Stratosphere-Troposphere Coupling:
Stability of the Annular Mode Time Scale and Role of the Stratosphere

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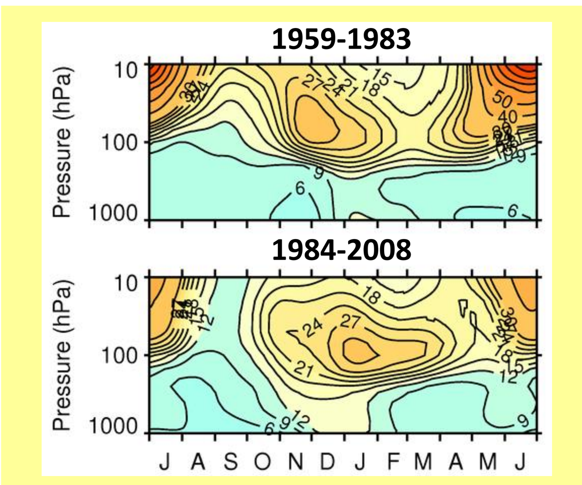
1. Introduction

The simulation of the annular mode (AM) time scale (τ) is regarded as an important benchmark for climate model performance. Previous research demonstrated that climate models systematically overestimate the AM time scale, which may imply that the model's climate circulation is overly sensitive to external forcing, as suggested by the fluctuation-dissipation theorem.

NCEP



Northern Annular Mode (NAM) time scale structure (in days) as a function of season and pressure, derived from the first (1959-1983) and last 25 years (1984-2008) of the National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) reanalysis data. Contour interval is 3 days up to 30 days, and 10 days thereafter.

It is of concern that τ converges very slowly and that it contains large uncertainties when determined from short periods of data. This difficulty becomes evident when we compute τ from reanalysis for two different 25 year long periods. Although the two resulting structures are broadly similar, there are also important differences. For example, the results from the first half period suggest that the wintertime peak in τ occurs first in the stratosphere and then in the troposphere, but the second half period shows the opposite behavior. Some of the differences seen in the reanalysis might be related to an artifact in the observations or trends associated with climate change. However, given the slow convergence of τ, it is also likely that 25 year length of observed data is not enough for deriving a reliable estimate of τ.

The goal of this study is to answer the question of:

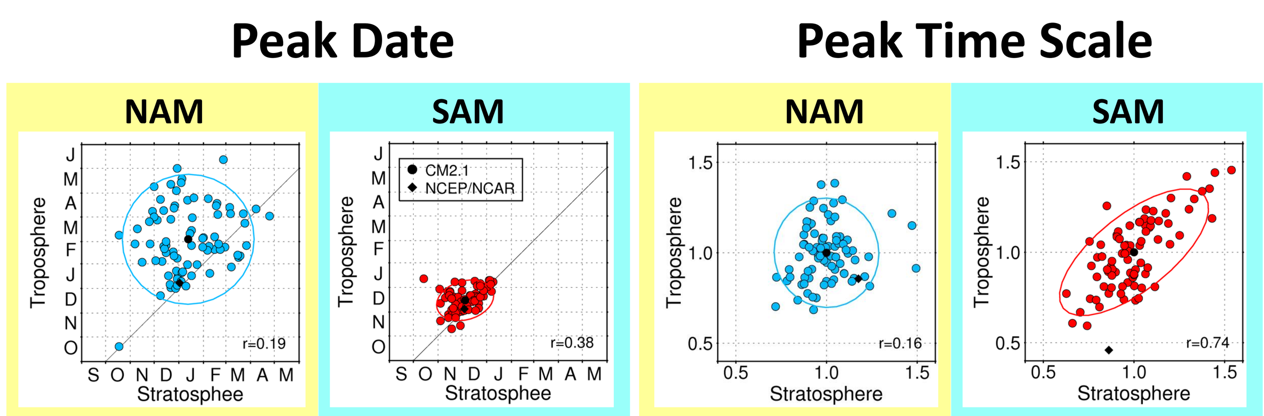
- how many years of data are actually required for a stable estimate of τ
- whether the differences in τ between models and reanalysis seen in previous studies are real or due to sampling uncertainty
- whether there is detectable influence of the stratosphere on the troposphere in terms of τ

2. Data and Methodology

We examine and compare the annular mode time scale in the NCEP/NCAR reanalysis and the coupled climate model CM2.1, developed at the Geophysical Fluid Dynamics Laboratory (Delworth *et al.* 2006). We use data from a 4000 year long control run.

