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Stratospheric data assimilation

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

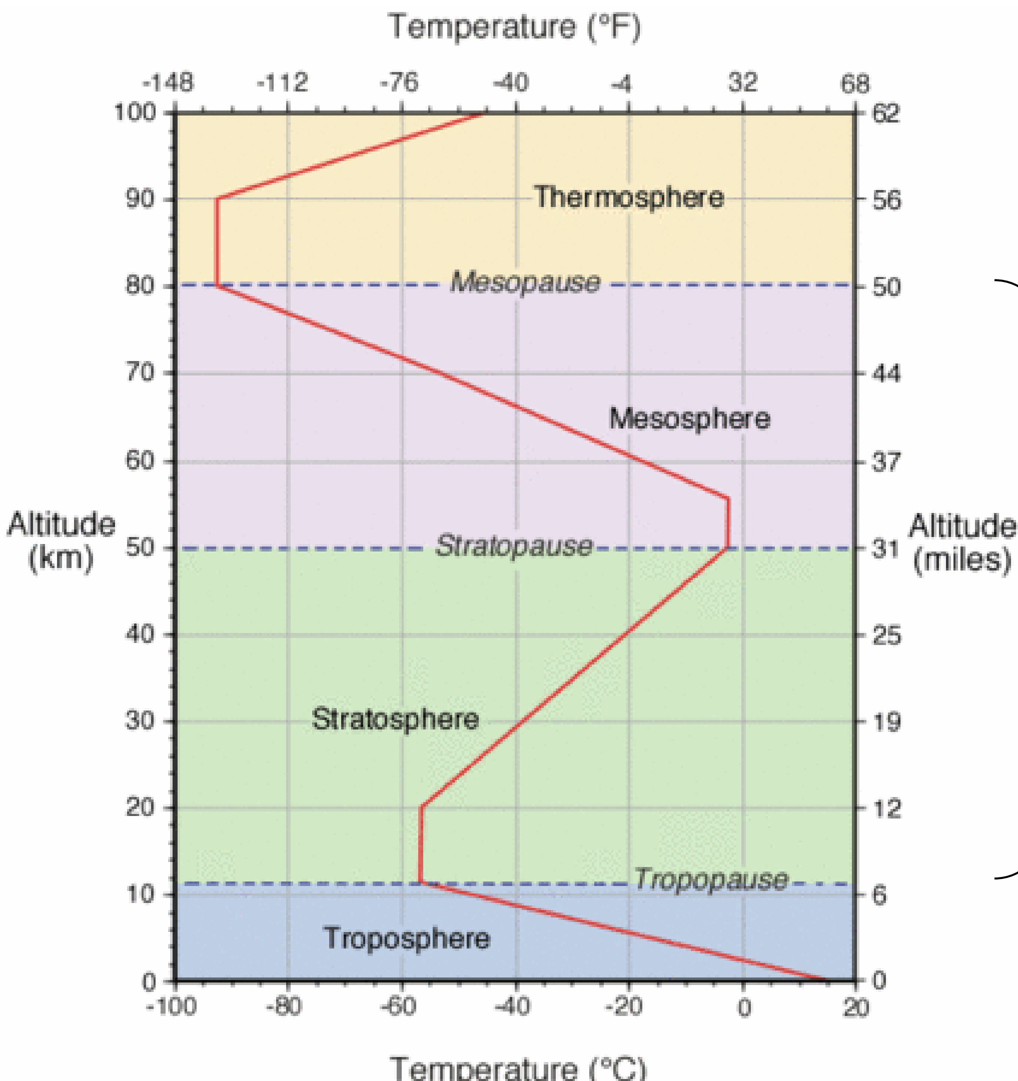
ECMWF Seminar on data assimilation for atmosphere and ocean, 6 Sept. 2011

OUTLINE

- Introduction/motivation
  - Why should data assimilators care about simulating the stratosphere and mesosphere?
  - Why consider the stratosphere separately from tropospheric data assimilation?
  - Brief overview of middle atmosphere dynamics
- Middle atmosphere data assimilation
  - Wave driven circulation
  - Stratosphere-troposphere coupling (polar dynamics)
  - Gravity waves in the mesosphere

The middle atmosphere

http://www.physicalgeography.net



The middle atmosphere

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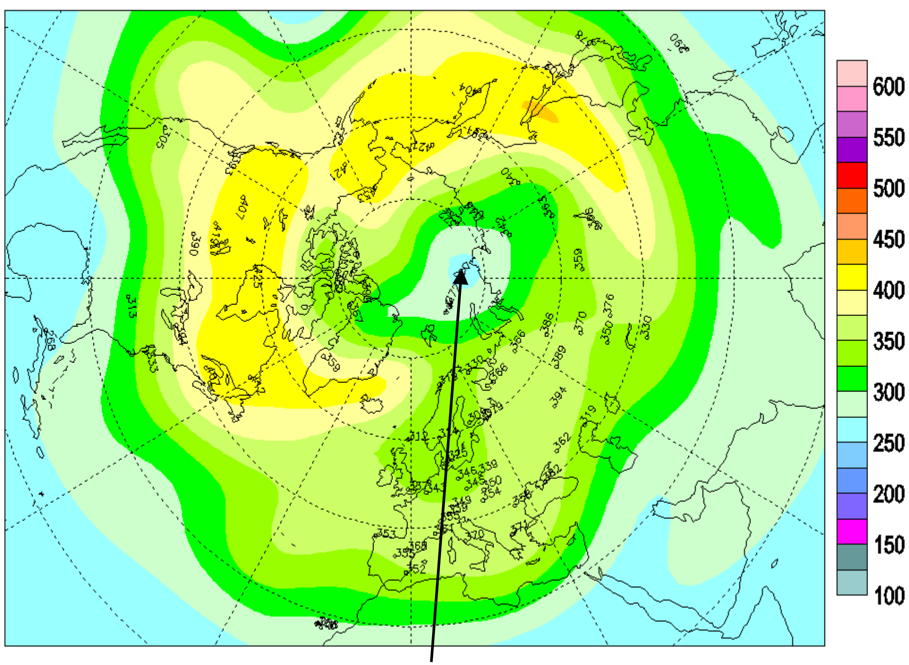
Why simulate the stratosphere?

http://exp-studies.tor.ec.gc.ca/cgi-bin/selectMap

- Estimate stratospheric ozone loss

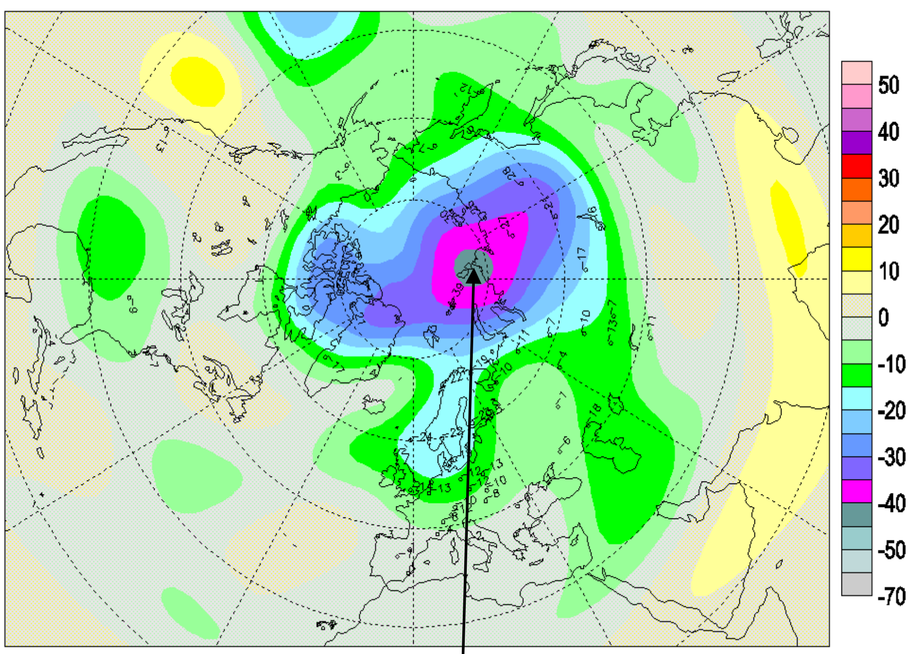
Arctic March 20-31, 2011

Mean total ozone (DU), 2011/03/20-2011/03/31



250 DU

Mean deviation (%), 2011/03/20-2011/03/31



50% lower than 1978-88 TOMS climatology

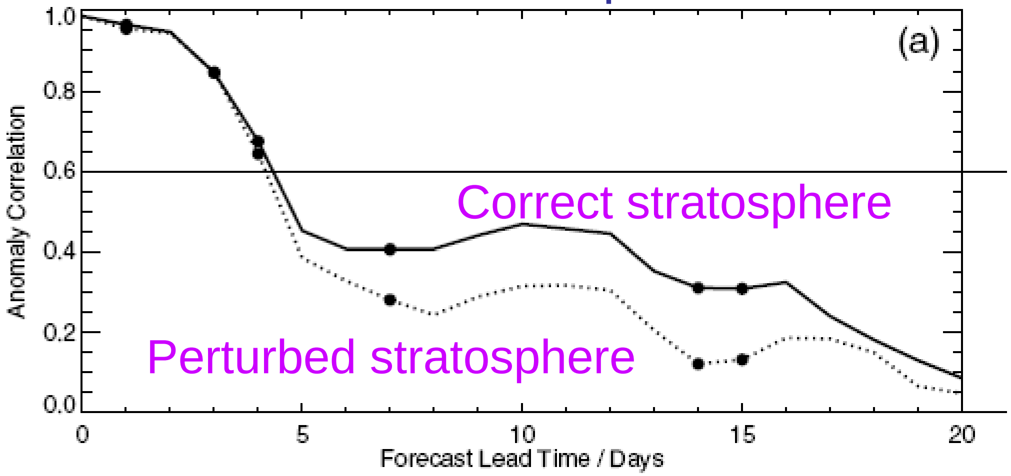
A good stratosphere can help improve tropospheric forecast skill

Charlton et al. (2005)

- Improve 10-15 day forecasts

500 hPa height anomaly correlation

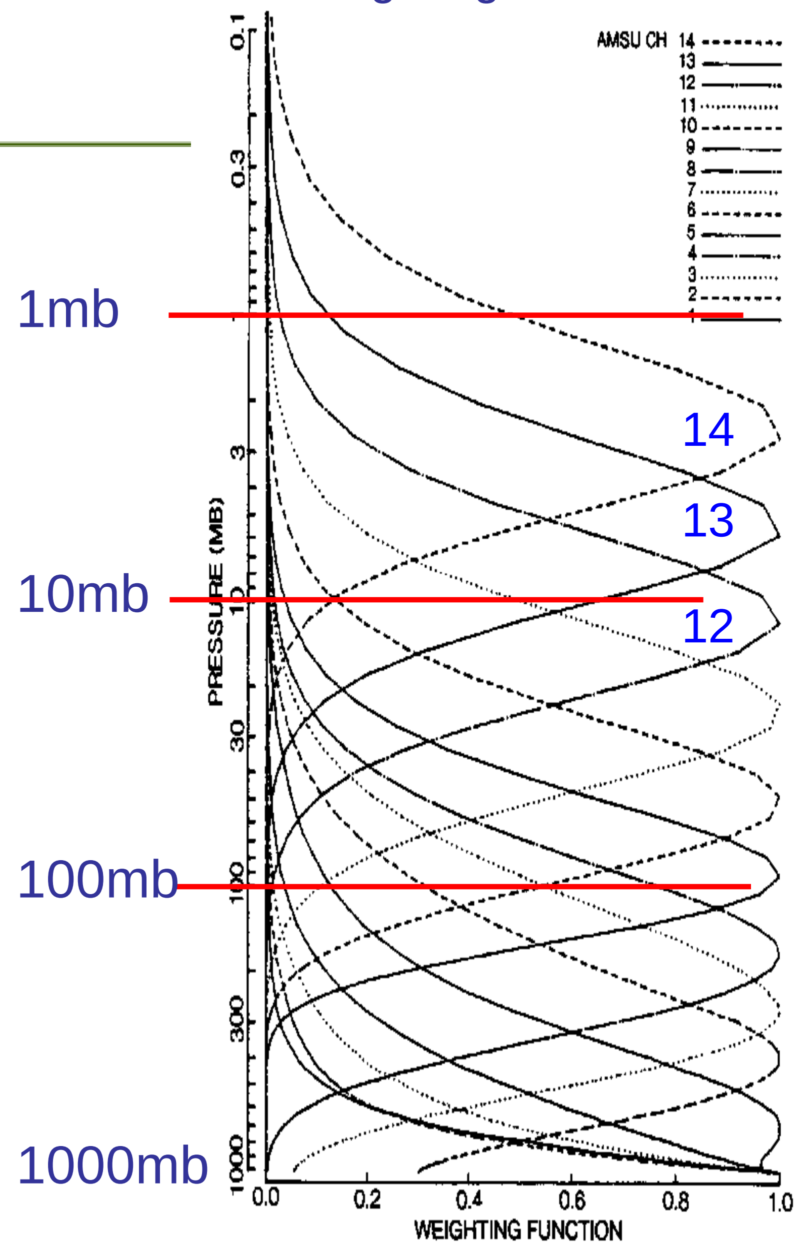
Northern hemisphere



Nadir satellite observations see the stratosphere

- Satellite radiances can sense up to 0.1 hPa
- A model lid at 0.1 hPa means a sponge layer below this so obs (e.g. ch. 12-14) may not be well assimilated

AMSU normalized weighting functions



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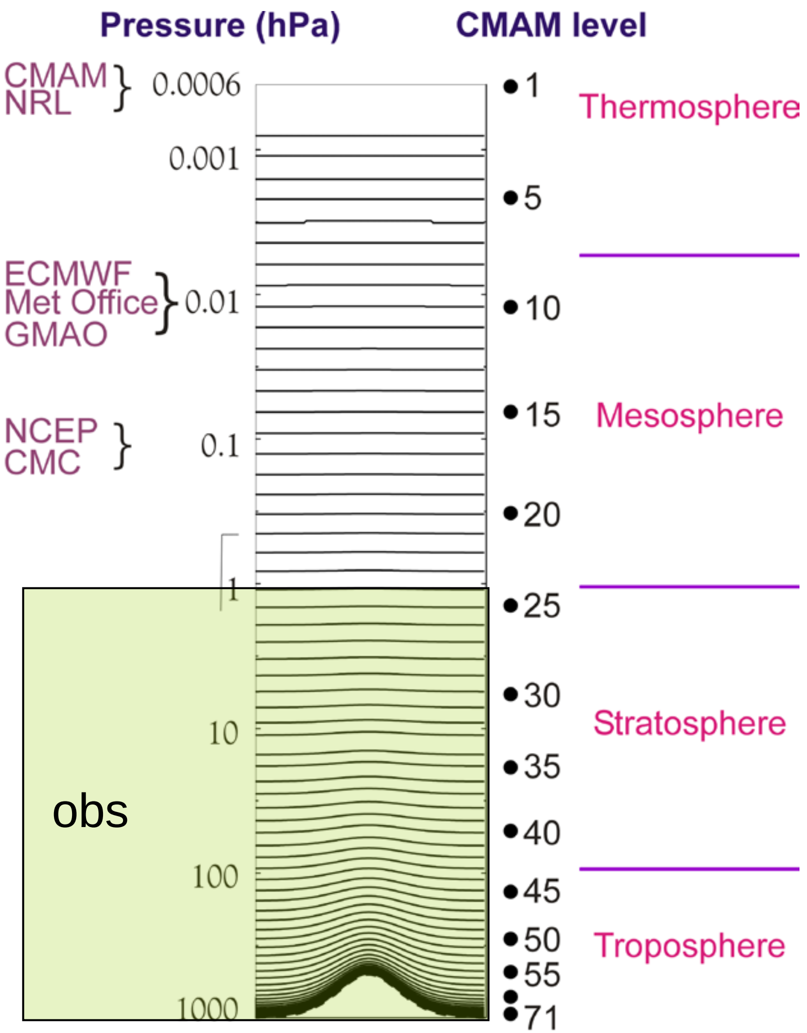
Why consider the stratosphere separately from tropospheric dynamics?

