2003-2004 Sudden Stratospheric Warming

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Integrated Zonal Means 60N-90N

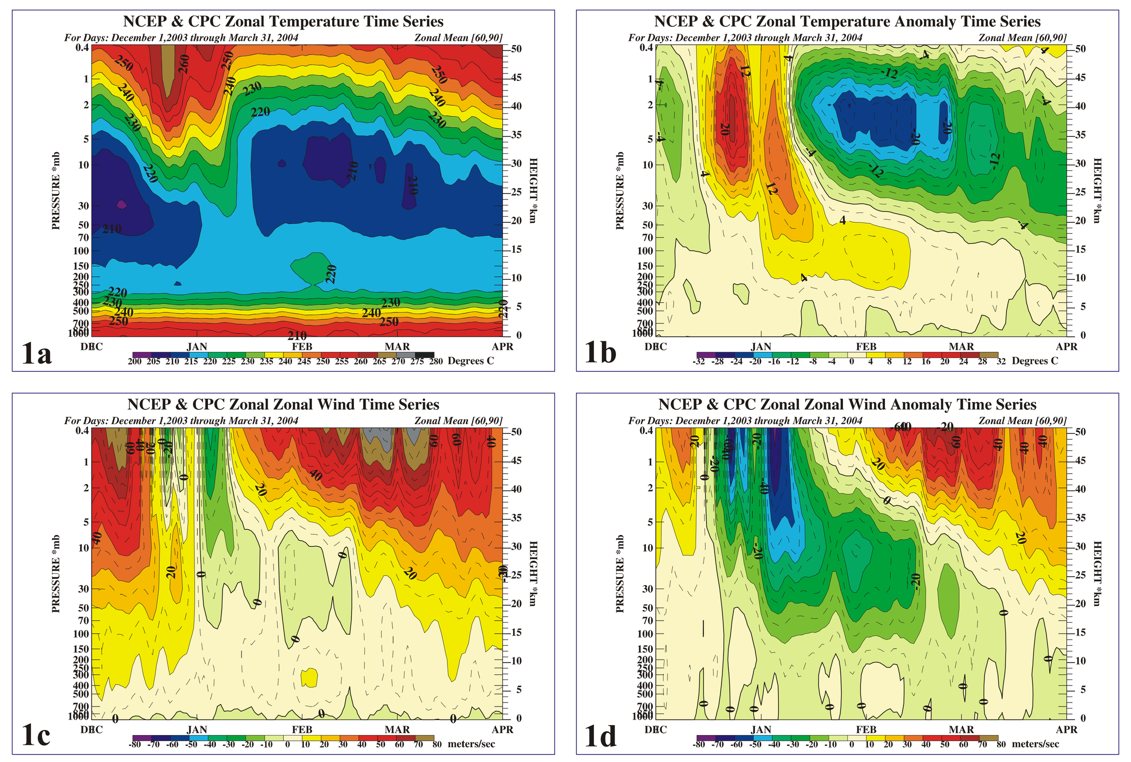

Figure 1. Integrated means from 60°-90°N for the period December 1, 2003 through March 31, 2004. Shown are: temperature (1a), temperature anomaly (1b), zonal wind (1c), and zonal wind anomaly (1d).

Take Home Message:
The 2003/2004 sudden stratospheric warming was a "major" warming. Large anomalies in the temperature and wind fields were not just confined to the stratosphere, but also influenced the circulation in the troposphere for most of January, 2004.

Introduction
Sudden stratospheric warmings (SSWs) are winter hemisphere phenomena characterized by the rapid increase in temperature in the polar stratosphere and the weakening of the zonal mean zonal flow. In the most dramatic cases, stratospheric temperatures locally can rise by 40°-50°C and the zonal mean zonal flow can reverse in direction in the span of just a few days. The WMO defines a sudden stratospheric warming as when the 10 hPa temperature gradient poleward of 65°N changes sign and becomes positive for at least five consecutive days. This is deemed a "minor" warming. Additionally, a "major" warming is defined as when the 10 hPa zonal wind at 65°N reverses and becomes easterly for more than 5 consecutive days. By this definition the 2003/2004 event was then a "Major" warming. During this event the stratospheric zonal mean temperatures increased by as much as 28°C. The zonal mean zonal wind changed from 65 m/s westerlies into 20 m/s easterlies over the span of two weeks. This wind reversal encompassed the entire stratosphere. This event was not just confined to the stratosphere, but anomalous features extended well into the troposphere impacting the surface for much of January and parts of February, 2004.

