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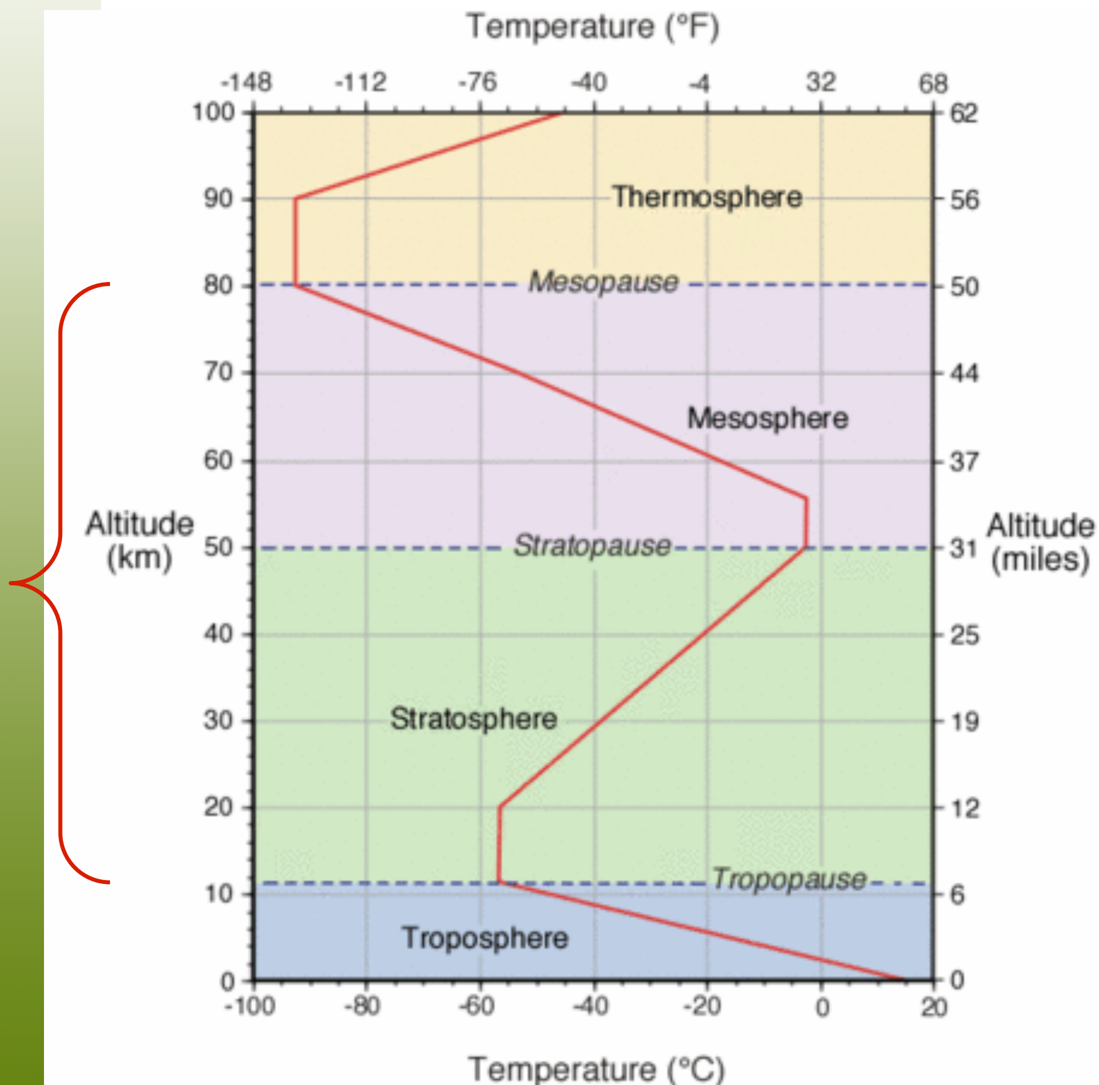
The unique challenges of middle atmosphere data assimilation

Saroja Polavarapu
Climate Research Division
Environment Canada, and,
University of Toronto

Fourth International Reanalysis Conference, 9 May 2012

The middle atmosphere

http://www.physicalgeography.net



- Model lids raised to 80 km at operationals centers in past 10 years
- Better assimilate satellite radiances with sensitivities to 0.1 hPa
- Some reanalyses include stratosphere and mesosphere
- New challenges for data assimilation related to dynamics of this region

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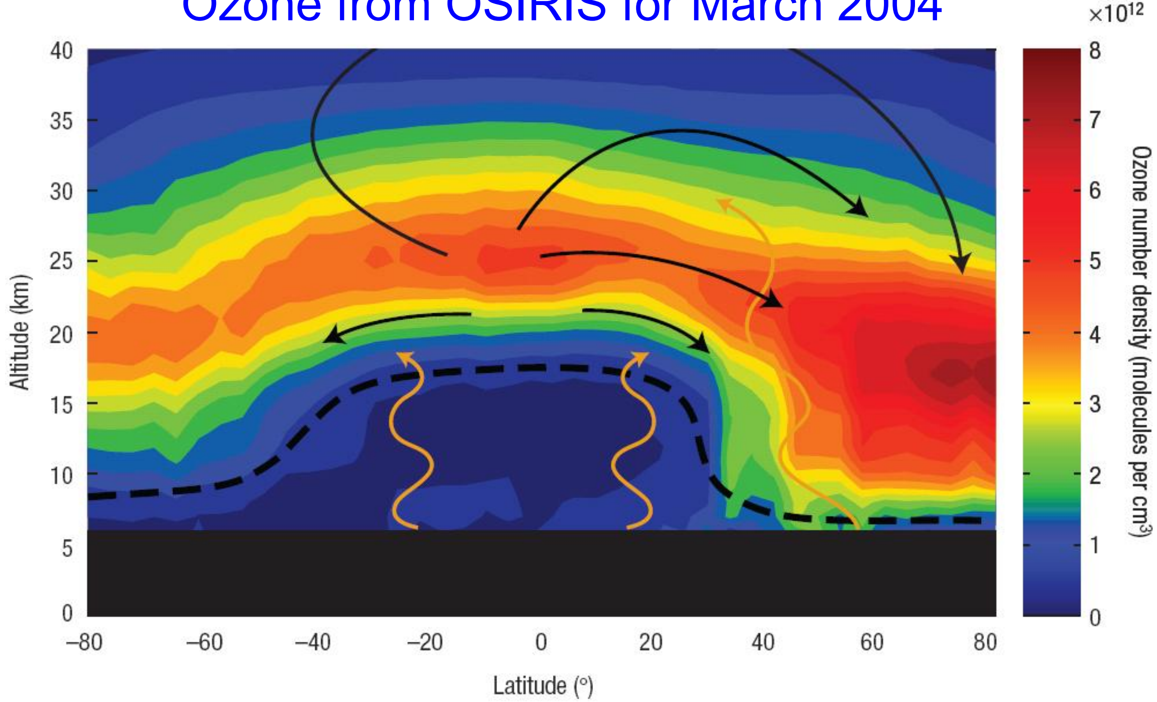
Stratospheric meridional circulation

Shaw and Shepherd (2008)

Ozone from OSIRIS for March 2004



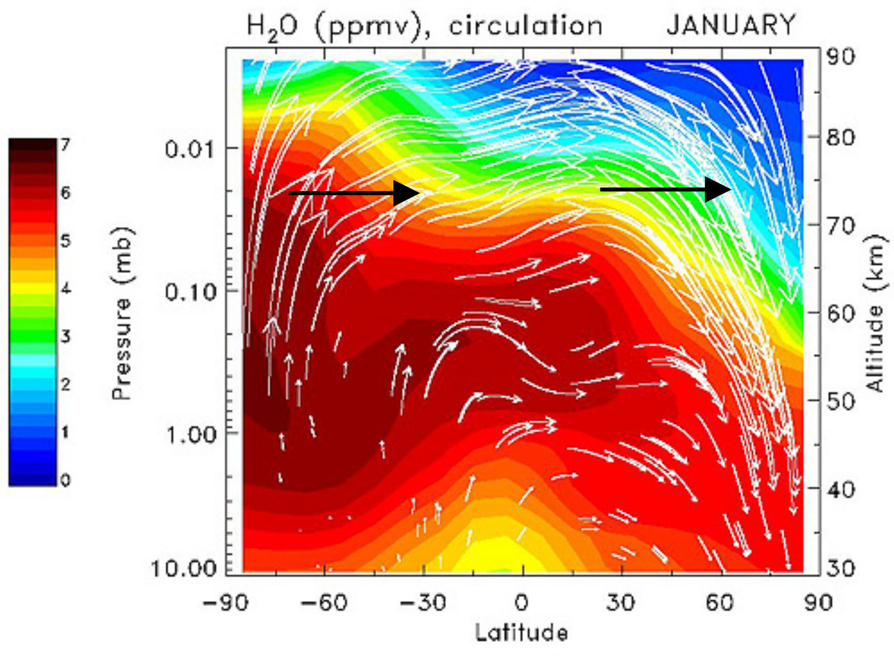
- Brewer-Dobson circulation
  - Stratospheric wave driven circulation, thermally indirect
  - warms the winter pole
  - affects temperature, transport of species

Mesospheric meridional circulation

http://www.ccpo.odu.edu/~lizsmith/SEES/

Drag on easterlies
Equatorward motion

Drag on westerlies
Poleward motion

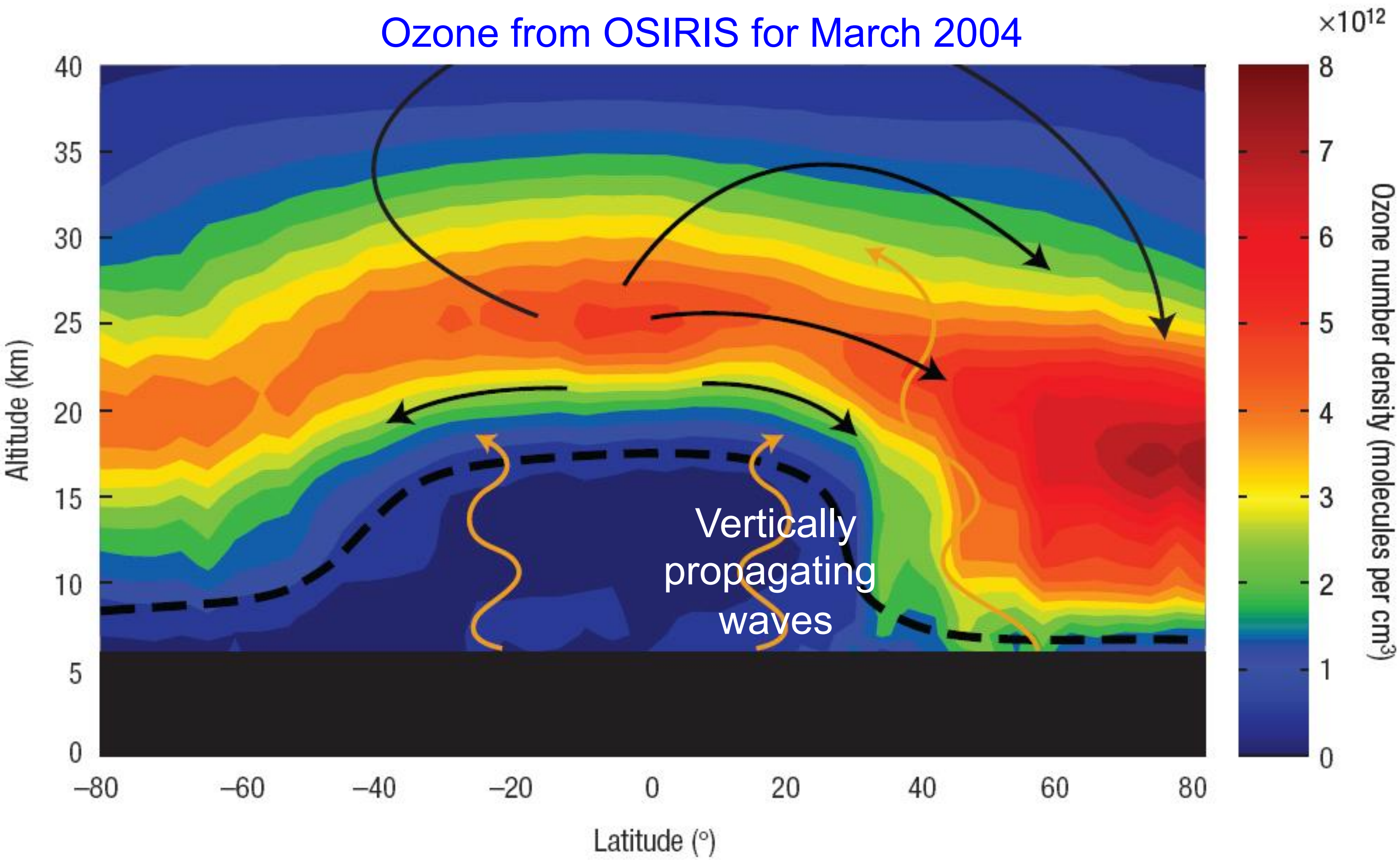


Zonally averaged water vapor distribution for January

- Winter: westerly zonal flow filters eastward GWs yielding net westward drag, poleward motion
- Summer: easterly flow filters westward GWs yielding net eastward drag, equatorward motion
- By continuity, upwelling over summer pole, downwelling over winter pole
- Gravity wave drag drives this pole-to-pole circulation seen in the water vapour plot

Wave driven circulation

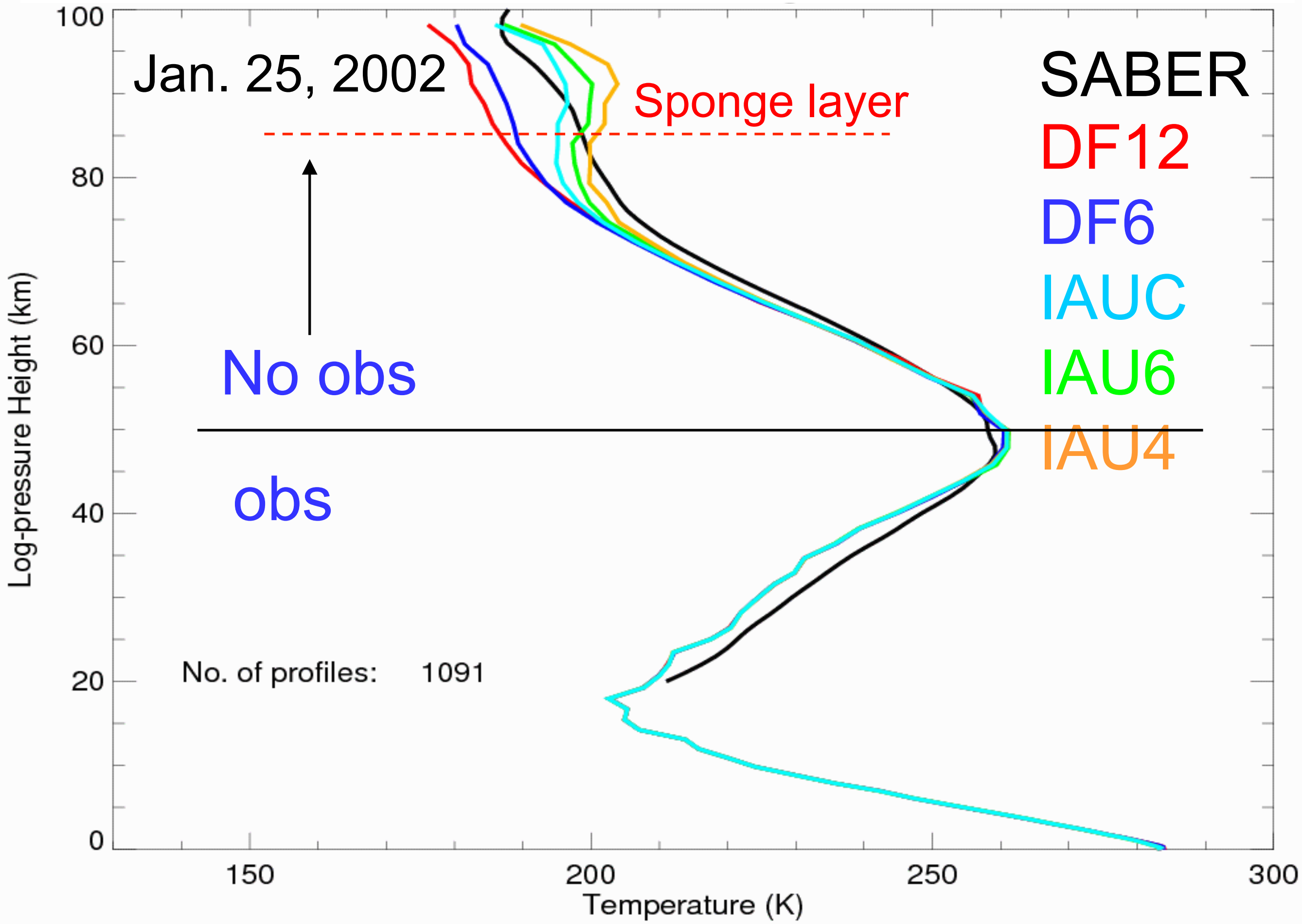
Shaw and Shepherd (2008)



Filtering of tropospheric increments affects global mean mesopause temperatures!

