Estimation of the Limit of Predictability in the Stratosphere versus Troposphere Using CFS

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1. MOTIVATION OF THE STUDY

The NCEP Climate Forecast System (CFS) shows a good forecast skill for the variability of large-scale circulation in the troposphere but a low skill for the stratosphere. Sudden stratospheric warming events are among the tests that not only CFS but also its contemporary coupled general circulation models (GCM) have yet to pass. Why this is a surprising result? Because most of the theories aimed to explain the mechanism of formation and maintaining of stratospheric warming events involve propagation of planetary waves from the troposphere up in the stratosphere. The realistic representation of the troposphere and stratosphere in the CFS confers the potential of a successful prediction of these events.

2. MODEL DESCRIPTION

This study used the NCEP Climate Forecast System (CFS). The atmospheric GCM has a horizontal resolution of T62 of about 200 km with 64 sigma levels and the top at 0.2 hPa. Above 150 hPa there are 27 levels. The oceanic GCM is MOM3. The coupling between the atmosphere and ocean is realized through the interactive ensemble (Stan and Kirtman, 2007). In this coupling strategy the ocean model is coupled to the ensemble average of 6 atmospheric models that in turn are forced by the same SST. There are 30 atmospheric ensembles corresponding to 5 interactive ensembles. Each atmospheric model is initialized on January from slightly different initial conditions, so that the 6 realizations of the atmosphere give a good sample of internal variability. The atmospheric initial conditions are taken from the NCEP/DOE AMIP R2 reanalyses, and are 6 hours apart. Thus, the atmospheric realizations can be interpreted as equally likely responses of the atmosphere to the same SST.

For predictability studies, the atmospheric realizations in a single interactive ensemble represent outcomes of so called "identical twin experiments," with 15 pairs of twins available. For each January in the 10-year period (1981-1990), 5 interactive ensemble forecasts (of length one year) were run from the same ocean initial condition representative of 1 January. Thus for each calendar year we have essentially 5 sets of identical twin experiments.

3. SUDDEN STRATOSPHERIC WARMING

Figure 1 shows the ensemble forecasts of the polar cap temperature at 10hPa and the zonal mean zonal wind at 60°N and 10hPa around an episode of sudden stratospheric warming event with the central date on 23 January 1987 (Charlton and Polvani). This figure shows that while some individual forecasts capture the strong easterlies, few if any capture the extent of the polar warming. The ensemble means clearly do not have any prediction skill for this sudden stratospheric warming event. Results from other warming events that occur near the start of the forecasts are similar.

Before we investigate why the model is not able to consistently forecast these events, it is useful to check if the model climatology agrees with the observed counterpart. We want to eliminate the possibilities that in the model the stratosphere is already too warm so it cannot get warmer, or that it is too cold and if it warms up, the temperature raise is not enough to catch up with the observations. Figure 2 shows the temperature bias in January and February. While the 10 hPa temperature bias in January is small poleward of 60°N, it does grow fairly substantially in February when CFS temperature is too cold by over 8 degrees. The zonal-mean zonal wind for observations and the model are shown in Figure 3; it is clear that the model generally simulates the jet

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structure well, although the 10 hPa winds near the pole are somewhat weak during January.

