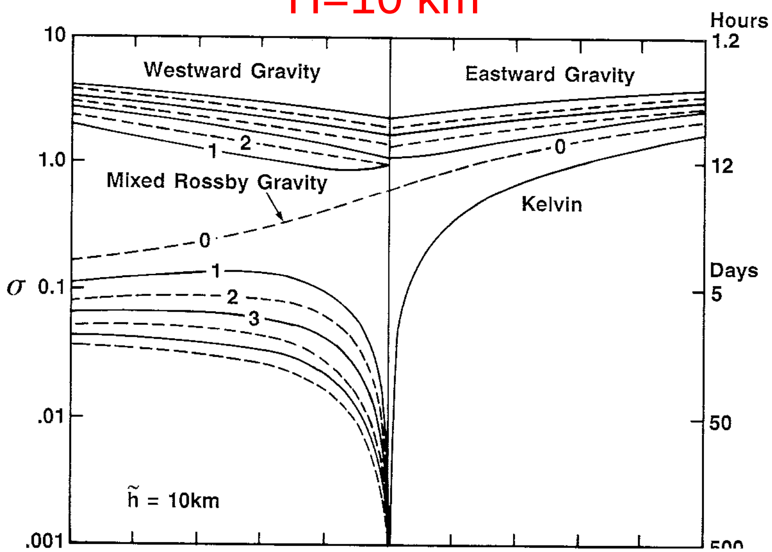
Define balance $$\frac{d\mathbf{c}_G}{dt} = i\Lambda\mathbf{c}_G + \mathbf{E}_G^{\mathrm{T}}N(\mathbf{E}_G\mathbf{c}_G, \mathbf{E}_R\mathbf{c}_R) = 0$$

Solution $$\mathbf{c}_G = i\Lambda^{-1}\mathbf{E}_G^{\mathrm{T}}N(\mathbf{E}_G\mathbf{c}_G, \mathbf{E}_R\mathbf{c}_R)$$

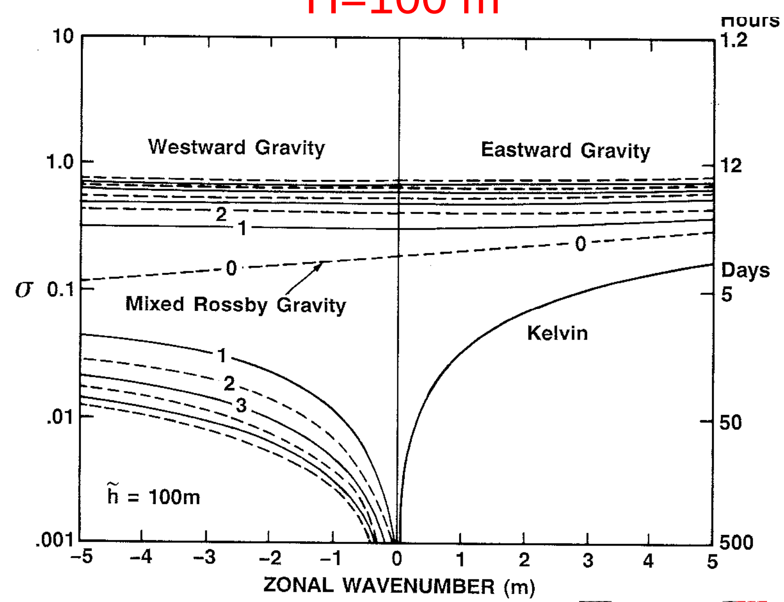
Equations support many free modes

- Normal mode frequencies on a sphere (primitive eq.)
- No frequency gap between fast and slow modes
- For small equivalent depths, gravity wave frequency is smaller

H=10 km



H=100 m



Daley (1991)

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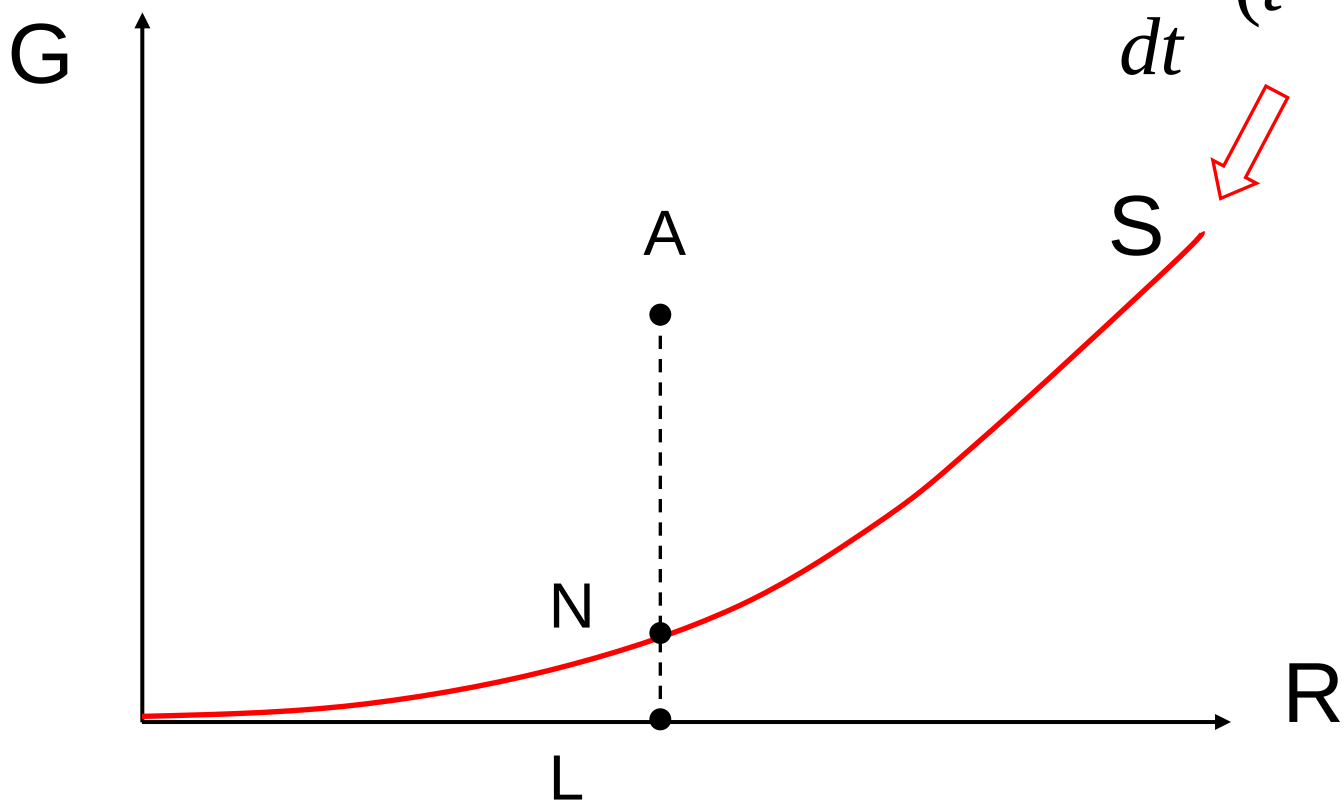
The slow manifold

$$\frac{d\mathbf{c}_{\mathbf{G}}}{dt}(t=0)=0$$



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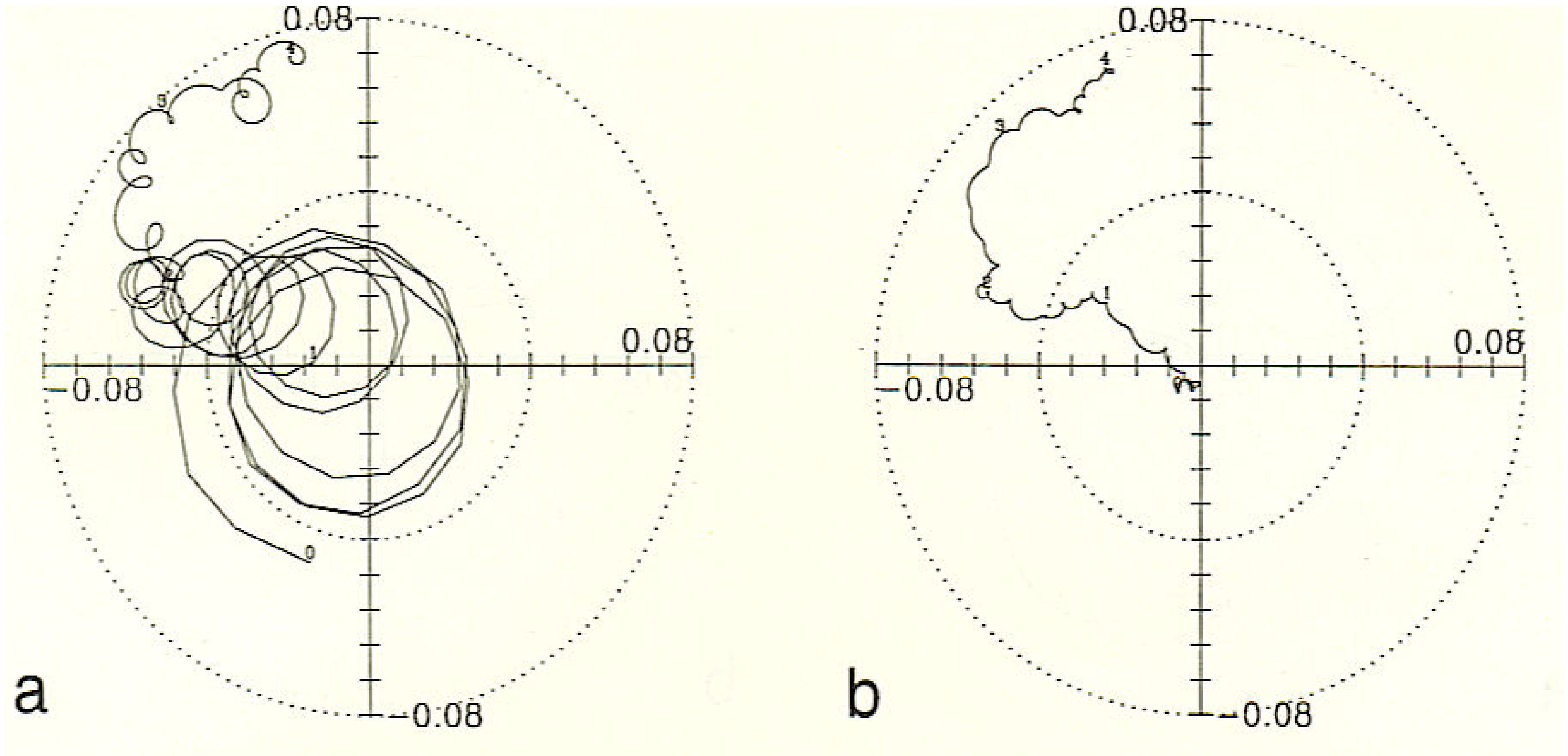
NNMI keeps slow motions

Harmonic Dial for External m=4 Mode, Period=3.7h

Without NNMI | With NNMI



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Errico 1997

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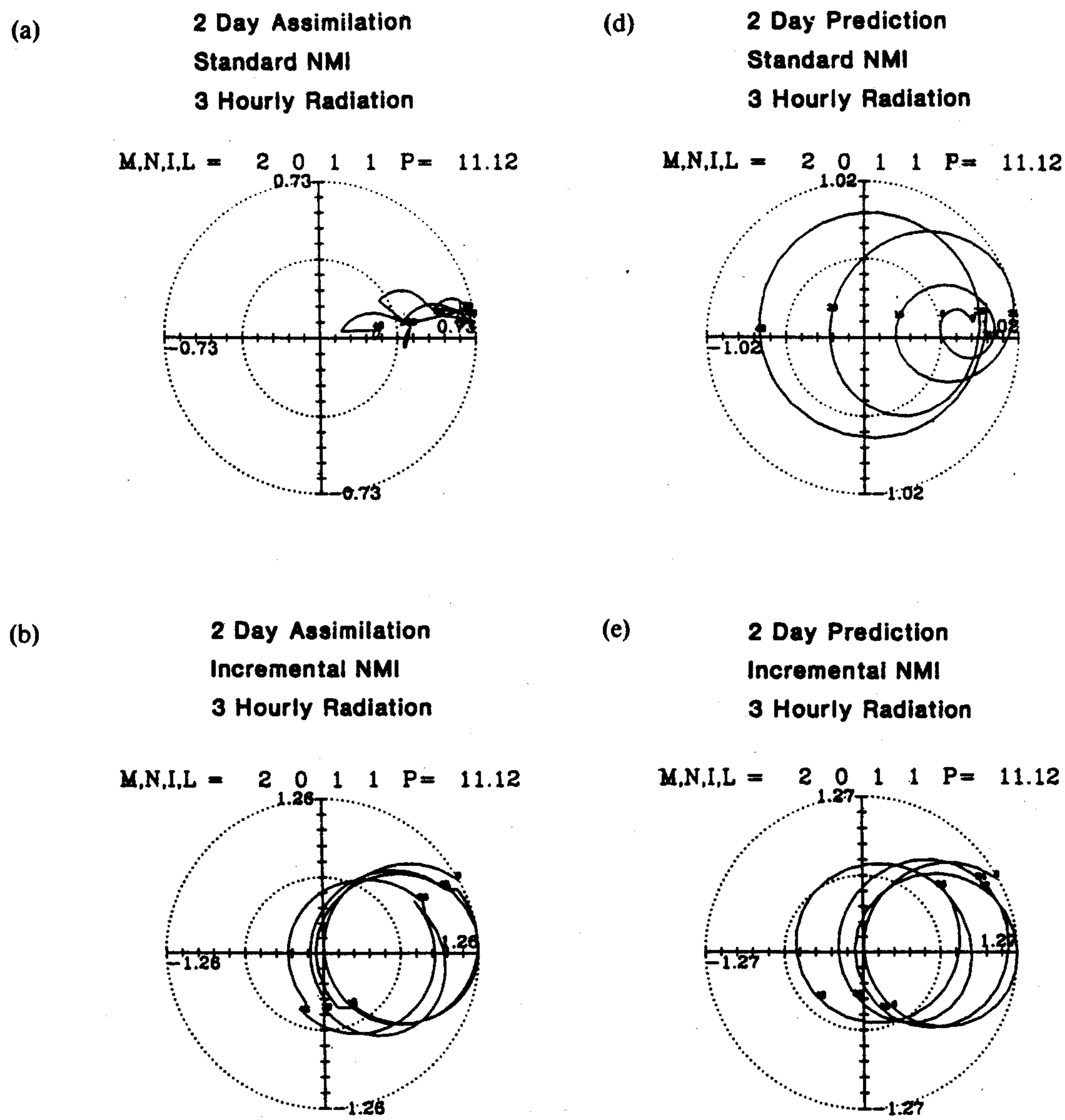
Fig. 6 Harmonic dials showing the trajectory of the semi-diurnal mode in the experiments (a) to (f) detailed in the text.