- 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

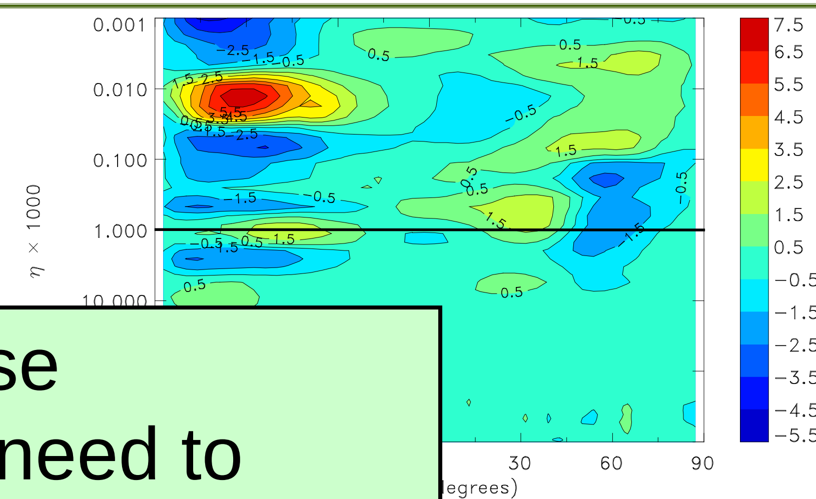


CMAM = Canadian Middle Atmosphere Model is a chemistry climate model (CCCma GCM3)

Feb. 22, 2002 18Z
zonally avg. fields

CMAM + 3DVar

U anal incr m/s

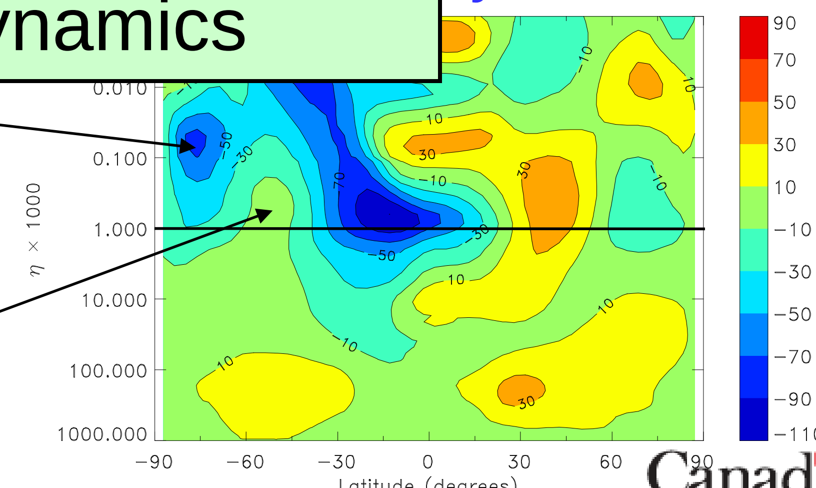


No obs

Why are incr largest in the mesosphere?

To answer these questions, we need to know a little about middle atmosphere dynamics

alysis m/s



Why do incr produce unphysical states?

spurious S. Hem. jet

reduced easterlies

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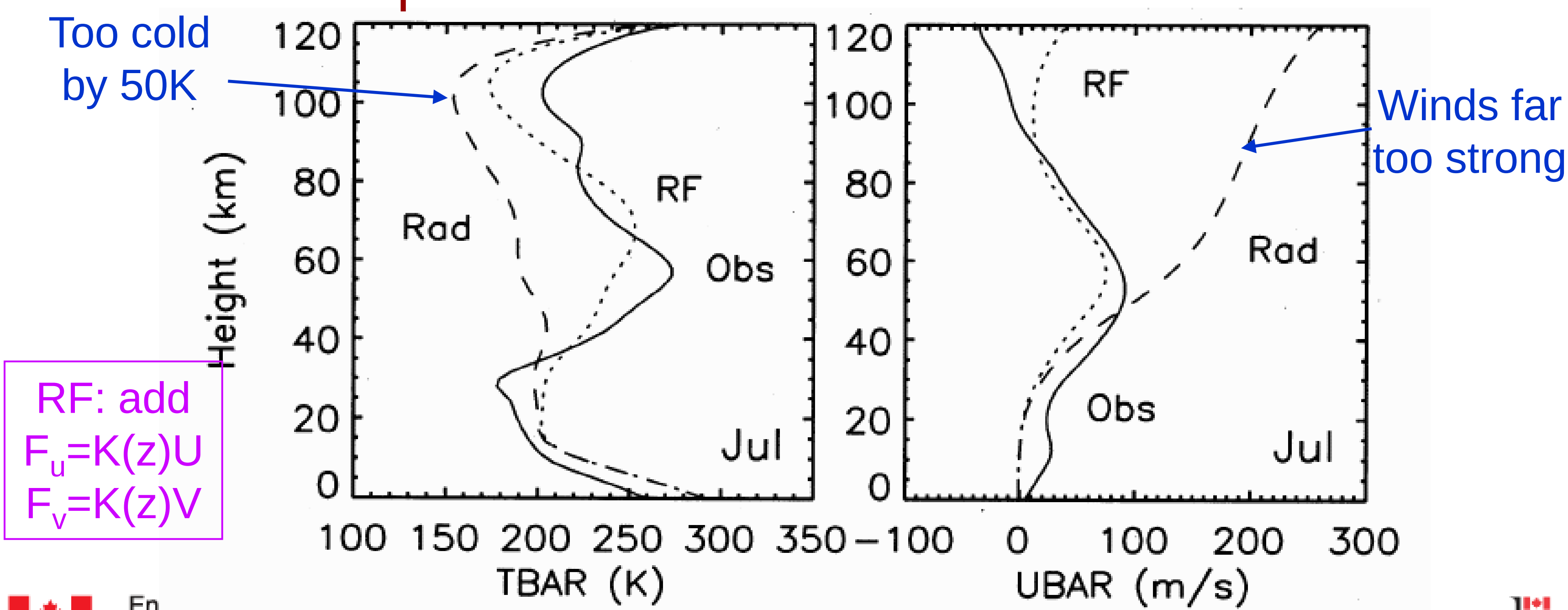
Missing zonal momentum force

McLandress (1998)

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

zonal mean fields in SH winter

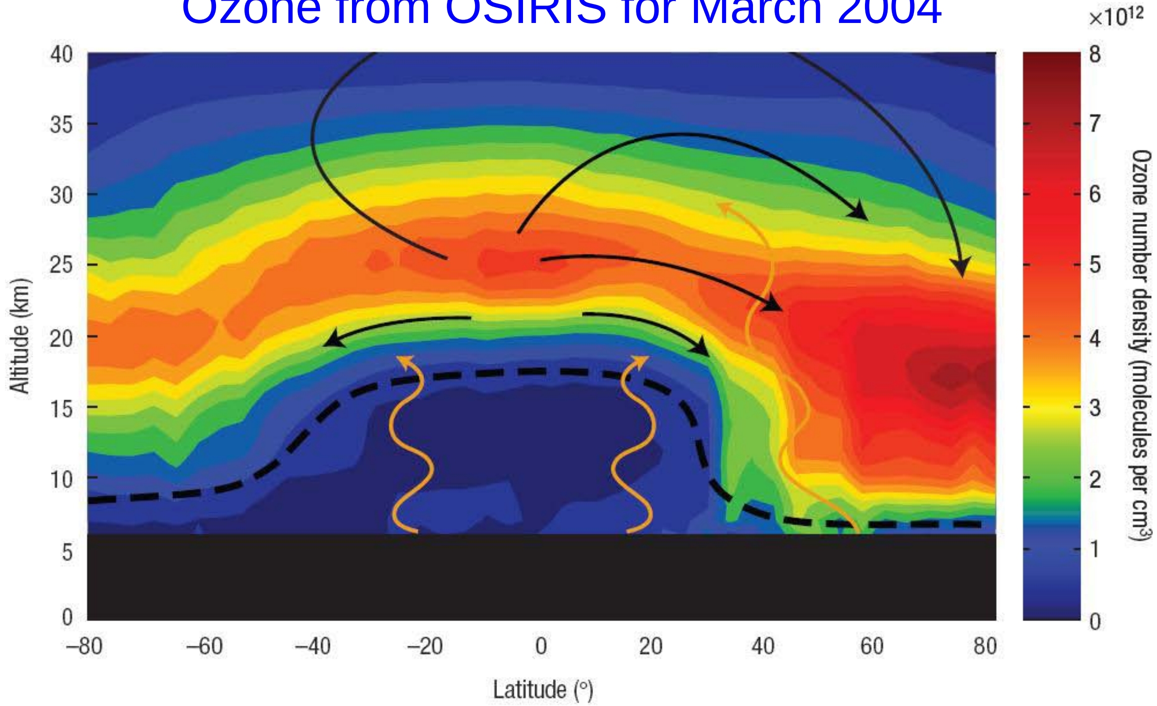
Temperature at 90°S　　Zonal wind at 40°S



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

Summer versus winter

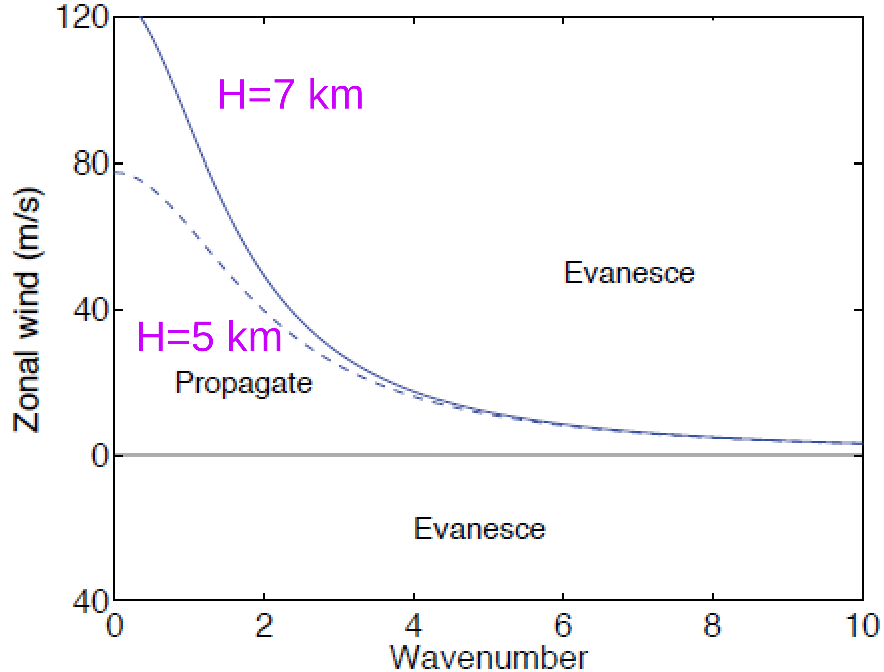
Vallis (2006)

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.



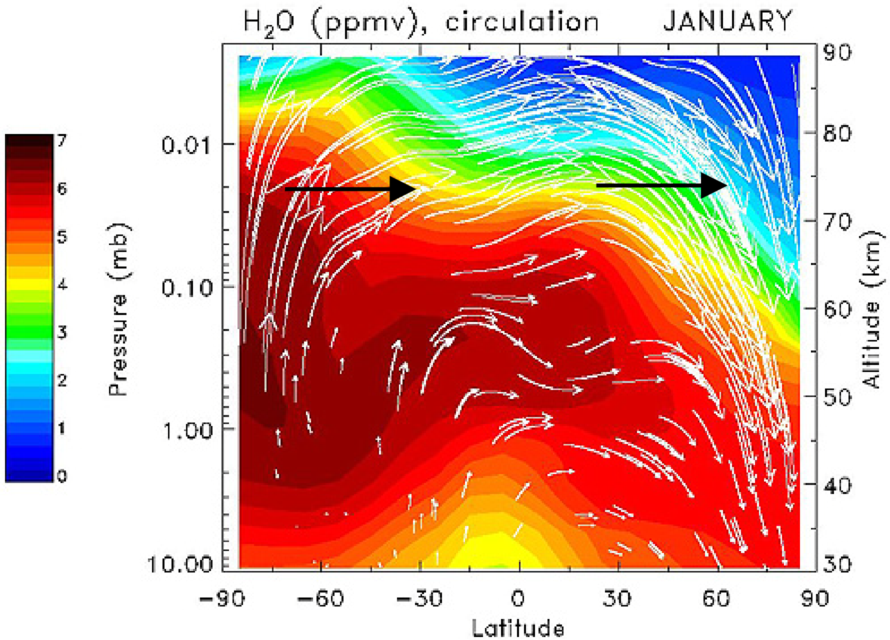
- Winter stratosphere (westerlies)
  - Dominated by large scales due to Charney-Drazin filtering
- Summer stratosphere (easterlies)
  - Rossby waves can't prop vertically due to critical level filtering

Mesospheric meridional circulation

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

Drag on easterlies
Equatorward motion

Drag on westerlies
Poleward motion



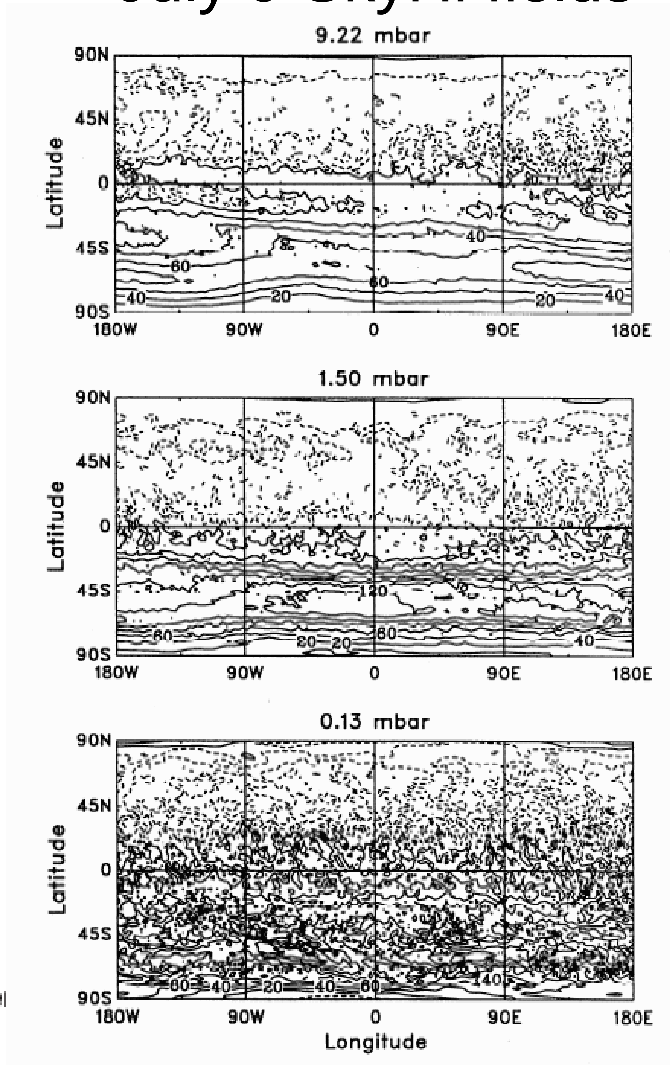
Zonally averaged water vapor distribution for January

