On the use of Potential Vorticity as a diagnostic of Solar influences on the stratosphere

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Introduction

This talk is a progress report on efforts by Chris Calvey to look for signatures of solar activity in the National Center for Environmental Prediction (NCEP) reanalysis database. In the past we had focused on standard atmospheric products, especially temperature as this allowed us to compare our results with those obtained by others, especially Labitzke and van Loon. Also, these quantities are most readily obtained by radars and satellite which assign data to specified locations and heights (the so-called Eulerian framework). However, from a dynamical perspective, it makes more sense to examine processes from the reference frame of the air parcels themselves. This is referred to as the Lagrangian co-ordinate system and is used in trajectory analysis studies.

Chemical tracers may be used, but it is often hard to label individual parcels and in the stratosphere they are either hard to detect or undergo chemical transformations over timescales that are similar or shorter than those needed to investigate the dynamics of the stratosphere. To overcome these problems, a derived product, Ertel's potential vorticity is often used. When the vertical co-ordinate is potential temperature, then this quantity has the useful property that it is conserved under adiabatic and frictionless conditions. As this quantity describes the flow completely, it also described the state of any chemically inert tracer once its initial distribution is known.

Inevitably, one must test the assumptions that have been made to get to this point. Whilst the winter polar vortex is outside direct sunlight, it is not true to say that there is no diabatic heating. As we have discussed previously, wave motions drive the circulation away from radiative equilibrium, enabling diabatic heating changes to occur. Similarly, irreversible small scale mixing will have an impact on the integrity of Q and it will be shown shortly that near the edges of the vortex wall, wave-breaking becomes an important process. Bearing the above caveats in mind, we shall now consider the use of potential vorticity in some detail.

Daily analyses of PV on an isentropic surface

For this illustration I have taken data from the web. 475 K corresponds to a mean pressure level just below 30 mb. The analysis is similar to that used with the NCEP data. The first plot is for 10^{th} January 2002. The polar vortex has been displaced towards Eurasia and there is a clear planetary wave number 3 perturbation. This combination of distortion and dislocation is a classic 'pre-condition' of a warming event. Note the fine structure in the plot. Some of this may be pure numerical 'noise', but it is possible to monitor the evolution of individual tendrils of high/low Q values as they get mixed in with other types of air..

Two days later the vortex has rotated Eastward and been further distended with a significant proportion being drawn to relatively low latitudes where it will experience direct solar heating. Meanwhile, lower latitude air has been drawn to the polar night. These twin processes will bring about an irreversible transfer of heat from low to high latitudes. Strands of high Q air are being drawn off the vortex edge into an emerging Aleutian anti-cyclonic feature over the North Pacific. This feature is more readily apparent two days later.

By January 16th, the conditions of a warming event are now fulfilled. Extra-tropical air is being drawn over the North Pole, whilst polar air has headed off towards the equator. The polar vortex is about to split into two components. Two days later, the vortex is quite distended leading to a breakup in the following slide. There is a narrow tendril still connecting them together, but much of the material will get mixed into the extra-tropical atmosphere, rather than merge with the main vortex again. The remaining vortex will never fully recover before the spring breakup of the vortex occurs in March/early April. In the next slide the two vortices have been separated, at least to the resolution of the assimilation model. By January 24th, the vortex has resumed its usual place near the North Pole, whilst the secondary vortex is beginning to 'evaporate'. On the next slide you would be hard pressed to identify this feature as new ones that are more clear are forming that are probably being fed by remnants of this phenomenon. Clearly, sub-scale mixing is taking place and the in-built model filters will remove structures on scales less than a couple of grid points ~ 100 km. How much of the detail is real and how much numerical, depends on the precise model configuration, but the so-called 'cascade to smaller scales' is a ubiquitous feature of fluid dynamics, so the qualitative picture will be correct. In the analysis that we are going to present we will consider the monthly averaged fields, so we shall assume that most of this fine structure is chaotic in nature and on average will cancel out. We know that this is not strictly true and I will return to this theme in future talks, but for the moment we shall assume that this is the case. As LvL have not thought about that, then neither will we for the time being.

Correlations with solar variability

You should be familiar by now with this slide. Chris has taken the temperatures from the twenty or so years when the winter was in the western phase of the QBO and a similar number of years in the East phase and computed the correlations at every point on a 30 mb pressure surface (~ 25 km) with the solar activity conditions present at those times. There are very significant positive correlations in the Northern Hemisphere polar region over a wide area with clear wave one and wave two structures embedded in the correlations. As there is no direct *in situ* heating, changes to the transport conditions can be the only reasonable explanation. The opposite conditions are true in the Eastern phase. Beyond the polar vortex, the correlations are in the opposite sense. This is especially interesting in the Western phase case because it implies that in the tropics where the direct uv effects might be expected to be important show no positive correlation. Transport is the dominant effect at all latitudes at this height. Since the result was first reported over

10 years ago, the statistical significance has continued to improve, suggesting a process more than simple coincidence is at work.

Coupled with changes in the temperatures one would expect there to be an analogous influence on the zonal winds. From the thermal wind equation, the strength of the jet is proportional to the temperature gradient. As you can see, there are indeed coherent structures in the correlation fields associated with the polar winter vortex. There are also some interesting features in the southern hemisphere, but I don't want to dwell on those today, especially as the data quality is more suspect in that region of the model.

Once we combine these quantities in the form of potential vorticity we can start to make out some features in the winter vortex. They are not as nearly well pronounced as the original fields, but the North Atlantic is particularly significant and suggests that the winter storm tracks and the North Atlantic Oscillation may be particularly sensitive to solar forcing variations. As we pointed out, PV is most useful on isentropic surfaces. 507 K corresponds most closely to the 30 mb pressure surface and the results are presented next.

The significance of the correlations has improved dramatically which can be attributed to the fact that because the winter vortex is relatively cold, the isentropic surface has a relatively steep gradient near the vortex edge. The 30 mb cross-section is effectively revealing two distinct regions on different theta surfaces. The western phase vortex has weakened with respect to its surroundings which has gained strength. Therefore, the vortex is far more vulnerable to subsequent planetary wave encroachments and thus warmer climatological temperature values. The opposite is true for the Eastern phase. The integrity of the vortex is enhanced, making further penetration more difficult, thus providing a positive feedback mechanism.

PV provides a new dimension to the analysis of solar influences on the stratosphere because it reduces the impact of reference frame changes. At 30 mb, the correlation between Ap and temperature is quite unremarkable, whereas some of the best results obtained so far can be achieved with the same data sets when Q is considered. Geomagnetic influences are short lived on the timescale of planetary wave/mean flow activity, so any rearrangement of the circulation between events can lead to an apparent cancelling out of interactions, however, in the frame of the air parcels, there has been an accumulated impact on the vorticity.

Summary and further work

Potential vorticity on isentropic surfaces have been computed for the entire NCEP database going back over forty years. It provides unique insights into the dynamics of the winter polar vortex that do not appear readily in the traditional temperature and wind data fields. Whilst there is reasonable qualitative agreement between Q and the other quantities, there are specific occasions when the latter produces enhanced correlations – in particular in the case of Ap during the Eastern phase of the QBO.

We intend to examine the short term variability of the data and whether the correlations still remain valid. Also with the aid of numerical models we shall look into the validity of the assumptions behind using PV as a diagnostic of material tracer transport. Subsequent years of data should reveal the extent of the correlations thus far obtained.