Sankey et al. (2007)

Global mean temperature profiles at SABER locations for various filtering options

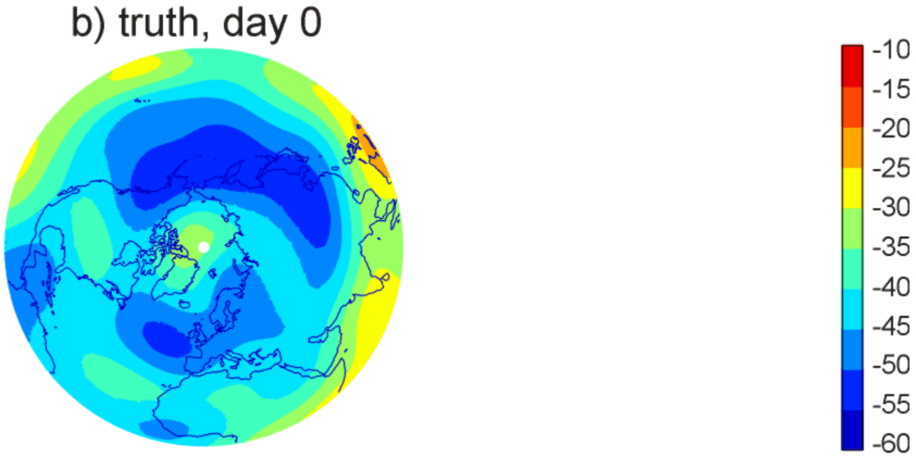


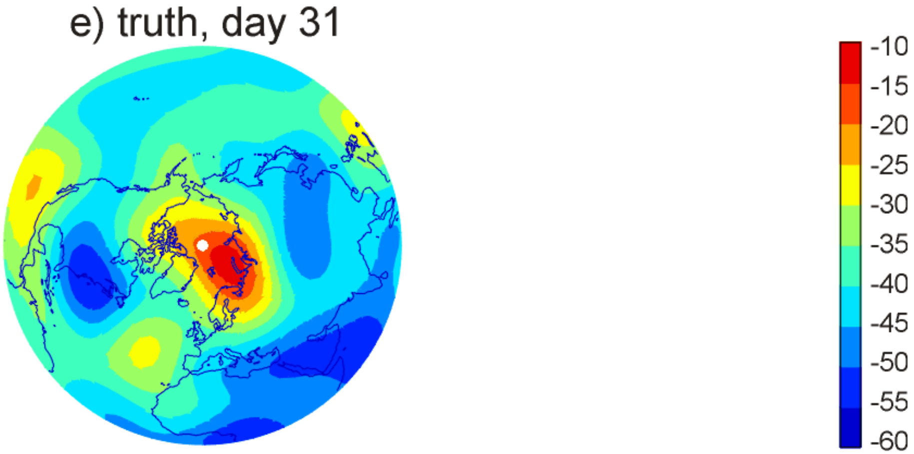
- Waves (real or spurious) in the troposphere propagate up to the mesosphere and impact the zonal mean flow, or even global mean fields
- Information is propagating up to the middle atmosphere through resolved waves
- Choice of filtering aimed at controlling noise in tropospheric analyses can impact amplitude of migrating diurnal tide in mesosphere (Sankey et al. 2007)
- Sensitivity of mesosphere can be used to "tune" filter parameters (Sankey et al. 2007)

Assimilating data below the mesosphere improves large scales in mesosphere

Nezlin et al. (2009)

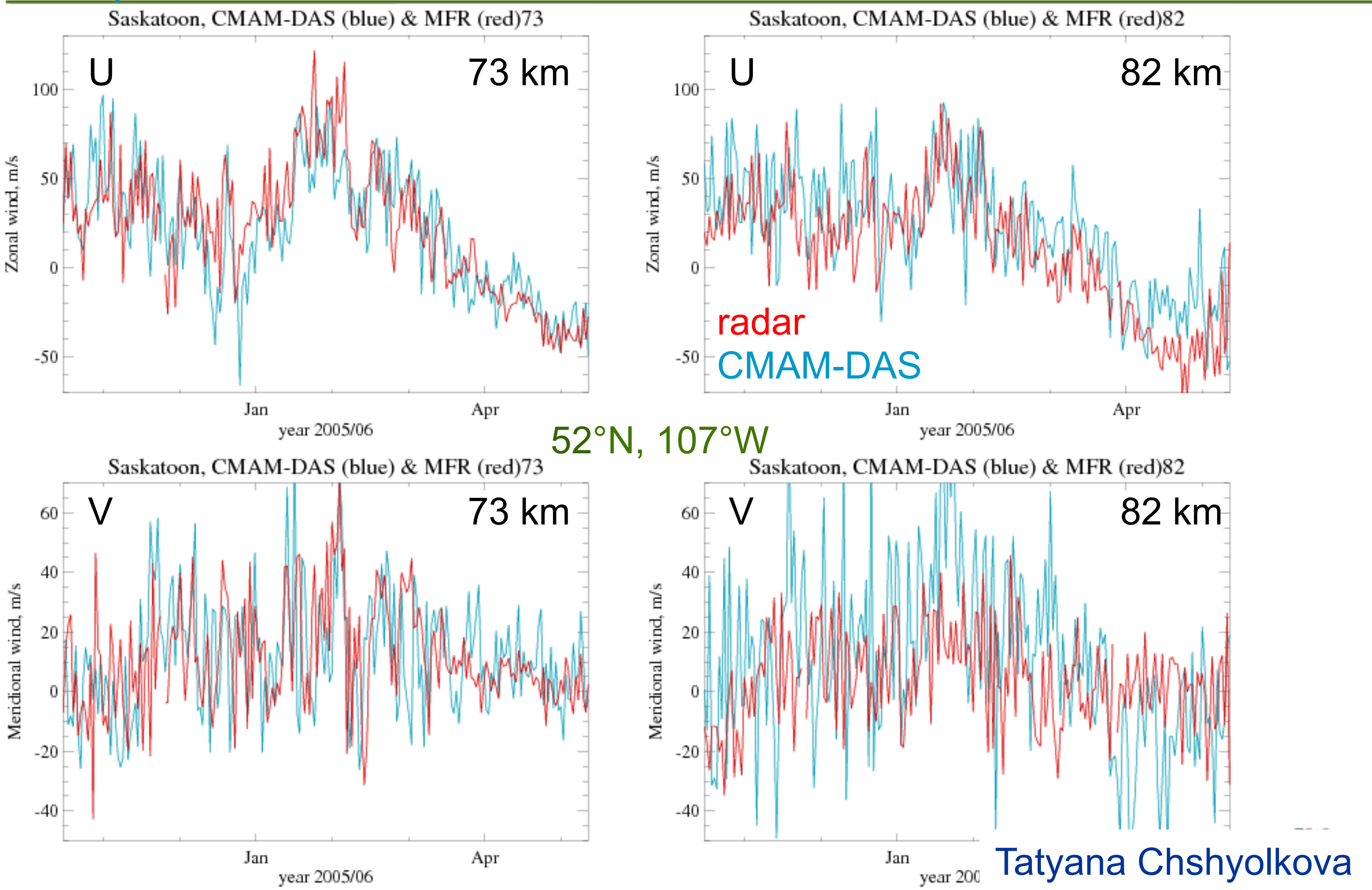
Temperature at 65 km spectrally truncated to T10





Mesospheric analyses have some value even when obs only below 45 km

Compare CMAM-DAS to Saskatoon radar winds at noon



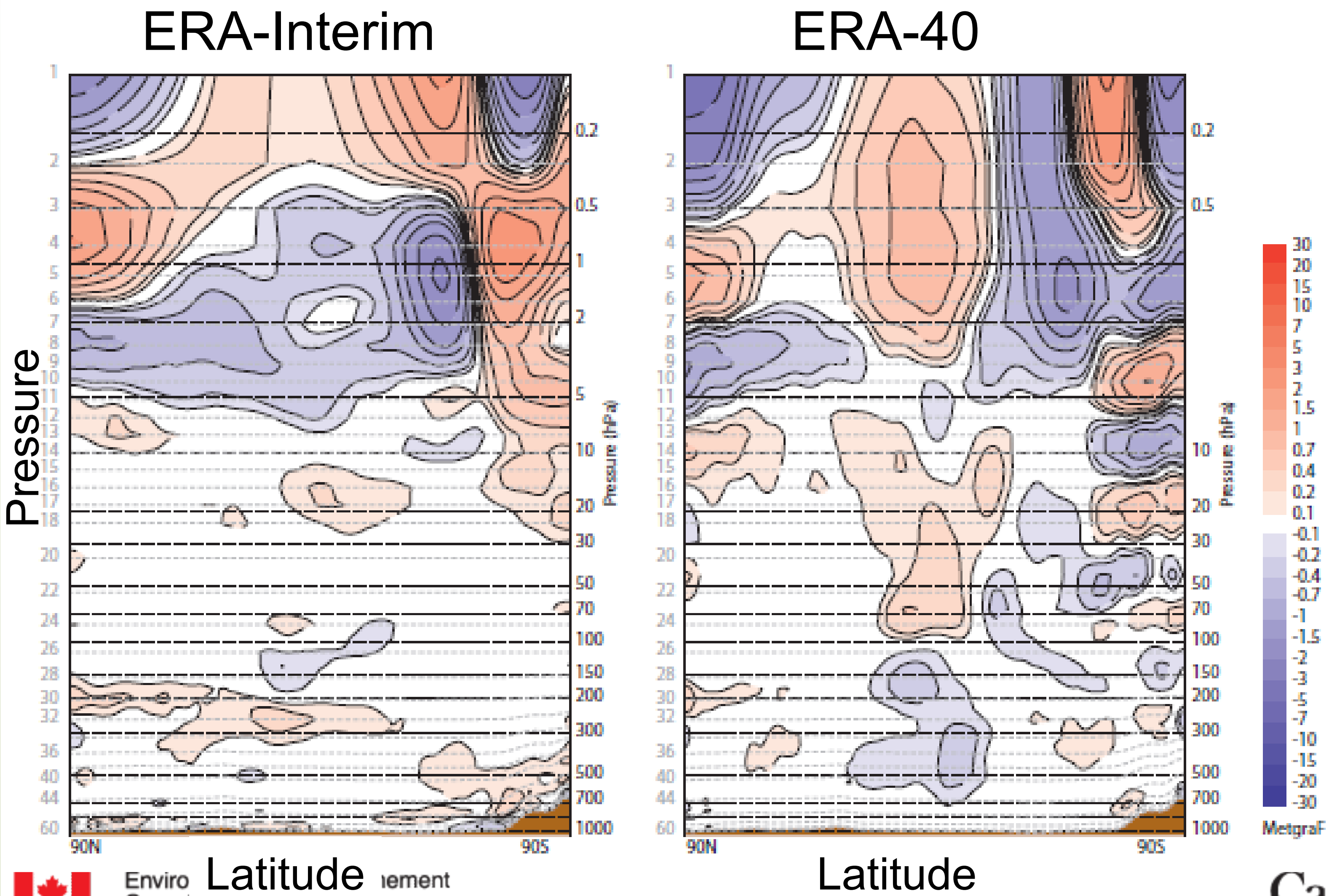
Tatyana Chshyolkova

Expect bias in stratosphere

- Since not all waves will be correctly analysed, and some waves are forced by uncertain parameterizations, we should expect errors in forcing of meridional circulation
- Errors in forcing of meridional circulation will create a latitudinally varying bias
- Measurements (e.g. nadir sounders) also have bias
- Obs bias corrections schemes often assume forecasts are unbiased

Zonal mean temperature analysis increments for August 2001

Dee and Uppala (2008)



Variational bias correction

Derber and Wu (1998)

Model for bias

Bias parameters

$$\mathbf{b}(\beta,\mathbf{x}) = \sum_{i=0}^{N_P} \beta_i \mathbf{p}(\mathbf{x}_i)$$

Model state — predictors

$$J(\mathbf{x},\beta) = (\mathbf{x}^b - \mathbf{x})^T \mathbf{B}_x^{-1} (\mathbf{x}^b - \mathbf{x}) + (\beta^\beta - \beta)^T \mathbf{B}_\beta^{-1} (\beta^\beta - \beta)$$
$$+ (\mathbf{y} - \mathbf{h}(\mathbf{x}) - \mathbf{b}(\mathbf{x},\beta))^T \mathbf{R}^{-1} (\mathbf{y} - \mathbf{h}(\mathbf{x}) - \mathbf{b}(\mathbf{x},\beta))$$

Bias parameters are determined using fit to all observations

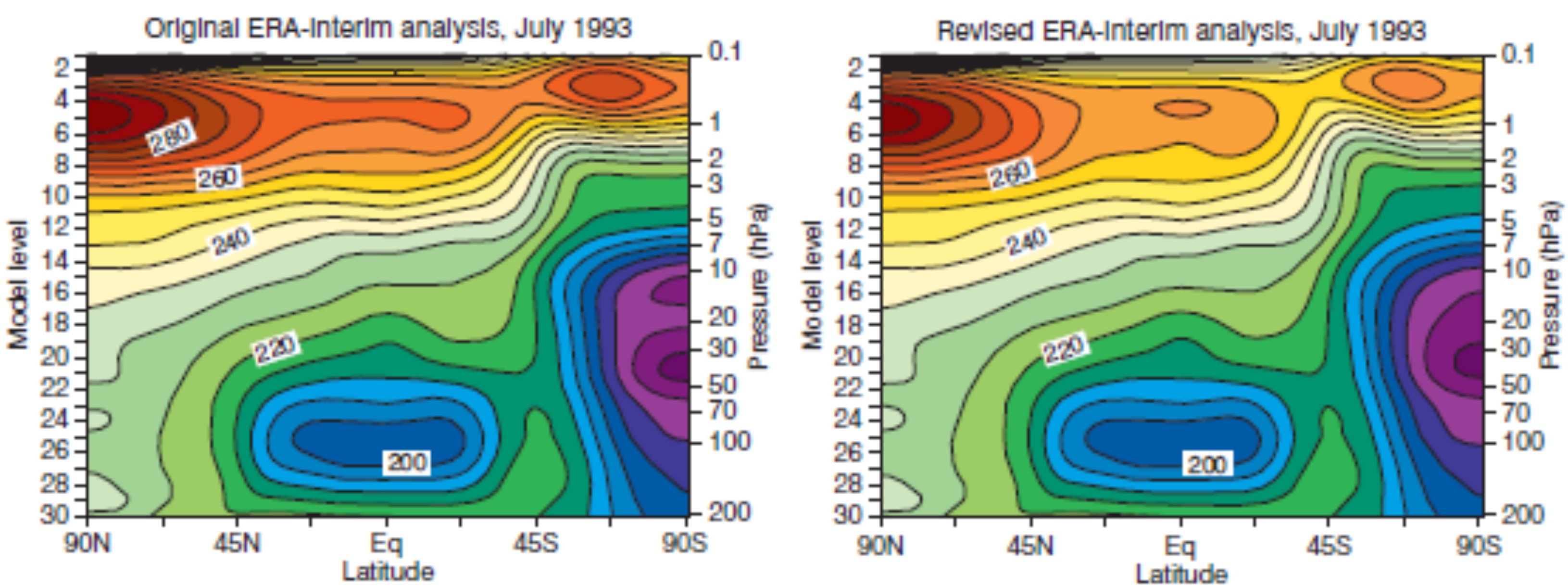
Bias correction will adjust for bias in observations ($\mathbf{y}$), obs operator ($\mathbf{h}$), and model state ($\mathbf{x}$)

Do not bias correct obs at model top

Dee and Uppala 2008

- Bias correction for SSU ch. 3 (peak ~2 hPa) too large compared to accuracy of instrument
- Assume SSU correct. Do not bias correct it (except scan angle bias)
- Zonal mean temperature reduced. (Model forecast was biased warm)

In general: anchor analyses at top using uncorrected data (SSU ch. 3 or AMSU ch. 14)



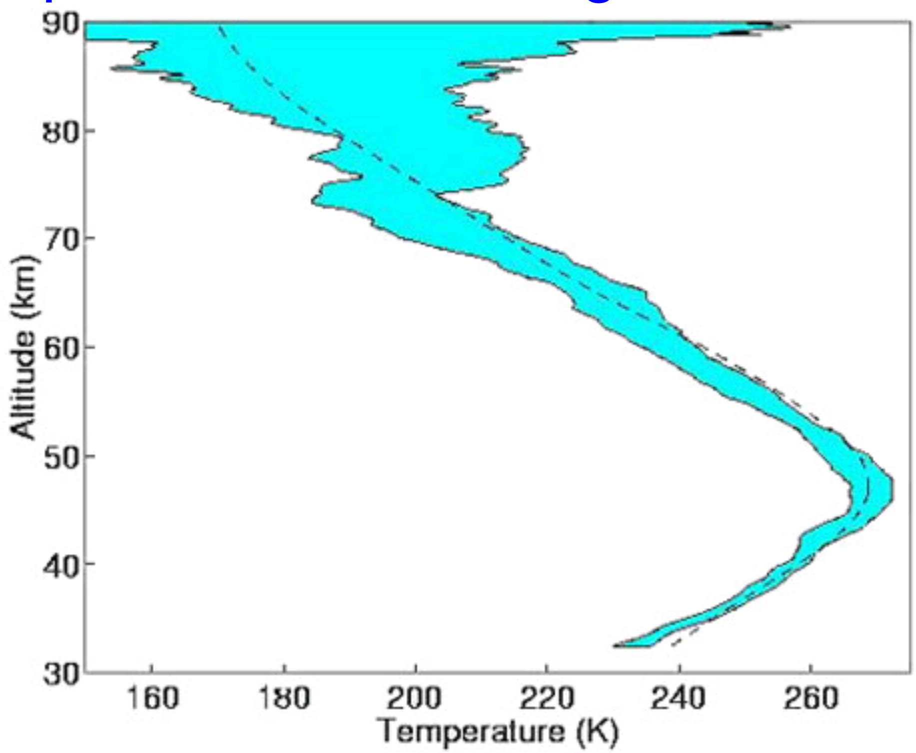
Vertically propagating waves
and their relevance to data assimilation

- Tropospheric waves (whether correctly simulated or not) impact zonal mean flow in strat/mesosphere
  - Random signals (waves) can produce nonlocal systematic errors (zonal mean bias)
- Since not all waves are correctly simulated, we should expect bias (errors in zonal mean) in meso/stratosphere
  - Implications for obs bias corrections schemes that assume background is unbiased
- Mesosphere is sensitive to errors in tropospheric analyses
  - Perhaps we can use sensitivity to help choose assimilation parameters in troposphere
- Information propagates up (through resolved waves)
  - Some of large scales in mesosphere can be improved even with no mesospheric obs if tropospheric wave forcing is captured

Gravity waves in the mesosphere

Gravity waves may be a nuisance in the troposphere, but they are prevalent in the mesosphere and are part of the signal!

