Atmospheric oscillations on time scales of 1-2 months

Jerald R. Ziemke
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Atmospheric oscillations on time scales of 1–2 months

Ziemke, Jerald R., Ph.D.
Iowa State University, 1990
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time scales of 1–2 months

by

Jerald R. Ziemke

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IV. SUMMARY 120
I. GENERAL INTRODUCTION

Low-frequency oscillations (LFO) in the atmosphere, which often result in large amplitude variations in temperature, pressure, and other variables, have periods extending from weeks to years. In the stratosphere, which is the main focus of this study, there are several crucial LFO that affect general wave activity and circulation. One of these is the QBO (quasi-biennial oscillation) of zonal wind in the low equatorial stratosphere, which has a period varying from approximately 24 to 30 months. Besides other LFO such as annual and semi-annual oscillations, there is a less understood class of smaller time-scale "intraseasonal" oscillations whose periods are shorter than a 3-month season. Within this class are 1-2 month oscillations, which is the subject of this work.

A. Past Studies

The first detailed studies on intraseasonal 1-2 month oscillations originated with Madden and Julian (1971, 1972) who discovered strong tropical tropospheric 40-50 day oscillations in zonal wind, temperature, water-vapor mixing ratio, and pressure from long time series of station pressure and rawinsonde data. For historical reasons, this phenomenon is known as the "Madden and Julian oscillation" (MJO).

According to Madden and Julian (1972), the 40-50 day phenomenon can be described as a large-scale quasi-wavenumber 1 eastward-propagating tropospheric circulation cell ("Walker" cell) oriented in the equatorial
plane, with maximum convection along the Indian Ocean-western Pacific Ocean path. (Wavenumber 1 means that one wavelength of the phenomenon fits around a latitude circle.) According to Madden and Julian, convection is strong when the cell propagates eastward along the Indian Ocean-western Pacific Ocean path, but becomes weak as it propagates further eastward across the Pacific Ocean and elsewhere. Later studies using OLR (outgoing longwave radiation) data have verified this quasi-wavenumber 1 tropical convection and attenuation feature, such as Weickmann et al. (1985), Lau and Chan (1985), and Weickmann and Khalsa (1990); the previous two investigations also observed a slow 5 m sec$^{-1}$ eastward phase speed of OLR anomalies along the Indian Ocean-western Pacific Ocean path. A model by Gill (1982) showed that convection reduces the bouyancy and leads to a reduction of the eastward phase speed. In an earlier model by Chang (1977), such eastward propagating disturbances must be accompanied by significant dissipation in order to exhibit the observed slow phase speed. Knutson et al. (1986), using nine years of OLR data and NMC winds for southern winters (May-October) identified zonal asymmetry of the basic state zonal winds contributing to the observed slow phase speed.

Seasonal variation of the 40-50 day oscillation in long time series (5-28 years) was shown by Madden (1986) from the 3-month partitions DJF (December, January, February), and JJA (June, July, August). Results based on rawinsonde zonal wind variance showed that the oscillation in the tropics was strongest during DJF, even though the oscillation exists at all times of the year.
Lau and Chan (1985) and Lau and Phillips (1986) identified a tropical dipole of convection anomalies which propagated slowly eastward at 4-5 m/s from the western Indian Ocean to the dateline (180° longitude). When maximum convection is located in the Indian Ocean, minimum convection occurs near the dateline. This dipole feature was also discovered by Gao and Stanford (1988) in four years of 90 hPa MSU4 brightness temperature data.

Madden and Julian (1972) noted a strong resemblance between the observed phenomenon and tropical Kelvin waves, for at least two reasons. One reason was that the oscillation appeared very weak in the meridional wind, and Kelvin waves are defined such that the meridional wind is identically zero. [Later, Madden (1986) found that the oscillation does actually have a significant meridional wind component, with upper tropospheric zonal and meridional winds out of (in) phase during DJF (JJA) at several stations along the tropical Indian Ocean-wester Pacific Ocean path.] A second reason was that tropical anomalies propagated eastward exhibiting nearly geostrophic balance of dynamical quantities, and tropical Kelvin waves, traditionally derived under quasi-geostrophic scaling, are eastward propagating. This simple Kelvin wave description for the oscillation proved incomplete, however, when Madden and Julian found that the phenomenon did not exhibit vertical phase propagation, a characteristic of conventional Kelvin waves. Although not a complete solution, the Kelvin wave is still a vital component of the 1-2 month tropical oscillations. Under the premise of a tropical forcing, models
show a coupling of eastward propagating tropical Kelvin wave and westward propagating anticyclonic Rossby wave responses about the heating (Garcia and Salby 1987, Lau and Peng 1987, Hendon 1988). Similar eastward propagating tropical features and anticyclonic subtropical patterns alongside or west of the Indonesian heat source region were identified in observational studies by Madden (1986), and Knutson and Weickmann (1987).

The complete mechanism initiating 1-2 month oscillations in the tropics is, as yet, not fully resolved. Part of the mechanism, first suggested by Madden and Julian (1972), is a structured interaction between sea-surface temperature and atmospheric circulation. Warm (cool) sea surface temperature is associated with enhanced (reduced) convection. Studies by Lau and Peng (1987), Sui and Lau (1989), and Lau and Peng (1990) represent a three-part theoretical investigation of the properties of intraseasonal oscillations originating from what they described as a mobile-wave CISK. Recent results by Hsu et al. (1990) provide observational evidence of a different nature, indicating that tropical convection in the Indian Ocean can be initiated by subtropical Rossby wavetrains. The above mentioned studies involving possible initiation should be seriously compared with the statistical correlation results by Gao and Stanford (1988) which indicated an apparent 90 hPa brightness temperature feedback path/wavetrain arching out of the tropics near the date line, into the SH midlatitudes, and back again into the tropical Indian Ocean region.

Madden and Julian (1971, 1972) found that the 40-50 day phenomenon
was limited in latitude to the tropics and subtropics, but observational studies in recent years indicate extratropical extent. Significant extratropical 1-2 month oscillations have been shown to exist in such variables as wind, temperature, OLR, and geopotential height (Lau and Chan 1983, Weickmann et al. 1985, Knutson et al. 1986, Lau and Phillips 1986, Gao and Stanford 1987, Knutson and Weickmann 1987, and Graves and Stanford 1989). Weickmann (1983) found a coupling between the extratropical windfield and tropical cloudiness for oscillation periods between 35 and 80 days.

Aside from detecting 40-50 day oscillations only in the tropics, Madden and Julian (1971, 1972) found them to be nonexistent in the vertical above 80 hPa. Recent studies show that statistically significant 1-2 month oscillations exist above the 80 hPa limit imposed by Madden and Julian. The observations show that above 80 hPa the oscillation is generally weak in the tropics, but strong in the extratropics; this property arises primarily from vertically propagating planetary waves occurring in the extratropical winter hemisphere. Gao and Stanford (1987) found strong statistical significance of signal-to-noise in this frequency band for Southern Hemisphere (SH) extratropical satellite brightness temperatures in the stratosphere, extending upward to 1.5 hPa. Sabutis et al. (1987) found significant 35-50 day oscillations in four years of extratropical stratospheric TOMS (total ozone mapping spectrometer) data.

The connection of 1-2 month oscillations with Asian monsoon convection (May-September) has received much attention in recent years.
Using 30-50 day filtered FGGE data, Krishnamurti and Gadgil (1985) noted storm systems propagating northward from the equator into the summer monsoon region along the Himalayas. Combining 30-60 day filtered data sets of OLR and NMC winds, Knutson et al. (1986) and Knutson and Weickmann (1987) found that the MJO produced a modulation effect on summer monsoon activity. Hartmann and Michelsen (1989) observed from 70-year Indian precipitation records that a strong 40-50 day spectral peak corresponding to the MJO occurs over most of India south of 23°N during northern summer monsoon.

B. Present Study

The present study investigates the causes and characteristics of stratospheric 1-2 month phenomena. In seeking a clue to the tropospheric MJO, virtually all research has focused on the troposphere, with little or no involvement with the stratosphere. To date, the most detailed studies investigating stratospheric 1-2 month oscillations have been Gao and Stanford (1987, 1988) and Graves and Stanford (1989). Gao and Stanford (1987) found highly statistically significant 40-50 day oscillations throughout the stratosphere, while Gao and Stanford (1988) noted a possible SH tropics-extratropics feedback path for 40-50 day oscillations in 90 hPa brightness temperatures. Using five years of globally gridded geopotential heights, Graves and Stanford (1989) found evidence of 1-2 month oscillations upwards to 2 hPa, and also discovered 95% statistically significant correlations at this height in conjunction with a 200 hPa SH
extratropical wavetrain.

Section II of this study uses seven years of stratospheric brightness temperatures to examine signal-to-noise, vertical propagation of planetary waves, and most important, the connection of the tropical Indian Ocean region with the extratropics. Observations will be compared with several models.

Section III is a continuation of Section II, combining eight years of globally gridded geopotential heights from 850 hPa up to 1 hPa. Planetary waves propagating out of the tropical 500 hPa Indonesian heat source region and upwards into the extratropical SH stratosphere will be shown to explain significant 1-2 month brightness temperature signals observed by Gao and Stanford (1987). We also extend the work by Graves and Stanford (1989) using a 3-year concatenation of their 5-year data sets. The 200 hPa SH wavetrain discovered by Graves and Stanford exhibited a statistical connection with the Indonesian tropics, although they stated that the evidence was inconclusive. The present study will show, by combining the statistics of correlation and coherence, that the wavetrain is likely forced at times by a tropospheric heat source lying along the tropical Indian Ocean–western Pacific Ocean path. Finally, Eliassen–Palm flux will be used to show the effect of 1-2 month eddies in changing the mean zonal stratospheric wind.
C. Explanation of Dissertation Format

The alternate dissertation format is followed, in which two papers are included that have been submitted to scholarly journals. The candidate had primary responsibility for both papers. All data analysis and other computer applications were performed by the candidate. Section II has been published in the 1990 July issue of the *Journal of Atmospheric Sciences*. Section III has been submitted to the same journal. The style required by the *Journal of Atmospheric Sciences* has been followed in both sections.
ONE-TO-TWO MONTH OSCILLATIONS
IN THE STRATOSPHERE
DURING SOUTHERN WINTER

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II. ONE-TO-TWO MONTH OSCILLATIONS IN THE
STRATOSPHERE DURING SOUTHERN WINTER

A. Abstract

Stratospheric disturbances on the 35-60 day time scale are
investigated with particular emphasis on the Southern Hemisphere. The
data used are stratospheric brightness temperatures from 90 to 1.5 hPa
covering seven 6-month southern winter periods (from April 1980 to March
1987).

