Measuring the Antarctic MLT gravity wave field

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1: Introduction

The Arrival Heights MF-radar is situated at Scott Base (78°S, 167°E) and measures horizontal wind speeds in the mesosphere-lower thermosphere (MLT). A recent upgrade to the radar system has allowed the measurement of internal gravity waves in this region. Gravity waves are an important atmospheric forcing mechanism in the MLT, particularly at high latitudes. For this reason atmospheric models attempt to include gravity wave effects. However, due to computational requirements, the grid size used in global climate models is too coarse to accurately portray gravity waves so parameterizations are used. To improve/validate these parameterizations measurements of the gravity wave field are necessary.

Gravity wave measurements are generally difficult due to the high temporal resolution required and the presence of strong longer period atmospheric waves, atmospheric tides and planetary waves, as well as noise in measurements. Thus, sophisticated signal processing techniques are required to separate the gravity wave field from observations. This poster examines the relative utility of a number of signal processing techniques in an attempt to determine an optimal technique which can be used to form a gravity wave field database over Scott Base.

2: Gravity Waves

Waves with the restoring forces of gravity and buoyancy are known as gravity waves. These waves are present though much of the atmosphere with periods of minutes to hours. There are many mechanisms by which these waves can form; however, the gravity waves above Scott Base are likely to be predominantly due to winds passing over the Trans-Antarctic mountain range. As the air passes over the ranges it is displaced from its equilibrium position and oscillates around this position as it moves down wind of the mountain, creating a wave. The air column above is also displaced, as such the gravity wave can propagate vertically well into the thermosphere.

These waves provide much of the coupling between the lower and upper atmosphere by transporting energy to higher altitudes. This is particularly important in the Antarctic MLT as this is the region of the atmosphere farthest from radiative equilibrium. For example, the winter temperature in the MLT above the polar regions is generally higher than that in summer. This unexpected observation has been shown to be related to the forcing associated with gravity waves. The energy transported by gravity waves has also been shown to control the strong mesospheric winds and play a significant role in closing the stratospheric jets, which is in turn important in ozone hole dynamics.

How EMD Works

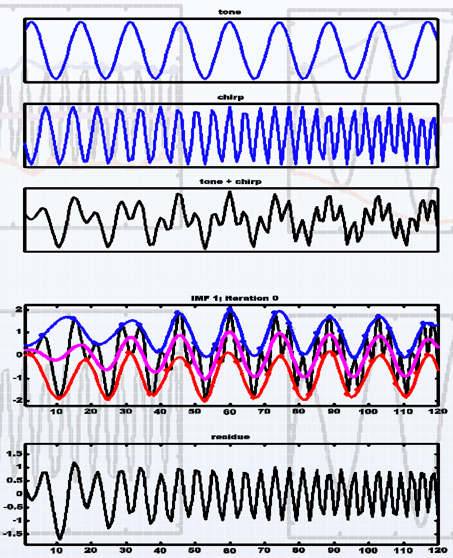

Figure 1 – The empirical mode decomposition sifting process. Diagrams from Flandrin. A time-series made up of a tone and a chirp can be sperated using EMD.

1. First, the maxima and minima of the signal are identified and cubic splines fitted between all maxima and all minima creating an envelope. Blue and red lines.
2. The mean of the envelope (called the detail) is computed. Magenta.
3. The detail is extracted from the original signal to form a residual signal.

- Steps 1-3 are repeated on the residue until the mean is close to zero, a flat line. This final residue is the first complete intrinsic mode function (IMF 1)
- The original mean from IMF 1, the magenta line above, is used as the signal in step 1. This begins the process of calculating IMF 2. The first mean produced from the IMF 2 sifting processes is used to produce IMF3.
- The process is halted when the mean used to produce a new IMF is close to zero.

3: Signal Processing techniques

The Scott Base MF radar measures horizontal wind speeds in the MLT. These measurements are composed of the background flow, gravity waves and longer period atmospheric waves. In order to extract gravity wave information from the data, the longer period waves as well as any noise, both environmental and instrumental, need to be removed. It should be highlighted that these wave are highly nonlinear and non-stationary, individual wave frequencies and amplitude change significantly and waves interact, and this means simple Fourier-based techniques are not appropriate.

There are several ways to attempt to remove the longer period waves from the data, the most common method is to use least squares fitting routines to remove the sine waves associated with the long period waves from the data. The remaining signal is assumed to be primarily due to gravity waves. The traditional method has the disadvantage that noise is not removed effectively.

Empirical mode decomposition (EMD) is a relatively new signal processing technique developed by *Huang et al.* (1998). The technique is essentially defined by a recursive 'sifting' algorithm for adaptively representing signals as sums of zero-mean amplitude- and frequency-modulated components called intrinsic mode functions (IMFs). Figure 1 provides a schematic which indicates how the EMD process works. These IMFs separate the individual components of the wind field. The particular strength of this method is that it can extract wave components from data without any a priori knowledge and it is designed for use on non-stationary time series. This potentially makes EMD a powerful tool for analyzing the gravity wave field. However, the EMD algorithm has several disadvantages. Primarily, a phenomena known as mode mixing can occur, whereby for a variety of reasons, part of a high frequency IMF can manifest in later IMF's which distort the wave on either side of the disturbance. Secondly, as it is a purely empirical method there is no easy way to gauge the quality of the IMF's produced.