T profiles over one night from lidar



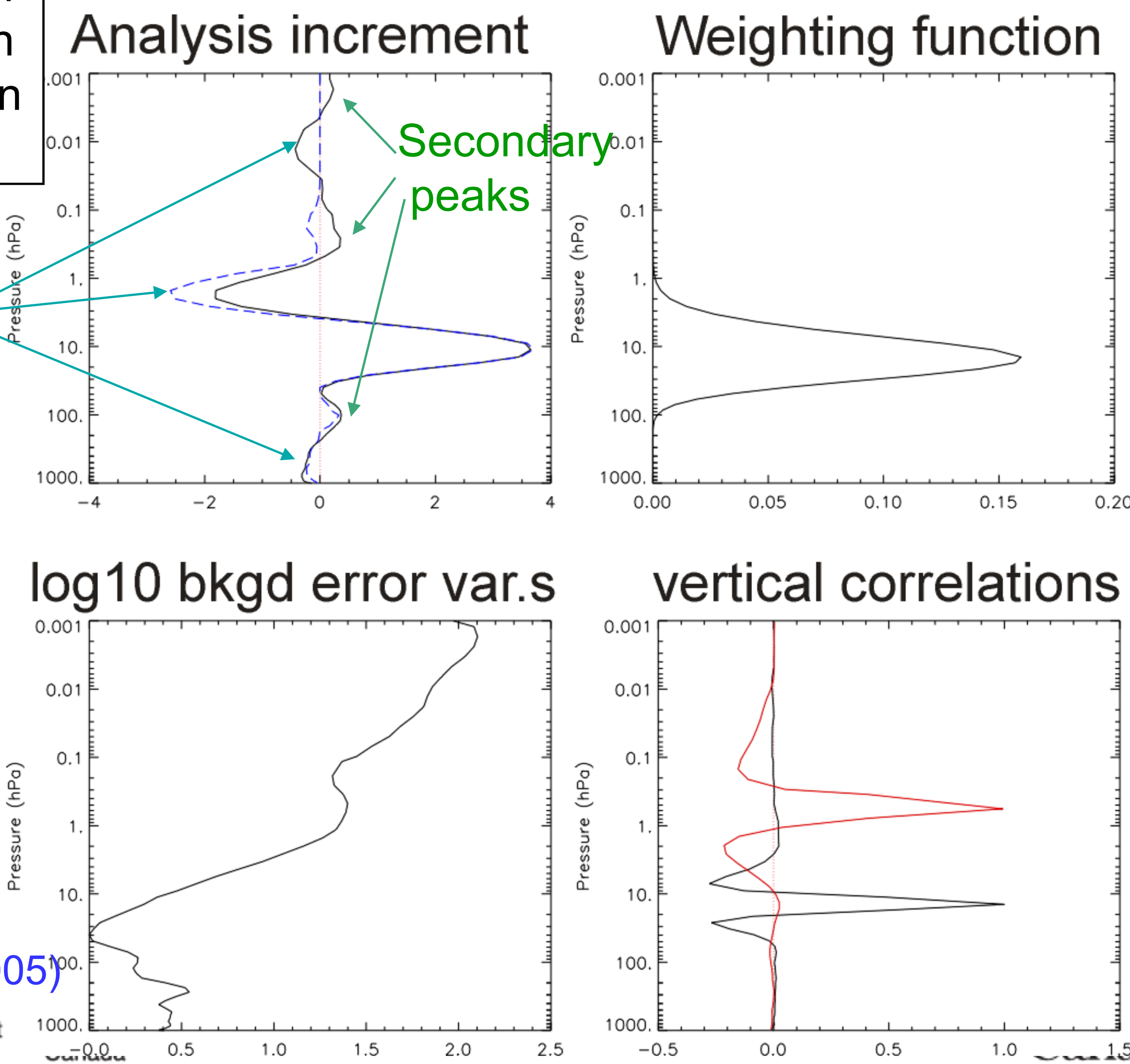
Geophysical variability is much larger than instrument error

R.J. Sica (U Western Ontario)

http://pcl.physics.uwo.ca/science/temperature/

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

AMSU ch. 11



Polavarapu et al. (2005)

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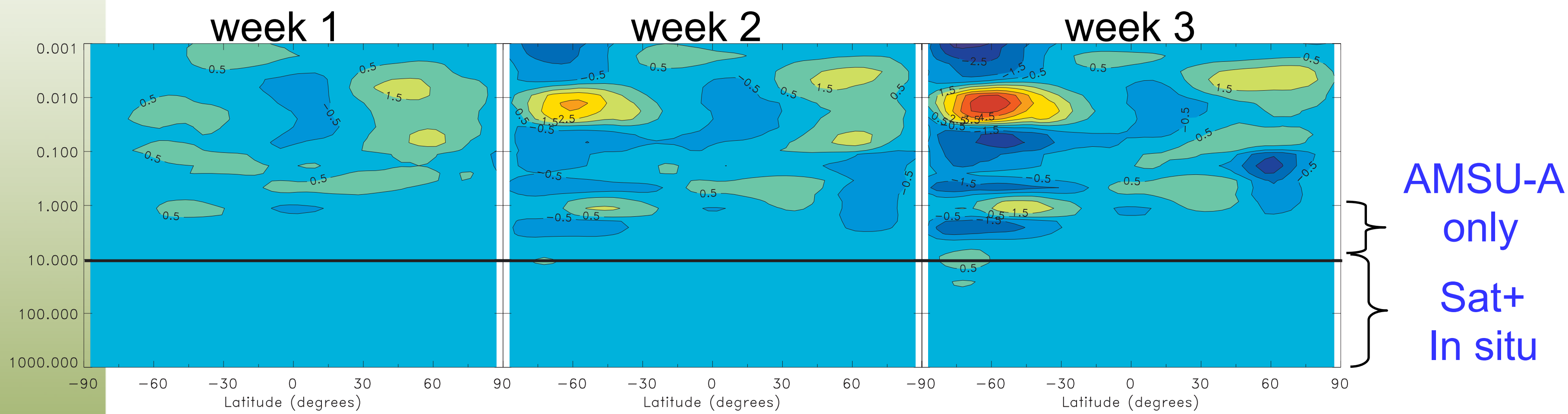
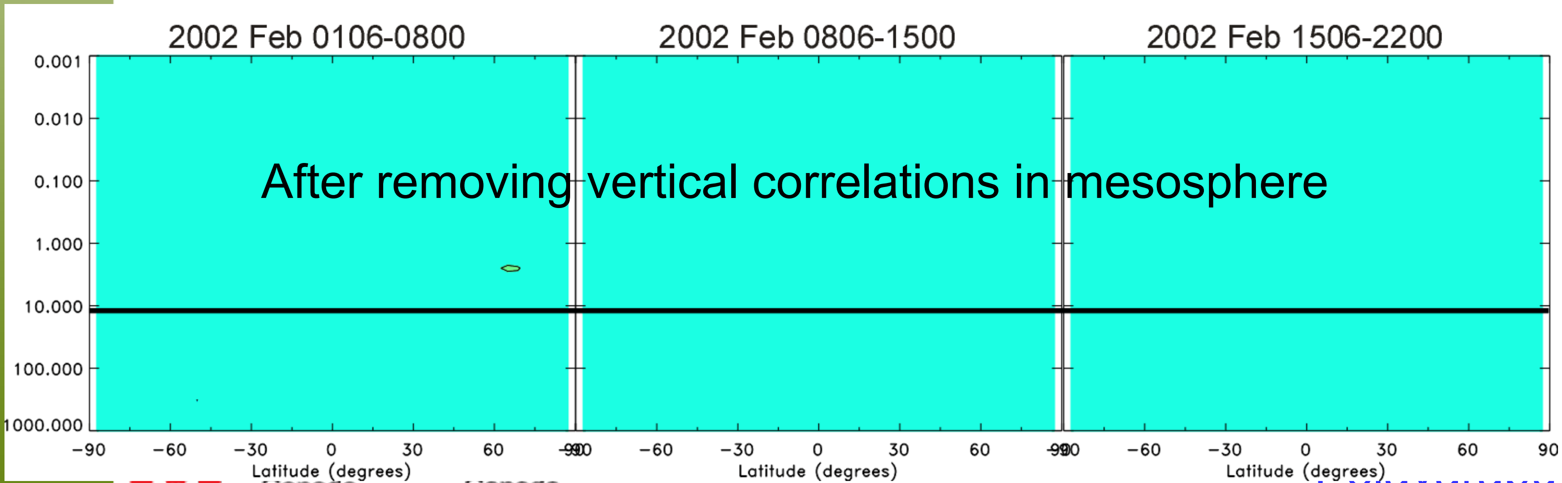
Extreme sensitivity to correlations

Zonal and time mean analysis increment for zonal wind





et al. (2006)

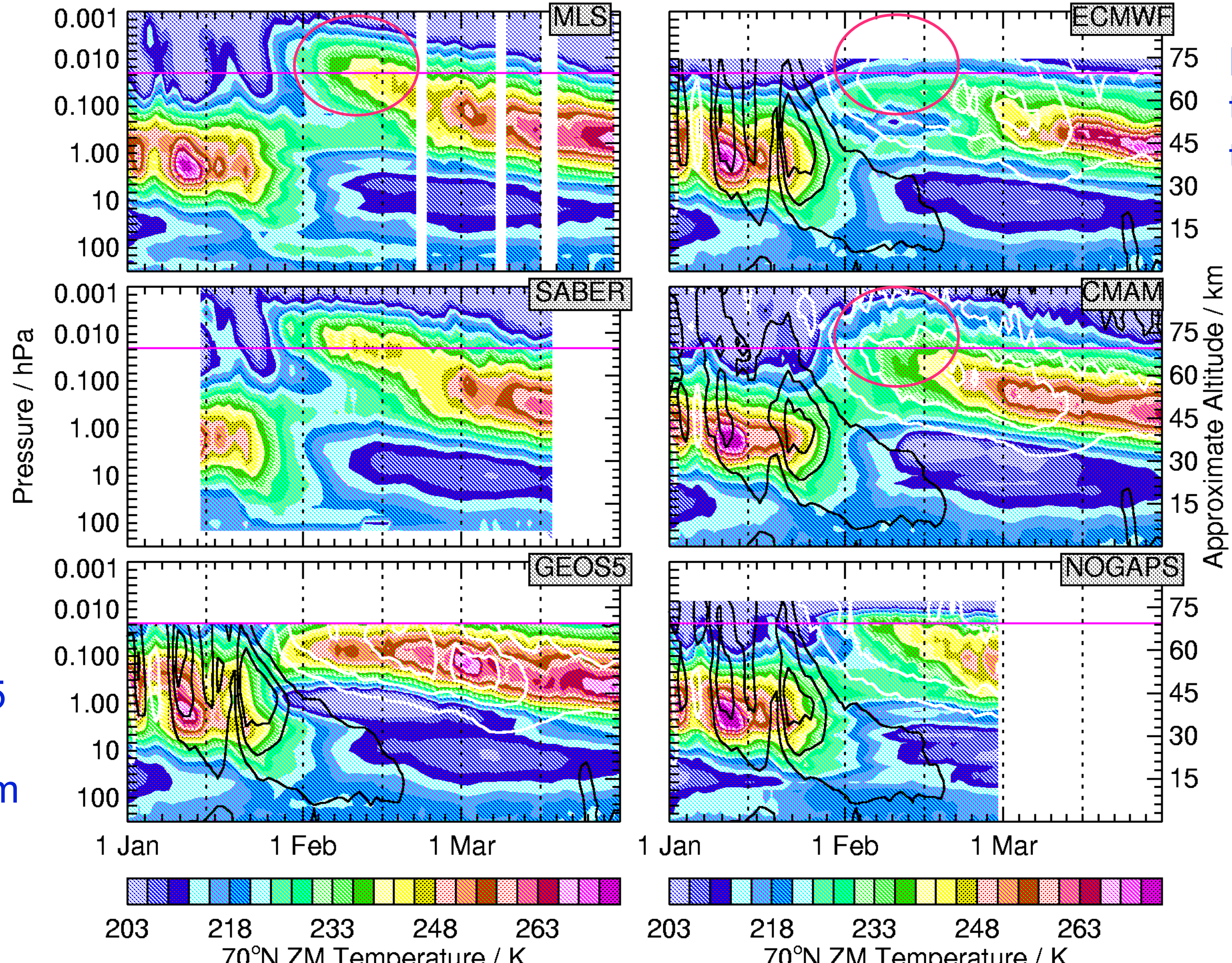
Information propagation through a Gravity Wave Drag (GWD) scheme

- A GWD scheme simulates the processes of gravity wave generation (in the troposphere), vertical propagation and breaking and computes a drag
- A forcing term is added to momentum equations
- Why are GWD schemes used?
  - Poor resolution of climate models means not enough gravity wave forcing of meridional circulation
  - Not enough downwelling or warming over winter pole leads to "cold pole problem". Evident in SH where fewer PWs.
  - To solve this, effect of subgrid scale GWs on mean flow is parameterized using assumptions about GW sources in the troposphere

70ºN zonal mean temperatures during 2006 SSW

Gloria Manney

Stratopause is above 0.01 hPa!



ECMWF too low too cold

GEOS-5 too low too warm

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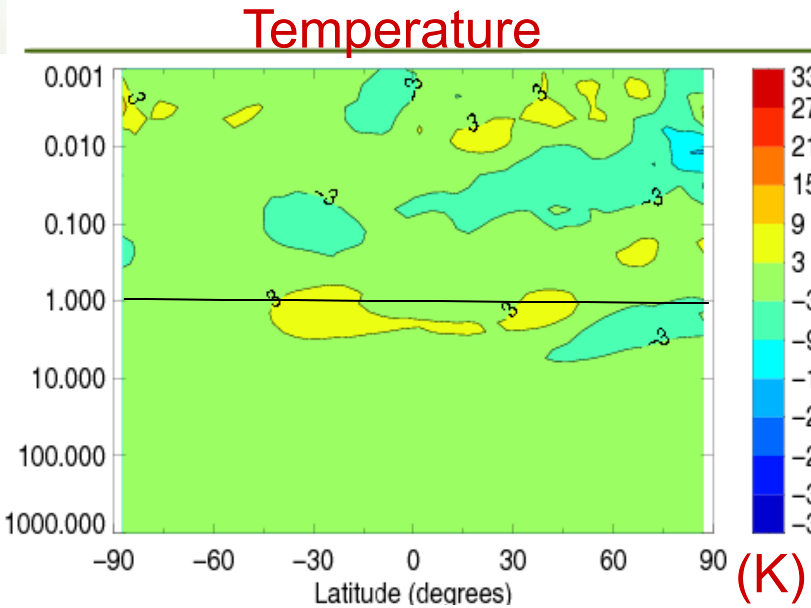
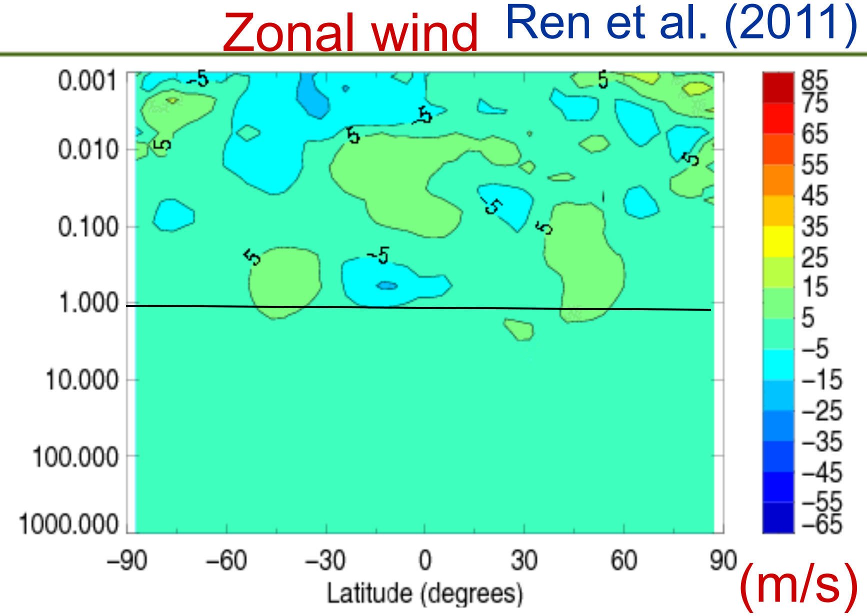
Zonal mean difference due to assimilation of mesospheric temperatures from SABER on 15 February 2006

Ren et al. (2011)



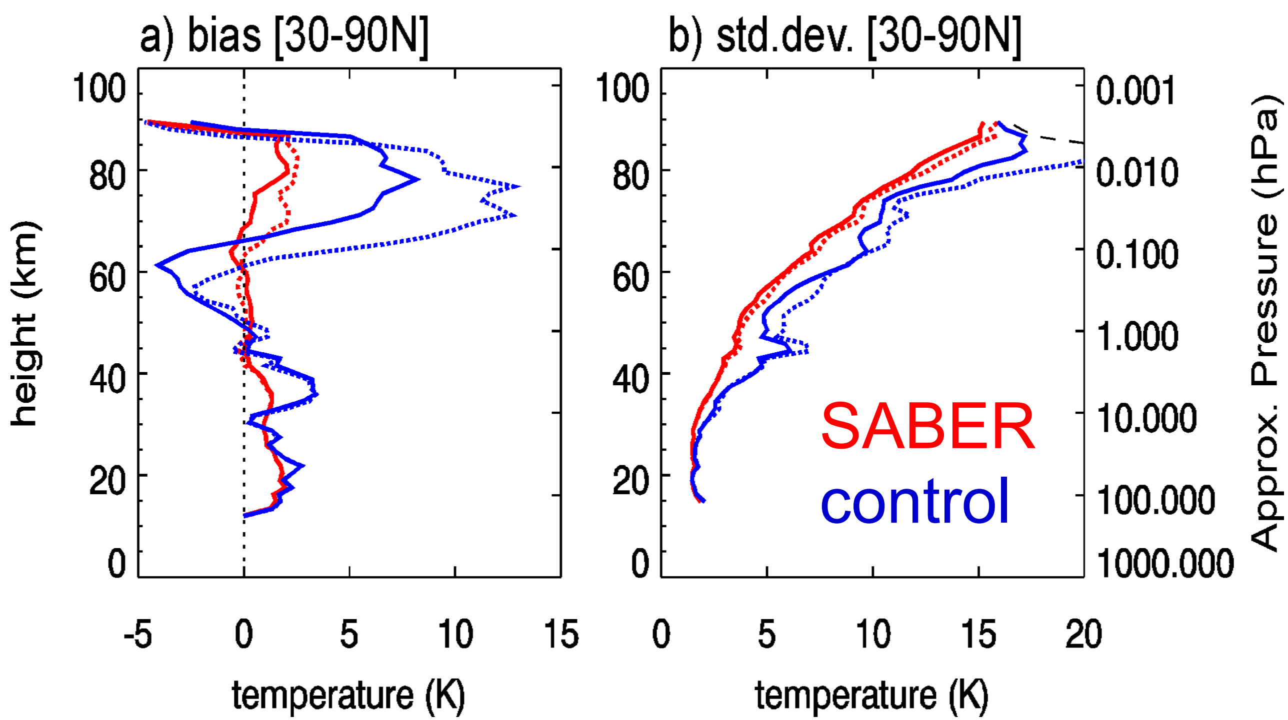


GWD improves fit to observations

Ren et al. (2011)

SABER T minus 6h forecasts (1-14 February 2006)