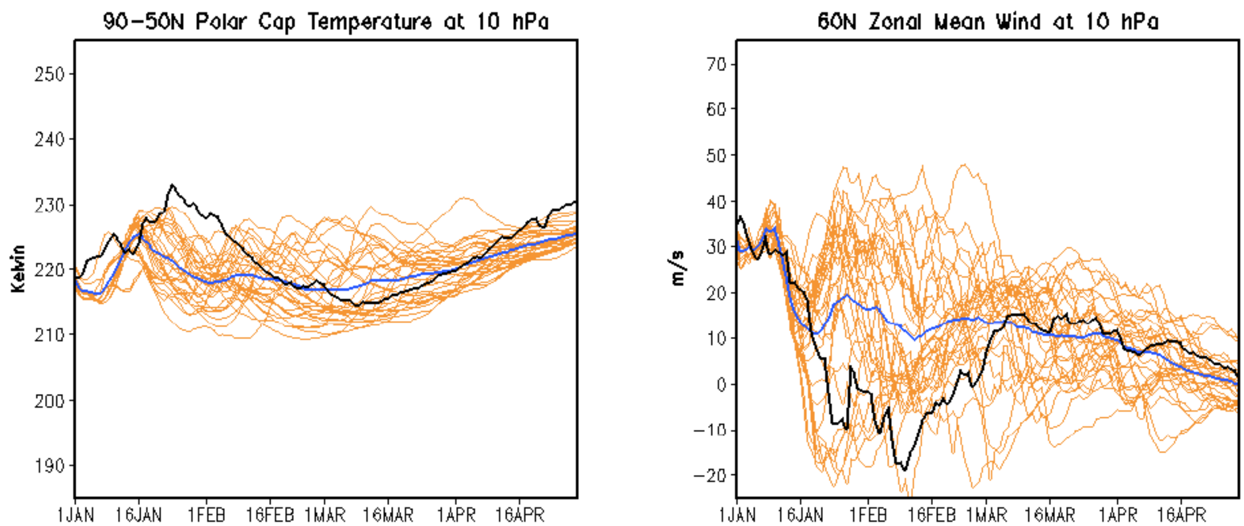

Figure 1 Left: Temperature averaged over the Polar Cap north of 50ºN at 10hPa in 1987. Right: Zonal mean of U wind at 60ºN at 10 hPa. The orange curves denote the 30 atmospheric realizations corresponding to the 5 interactive ensembles, the blue curve is the ensemble mean and the black curve corresponds to observations.

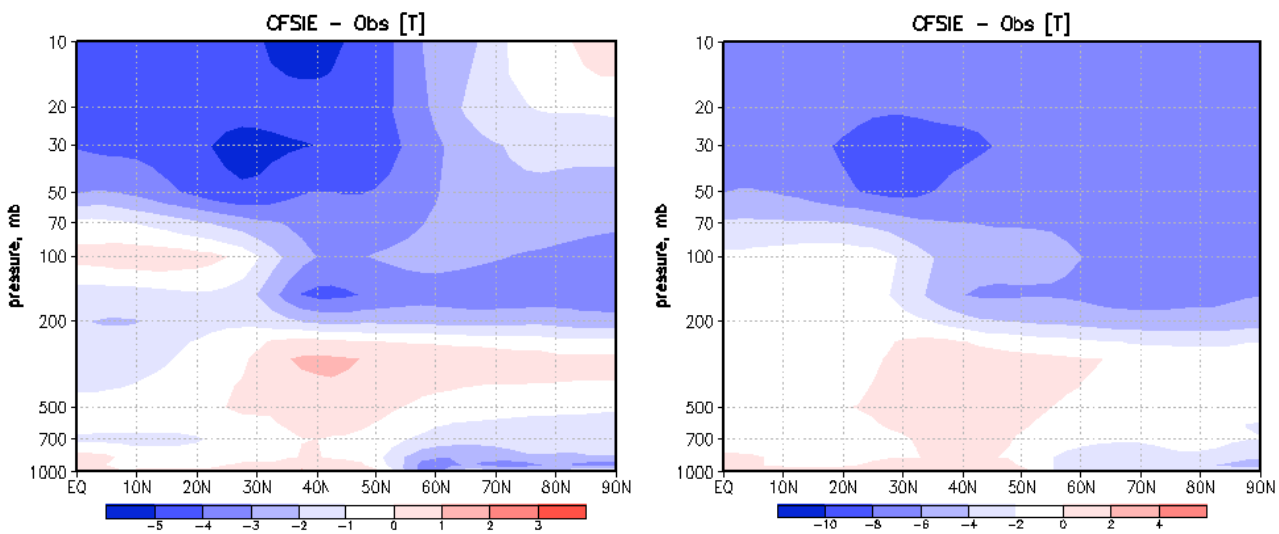

Figure 2 Model error of the zonal mean temperature simulation during January (left) and February (right).

4. PREDICTABILITY

Another possible explanation for the model failure might be related to the intrinsic nature of stratospheric predictability. The experimental design offers the perfect opportunity to look into the limit of predictability in the stratosphere versus troposphere. For each interactive ensemble, the atmospheric realizations in a single interactive ensemble represent outcomes of so called "identical twin experiments". There are 15 pairs of twins available for which the squared error of any quantity may be computed. Averaging the squared error over all pairs, then over all 5 interactive ensembles, and finally over 10 years, yields a good estimate of error growth due solely to differences in the initial conditions. This error growth is driven by the degree of deterministic chaos that characterizes the dynamics of the region in which the prediction is made. Zonally averaging the mean squared error allows for an expansion in terms of zonal wave numbers.