The AM time scale from the simulations is calculated by splitting the 4000 year long simulation into several N-year long segments. In most cases, we use N=50 years, which enables a direct comparison with the observations and which results in eighty individual 50 year long segments. We derive the AM time scale individually for each segment and then use the overall mean as our best estimate. The variability of the AM time scale is given by the standard deviation across all segments. The uncertainty of the AM time scale is measured by the ratio of the standard deviation to the mean AM time scale, which is the inverse form of the signal-to-noise ratio.

5. Stratosphere-Troposphere Linkage



Relationship between stratospheric and tropospheric time scale maxima derived from 80 model segments. (left) Date of lower stratospheric (200-30 hPa) and lower tropospheric (1000-500 hPa) time scale maxima. (right) Relative strength of time scale maxima, given by the ratio of time scale maxima and the mean of all maxima (23 days for stratospheric NAM, 15 for tropospheric NAM, 71 for stratospheric SAM, and 47 for tropospheric SAM). Colored circles show outcomes from individual model segments and black circles indicate the mean. Ellipses are centered on the mean, oriented along the direction of maximum scatter, with the two axes showing four standard deviations along the major and minor direction. Numbers at the right bottom are correlations between stratospheric and tropospheric scatters. Black diamonds show outcomes from NCEP/NCAR reanalysis (1959-2008). Lines in top panels represents matching stratospheric and tropospheric date.

