From The Line Islands Experiment to Normal Mode Rossby-Haurwitz Waves

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Introduction

The Line Islands Experiment (February-April 1967, LIE) was the first NCAR directed large field experiment (Zipser, 1970). It took place in the equatorial Pacific and "was designed to provide comprehensive meteorological data in the oceanic part of the Equatorial Trough Zone for a variety of basic studies, to provide data with which to evaluate cloud photography performed by the ATS-I synchronous satellite, and to serve as a pilot program for future experiments in tropical meteorology" (Zipser and Taylor, 1968). Ed Zipser was the Chief Scientist for the experiment and my boss at NCAR. He introduced me to Tropical Meteorology and his curiosity and enthusiasm for research made work fun.

Among the important findings of the LIE was Ed's 1969 paper describing a squall line in the equatorial zone (Zipser, 1969). It was awarded the NCAR Outstanding Publication Award for 1969. We also looked at high vertical resolution rawinsonde data collected during the experiment (Madden and Zipser, 1970). At that time, Yanai at Tokyo University and Wallace at the University of Washington and their colleagues (eg. Yanai and Maruyama, 1966; Wallace and Kousky, 1968, and more) were using spectrum analysis effectively, discovering mixed Rossby-gravity waves and Kelvin waves and providing details on the structure of other synoptic scale features. It was natural for us to apply their methods to our Line Islands Data.

I reported on a spectrum analysis, determined by the lag-correlation method, of a time series from the LIE at the Tropical Meteorology Meeting at the University of Hawaii in 1970 (Madden, 1970). These time series were relatively short (47 days) and it was clear that longer ones would be necessary to support any conclusions that might be made. Fortunately, Roy Jenne's Data Support Section at NCAR was in the process of gathering longer time series and Paul Julian, an expert on spectrum analysis and a member of our group, had a code to perform the recently discovered Fast Fourier Transform procedure.

Upon our return from the Hawaii Meeting, Julian and I embarked on spectral analyses of NCAR's newly acquired longer records in order to study non-stationary aspects of the LIE results. Instead we found very large variations near a 45-day period that are now referred to as the MJO (Madden and Julian, 1971; 1972). There was also evidence of a zonal wave number one, westward propagating wave with a five day period (Madden and Julian, 1972). We learned that this wave had been previously identified and linked to theoretically predicted Normal Mode Rossby-Haurwitz Waves (Deland, 1964; Eliassen and Machenhauer, 1965; 1969).

Normal Mode Rossby-Haurwitz Waves (NMRHW) became a continuing interest of mine. I had the good fortune to have Bernhard Haurwitz as my Phd Advisor at Colorado State University. My thesis, "Traveling Planetary Waves and Their Effect on the General Circulation" dealt with the first two symmetric zonal wave number one NMRHW, the "5-" and "16-day waves" (published in Madden, 1978).

This paper relates the theory of NMRHW as described by Kasahara (1976; 1980) and Kasahara and Puri (1981), and comparisons with that theory of analyses based on a three year record of ERA-Interim Data. The results, and that of others, support the existence of most of the theoretically predicted NMRHW discussed by Kasahara. They have non-zero projections in the Tropics, but at this point their role in the meteorology of the Tropics is essentially unexplored.

Theoretical Expectations

The theory for NMRHW goes back more than 200 years. It has been reviewed by Holton (1975), Madden (2007), and many others. Suffice to say here, NMRHW are external waves with a slight amplitude growth in the vertical (see Kasahara and Puri, 1981, Fig. 2), and Hough Functions in the horizontal as shown in Fig. 1 here.

The largest scale modes have discrete predicted frequencies modified by background winds. Figure 2, adapted from Kasahara (1980), shows expected wave periods in days in the face of average December-January-February winds.