- 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
- 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

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

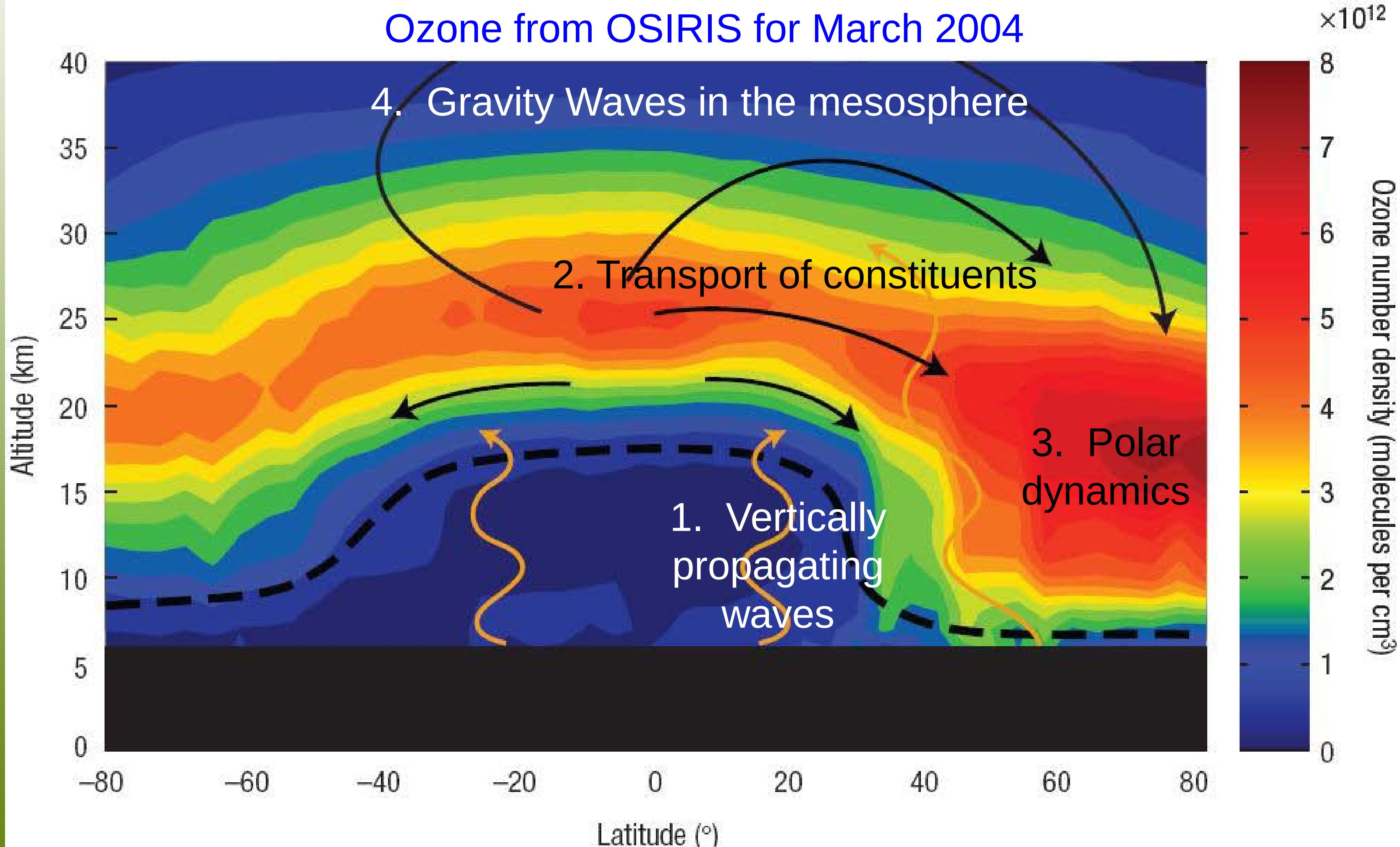
Mesosphere

GWs are Important!

Processes impacting data assimilation

Shaw and Shepherd (2008)

Ozone from OSIRIS for March 2004

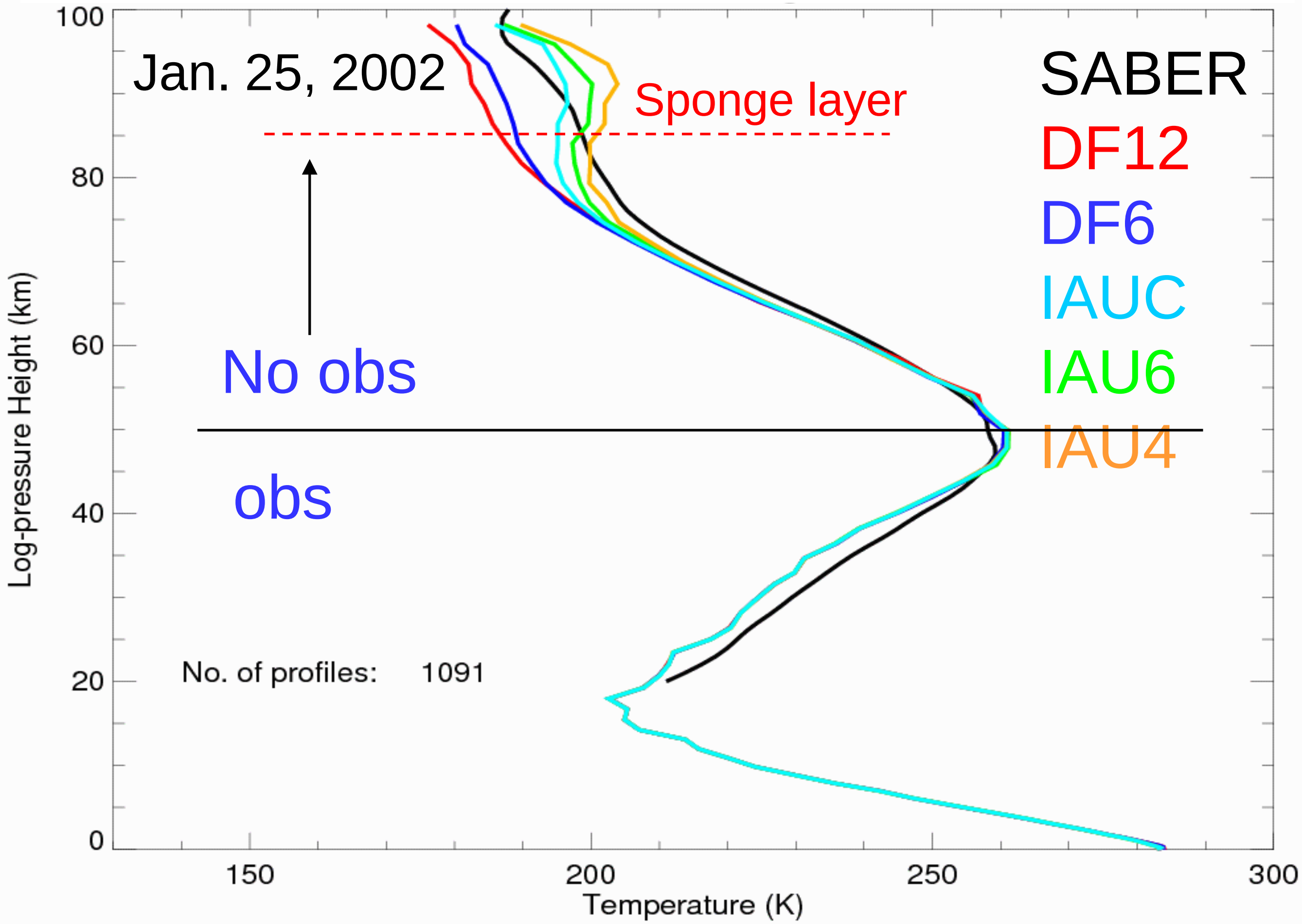


1. Vertically propagating waves

Filtering of tropospheric increments affects global mean mesopause temperatures!

Sankey et al. (2007)

Global mean temperature profiles at SABER locations for various filtering options



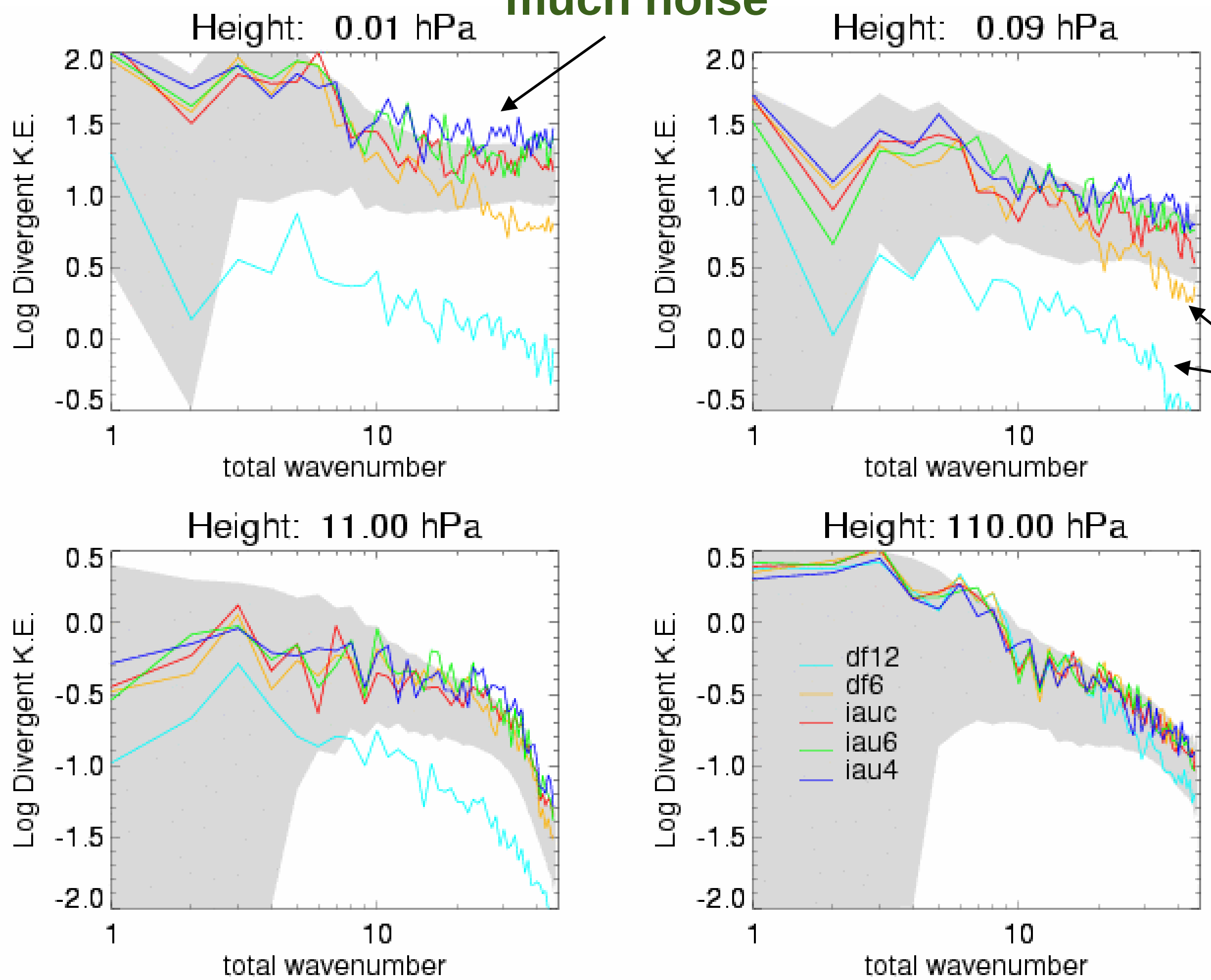
- Waves (real or spurious) in the troposphere propagate up to the mesosphere and impact the zonal mean flow, or even global mean fields
- Information is propagating up to the middle atmosphere through resolved waves
- Choice of filtering aimed at controlling noise in tropospheric analyses can impact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

Here we view filters as acceptable if they produce reasonable spectra

Sankey et al. (2007)

IAU4 leaves too much noise

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



DF12, DF6 are below range of model spectra

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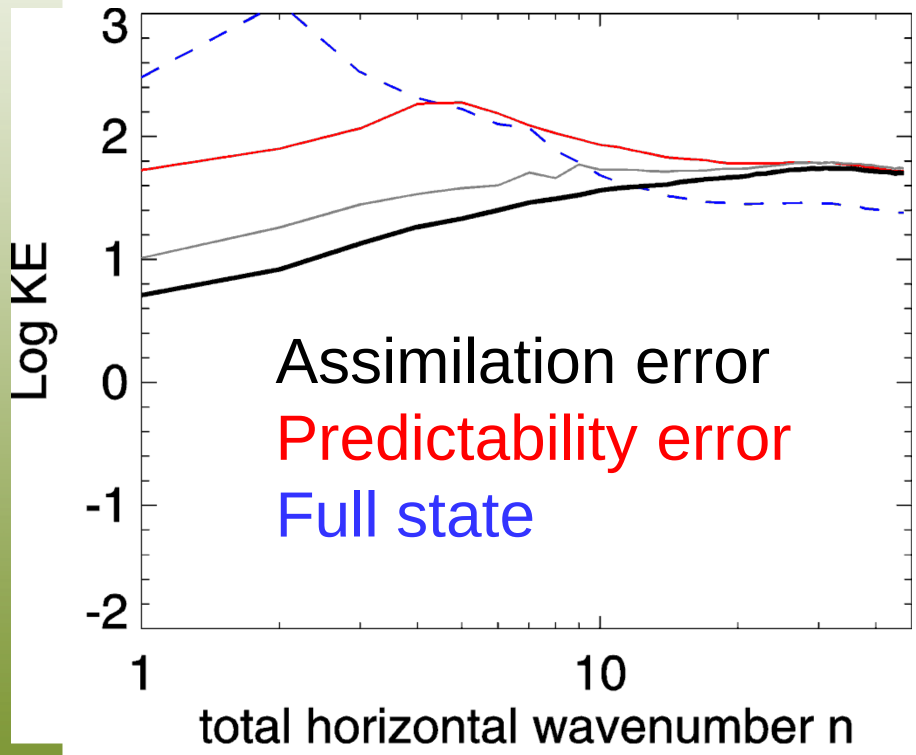
Tropospheric and stratospheric obs help determine large scales in mesosphere

Nezlin et al. (2009)