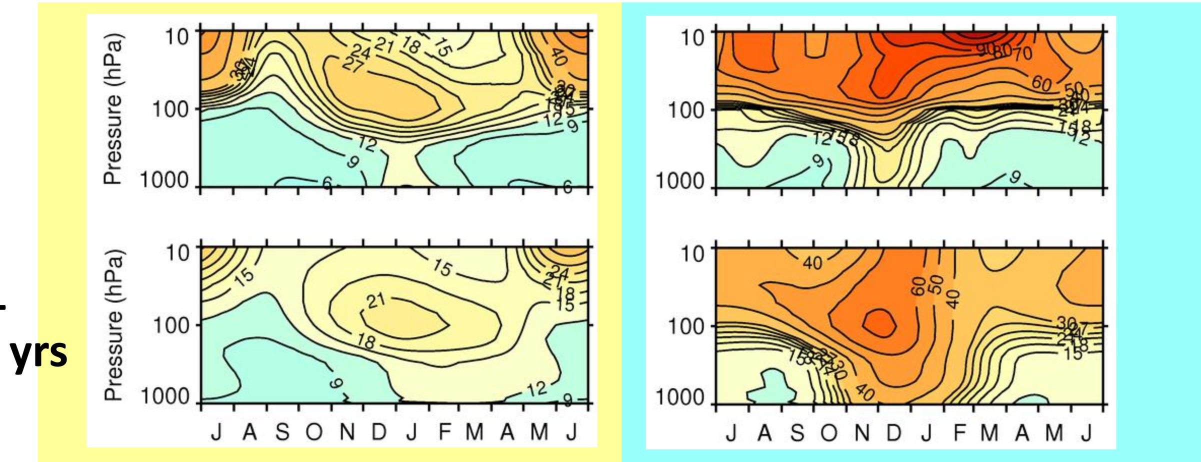
3. AM Time Scale and its Uncertainty

NAM	SAM

AM Time Scale

NCEP 50 yrs

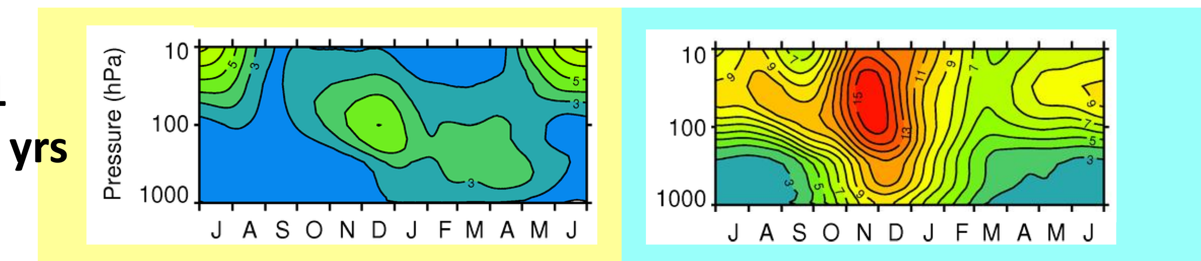
CM2.1 80x50 yrs



NAM and SAM time scale structure (in days) as a function of season and pressure. Results are shown for (top) NCEP/NCAR reanalysis (1959-2008) and (bottom) simulation (mean over eighty 50 year long model segments). The time scale at 1000 hPa is derived from zonal mean sea level pressure. For all other levels, zonal mean geopotential heights are used. Contour interval is 3 days up to 30 days, and 10 days thereafter.

Variability of AM Time Scale

CM2.1 80x50 yrs

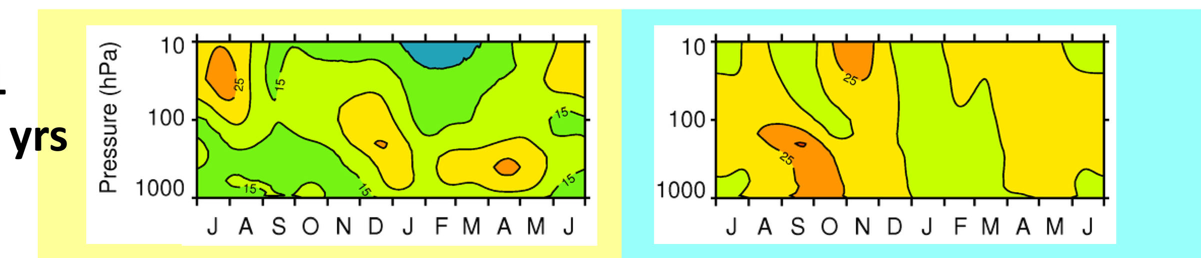


Variability of model derived time scale. Shown are standard deviation of NAM and SAM time scale (in days), derived from 80 samples of 50 year long segments

The large variability of the NAM time scale in the lower stratosphere during winter may be related to the occurrence of stratospheric sudden warmings (SSWs). The timing of SSWs is highly variable, which may lead to an increased variability of the NAM time scale. The variability of the SAM time scale during spring is even larger. This is probably related to year-to-year variability in the timing of the final breakdown of the southern polar vortex.

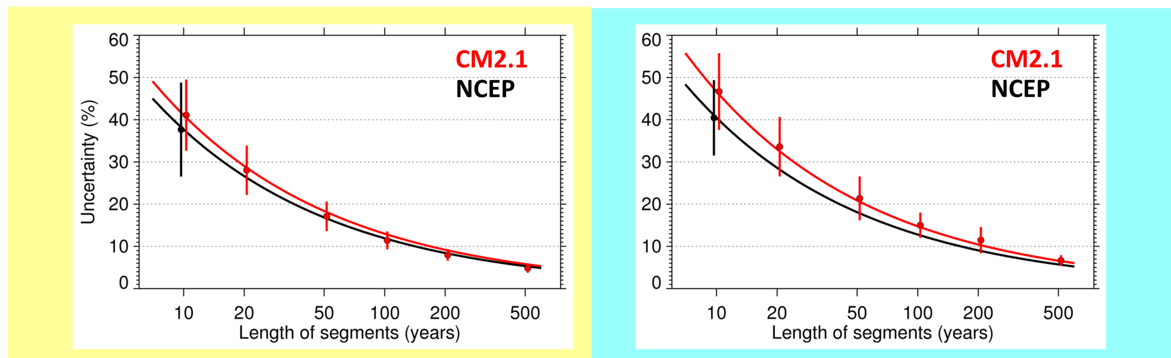
Uncertainty of AM Time Scale

CM2.1 80x50 yrs



Uncertainty of model derived time scale (in %), given by the standard deviation of time scale divided by the mean time scale.

