THE STRATOSPHERIC MEAN MERIDIONAL CIRCULATION AS DIAGNOSED FROM REANALYSES

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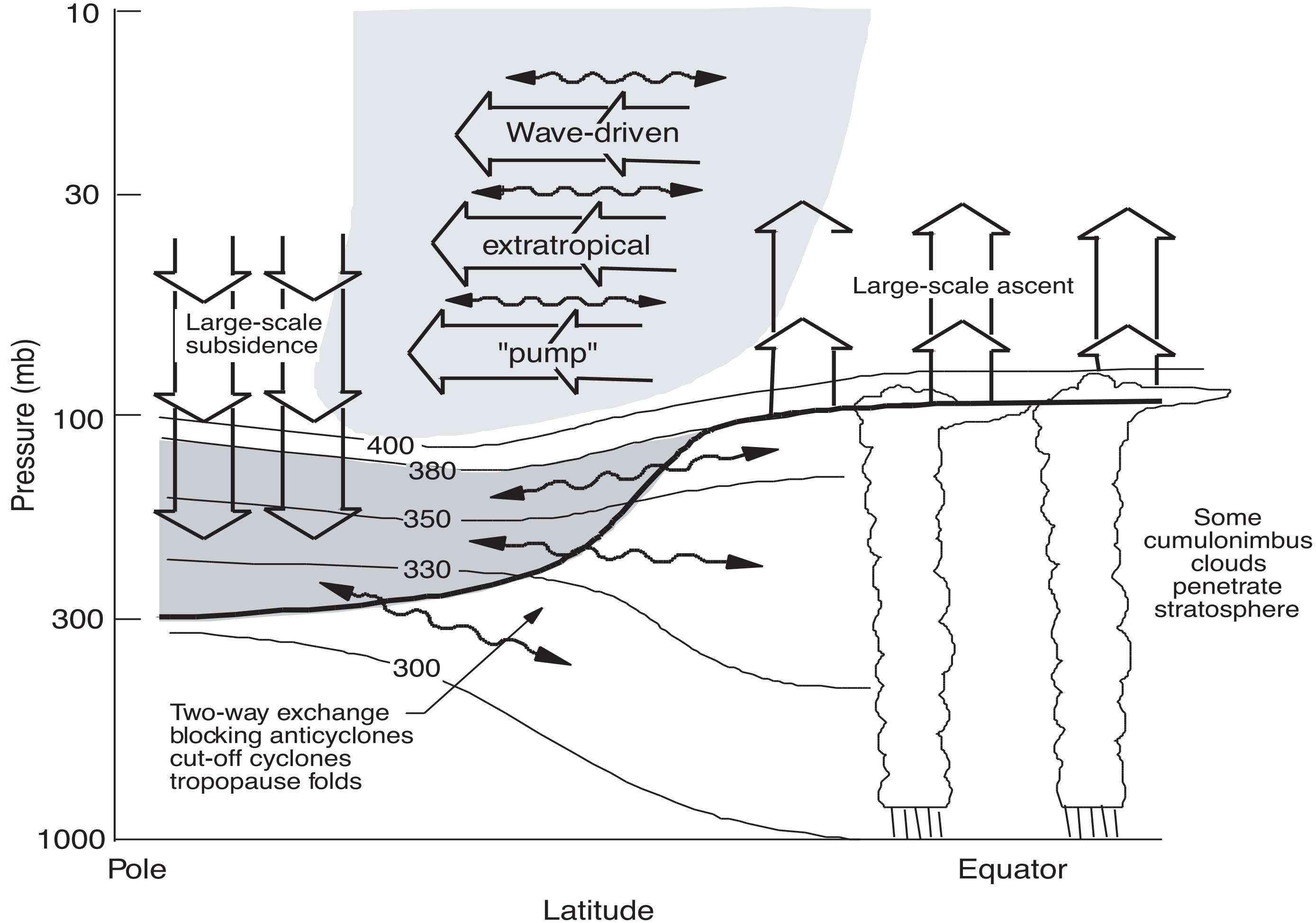
What is the stratospheric mean meridional circulation?

It is commonly referred to in the literature as the Brewer-Dobson circulation.



Schematic from Holton et al., 1995, Review of Geophysics

Fundamentally, the BDC is a transport circulation. We're interested in it (and how it changes in a changing climate) because it transports trace species into the stratosphere in the tropics, and out of the stratosphere at mid to high latitudes.

An important thing to note is that it is a Lagrangian-mean circulation, and cannot be directly measured.

Trace species measurements are how the BDC was first inferred.

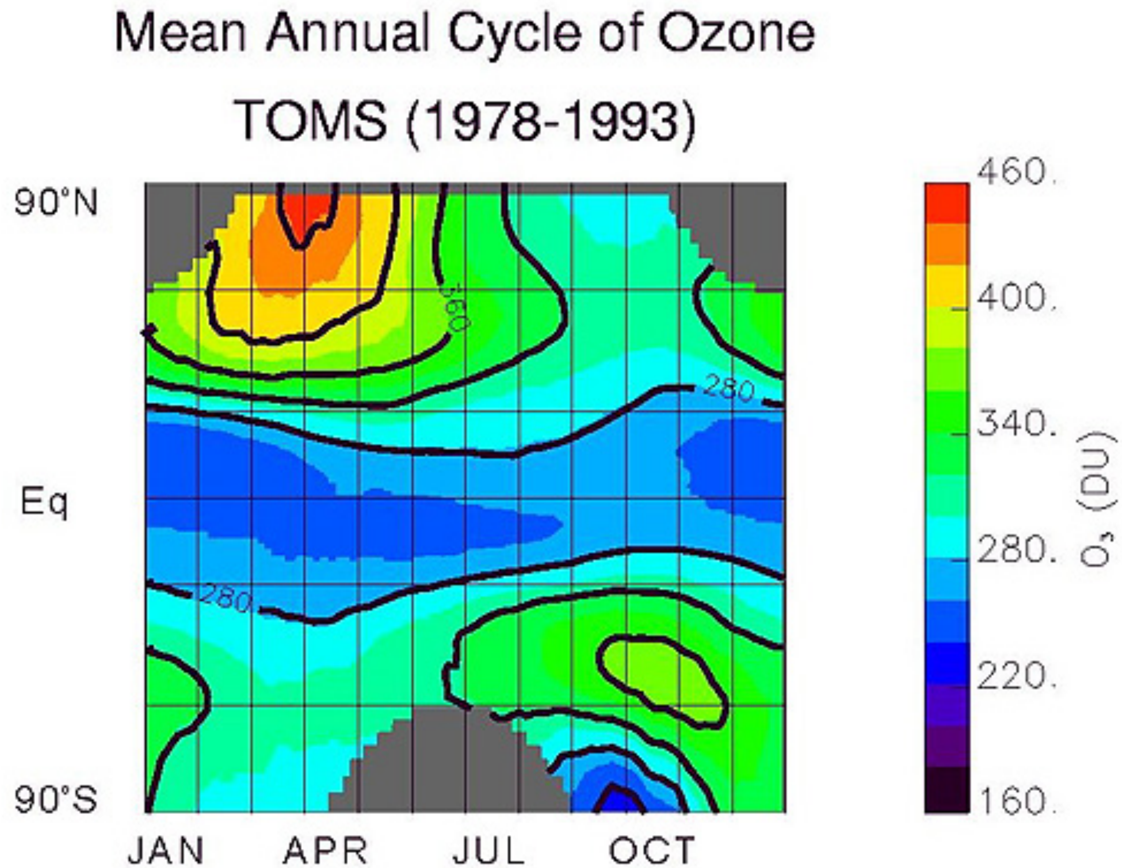
Prior to taking many measurements in the stratosphere, the general view was that the stratosphere was essentially free from vertical motions, and transport of trace species was a diffusional process.

However, this picture was not consistent with the latitudinal gradients in ozone that Dobson measured, nor the vertical profiles of water vapor that Brewer measured.

First line of evidence showing there is a circulation in the stratosphere

Although produced in the tropics, ozone columns are larger at mid to high latitudes.

Also, Dobson (1956) noted high ozone in the lower polar stratosphere, far from the source region.



The only way in which we could reconcile the observed high ozone concentration in the Arctic in spring and the low concentration within the Tropics, with the hypothesis that the ozone is formed by the action of sunlight, would be to suppose a general slow poleward drift in the highest atmosphere with a slow descent of air near the Pole. Such a current would carry ozone formed in

From Dobson, Harrison and Lawrence, 1929, Proc. Roy. Soc. A

Second line of evidence for the sense of the stratospheric circulation: Water Vapor

Alan Brewer developed an aircraft borne frost point hygrometer during WW-II specifically to assess conditions where contrails may form (to determine how to avoid making contrails). They flew on a B-17 (up to 38 Kft) and then a Mosquito (up to 44 Kft), and got just into the stratosphere over the UK.

CONDENSATION TRAILS

By A. W. Brewer, M.Sc.

Weather, 1946, pg 38-40

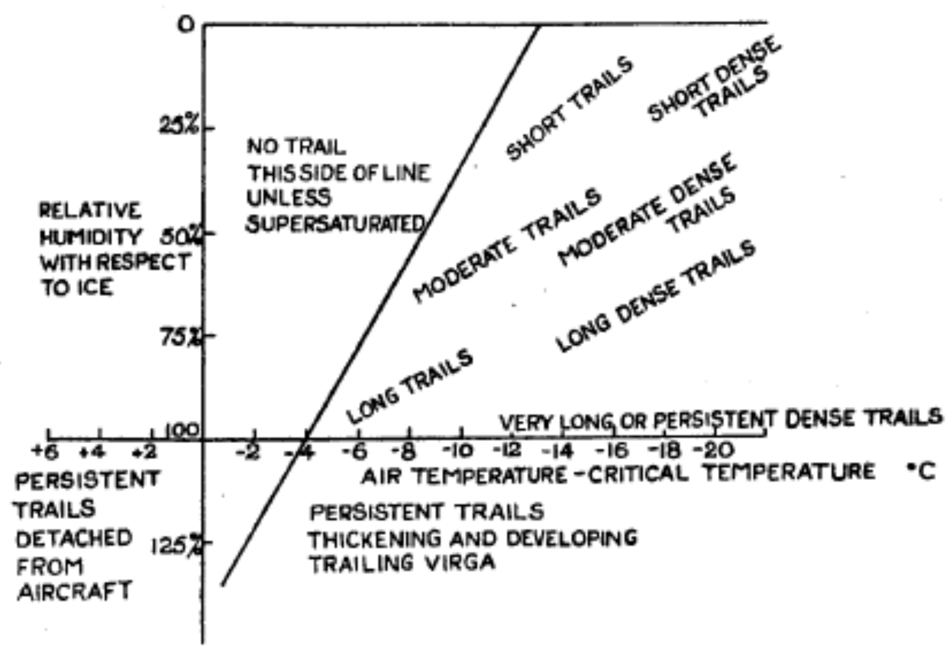


Fig. 3. The variation of condensation trail length with humidity and the depression of the air temperature below the calculated critical temperature.

551.510.5

EVIDENCE FOR A WORLD CIRCULATION PROVIDED BY THE MEASUREMENTS OF HELIUM AND WATER VAPOUR DISTRIBUTION IN THE STRATOSPHERE

By A. W. BREWER, M.Sc., A.Inst.P.