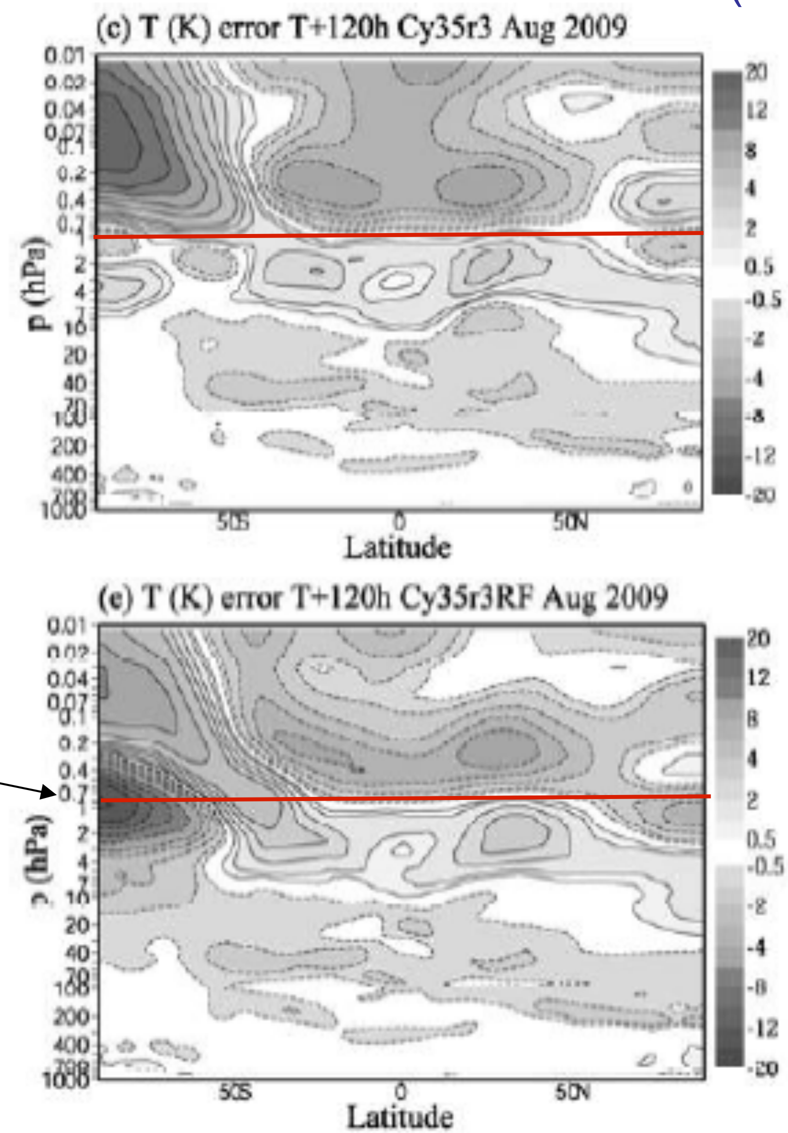
____ with GWD
- - - - w/o GWD



Impact on ECMWF forecasts

Orr et al. (2010)

Mean 5-day forecast error for Aug 2009 (ECMWF,T511L91)



Scinocca (2003) nonoro GWD scheme

Bias at winter pole stratopause

Rayleigh friction

Gravity waves in the mesosphere
and their relevance to data assimilation

- Extreme sensitivity of mesosphere to errors in background error covariances. Can propagate information from stratosphere to mesosphere creating persistent spurious increments if forecasts are biased
- Covariances can also spread information to small vertical scales. This is risky because nadir observations lack detailed vertical information to correct erroneous structures. Need more limb obs (e.g. GPSRO, MLS)!
- Information from troposphere/stratosphere also coupled to mesosphere through gravity wave drag schemes

Summary

- Some challenges in stratospheric and mesospheric data assimilation
  - Observations (not much vertical information, no winds)
  - Bias comes from random errors! (dissipating waves→ zonal flow)
  - Both models and obs are biased
  - Gravity waves are part of the signal
  - Errors propagate vertically
- Information propagation: role of model versus observations
  - Even without observations, larger scales of mesosphere are defined
  - Gravity wave drag scheme can be helpful

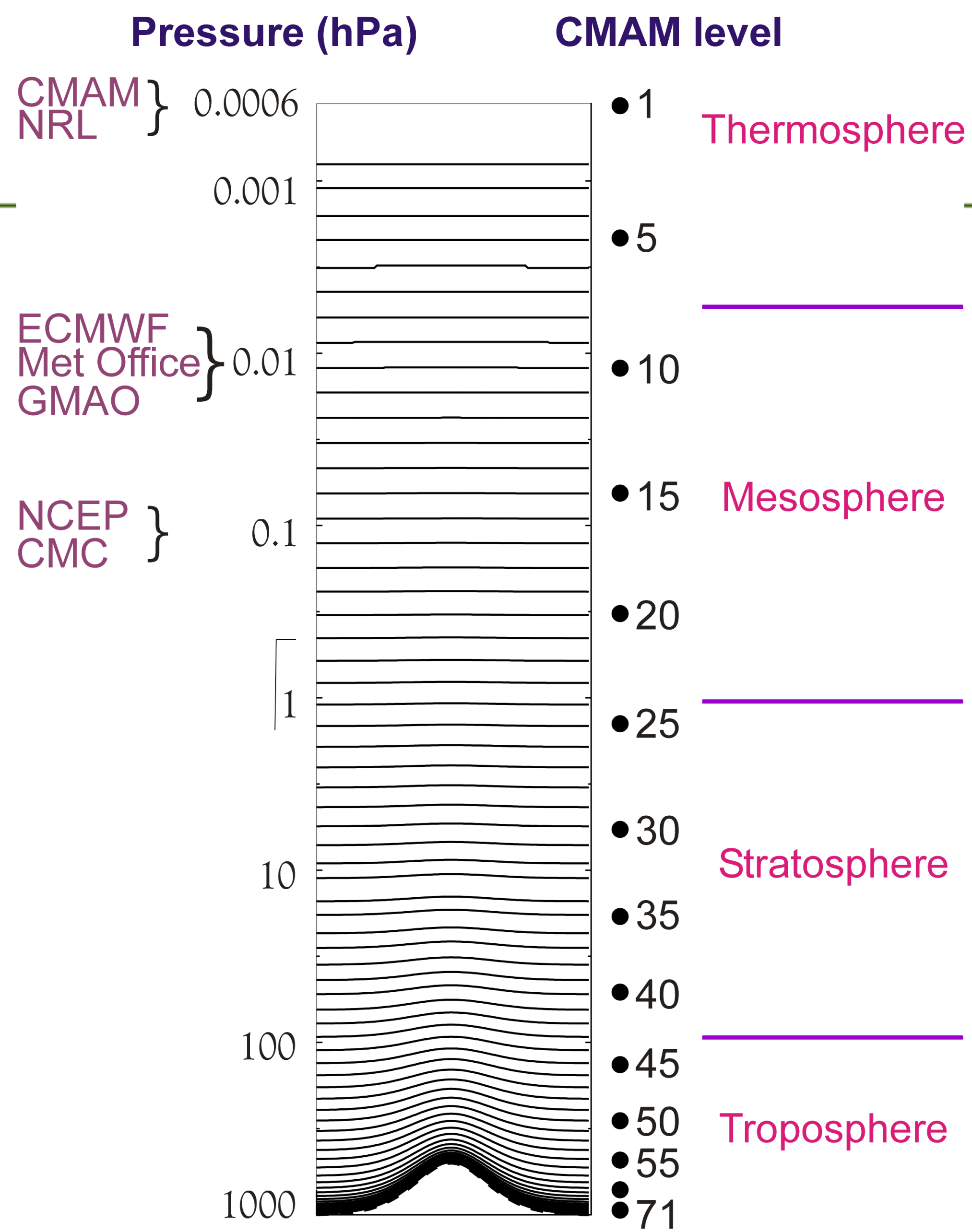
EXTRA SLIDES

CMAM = Canadian Middle Atmosphere Model is a chemistry climate model (CCCma GCM3)

No obs

Nadir sounders

conventional obs + sat.



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Missing zonal momentum force

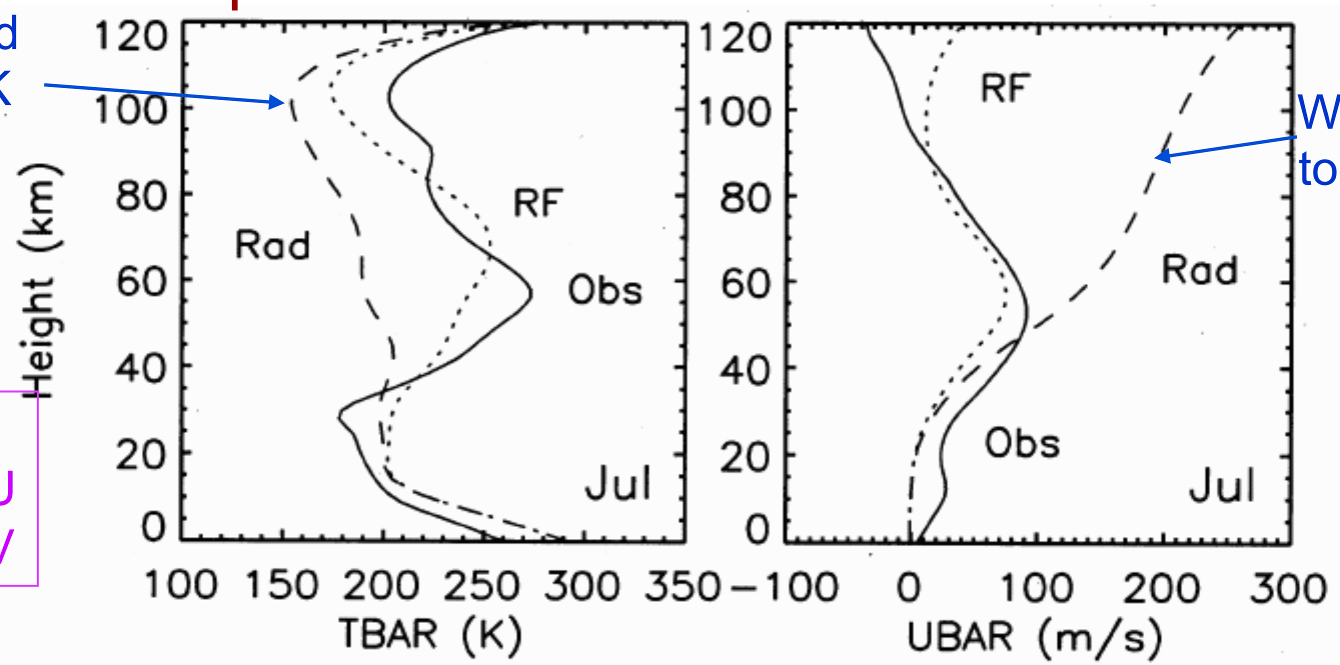
McLandress (1998)

Consider 2D, steady, geostrophic, hydrostatic flow. Why is radiative equilibrium temperature much colder than that observed?

zonal mean fields in SH winter

Temperature at 90°S Zonal wind at 40°S

Too cold by 50K



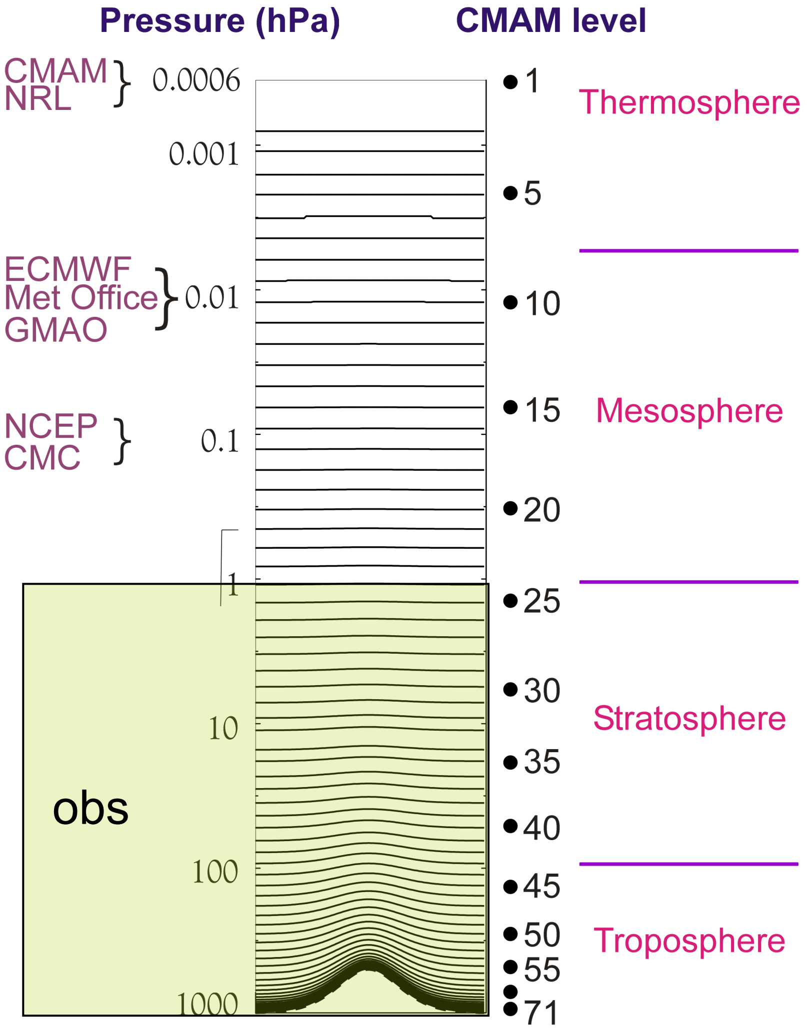
Winds far too strong

RF: add
$F_u=K(z)U$
$F_v=K(z)V$

Why consider the stratosphere separately from tropospheric dynamics?

- Assume we want to simulate the stratosphere
- Why should we worry about middle atmosphere dynamics? The troposphere has 80% of the mass of the atmosphere.
- Let's just raise the model lid

CMAM = Canadian Middle Atmosphere Model is a chemistry climate model (CCCma GCM3)



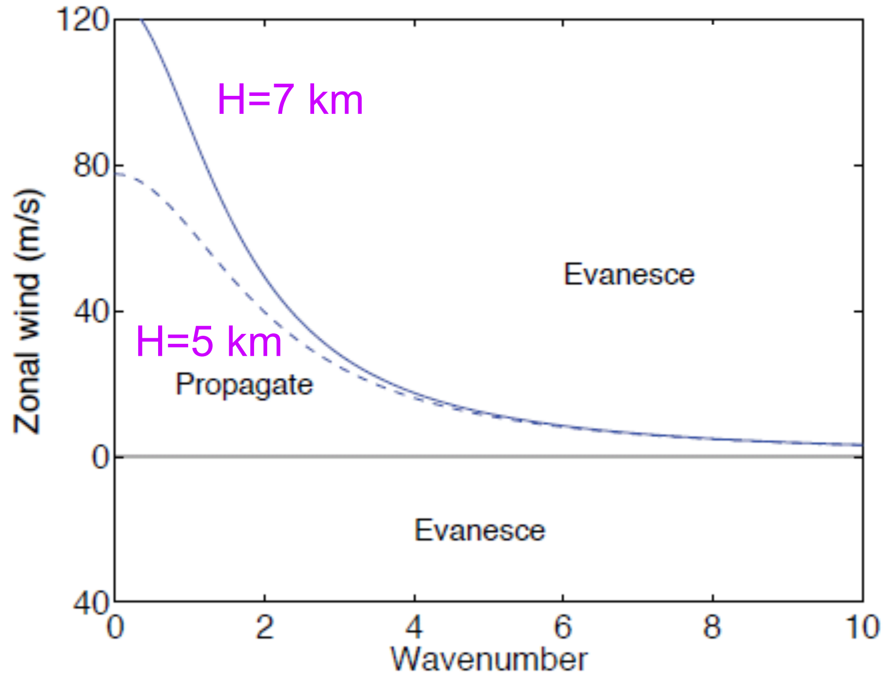
Summer versus winter

Vallis (2006)

Charney-Drazin criterion:

- For linearized Q-G PV equation forced by wave at bottom boundary, for constant U:

  $0 < U\text{-}c < U_{crit}$
- Rossby waves can propagate vertically only in eastward winds that are not too strong.
- Large scale waves more likely to meet criterion.