Some signals in the forecast e.g. tides should NOT be destroyed by NNMI!

So filter analysis increments only

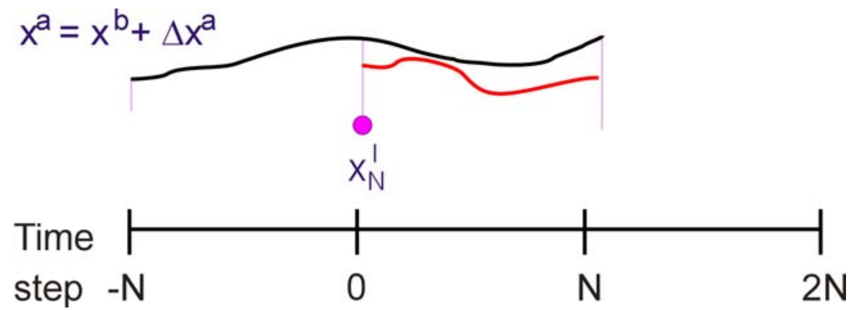
Semi-diurnal mode has amplitude seen in free model run, if anl increments are filtered

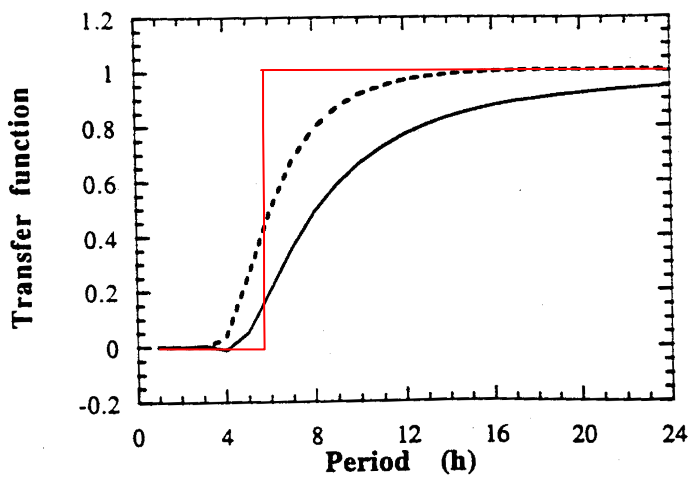
Seaman et al. (1995)

Digital Filter Initialization

Lynch and Huang (1992)

$$\boxed{x_0^I = \sum_{k=-N}^{N} h_k x_k^u}$$





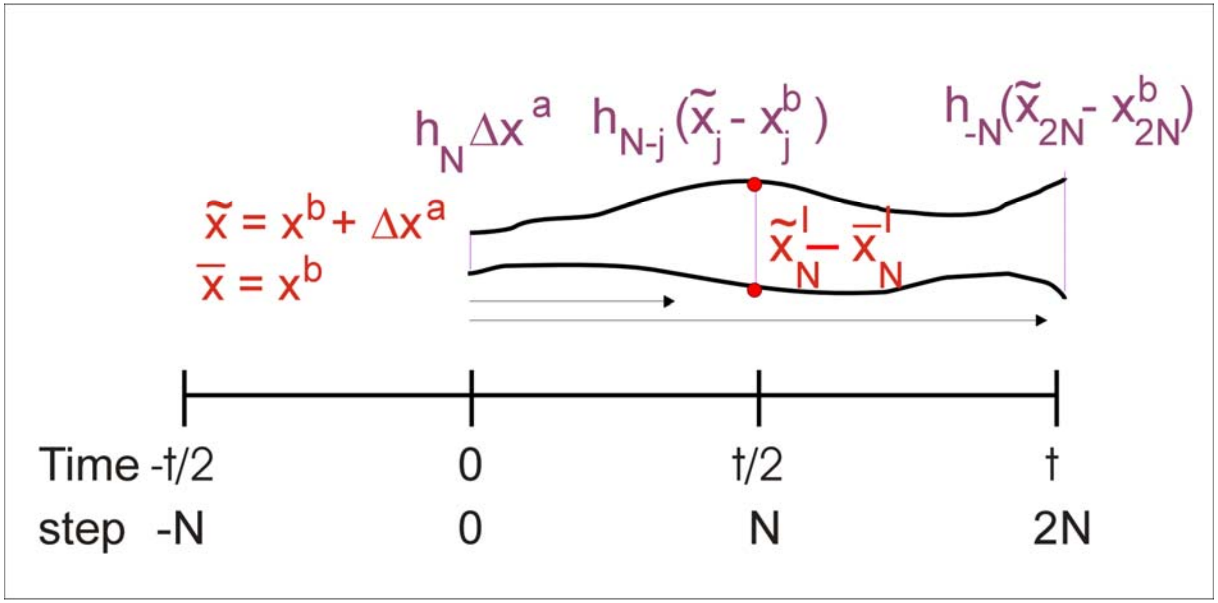
T_c=6 h

T_c=8 h

N=12, Δt=30 min

Fillion et al. (1995)

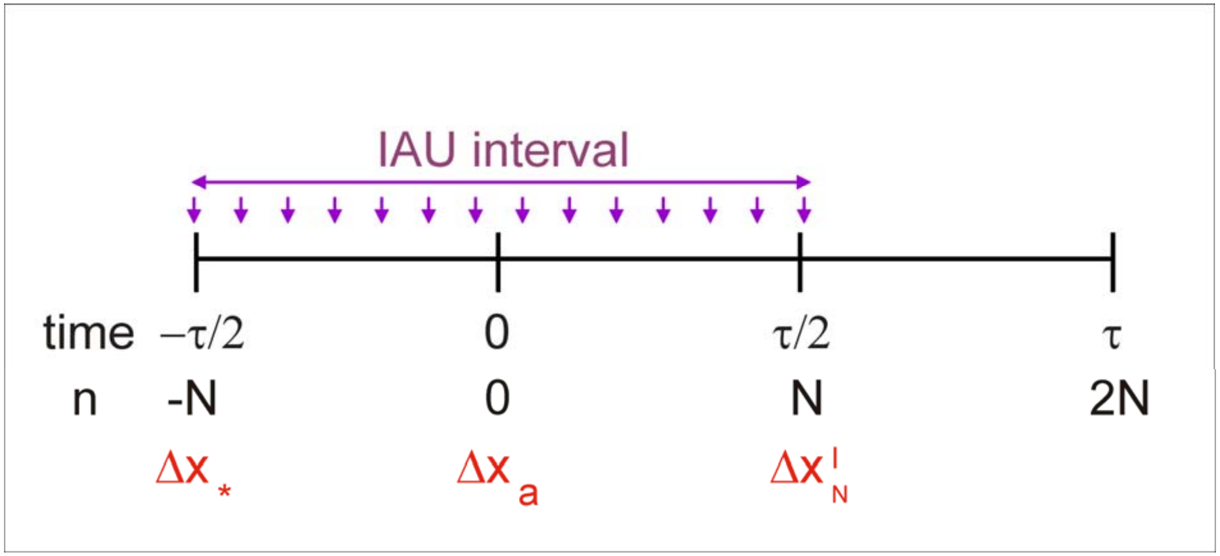
Incremental Digital Filter (IDF)



$$\mathbf{x}_N^I = \mathbf{x}_N^b + \left(\tilde{\mathbf{x}}_N^I - \bar{\mathbf{x}}_N^I\right)$$

- IDF is a digital filtering of analysis increments
- Need to keep diurnal, tidal signals in background (Ballish 1982)

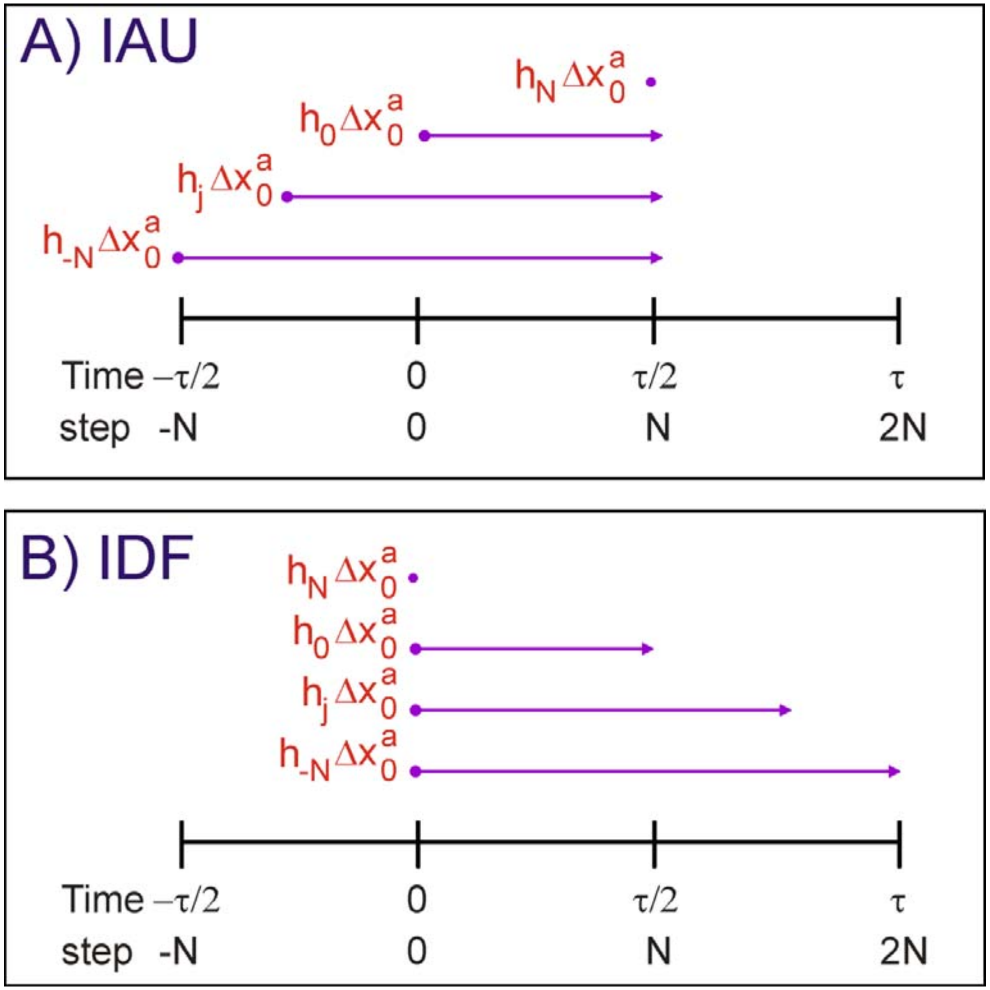
Incremental Analysis Updates (IAU)



$$\mathbf{x}_{n+1} = M_n(\mathbf{x}_n) + g_{n+1}\Delta\mathbf{x}_a$$

- Introduced by Bloom et al. (1996, MWR)
- IAU allows slow insertion of a fraction of analysis increment so model can adjust nonlinearly to shock