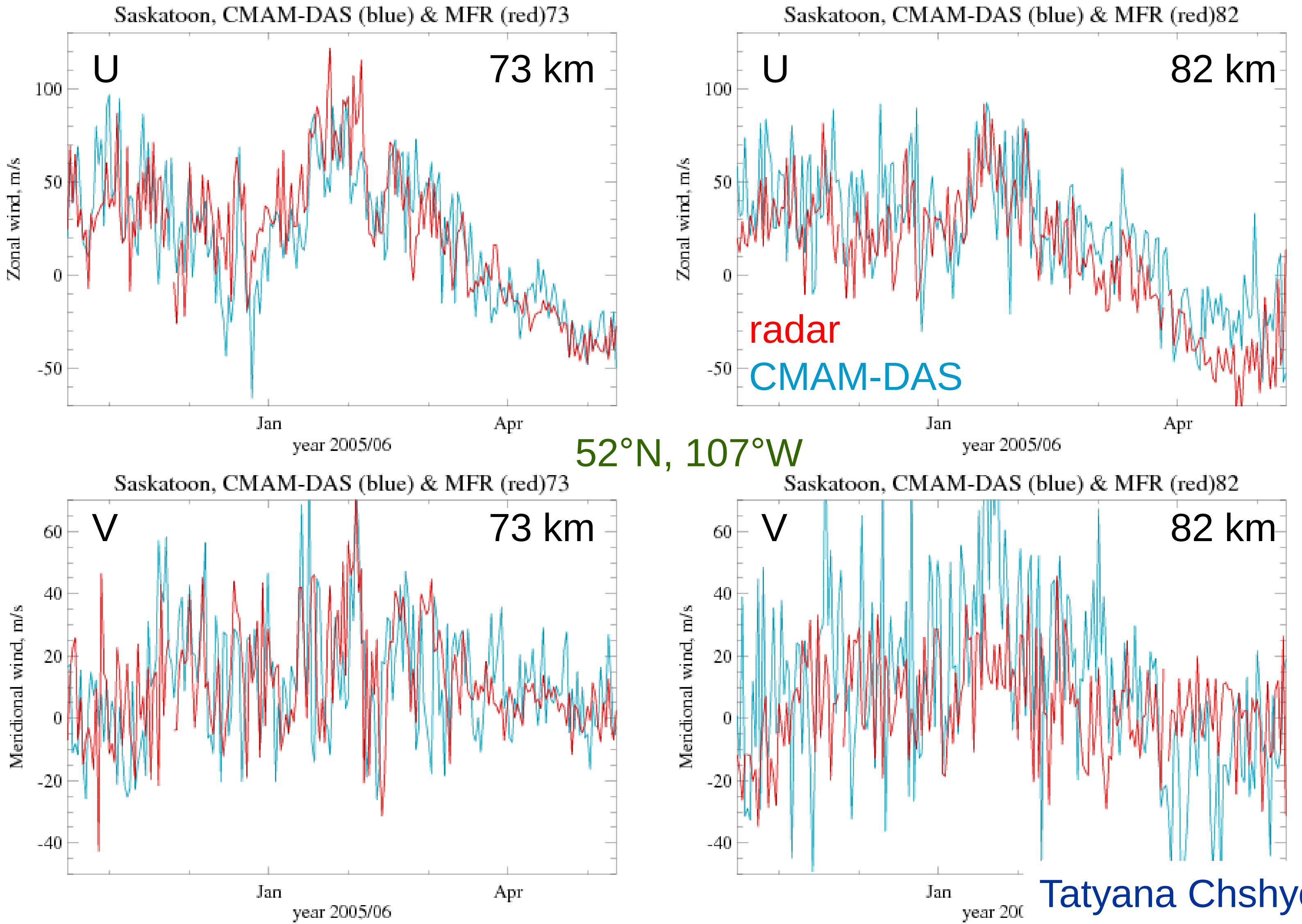
January mesosphere



- “Reference” is model generated, so known
- Obs below mesosphere only in CMAM-DAS
- Model forecast propagates information from troposphere and stratosphere to mesosphere

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

Compare CMAM-DAS to Saskatoon radar winds at noon



Tatyana Chshyolkova

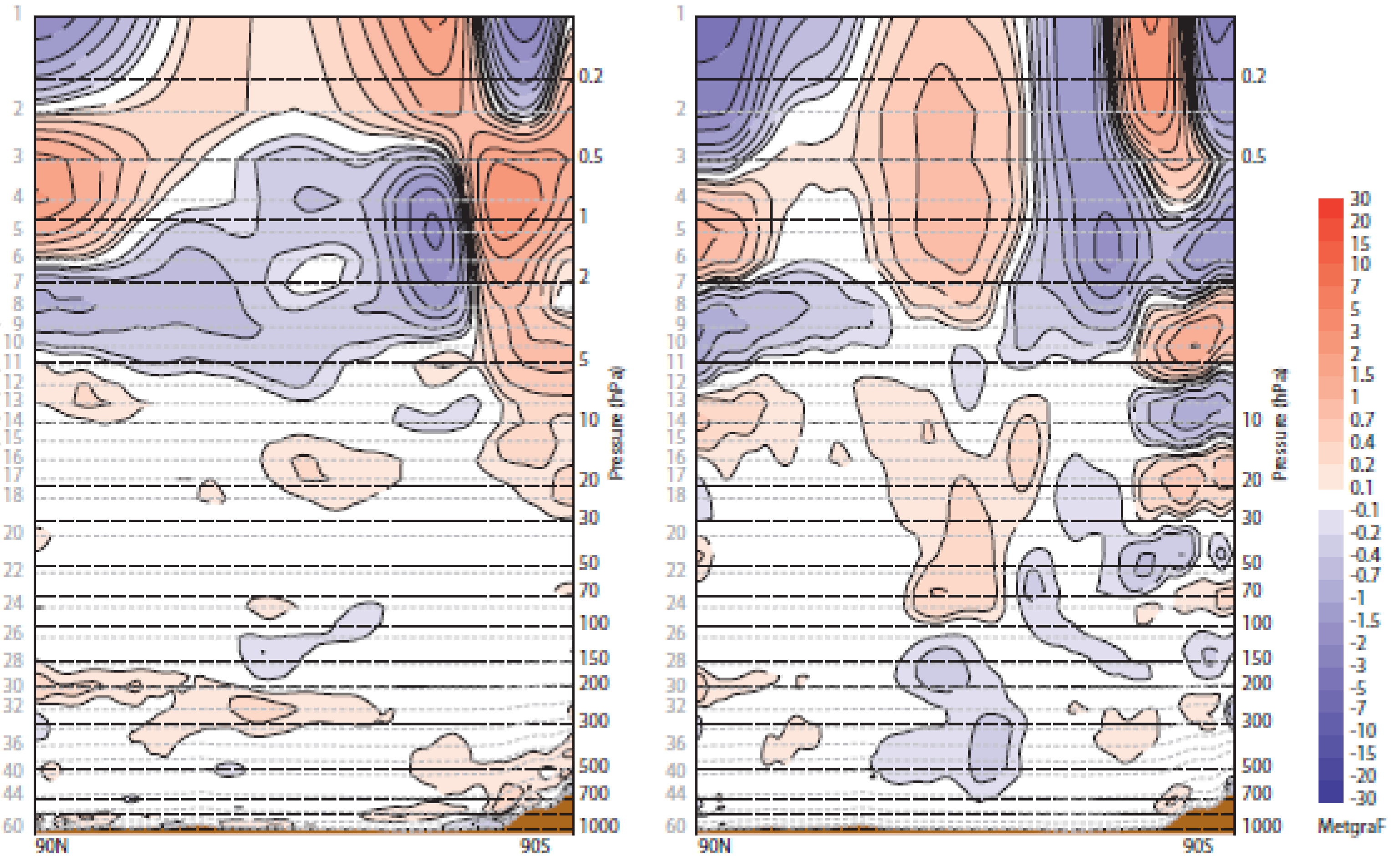
Expect bias in stratosphere

- 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)

ERA-Interim ERA-40



Pressure

Latitude Latitude

Variational bias correction

Derber and Wu (1998)

Model for bias

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

Bias parameters

Model state

predictors

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

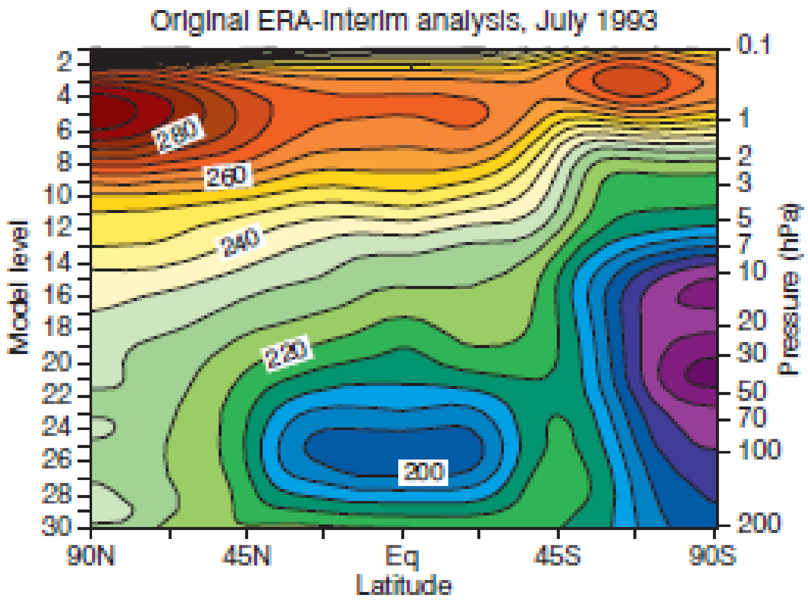
Bias parameters are determined using fit to all observations

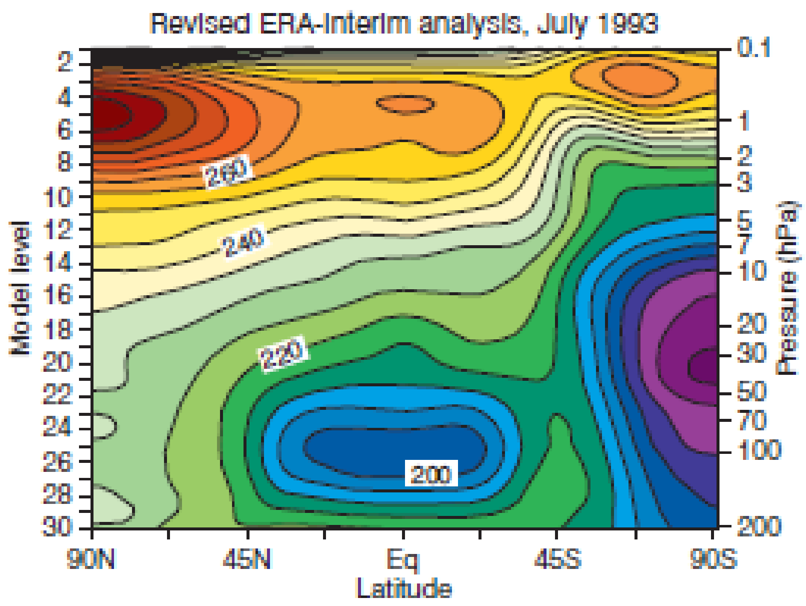
Bias correction will adjust for bias in observations ($\mathbf{y}$), obs operator ($\mathbf{h}$), and model state ($\mathbf{x}$)

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)





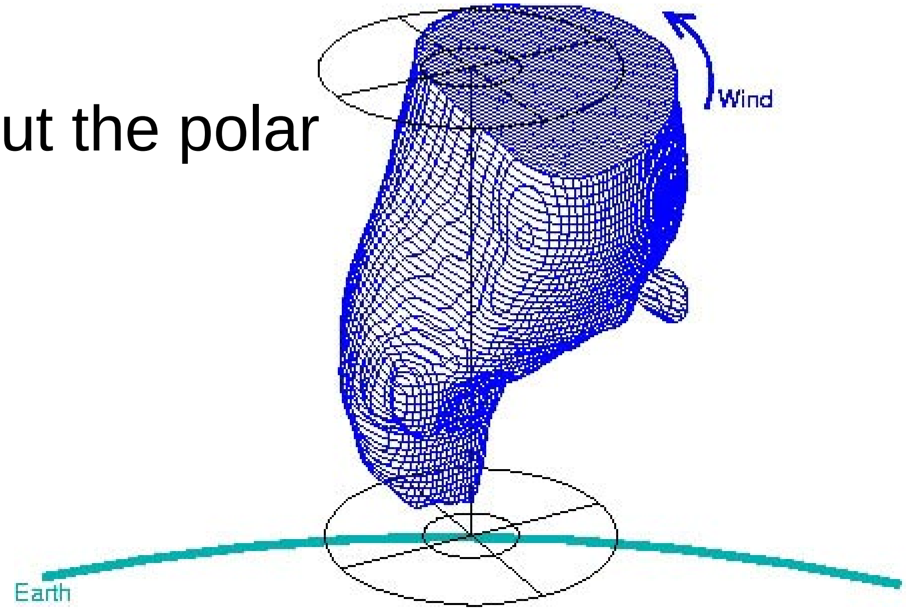
Vertically propagating waves
and their relevance to data assimilation

- 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

3. Polar dynamics

Winter Polar Stratosphere

- Dominated by westerly wind increasing with height: Polar night jet
- Occasional disruption of polar vortex by sudden warming events (in Arctic)
- Stratospheric vortex does not extend into troposphere
- So why should we care about the polar stratosphere?