What causes sudden stratospheric warmings?
Stratospheric warmings involve interactions between the zonal flow of the polar stratosphere and upward propagating planetary waves consisting primarily of zonal wave numbers 1 and 2. Normally, the zonal flow is very strong in the wintertime lower polar stratosphere and vertically propagating waves tend to be deflected equatorward. But if the lower stratosphere is "pre-conditioned" by earlier wave activity, the zonal flow is weakened or moved poleward and vertically propagating waves tend to be deflected poleward. The vertical component of the E-P Flux (Fz) which is proportional to the poleward heat flux maximizes at about 10 hPa at this time. The area above the heat flux maximum (divergence of wave forcing) acts to decelerate the eastward zonal flow. A residual circulation then induces sinking motion below and poleward of this forcing region. The sinking motion causes the temperatures to increase due to adiabatic warming. This reduces the thermal gradient which in turn reduces the zonal wind speed. These large temperature and wind anomalies then propagate downward into the lower stratosphere (Baldwin and Dunkerton, 1999; Limpasuvan et al., 2004).

Almost all stratospheric warming events get to this stage. It is still a research topic as to what allows the warming influences to proceed further into the troposphere or be impeded from further downward propagation. Zhou et al. (2002) show that warmings that penetrate into the troposphere are characterized in the onset by a double pulse of the vertical component of the E-P Flux (Fz). The 2003/2004 stratospheric warming event had such a double pulse.

Discussion of the 2003/2004 Sudden Stratospheric Warming event.
Figure 1 shows the time evolution of polar temperature and zonal wind changes during the onset, growth, maturation, and decline of the SSW. **Figure 1a & 1b** show the warming of the polar temperatures (and the large increase in temperature anomalies) in the upper stratosphere in late December. Note the large initial warming followed a few days later by a second weaker warming. These double warmings are in direct response to the double pulse of E-P Flux (Fz). **Figure 1c & 1d** show the wind decelerations associated with each of these pulses. Note that the first pulse produced only minor decelerations. But the second pulse resulted in the larger decelerations and wind reversal throughout the stratosphere. **Figures 1b & 1d** show how the large anomalies proceeded to downward into the troposphere. Note also that the anomalous winds and temperatures persisted well into March. These lower anomalies were mirrored by large anomalies of the opposite sign in the upper stratosphere.