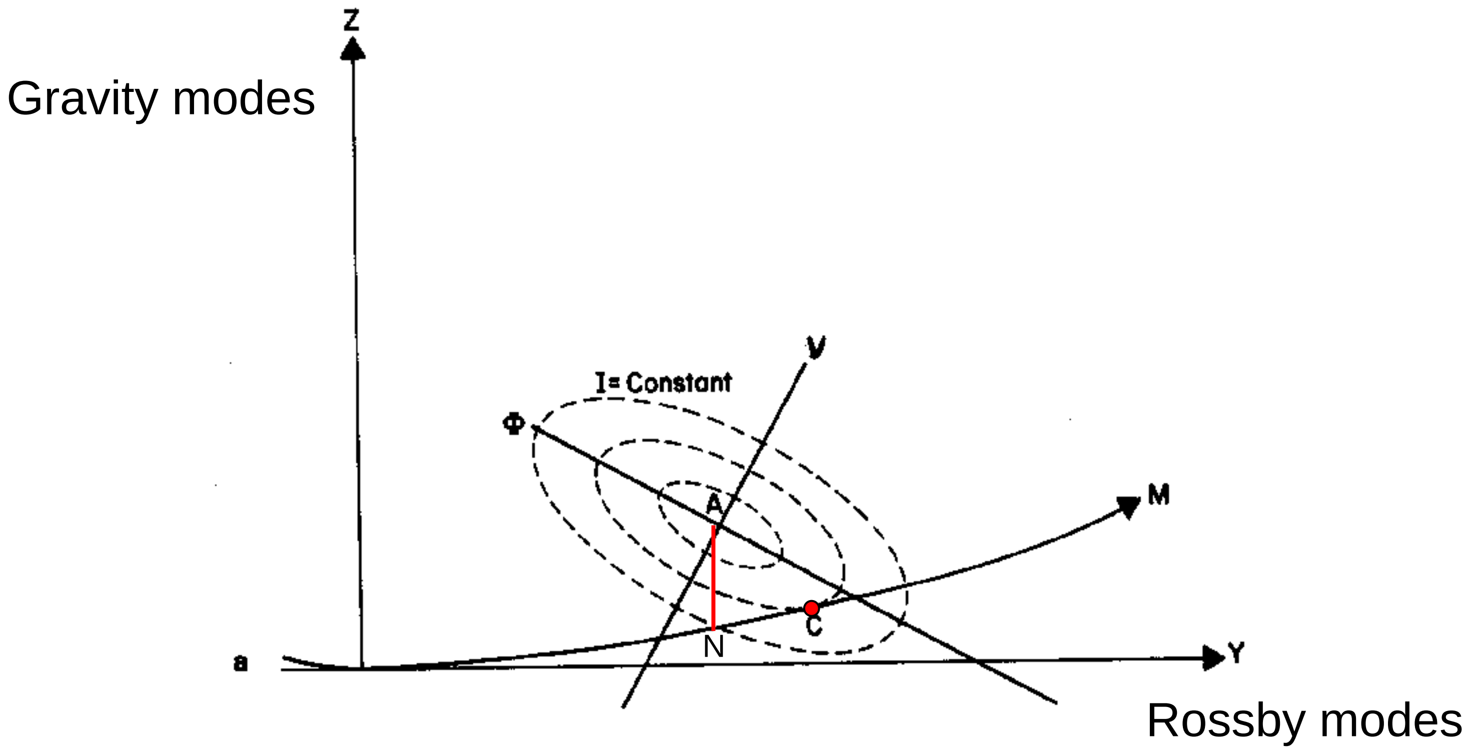
IDF and IAU



- For linear models, the IAU and IDF response functions are identical if same h_j's used (Polavarapu et al. 2004)
- Even a nonlinear chemistry climate model shows approximate equivalence of IDF and IAU (Sankey et al. 2007)

Combining Analysis and Initialization steps

- Doing an analysis brings you closer to the data.
- Doing an initialization moves you farther from the data.



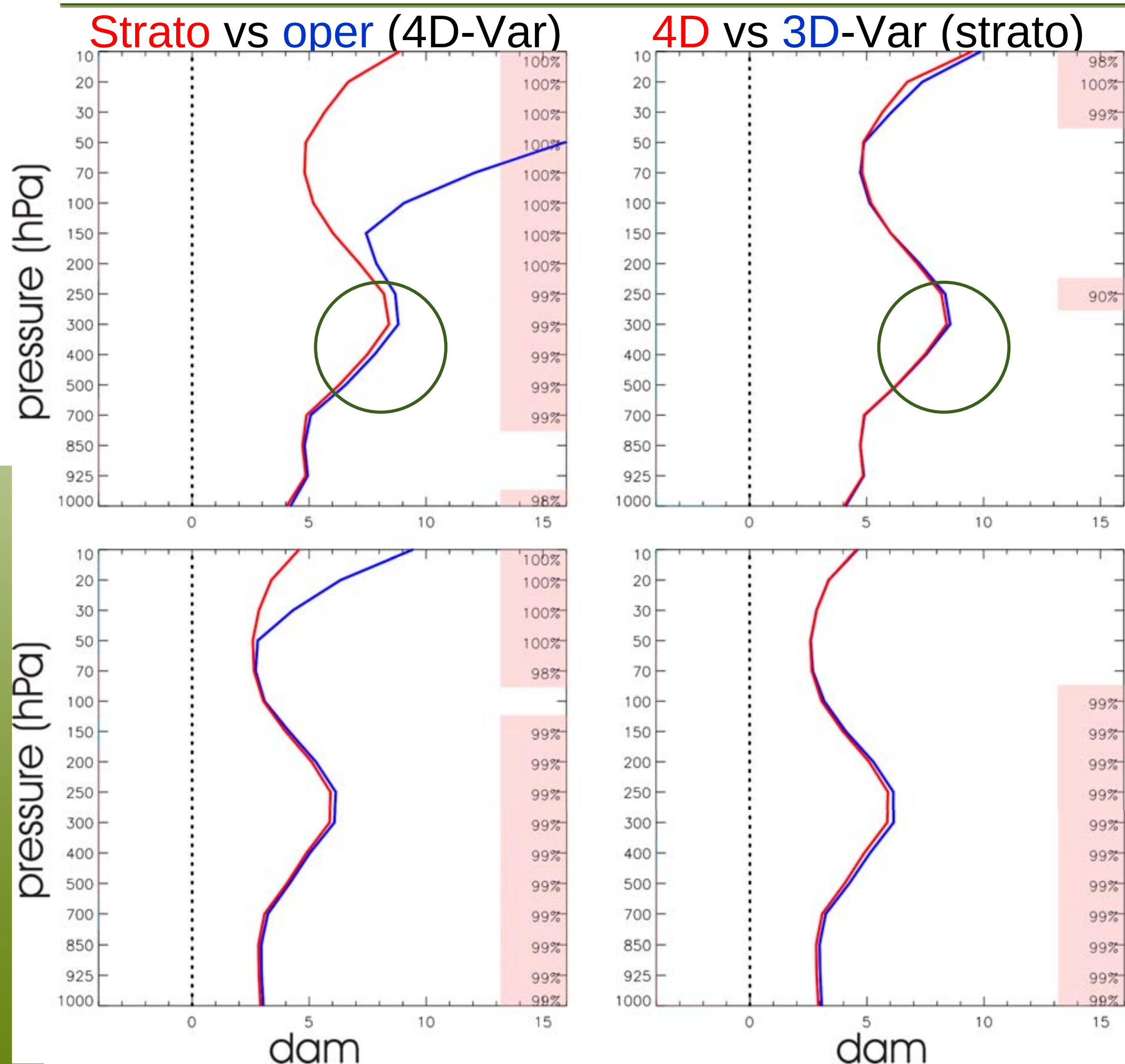
Daley (1986)

- Notions of balance formed in the context of midlatitude tropospheric dynamics
- What about the tropics and the middle atmosphere?

Why should we care about the stratosphere and mesosphere?

- ECMWF, GMAO have model lids at 0.01 hPa or 80 km (since Feb. 2006 and Jan. 2004, respectively)
- Most weather forecast models have a lid at 0.1 (65 km) above the stratopause
- Nadir sounders like AMSU, SSMIS are sensitive to temperatures up to 0.1 hPa. A good representation of the stratosphere and mesosphere may help improve the assimilation of tropospheric sensitive channels.
- Although weather forecast centres are primarily concerned about tropospheric forecasts, a good representation of the stratosphere can greatly improve tropospheric forecasts in the winter mid to high latitudes (next slide)

Improving the stratosphere improves forecasts even in the troposphere



O-F(5 day) against NH sondes for GZ

Winter

Impact of strato is bigger than that of 4D-Var

Summer

Impact of 4D-var is bigger than that of strato

Charron, Vaillancourt, Roch

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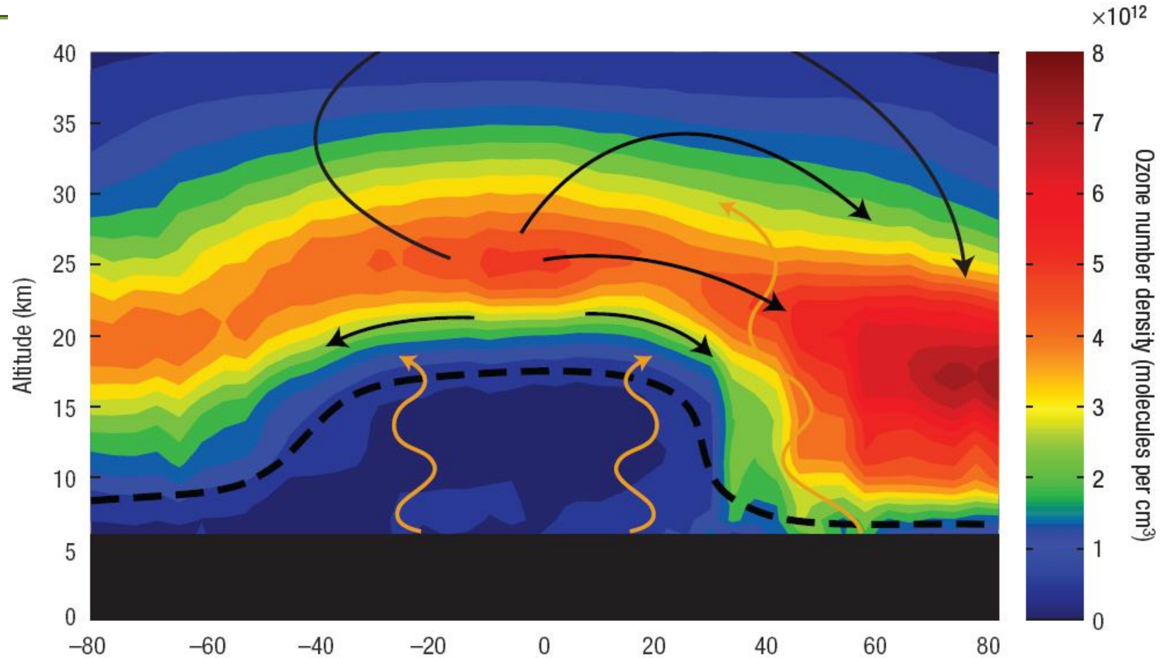
The stratosphere and mesosphere

Gravity waves are important in the stratosphere and mesosphere

Ozone from OSIRIS for March 2004

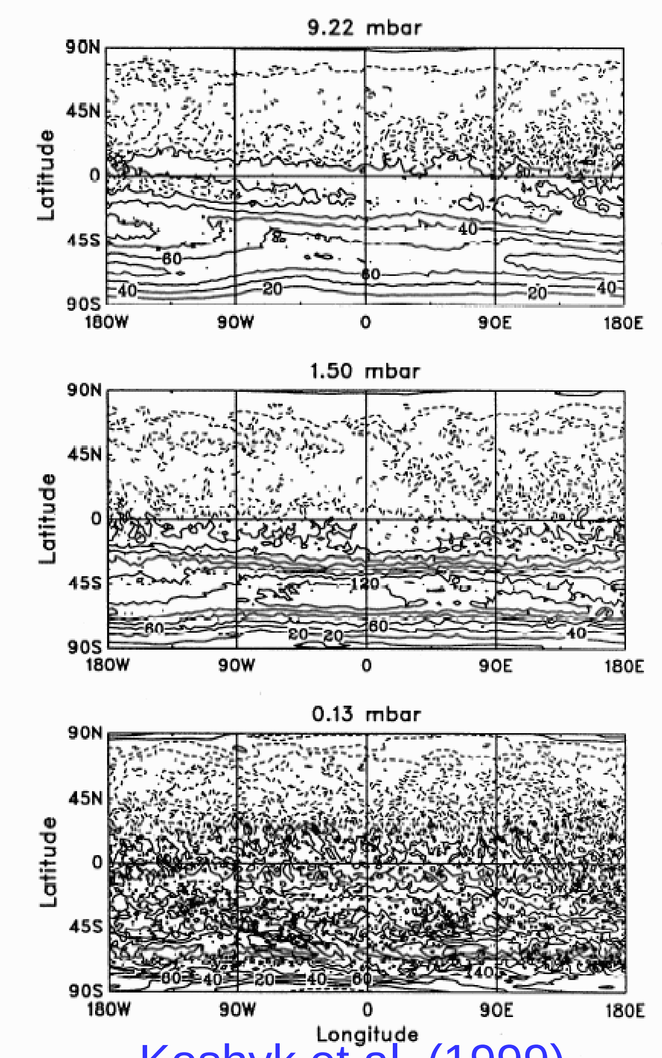


Shaw and Shepherd (2008)

- Brewer-Dobson circulation
  - wave driven, thermally indirect
  - affects temperature, transport of species
- Gravity waves also important
  - Exert a “drag” on mean flow, keeping the middle atm far from radiative equilibrium, driving pole-to-pole meridional circulation
  - Warm the winter pole in stratosphere
  - Impact on tides
  - Help drive Quasi-Bienniel Oscillation (QBO)

Gravity waves are ubiquitous in the mesosphere

Zonal wind snapshot in July



Lower stratosphere

Dominated by large scales

stratopause

mesosphere

GWs are Important!