(Manuscript received 23 February 1949)

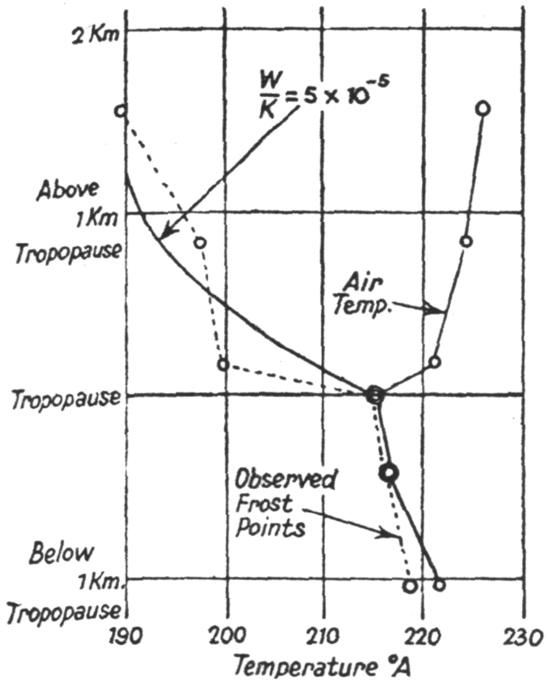
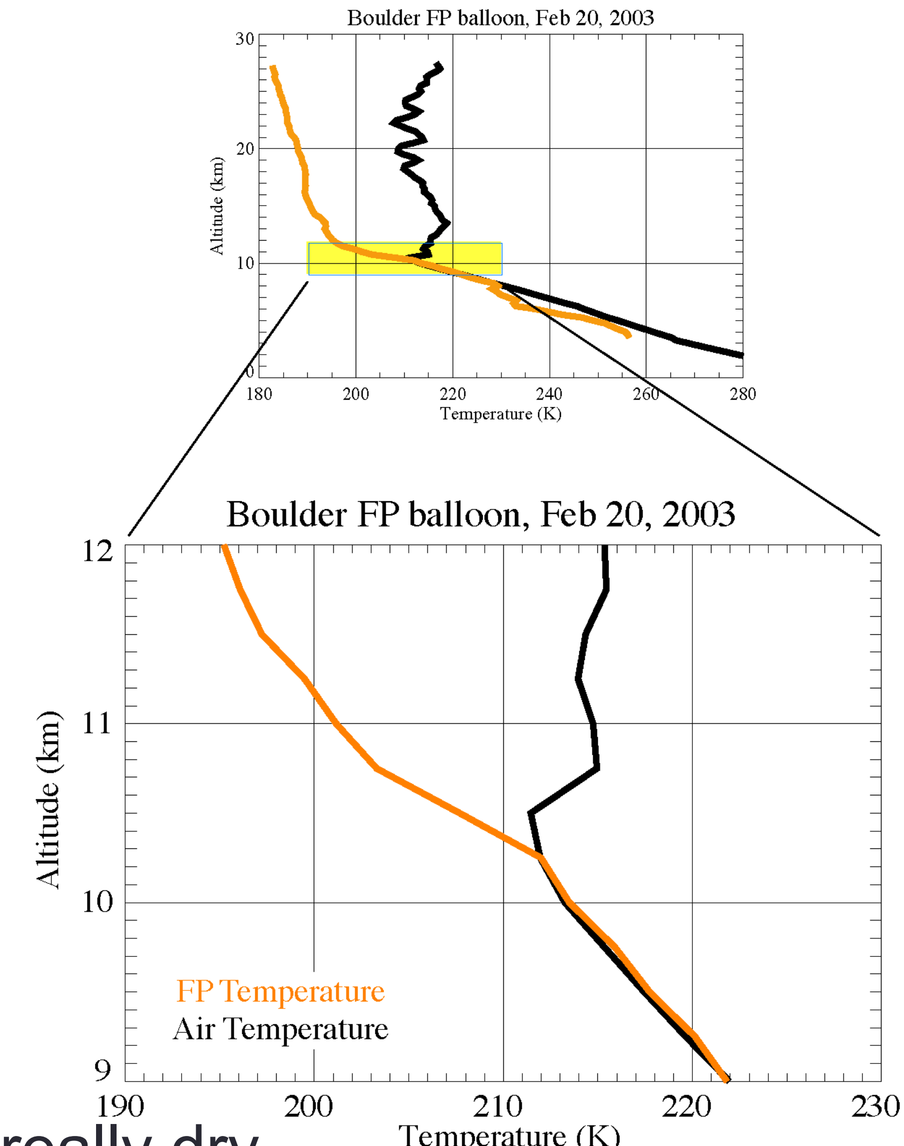


FIG. 1. 30 May 1945. Tropopause ht 33,400 ft.

~50°N, 1945, Southern England

~40°N, 2003, Boulder, CO

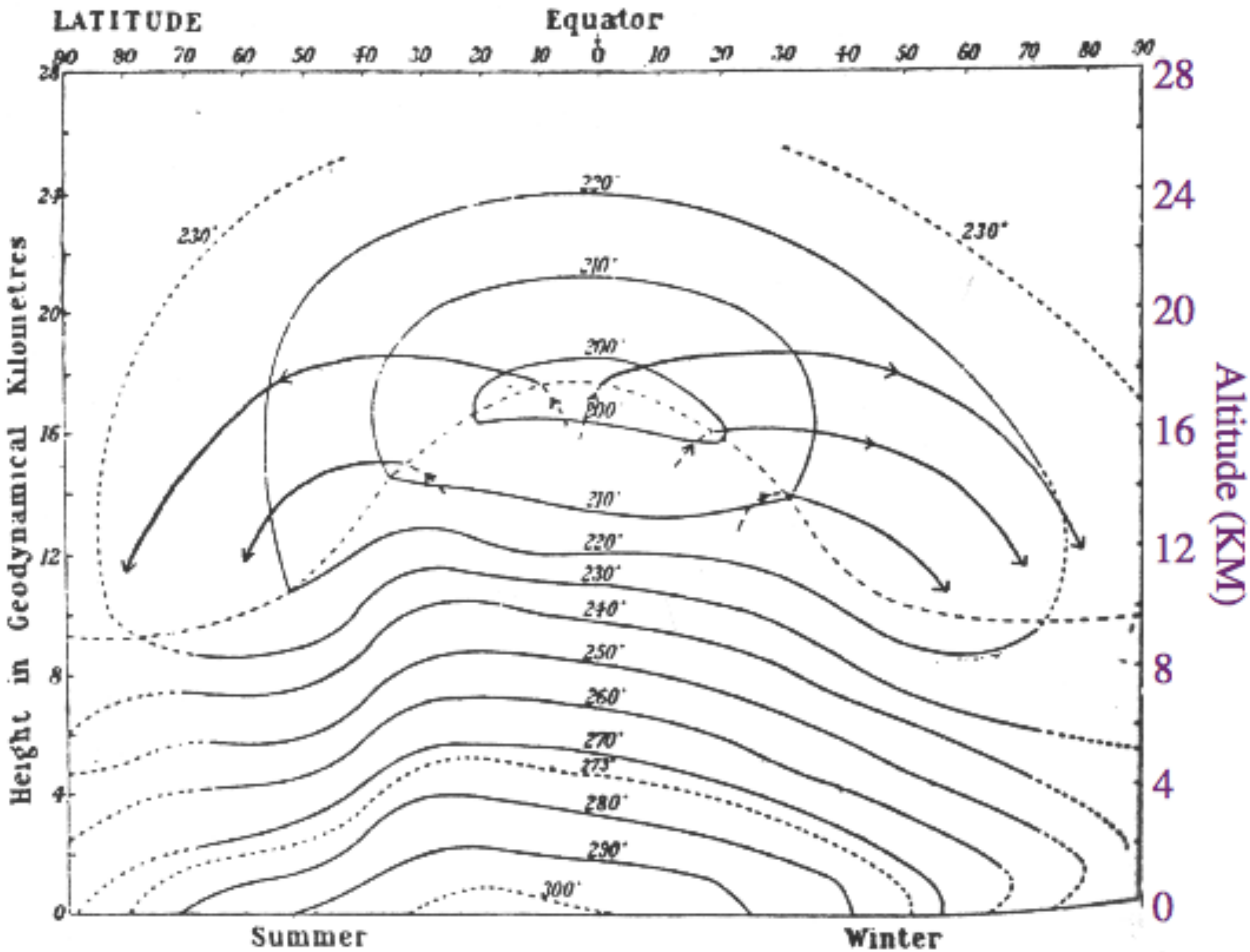


Bottom line, the stratosphere is really dry.

Brewer (1949) noted that the stratosphere sampled in the UK was much drier (~3-5 ppmv) than the local minimum temperatures would produce (~50 ppmv).

Because this air was drier than ice saturation over the UK, that implied there had to be a circulation bringing that air from somewhere.

The only location he knew of where temperatures were cold enough was near the tropical tropopause.



Isotherms over the Globe

How has the mean meridional circulation been quantitatively estimated?

Murgatroyd and Singleton (1961) calculated what's come to be known as the diabatic circulation.

$$\cancel{\frac{\partial \bar{T}}{\partial t}}+\cancel{\frac{\bar{v}}{a}\frac{\partial \bar{T}}{\partial \phi}}+(\Gamma_d-\Gamma)\bar{w}$$

$$=\bar{Q}-\cancel{\frac{1}{a\cos\phi}\frac{\partial}{\partial \phi}(\overline{v'T'}\cos\phi)}-\cancel{\frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0\overline{w'T'})},$$

$$\frac{1}{a\cos\phi}\frac{\partial}{\partial \phi}(\bar{v}\cos\phi)+\frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0\bar{w})=0.$$

Dunkerton, 1978, showed that this is actually representative of air parcel motions in the stratosphere and mesosphere.

132 R. J. MURGATROYD and F. SINGLETON

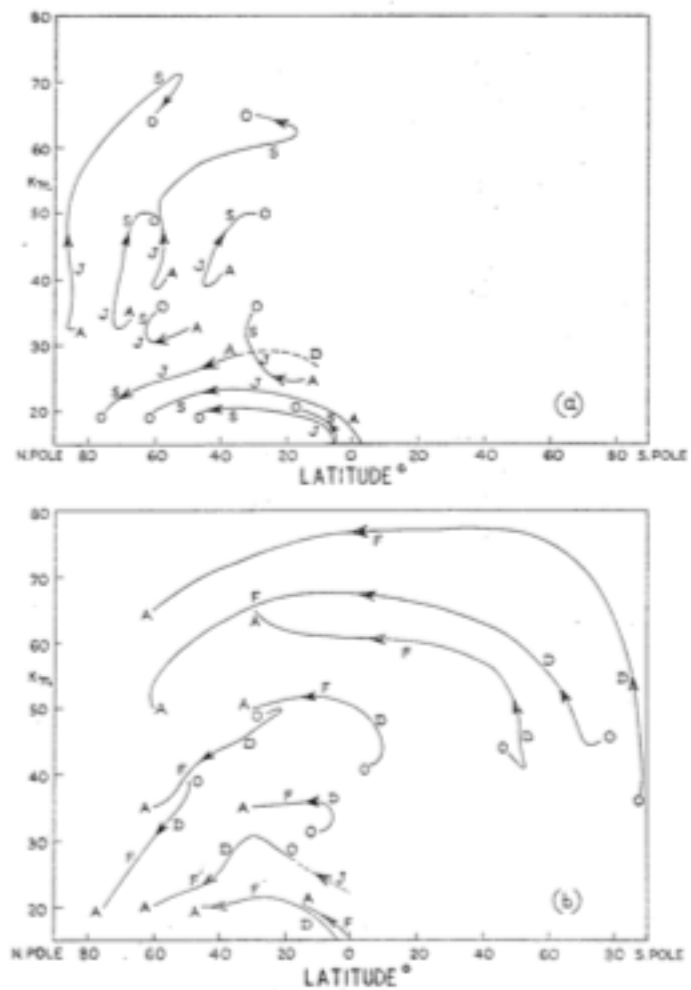


Figure 3. Selected air trajectories over six-monthly periods. Upper diagram shows trajectories ending in autumn, lower in spring in northern hemisphere. Dashed lines indicate movement in preceding six months. F denotes February position, A April, J July, S September, O October, D December.

Kida, 1977 (JMSJ) ran many forward trajectories using GCM. (interested in both the troposphere and stratosphere.)

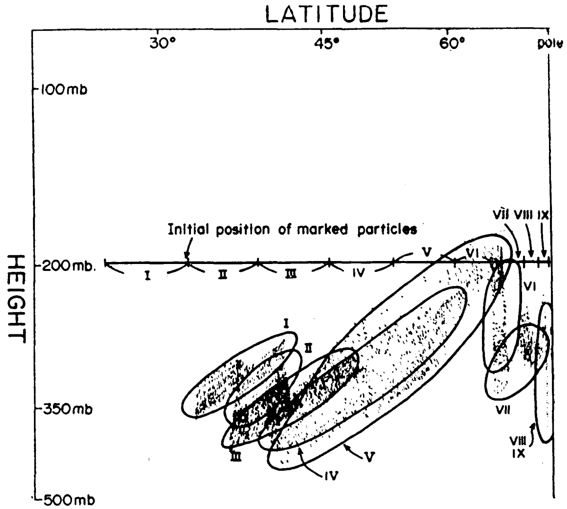
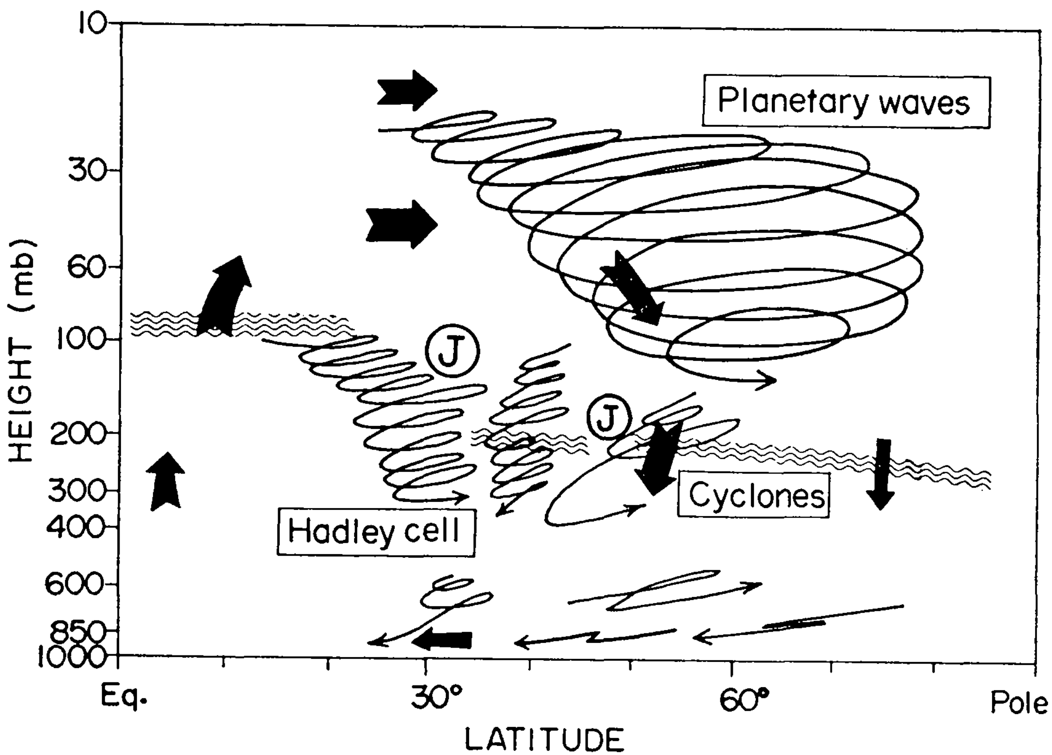


Fig. 3c The same as Fig. 3a except for the 30th day.