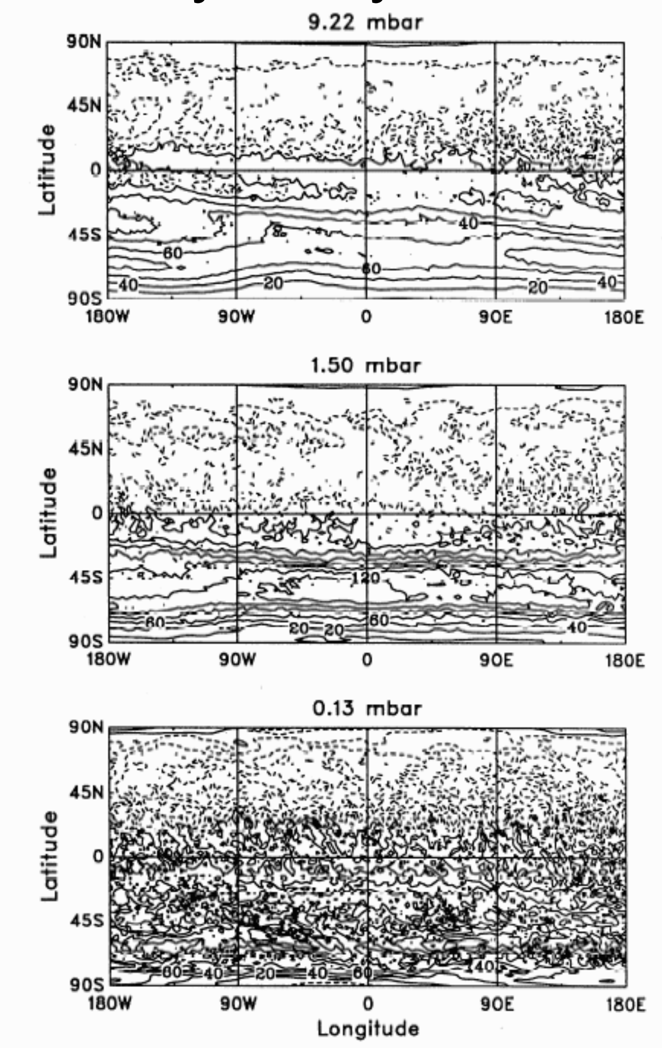


- Winter stratosphere (westerlies)
  - Dominated by large scales due to Charney-Drazin filtering
- Summer stratosphere (easterlies)
  - Rossby waves can't prop vertically due to critical level filtering

Zonal wind snapshot

Koshyk et al. (1999)

July 9 SkyHi fields



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

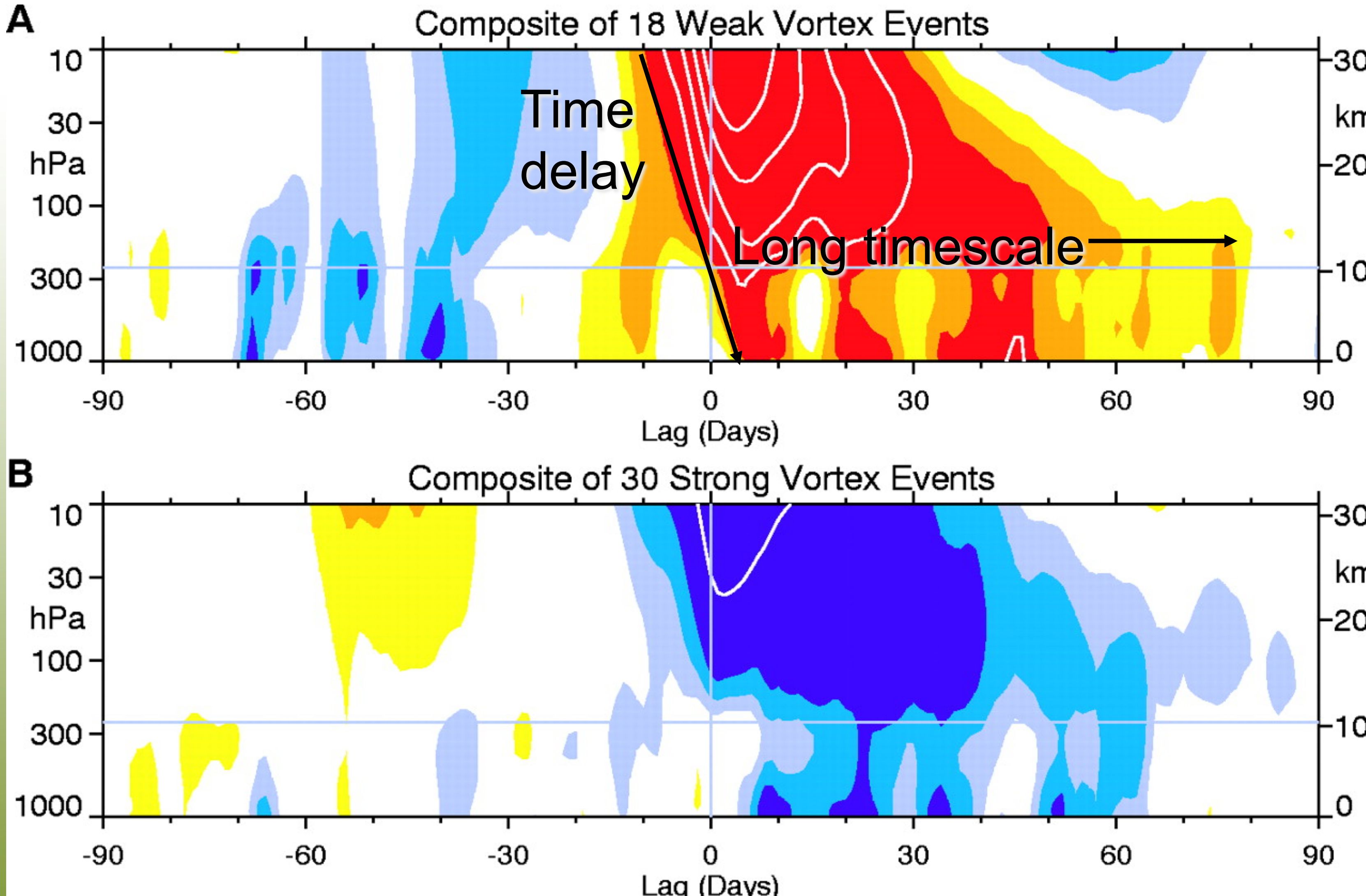
Middle stratosphere

Dominated by large scales

Stratopause

Mesosphere

GWs are Important!



The events are determined by the dates on which the 10-hPa annular mode values cross -3.0 and +1.5, respectively.

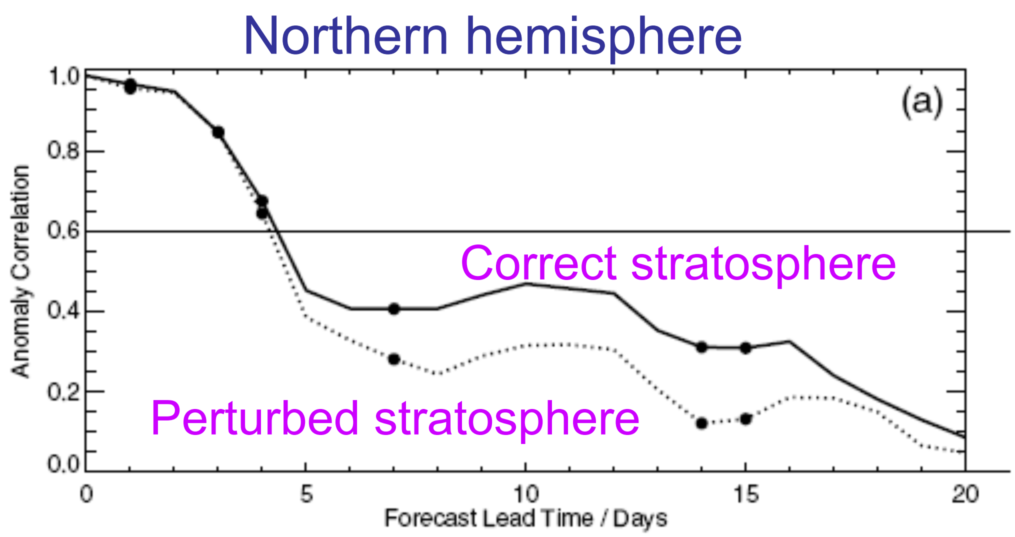
Baldwin and Dunkerton (2001)

A good stratosphere can help improve tropospheric forecast skill

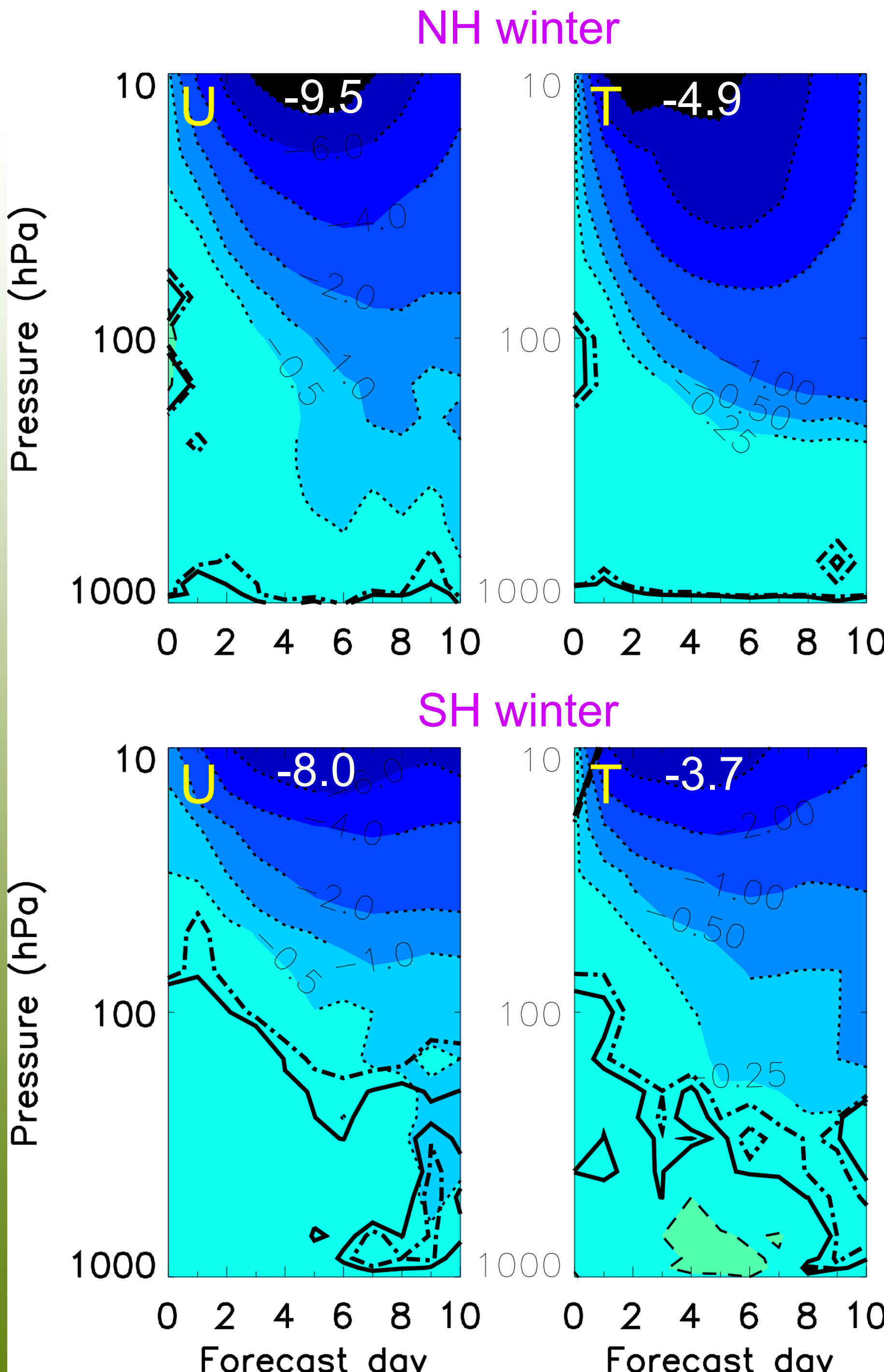
Charlton et al. (2005)

- Improve 10-15 day forecasts

500 hPa height anomaly correlation



Winter polar dynamics



Improvement in forecast error stddev

Winter NH

Dec. 26 – Feb. 2, 2007 (77 cases)

Winter SH

June 22 – Aug. 21, 2006 (122 cases)

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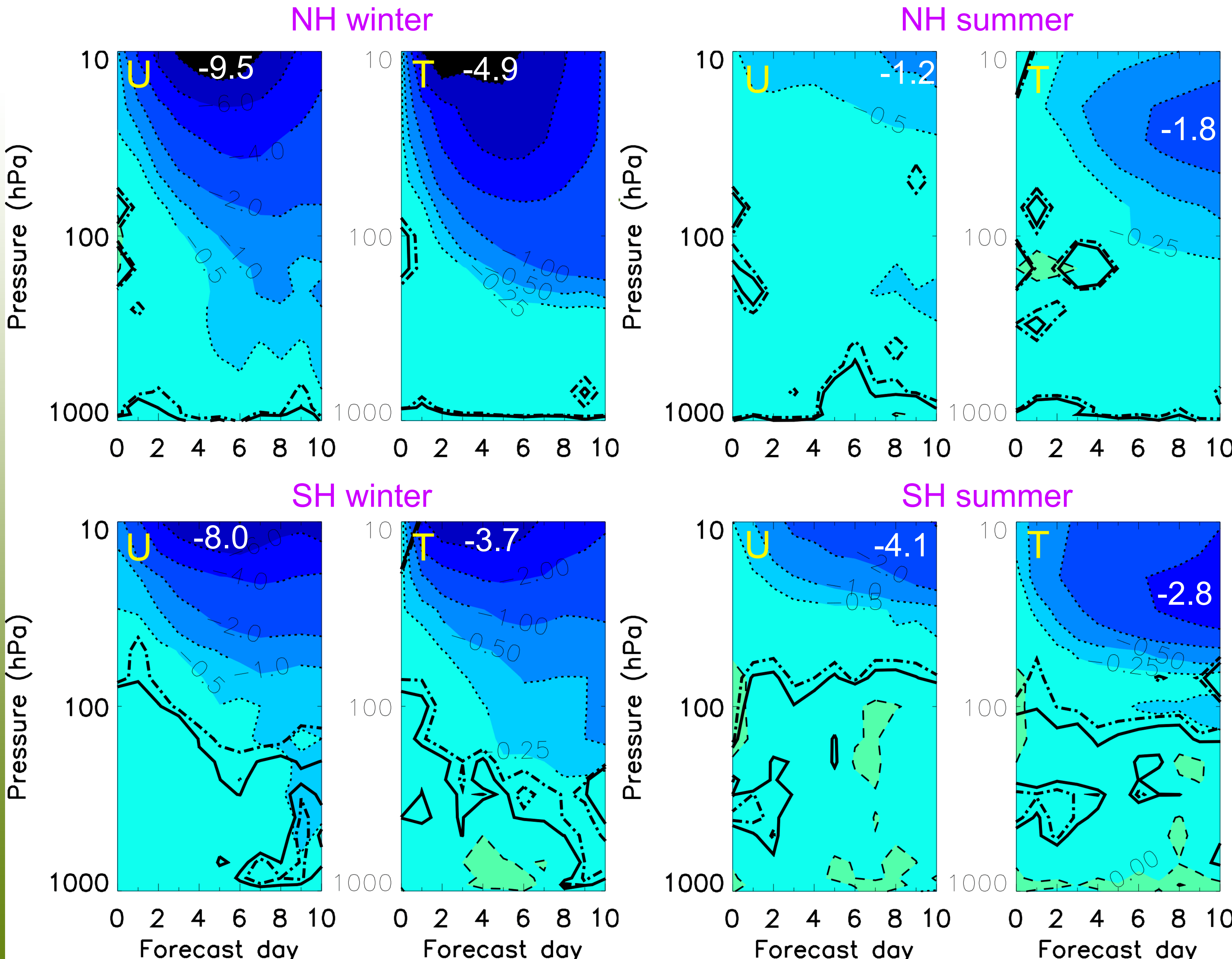
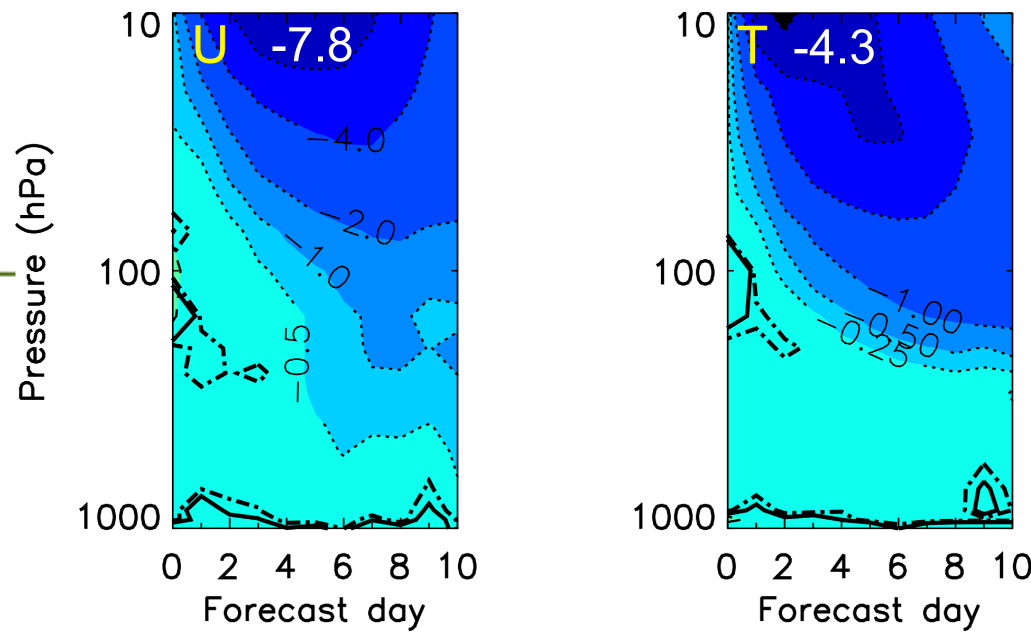


NH winter
NH summer
SH winter
SH summer
U
T
-9.5
-4.9
-1.2
-1.8
-8.0
-3.7
-4.1
-2.8
Pressure (hPa)
Forecast day
10
100
1000
0 2 4 6 8 10

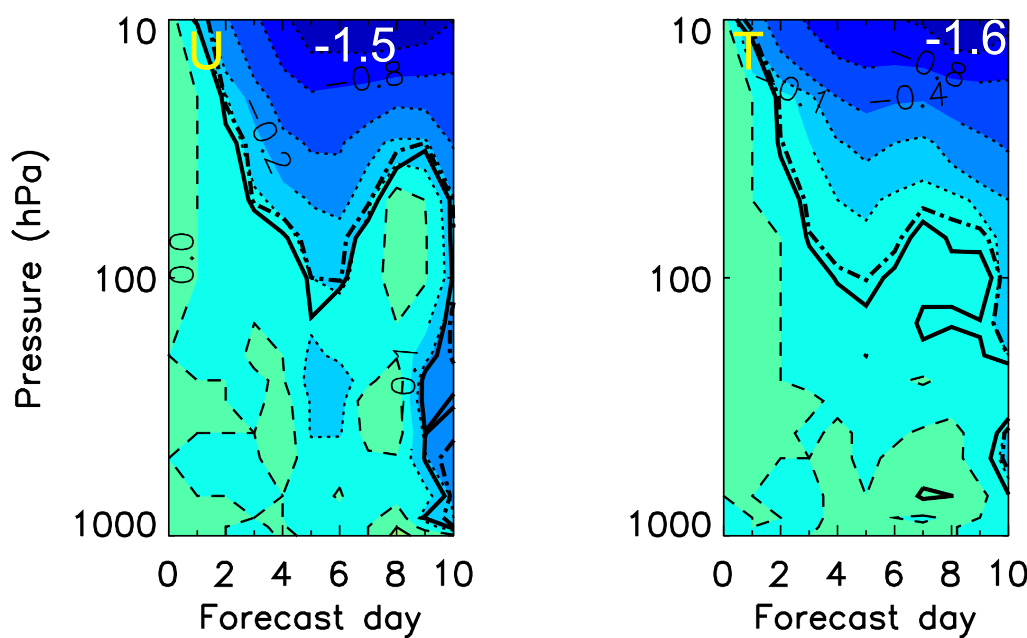
Winter NH stddev obs vs model

Impact of model changes



Most of the improvement is due to changes in model

Contour intervals not the same!