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

Koshyk et al. (1999)

Consider various spurious wave filtering methods

Anal = bkgd + anal incr

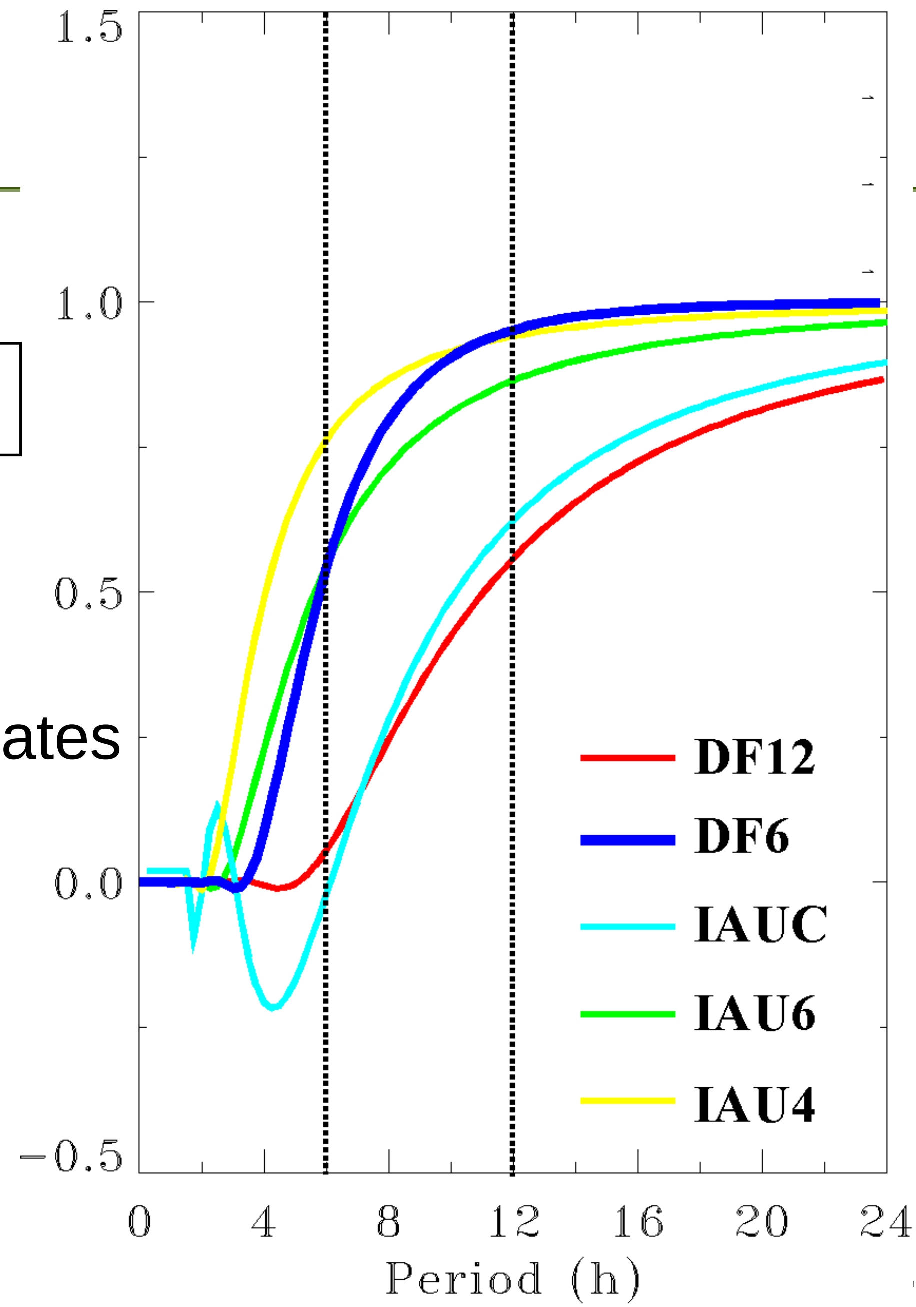
DF = Digital Filter

Applied to full analysis

IAU= Incremental Anal Updates

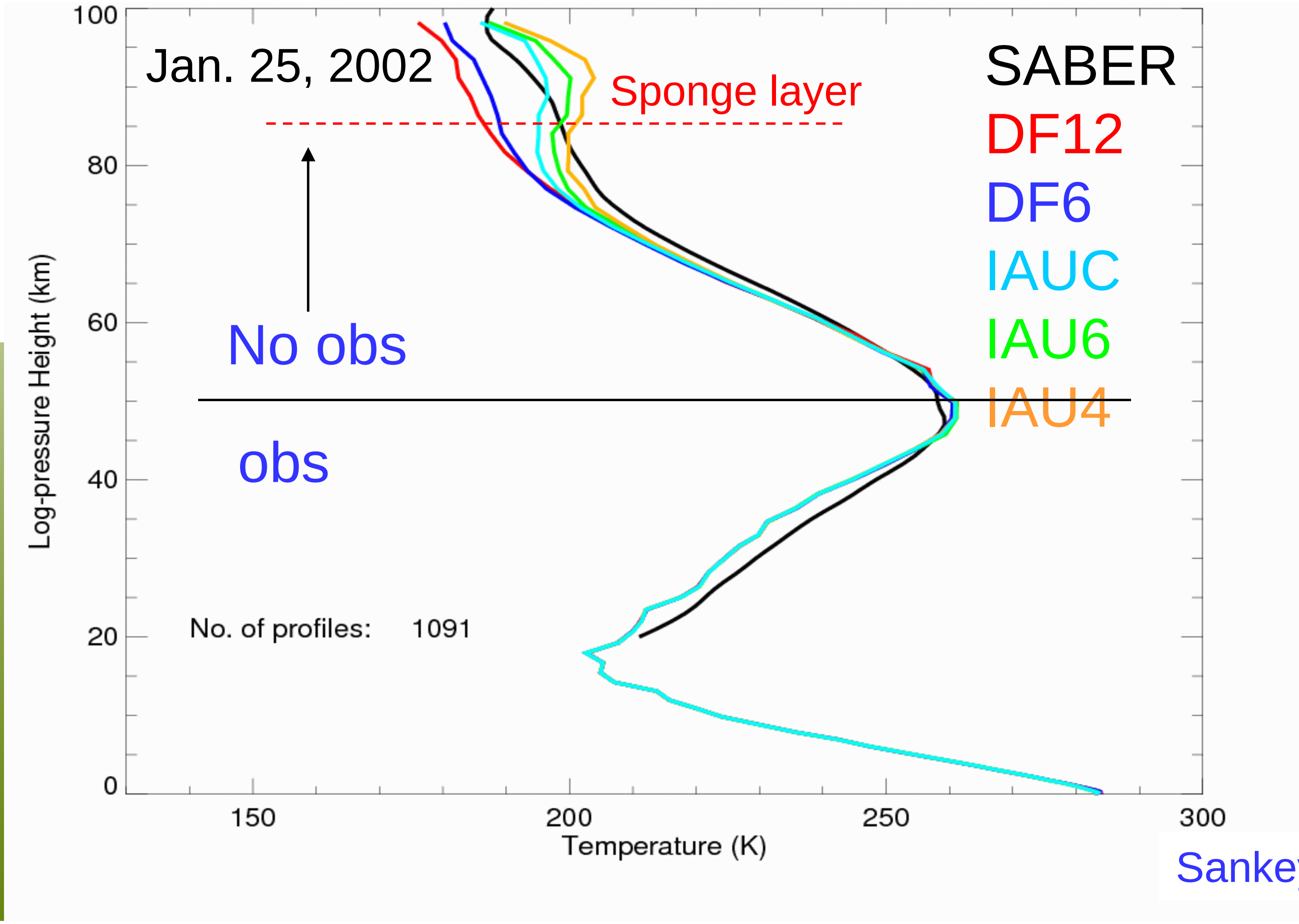
Applies to anal incr only

Filter Response Functions



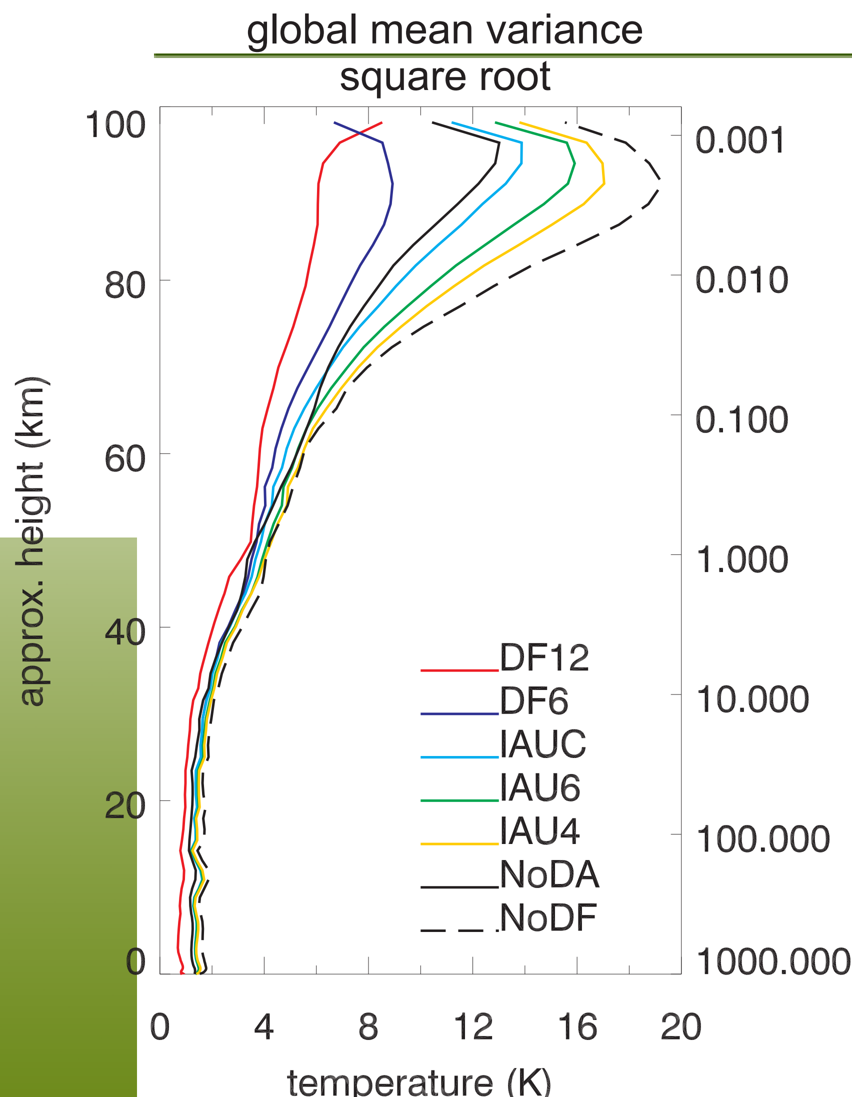
Filtering of GWs in troposphere affects global mean mesopause temperature!

Global mean temperature profiles at SABER locations

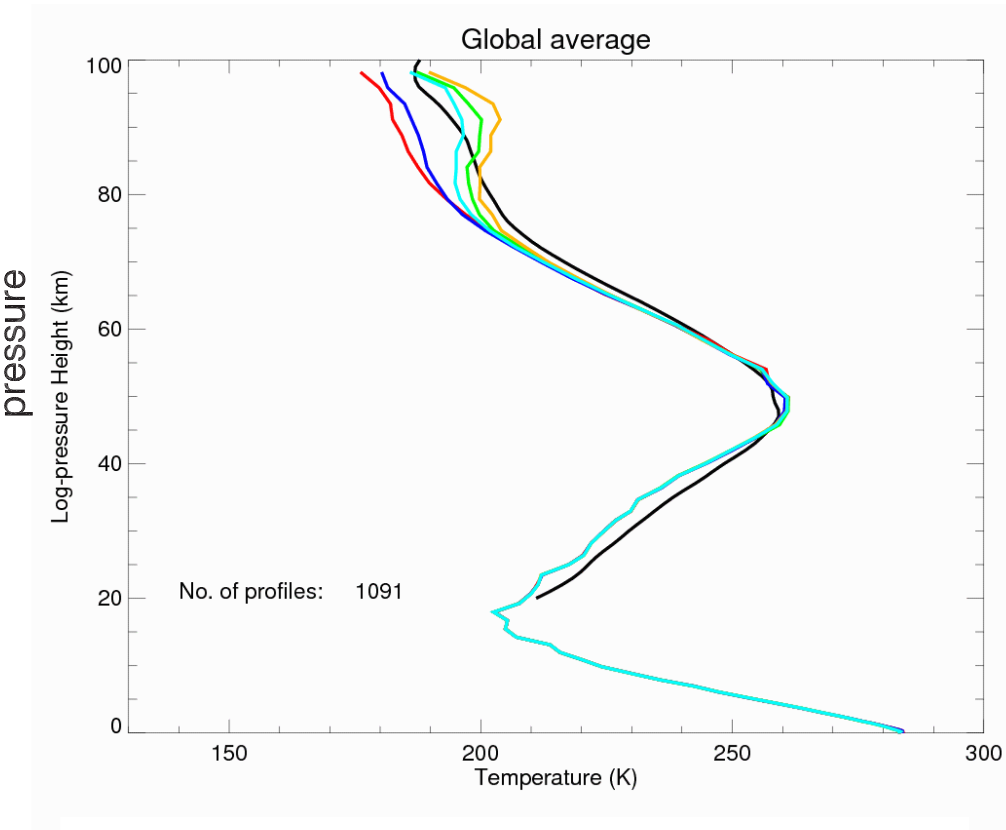


Sankey et al. (2007)

There are more resolved waves in the upper mesosphere with less filtering



Sankey et al. (2007)