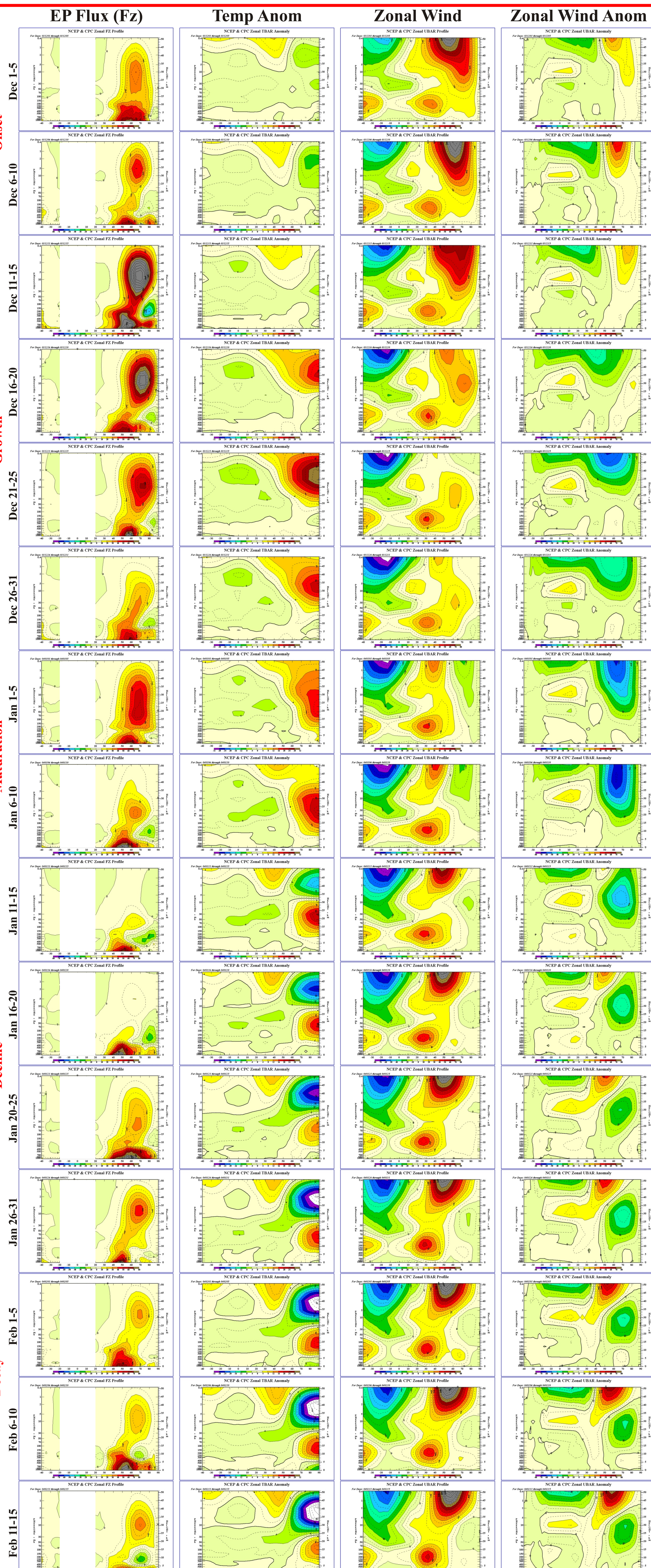

Figure 2. Series of five day average zonal mean vertical cross-sections extending from 40°S to 90°N beginning with the period December 1-5, 2003 and ending with the period February 11-15, 2004. Shown are cross-sections for temperature anomaly, zonal wind, zonal wind anomaly, and Fz.