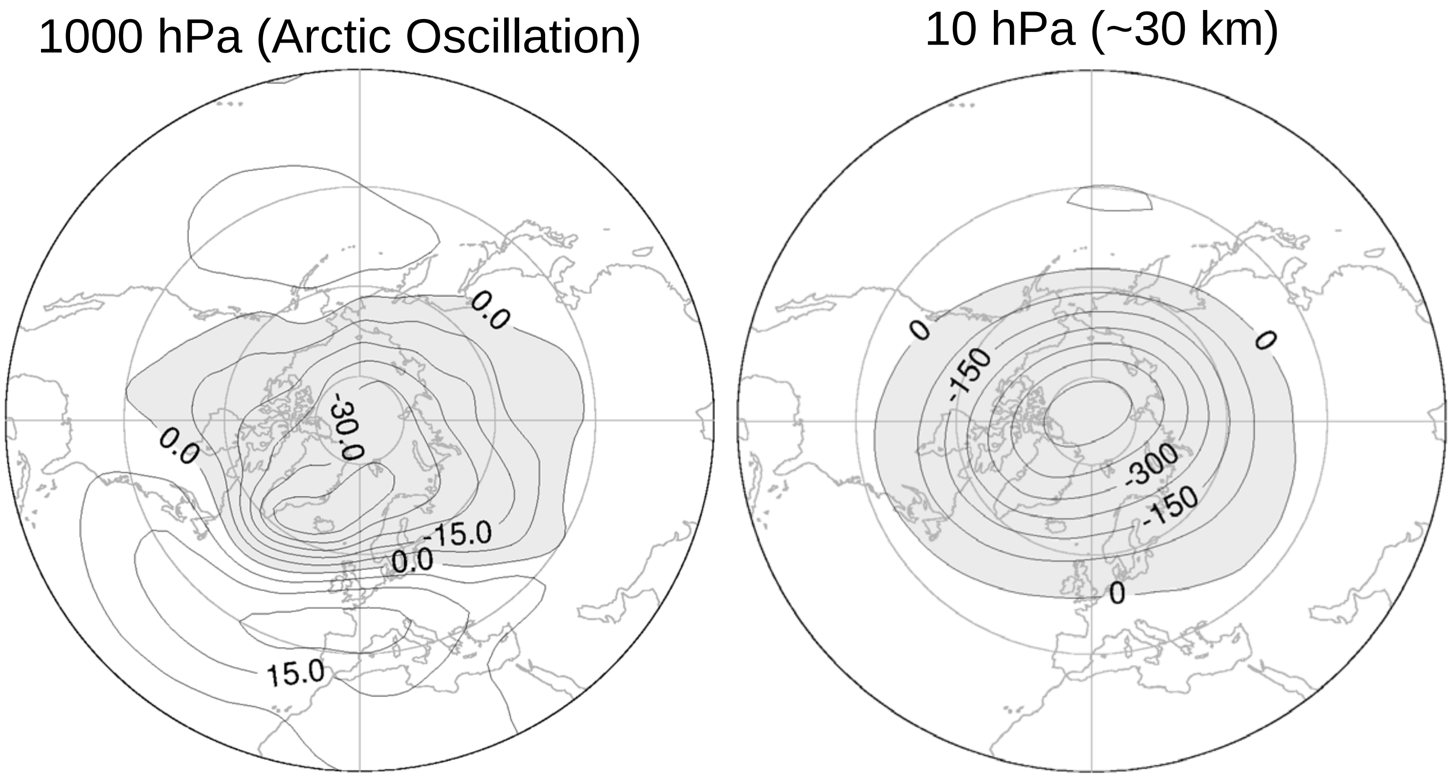


http://www.nasa.gov/images/content/113260main_arctic-vortex-447.jpg

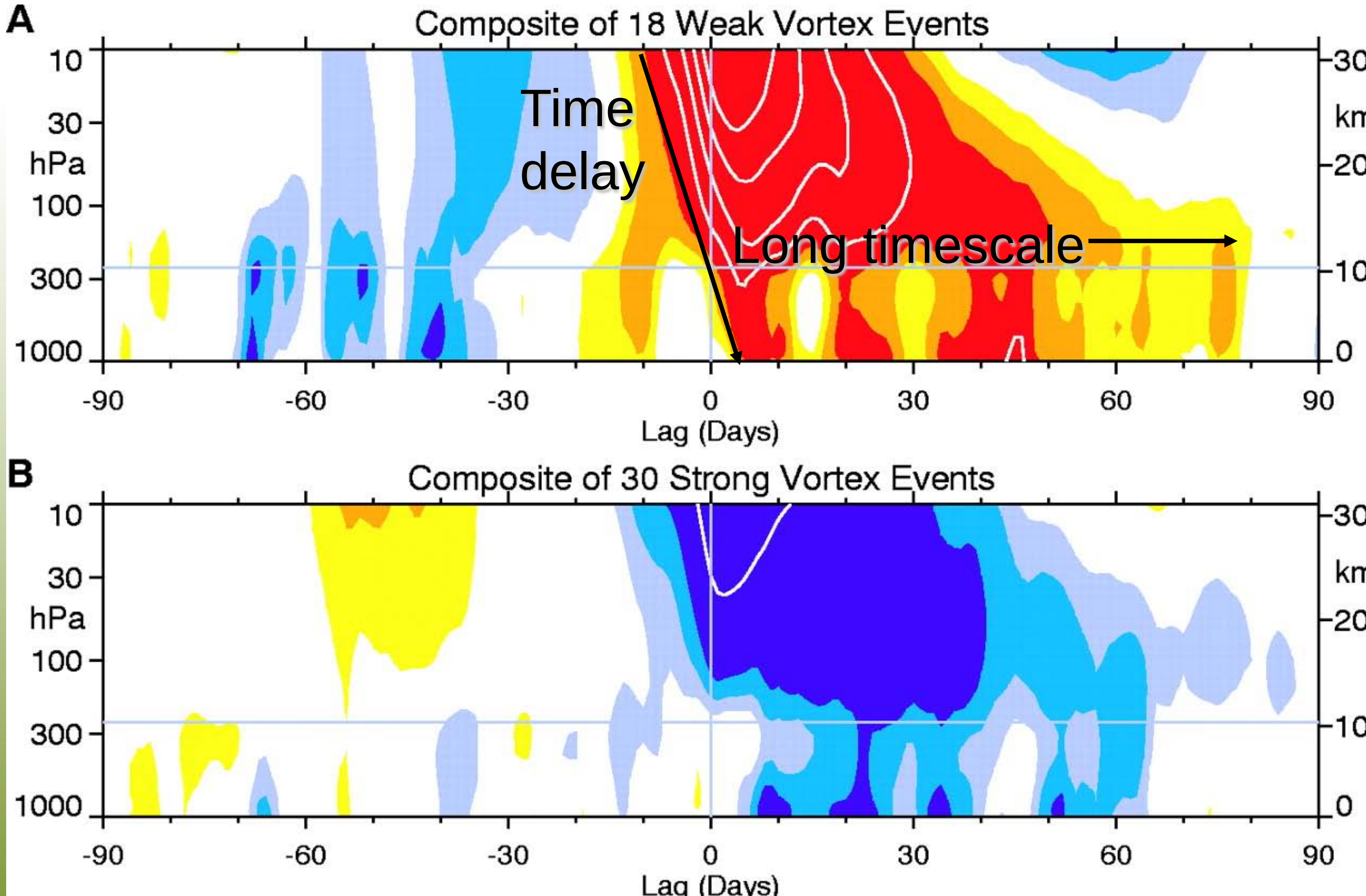
The stratosphere and troposphere are often coupled in winter

Baldwin and Dunkerton (2001)

Northern annular mode



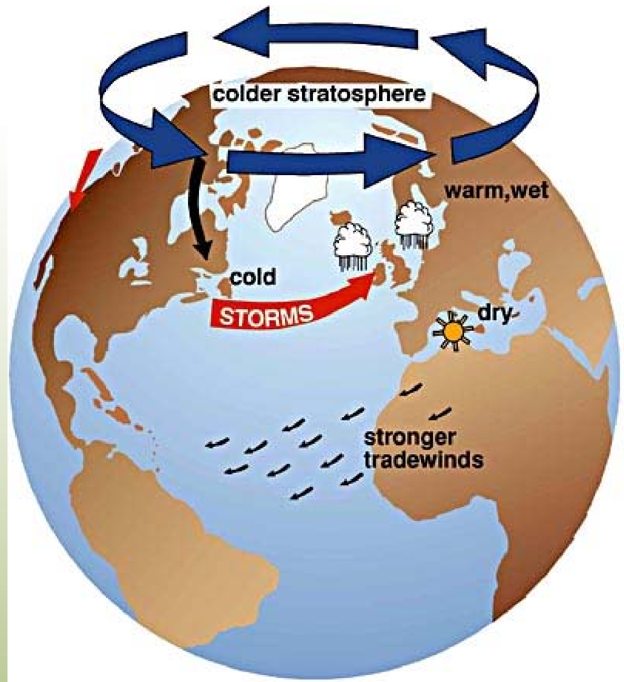
Annular mode patterns are similar from the surface to 50+ km



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

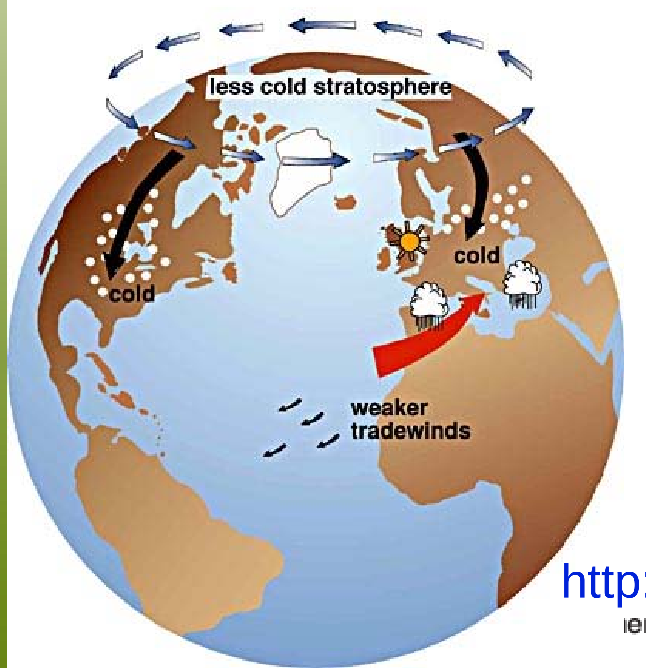
Baldwin and Dunkerton (2001)

Thompson and Wallace (2001, Science)



Strong vortex: +NAM

- cool winds across eastern Canada,
- North Atlantic storms bring rain and mild temperatures to northern Europe
- drought conditions prevail in the Mediterranean region



Weak vortex: -NAM

- cold air plunges into the midwestern United States and western Europe
- storms bring rain to Mediterranean

http://depts.washington.edu/uweek/archives/1999.07.JUL_22/

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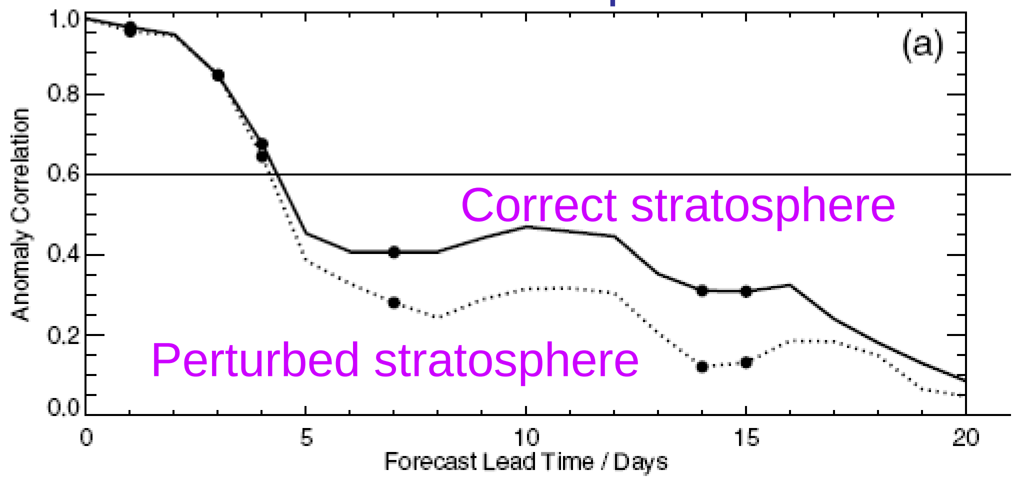
A good stratosphere can help improve tropospheric forecast skill

Charlton et al. (2005)

- Improve 10-15 day forecasts

500 hPa height anomaly correlation

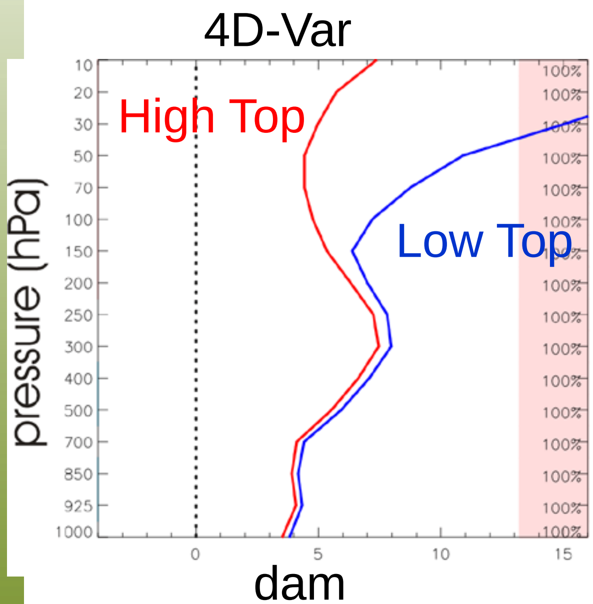
Northern hemisphere



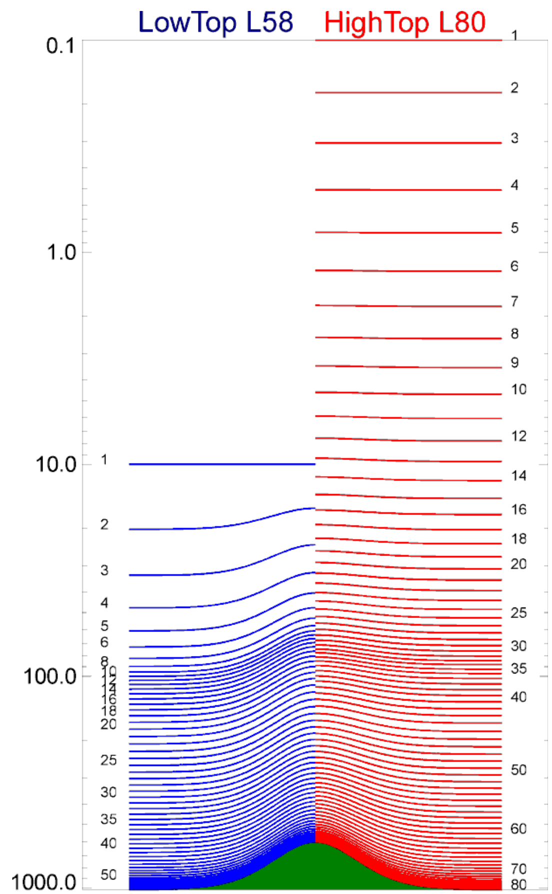
Improving the stratosphere improves 5-day forecasts in the troposphere

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



Polavarapu et al (2011)



Winter

Dec. 20 – Jan. 26, 2006 (75 cases)

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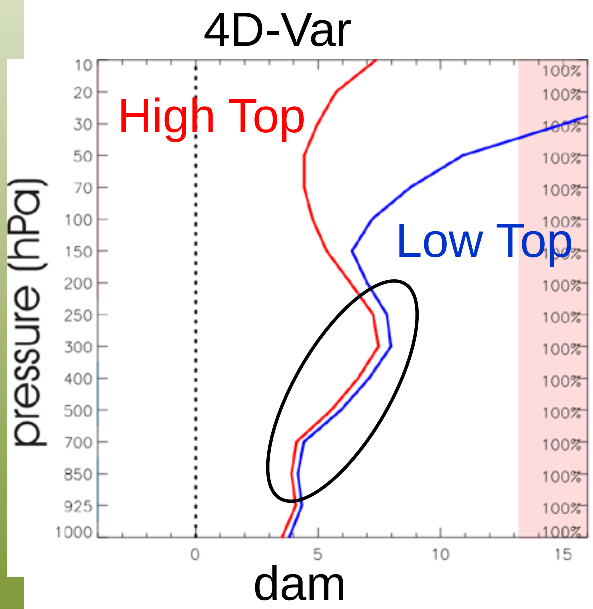
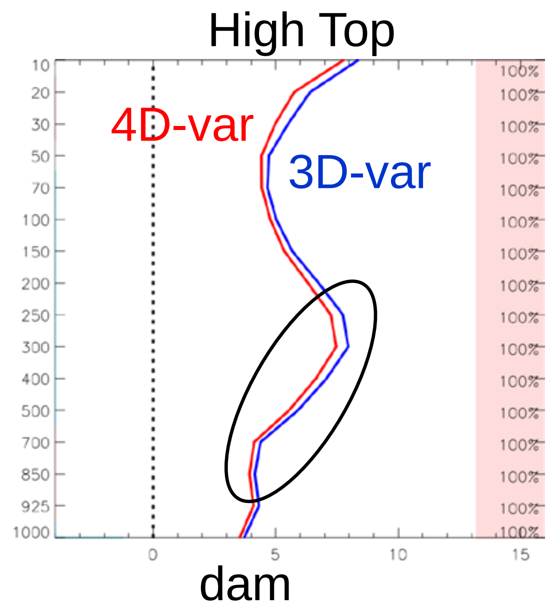