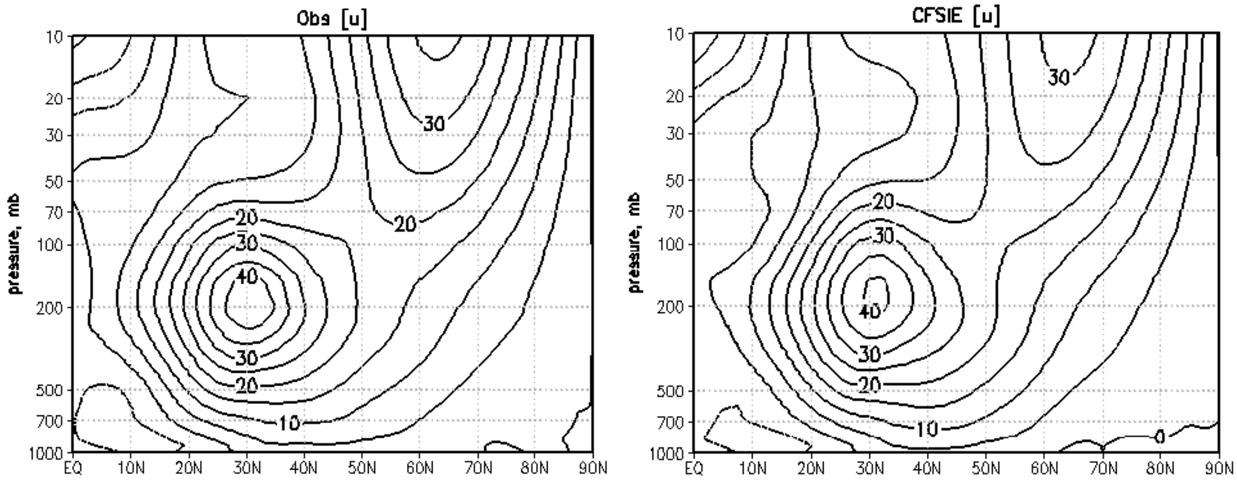

Figure 3 Meridional cross-section of the January zonal mean zonal wind climatology from observations (left) and model simulations (right).