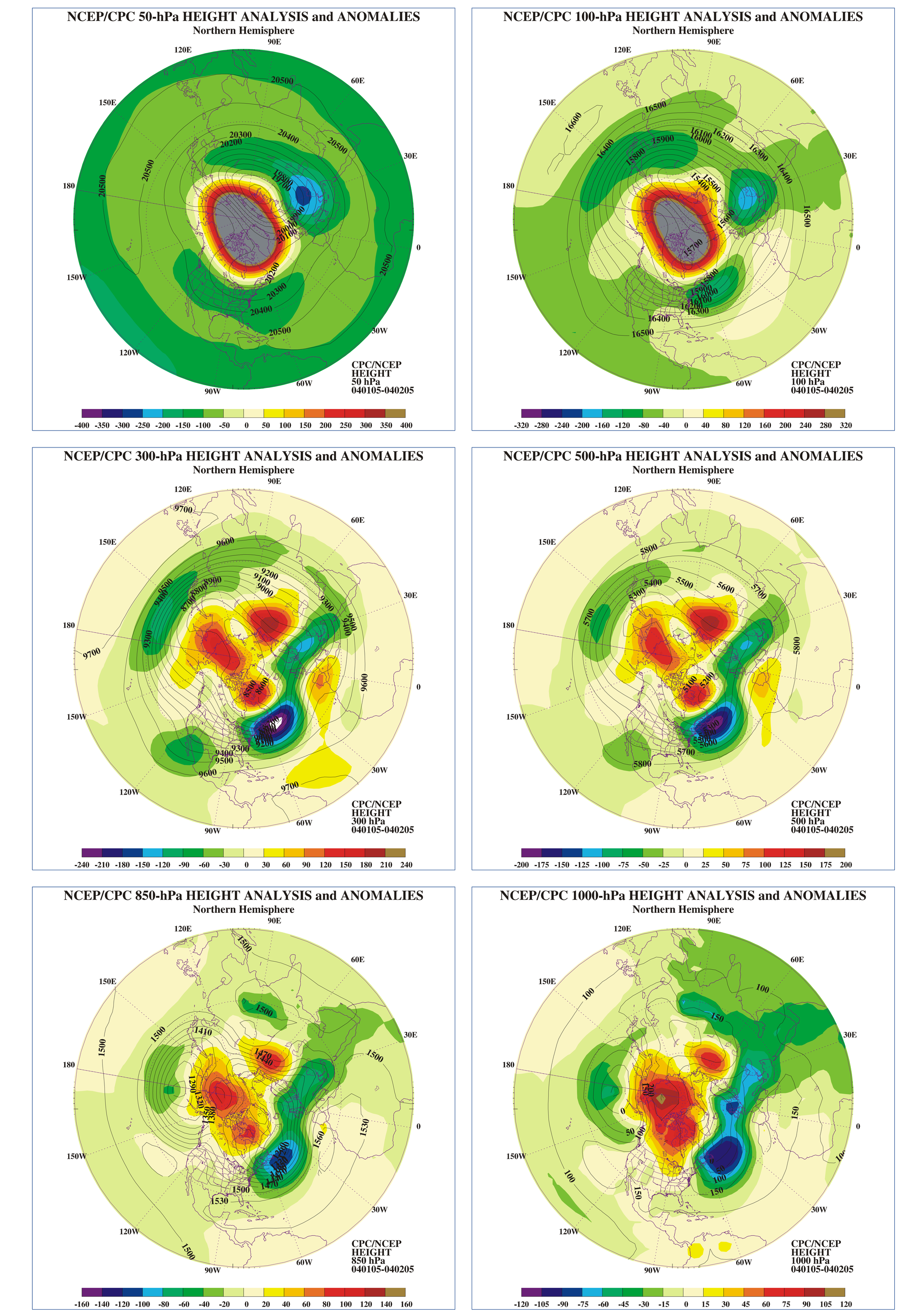

Figure 3. Northern hemispheric analyses of the mean geopotential heights (isolines) and their anomalies (color contours) at 50, 100, 300, 500, 850, and 1000 hPa for the over the period January 5 through February 5, 2004.