Uncertainty Estimates



Uncertainty of NAM and SAM time scale structure as a function of length of underlying index time series for (black) NCEP/NCAR reanalysis and (red) coupled model. Circles are actual values (slightly shifted along the x-axis for clarity), and lines represent extrapolations using the analytical expression (inversely proportional to the square root of the length of the segment, see text) and the calculated result for 10 years as initial value. Error bars denote 95% confidence intervals, calculated from bootstrapping by randomly selecting 5 samples with replacement and repeating this 100 times.

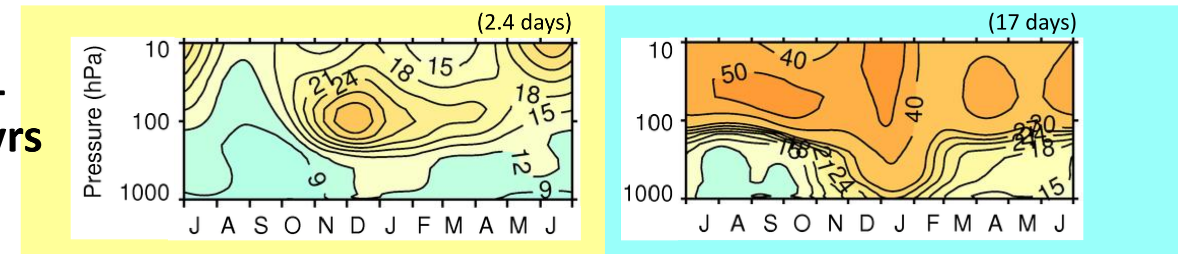
Even under the fixed forcing conditions of our control run, at least 100 years worth of data are needed to keep the uncertainty of the NAM time scale below 10%; for the SAM, the required length increases to 200 years. If the AM time scale in the real atmosphere is similar to that of the model, then it is questionable whether the 50 year reanalysis record is long enough to produce representative results for model evaluation.