More waves --> more damping --> more heating

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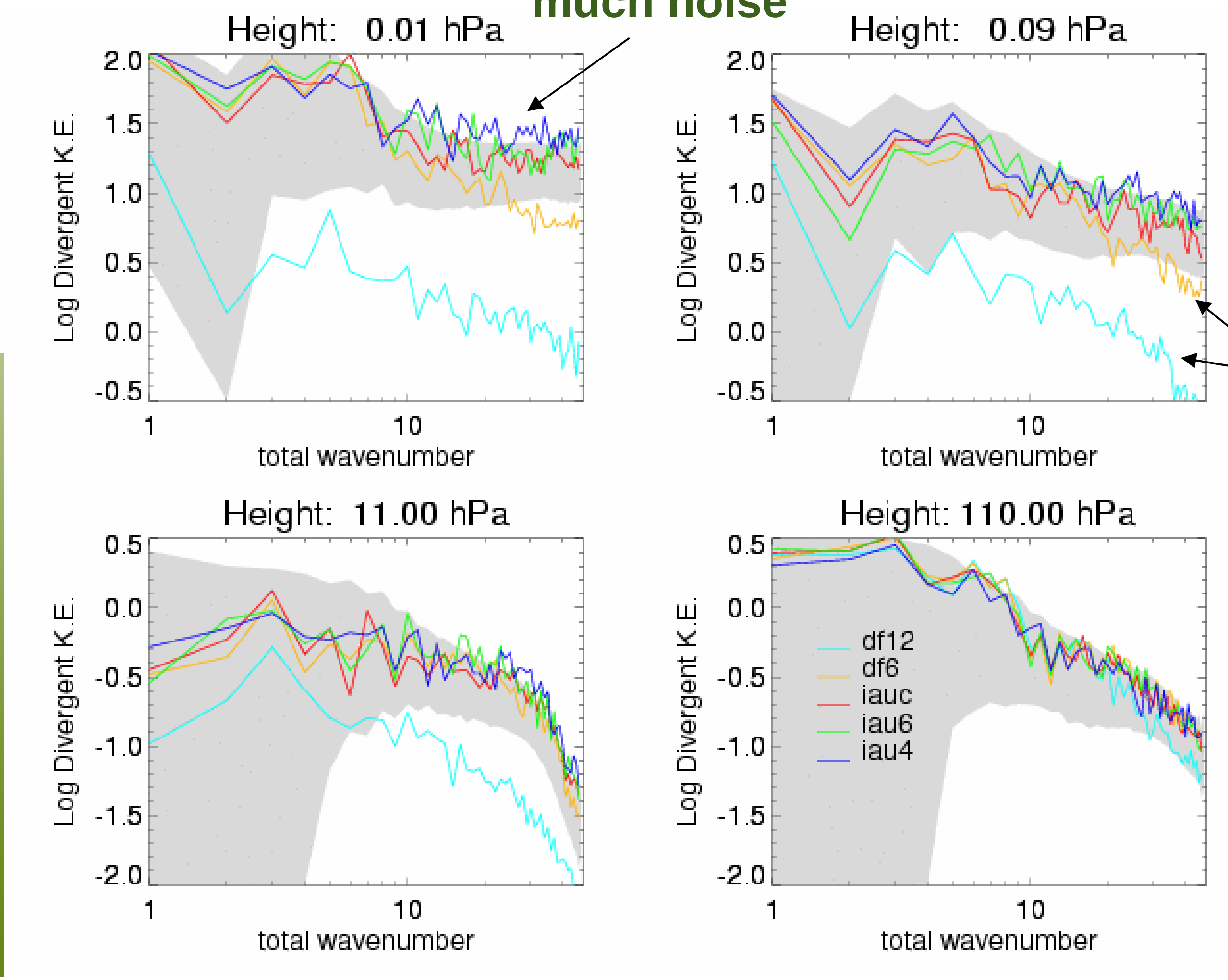
Here we view filters as acceptable if they produce reasonable spectra

IAU4 leaves too much noise

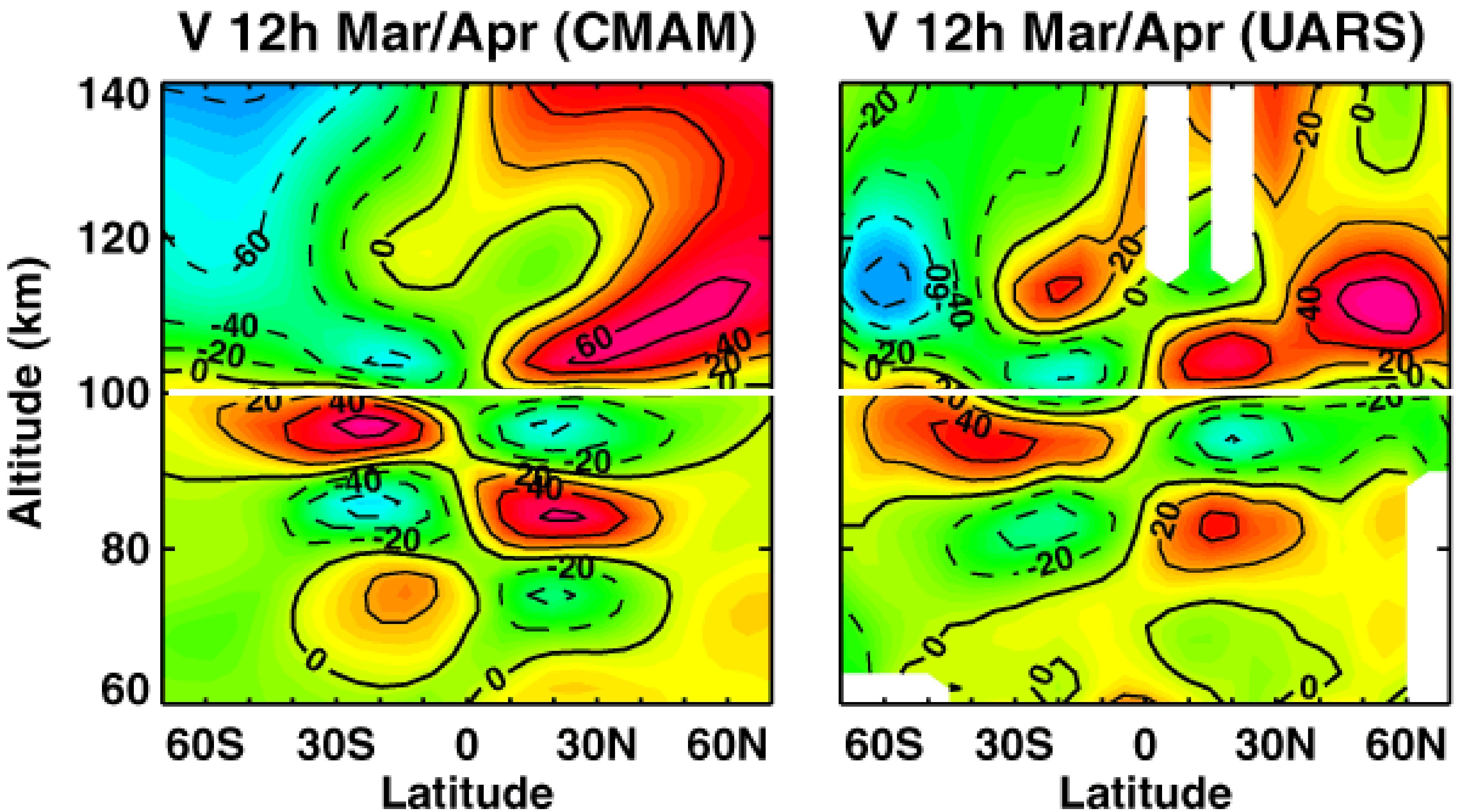
Shading: mean ± 2σ for 5 yrs of Jan-Feb fields every 6 h



DF12, DF6 are below range of model spectra

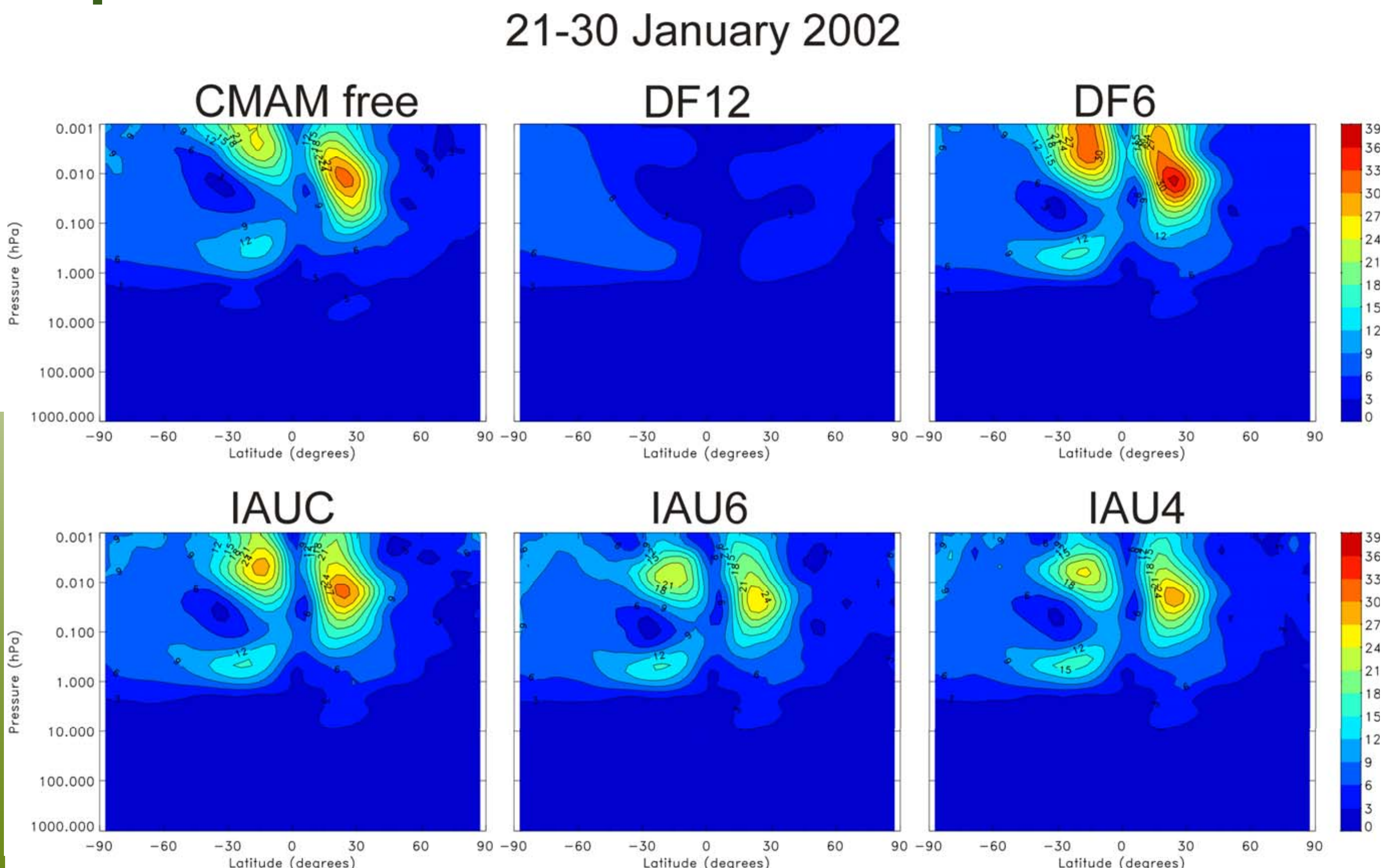
Sankey et al. (2007)

Free running model gets the propagating diurnal thermal tide roughly right



Beagley *et al.* (GRL 2000)

Initialization scheme can enhance or wipe out the diurnal tide



Sankey et al. (2007)

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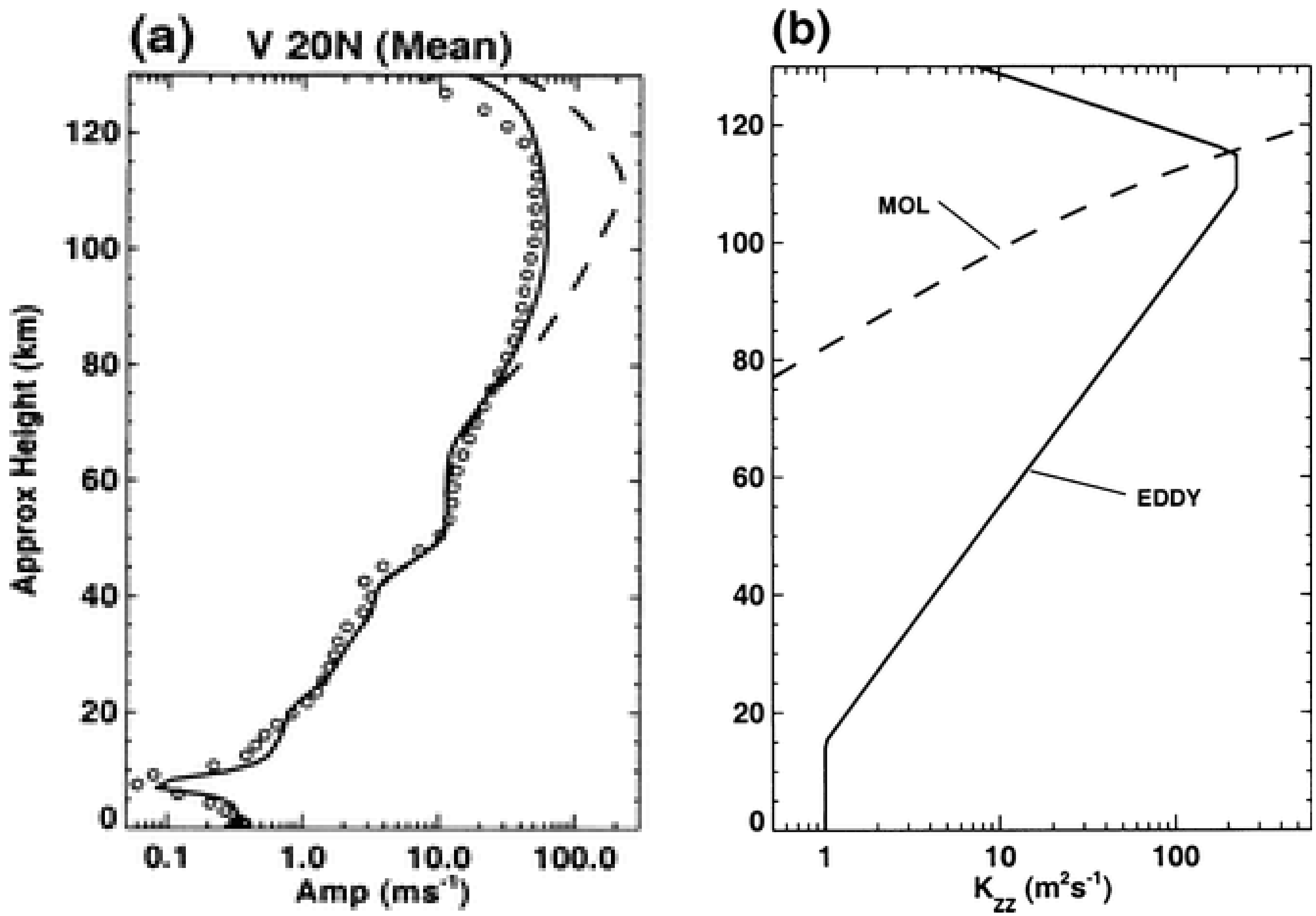
- To represent the CMAM tide (circles) in a linear tidal model, strong eddy viscosity must be invoked (lines)
  - The linear model is missing nonlinear interactions among GWs that damp the tidal amplitude
  - Too much damping of GWs can prevent this nonlinear interaction and result in too large tidal amplitudes



McLandress (2002 JAS)

Suggestion

- Waves generated in the troposphere propagate up to the mesosphere, increasing in amplitude as the density decreases
- Because of the large sensitivity of the mesosphere to what happens in the troposphere, we should be able to use mesospheric observations to help us tune filtering parameters applied to analysis increments in the troposphere

Impact of noisy analyses on tracer transport

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Stratospheric transport

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.