Global time-lag correlation plots are constructed from which
tropical/extratropical connections, three-dimensional wave structure, and
propagation characteristics are studied. Horizontal correlation patterns
at 90 hPa reveal a strong connection between the Indonesian tropics and
the winter extratropics. Vertical correlation patterns in the southern
winter extratropics reveal westward tilt with height and vertical
propagation of 35-60 day zonal wavenumber 1 perturbations, from
tropospheric regions up to great heights, at least as high as the
stratopause region. Disturbances are found to propagate from 90 hPa to
1.5 hPa in generally 6 to 9 days. In contrast, the vertical correlation
plots in the tropics indicate little or no vertical propagation or
westward tilt with height.

Statistical coherence studies provide supporting evidence that the
observed extratropical disturbances may result from tropical forcing, with
the ensuing connection favoring a period close to 50 days.
The observations are in qualitative agreement with model calculations featuring a tropical forcing and suggest, at least for the disturbances captured by the broad vertical weighting functions of the satellite instruments used, that the low frequency disturbances move out of the tropical latitudes before propagating vertically to the stratopause region.

B. Introduction

Intraseasonal oscillations of the atmosphere on 35-60 day time scales have been the focus of many studies since their report in the seminal papers of Madden and Julian (1971, 1972). Using long time series of rawinsonde observations, they found strong 40-50 day signals in temperature, pressure, and zonal wind throughout much of the tropical troposphere. The majority of subsequent investigations of the phenomenon have dealt primarily with the troposphere. The present paper is an investigation of oscillations on the 35-60 day time scale based on satellite observations of the stratosphere, with emphasis on vertical structure and the connection between tropics and extratropics.

Previously, oscillations in the stratosphere at these time scales have been reported by Gao and Stanford (1987, 1988a), Sabutis et al. (1987), and Graves and Stanford (1989). Sabutis et al. used satellite-derived TOMS total column ozone measurements primarily sensitive to the lower stratosphere, while Graves and Stanford studied globally gridded geopotential height fields. The latter found some evidence for
the oscillations up to the 2 hPa level.

Gao and Stanford (1987), while concentrating on the lower
stratosphere, noted a posteriori statistical significance for 35-60 day
periods up to near stratopause heights, using 4 years of the same
microwave and infrared satellite data as used here. They found that the
most statistically significant signal-to-noise levels occurred in the
Southern Hemisphere. The present investigation extends these studies by
utilizing a longer 7-year data set, with particular focus on the upper
stratosphere and its connection with possible forcing from below. As will
be seen, power spectra confirm that statistically significant oscillations
with 35-60 day periods reach at least as high as stratopause levels. Some
of the power spectra shown are decomposed into traveling zonal wavenumbers
1-3 and reveal notable 35-60 day oscillations in both westward and
eastward components.

Coherence and detailed cross-lag-correlation plots for the southern
winter season are used to investigate the connection between tropics and
extratropics for the oscillations, along with vertical and horizontal
propagation and structural characteristics. The results suggest a
connection between the Indonesian tropics and the extratropics of both
hemispheres, as well as upward vertical propagation from the 90 hPa to the
1.5 hPa level in the winter latitudes.

II.C and II.G discuss data and analysis procedures, while II.D
presents results for power spectra, lag-correlation, and coherence. A
short final summary and discussion is given in II.E.

C. Data and Analysis Methods

1. Data

The data used in this study are daily NOAA satellite-derived brightness temperatures, derived from seven years (2556 daily values from 1 April 1980 to 31 March 1987) of MSU4, SSU1, and SSU3 radiative brightness temperature channels. MSU4 (Microwave Sounding Unit, Channel 4), which measures the 5.5mm oxygen band, has a weighting function peak near 90 hPa. SSU1 and SSU3 (Stratospheric Sounding Unit, Channels 1 and 3), which employ a selective absorption technique for carbon dioxide, have maximum weighting functions near 15 hPa and 1.5 hPa, respectively. The 90, 15, and 1.5 hPa pressures correspond to approximate heights of 17, 28, and 44 km. Each of these channels is representative of a rather broad vertical extent of the atmosphere: MSU4 has half-amplitude weighting function near 150 hPa and 50 hPa, SSU1 near 50 hPa and 5 hPa, and SSU3 near 5 hPa and 0.5 hPa. These pressures are only approximate and refer to 35° off nadir. It is important to note that MSU4 and SSU3 are essentially independent data sets since their weighting functions overlap only very slightly and they originate from entirely different satellite instruments. The data sets were produced by the British Meteorological Office in a format of 5° × 5° area-averaged grid locations over the entire globe.

No data sets poleward of 80° latitude were used, due to possible data distortions from wide instrumental scan angles; this resulted in a 72 × 33
grid for each of the three channels. Approximately 12% of MSU4 and 11% of each of the SSU channel temperatures had gaps of either bad or missing data in the time series; the largest gap, 24 days, was in MSU4. These gaps were filled using linear interpolation in time prior to harmonic decomposition at each grid location. Exactly seven years (2556 days) of temperature data were Fast Fourier transformed at each grid location; the integral number of years chosen ensures little if any leakage from the harmonics of the strong annual oscillation (semiannual oscillation inclusive). The harmonic decomposition at each latitude $y$ (33 latitudes, $80^\circ N$ to $80^\circ S$) was done in time $t$ (2556 daily values) and space $x$ (72 values along each latitude) with the following formalism for brightness temperature $T_b(x,y,t)$:

$$T_b(x,y,t) = \sum_{p=0}^{1278} \left[ A(p,x,y)\cos(\omega_p t) + B(p,x,y)\sin(\omega_p t) \right]$$

$$A(p,x,y) = \sum_{k=0}^{36} \left[ A_1(p,k,y)\cos(\Omega_k x) + A_2(p,k,y)\sin(\Omega_k x) \right]$$

$$B(p,x,y) = \sum_{k=0}^{36} \left[ B_1(p,k,y)\cos(\Omega_k x) + B_2(p,k,y)\sin(\Omega_k x) \right]$$

where $\omega_p = 2\pi p/2556$ and $\Omega_k = 2\pi k/72$. 
Only wavenumbers k = 0 to 10 were used in this study, with the exception of the coherence calculations which use nontruncated (all zonal wavenumbers present) time series. The truncation in wavenumber filters out unwanted small-scale disturbances and escapes an instrumental scan angle effect near wavenumber 14 (Yu et al. 1983). As a note, wavenumber k=0 was not used in correlation analysis, since it represents a zonal average at a particular latitude; if included, the global plots would be dominated by wavenumber k=0 contours with much less spatial variation from the other wavenumbers.

Daily 10.7 cm solar flux data were obtained for the above 7-year period from World Data Centre Cl, Solar Terrestrial Physics, Rutherford Appleton Laboratory, U.K.

2. Power spectra

For this study, power spectra (smoothed periodograms) in various forms were computed from the complete 7-year (2556 day) data sets. For all three channels (90 hPa, 15 hPa, and 1.5 hPa), power spectra were computed and tested for signal-to-noise ratio. The statistical method tests the power signal in an approximate 30–60 day band by dividing this power by the estimated red noise background; a spectral peak is statistically significant to a certain level of confidence, depending on the actual magnitude of the ratio. For a further explanation of the methods used for these signal-to-noise significance plots, see II.G.1.

A space-time spectral method developed by Hayashi (1971, 1977) (see
also Speth et al. 1983) was used in decomposing power spectra for each of the wavenumbers 1-3 over the full 7-year data sets. This method is useful in that it decomposes the power into standing, eastward-traveling, and westward-traveling components for the 35-60 day band considered here. Prior to the Hayashi method, the raw power ordinates for the first eight harmonics of the strong annual cycle were replaced by the arithmetic mean of their two nearest neighbors of raw power ordinates. During the Hayashi analysis, all of the power spectra and cross-spectra were smoothed by applying a 13-point running mean.

3. Correlation plots, coherence, and coherence-phase

Spatial and temporal properties were investigated using global cross-lag correlation plots with one reference point. All of the reference points were taken at the 90 hPa level in regions having high statistical significance, with the exception of two equatorial regions associated with eastward-only components for a narrower 40-50 day frequency band. Some of the correlation plots presented are horizontal cross sections of latitude versus longitude, while others are vertical cross sections in a pressure versus latitude, longitude, or time-lag plane. The vertical correlation plots should be interpreted with caution, as they are determined from only three vertical levels.

The correlation statistic in this study was calculated in the frequency domain following filtering of the harmonic Fourier coefficients. Two filters were used in this study and are shown in Fig. 1. The wider
Figure 1. 40-50 day and 35-60 day frequency filters used for the correlation plots in this study. The filters are applied by multiplying the Fourier cosine and sine coefficients at a given frequency by the respective filter value. The narrower 40-50 day filter is used only for the eastward-only plots while the wider 35-60 day filter is used for all other plots in this study. Both filters are equivalent to the frequency response of 231 nonrecursive weights in time.
filter was used for the majority of the correlation plots in this study for 35-60 day signals, while the narrower filter was used to capture specific symmetry properties of the 40-50 day Madden and Julian signal in the eastward components (discussed below). For either filter, each Fourier cosine and sine coefficient in frequency space is multiplied by the filter amplitude. In the correlation statistic, the indicator of frequency bandwidth is given by the square of the filter amplitude. For a general discussion of the correlation statistic used, refer to II.G.2.

The seasonal projection technique of Gao and Stanford (1988b) was used for obtaining 7-year correlation plots for Southern Hemisphere winters (defined as 1 April to 1 October). All lag-correlation plots in this study pertain to such time periods, and will be referred to as seasonal correlation plots.

The time series of brightness temperature for some of the correlation analyses are separated into eastward components by a method employing a simple modification of the harmonic coefficients (see II.C.2). This method is not directly related to the Hayashi method mentioned in II.C.2. Coherence and coherence-phase involving the Hayashi method could have been incorporated in place of this correlation method, but we chose the eastward correlation method for both simplicity and homogeneity with the other correlation statistics in this study. Eastward-only self-correlation plots with equatorial reference points in the Indonesian region at 90 hPa will later be shown to indicate an intriguing symmetry of extratropical correlations about the equator. For these eastward plots,
the narrower 40–50 day filter in Fig. 1 was used; the wider 35–60 day filter did not capture the symmetry and patterns as well.