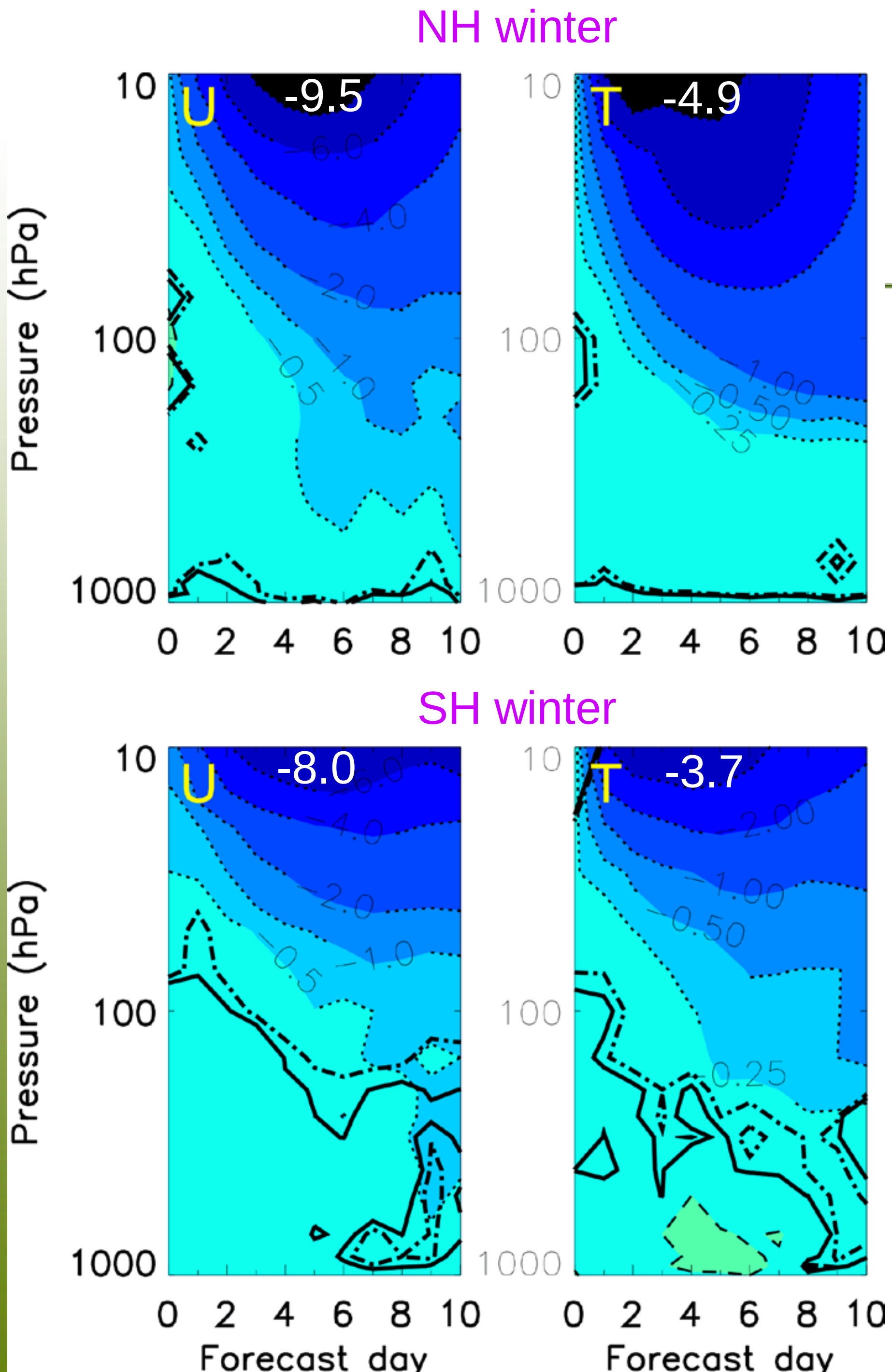
Polavarapu et al (2011)

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

Winter

Dec. 20 – Jan. 26, 2006 (75 cases)

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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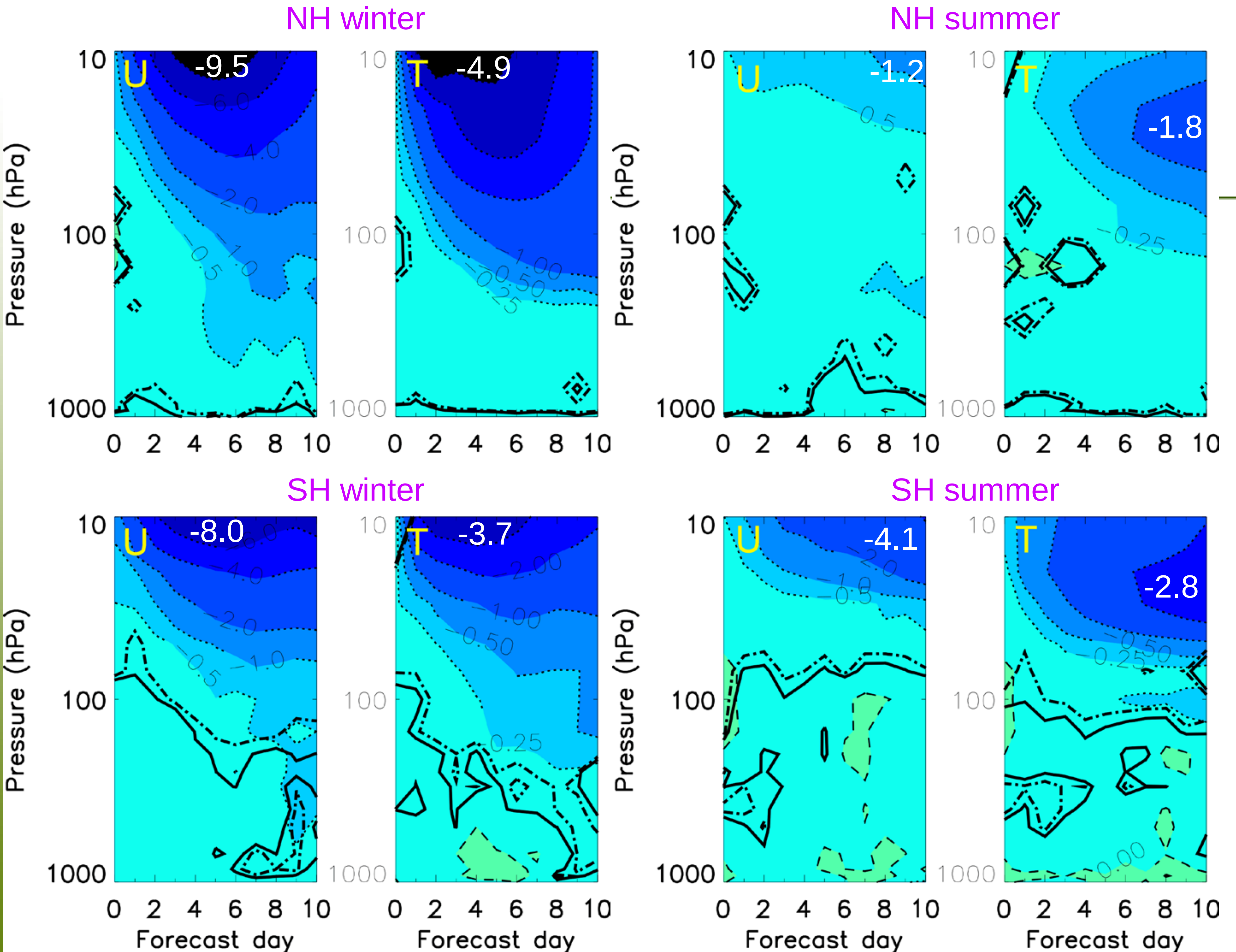
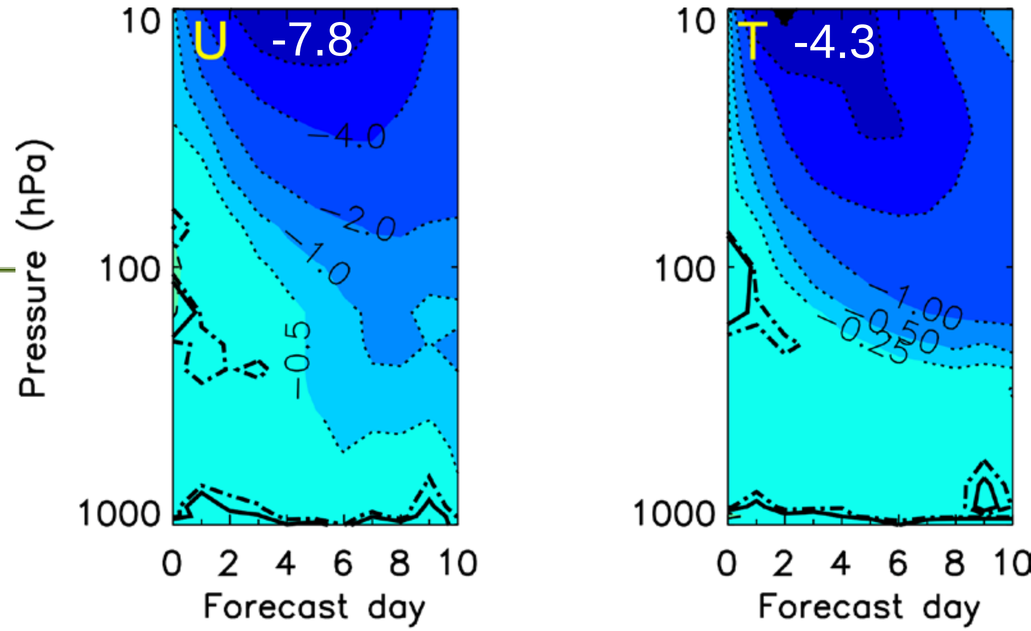


NH winter
NH summer
SH winter
SH summer
U
T
-9.5
-4.9
-1.2
-1.8
-8.0
-3.7
-4.1
-2.8
Pressure (hPa)
Forecast day

Winter NH stddev obs vs model

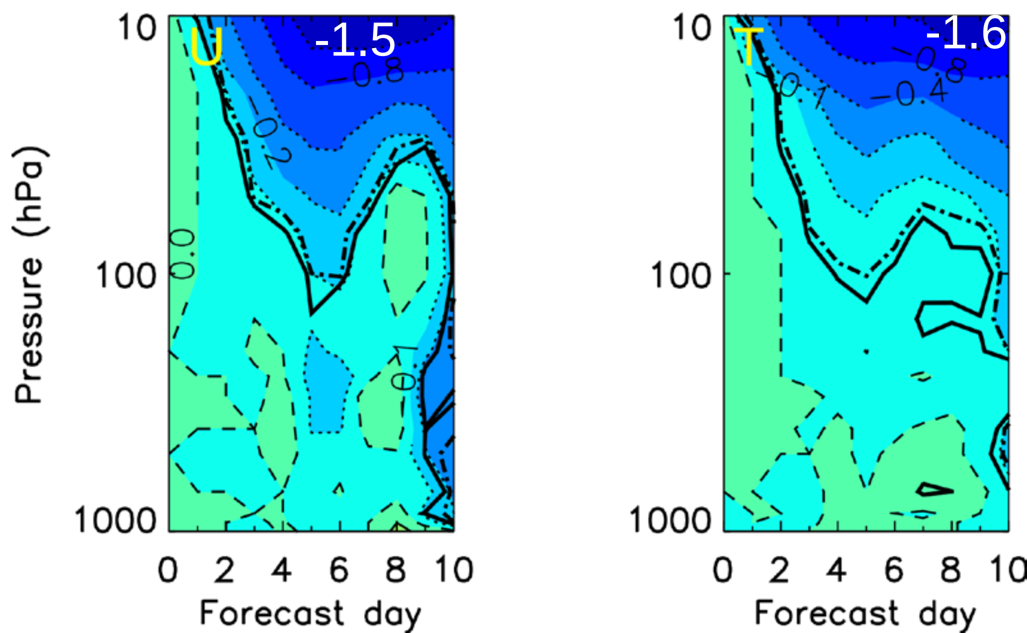
Impact of model changes



Most of the improvement is due to changes in model

Contour intervals not the same!

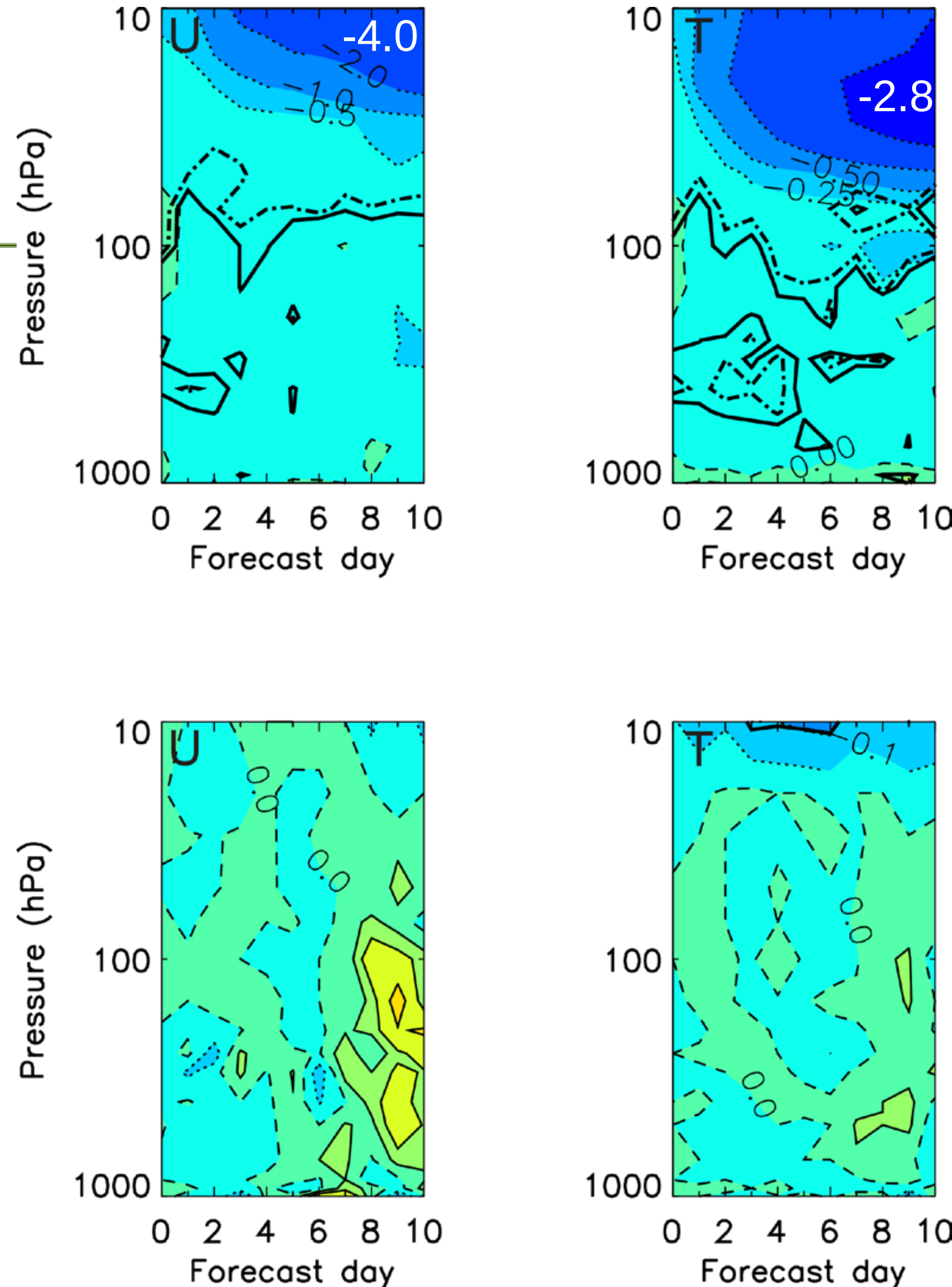
Impact of obs changes
(adding AMSUA 11-14 and GPSRO 30-40 km)



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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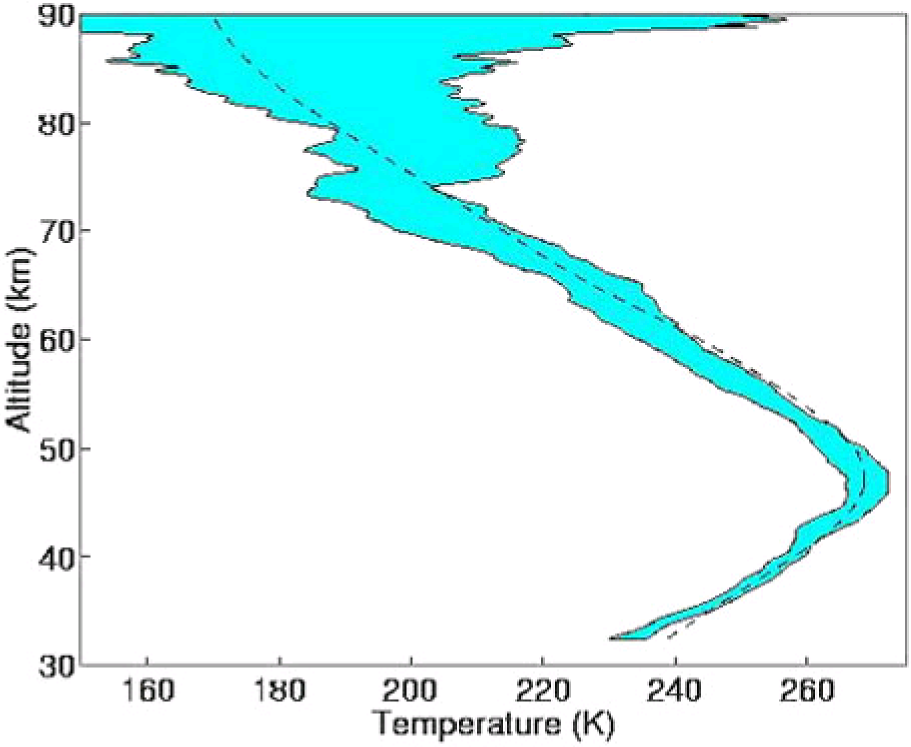
Results and questions

- 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
- Improvement in skill spreads downward with forecast range in winter. What is the reason for this?
- Is the improvement in tropospheric forecast scores due to the improved stratospheric depiction, or some other model change?