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

Note the weak latitudinal gradients

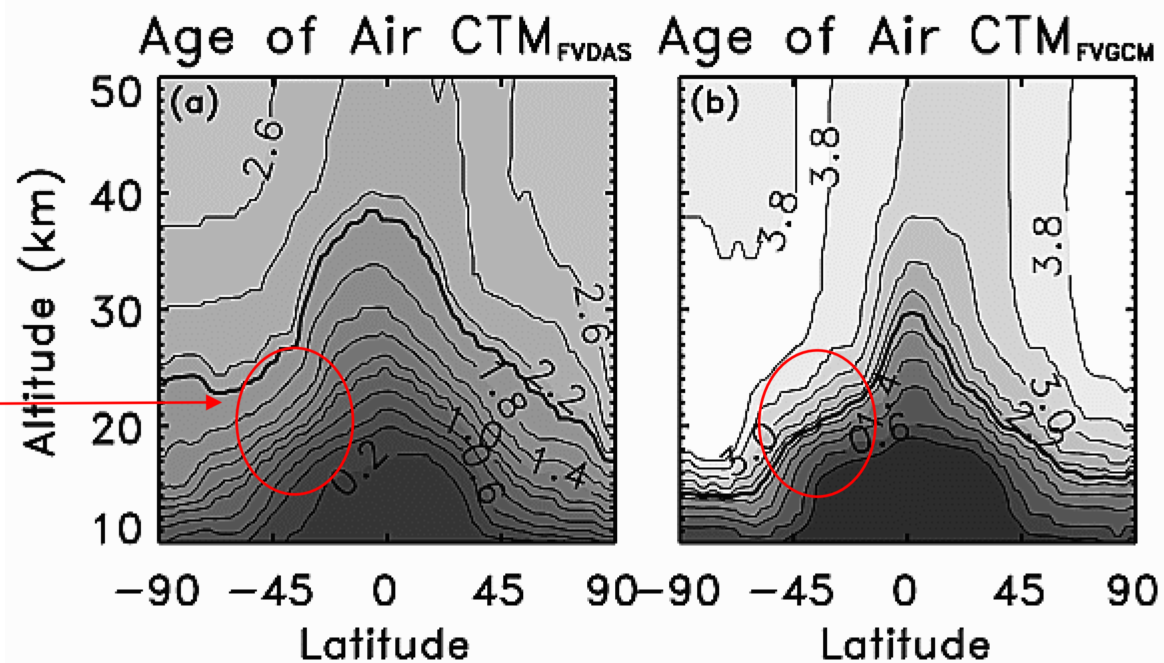


Figure 6. (a) Age of air (years) calculated from an SF-6 simulation using CTM_{FVDAS}. The age calculation converges after 5 years integration. (b) Same as Figure 6a but using CTM_{FVGCM}. The age calculation converges after 9 years integration. The contour interval is 0.2 years; the 2-year contour is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

Douglass et al. (2003)

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)

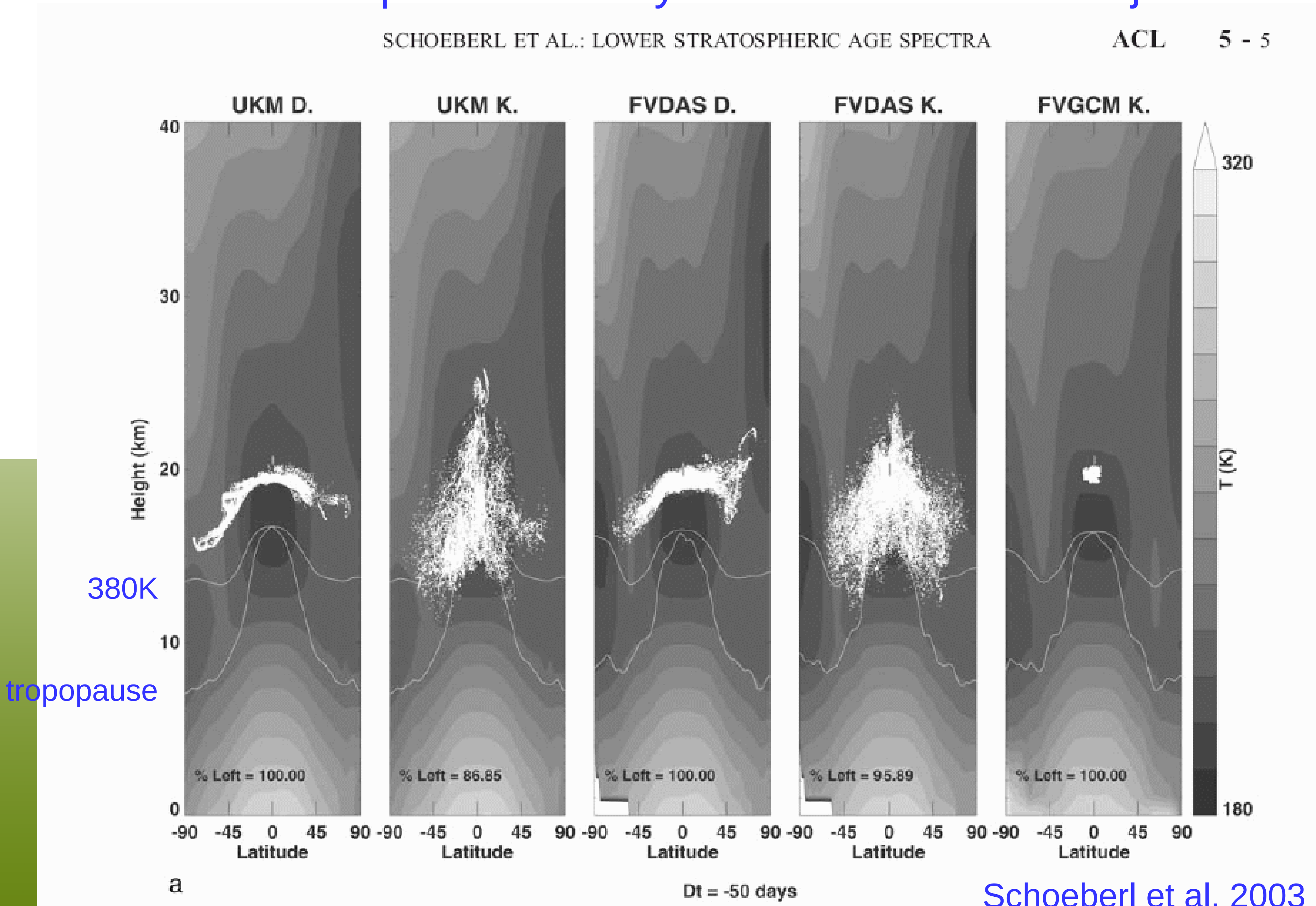
Problems with analysed winds:

- Vertical motion is noisy
- Horizontal motion is noisy in tropics
- Leads to too rapid tracer transport

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

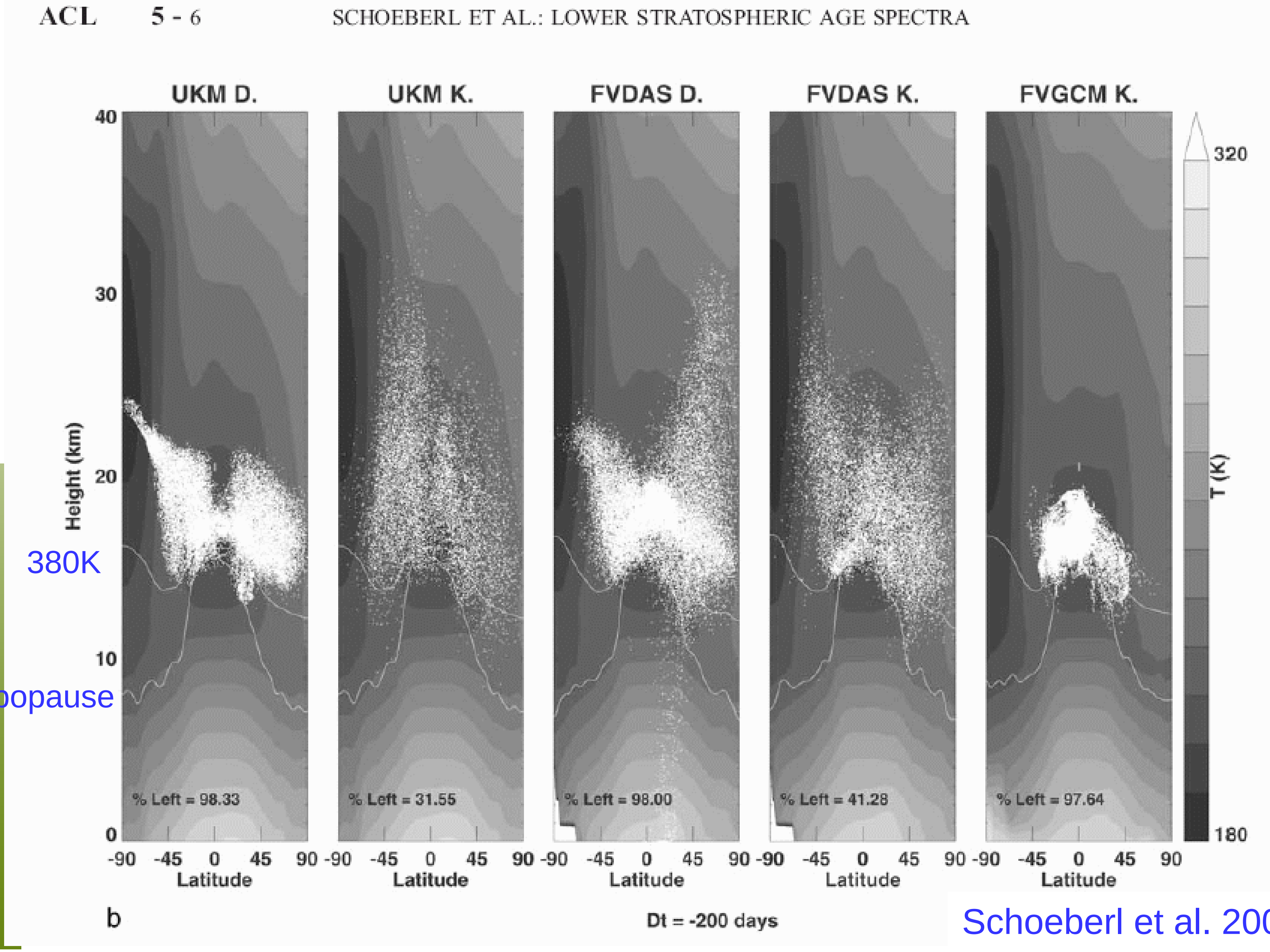
- Imbalance due to insertion of data excites spurious gravity waves which creates excessive vertical motion. Weaver et al. (1993)
- Impact of data insertion important when model and obs biases exist. Douglass et al. (2003)
- Assimilation of tropical data leads to spurious PV anomalies (wave activity)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