With all correlation reference points in this study being at the 90 hPa level, large correlation values at the 1.5 hPa level may indicate vertical propagation of phase or wave activity. In the extratropics, vertically propagating waves may be in the form of Rossby waves, where an upward flux of wave activity is associated with a downward phase propagation, and vice versa.

Along with evidence for vertical propagation of phase or wave activity, a westward tilt with height of the correlation patterns is commonly found in the plots; such a tilt may indicate a disturbance which is growing in time. Vertically propagating Rossby waves may also produce such a westward tilt with height. Textbooks (for example, Holton 1975) discuss the topic of vertical propagation of planetary waves along with baroclinic instability in the stratosphere in reference to the Charney-Stern theorem. One result of the theorem is that a strong vertical gradient of vertical shear of the zonal wind may lead to baroclinic instability; such a situation sometimes occurs in the extratropical stratosphere during winter.

For statistical analysis of the correlation plots, local significance is established via a bivariate normal distribution model, and global significance is established using Monte Carlo tests (see II.G.2). For plots involving the wider 35–60 day filter shown in Fig. 1, statistical significance at 95% is achieved in the figures to follow if the absolute
value of correlation exceeds 0.4; for eastward-only plots involving the narrower 40–50 day filter shown in Fig. 1, the absolute value of correlation must exceed 0.6. Due to the approximation of a bivariate normal model and some global variation of the associated degrees of freedom, all critical correlation values in this study should be regarded as approximate.

Coherence and coherence–phase plots are presented to strengthen confidence in the correlation results for tropical/extratropical connections and vertical propagation in the extratropics. Using a simple 21-point running mean (bandwidth=0.0082 day$^{-1}$), the 95% critical coherence level is approximately 0.37; this follows from an F-distribution under an asymptotic multivariate approximation (see, for example, Koopmans 1974).

D. Results

1. Signal-to-noise estimation

Figure 2 indicates statistical significance for the three levels 90 hPa, 15 hPa, and 1.5 hPa. For comparison with a 40–50 day band of oscillations described in earlier studies, a test involving a narrower 37–52 day band was included. One of the most obvious features in both sets of plots is that the higher altitude SSU levels have little statistical significance in the tropics; this implies that vertical propagation of 35–60 day time-scale planetary waves into the upper stratosphere occurs primarily in regions outside of the tropics. Another feature of the plots in Fig. 2 is that both 1.5 hPa and 90 hPa levels in
Figure 2. Approximate statistical significance contours for the complete 7-year data sets (April 1980 to April 1987) of power spectra signal-to-noise ratio, with the noise background approximated by a first-order autoregressive model. The testing bands pertain to time periods from 32 to 56 days and from 37 to 52 days, respectively. For the wider 32-56 day band tested, the contour values are 95%, 98%, 99.5%, and 99.9%, corresponding to signal-to-noise ratios of 1.69, 1.92, 2.24, and 2.58, respectively. For the 37-52 day band tested, contours for the same significance levels correspond to signal-to-noise ratios of 1.83, 2.12, 2.52, and 2.96, respectively. In all plots in the figure, 95% corresponds to the outer-most contour.
37-52 DAY PERIODS

32-56 DAY PERIODS

SSU3 (1.5 hPa)

SSU1 (15 hPa)

MSU4 (90 hPa)
the Southern Hemisphere contain large areas of statistical significance, whereas the middle 15 hPa level generally does not. One possible explanation is that 15 hPa lies more closely, overall, to a quasi-stationary node in vertical structure, compared with either 90 hPa or 1.5 hPa levels. Another explanation is that it may be possible for a large vertical phase variation to occur near 15 hPa, resulting in a smaller detected signal-to-noise due to the broad instrumental weighting function.

At 90 hPa, localized regions of statistical significance appear along the equator near longitudes 90°E and 130°E. This is above a general region in the troposphere involving deep convection cells related to a 40–50 day oscillation of temperature, pressure, and zonal wind (Madden and Julian 1972). Lau and Chan (1985) also found strong 20–60 day activity in this general region from OLR (outgoing longwave radiation) data; in fact, they found that this time scale dominated the intraseasonal variability in tropical convection. In comparing the global OLR data with the radiance data used in this study, the latter data sets are not as locally biased since they do not require high cloud cover.

Power spectra indicating spatial variation for 90 hPa and 1.5 hPa are shown in Fig. 3. These plots correspond to the 32–56 day statistical testing results indicated in Fig. 2. Figure 3 indicates that 35–60 day amplitudes at 1.5 hPa are as large as those at the lower 90 hPa level. It is also evident in Fig. 3 that the 90 hPa equatorial point has much smaller power than the other 90 hPa extratropical points. For all three
Figure 3. Selected power spectra (smoothed periodograms) for the full 7-year data sets for MSU4 (90 hPa) and SSU3 (1.5 hPa). These plots correspond to the testing in Figure 2 involving 7-point non-overlapping means. The vertical axis is the power spectral density, \((C^2+S^2)/2\Delta f\), with \(C\) and \(S\) the Fourier cosine and sine coefficients and \(\Delta f = \text{unit frequency interval} = 1 \text{ day}^{-1}\); vertical axis units are \(K^2\text{ day}^{-1}\). Note scale changes. The horizontal axis denotes frequency and spans frequency indices 1 to 200, corresponding to periods from 7 years to 12.8 days. The long curved line in the figures is the first-order autoregressive noise background fit. Shorter curved lines indicate confidence levels of 95\%, 98\%, and 99.5\% (95\% is the bottom short curve). Plots marked with a large letter "R" denote a reference point used for the lag-correlation method.
levels in this study, 90 hPa, 15 hPa, and 1.5 hPa, it is a general result that much smaller power is found in the tropical latitudes. The smaller tropical power may partly be caused by our wide satellite weighting functions failing to detect relatively shorter vertical wavelengths in the tropics than in the extratropics. It may also be that the extratropical stratosphere, as opposed to the tropics, simply has planetary-wave disturbances with larger amplitudes propagating upward from below, especially during winter, resulting in larger power.

2. Eastward and westward power spectra

In Fig. 4 we present both westward and eastward decomposed power plots for the complete 7-year data sets, derived from the Hayashi method mentioned in II.C.2. These plots are essentially the decomposition of traveling power into eastward and westward components, after standing-wave power has been removed from the total power. We note that the eastward and westward power amplitudes at many frequencies appear to be nearly equal. This gives the impression that there still remains a significant amount of standing-wave power, but this is misleading since the spectra are computed from seven years of data, where for example, eastward traveling waves may dominate one season with westward traveling waves dominating another season.

As in Fig. 3, Fig. 4 also indicates that the largest power amplitudes occur in the extratropics, especially for 90 hPa. For the 20°N to 20°S plots, an interesting feature at 90 hPa is eastward power along the
Figure 4. Eastward and westward traveling power spectral densities at 
MSU4 (90 hPa) and SSU3 (1.5 hPa), from the tropics to 70°S for 
the complete 7 years (2556 daily temperatures). Note that 
standing-wave power has effectively been subtracted out of the 
total power to obtain these traveling spectra. The periods 
from 20 to 80 days correspond to 97 spectral indices. The 
contours, indicated to the far right, represent both the 
beginning value and the increment. The units are $K^2/\Delta F$, with 
K=Kelvin degrees and $\Delta F$=unit frequency interval (day$^{-1}$)
equator and westward power at 10° north and south. The 1.5 hPa level for these same latitudes indicates a notable 40-50 day signal, and is dominantly westward. At 40°S and 50°S, both 90 and 1.5 hPa indicate a relatively significant 40-50 day signal in the westward components. Although westward power appears for 60°S and 70°S at both 90 and 1.5 hPa, the eastward power dominates, especially at 90 hPa; the reason must involve strong westerly winds at these latitudes during the southern winter, which is when vertical propagation of planetary waves from below is most likely to occur.

3. Indonesian tropics

The equatorial Indian Ocean-Western Pacific region of the troposphere is well known for eastward-moving deep convection cells involving 1-2 month oscillations. Using rawinsonde data, Madden and Julian (1971, 1972) detected this oscillation up to the 100 hPa level in some cases. Using coherence and lag-correlation plots with reference points at level 90 hPa, we investigate this general region for connections with the extratropics, as well as for occurrence of vertical propagation.

Several seasonal (6-month, Southern Hemisphere winters only) correlation plots were constructed with equatorial 90 hPa reference points in the tropical Indian Ocean-Western Pacific region at longitudes 90°E, 130°E, 145°E, and 160°E, the first two coinciding with regions of signal-to-noise significance as seen in Fig. 2. Of these four reference points, only 90°E will be discussed in detail. The other reference points
exhibited less significant correlations at the 1.5 hPa level, especially in the extratropics. This indicates that the 90°E reference point may be more suited for investigating a possible forced global stratospheric response from a source lying in the Indonesian tropics.

a. Correlation patterns for 90 hPa reference point at equator.

90°E Figure 5 shows global correlation plots for this reference point (indicated at lag=0 by the intersection of line segments AA' and BB'). It should be emphasized that the correlation contours involve statistical estimates of confidence in measured signals, with each succeeding contour having a higher level of confidence. In these plots we accept a correlation of 0.4 (calculated in II.G.2) or above as statistically significant at the 95% level. This 95% contour is shown in the plots as the fourth solid (dashed) line for positive (negative) 0.4. A correlation absolute value greater than 0.67 is accepted as a posteriori significant at the 95% level (see II.G.2).

One obvious feature of the plots in Fig. 5 is the appearance of extratropical patterns which suggest some degree of symmetry about the equator, especially at lags 0 and 6 days. The high-latitude patterns in either hemisphere have a wavenumber 1 zonal structure which approximately coincides with a zonal wavenumber 1 structure along the equator. In between, at middle latitudes, there are correlations of opposite phase. We may summarize by saying that at 90 hPa, significant zonally asymmetric (predominantly wavenumber 1) 35–60 day oscillations occur in phase in equatorial and high-latitude regions, with out-of-phase oscillations in
Figure 5. Self-correlation time-lag plots for 7 years of Southern Hemisphere winters at level 90 hPa and reference point 90°E, Equator (at intersection of AA' and BB' line segments). Positive (negative) correlations, indicated by the solid (dashed) contours, begin at 0.1 (-0.1) and increment by 0.1. Local significance at the 95% level is given by absolute correlations of 0.4. All plots shown passed a 95% global Monte Carlo test.
between. The latter occur slightly closer to the equator (15°-30°
latitudes) in the Southern (winter) Hemisphere, compared with 20°-40°
latitudes in the Northern (summer) Hemisphere.