Over all features are similar to the Murgatroyd and Singleton and Dunkerton studies.

How do we estimate the BDC using output from reanalyses?

1) We can use the Andrews and McIntyre definition of the TEM residual velocities.

$$\bar{v}^* = \bar{v} - \frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\rho_0 \overline{v'\theta'}/\bar{\theta}_z\right)$$

$$\bar{w}^* = \bar{w} + \frac{1}{a\cos\phi}\frac{\partial}{\partial \phi}\left(\cos\phi\, \overline{v'\theta'}/\bar{\theta}_z\right),$$

Whether both vbarstar and wbarstar can be calculated depends on whether vertical velocities are a saved parameter. And, as a caveat, the wbar term seems to be a better calculation when wbar is saved as an averaged rather than instantaneous field.

Or the mass-weighted isentropic zonal mean (MIM) meridional velocity from Iwaski (1989) see http://wind.gp.tohoku.ac.jp/mim/

2) We can use the TEM thermodynamic and continuity equations.

$$\frac{\partial\bar{\theta}}{\partial t} + \frac{\bar{v}^*}{a}\frac{\partial\bar{\theta}}{\partial\phi} + \bar{w}^*\frac{\partial\bar{\theta}}{\partial z} = \bar{Q} - \frac{1}{\rho_0}\frac{\partial}{\partial z}\left[\rho_0\left(\overline{v'\theta'}\,\bar{\theta}_\phi / a\bar{\theta}_z + \overline{w'\theta'}\right)\right]$$

$$\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\bar{v}^*\cos\phi\right) + \frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\rho_0\bar{w}^*\right) = 0.$$

Where Qbar can either be taken from reanalysis output or calculated using temperatures (and possibly cloud info) from reanalysis, and constituent information from another source.

How do we estimate the BDC using output from reanalyses?

3) We can use TEM zonal momentum and continuity equations. (Haynes et al., 1991)

$$\frac{\partial \bar{u}}{\partial t} + \bar{v}^*\left[\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}(\bar{u}\cos\phi) - f\right] + \bar{w}^*\frac{\partial \bar{u}}{\partial z} = \frac{1}{\rho_0 a\cos\phi}\nabla\cdot\mathbf{F} + \bar{X} = \bar{\mathcal{F}}$$

$$\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}(\bar{v}^*\cos\phi) + \frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0\bar{w}^*) = 0.$$

substituting $\bar{v}^* = -\frac{1}{\rho_0\cos\phi}\frac{\partial\Psi}{\partial z},\ \bar{w}^* = \frac{1}{\rho_0 a\cos\phi}\frac{\partial\Psi}{\partial\phi}.$

And estimating $\nabla\cdot\mathbf{F}$ from reanalyses products

Solve for $\Psi(\phi,z) = \int_z^\infty \left\{\frac{\rho_0 a^2\bar{\mathcal{F}}\cos^2\phi}{\bar{m}_\phi}\right\}_{\phi=\phi(z')} dz'$ TEM stream function

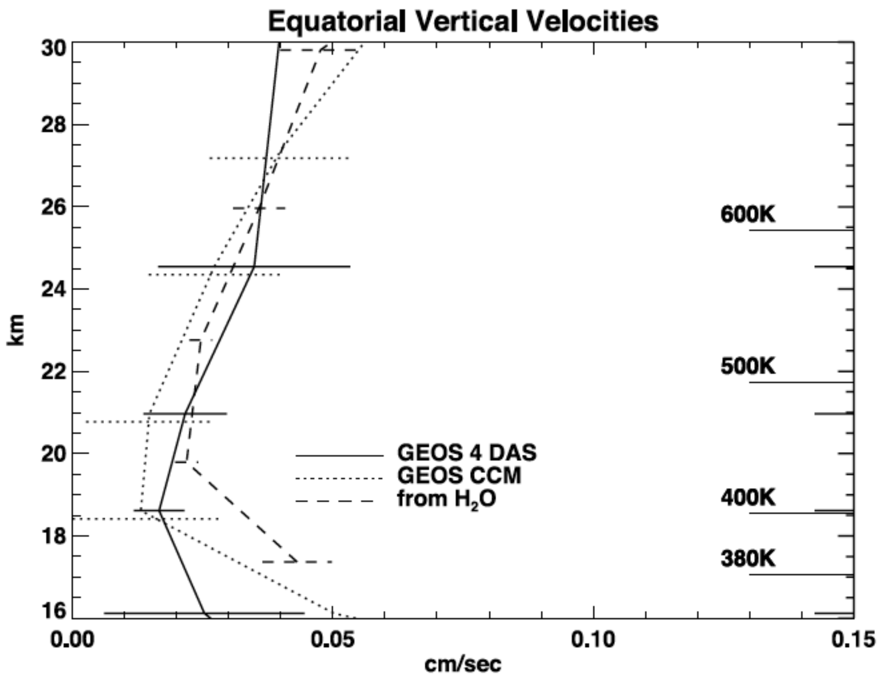
Calculate the mass flux across a pressure surface poleward of a given latitude ϕ

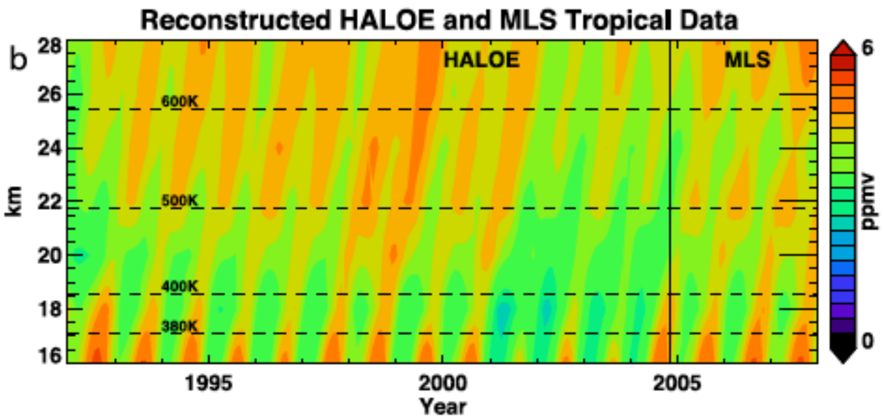
$2\pi\int_\phi^{\text{pole}} \rho_0 a\cos\phi\,\bar{w}^*\,a\,d\phi = 2\pi a\Psi(\phi)$ and, **Tropical upward mass flux** $= 2\pi a\left(\Psi_{\max} - \Psi_{\min}\right).$

Downward Control

How do we estimate the BDC using output from reanalyses?

4) Derive constituent distributions using reanalyses winds in a CTM, and look at the propagation of seasonal signals.

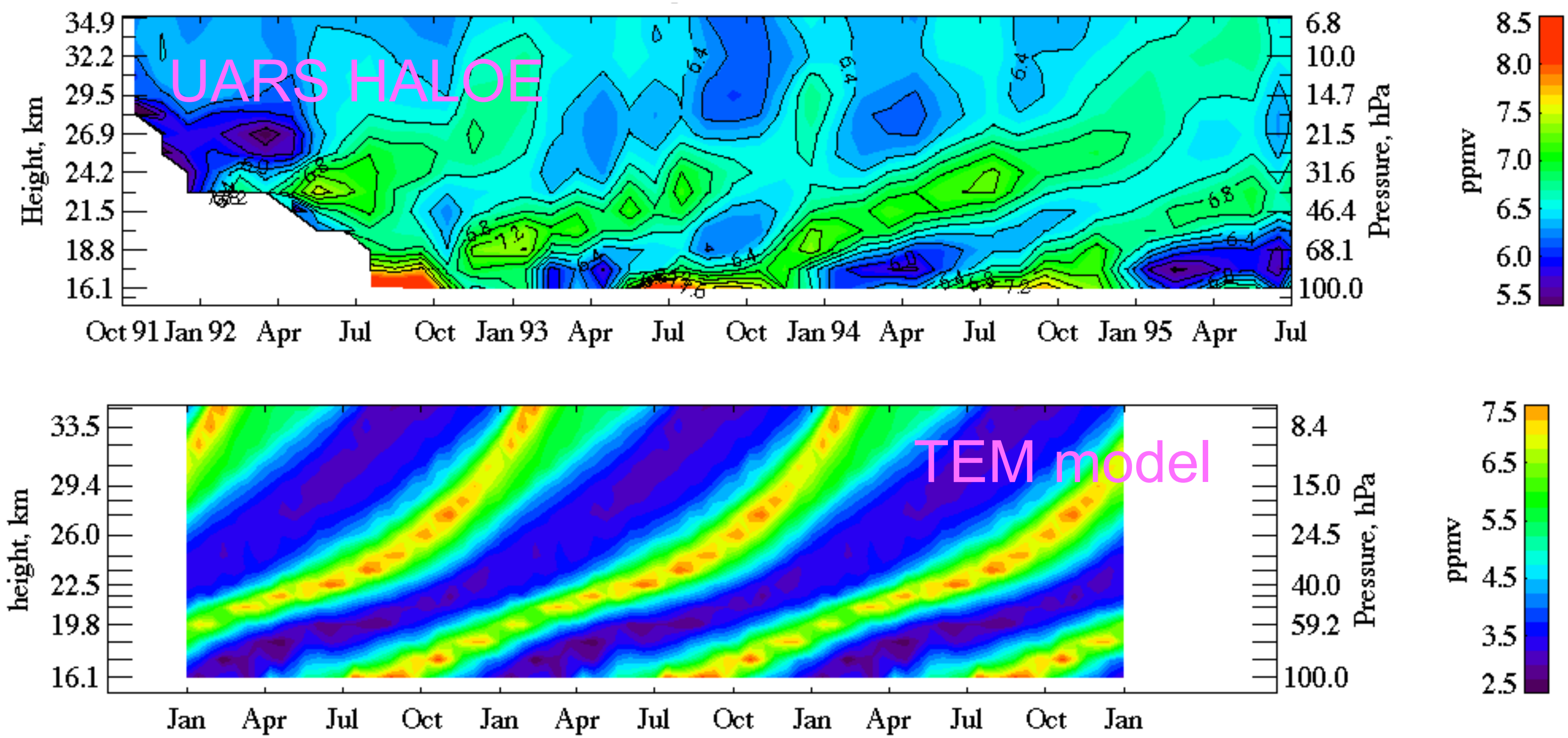




Velocities were estimated by using lag correlation between levels in the vertical following a method described in Niwano et al., 2003.

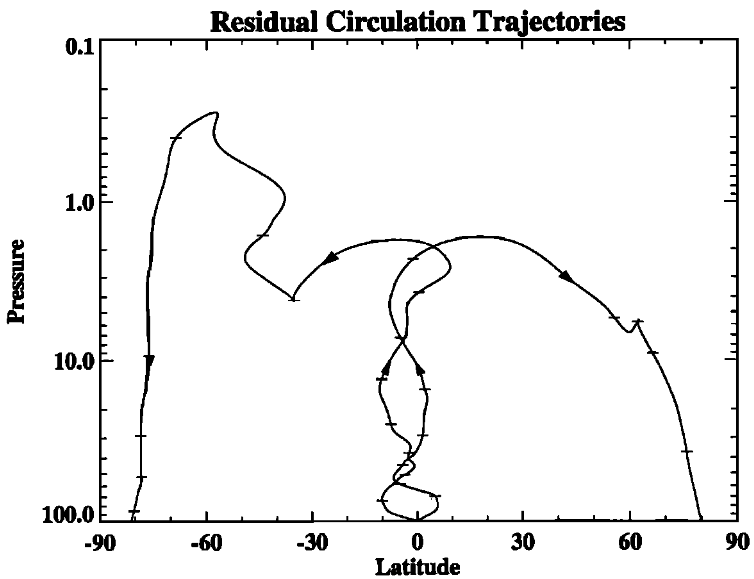
Schoeberl et al., 2008 used the vertical propagation of the annual cycle in tropical water vapor to estimate Lagrangian-mean vertical velocities.