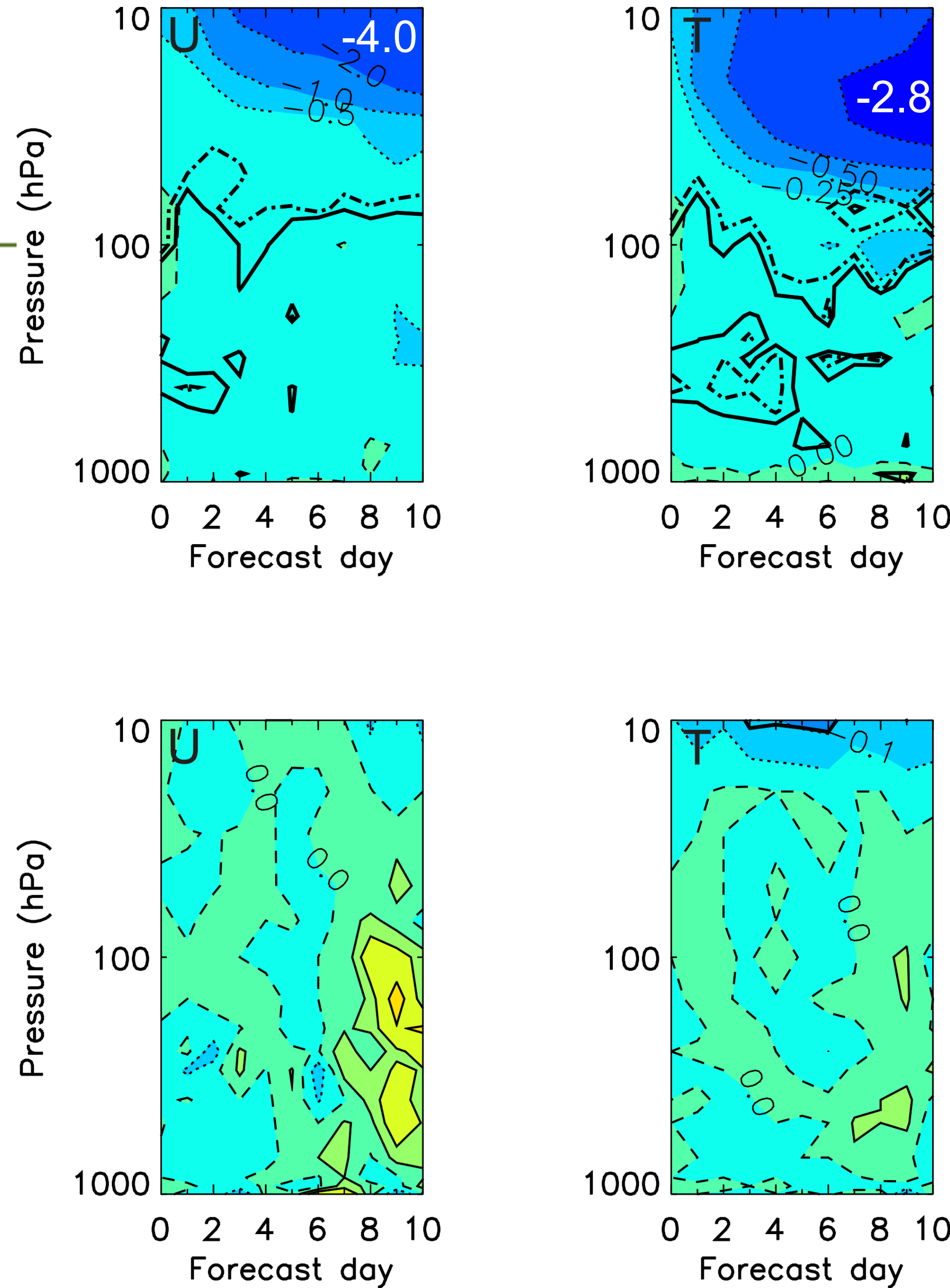
Impact of obs changes
(adding AMSUA 11-14 and GPSRO 30-40 km)

Summer SH stddev obs vs model

Impact of model changes

Only changes in model contribute to improvement

Impact of obs changes
(adding AMSUA 11-14 and GPSRO 30-40 km)



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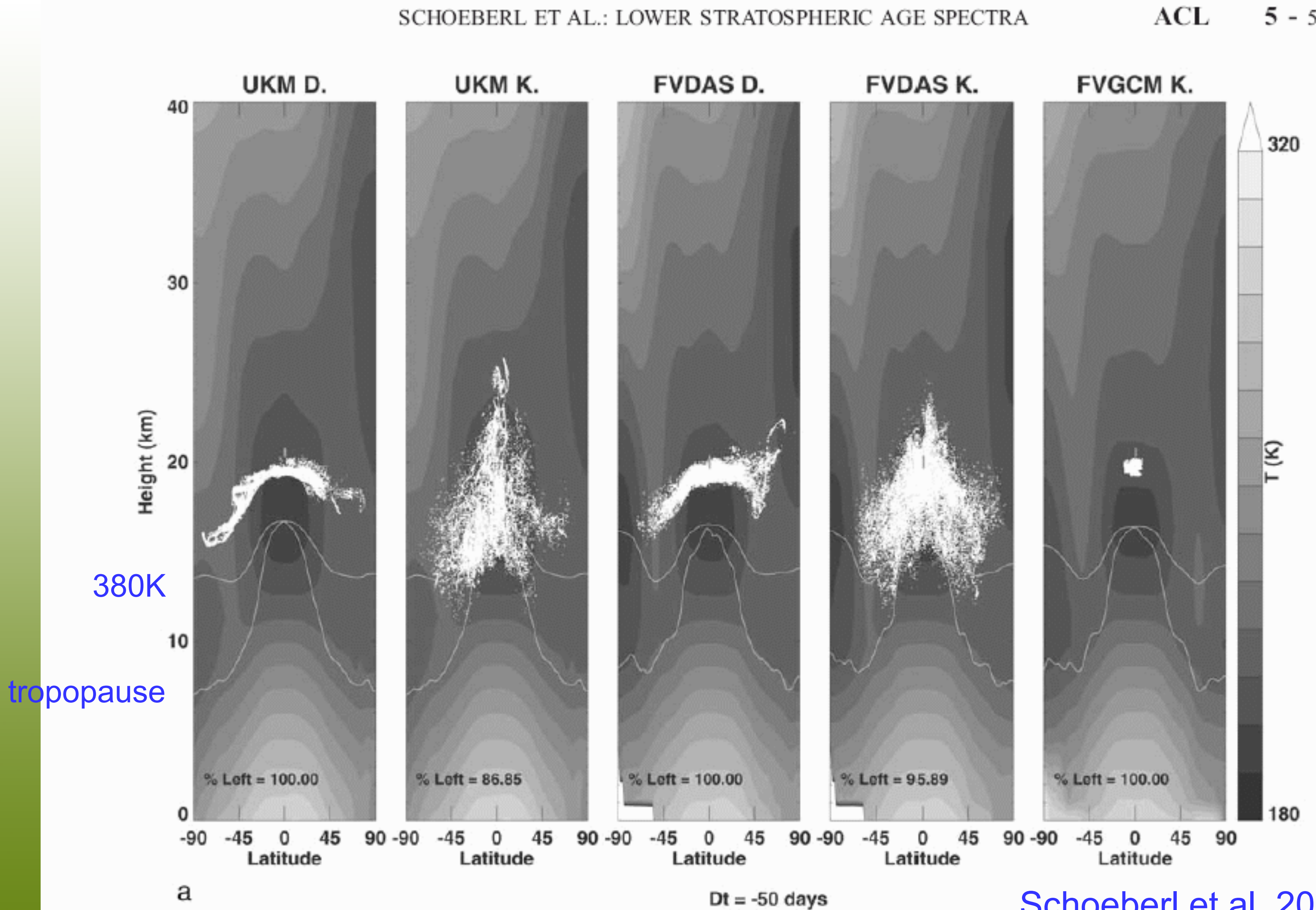
Winter polar dynamics and data assimilation

- Improvement is much greater in winter than summer (improvement depends on season, not hemisphere)
- Extra obs in upper stratosphere are useful in winter but have no impact in summer
- Improvement achieved without adding new obs in upper stratosphere
- Is the improvement in tropospheric forecast scores due to the improved stratospheric depiction, or some other model change?

2. Transport of constituents

Distribution of parcels 50 days after start of back trajectories



Schoeberl et al. 2003

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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)

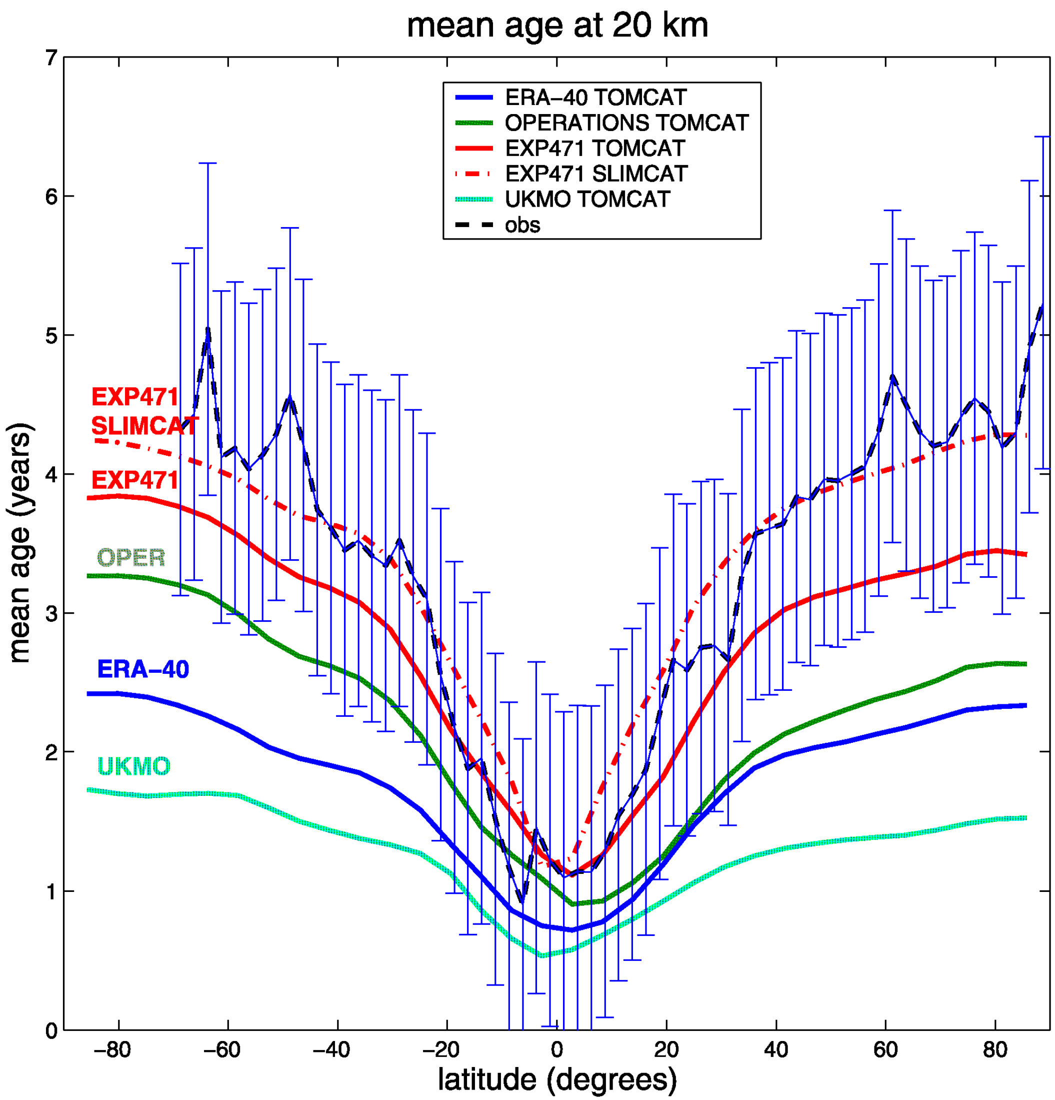
Problems with analysed winds:

- Vertical motion is noisy
- Horizontal motion is noisy in tropics
- Leads to too rapid tracer transport
- Tropical ascent: obs: 24 mo., GCMs: 12 mo., analyses: 6 mo.

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)

Improvements in assimilation techniques impact age-of-air



Monge-Sanz et al. (2007)

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

Operational 4D-Var (6h)

ERA40 3D-Var

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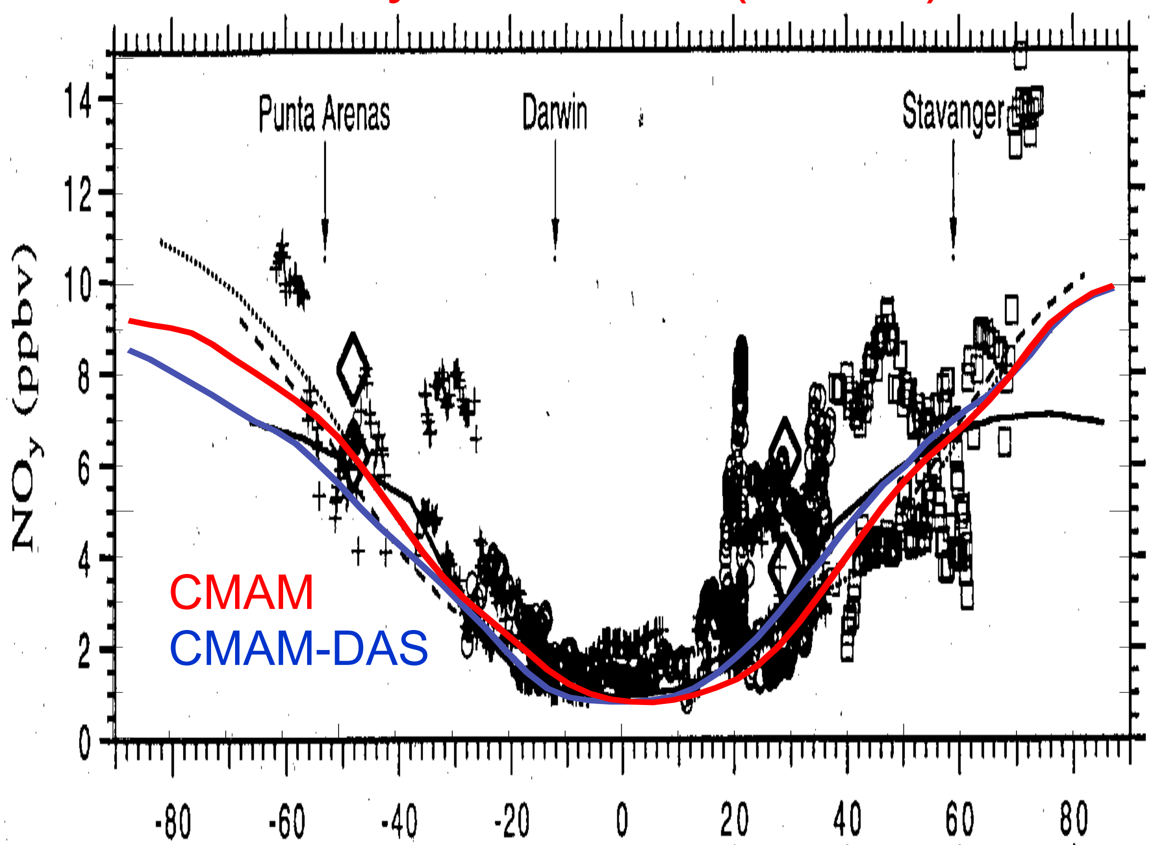
Latitudinal gradients can be well maintained even in 3D-Var analyses

Figure courtesy of Michaela Hegglin

NOy at 62 hPa (19 km)



ER2 aircraft data from Murphy et al. (1993)

CMAM-DAS - March 03

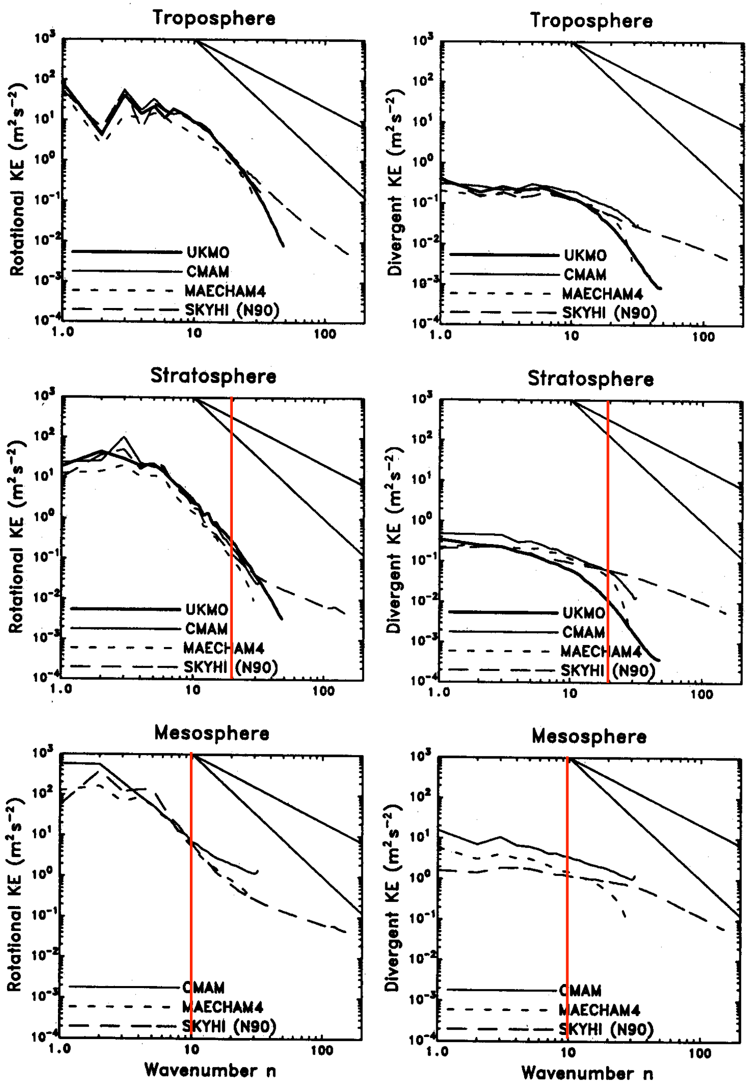
CMAM-DAS uses 3D-Var (not 4D-Var)!

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

	Low Top	High Top
Horizontal grid points	800 x 600	800 x 600
Vertical coordinate	Normalized sigma	Hybrid
No. of vertical levels	58	80
Lid height	10 hPa	0.1 hPa
Sponge layer at lid (Del2)	4 levels Acts on full fields	6 levels Acts on departures from zonal mean
Tropical sponge near lid	4 levels (coef=450) Down to 50 hPa	8 levels (coef=50) Down to 3 hPa
Radiation scheme	Fouquart/Bonnel + Garand	Li and Barker
Non-orographic GWD scheme	No	Hines
Methane oxydation	No	Yes
Ozone climatology	Kita and Suma (1986)	Fortuin et Kelder (1998) below 0.3 hPa, HALOE above 0.3hPa, Transition between 2 to 0.3 hPa
Total cost	1.0	1.5

Rot KE Div KE

Koshyk et al. (1999)



troposphere

stratosphere

mesosphere

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.