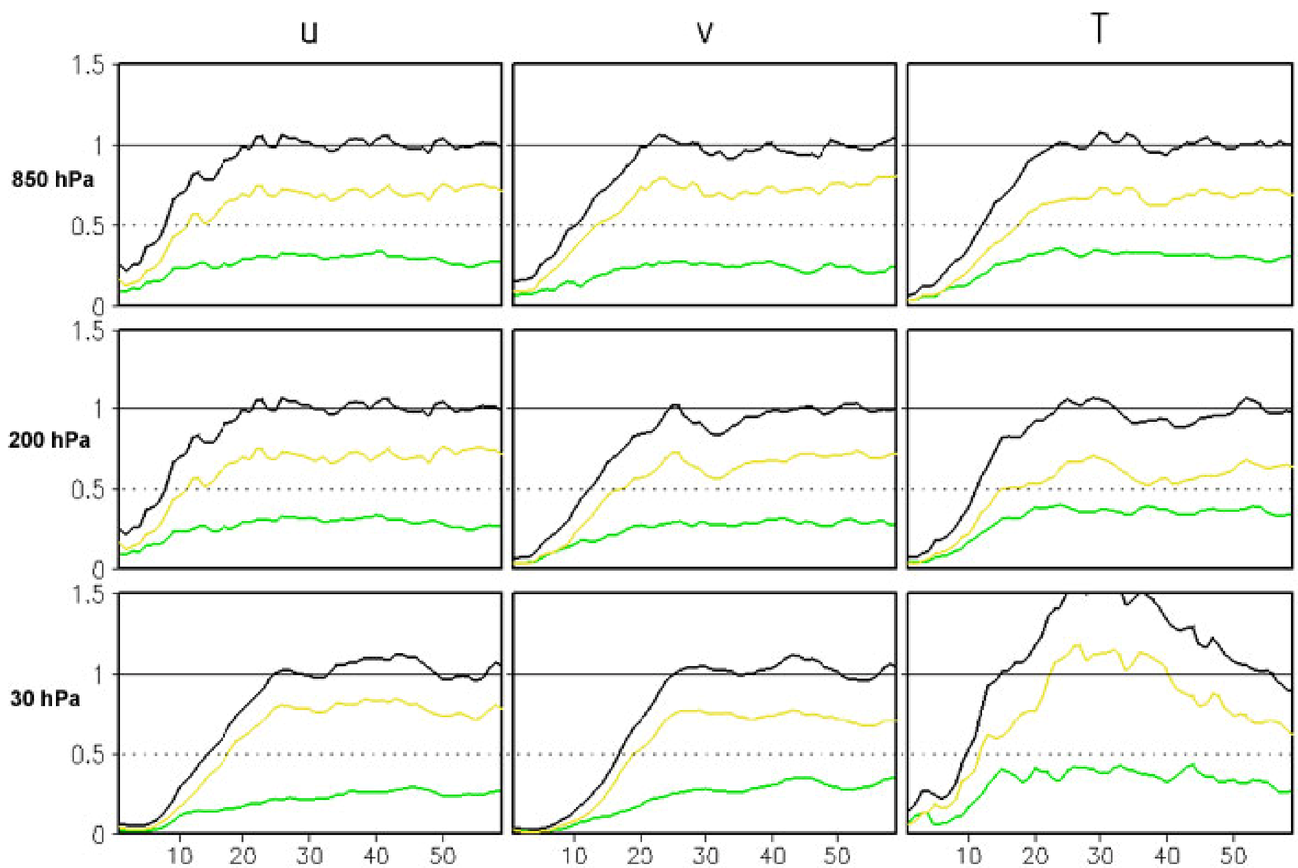

Figure 4 The normalized forecast errors in the zonal wavenumber 1 field of zonal wind, meridional wind and temperature for three different levels: 850, 200 and 30 hPa. The black line denotes the total amplitude, the yellow line represents the squared error due to the phase difference between the waves and the green line denotes the error due to the amplitude difference between the waves.

Figure 4 shows the normalized forecast errors in the zonal wave number 1 field of zonal wind, meridional wind and temperature for three different levels: 850, 200 and 30 hPa. The saturation value (which provides the normalization) is calculated as the 10-day mean at the end of February. The squared errors are averaged between 50° and 70°N. The black line denotes the total amplitude, which can be written as a sum of two terms, one giving the squared error due to the phase difference between the waves (shown in the yellow line) and the second giving the error due to the amplitude difference between the waves (shown in the green line). A first important result is that the magnitude of the (squared) error is dominated by the magnitude of the phase error. This suggests that the phase of the wave is an important factor in limiting the predictability. For wave number 1, the predictability time (defined here as the time at which the normalized error reaches 0.75) is comparable at all levels, about 20 days. For wave number 2 (shown in Figure 5), the predictability time appears to become somewhat shorter at higher levels. Another interesting, and likewise surprising result, is the shape of the error curve in temperature at 30 hPa. Rather than simply growing and saturating, the error decreases at large time, indicating a systematic decrease in variability towards the end of the winter season.

Figure 5 Same as Figure 4, but for zonal wavenumber 2.

As we know, sudden stratospheric warming events occur as a result of a special pattern in the wind and temperature fields. A good measure of the wave activity flux is the Eliassen-Palm (EP) flux and its divergence. Since the EP flux and its divergence are by definition zonally averaged quadratic quantities in the eddy fields, they can also be expressed as a sum over zonal wave numbers. For each zonal wave number separately, we computed the squared error of EP flux divergence averaged over all 15 identical twin pairs in each ensemble, over each ensemble and over all 10 years.

Figure 6 shows the result for wave numbers 1 and 2. The errors are also normalized by the saturation value, which is calculated as the last 10-day time average. The black curve corresponds to the 850 hPa level, the blue curve to the 500 hPa level, green to the 200 hPa level, yellow to the 100 hPa level, red to the 50 hPa level and purple to the 30 hPa level. The first feature of note is the large value of the initial error when compared to errors in the individual fields, and this is true for all levels. This result indicates that small errors in individual fields lead to large errors in the wave fluxes and their divergence. One might be tempted to say that this is an obvious result because the EP flux involves derivatives of second-order quantities.