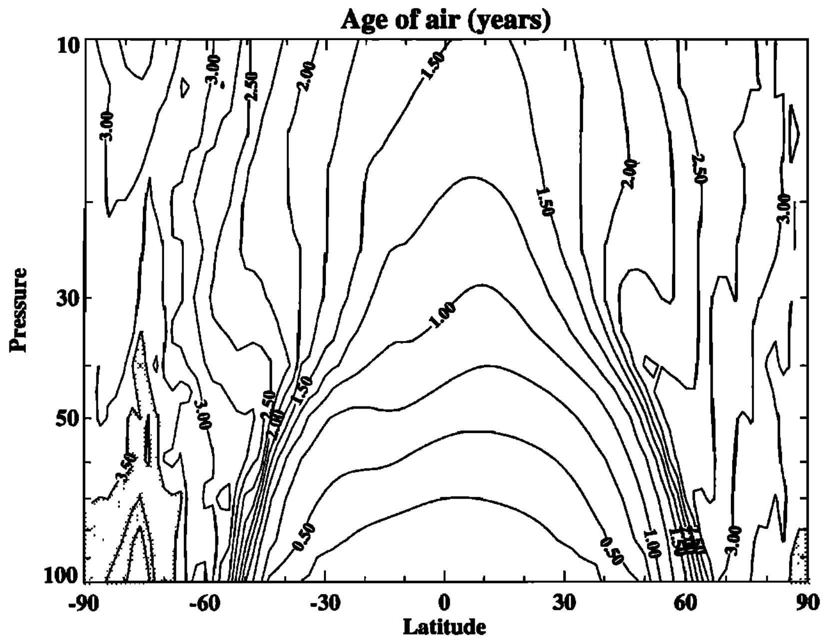
Another way to judge the accuracy of the BDC in reanalyses; compare water vapor derived from a simplistic calculation to observations. Here, NCEP wbarstar and tropopause temperatures were used. Note that temperatures had to be adjusted (this used the NCEP reanalysis from the early 1990s), and the circulation appears to be too fast.



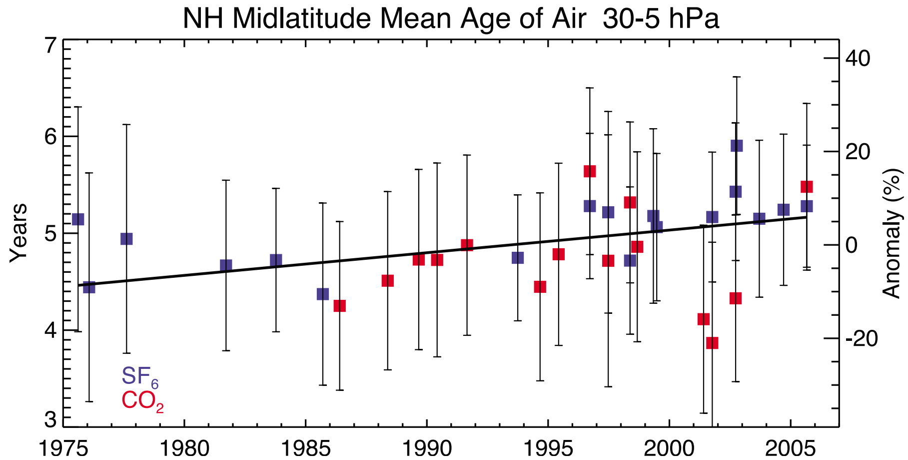
Tropical tape recorder, Mote et al, 94&95

Another metric to look at: Circulation Transit Time (related to age of air)

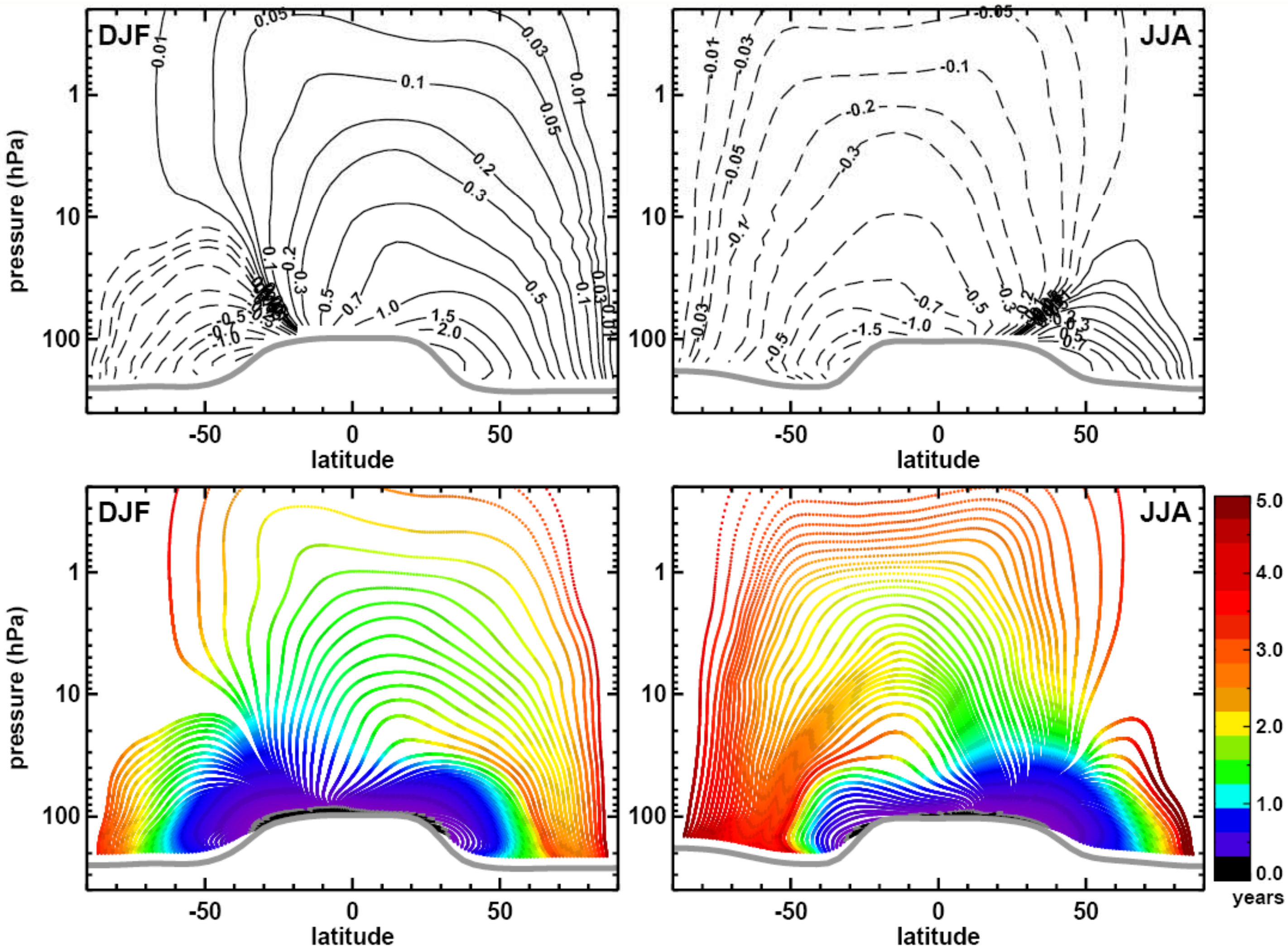




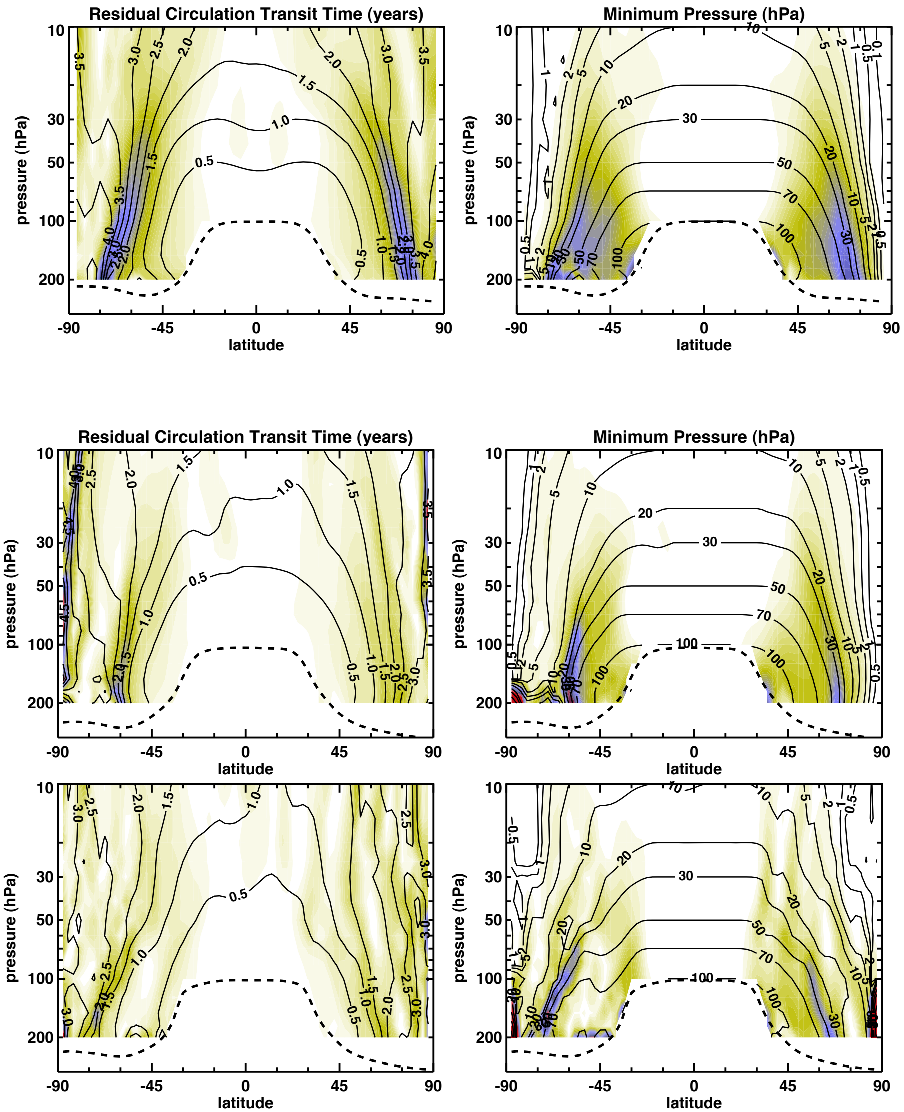
From Rosenlof, 1995 (used UKMO method 2 (radiative calculation)



Data based age estimates to compare with. Ray et al., 2010



Birner and Boenisch 2011 did a similar calcultion…shown here are results from CMAM



CMAM

JRA

ERA-40

From B&B text:

Transit times along the residual streamlines are generally smaller for ERA40 and JRA25 that for CMAM, especially in the polar regions. It is important to note that transit times here do not include the effect of two-way mixing. It can be concluded that the residual circulation in the reanalyses is biased fast compared to CMAM.

Prelim analysis of ERA-I showed better agreement with CMAM.

In regards to S-RIP: We need to be able to assess both

1) Differences between the various reanalyses

    and

2) Effective accuracy

Another consideration is whether it's possible to ascertain trends and variability.

And, we need to keep in mind that the mean meridional circulation is not directly measurable…it has been inferred from constituent observations.

To assess accuracy, we can look at both absolute values and variations in quantities that are likely a function of the mean meridional circulation.