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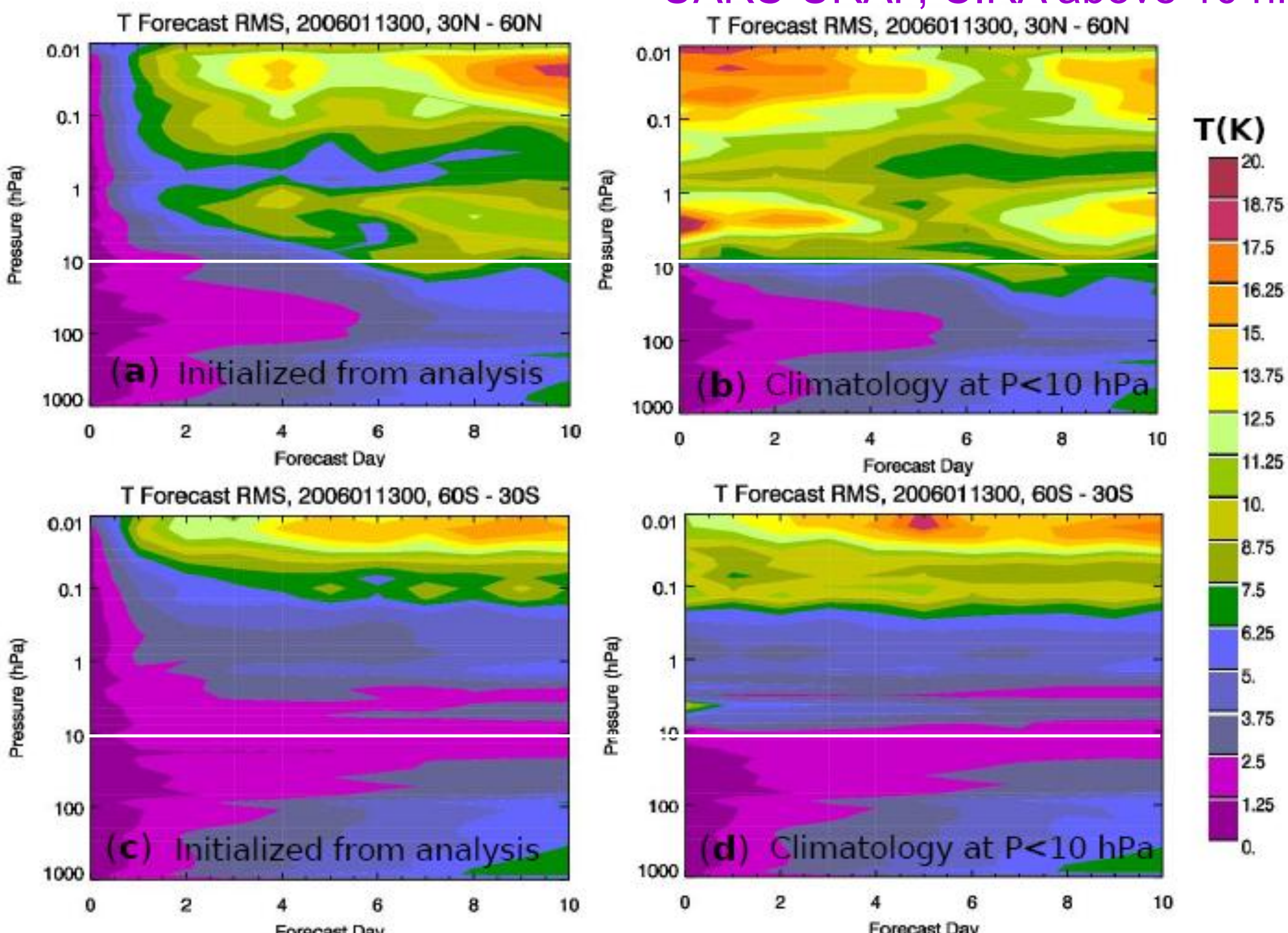
Assimilating mesospheric obs is useful esp in winter

Hoppel et al. (2008, SPARC Newsletter no. 30, p.30)

Forecasts from analyses

Forecasts from climatology
UARS-URAP, CIRA above 10 hPa



- NRL's model NOGAPS-ALPHA T79L68, lid at 96 km
- SABER, MLS temperature assimilated 32-0.01 hPa
- 12 forecasts during Jan-Feb 2007

Critical level filtering of waves by background mean winds

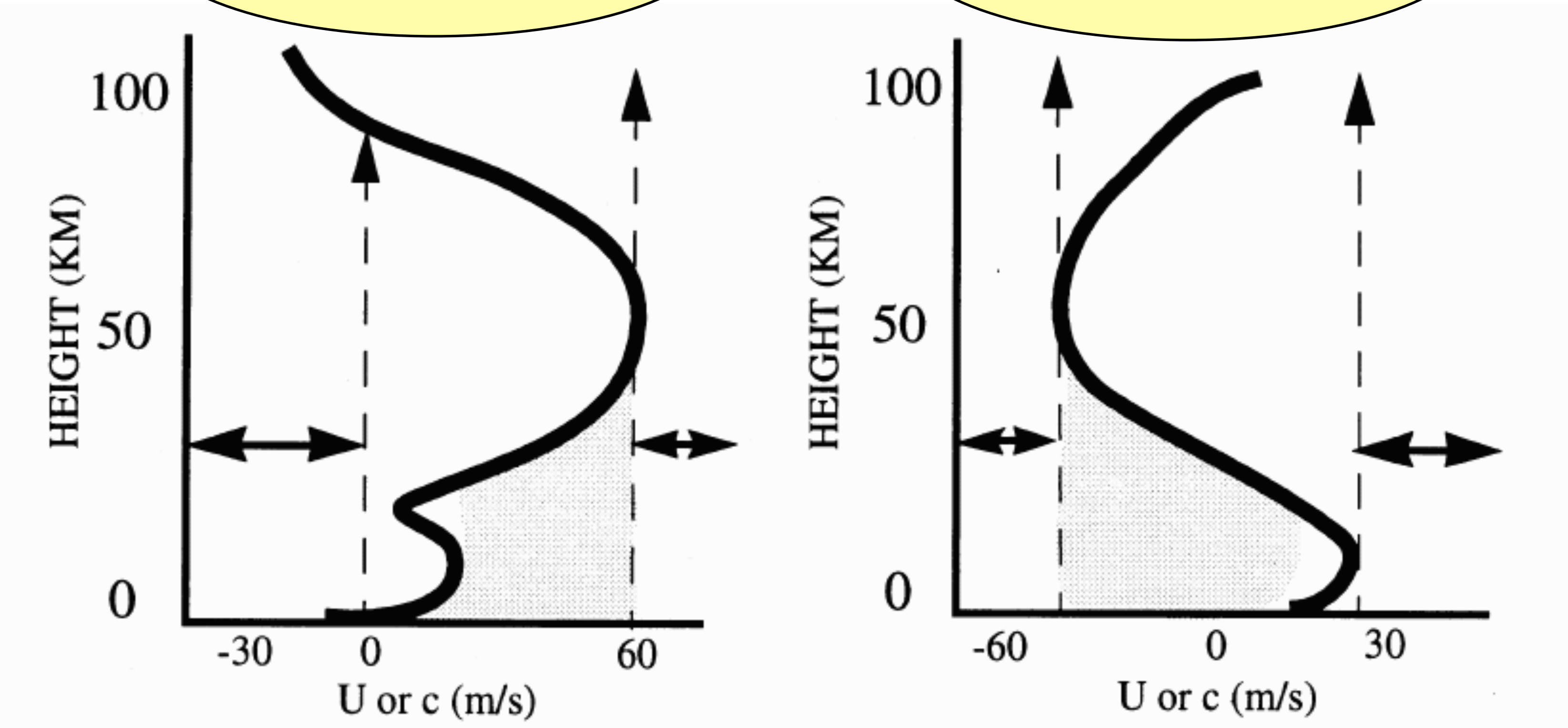
McLandress (1998)

WINTER

GWs c<0 break, drag reduces westerlies

SUMMER

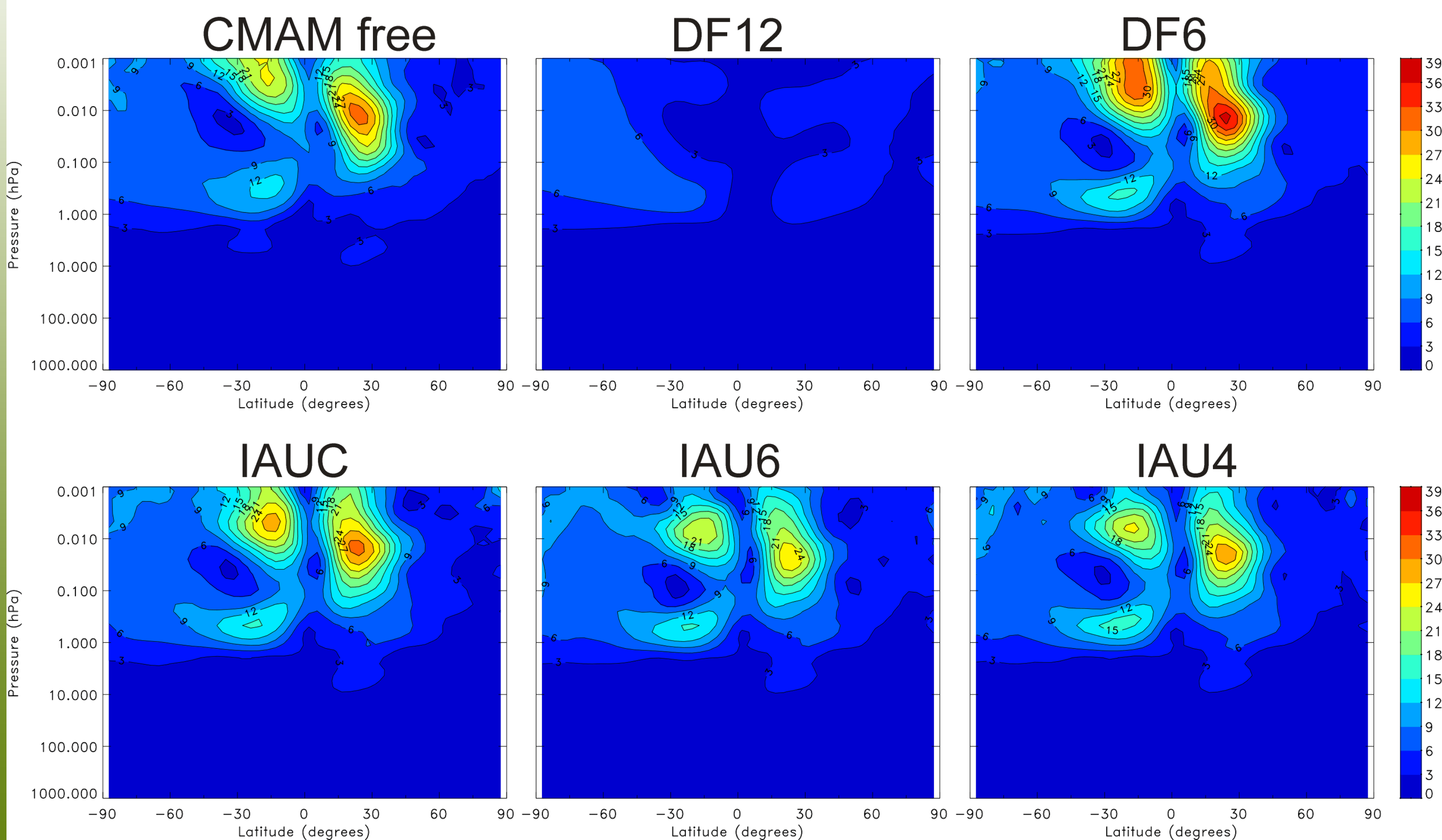
GWs c>0 break, drag reduces easterlies



Tropospheric waves impact mesospheric migrating diurnal tide

Sankey et al. (2007, JGR)

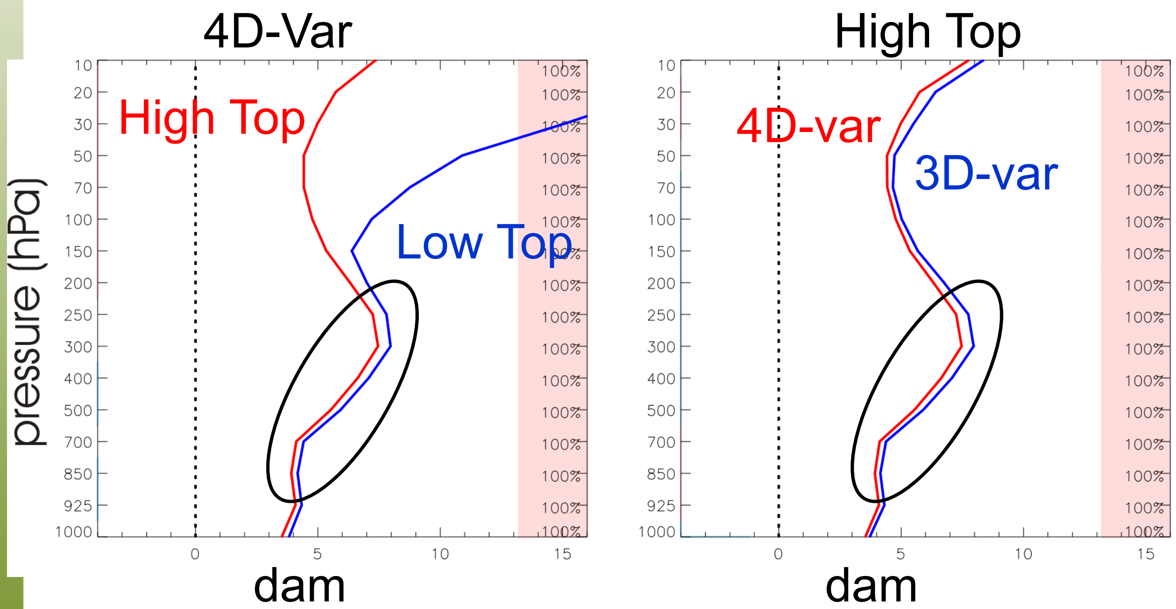
21-30 January 2002



Improving the stratosphere improves 5-day forecasts in the troposphere

On June 22, 2009 Canadian Meteorological Centre implemented operationally a global stratospheric model (0.1 hPa) for medium range weather forecasts

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



A good stratosphere impacts troposphere forecasts as much as 4D-Var

Winter

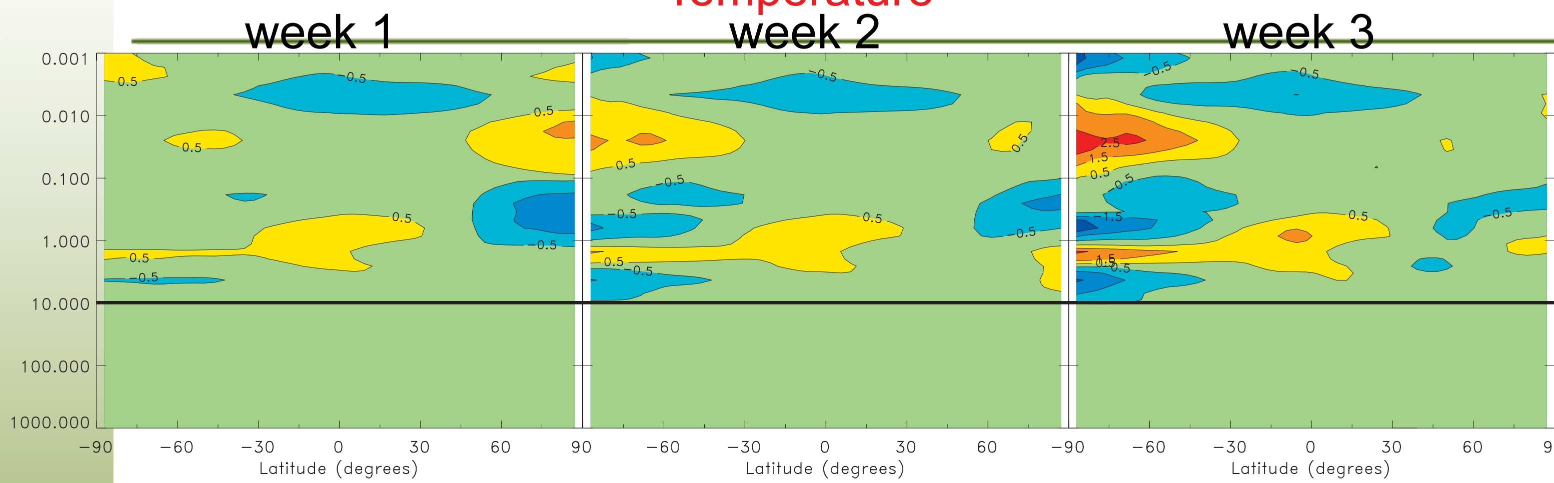
Dec. 20 – Jan. 26, 2006 (75 cases)

Polavarapu et al (2011)

Obs and/or model forecast is biased

Zonal mean and time mean anal. incr.