The largest extratropical correlations are, for the most part,
located in the Southern Hemisphere. This property may be a result of the
subtropical jet in the Southern Hemisphere lying closer to the tropics
than that in the Northern Hemisphere during these southern winters.
Largely because of such a subtropical jet, the model by Garcia and Salby
(1987) indicated that the response from a slowly-evolving red-spectrum
tropical heating source dominated the extratropics of the winter
hemisphere, rather than the summer hemisphere. Notice also that the
correlation values are very strong, exceeding 0.6 for the large wavenumber
1 extratropical pattern in the Southern Hemisphere. This implies a strong
connection between this region and the tropical reference point. Such a
connection may be the forced response in the extratropics by a source in
the tropics, namely the convective heating and associated dynamics of the
Madden and Julian (1971, 1972) oscillation.

Also evident in the plots is an initially slow eastward propagation
of the wavenumber 1 equatorial patterns; this is a recognized
characteristic of such low-frequency oscillations in the tropospheric
Indian Ocean-Western Pacific. In fact, the lag=0 and lag=12 plots imply
an approximate 4 to 5 degrees longitude per day initial eastward
propagation (Gao and Stanford 1988a). Figure 5 also indicates little
meridional propagation of the tropical correlation patterns in subsequent
lags. There is a striking change in the tropical reference point
correlation patterns between days 12 and 18; in only six days, the
positive correlation patterns have extended from approximately 140°E, to
the east coast of South America near 45°W.

One unfortunate property of the correlation statistic is that it is a
normalized quantity and cannot indicate either actual amplitudes or
amplitude growth of our stratospheric temperatures. The result of this is
that much of the true dynamics is not exhibited in the statistics. A
study by Lau and Chan (1985), for example, indicated that 20–60 day scale
disturbances in OLR (outgoing longwave radiation) stall and intensify as
they propagate eastward toward the equatorial central Pacific, but
diminish substantially as they propagate further toward the eastern
Pacific. As discussed above, the correlations in Fig. 5 indicate such a
stall in the patterns at small time lags, but they are incapable of
showing intensification.

The lag=0 plot in Fig. 5 also indicates a characteristic equatorial
"dipole" structure for tropical 35–60 day oscillations, seen here with
positive correlation around the reference point at 90°E and negative
correlation (exceeding -0.4) in the western Pacific Ocean region near
180°W. This 90 hPa equatorial dipole pattern was also observed by Gao and
Stanford (1988a) using the first four years of our 7-year data sets.

The Southern Hemisphere high-latitude patterns in Fig. 5 appear to
propagate eastward faster than the equatorial patterns; this is most
likely due to strong westerlies during the southern winters. The behavior
in the Northern Hemisphere is that of complex quasi-standing patterns. At initial glance, these Northern Hemisphere patterns almost take on a wavetrain appearance into and out of the tropics at different time lags. According to several models, including Garcia and Salby (1987), the structure of the zonal wind is a key ingredient for tropics-to-extratropics radiation. As noted earlier, the Garcia and Salby model showed that the extratropical response to a slowly-evolving red-spectrum heating source in the tropics dominated the winter hemisphere, where the subtropical jet lies closest to the equator. However, there may also be wavetrain activity in the northern (summer) latitudes of Fig. 5, as a westerly jet, although further from the equator, still exists near 90 hPa in the Northern Hemisphere for these 6-month southern winters (Randel 1987b). It is possible that the Southern Hemisphere winds at 90 hPa are strong enough to filter-out most planetary waves with wavenumber greater than one; the wavenumber 1 Southern Hemisphere patterns in Fig. 5 may resemble the stratospheric behavior of in the Garcia and Salby model. In the Northern Hemisphere, the 90 hPa westerlies are presumably weaker, allowing vertical propagation of wavenumbers greater than one, which may then superimpose to form the observed wavetrain. Nevertheless, actual temperature amplitudes and any associated wavetrain activity in the Northern Hemisphere may be small compared with that in the Southern Hemisphere. [Global maps (not shown) of 35-60 day 90 hPa reconstructed brightness temperatures indicate that Northern Hemisphere temperatures are typically much smaller than those in
the Southern Hemisphere during the southern winter months.] The large correlations in the Northern Hemisphere may mislead one to interpret large amplitudes, when in fact, the amplitudes involved are relatively small. More will be said later on the topic of tropical/extratropical radiation.

We also mention that the lag=0 plot indicates a strong negative correlation at 90 hPa, just 15° north and south of the reference point. This correlation pattern is like the signature of a Hadley cell. However, since our correlation statistic does not show vertical motion in these subtropical regions, it may not be proper to draw such a conclusion.

Correlations between our 90 hPa equatorial reference point and the higher equatorial stratosphere are shown in Fig. 6. These plots refer to vertical cross-sections along AA' shown in Fig. 5. Some of the observations previously noted for Fig. 5 can also be found in Fig. 6, including the initially slow eastward motion of wavenumber 1 equatorial structure at the lowest level 90 hPa. As with Fig. 5, there is a dramatic change in the correlation patterns from lag=12 to lag=18 days. The zonal wavenumber 1 structure appears dominant throughout the vertical, but appears statistically significant only for 90 hPa. A related result appears in the model results of Garcia and Salby (1987) for the case involving slow-heating. We compare our Fig. 6 with their Fig. 25 for the slow-heating case II.1 between two and six scale heights; they denote one scale height as 7300 meters. Their model indicates a wavenumber 1 response which is limited mostly to the levels of the forcing, extending upward to approximately 2 scale heights. Above this height, up to
Figure 6. Lag-correlation plots in a longitudinal vertical section (along AA' of Figure 5). Reference point: 90 hPa at 90°E, Equator. The correlation contour plotting and local statistical significance is the same as for Figure 5. Some care should be exercised in the interpretation of these and similar vertical section correlation plots since they are determined from only three levels.
approximately six scale heights, the response in their Fig. 25 appears severely damped. They attribute the damping to dissipation, and in the limit of small frequency the response collapses to levels of the heating where it is dominated by the particular solution of the model. With this in mind, the small correlations at 15 hPa and 1.5 hPa would be understandable in terms of such a tropical heating source response.

Meridional structure in the vertical above the reference point is shown in Fig. 7 and corresponds to the path BB' in Fig. 5. The lag=0 plot indicates the strong negative correlation at 90 hPa north and south of the reference point as previously noted for Fig. 5. Throughout the vertical, the plots indicate statistically significant correlations with the high latitudes of the Southern Hemisphere, but not with those of the Northern Hemisphere; the lower correlations in the Northern Hemisphere, particularly at 15 and 1.5 hPa, most likely result from strong easterly winds which prevent vertical propagation of planetary waves from below. The high correlations in the Southern Hemisphere also indicate some evidence for vertical propagation from 90 to 1.5 hPa in subsequent lags, although it must be noted that the reference point is still in the tropics; later, an extratropical reference point at 90 hPa for correlation will be used in these high latitudes and will show evidence for such vertical propagation.

b. Extratropical connections. One important purpose of this study is to verify the existence of, and characterize, low-frequency connections between the tropics and extratropics, under the hypothesis
Figure 7. Same as Figure 6, but for a latitudinal vertical section along BB' in Figure 5
that an Indonesian tropical source may be forcing a response in the winter extratropics. We refer back to Fig. 5 which indicates strong correlations between the tropics and extratropics. As mentioned the previously, the extratropical patterns take on the appearance of rather complex structures, which at certain times appear as wavetrains propagating into and out of the tropics. Gao and Stanford (1988a) also noted wavetrain signatures in both hemispheres that indicated a positive-feedback mechanism for 40-50 day disturbances having a tropical forcing in the Indonesian sector. The patterns in Gao and Stanford (1988a) are consistent with our Fig. 5, given the wider filter used here and, especially, the different reference point used.

We now compare our results with the model by Garcia and Salby (1987) for their special slow-heating case. Their model involved the northern winter during the easterly phase of the quasi-biennial oscillation, while our analysis is for seven consecutive years of 6-month southern winters. It must also be noted that Garcia and Salby (1987) plotted contours of normalized response amplitude, while our Fig. 5 plots correlation; a potential weakness of correlation patterns is that they are relative to the ever-changing reference point temperature. Even with these differences, a comparison between their model and our results yield several notable similarities. The Garcia-Salby model indicated that radiation from a slowly-evolving red-spectrum tropical heating source takes place in the Northern Hemisphere winter where the subtropical jet lies closer to the source and depends strongly on the westerly shear
involved. The response to this heating source in their model indicated spectral variance which was confined to frequencies in the vicinity of a 50-day period. This slowly-evolving model indicated a Rossby wavetrain in the form of a barotropic wavepacket which propagated poleward into the winter hemisphere with a slight westward drift. In comparison, our Fig. 5 indicates an eastward rather than a westward drift in the winter high-latitude patterns; the difference may be due to the fact that the model calculations used winds typical of the northern winters, rather than our southern winters where westerly winds are stronger (Randel 1987b).

Of more importance than the zonal extratropical motion is that of identifying propagation out of the tropics. We first note that the lag=0 plot in Fig. 5 indicates a negatively correlated lobe centered near 20°S, 110°E immediately southeast of the reference point. At lag=6 days this feature is seen to have extended eastward, and by lag=12 days it has intensified to very strong correlations exceeding -0.7 (passing a posteriori statistical assessment) near 20°S, 180°W. By lag=18 days, the wavenumber 1 negatively-correlated region in the high southern latitudes (70-80°S) has grown to correlations exceeding -0.6.

Besides the possibility of 35-60 day wavetrains, another related question of importance arises about the relative significance of this low-frequency oscillation connection compared to other frequencies of the spectrum. The statistics of coherence and coherence-phase have been employed to investigate this. (Some authors refer to coherency rather than coherence.) Coherence testing can also strengthen confidence in the
correlation results, in that our correlations are calculated over a fixed frequency bandwidth (35–60 days here), whereas, coherence can indicate statistical significance over the full spectrum of frequencies. Some chosen plots for the lower frequencies are shown in Fig. 8. This figure relates the previous Indonesian correlation reference point with one of the highly correlated points at the same 90 hPa level in the high southern latitudes. We note that other such high-latitude reference points could have been presented here – this one was used since it indicates typical results. [A similar study (not shown) using time series at 90 hPa (Equator, 90°E) and 1.5 hPa (70°S, 120°E) yields similar behavior, except that at periods of 16–19 days the coherence is much weaker.] The plotted low frequencies in Fig. 8 were chosen to span periods between 95 and 12.8 days. Lower frequencies are not plotted since original time series, not filtered in either space or time were used; the presence of naturally coherent oscillations such as the annual oscillation and its lower harmonics, together with the smoothing procedure, yields high biased coherence estimates for those lower frequencies. The most important result in Fig. 8 is that the most coherent signal observed between the tropical and extratropical points is a low-frequency signal centered near a period of 50 days. The phase plot, which shows a nearly constant phase near zero radians over the general width of this coherence peak, strengthens our confidence that it is indeed a true signal. (Rapidly varying phase would suggest noise.) Because of coherence, the 35–60 day wavetrain previously discussed now appears more plausible, and perhaps
Figure 8. Coherence and phase between the Figure 5 correlation reference point and a high-latitude winter extratropical point at the same 90 hPa level. A running mean of 21 points was applied for smoothing, yielding a bandwidth of 0.0082 day$^{-1}$. The approximate 95% confidence level in the coherence plot is equal to 0.37 and is indicated by a long horizontal line segment in the top plot.
even robust, for this low-frequency band.