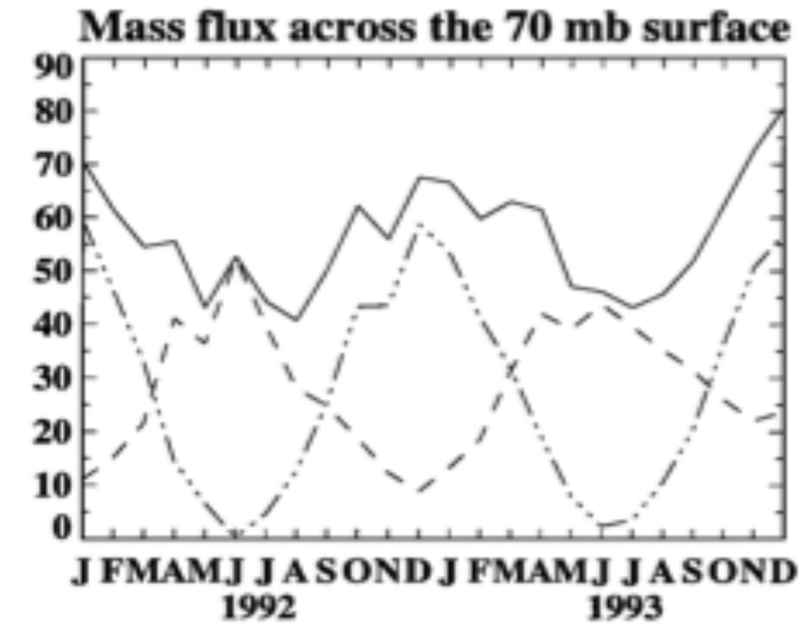
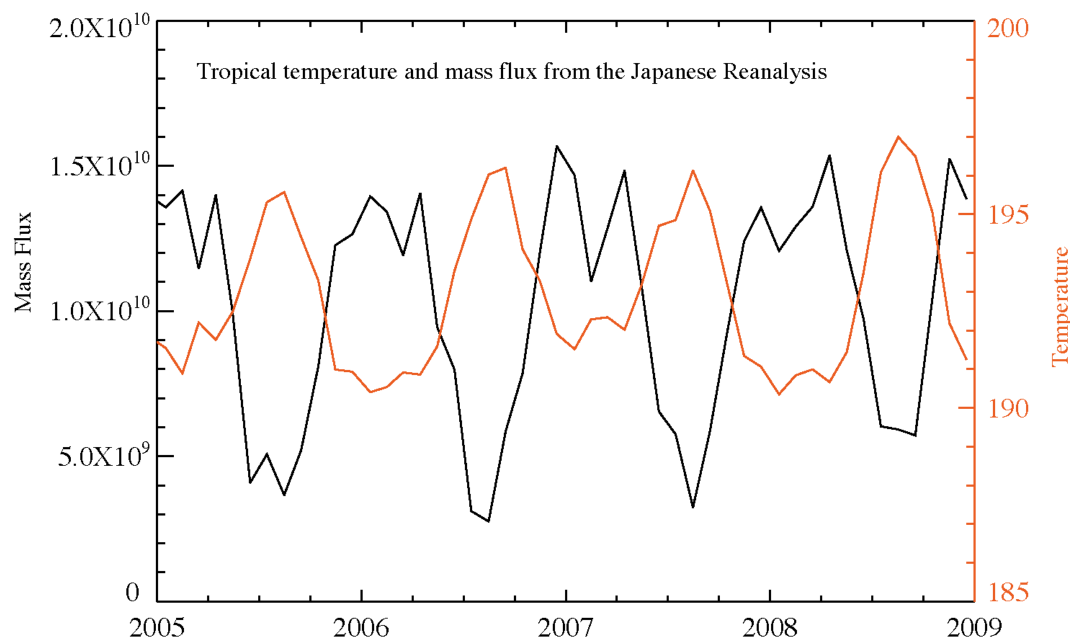


Figure 14. Time series of mass flux across the 70-hP surface in units of 10^8 kg/s computed from the radiativel derived stream function. Solid curve is the net upward tropic flux; dotted-dashed curve is downward flux into the norther hemisphere; dashed curve is downward flux into the souther hemisphere.

Seasonal cycle lower stratospheric mass flux

Below: shows mass flux and temperature relationship



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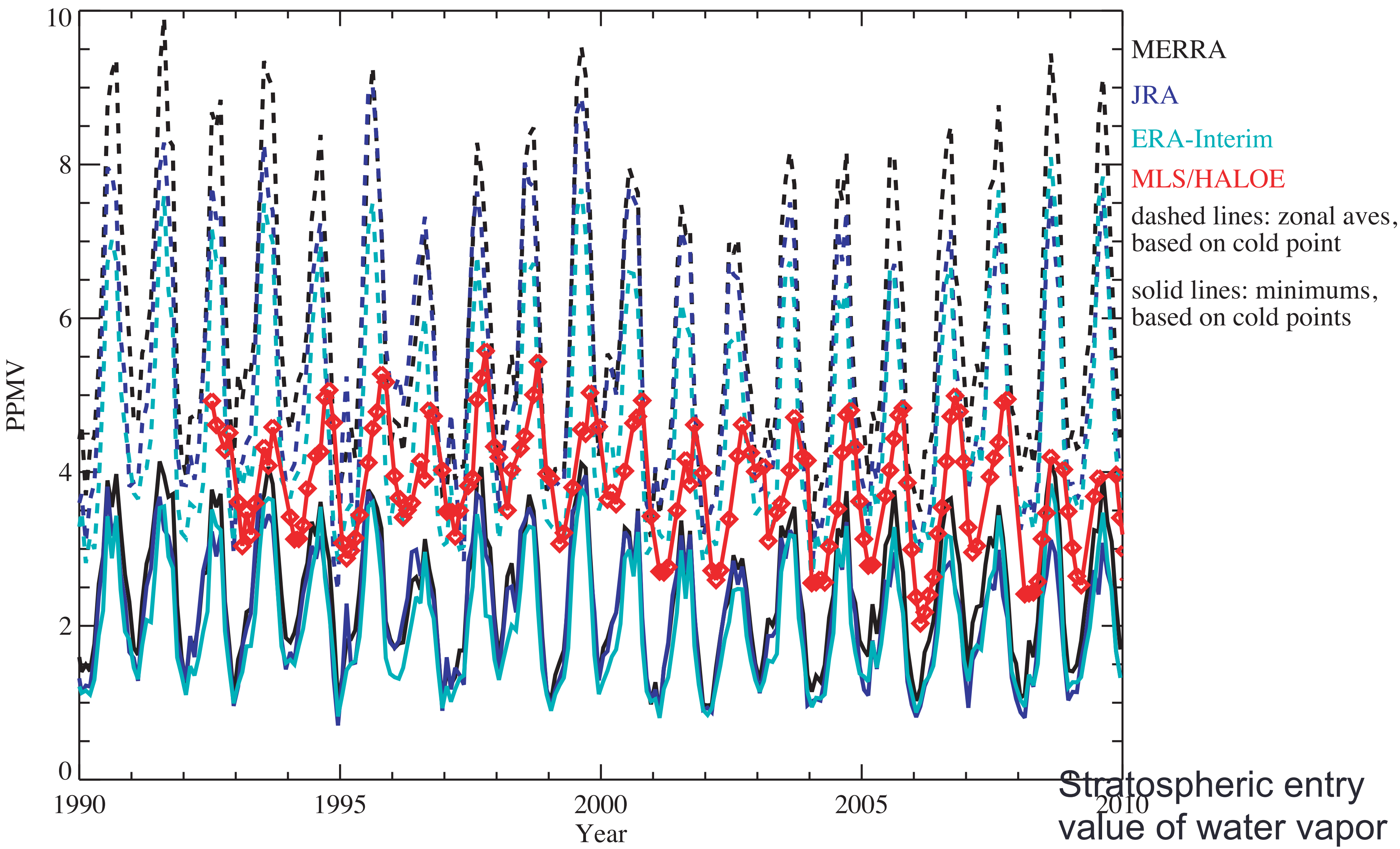
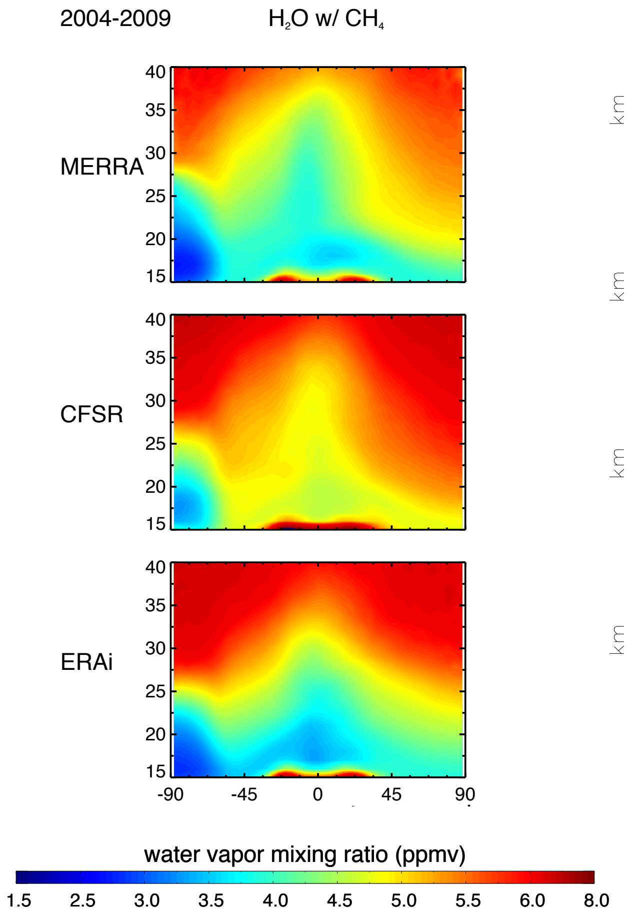
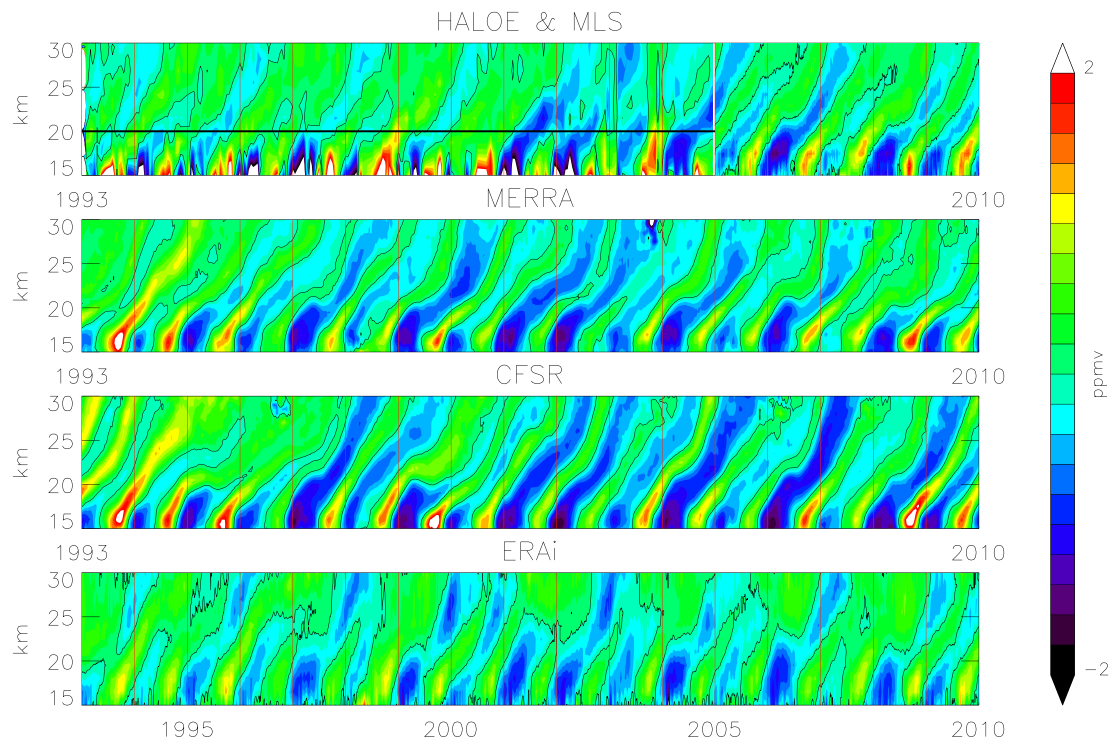


Stratospheric entry value of water vapor

Example of using different reanalyses to derive a stratospheric field that can be compared with observations; another way to assess accuracy

Schoeberl, Dessler, and Wang (ACPD, 2012): Used a domain-filling, forward trajectory calculation model to generate time dependent water vapor fields and compared with satellite and balloon observations.