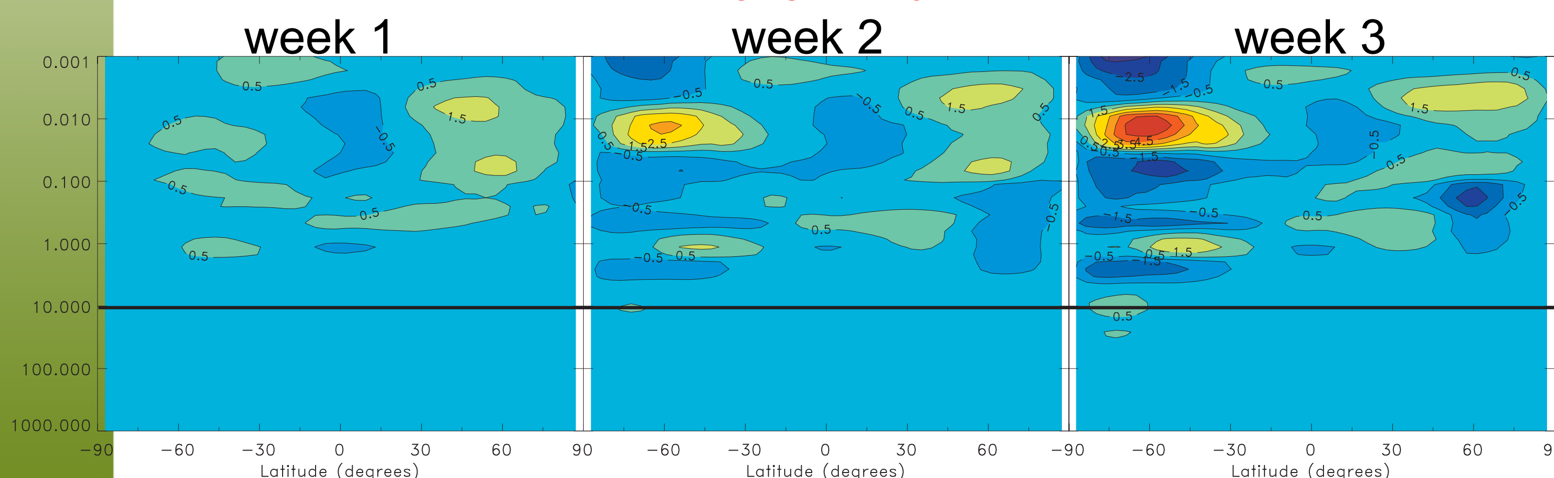
Temperature



AMSU-A only

Sat+ In situ

zonal wind



AMSU-A only

Sat+ In situ

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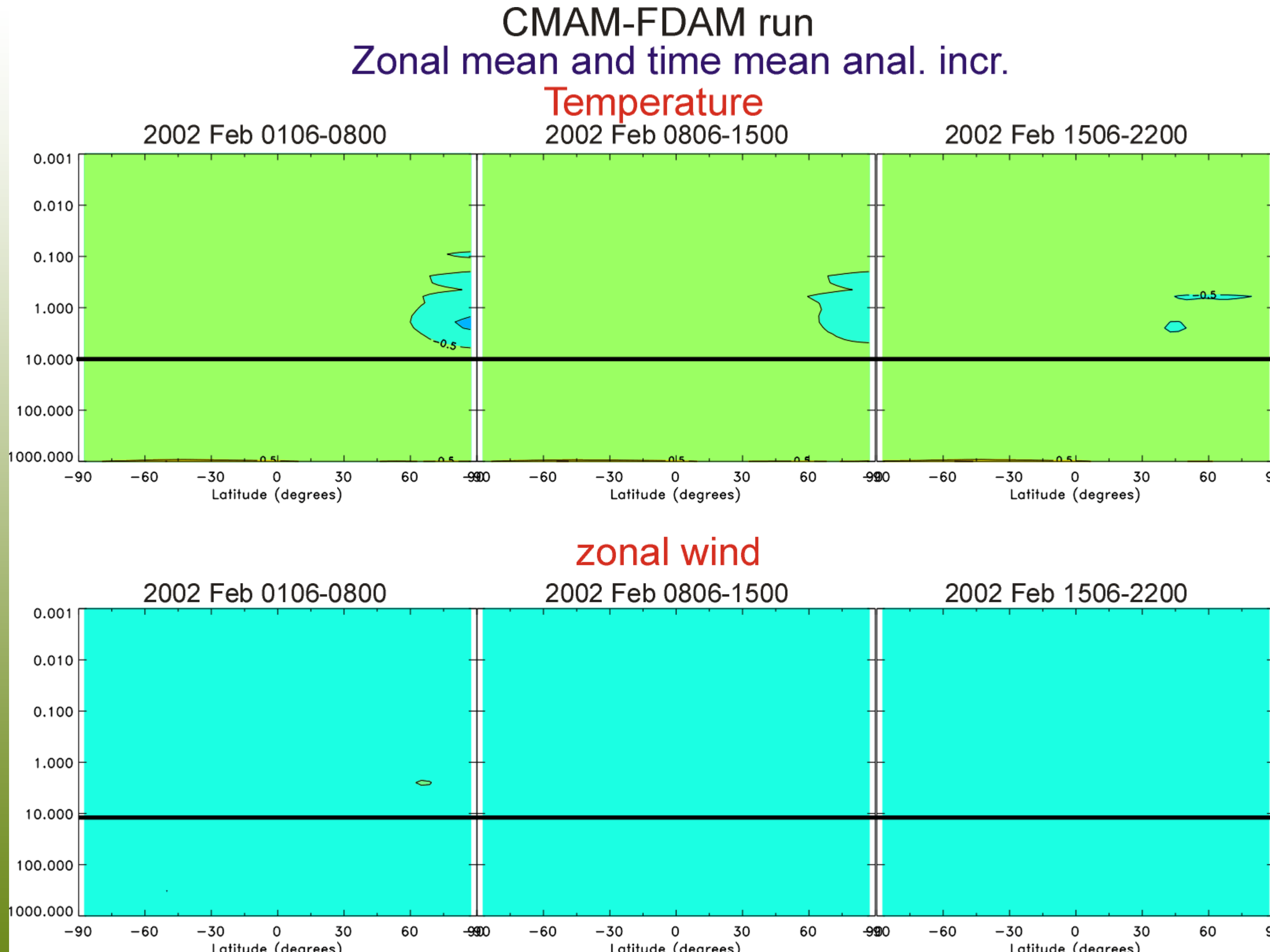
Polavarapu et al. (2006)

Canada

After removing vertical correlations in the mesosphere



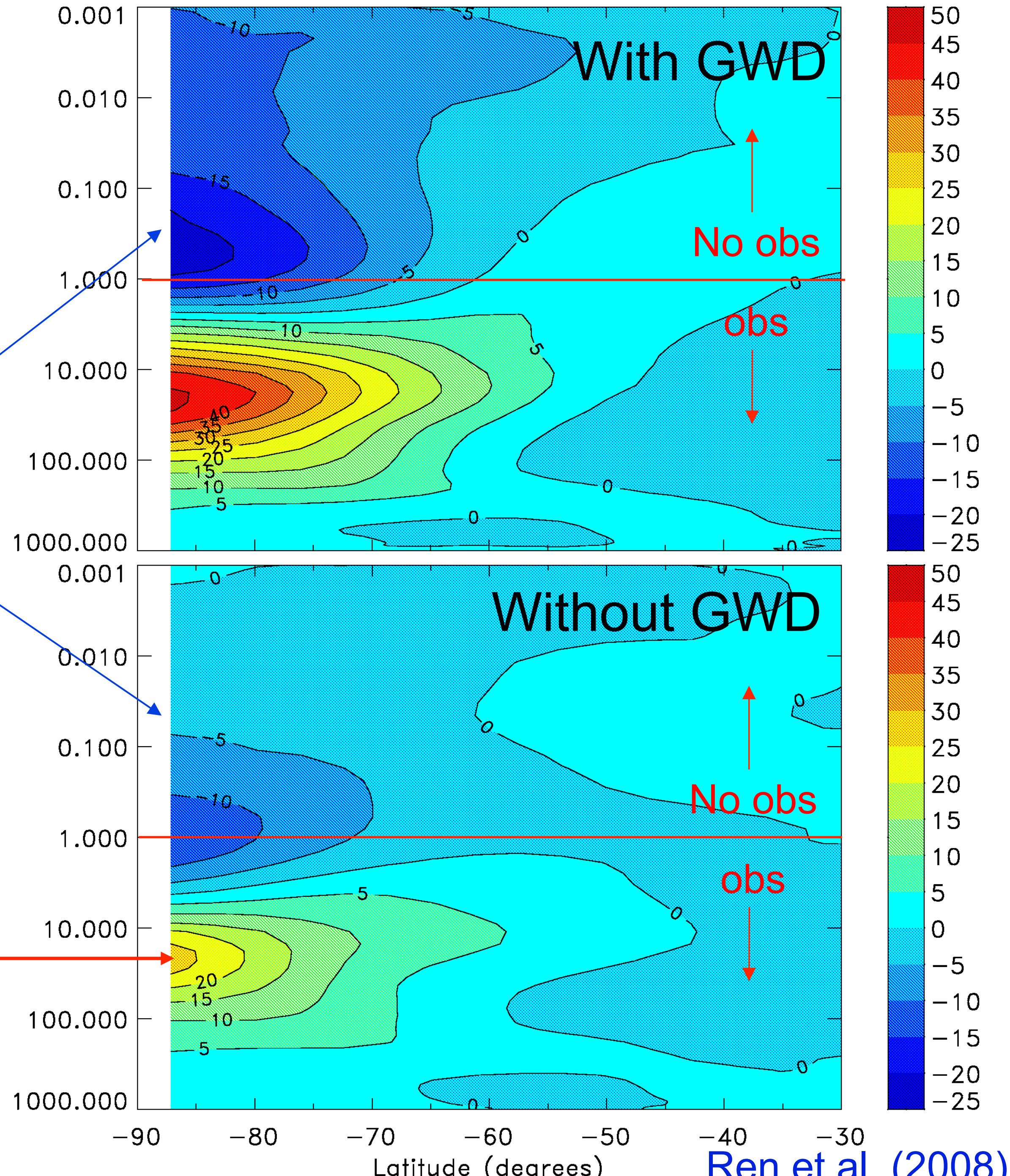
Gravity Wave Drag couples information in troposphere and mesosphere

Time mean: Sept. 25-Oct. 1
Ensemble mean, zonal mean

Vertical extent of mesospheric cooling is reduced

Zonal mean temp. difference between “hits” and “misses”

Stratospheric warming is half the amplitude



Ren et al. (2008)

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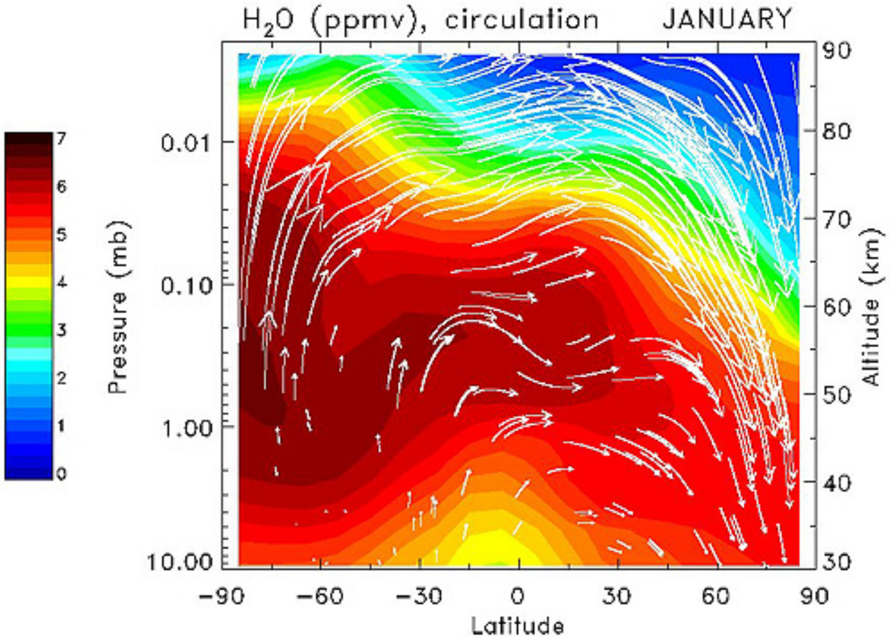
Mesospheric meridional circulation

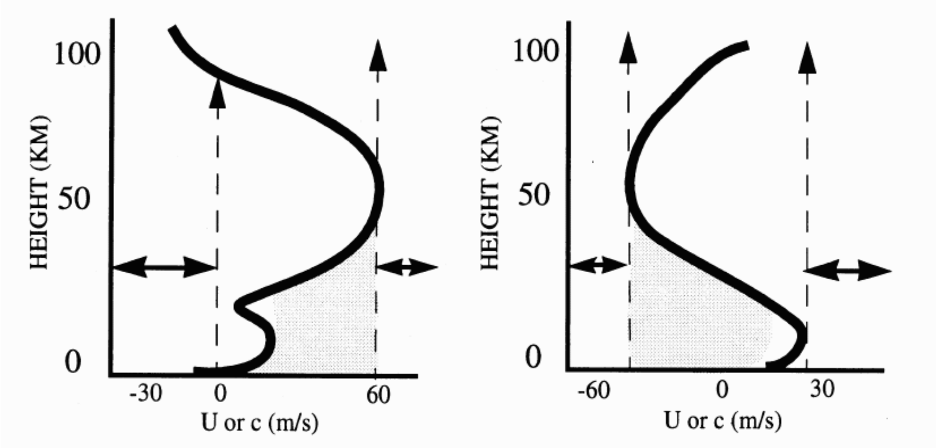
Zonally averaged water vapor distribution for January



http://www.ccpo.odu.edu/~lizsmith/SEES/

Gravity waves drive a pole-to-pole circulation

WINTER SUMMER

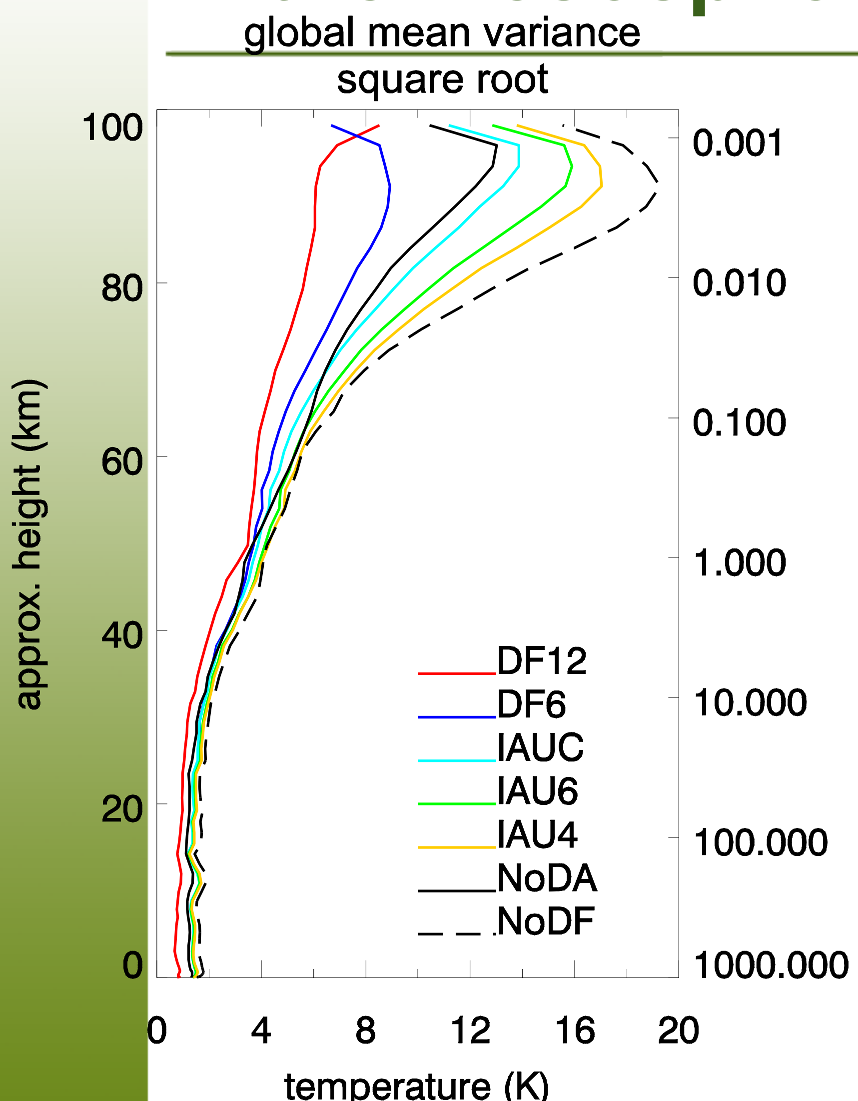


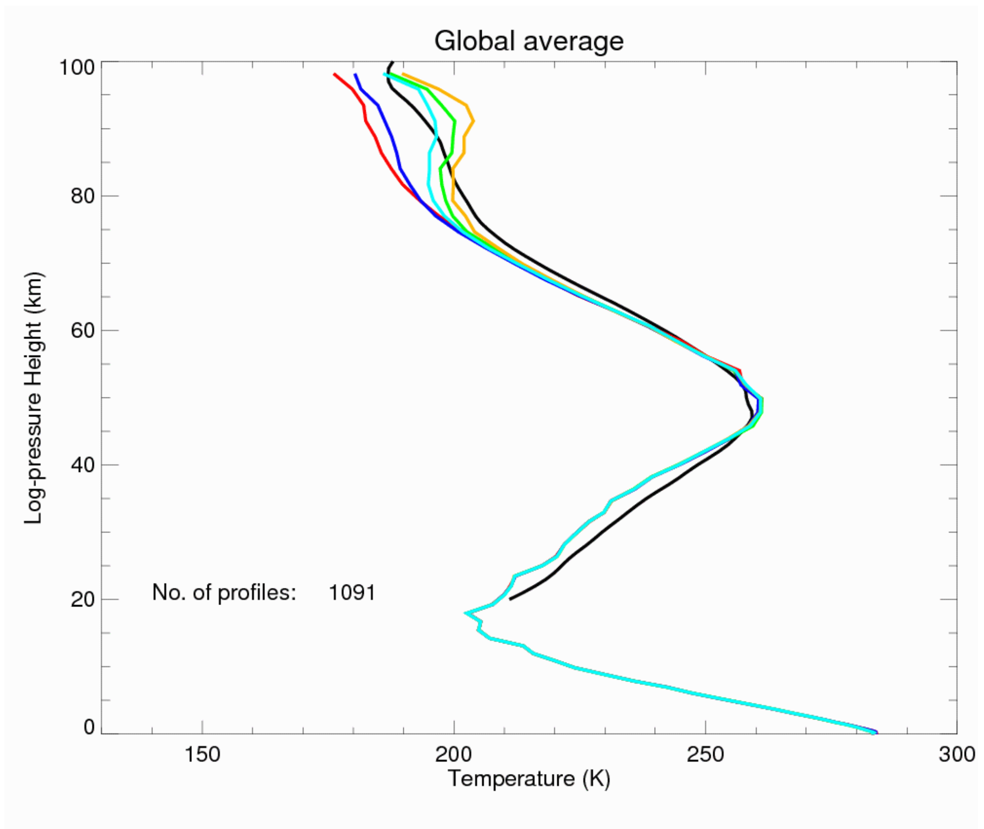
McLandress (1998)

- Zonal flow filters eastward (westward) GWs in winter (summer) yielding net westward (eastward) drag
- Deceleration of westerlies (easterlies) at winter (summer) pole produces poleward (equatorward) motion through Coriolis torque

Waves in the troposphere produce bias in the mesosphere

Sankey et al. (2007)





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

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