Ensemble Empirical Mode Decomposition (McDonald et al., 2007) is a method which attempts to improve on EMD by forming an ensemble by running the EMD algorithm on the same data set adding random white noise each time. Each resultant time series produces a set of IMFs which are somewhat different to the preceding one. The mean of the ensemble can then be regarded as the best or ideal IMF, in addition the standard deviations of the ensemble provides a good indication as to the uncertainties of the resultant IMF.

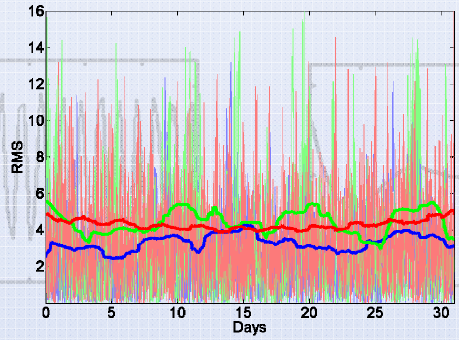

Figure 2 - The root mean squared (RMS) differences between the synthetic gravity wave field and the gravity wave field as calculated by least-squares fitting, EMD and EEMD. The RMS difference between the synthetic field and the field calculated by the least squares fitting is shown in red, EMD in green and EEMD in blue. The lines across the graph are the four day running means of the RMS differences.

4: Results

Empirical Mode Decomposition, Ensemble Empirical Mode Decomposition and the commonly used least squares method were used to analyse a single months worth of synthetic radar data. The synthetic wind fields comprised of sinusoids making up commonly observed atmospheric waves, 8h, 12h and 24h hours waves and a pair of gravity wave signals with periods of 3 and 4.5 hours. This data was designed to favour the least-squares method as the longer period atmospheric waves have fixed frequencies which matched those that the least-squares technique was tailored to remove.

The short period IMFs produced by both normal and Ensemble Empirical Mode Decomposition were added together so that these techniques could be directly compared to the least squares fit technique which returns everything which is not one of the longer period atmospheric waves.

The root mean square difference between the gravity wave field determined by each technique and the true values used to synthesise the data are displayed in Figure 2. The technique which performed the worst (had the largest RMS) was empirical mode decomposition (green line), this was mostly due to mode mixing occurring.

5: Results

The Ensemble Empirical Mode Decomposition mitigates mode mixing and it can be seen to perform better than the least squares fitting technique (blue line in Figure 2). The reason for its better performance is mostly due to its noise rejection properties.

Least squares technique removed the long period wave effectively and was the least computationally expensive technique of the three. However its lack of noise rejection effected its performance (see red line in Figure 2).

Application of the EEMD to real data (see Figure 3) displays significantly less mode mixing. It is likely that this is due to the higher complexity of real observations. This suggests that our analysis of the three signal processing techniques were tested against data with parameters favourable to the traditional method(i.e. fixed period waves with periods which match the traditional method fitting frequencies).

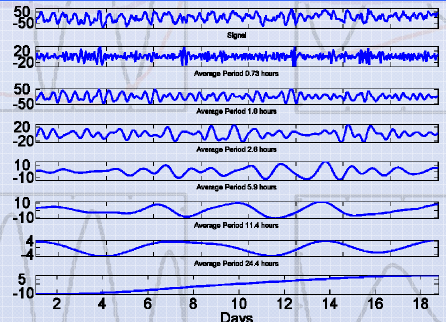

Figure 3 – Ensemble empirical mode decomposition of zonal wind speeds (ms^{-1}) at 90km from MF-radar data from Scott Base in January 2006. 741 EEMD runs passed quality control criteria, each run had white noise of 10% of the signal standard deviation added. The average period of each intrinsic mode function was calculated using the Hilbert-Huang spectrum.

Conclusion

Ensemble Empirical Mode Decomposition (EEMD) is a potentially powerful technique for analyzing the gravity wave field observed by the Scott Base MF-radar. It can extract simulated gravity wave fields with no a priori knowledge of the atmospheric wave spectrum. This contrasts with the traditional techniques which requires significant assumptions to be made. However, the EEMD method still suffers from significant mode mixing which reduces the utility of the technique. For this reason care is needed in selecting which modes are identified as being related to the gravity wave field.

When EEMD was tested against real data, mode mixing occurs less, it is likely that this is due to the higher complexity of real observations (see Figure 3). This suggests that our analysis of synthetic data is perhaps overly conservative.

The least squares method was quite good at removing the long period waves. However, even the long period atmospheric waves do not typically have constant periods. This would impact on the least squares fitting technique.

If the least squares technique could be made robust in the presence of varying periods, for example by performing Fourier transforms to get periods each day, it might be possible to develop a hybrid EEMD least squares fitting technique. The advantage of this might be a reduction of the computational requirements for EEMD.

Acknowledgements
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