Figure 1

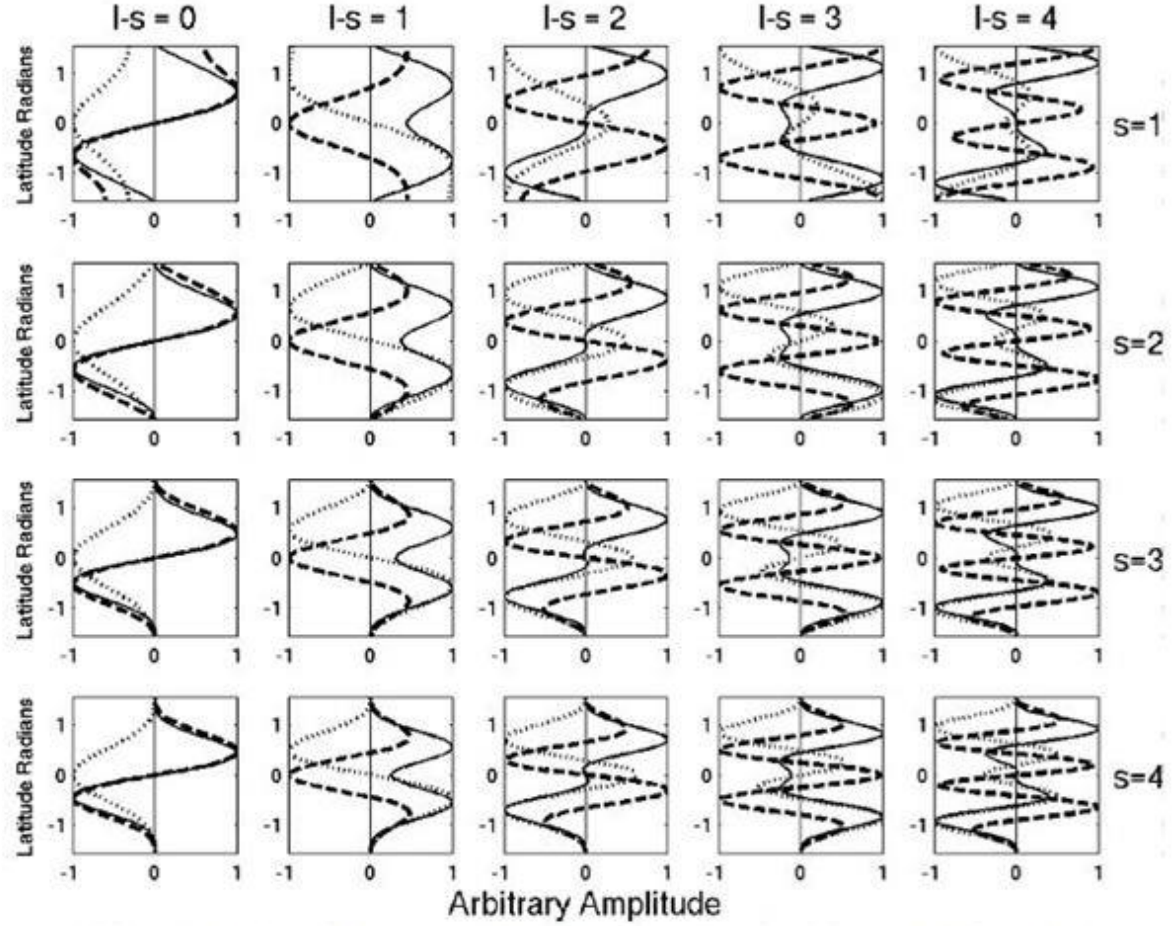
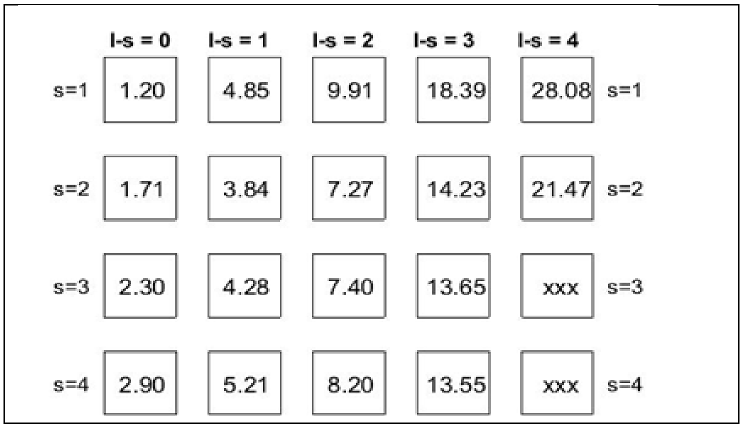


Figure 1. Hough Function depictions of the latitudinal structure of ***u*** (dashed), ***v*** (dotted), and ***Z*** (solid) for zonal wave number ***s*** (rows), and meridional Index ***l-s*** (columns). Hough Functions are after Kasahara (1976). Each Variable is normalized to a maximum amplitude of one.