Distribution of parcels 50 days after start of back trajectories



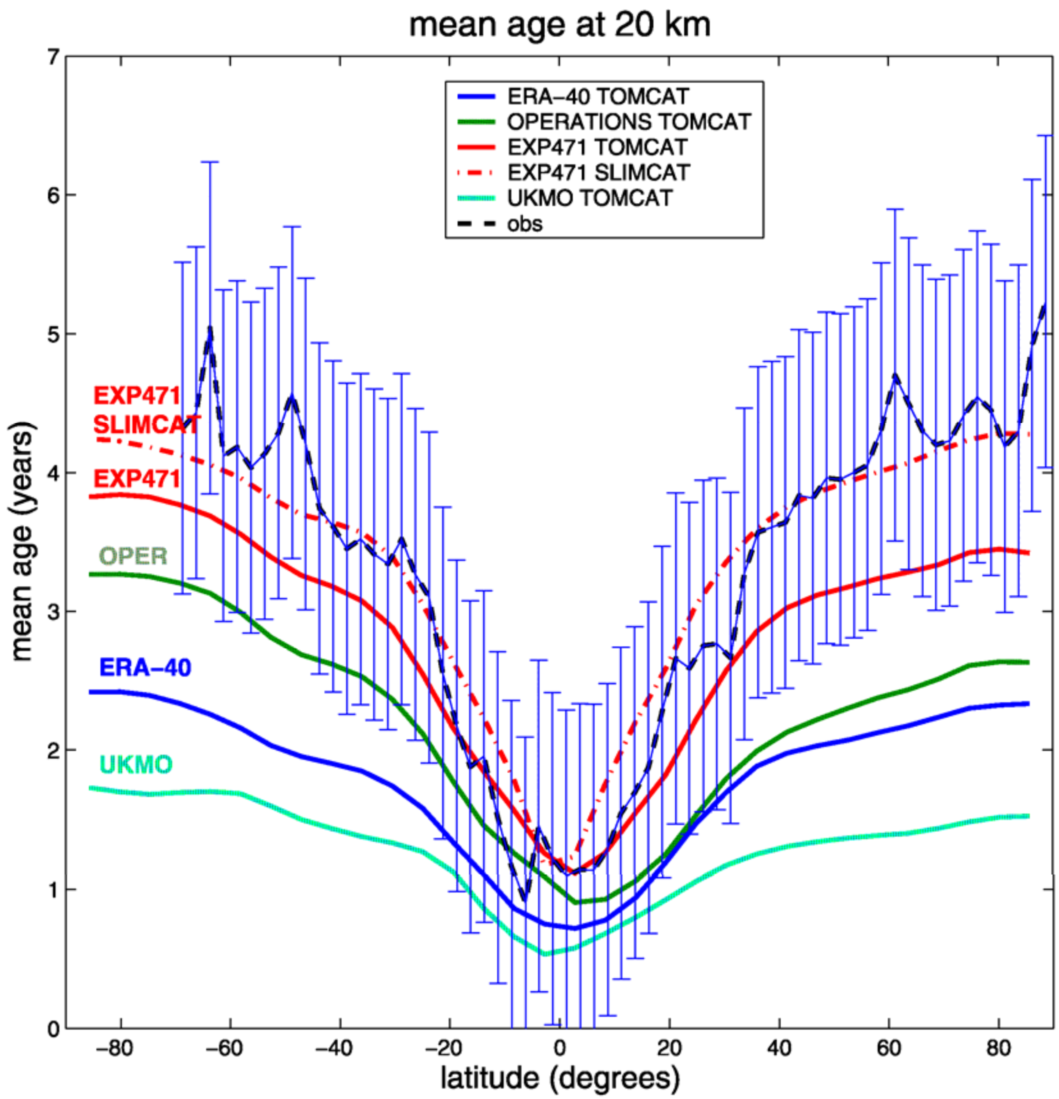
Schoeberl et al. 2003

Distribution of parcels 200 days after start of back trajectories



Schoeberl et al. 2003

Improvements in assimilation techniques impact age-of-air



Reasons for improvement not yet identified. Suspect improved balance with 4D-Var and choice of control variable are important.

4D-Var (12h) + better balance + TOVS bias corr. + lower model bias +…

Operational 4D-Var (6h)

ERA40 3D-Var

Monge-Sanz et al. (2007)

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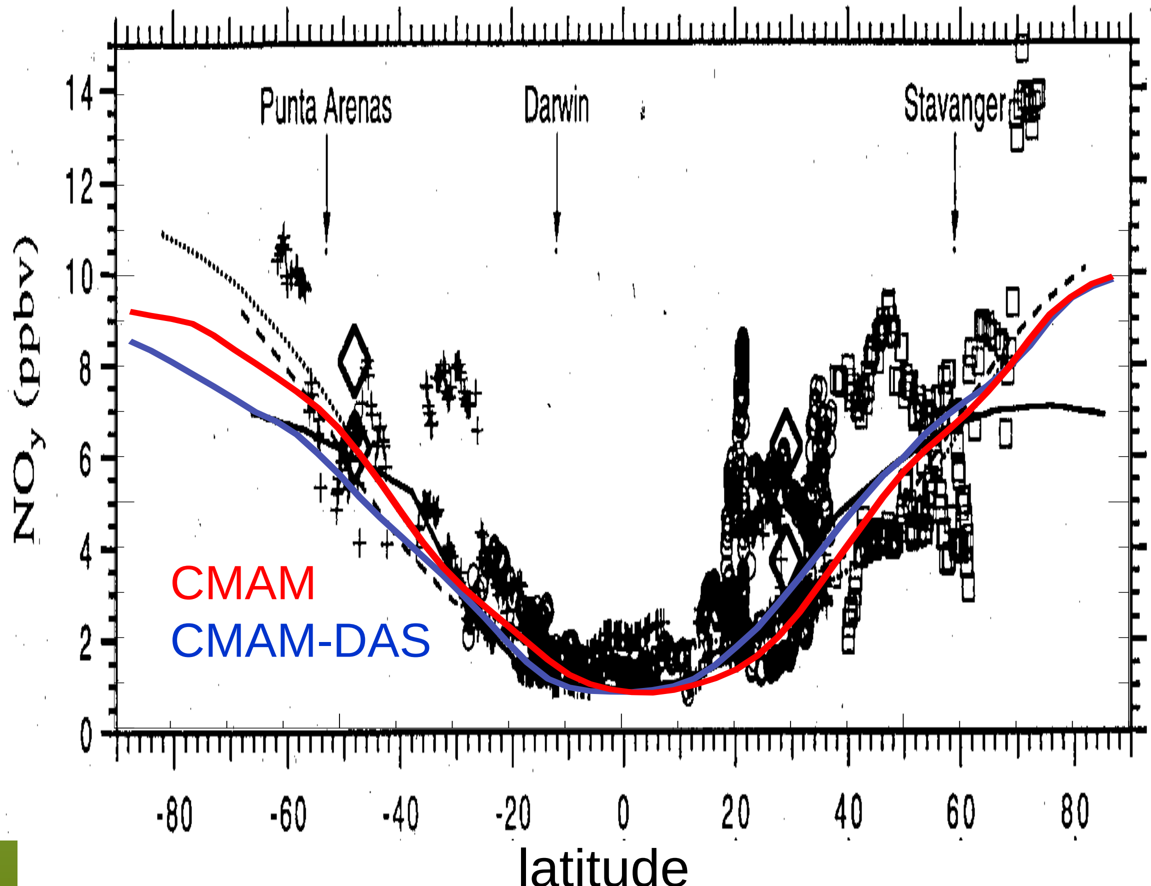
Latitudinal gradients can be well maintained even in 3D-Var analyses

Figure courtesy of Michaela Hegglin

NOy at 62 hPa (19 km)



ER2 aircraft data from Murphy et al. (1993)

CMAM-DAS - March 03

CMAM-DAS uses 3D-Var (not 4D-Var)!

Improvements due to:
(1) online transport and/or (2) improved balance in increments due to IAU ?

Summary of transport issues

- Assimilated winds are often used to drive chemistry-transport models
- Tracer distributions are wrong if analysed winds are noisy or residual circulation is too fast
- Improvements in balance of analyses seem to improve mean age-of-air
- However the diagnostic itself (age-of-air) may be flawed
  - Horizontal dispersion of parcels strongly depends on release height (Bregman et al. 2006)
  - Offline transport using “frozen” or interpolated analyses may not reflect what is going on in a GCM where transport is online

Using assimilation to define model parameters

- Gravity wave drag due to subgrid scale GWs is a major source of uncertainty in climate model simulations
- Methods to estimate GWD need to separated drag due to resolved waves and drag due to unresolved waves
- But drag due to unresolved (parameterized) waves helps drive the zonal mean flow which filters the resolved waves, so both are related
- Using analyses, obs in the troposphere and stratosphere are used to define the zonal mean flow
- Then GWD due to parameterized waves can be estimated

Using 4D-Var to estimate forcing due to gravity wave drag

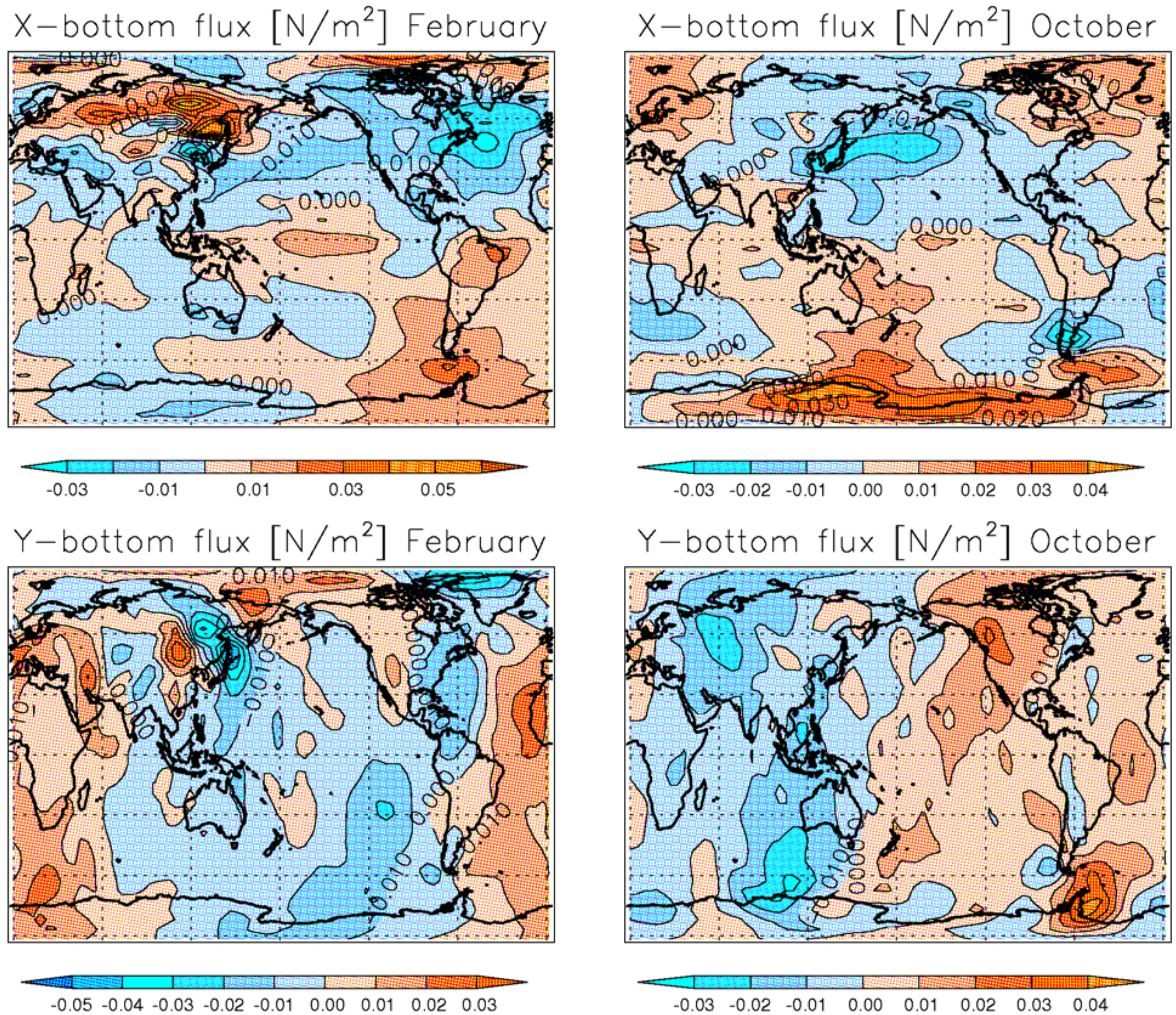
Pulido and Thuburn (2005,2006,2008)

- Instead of using mismatch between observations and forecast to determine initial conditions (ICs), assume ICs correct and determine drag on u and v
- Knowns: u,v,T (Met Office analyses)
- Observed divergence not reliable, so not used. Thus only rotational part of drag is estimated (one 3D field)
- Can estimate 3D daily drag field. Drag assumed constant over 24 h.
- Resulting drag field consistent with previous estimates
  - Strength and location of winter deceleration centres
  - Descent of drag with QBO, SAO in tropics

GW sources? vertically integrate estimated drag

Pulido and Thuburn (2008)

- Drag at a given level reflects GW sources and filtering by wind
- Contribution mainly from stratosphere where estimates are noisy
- Does this reflect GW sources? Need to compare to obs
- Could be used to estimate parameters in GWD schemes



Climate uses of data assimilation

- Reanalyses can be used as “proxies” for the real atmosphere to study atmospheric processes
- Ideally, long reanalyses could be used for trend analyses
- Drive chemistry-transport models
- Climate models are partly evaluated based on ability to capture robust modes of atmospheric variability (e.g. QBO, SAO, etc.) If analyses capture these signals, they can be used for comparisons
- Climate model parameterizations can be tested in “forecast mode” to ensure reasonable short term tendencies
- Can use data assimilation to “tune” uncertain parameterizations