4. 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

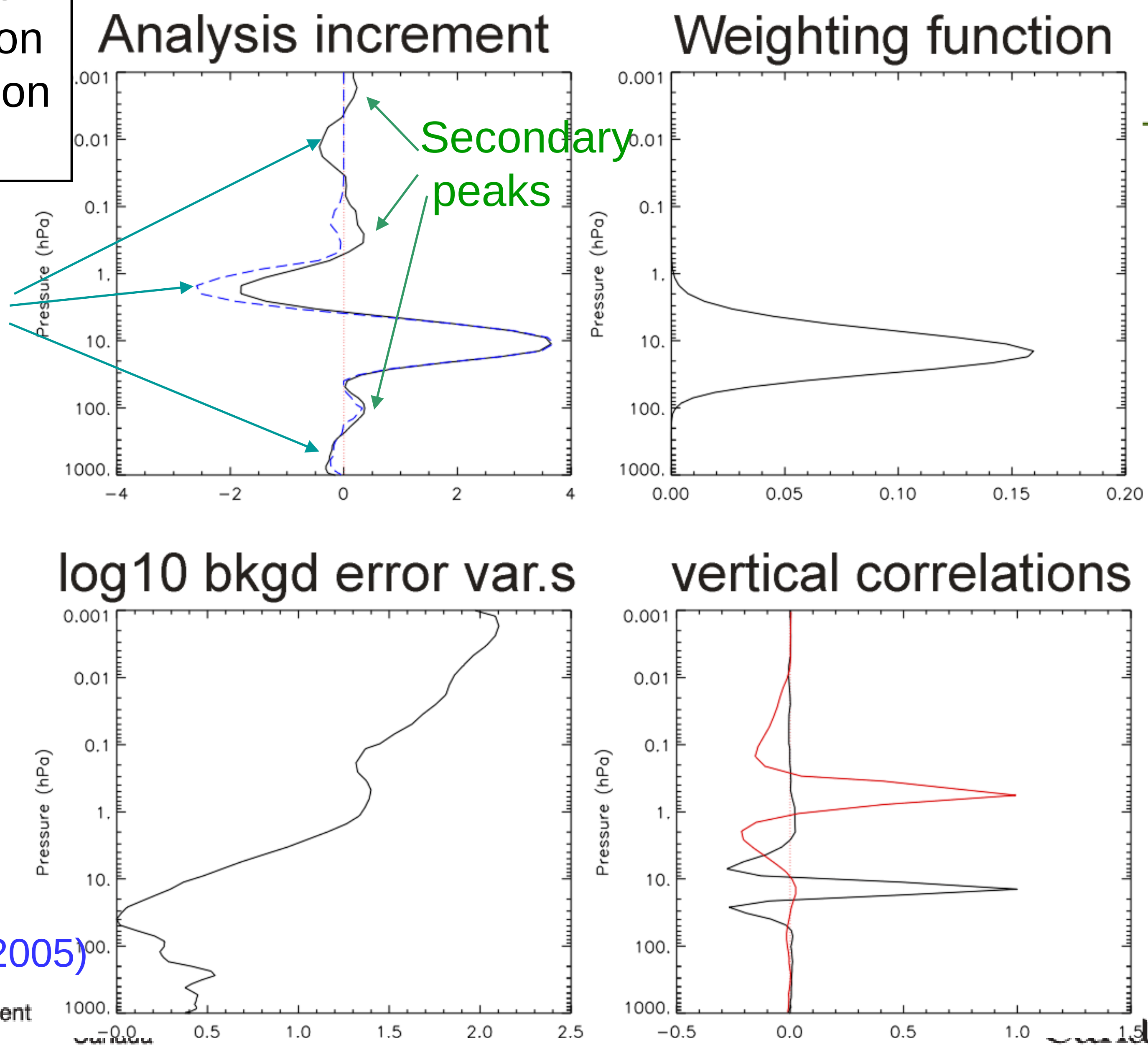


R.J. Sica (U Western Ontario)

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

AMSU ch. 11

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



Polavarapu et al. (2005)

Feb. 22, 2002 18Z
zonally avg. fields

CMAM + 3DVar

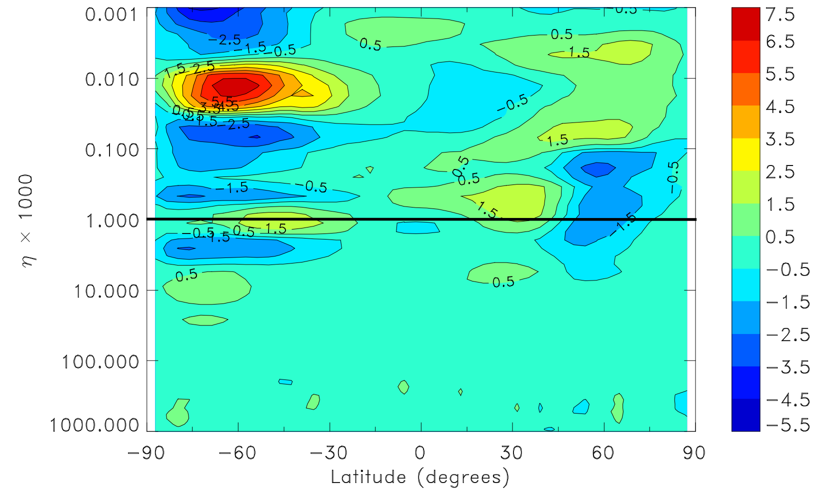
Why are incr largest in the mesosphere?

No data

data

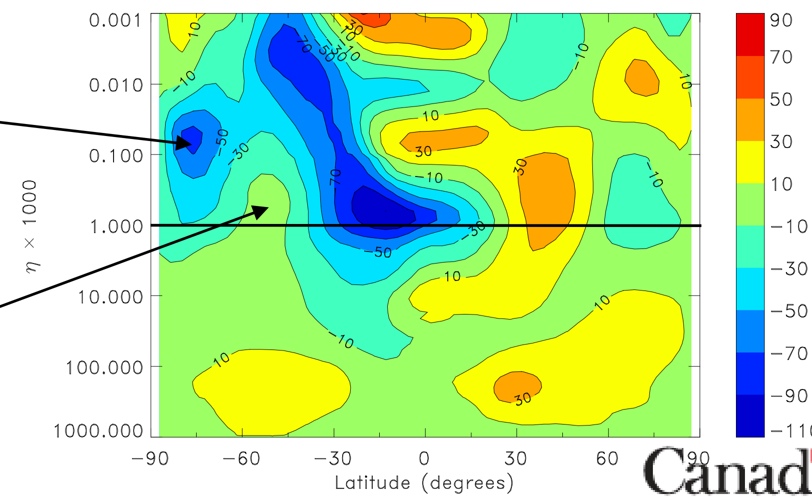
U anal incr

m/s



U analysis

m/s



Why do incr produce unphysical states?

spurious S. Hem. jet

reduced easterlies

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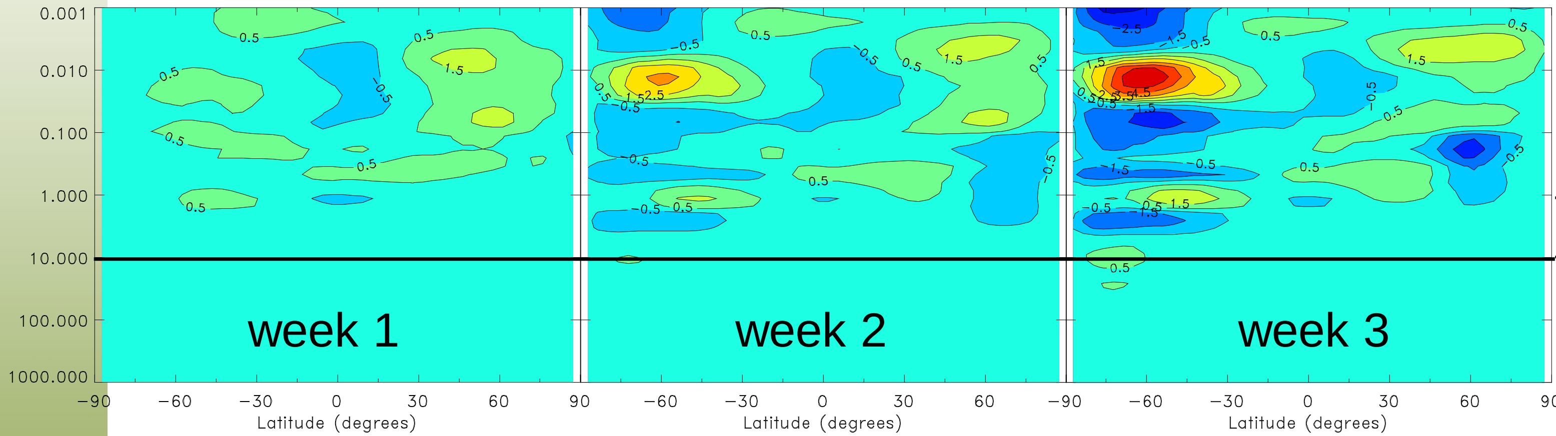
Obs and/or model forecast is biased

Polavarapu et al. (2005)

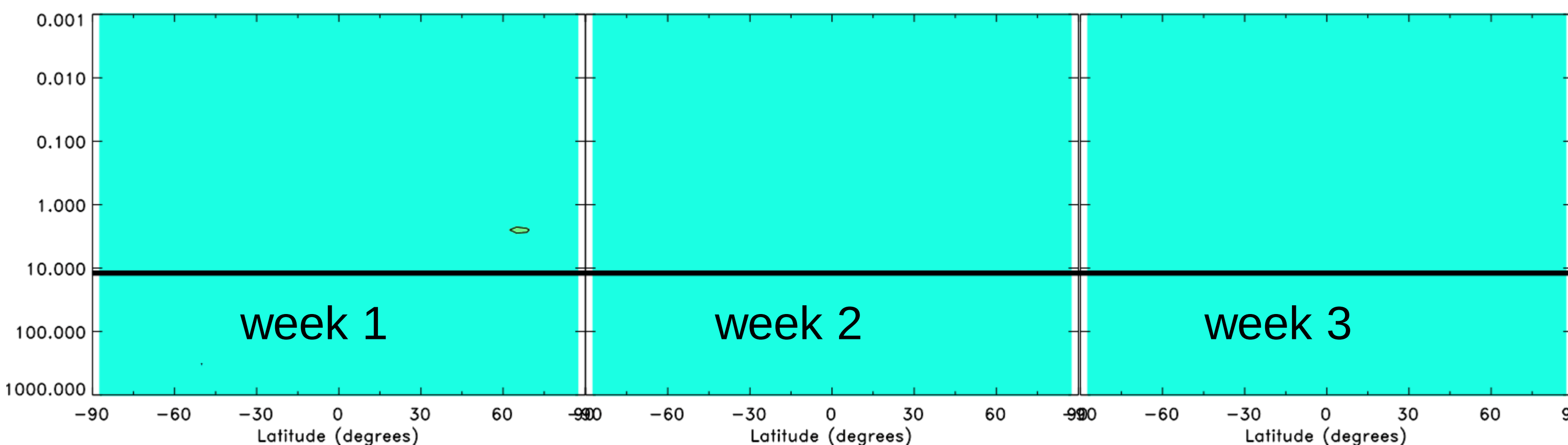
Zonal mean of weekly averaged zonal wind analysis increments



AMSU-A only

Sat+ In situ

After removing vertical correlations in the mesosphere



Information propagation through background error covariances

- Information propagation through background error covariances from stratosphere to mesosphere creates persistent spurious increments if forecasts are biased
- This information cannot be corrected if no mesospheric observations are assimilated
- Here we prevented the spurious increments by forcing tiny correlations to exactly zero.
- 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)!