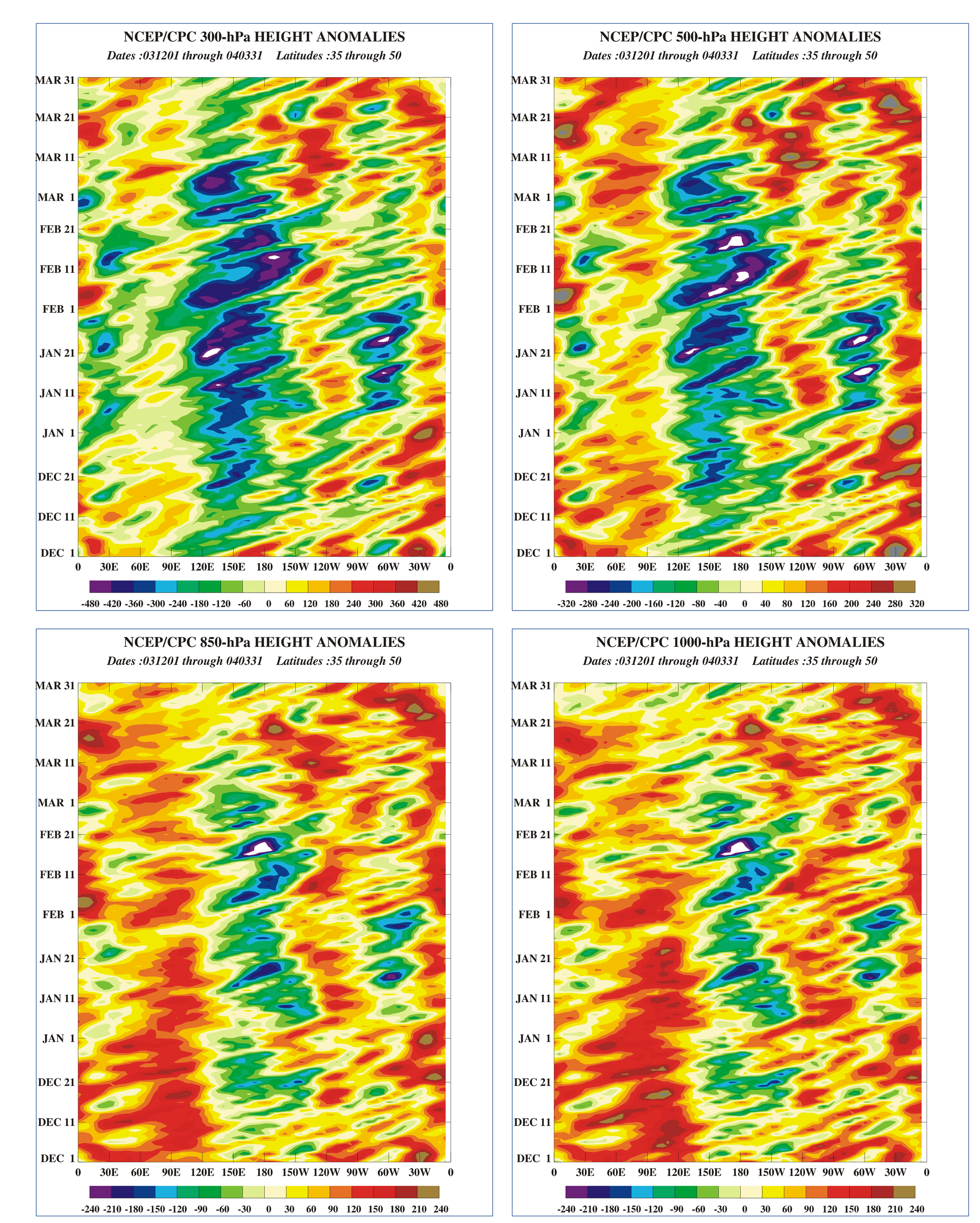

Figure 4. Time-longitude section of geopotential heights for the latitude zone of 35°-50°N at pressure levels: 300 hPa, 500 hPa, 850 hPa, and 1000 hPa. The range of time extends from December 1, 2003 through March 31, 2004.