We now investigate the 90 hPa horizontal structure in a slightly different manner using eastward-only component correlation plots (see II.G.2). The primary motivating factor for trying eastward-only plots stems from the eastward propagation features observed in the equatorial reference-point correlation maps of Fig. 5. Figure 9 shows correlation plots at lag=0 days for equatorial reference points in the Indonesian region at several different longitudes. The frequency filter used in these plots is the narrower 40-50 day filter (Fig. 1) which captures the symmetry patterns better than the wider filter. Plots similar to Fig. 9 were constructed for westward-only components, but they did not reveal either the high degree of symmetry or the large correlation amplitudes. Eastward propagation of the equatorial Indonesian correlation patterns partly explains why these eastward plots have large correlation values, at least in the vicinity of the reference point. The extratropical patterns in both hemispheres require further explanation, to which we now turn our attention.

A three-dimensional model by Kasahara and Silva Dias (1986) will be used to compare with Fig. 9. Their results showed the response of planetary waves to a stationary tropical forcing, all within a global stratified atmosphere linearized with respect to a basic zonal flow. The forcing was distributed in space as a wavenumber 2 in longitude, a symmetric-bell shape in latitude (maximum at the Equator), and parabolic in pressure (zero heating at 200 and 1000 hPa). The basic zonal wind flow
Figure 9. Self-lag-correlation plots at lag=0 days for the eastward 90 hPa temperature components only, with equatorial MSU4 (90 hPa) reference points at 90°, 130°, 145°, and 160°E longitudes. All plots use the narrower 40-50 day filter shown in Figure 1. Local significance at the 95% level is 0.60. Positive (negative) correlation, indicated by the solid (dashed) contours, begins at 0.1 (-0.1) and increments by 0.1 between successive contours. All plots shown passed a 95% global Monte Carlo test.
had both meridional and vertical shear; for this structure, they chose a simple shear to be linear in pressure, and a climatological westerly (nearly equatorially symmetric) zonal wind distribution at 500 hPa as the meridional profile. The equatorial reference-point correlation regions in Fig. 9 do not exhibit the stationarity of the Kasahara-Silva Dias tropical heating source, but they do exhibit a very slow eastward propagation at small time lags along the Indian Ocean-Western Pacific path, as was shown earlier in Fig. 5. The result is that Fig. 9 very likely reflects much of the stationarity of the source region relative to a westerly and nearly symmetric basic zonal flow. One important result of their model (as vividly seen in comparing Kasahara and Silva Dias Figs. 4 and 5 at level 227 hPa) was that the vertical shear of the zonal wind permitted the coupling of the external mode ("barotropic mode") with the internal mode ("baroclinic mode"), resulting in a larger external mode response and significantly increased planetary-wave intensity in the middle-to-higher latitudes in both hemispheres. Without a vertically-sheared westerly wind, their Fig. 5 indicated a very small response at 227 hPa in the high extratropics.

In comparison with their model, one signature apparent in Fig. 9 is the global effect caused by the vertical shear of a westerly (and perhaps nearly equatorially-symmetric) tropospheric wind on the observed connection between tropics and extratropics. A second result from Fig. 9 is that a slow eastward-moving tropical Indonesian heating source with a high degree of symmetry about the equator would be a reasonable
explanation for such global symmetry patterns, in view of the symmetry in the Kasahara and Silva Dias model results. What we see in Fig. 9 appears to result from an equatorially-symmetric tropical forcing, which excites equatorially-symmetric modes extending well into the extratropics, where the higher-latitude response depends strongly on the wind shear and general westerly wind structure in the troposphere.

4. Winter extratropics

The extratropics, in reference to the simplest models, provide a suitable environment for vertical propagation of planetary waves for lowest wavenumbers during winter when winds are westerly (e.g., Holton, 1975). Since such propagation is observed, it should not be surprising that such behavior is found in our study. Regions of statistically significant 35-60 day signals have been noted in the signal-to-noise estimation plots of Fig. 2; we now show that vertical propagation of 35-60 day signals from below represents one explanation for the occurrence of such significant signals at the highest level, 1.5 hPa. Another result from this will be that of establishing an "out-then-up" conceptual model of 35-60 day wave activity in the stratosphere - that is, these signals generally propagate out of the tropics in the lower levels to the extratropics before propagating vertically upward to the high levels.

A model by Simmons et al. (1983) suggested a second possible source for these low-frequency signals: it is possible that barotropic instability in the extratropics may be responsible for such low-frequency
signals. Their model involved a global barotropic set of equations linearized about a climatological 300 mb January basic state which was not a zonal-mean basic state. It is interesting to note that their model indicated, in the absence of damping, a mode with an e-folding time approximately equal to a week and an oscillation period close to 50 days. Related to their model results, Graves and Stanford (1989) found a significant 35–60 day wavetrain extending throughout the winter extratropical troposphere, in the form of a large standing wave pattern having little apparent connection to the tropics.

a. Coherence between 1.5 hPa temperatures and 10.7 cm solar flux Another possible forcing mechanism for low-frequency signals at 1.5 hPa is that of incoming solar radiation. To test for this possibility, coherence and coherence-phase plots between 10.7 cm solar flux and zonal-mean 1.5 hPa time series were constructed. No significant coherence was found in any of the time series near the 35–60 day band, or any other frequency band down to periods as short as 13 days. One exception, found at high southern latitudes, was a weak coherence at 95% confidence near the rotation period of the sun — approximately 27 days.

b. Vertical propagation/response in the high stratosphere Figure 10 reveals evidence for upward vertical propagation of signals. The reference point was chosen to be in a region of significant signal-to-noise as seen in Fig. 2. The 90 hPa reference point at 65°S, 60°E also corresponds to a general region which is highly correlated with the tropics, as can be seen by referring back to Figs. 5 and 7. We see in
Figure 10. Time-lag horizontal correlation plots between levels 90 hPa and 1.5 hPa for 7 years of Southern Hemisphere winters. The reference point is at 90 hPa 65°S, 60°E (indicated by the large letter "X" in the 90 hPa plot). The local statistical significance and contour plotting indicated in Figure 5 also applies here. All plots shown passed a 95% global Monte Carlo test.
Fig. 10 that the onset of the disturbance occurs at 1.5 hPa near lag=9 days (see arrow), suggesting a time of at least 9 days for vertical propagation from 90 hPa to 1.5 hPa.

Figure 11 shows coherence and coherence-phase plots for time series coinciding with vertical propagation regions of Fig. 10. As noted earlier, the 90 and 1.5 hPa data are essentially independent, so that the results of Fig. 11 are not caused by spatial overlap. A statistically significant broad-band peak and nearly constant associated phase indicate that the 90 and 1.5 hPa temperature time series contain coherent fluctuations over the 40-60 day range of periods. Note also in comparison with the previous coherence plot (Fig. 8) that there is significant coherence in Fig. 11 in the two-to-three week period band. We interpret this coherence as being due to well-known long waves of this range of periods which propagate vertically in the southern winter stratosphere jet region (Randel 1987a).

It appears evident from Figs. 10 and 11 that upward vertical propagation occurs in the high Southern Hemisphere latitudes during winter months and this partially explains how 35-60 day oscillations come to exist at the 1.5 hPa level.

The lower latitudes also indicate such vertical propagation. For conciseness we show (Fig. 12) only one plot of correlation contours with pressure versus time lag. The 90 hPa reference point is taken at 25°S, 110°W, which can be seen from Fig. 2 to be located inside a region of statistically significant 32-56 day period oscillations. Figure 12
VERTICAL COHERENCE IN HIGH LATITUDES

90 hPa 60E 65S (REFERENCE)
WITH 1.5 hPa 120E 70S

Figure 11. Same as Figure 8, except for two high-latitude Southern Hemisphere points, one at level 90 hPa, the other at 1.5 hPa
Figure 12. Time-lag vertical correlations for a low-latitude Southern Hemisphere reference point, plotted with pressure levels against time-lag. Positive (negative) correlation, indicated by the solid (dashed) contours, begins at 0.1 (-0.1) and increments by 0.1 between successive contours. The arrow indicates approximate propagation time upward through the levels.
implies a vertical propagation time of approximately 3 to 6 days from 90 hPa to 1.5 hPa. This time is comparable to results from a study by Randel (1987a) for vertically propagating planetary waves during Southern Hemisphere winter. For example, he found that zonal wavenumber 1 disturbances in the extratropics propagated upward from roughly 300 hPa to 10 hPa in approximately 4 days.

c. Vertical structure in the extratropics

An interesting comparison of the vertical structures at different latitudes is given in the lag=0 day pressure versus longitude correlations shown in Fig. 13. Two previous extratropical correlation reference points (25°S and 65°S) are used, along with another 90 hPa point in the middle latitudes (45°S). All three reference points are located in regions deemed statistically significant for 32-56 day periods from Fig. 2. All three reference points reveal dominant zonal wavenumber 1 structure throughout the vertical. Also evident is a strong westward tilt with height in the 45°S and 65°S vertical sections, but not at 25°S. The model by Garcia and Salby (1987) indicated a similar dominant zonal wavenumber 1 structure and westward tilt, at latitude 45°N in their Fig. 26 for northern winter between 2 and 6 scale heights. Garcia and Salby state that the westward tilt with height in their model is due to absorption of the waves in tropical easterlies and the effects of damping. It should be noted that westward tilt with height is consistent with both simple models of vertically propagating forced Rossby waves and baroclinically unstable waves.
Figure 13. Correlation plots (at lag=0 days) in vertical zonal planes at 25, 45, and 65°S 90 hPa reference points (reference points are indicated above each individual plot). Local statistical significance and contour plotting are the same as in Figs. 6 and 7. Note that some of the abrupt bends in contours are due to the limited number (three) of pressure levels.
EXTRATROPICAL VERTICAL CORRELATIONS (LAG=0 DAYS)

- 25S 110W 90 hPa
- 45S 60W 90 hPa
- 65S 60E 90 hPa
E. Summary and Discussion

Our observations corroborate previous observational results which show that statistically significant low-frequency oscillations in the 35-60 day band occur throughout much of the stratosphere, extending from 90 hPa, upward to the highest level (1.5 hPa) used here. Our overall findings, in agreement with model results, provide evidence that some low stratospheric 35-60 day signals, perhaps forced from below by a tropical heating source in the Indonesian sector, propagate out of the tropics and into the winter extratropics, from where they propagate vertically to at least the stratopause region.