EXTRA SLIDES

KE spectrum changes with height

Rot KE Div KE

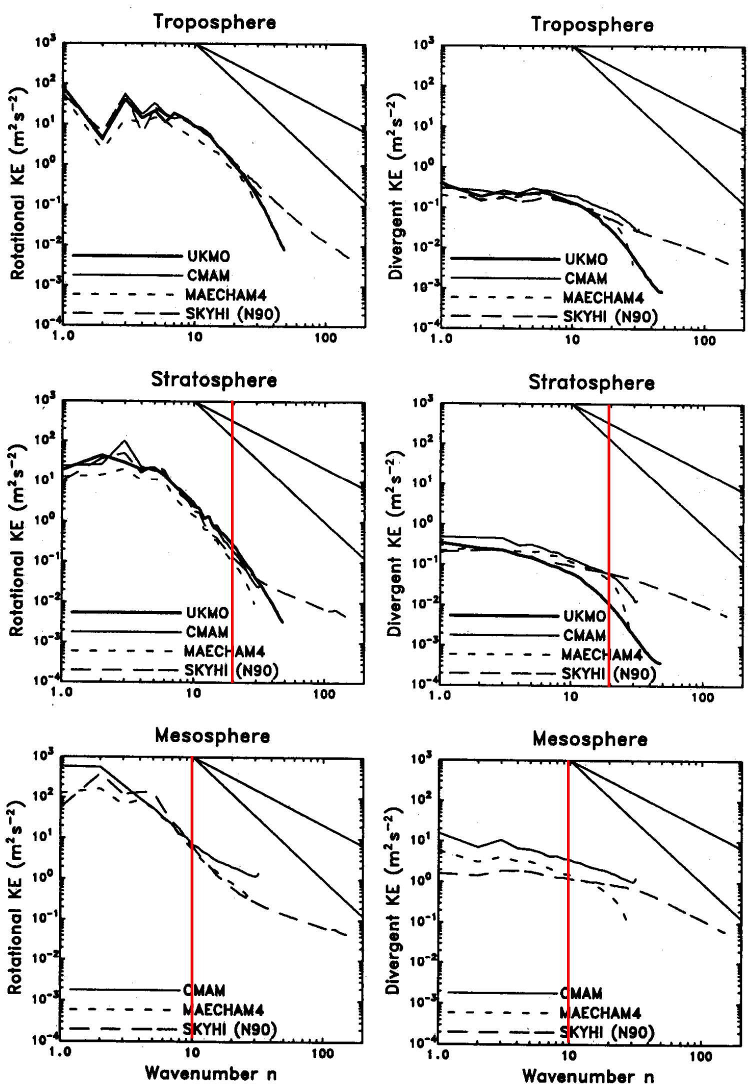


Figure 4. Rotational and divergent parts of the monthly mean kinetic energy per unit mass versus total horizontal wavenumber for January data from the UKMO assimilation, CMAM, MAECHAM4, and SKYHI (N90) models. The curves represent vertically averaged values over the troposphere (top), stratosphere (middle),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

troposphere

stratosphere

RotKE = DivKE
around n=20

mesosphere

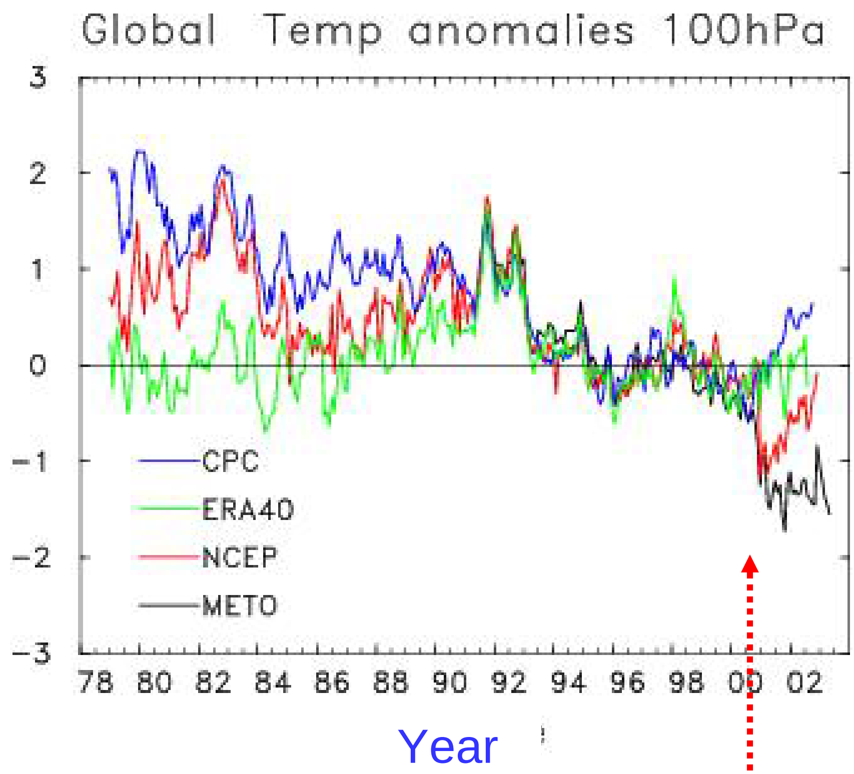
RotKE = DivKE
around n=10

Koshyk et al. (1999)

Canada

Even lower stratosphere temperatures are problematic

each data set normed to zero for 1992-1999



TOVS – ATOVS change

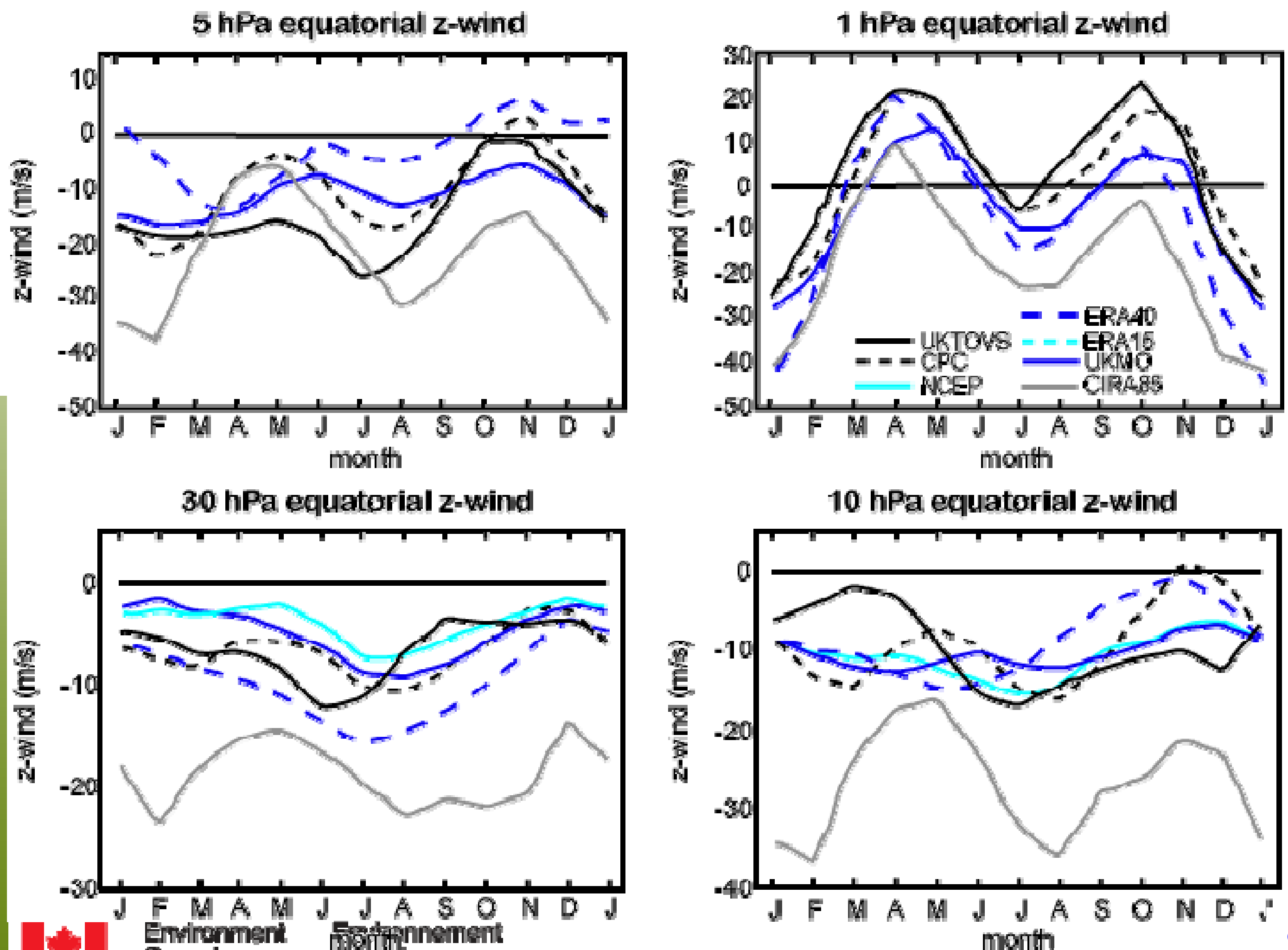
Note spurious changes due to evolution of data / analysis systems

Environment Canada Environnement Canada

William Randel

Climatological seasonal cycle

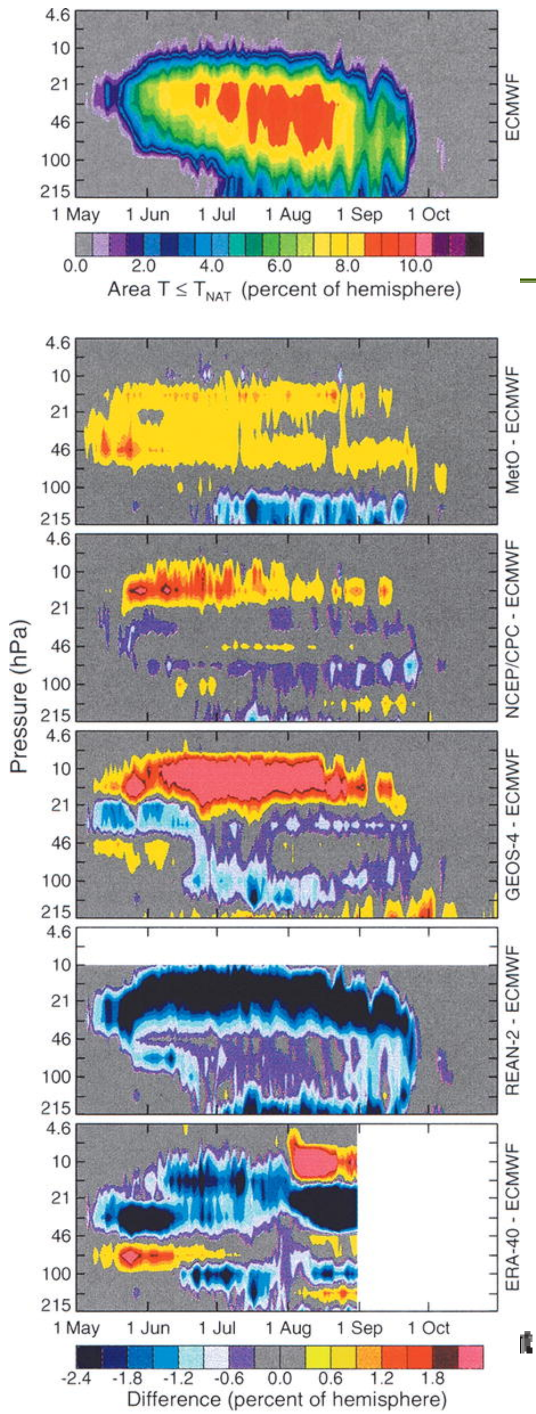
Zonal mean zonal wind at the equator



Environment Canada Environnement Canada

SPARC (2002)

Polar processes



Area of temperatures below NAT threshold highlights temperature differences between analyses

FIG. 11. Pressure–time cross sections of the area with *T* <*T*NAT(percent of a hemisphere) for May–Oct 2002 in the SH from (top) ECMWF, and the differences between ECMWF and (top to bottom) MetO, NCEP/CPC, GEOS-4, REAN-2, and ERA-40 (through Aug). Red–oranges–browns indicate a larger cold region (associated with lower temperatures) in the analysis being compared to ECMWF.

Manney (2005, MWR)

UKTOVS – obj.anal GZ,T,bal wind, 1979-97 (100-1 mb)

- From TOVS radiance, thickness produced at 100-20, 100-10, 100-5, 100-2, 100-1 mb, then mapped to 5 deg global grid and added to oper anl at 100 mb to get GZ to 1 mb.
- T, bal. winds derived from GZ
- Winds at equator interpolated from low latitudes

CPC – Successive Corrections (GZ, T, bal wind), 1978-now (10000-0.4 mb)

- CPC = Climate Prediction Center
- TOVS layer mean T between std P levels thicknesses
- Add to 1000 mb NCEP global anal to get 70, 50, 30, 10, 5, 2, 1, 0.4 mb T
- Valid at 12 Z using 06-18Z TOVS data
- NCEP oper anal below 100 mb

CIRA86 – GZ,T,U 1960's-70's (1000-0.001 mb) 0-120 km

- COSPAR International Reference Atmosphere
- 1000-50 mb Oort climatology (radiosonde data of 60's and early 70's)
- 10-2.5 hPa satellite Nimbus 5 SCR (Selective Chopper Radiometer) for 1973-4
- 2.5 – 0.34 mb SCR merged to Nimbus 6 PMR for 1975-8
- 0.34-0.01 mb (56-80 km) Pressure Modulated Radiometer
- Above 0.002 mb (~90 km) MSIS (mass spectrometer and incoherent scatter) empirical model
- GZ from T climatology and integrating up and down from 30 mb GZ from FUB for NH and Knittel (1974) for SH.
- Wind climatology from Oort (1983)
- Wind above 100 mb from gradient wind balance with GZ field
- At high latitudes, zonal wind from assuming constant ang momentum poleward of 70 deg
- At equator, second derivative of GZ used
- Between 0 and 15 deg linearly interpolate