Figure 2. Predicted period in days with D-J-F winds after Kasahara (1980) Rows are zonal wave numbers and columns meridional indices as in Fig. 1.



	l-s = 0	l-s = 1	l-s = 2	l-s = 3	l-s = 4	
s=1	1.20	4.85	9.91	18.39	28.08	s=1
s=2	1.71	3.84	7.27	14.23	21.47	s=2
s=3	2.30	4.28	7.40	13.65	xxx	s=3
s=4	2.90	5.21	8.20	13.55	xxx	s=4

Observations

NMRHW appeared in the earliest numerical models (Charney and Eliassen, 1949). Early observational evidence of them was found in geopotential height data at single latitudes by Kubota and Iida (1954), and in Hemispheric and Global data by Eliasen and Machenhauer (1965,1969). In the half-century since the publication of those results, considerable additional observational evidence has appeared supporting the existence of all the largest-scale (mid-latitude east-west and south-north scales exceeding about 5000 km) NMRHW. Reviews of early evidence are contained in Madden (1979), Ahlquist (1982), and Salby(1984). For a summary of published evidence from 1982 to 2007, see Table 5 of Madden (2007).

Here, results of a search for evidence of NMRHW in ERA-Interim Data from the period 2010-2012 are described. Data used in the analyses are four-per-day vorticity fields. Theory indicates that the normal modes we are looking for are external (no sign changes in the vertical), and that their horizontal structures are sums of associated Legendre polynomials called Hough Functions. Readily available routines coded in NCL (NCAR Command Language) were used to make and analyze projections very similar to these external Hough modes.

Because of the external nature of predicted waves, the vorticity data from 00, 06, 12 and 18GMT were first averaged in the vertical from 850 to 100 hPa. They were then projected onto spherical harmonics (Associated Legendre Polynomials) using the NCL *shagC* routine. Single Associated Legendre Polynomials are reasonable approximations to the full Hough sums for the largest scale NMRHW (Diky, 1965; for a direct comparison of relevant Hough Functions and single Associated Legendre Polynomial see Fig. 1 in Madden, 2007). The resulting vertically averages and horizontally projected data are very similar to those of external Hough Functions of Kasahara and Puri (1981).

Figure 3

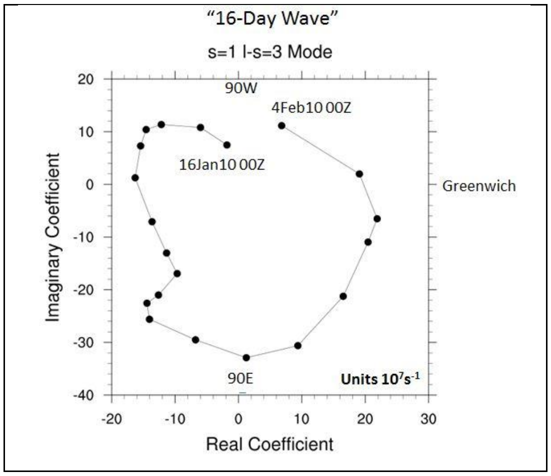


Figure 3 shows a hodograph of the behavior of the ***s***=1, ***l-s***=3 or second symmetric mode (16-Day Wave) for a selected 19-day period. Regular westward propagation is evident. The vertical and horizontal filtering has served to isolate this NMRHW without need of time filtering. We expect that this and other projections should show coherence between the real and imaginary spatial coefficients at the corresponding predicted frequency and that the real should lead the imaginary coefficient by one quarter cycle. Hayashi's (1971) "westward variance" reflects these expectations in a single variable. Figure 4 shows the westward variance of the projections corresponding to Fig. 1. The time spectra (C(f) and S(f)) of the spatial coefficients and the quadrature spectra (Q(f)) between them were determined by the NCL routine *specxy_anal*. The time series are each four observations per day for three years. Twenty nine periodogram estimates were averaged to provide smooth spectra, resulting in a frequency resolution close to 0.025