During the southern winter, 35-60 day stratospheric oscillations at 90 hPa appear to have a dynamic relationship with the tropical Indonesian region: time-lag correlation plots at 90 hPa with a reference point in the Indonesian tropics indicate wavetrain signatures in the Northern (summer) Hemisphere and highly correlated wavenumber 1 anomaly structure in the southern (winter) Hemisphere. Coherence and coherence-phase statistics support the connection between tropics and winter extratropics for the 35-60 day frequency band, and also indicate that an oscillation near a period of 50 days may be the most coherent over the lower frequencies of the spectrum. The proximity of the tropospheric zonal wind jets, along with their vertical and meridional shear, can strengthen the response in the extratropics from a hypothetical heating source in the tropics; this is, according to the model by Kasahara and Silva Dias (1986), true for a stationary forcing in the tropics. In relation to this
model, our eastward-only correlation plots for 90 hPa show that eastward components of the Indonesian reference points maintain sizable correlation patterns with symmetry north and south of the equator.

On the basis of our study of vertical propagation, it may be stated that, overall, during the southern winters investigated here, vertical propagation of 35-60 day signals occurs in the winter extratropics, but not in the tropics. The 35-60 day connection in the vertical for the extratropics appears very strong in both correlation plots and coherence results, and is consistent with the general concept of vertical propagation of planetary waves during the winter months. Typical vertical propagation times in the extratropics were found to be approximately 6 to 9 days from 90 to 1.5 hPa, agreeing reasonably well with other studies related to the specific topic of vertical propagation. Extratropical vertical propagation (at least partially) explains the existence of statistically significant 35-60 day signals at levels as high as 1.5 hPa. There was also an observed westward tilt with height in the vertical correlation patterns in the middle-to-higher southern latitudes, and is consistent with baroclinic processes or vertically propagating Rossby waves.

The source of the 1-2 month oscillations could be forcing from tropical heating sources, or barotropic instability in the extratropical troposphere. (As an added note, we also found insignificant coherence in the 35-60 day band between 1.5 hPa temperatures and 10.7 cm solar flux.) Barotropic instability has been suggested as a source for the
oscillations, particularly in the troposphere (Simmons et al. 1983). The other hypothesis, that of tropical forcing, appears plausible in light of our correlation and coherence results, and in comparison with the detailed model results of Garcia and Salby (1987). The comparison is for opposite winter hemispheres, and their model only indicated results for the easterly phase of the quasi-biennial oscillation. Nevertheless, their slow-heating case II.1 model predictions have several notable similarities with our observational analyses:

1) Our tropics/extratropics low-frequency coherence maximum near a period of 50 days (Fig. 8) closely reflects their maximum frequency response, also near the same period.

2) Weak equatorial 35-60 day oscillations in the upper stratosphere is one characteristic of both their model and our results. (There may also be some intrinsic weakness in our data for tropical latitudes, due to the inability of the broad satellite weighting functions to detect short vertical wavelengths.)

3) Similar to the stratospheric model predictions, we also found strong, wavenumber 1 35-60 day oscillations throughout the stratosphere. However, there is disagreement in the horizontal propagation of these patterns in the winter extratropics: the model results predict a slow westward propagation of patterns, while our correlation patterns propagate eastward. This is likely caused by strong westerlies during our Southern Hemisphere winters, while their model used northern winter wind fields.

4) The maximum stratospheric model response to heating was in the
winter hemisphere; our seasonal correlation plots reveal largest correlation and largest correlation regions in the winter hemisphere.

5) Their model indicated a westward tilt with height of wavenumber 1 perturbation patterns in the winter stratosphere extratropics; we find similar westward tilt in the vertical correlation plots in the middle-to-higher winter latitudes (Fig. 13).

6) Apparent in Figs. 5 and 9 for 90 hPa are gyre-like features north and south of the Indonesian reference points; their model indicated, at one scale height (7.3 km), such features north and south (and west) of the heating.

7) They described a barotropic wavepacket-wavetrain radiating from the tropics into the winter extratropics; however, our Fig. 5 does not indicate propagation in the clear form of a wavepacket-wavetrain, and may be due to the fact that Fig. 5 plots correlations rather than anomaly amplitudes. Nevertheless, correlation may support such a connection: the strong correlation patterns in Fig. 5 do provide some evidence of propagation from the tropics into the high winter (southern) extratropics.

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G. Appendix

1. Statistical significance

The background noise estimates in all plots of Fig. 2 entailed a least-square fit over frequency indices \( p = 30, 31, \ldots, 250 \) (corresponding to periods of 85 to 10 days) for a first-order AR (Autoregressive) time series model. Statistical testing was done by first partitioning the frequency indices \( (p=1, 2, \ldots, 1278) \) into nonoverlapping groups of size \( M \), along with \( M \)-point averaging in each partition. This yielded signal-to-background power ratio proportionately distributed as chi-square with approximately \( 2M \) degrees of freedom, where the frequencies were then taken at the midpoints of each \( M \)-point interval.

Most statistical testing done in this study refers to a priori testing, meaning that a lower-level test can be used for establishing statistical significance in the case that statistical significance at the location has been previously established. Gao and Stanford (1987), using the first four years of the 7-year data set used here, previously established statistical significance up through the 1.5 hPa level at many locations by using a much more stringent test (an a posteriori test, described in Madden and Julian 1971). In this study, we accept a priori
testing as sufficient at all three levels 90 hPa, 15 hPa, and 1.5 hPa, but only if the signal was previously established as being statistically significant (compare Fig. 2 with similar plots by Gao and Stanford 1987).

If any region has never been previously reported as statistically significant, then we use a posteriori statistics. This means in general that we raise the local testing level high enough that there appears little chance of random noise resulting in a region being assessed statistically significant. For such a posteriori statistics applied only to the test band indices in Fig. 2, 95% a posteriori statistical significance is achieved for local test levels of 99% and 99.5%, corresponding to the plots involving 5-point and 7-point means, respectively. We therefore may regard 99.5% contours as sufficient to establish at least 95% a posteriori statistical significance applied to either of the respective frequency test bands in Fig. 2.

2. Correlation statistic

The correlation statistic in this study is the common one-point lagged correlation statistic, but computed in frequency space following filtering (see filters, Fig. 1). In frequency space with a time lag $\tau$ given to series 1, the correlation statistic $R$ is

$$R = \left[ \sum_{\omega} \left[ C1(\omega)C2(\omega)+S1(\omega)S2(\omega)\right] \cos(\omega \tau) \right] + \left[ \sum_{\omega} \left[ C2(\omega)S1(\omega)-C1(\omega)S2(\omega)\right] \sin(\omega \tau) \right] / (\sigma_1 \sigma_2)$$
where \( C_1 \) and \( C_2 \) are, respectively, the filtered Fourier cosine coefficients for time series 1 and 2 at angular frequency \( \omega \), \( S_1 \) and \( S_2 \) are the filtered Fourier sine coefficients, and \( \sigma_1 \) (similar definition for \( \sigma_2 \)) is defined as

\[
\sigma_1 = \left[ \sum_{\omega} \left[ C_1(\omega)^2 + S_1(\omega)^2 \right] \right]^{1/2}.
\]

In the above formulas, each Fourier coefficient has been multiplied by the respective filter value in Fig. 1 at frequency \( \omega \). For the correlation statistic above, this effectively results in a narrower bandwidth, given by the square of the respective filter amplitude in Fig. 1.

If we model the two time series as bivariate normal, then it can be shown under the null hypothesis (correlation coefficient in bivariate distribution equals zero) that with \( N \) values in the original time series, the statistic

\[
T = R \left[ \frac{(N-2)}{(1-R^2)} \right]^{1/2}
\]

is distributed as Student's \( t \) with \( N-2 \) degrees of freedom (Hogg and Craig 1978).

The effective number \( N \) was reduced drastically due to the frequency filtering and was approximated here as the area of the respective filter used in Fig. 1 multiplied by a factor of 2 (for the independent Fourier
cosine and sine coefficients). With the method of (6-month) seasonal projection (Gao and Stanford 1988b) used for all plots in this study, effectively only half of the data set was used; the number N must be divided by 2 for this time series alteration. In the presence of one very strong annual harmonic inside of the main lobe of the respective filter, the seasonal projection method would result in possible distortion of other annual harmonic coefficients (possibly yielding incorrectly large correlation between similar time series). To reduce such an effect, no annual harmonics inside of the respective filter were used, further reducing the degrees of freedom. After all of the above considerations, the temporal number of degrees of freedom for the 35-60 day filter in Fig. 1 becomes 26 for the seasonal correlation plots. For all correlation plots which use the 35-60 day filter, the absolute value of the correlation statistic must exceed 0.4 to establish at least 95% local statistical significance.

Since we truncate using zonal wavenumbers 1-10, there are approximately only 20 independent longitudinal locations at any particular latitude. Assuming that the meridional resolution is equal to the actual number of latitudes used (33 latitudes in our study), then the total number of independent locations on one global map is approximately 660. A 95% confidence level would mean, on the average, that the correlation for even a pure noise process would exceed the critical correlation for 5% of the independent locations (here, 33 locations); for a ensemble of 20 such global plots, the total number of locations expected to exceed is then
660. It can be seen that raising the local significance level to 99.99% ensures that no more than one location over all 20 global plots would exceed critical correlation — this critical correlation (the a posteriori value) was computed to be approximately 0.87 for the 35-60 day filter. The a posteriori critical correlation was not computed for the narrower 40-50 day filter in Fig. 1.