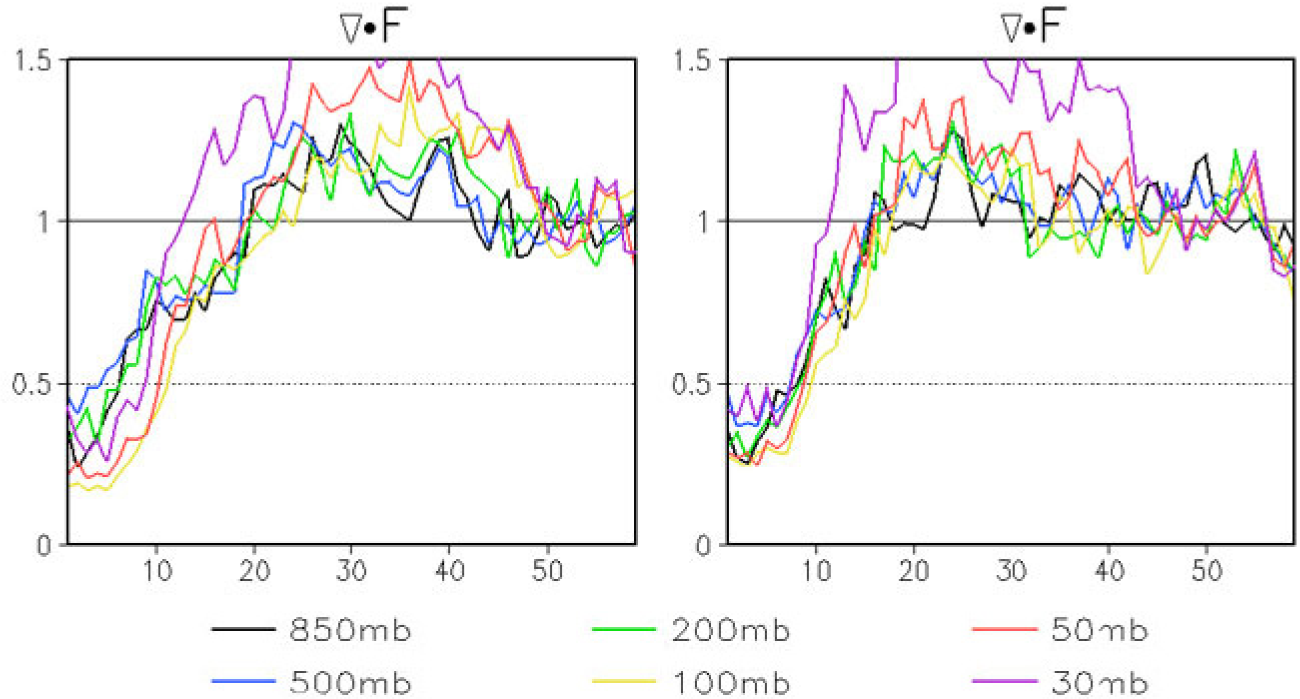

Figure 6 The squared error of EP flux divergence for wavenumbers 1 (left) and 2 (right).

5. SUMMARY

The results suggest that *the predictability of sudden stratospheric events is low* because small errors in individual fields lead to large errors in the EP flux. The connection between the behavior of the temperature and EP flux divergence is consistent with previous work, which emphasizes that the vertically propagation of planetary waves in the stratosphere depends on the permeability of the tropopause. The second feature worth emphasizing is *the systematic decrease in variability towards the end of boreal winter seen at upper levels*. In the individual fields, this type of variation is characteristic mostly of the temperature field. The non-stationarity of the variability poses challenges for predictability theory, because it makes difficult to define the saturation value of the error growth. The last aspect we like to point out is *the shorter time of predictability in the stratosphere when compared to the troposphere*. At lower levels, the predictability time is around 20 days for wave number 1 and 15 days for wave number 2. At upper levels, the predictability time is reduced to about 10-12 days.

6. REFERENCES

Charlton, A. J. and L. M. Polvani, 2007: A new look at stratospheric sudden warming events: Part I. Climatology benchmarks. J. Climate, 20, 449-469.

Stan, C. and B. P. Kirtman, 2007: The influence of atmospheric noise and uncertainty in ocean initial conditions on the limit of predictability in a coupled GCM. (under revision for J. Climate).