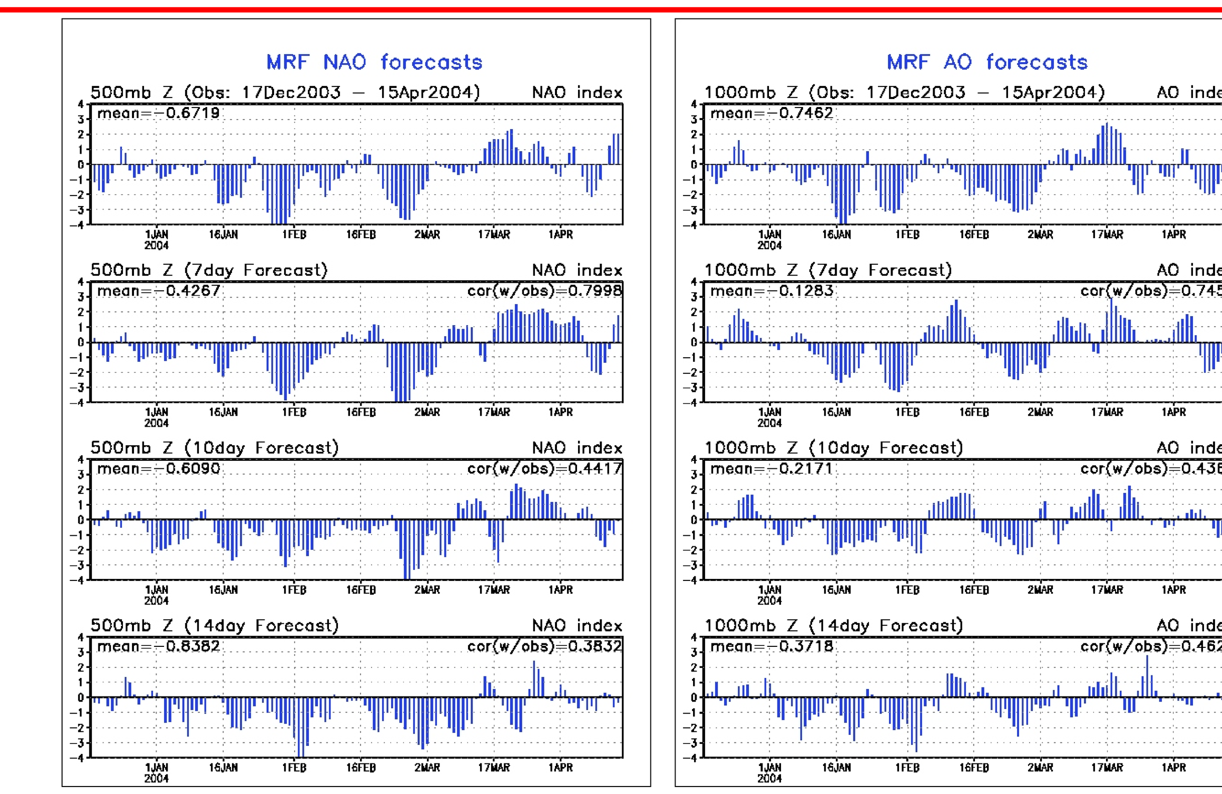

Figure 5. Observations and seven, ten, and fourteen day GFS model forecasts of the Northern Atlantic Oscillation (NAO) index (left) and the Arctic Oscillation (AO) index (right) for January through March, 2004. Mean index values for the period and forecast correlations with the observations are given on the graphs.

An in depth look at the evolution of the SSW in the form of vertical cross-sections extending seven pentads prior and post the peak period are presented in **Figure 2**. The vertical cross_sections show how the different parts of the atmosphere responded to the double pulse of E-P Flux (Fz) in mid and late December. Note the order of events beginning with the initial pulse of Fz followed 20 days later by the maximum temperature anomaly. This anomaly proceeded to move downward through the stratosphere into the upper troposphere. Meanwhile, the zonal wind reached its maximum anomaly following the second Fz pulse. Once the zonal wind maximum anomaly was reached, the zonal wind anomalies also proceeded to move downward through the stratosphere into the upper troposphere. Note also that there are negative zonal wind anomalies all the way down to the surface. Note again that the winds in the equatorial region indicate an easterly phase of the quasi-biennial oscillation (QBO) which favors an increased frequency of occurrence of SSWs (Holton and Tan, 1980)

Figure 3 further shows how the tropospheric geopotential height fields at 300, 500, 850 and 1000 hPa were impacted following the peak warming/wind reversal. Following the peak of the warming, the atmosphere favored longer planetary waves. This allowed for the persistence of a wave three pattern throughout most of the troposphere and lower stratosphere. Three large area of negative height anomalies are associated with the troughs of this wave three pattern. Positive height anomalies are present throughout most of the polar region.

Figure 4 shows how the wave three pattern in the middle latitudes persisted from January 5 through February 5, 2004 throughout the entire troposphere. Note the persistent negative anomalies at 60°W, 170°E and to a lesser degree 10°E.

The mid-latitude negative height anomaly situated off the east coast of the U.S. and positive height anomalies in the polar regions persistently resulted in negative indices of the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO) throughout most of January and parts of February. An atmospheric model which captures the warming process and subsequent impacts upon the stratosphere and troposphere would accurately forecast such an event. The fact that there is about a 15 day period between the initial Fz pulse in the upper stratosphere to when the troposphere (and surface) are impacted implies that such a model should be able to forecast such an event two weeks in advance. **Figure 5** shows the observed and forecast AO and NAO indices for the January-March time period. The correlation between forecasts and observations are reasonably good for seven day forecasts. However, the correlations are lower for the ten and fourteen day forecast. However, these correlations are for the entire three month period. A closer look at the January and February indices suggest quite good forecastablilty by the GFS even for a two week forecast.

References:

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