For eastward-only plots using the narrower 40-50 day filter in Fig. 1, half of the original Fourier coefficients in frequency space remain independent for a pure-noise process — we might furthermore divide the value N by a factor of 2; however, even random noise could be dominated by eastward components due to strong westerly zonal winds in the seasonal plots used in this study. To take such an effect into account, the decomposed power spectra (Fig. 4) were used to better approximate the eastward-only temporal degrees of freedom, even though the decomposed power spectra plots pertain to the complete seven years. For the 40-50 day band, the decomposed power spectra plots indicate that approximately 60-65% of the traveling power is eastward — the number of degrees of freedom was approximated here as 60-65% eastward, resulting in 9 degrees of freedom for the eastward-only self-correlation plots. For the eastward-only correlation plots, the absolute value of the correlation statistic must exceed 0.6 to establish at least 95% local statistical significance.

The eastward-only correlation method involves a simple east/west separation of the time series. Standing components are not taken out in
this correlation method, as they are with the coherence approach used by Hayashi (1971, 1977). From the formalism of II.C.1 we can write

\[ T_b(x,y,t) = \sum \sum \left[ CC(k,p,y)\cos(\omega_p t)\cos(\Omega_k x) + CS(k,p,y)\cos(\omega_p t)\sin(\Omega_k x) \\
+ SC(k,p,y)\sin(\omega_p t)\cos(\Omega_k x) + SS(k,p,y)\sin(\omega_p t)\sin(\Omega_k x) \right] . \]

With the uniqueness of the above mixed Fourier coefficients, it follows that the eastward part of \( T_b(x,y,t) \) can be written in identical form, but with the following new eastward coefficients:

\[ \begin{align*}
CC_{\text{east}} &= (CC+SS)/2 \\
CS_{\text{east}} &= (CS-CS)/2 \\
SC_{\text{east}} &= (SC-CS)/2 \\
SS_{\text{east}} &= (CC+SS)/2 .
\end{align*} \]

For completeness, we also give the westward coefficients:

\[ \begin{align*}
CC_{\text{west}} &= (CC-SS)/2 \\
CS_{\text{west}} &= (CS+SC)/2 \\
SC_{\text{west}} &= (SC+CS)/2 \\
SS_{\text{west}} &= (SS-CS)/2 .
\end{align*} \]

For the Monte Carlo testing with the lag-correlation statistic, raw reference-level Fourier coefficients were taken 300 times from a uniform distribution \([-0.5,0.5]\) having an approximate white-noise power spectrum; the filters (Fig. 1) used for the correlation statistics were narrow enough relative to the slope of the reference-point background power estimates that there was little difference between using white or red-noise.
H. References


ONE-TO-TWO MONTH OSCILLATIONS: OBSERVED
HIGH LATITUDE TROPOSPHERIC AND
STRATOSPHERIC RESPONSE TO
TROPICAL FORCING

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III. ONE-TO-TWO MONTH OSCILLATIONS:
OBSERVED HIGH LATITUDE TROPOSPHERIC
AND STRATOSPHERIC RESPONSE
TO TROPICAL FORCING

A. Abstract

Careful spectral, correlation and coherence analyses of very low-
frequency fluctuations in global geopotential height data are presented.
Attention is paid to proper statistical assessments. The main results
are:

1. One-to-two month oscillating quasi-stationary wavetrains have
recently been reported in the extratropical Southern Hemisphere
troposphere, as far south as the edge of Antarctica. However, only weak
correlations were observed with the supposed tropical forcing region,
leading to the question of whether the wavetrain is a response to tropical
forcing or possibly due to in situ instabilities on 1-2 month time scales.
The present paper clears up this enigma with analyses of other tropical
data sets which reveal clear correlation between low-latitude source
regions and the SH extratropical troposphere.

2. An earlier investigation found strong correlations between 1-2
month oscillations in the upper stratosphere and tropical troposphere, yet
no vertical propagation was found directly above the tropics. This is
explained in the present work with evidence of temperature fluctuations
propagating initially quasi-horizontally towards higher latitudes from the
Indonesian tropical troposphere, along the bottom of the tropopause to near 35° S. At this latitude, stratospheric winter westerlies allow vertical propagation of the 1-2 month perturbations up to the middle stratosphere where the wavetrain arches equatorward and upward to the stratopause.

3. Finally, Eliassen-Palm flux diagnostics reveal that while the 1-2 month perturbations occasionally cause significant forcing of the stratospheric zonal mean wind, on the long term average only about 10% of the forcing can be attributed directly to these low-frequency eddies.

B. Introduction

Several extensive observational studies have been conducted on the subject of intraseasonal oscillations with periods varying from 1-2 months. The studies were generally in response to the discovery by Madden and Julian (1971, 1972) of strong oscillations in convection involving tropical tropospheric wind, temperature, and pressure with 40-50 day periods, which has become known as the Madden and Julian oscillation (MJO). Madden and Julian (1972) described this phenomenon as a large-scale eastward propagating Walker Cell in the tropics with largest convection along the Indian Ocean-Western Pacific path. We emphasize that this region of strongest tropical convection over 1-2 month periods may represent a viable forcing of extratropical wave patterns extending upward to at least stratopause heights. The present study will attempt to connect this strong convective region with the extratropical troposphere
and stratosphere by using correlation and coherence.

The first topic in this study is an extended analysis of a 200 hPa wavetrain observed by Graves and Stanford (1989) in the Southern Hemisphere (SH) extratropics during wintertime. The lack of clear correlation between tropical and mid to high latitude SH regions in their study led to the question of whether the extratropical SH patterns were a response to tropical forcing or were perhaps due to in situ instabilities on 1-2 month time scales. This enigma is resolved in the present work, where we use different tropical data and the combined statistics of coherence and correlation to show a significant connection between tropical disturbances along the Indian Ocean-Western Pacific path and the wavetrain. Besides addressing tropical forcing of the wavetrain, we also consider a possible return of the wavetrain back into the tropics.

The second topic presented shows, among other things, apparent propagation of 1-2 month temperature perturbations from a tropical Indian Ocean heating source region in the troposphere, into the SH winter midlatitudes, and upward into the high stratosphere. This propagation route into the stratosphere would explain the large statistical significance of 1-2 month signals throughout much of the SH stratosphere found in MSU4 and SSU brightness temperatures by both Gao and Stanford (1987) and Ziemke and Stanford (1990). The latter study, in particular, indicated statistically significant 1-2 month correlation and coherence of brightness temperatures between the tropics at 90 hPa and much of the winter extratropical stratosphere. After comparing their results with a
model by Garcia and Salby (1987), they concluded that a tropical forcing was probably being detected in the statistics. The model by Garcia and Salby (1987) involved a randomly-evolving red-spectrum tropical heating, and showed a strong extratropical response of normalized geopotential in the winter hemisphere high latitudes that extended from the troposphere upward well into the mesosphere. In the present study, we extend the results of Ziemke and Stanford (1990) by including calculated tropospheric temperatures.

The final topic discussed is a comparison of the Eliassen-Palm (EP) flux diagnostics for 1-2 month band-passed versus no band-passed stratospheric data. A short case study is presented to indicate general characteristics of 1-2 month waves, which includes spatial structure and the EP flux eddy influence from these waves on the mean zonal wind. EP flux was also averaged over the eight years of southern winters for 1-2 month band-passed versus no band-passed datasets, which were then compared to indicate the overall eddy contribution of the 1-2 month signals.

C. Data and Analysis Methods

For this study, eight years (1 April 1980 to 31 March 1988) of daily geopotential heights from the British Meteorological Office were analyzed. These data sets extend from the lower troposphere up to the stratosopause on the following 11 pressure surfaces: 850, 500, 300, 200, 100, 50, 20, 10, 5, 2, and 1 hPa. Up to 100 hPa, the grids are NMC analyses; satellite radiances are used to obtain stratospheric levels. Horizontally, each
pressure surface is represented on a rectangular grid having 72 longitudinal indices (180°W to 175°E by 5° increments) by 37 latitudinal indices (90°N to 90°S by 5° increments), although in this study we omit data poleward of 80° due to possible gridding errors arising from satellite geometry. The eight years of data represent a 3-year concatenation of the 5 years of data used by Graves and Stanford (1989). Approximately 12% of the data was either originally flagged bad or suspected bad. Bad data values were replaced by using a linear interpolation in time between good values (the largest bad data gap was 28 days). After the data were suitably cleaned, there followed a harmonic decomposition using a Fast Fourier Transform (FFT) in both time and the zonal direction as described by Ziemke and Stanford (1990). In time, 2920 daily values were employed in the harmonic analysis, while in the zonal direction, all 72 longitudinal points were used. Only zonal wavenumbers 0-10 were retained in this study for filtering out small scale features, and also to avoid possible satellite scan angle effects near wavenumber 14 (Yu et al. 1983). Using all original 72 longitudinal points in the harmonic analysis provided spatial resolution up to zonal wavenumber 36, ensuring that there was no direct aliasing due to this scan angle effect. Because of zonal wavenumber truncation, each grid point is effectively a box with approximately 20 degrees longitudinal resolution.

Three-dimensional stratospheric winds were derived using the iterative algorithms of Marks (1989). This method required stratospheric heating rates, and we have used the calculated values of Shine (1988).
Prior to using this method, an exact, running 3-point parabolic fitting procedure was used to map geopotential heights from several of the above pressure surfaces onto 10 equally-spaced log-pressure surfaces at 2.0 to 6.5 (increment 0.5) scale heights, where one scale height is 7 km. Horizontally, the original 5° latitudinal resolution was retained, but 15° longitude increments (24 longitude locations) were chosen, since the zonal Fourier decomposition retained only wavenumbers smaller than 11. Temperatures from this gridding were derived from a standard 5-point finite difference in the vertical, except for the two lowest and two highest levels which involved three points. The resulting temperature time series compared well with MSU4 and SSU channels of brightness temperature used by Ziemke and Stanford (1990). The iteration method by Marks (1989) ignores the local time change in horizontal wind speeds, and so it was necessary to apply the response of a low-pass filter (Fig. 1a) in frequency space prior to reconstructing the time series from an inverse FFT. After reconstructing the time series, data were retained for 730 values at 4-day intervals, and without 4-day averaging. With the 4-day sampling interval, note that there was no aliasing from frequencies larger than the folding frequency (8⁻¹ day⁻¹) because of the low-pass filter.