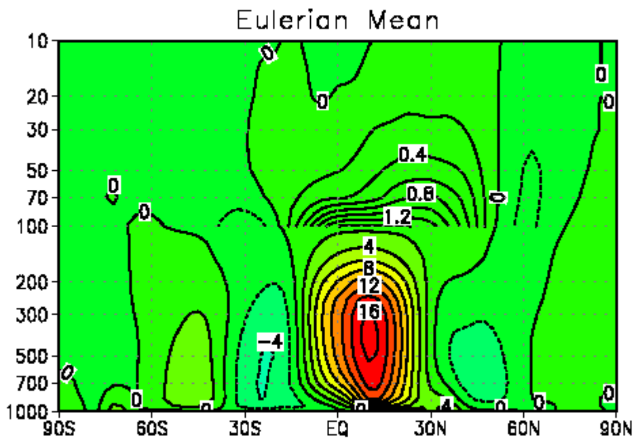


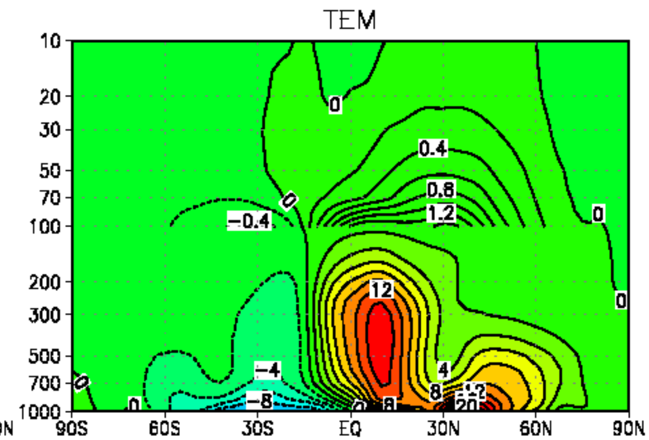


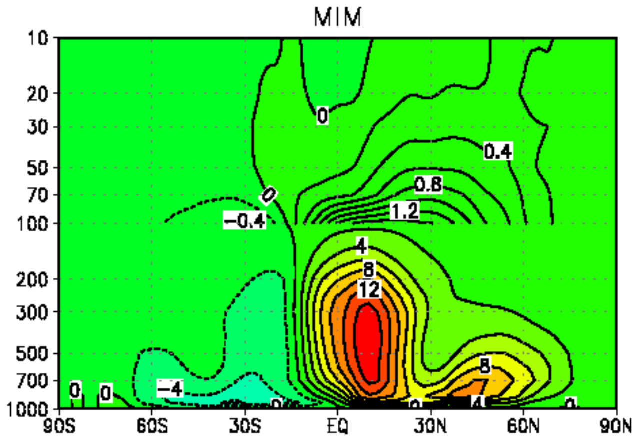
There are differences between calculations based on different models, and from observations. Perhaps possible to devise some sort of ranking of reanalyses based on this sort of calculation.

There are a few papers that have compared the mean meridional circulation between different reanalyses:

Iwasaki et al. 2009 calculated the MIM for JRA-25, ERA-40, ERA-Interim, NCEP/NCAR and NCEP/DOE.







From Toshiki Iwasaki's Tohoku University web page

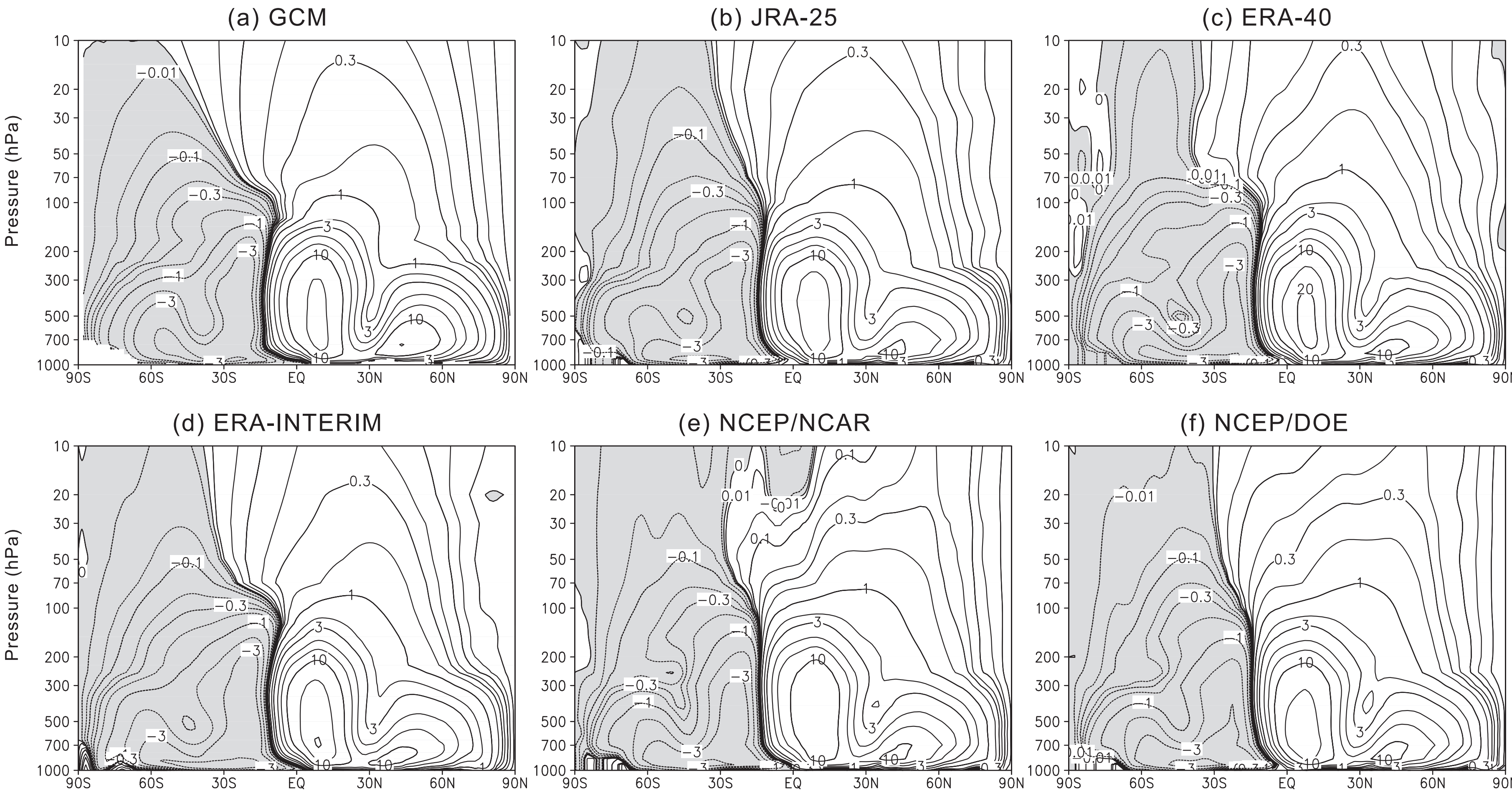

(a) GCM
(b) JRA-25
(c) ERA-40
(d) ERA-INTERIM
(e) NCEP/NCAR
(f) NCEP/DOE
Pressure (hPa)
10
20
30
50
70
100
200
300
500
700
1000
90S
60S
30S
EQ
30N
60N
90N

Fig. 1a: DJF

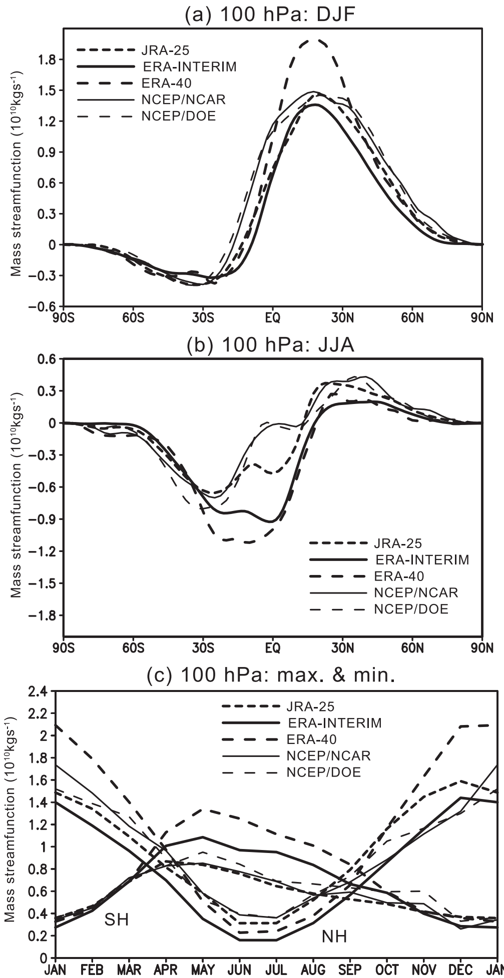


Fig. 2. Mass streamfunctions at 100 hPa (vertically integrated northward mass flux above 100 hPa) for DJF (top) and JJA (middle), and seasonality of their maxima and minima (bottom) diagnosed from JRA-25, ERA-40, ERA-Interim, NCEP/NCAR and NCEP/DOE. In the bottom panel, signs of maxima are changed to show the southern-hemispheric poleward mass flux. Years averaged are the same as in Fig. 1.