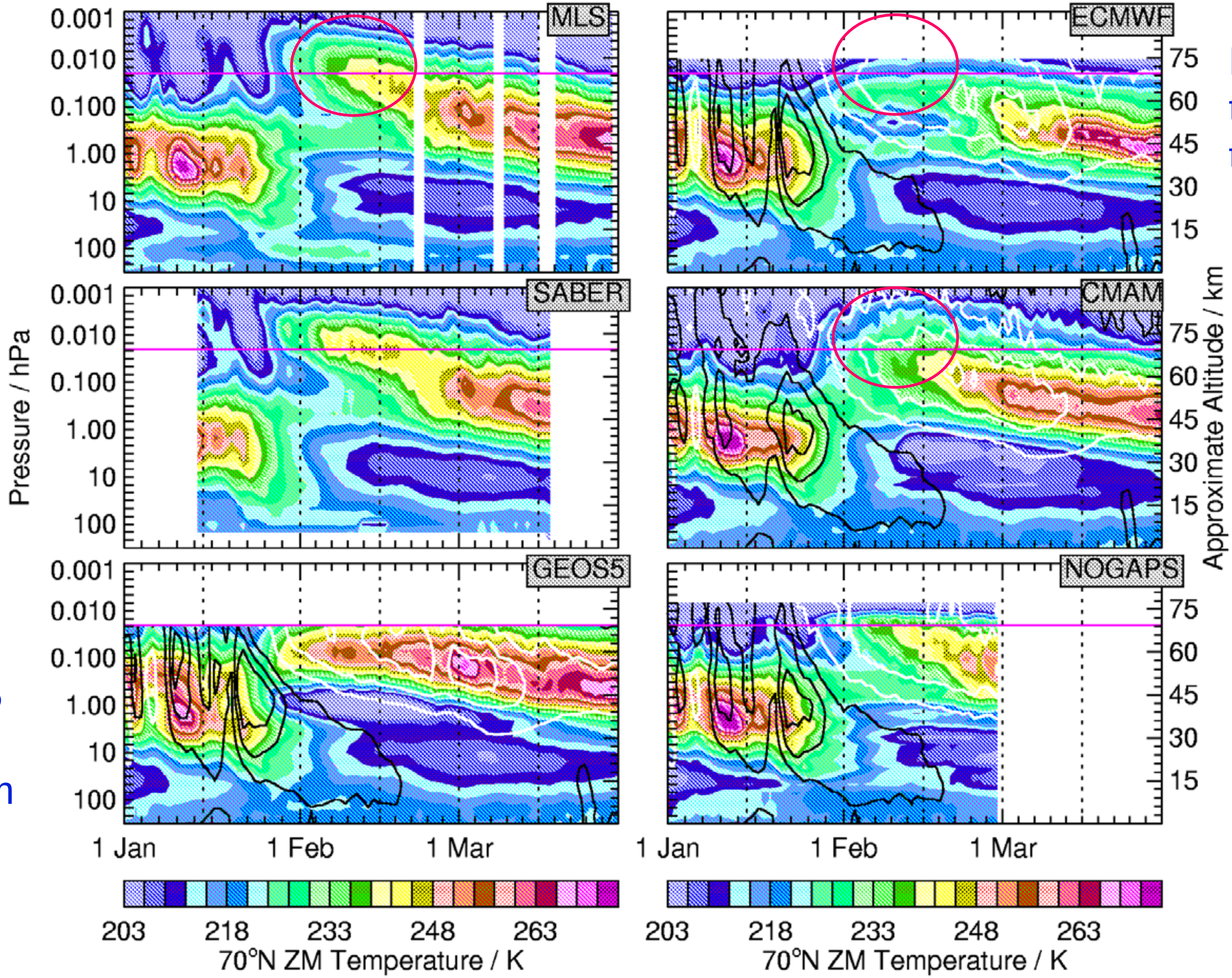
Information propagation through a Gravity Wave Drag (GWD) scheme

- 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

Stratopause is above 0.01 hPa!

Gloria Manney



ECMWF
too low
too cold

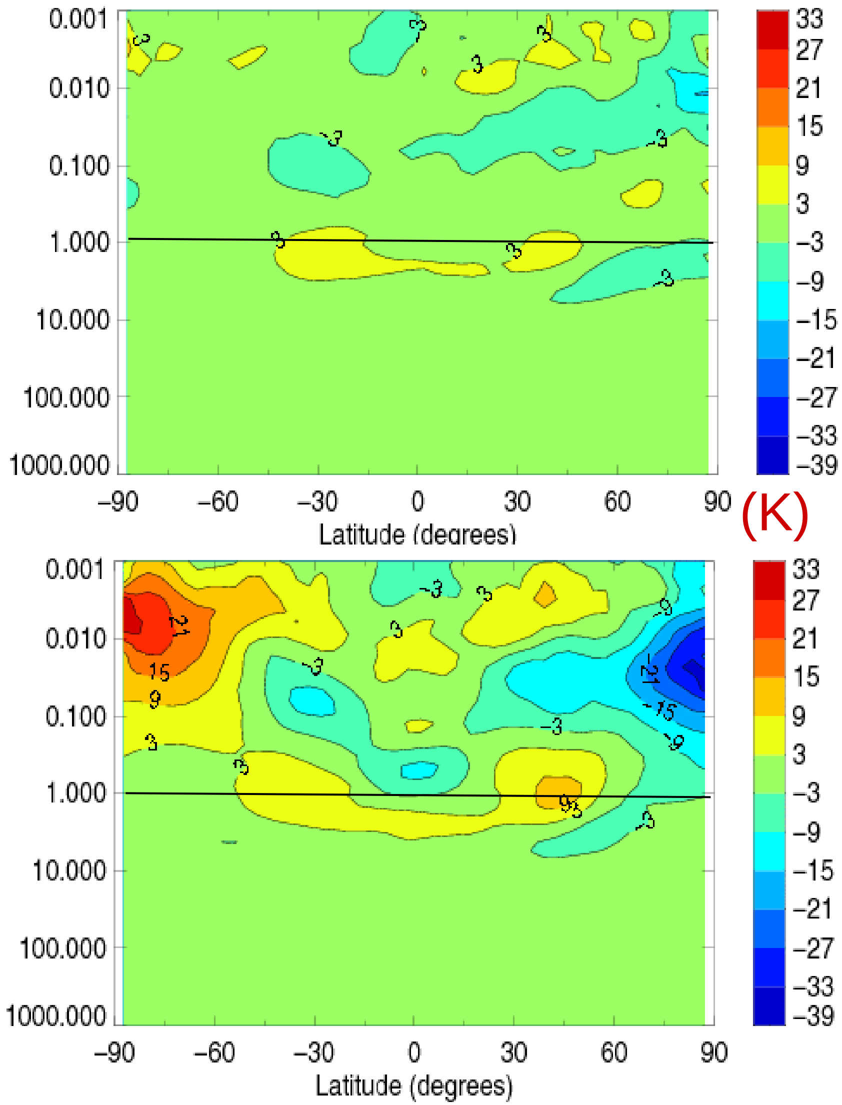
GEOS-5
too low
too warm

Canada

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

Temperature

Ren et al. (2011)



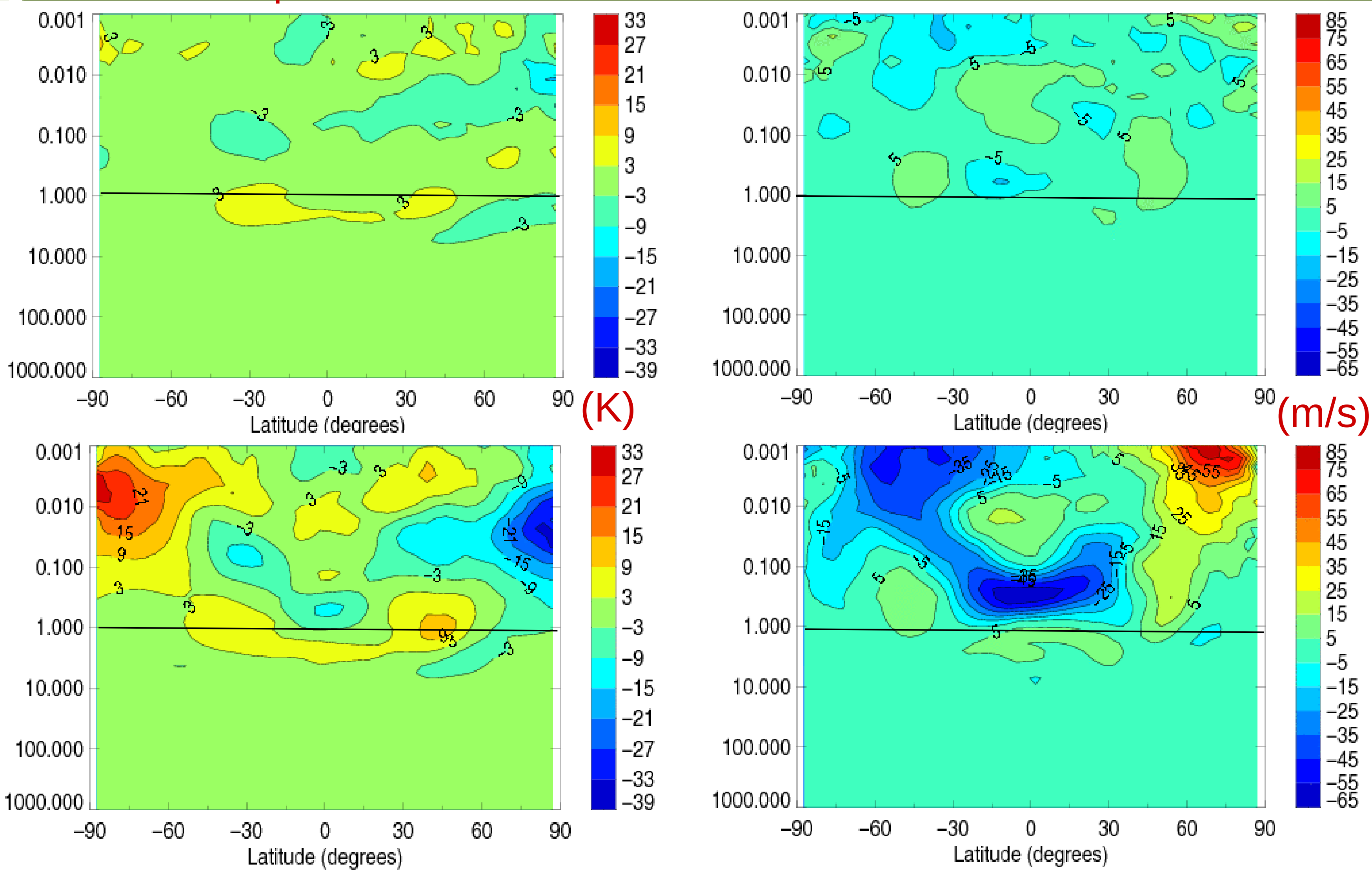
Assimilation cycle with GWD schemes

Repeat but with no nonorographic GWD

Canada

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

Temperature Zonal wind Ren et al. (2011)



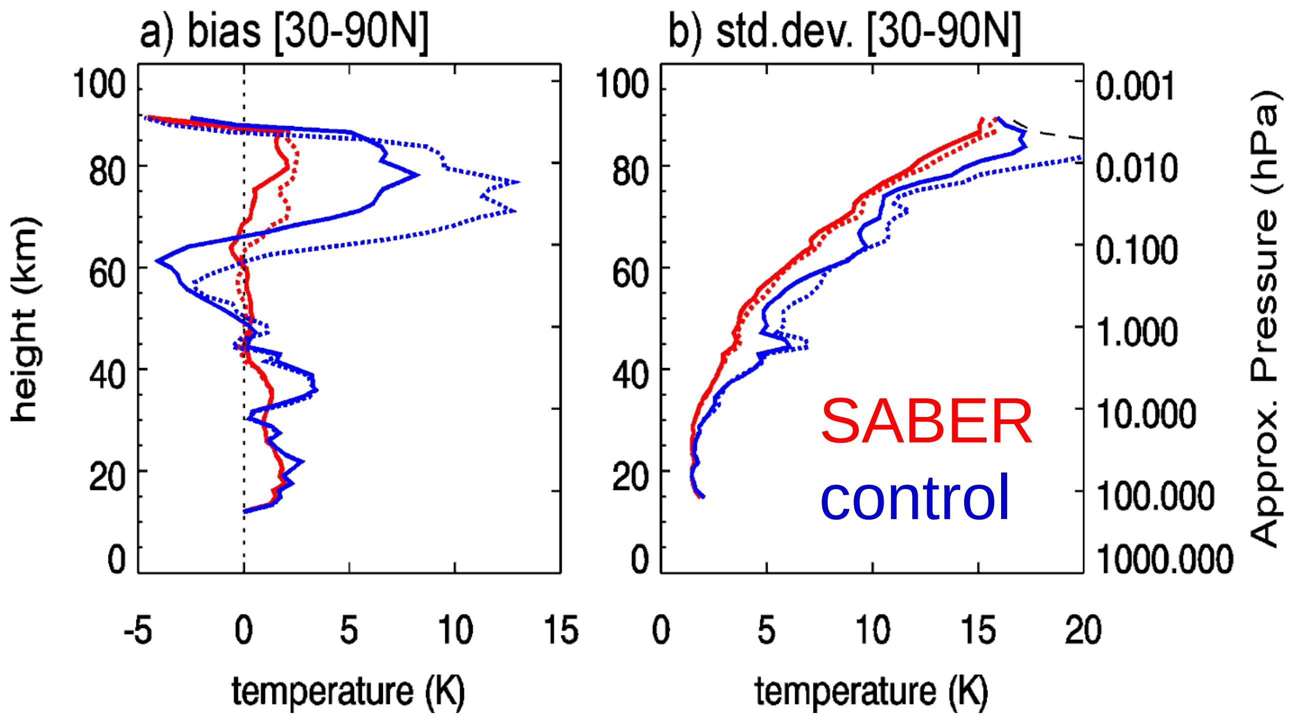
GWD improves fit to observations

Ren et al. (2011)

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

____ with GWD

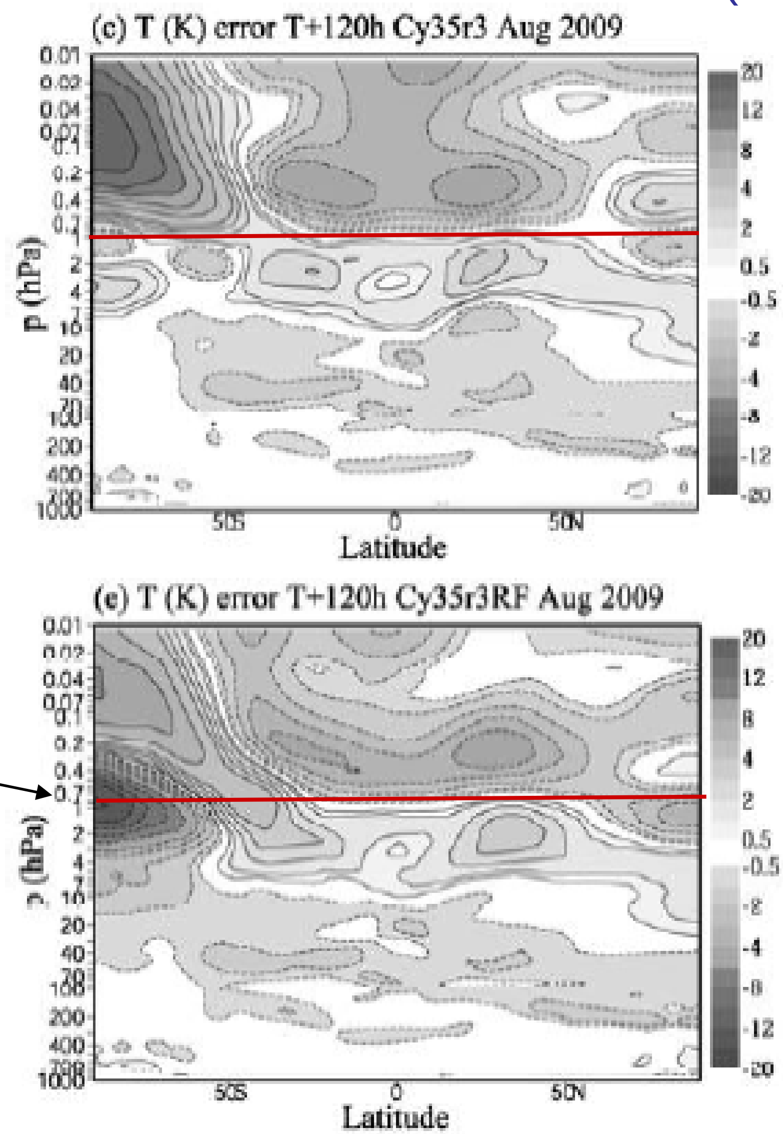
- - - - w/o GWD



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

Summary

- What are the 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

Outstanding problems

- Separation of model and observation error biases
  - Add more low-bias obs with vertical structure information such as GPSRO?
- Vertical spreading of information through covariances
  - Are background error covariances appropriately defined in the upper stratosphere given the poor vertical resolution provided by the observing system?
  - Ad hoc measures prevent spurious increments from contaminating mesosphere. Is there a better way?
- Lack of wind information in tropics
  - Without clear mass-wind balance, temperature information of limited use. Solution: new obs such as ADM or SWIFT? 4D-var and tracer assimilation?