4. Model-Reanalysis Comparison

NAM	SAM

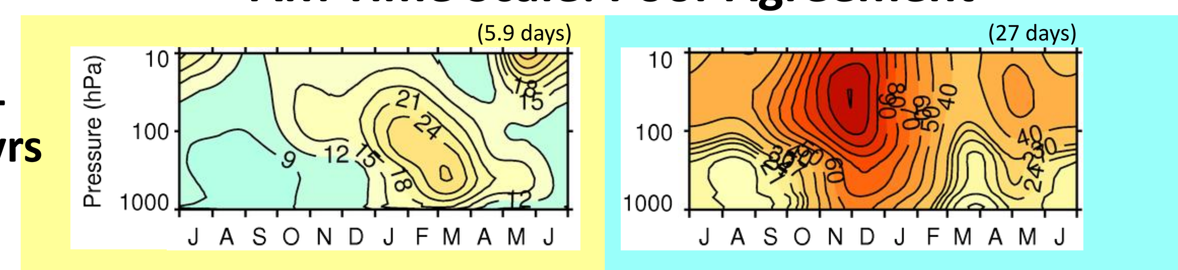
AM Time Scale: Good Agreement

CM2.1 1x50 yrs



AM Time Scale: Poor Agreement

CM2.1 1x50 yrs

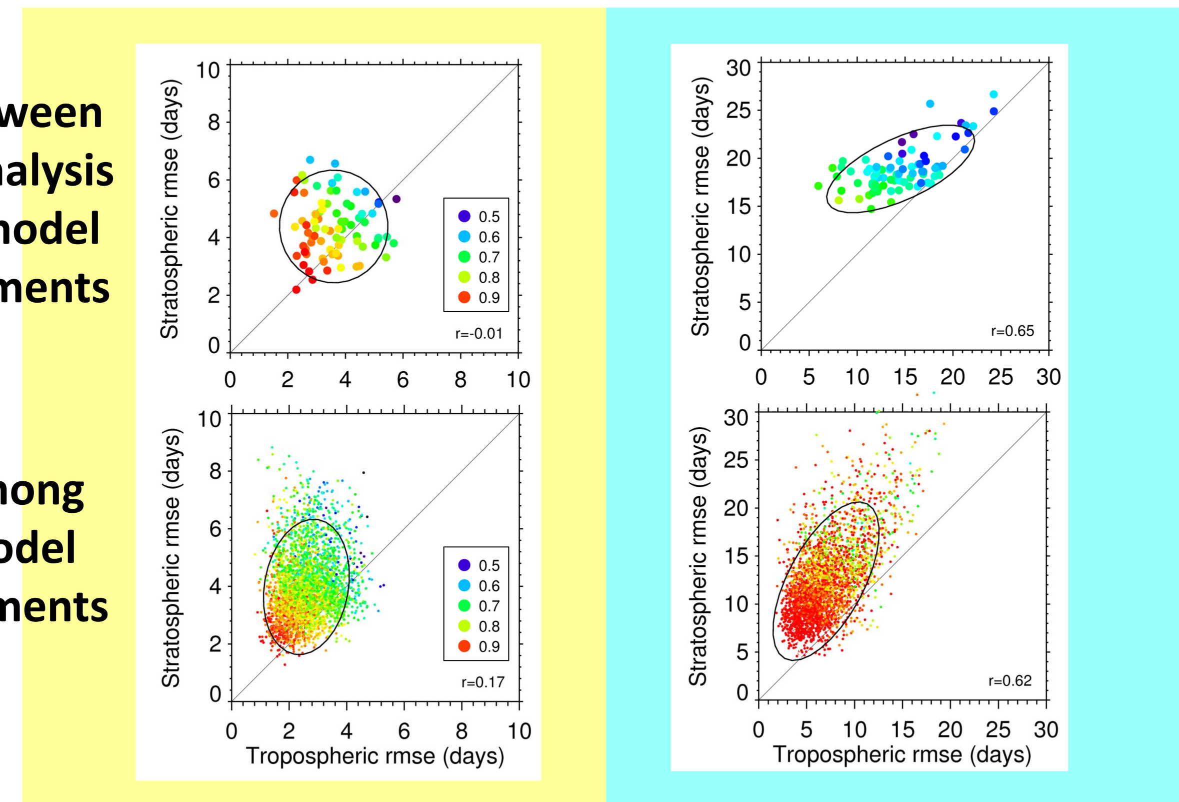


Time scale structure computed from selected 50 year long segments. The top two are examples in reasonably good agreement with the NCEP/NCAR reanalysis for NAM and SAM, whereas the bottom examples show poor agreement with the reanalysis. Numbers in the parenthesis on top right of each panel indicate the root-mean-square (rms) error between time scale from NCEP/NCAR reanalysis (1959-2008) and time scale from model segments. For the NAM time scale in the stratosphere, we only focus on eight months from September to April, because the NAM is not active during summer from May to August (Gerber *et al.* 2010)

Agreement in Troposphere-Stratosphere Time Scale

Between reanalysis & model segments

Among model segments



Relationship between tropospheric (1000-500 hPa, September-April) and stratospheric (200-30 hPa, September-April) time scale structure. (Top) correlations between 80 model segments and reanalysis. (Bottom) RMS errors between all paired combinations of 80 model segments. Color denotes correlations calculated over all levels (1000-10 hPa, Jan-Dec). Ellipses are centered on the mean, oriented along the direction of maximum scatter, with the two axes showing four eigenvalues along the major and minor direction. Lines represent the diagonal where tropospheric and stratospheric RMS errors match. Numbers at the left bottom are correlations between stratospheric and tropospheric scatters.

6. Summary

- At least 100 (200) years of simulation data are required in order to keep the uncertainty in the NAM (SAM) time scale below 10%.
- The model reproduces the NAM time scale structure more realistic than the SAM time scale.
- For both NAM and SAM, the stratospheric peak in time scale almost always leads the tropospheric peak, confirming that the tropospheric AM is under the influence of the stratosphere.
- For the SAM, longer time scales in the stratosphere are almost always followed by longer time scales in the troposphere. For the NAM, such a relationship does not hold.