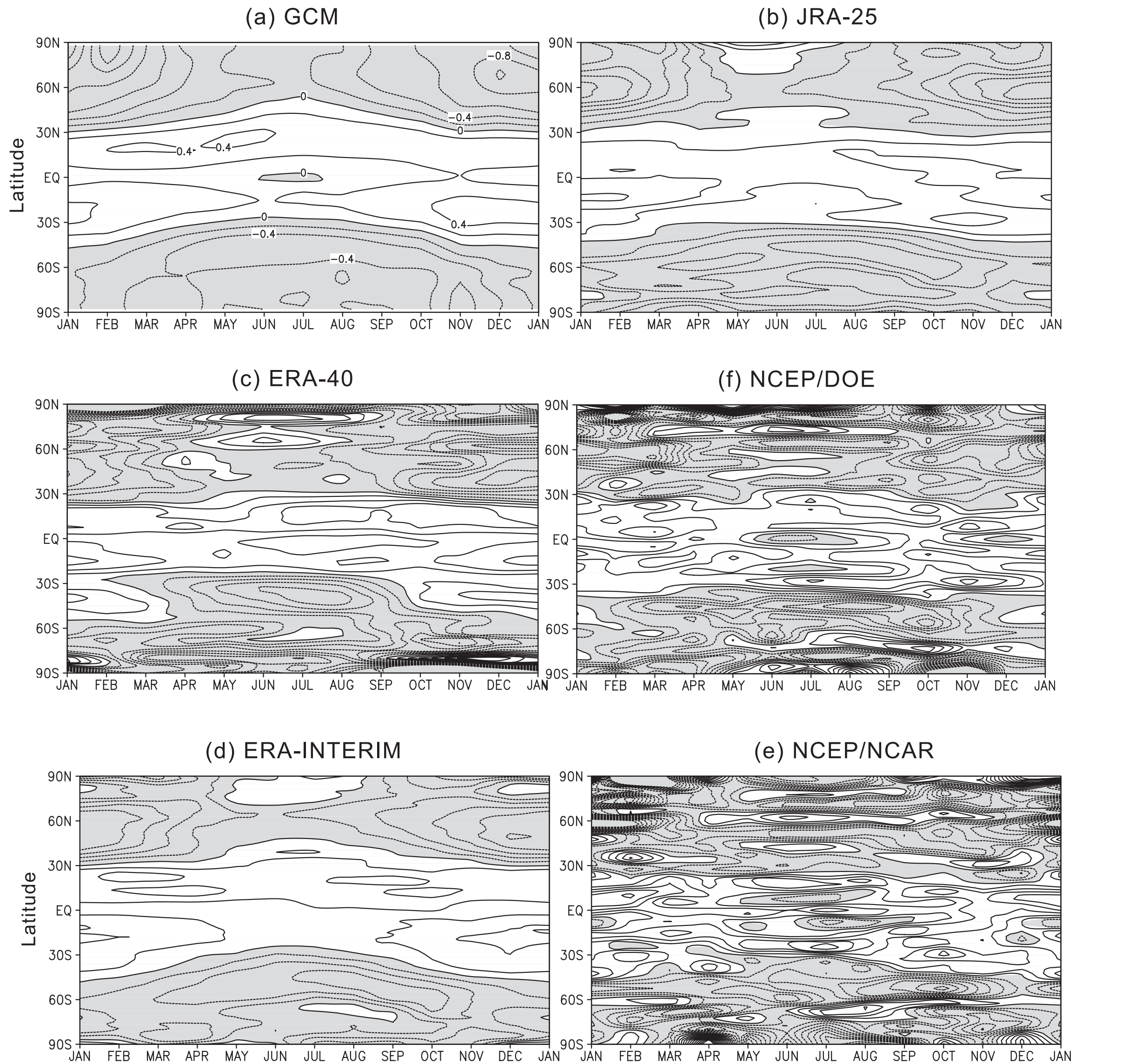
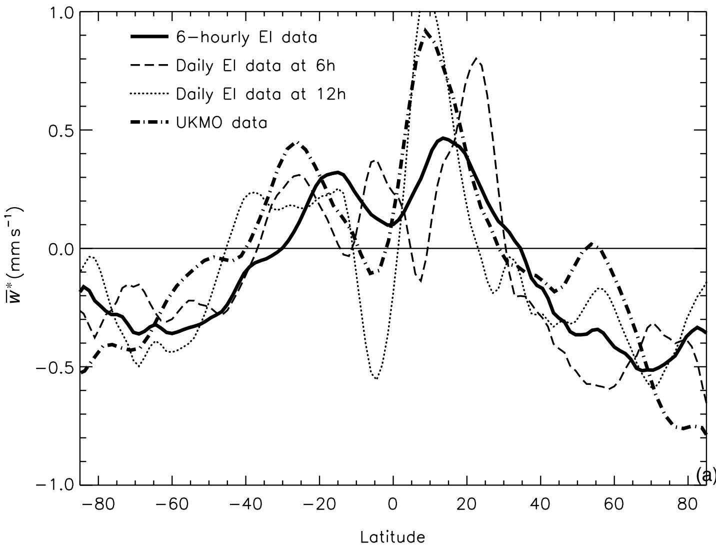
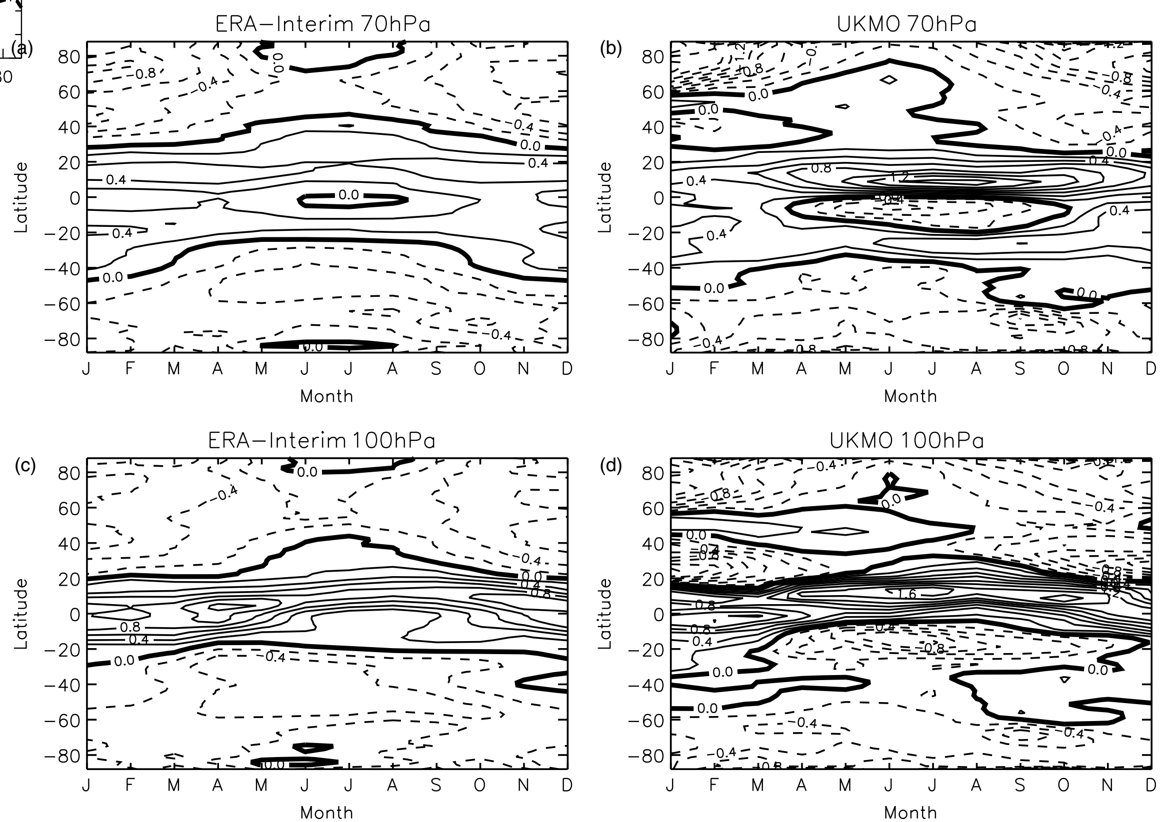


Fig. 4. Seasonality of mean vertical velocity at 50 hPa (mm s^{-1}) diagnosed from a:GCM, b:JRA-25, c:ERA-40, d:ERA-Interim, e:NCEP/NCAR and f:NCEP/DOE averaging over 1979–2001 (exception for GCM, 1 year; ERA-Interim, 1989–2001). Negative values are shaded.

Seviour et al., 2011 show comparisons between ERA-I and UKMO





Attribution type calculation

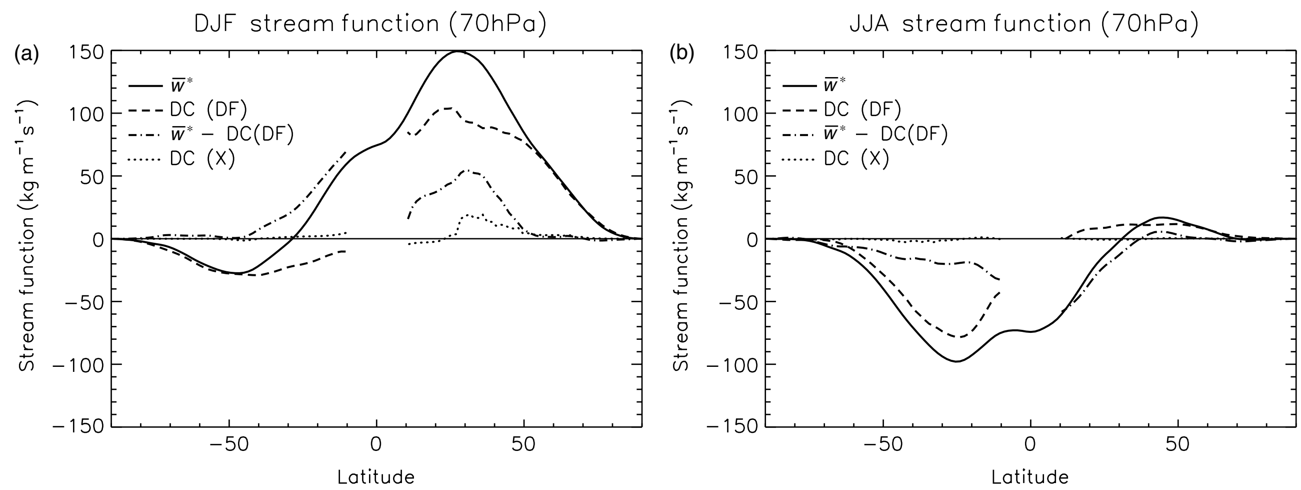


Figure 8. For ERA-Interim for 1989–2009, mass stream function at 70 hPa for (a) DJF and (b) JJA calculated from $\overline{w}^*$, resolved waves (DF) and parametrized processes ($\overline{X}$) using downward control (DC), and the difference between stream functions calculated from $\overline{w}^*$ and DF.

From Seviour et al., 2011

7 OKAMOTO ET AL.: FORMATION AND TREND OF THE BREWER-DOBSON CIRCULATION

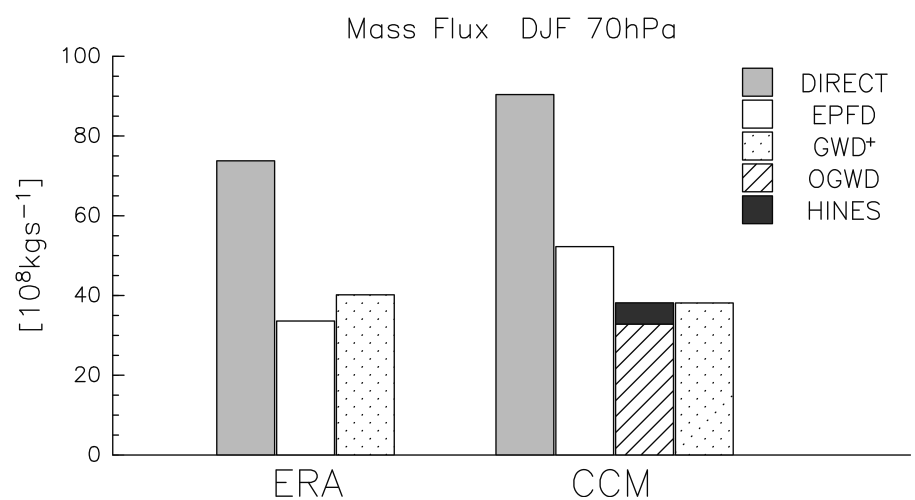


Figure 4. Contribution of each wave forcing to the net upward mass flux for DJF for the present1 climate (2000–2008).

From Okamoto et al., 2011

What about trends (or decadal variability)?

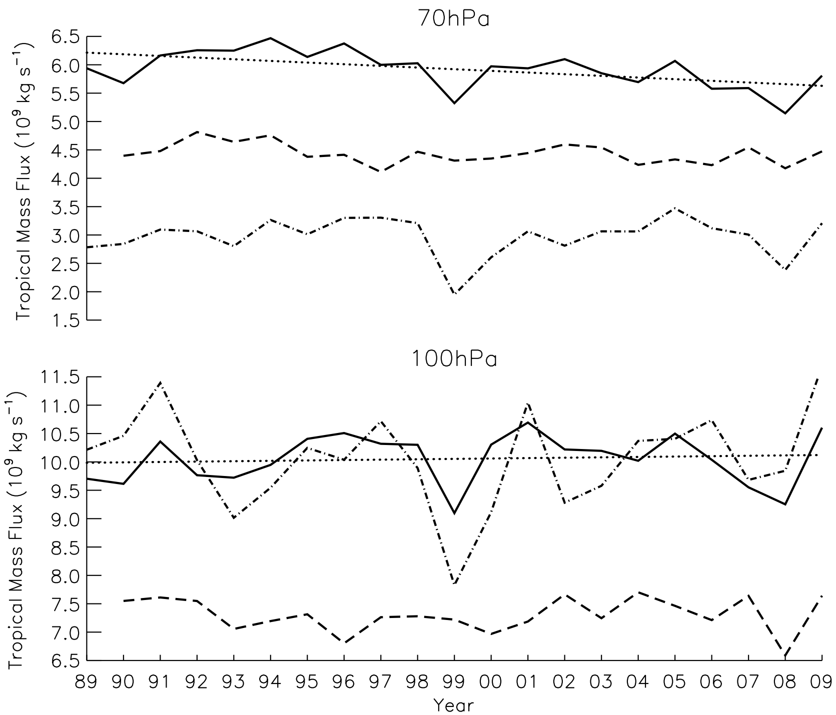
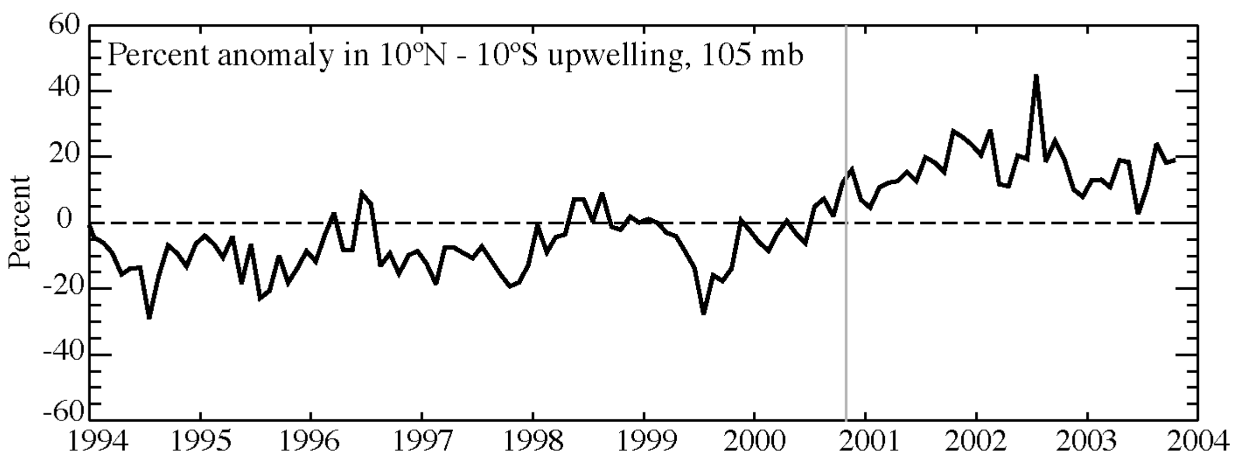


Figure 9. Time series for ERA-Interim of annual mean (top) temperature averaged between turnaround latitudes at 70 hPa (solid line) and 100 hPa (dashed line), and (middle and bottom) tropical upwelling at 70 hPa and 100 hPa, calculated between turnaround latitudes (solid line), between fixed latitudes 15°S–15°N (dot-dashed line) and via downward control between turnaround latitudes (dashed line).