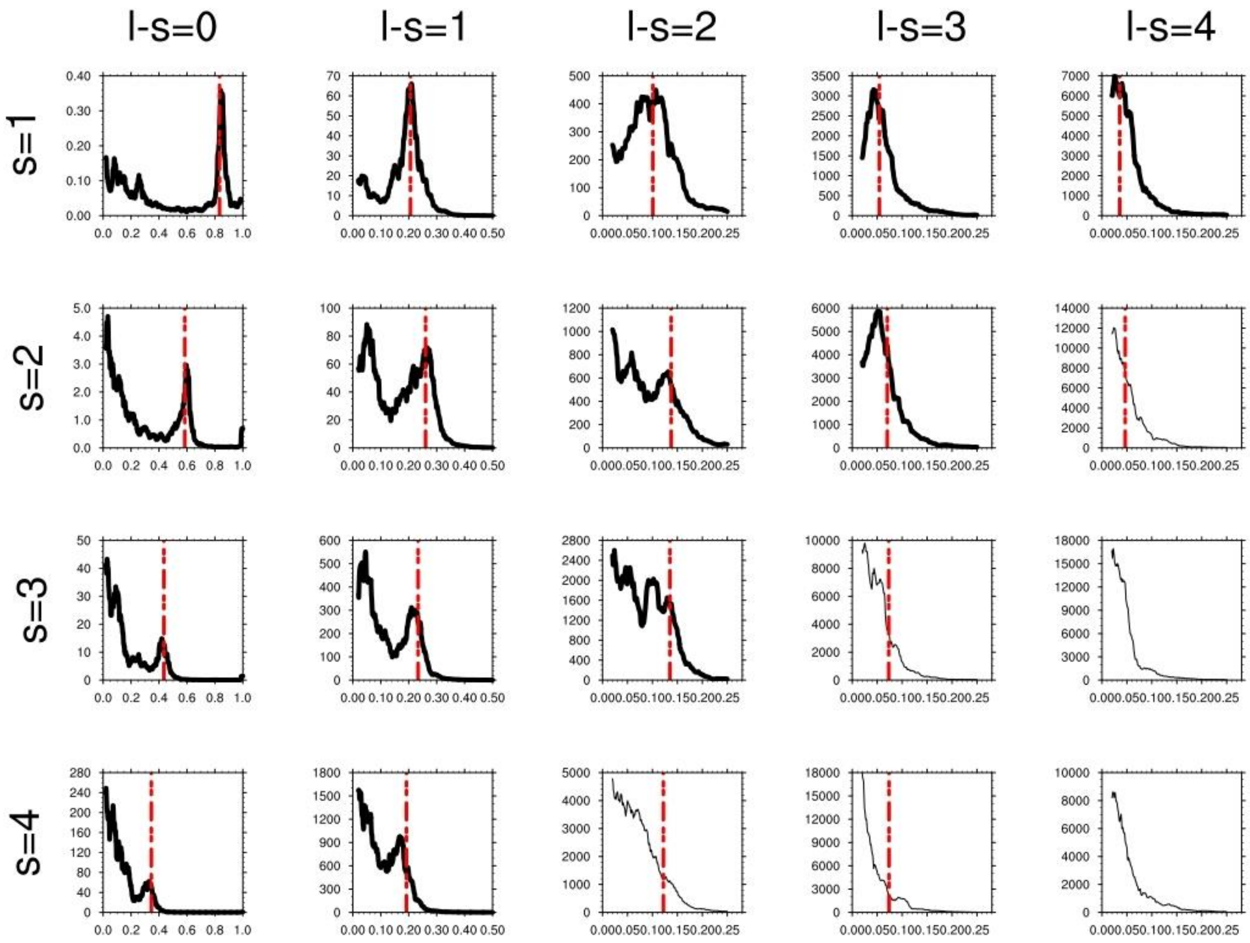


Figure 4. Westward variance for zonal wave number ***s*** (rows), and meridional Index ***l-s*** (columns) given by ¼[S(f)+C(f)+2Q(f)] (eq.4-4, Hayashi, 1971). S(f) and C(f) are the power spectra of the spatial coefficients and Q(f) is the quadrature spectrum between them. Red vertical dashed lines indicate predicted frequencies corresponding to Fig.2. Highest frequency plotted is 1c/d in column one, .5c/d in column two, and .2c/d in remaining columns.

c/d. Heavy lines are to indicate our subjective estimate of modes that are most likely present.

Summary

My introduction to tropical research was working for the Chief Scientist of the LIE, Ed Zipser. He (Marelynn too) helped make our transition to NCAR smooth and exciting. His enthusiasm for research made coming to work each day fun. As a rookie I couldn't have found myself in a better place, with better people, or at a better time. We were looking at LIE data when Matsuno (1966), Yanai and colleagues, and Wallace and colleagues were opening the doors to the theory and diagnoses of tropical waves. Work on the LIE led to analyses of longer time series with Paul Julian. These in turn led to the MJO and, for me a career long interest in NMRHW. Here, expectations of NMRHW were outlined based on theory and modeling of Kasahara(1976; 1980) and Kasahara and Puri (1981). Comparison with ERA-Interim Data shows that many of the largest scale modes are easily identified.

Figure 1 points to zonal wind variations over the equator associated with the symmetric NMRHWs and Hendon and Wheeler (2008) found them in their space-time spectra. Some have also argued that, despite its small associated convergence, the 5-Day Wave affects tropical convection (Burpee, 1976; Patel, 2001); but, with only a few exceptions, effects of NMRHWs on tropical meteorology remain largely unexplored. More work on NMRHW and tropical weather needs to be done.

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