From Seviour et al, 2011 (ERA-I)



From Rosenlof and Reid, 2007 (NCEP/NCAR)

Do the reanalyses explain decadal variability in stratospheric species?

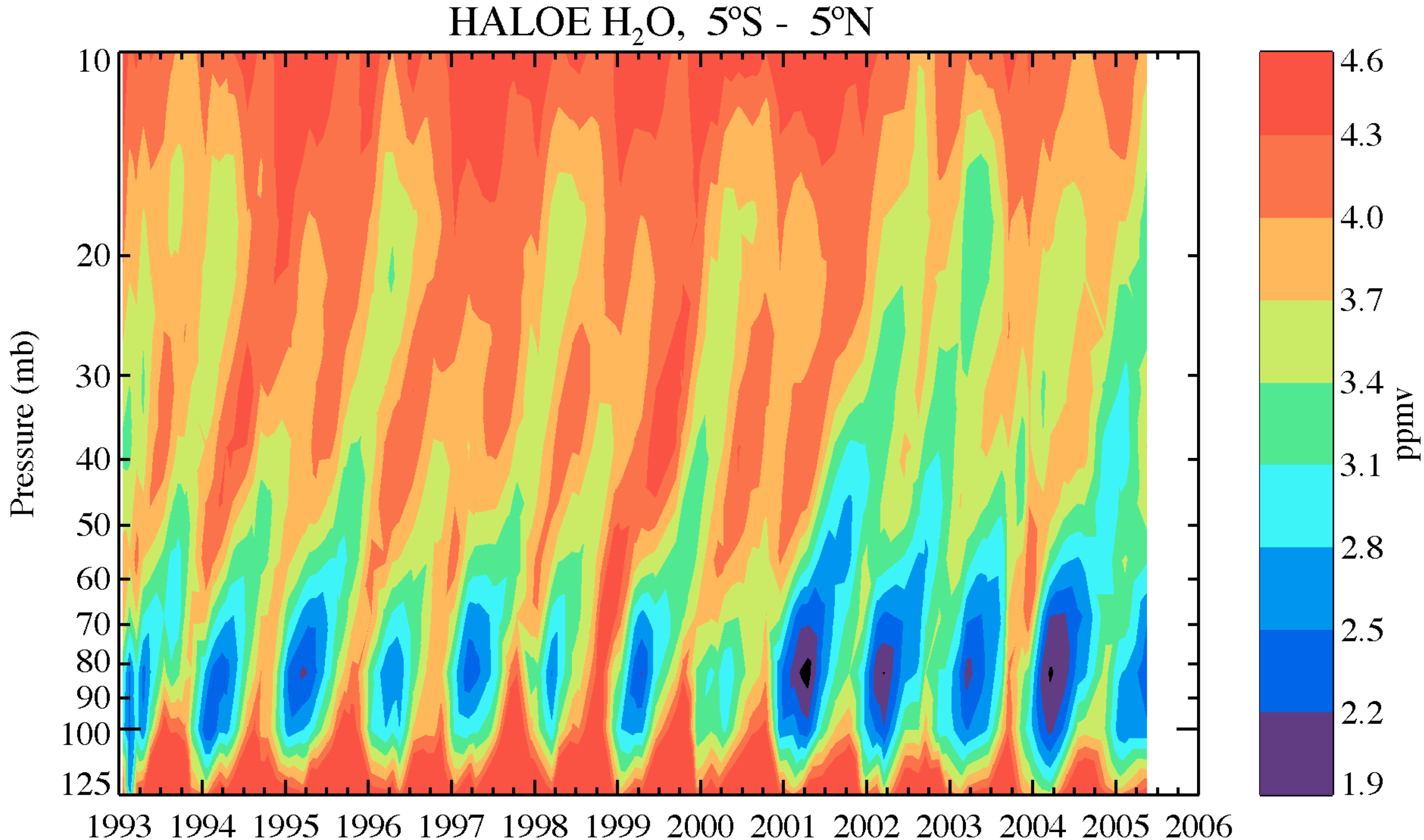
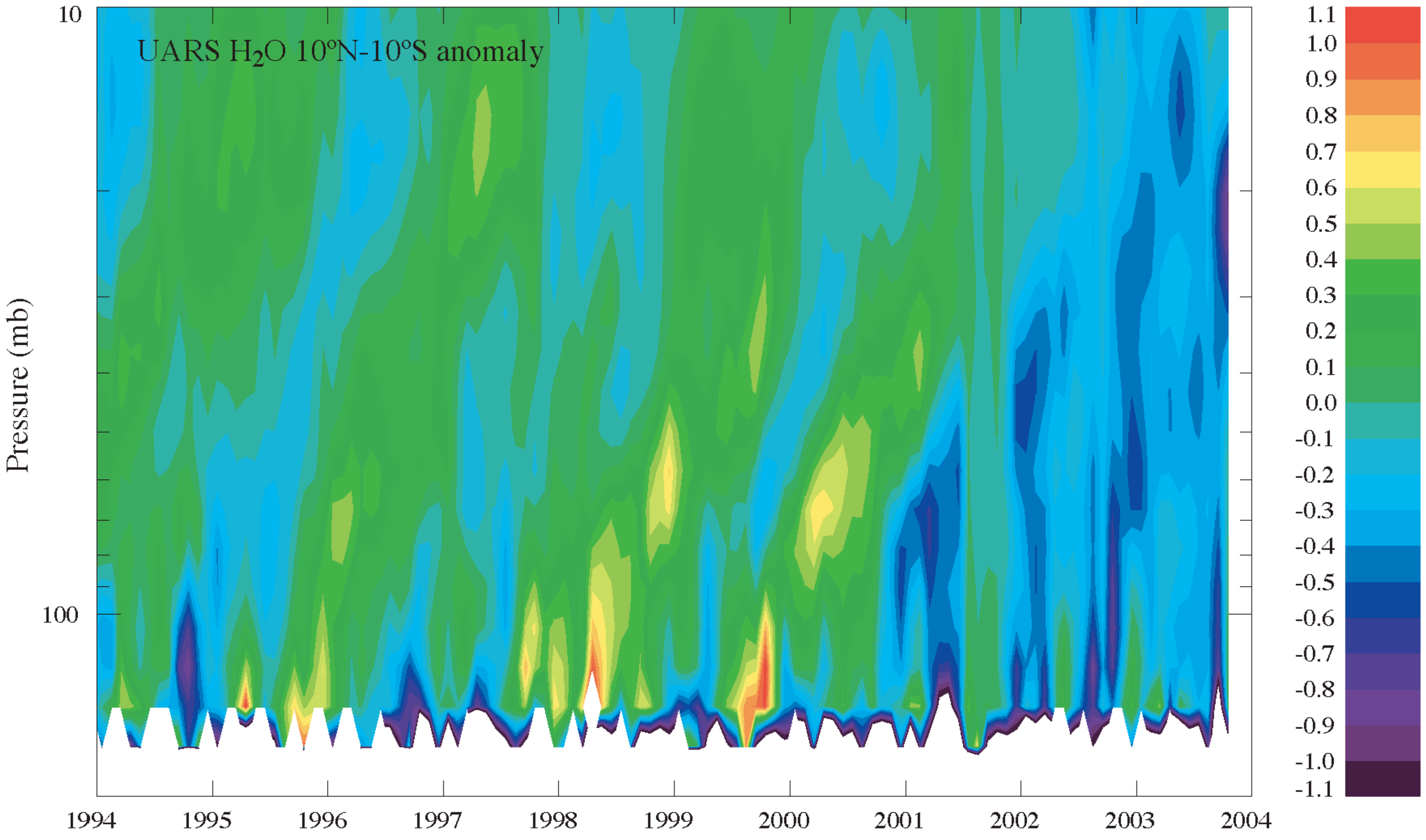
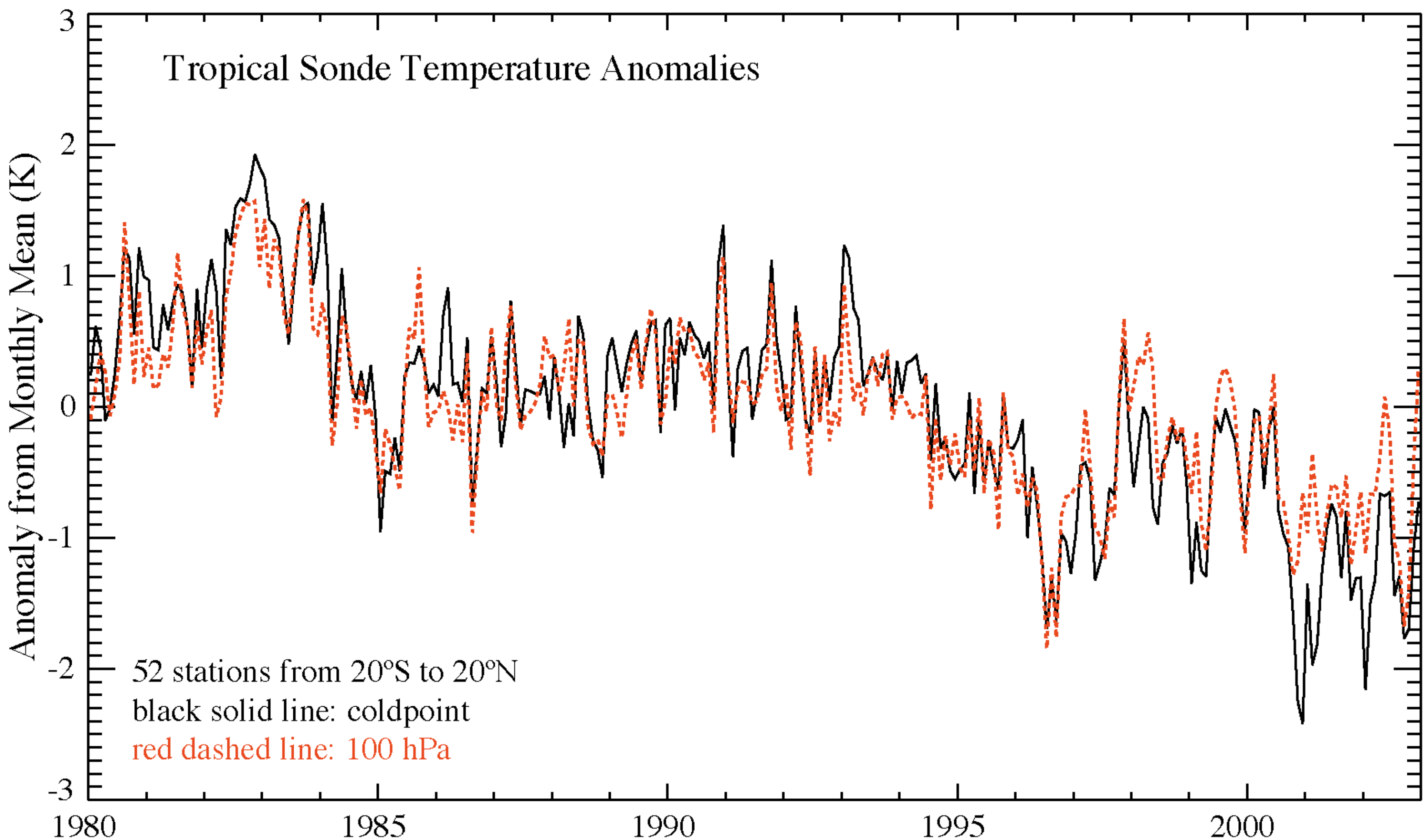


Figure 10. Tropical HALOE water vapor (tape recorder), 5ºS-5ºN, plotted versus time. Note the change to lower values of the hygropause at the end of 2000, and the upward propagation of those lower values in subsequent years.



Tropical water vapor anomalies, HALOE

Do the reanalyses have the vertical resolution to start explaining the stratospheric water vapor decadal variability?



In an average of tropical sonde data, we see a temperature decrease in the cold point temperatures that is not obvious in the 100 mb temperatures.

Summary

What I'd like to see from S-RIP

1) An assessment of accuracy for the various reanalyses, with an eye towards looking at how reasonably the fields can be used to reproduce constituent fields that are independently observed. (thinking water and ozone, possibly measurements related to age of air as well, and any temperature measurements that haven't already gone into the reanalysis process)

   Perhaps looks for big signals that we know about…the post 2000 tropical circulation change, the recent NH ozone depletion event.

2) An examination of metrics that describe the upper and lower branches separately.

3) A comparison of metrics that help with untangling driving factors (resolved versus unresolved forcings…ie, downward control type calculations)

4) Do we even consider anything regarding trends?