The statistics used in this study are correlation, coherence, and coherence-phase, with critical testing levels established by modeling each time series as multivariate noise under the null hypothesis. All statistics (and also power spectra) were computed on the original pressure surfaces (850, ..., 1 hPa), and for wavenumbers 1-10 (that is, removal of
Figure 1. Filter frequency responses vs. frequency (day$^{-1}$). (a) The low-pass filter which was applied to the original geopotential heights for all dynamical analyses involving winds. It was derived as a symmetric nonrecursive type using 49 weights in time. (b) A recursive filter following Murakami (1979) used for all analyses in this study involving 1–2 month periods. The response represents four successive applications of the filter algorithm. Phase amplitude for either filter is zero at all frequencies. Folding (Nyquist) frequencies for (a) and (b) are 2$^{-1}$ and 8$^{-1}$ day$^{-1}$, respectively.
the zonal mean time series) to highlight wave properties that are often obscured when zonal mean time series are included.

Correlation was calculated in frequency space for 1-2 month band-passed (see filter, Fig. 1b) 8-year data sets of both temperature and geopotential heights over 6-month southern winters, defined as the months April through September. This 6-month partitioning of time series was accomplished using a seasonal projection technique (Gao and Stanford 1988b) which is described in a generalized form, along with correlation, in III.H. Correlation is plotted in both horizontal and vertical cross-sections to highlight 3-dimensional characteristics.

A Monte Carlo method similar to Livezey and Chen (1983) was incorporated to test for global significance of all horizontal and vertical cross-section correlation plots. This method involved the calculation of correlations after generating (500 times) a reference point time series of red-noise matching a red-noise spectral fit of the original reference point; each grid point that passed local significance was weighted by cosine of latitude (proportional to area in horizontal cross-sections).

The temporal degrees of freedom for correlation analysis under seasonal projection is approximately 33, obtained from the twice the area under the curve in Fig. 1b with an additional factor of 1/2 due to the 6-month seasonal projection operator used. The Student’s t-distribution yields 0.33 as the critical correlation magnitude at 95% local significance. This number compares closely to the Monte Carlo results.
which indicated $0.32 \pm 0.01$ in each experiment for either horizontal or vertical cross-section correlations. The Monte Carlo method tested for 95% global significance; local significance in the method was also taken at 95%, and used 0.33 as the critical correlation magnitude.

For all correlations involving temperatures, a mean estimate of temperature at a given pressure level was calculated in frequency space by differentiating the harmonic coefficients of geopotential height in the vertical log-pressure coordinate, using a nonsymmetric three-point finite difference.

Coherence and coherence-phase were calculated over the complete eight years of data (2920 daily values) with a 21-point running mean applied as a spectral estimator. The band-width of this estimator is approximately $0.0072$ day$^{-1}$.

For all 1–2 month analyses presented in this study involving either dynamics or statistics, the band-pass filter response shown in Fig. 1b was applied to all harmonic coefficients in frequency.

D. Results: Connection Between Tropics and Extratropics

In the following we present two separate parts involving statistics over the eight years of southern winters. The first part relates to a previously observed 35–60 day SH wavetrain in 200 hPa geopotential height correlations by Graves and Stanford (1989). Their results indicated a pattern which appeared quasi-stationary, but with an apparent group velocity of correlation amplitudes which moved eastward from the
subtropics of Indonesia, around the South Pole at high latitudes, and back again toward Indonesia. Part of our analysis will show that the observed wavetrain is probably excited at times by a 1–2 month tropical forcing lying along the Indian Ocean-Western Pacific path.

The second part presented is a collection of temperature correlation plots which indicate, among other things, an apparent propagation of 1–2 month temperature fluctuations out of the tropical troposphere, into the winter extratropics, and then upward into the high stratosphere. Such a propagation might explain large statistical significance of 1–2 month scale brightness temperature oscillations in the high SH extratropical stratosphere as found in the studies by Gao and Stanford (1987), and Ziemke and Stanford (1990).

1. SH wavetrain in 200 hPa geopotential heights

The 35–60 day SH wavetrain discovered by Graves and Stanford (1989) suggested a possible, although weak, connection between the extratropics (20°S to 80°S) and the Indian Ocean-Western Pacific tropics. They correlated five years of 200 hPa extratropical (20°S to 80°S) geopotential heights with MSU4 tropical brightness temperatures representative of 90 hPa atmospheric temperatures. MSU4 temperatures in the tropics were used rather than geopotential heights, under the premise that the data would be less noisy for the 1–2 month time scale. The results presented an enigma: while it was thought that tropical forcing might be responsible for the extratropical signals, the lack of clear correlation between the regions
could also be explained on the basis of in situ instability on 1-2 month time scales.

The present analysis uses only geopotential heights over the entire globe, except polewards of 80° as mentioned in III.C. As will be seen, these data reveal a clear connection between tropics and SH winter tropospheric 1-2 month oscillations.

To test the validity of the tropical data, temperatures were derived from the geopotential heights as described in III.C, and compared with MSU4 and SSU temperatures in the form of correlation plots with an equatorial reference point. The resulting plots (not shown) with 100 hPa reference points compared well, and in some cases were nearly identical with those of Gao and Stanford (1988a), and Ziemke and Stanford (1990), all of which used MSU4 and SSU brightness temperatures with 90 hPa MSU4 equatorial reference points.

Figure 2 shows 1-2 month SH 200 hPa correlation plots with reference point at 45°S, 15°W; these results closely resemble those of Graves and Stanford (1989) who used a similar reference point at 45°S, 10°W. They chose their reference point not just for statistical significance of 1-2 month signals, but also for its location near an apparent midlatitude turning point of arching extratropical correlation patterns in 90 hPa 40-50 day MSU4 brightness temperatures noted by Gao and Stanford (1988a). In Fig. 2, the arrowed wavetrain path and the lettered regions A-G correspond to similar markings in the plots shown by Graves and Stanford (1989). One interesting feature in Fig. 2 is an apparent tropical dipole
Figure 2. Southern Hemisphere 200 hPa 1-2 month band-passed (see filter, Figure 1b) lag correlations calculated from eight years of SH winters (April-September) with reference point centered in region D at 45°S, 15°W. Concentric circles are equator, 40°S, and 80°S. Time lags for correlation are indicated in each plot. Positive (negative) correlations, indicated by the solid (dashed) contours, begin at 0.1 (-0.1) and increment by 0.1. See text for remaining symbolism. Local significance at the 95% (99.5%) level is given by absolute correlations of 0.33 (0.46). Global significance (see III.C for details) is satisfied at the 95% level when correlation is greater than (less than) 0.33 (-0.33) over 5.7% (5.5%) of total area; lag=-6, 0, and 6 day plots pass this two-tailed test.
CORRELATIONS OF 200 hPa GEOPOTENTIAL HEIGHTS
in correlation from $90^\circ$ to $180^\circ$E in several of the plots, and is likely related to the large-scale tropical circulation cells of the MJO involving structured winds, temperatures, and pressures. A similar dipole feature in correlation was noted previously by Gao and Stanford (1988a) using 90 hPa MSU4 temperatures.

The power spectrum of our correlation reference point is shown in Fig. 3, along with spectra of several other important time series in this study. Red noise background power and the corresponding 95% significance level are indicated in each plot by the lower and upper dashed lines, respectively. These dashed lines were calculated using an approximation to a first-order autoregressive time series model (Markov model) by a least squares fitting of raw power ordinates between 120 and 12-day periods.

We now describe a possible tropics/extratropical wavetrain connection starting with the top lag=-9 day plot in Fig. 2. Note that the patterns at lag=-9 days represent the fluctuations in geopotential heights that occurred 9 days before those of the reference point time series. In this figure, the two largest regions passing 95% local statistical significance (critical correlation magnitude = $R_c = 0.33$) are regions G and T. Note that the magnitude of correlation in tropical region T near $105^\circ$E, even though far from the reference point, exceeds 0.5 and passes a much higher 99.5% test level ($R_c = 0.46$). Combining the remaining plots, we describe the pattern development as follows:

(i) From lag=-6 to 0 days, region T remains significantly
Figure 3. Power spectral densities vs. frequency at selected SH locations. Oscillation periods in days are indicated. Power spectral density is defined as \( \frac{C^2 + S^2}{2\Delta f} \) where \( C \) and \( S \) are Fourier cosine and sine coefficients, and \( \Delta f \) is the unit frequency bandwidth = 1 day\(^{-1}\). Plots with letter Z (T) denote geopotential height (temperature) having power spectral density units \( m^2 \text{-day} \) (K\(^2\)-day). In each plot, a 7-point running mean was applied to the power ordinates as a spectral estimator.
anticorrelated with the reference point while propagating eastward. Concurrently, region G meets up with region A and disappears.

(ii) At lag=0 days, the wavetrain has achieved maximum intensity, and includes a newly generated region F. (We must note that region F does not originate directly from region G.)

(iii) By lag=6 days the wavetrain exhibits characteristics of a pulse or group of correlations, as magnitudes have diminished along regions A to E while intensifying for region F. There is also the appearance of a region located near former region G, but anticorrelated now with point D. This region, which we still denote as G, appears to be a continuation of the wavetrain from region F, but at the same time tropical region T is developing.

(iv) At lag=12 days, region F is diminishing in correlation strength while both regions G and T are increasing. If the wavetrain propagation occurs from region F to region T between lag=6 and 12, the wavetrain would in effect constitutes a feedback into the tropical Indian Ocean region. At least a portion of the wavetrain moves towards region G, however. It is possible that the wavetrain A–F experiences partial reflection towards region G and partial transmission towards region T, due to low-latitude wind curvature effects.

In relation to a possible tropical forcing of the wavetrain, we again refer to the barotropic model by Simmons et al. (1983), which was for a linearization about a 300 hPa climatological mean January flow. Although for the opposite winter season from that investigated here, their model
showed that because of disproportionately large amplitudes in response to steady-state anomalous forcing, the position of the wavetrain amplitude may not directly indicate the position of the tropical source; this may be occurring in some sense with tropical region T.

The band-passed correlation plots certainly indicate a significant statistical connection for 1-2 month signals between reference point D and a large portion of the Indian Ocean-Western Pacific tropics, but for comparative purposes it is important to consider frequencies other than just the 1-2 month band. For this reason we constructed several plots of 200 hPa coherence and coherence-phase, between point D as reference and the entire equatorial Indian Ocean-Western Pacific path. These plots, shown in Fig. 4a, indicate that the most consistent coherence values passing 95% confidence are in the 1-2 month frequency band, particularly near 50 and 60-day periods. Figure 4b shows that the coherence phase changes from approximately 270° to 90° for these frequencies along 90°E to 180°E, respectively, with the most out-of-phase case appearing at 150°E. Relative to other frequencies, the phase also appears smooth and nearly constant about the peaks of significant coherence within the 1-2 month band, implying real signal rather than noise. In brief, coherence supports the previous correlation results relating to a connection between the wavetrain and the tropics; in addition, coherence dominance and broadness in frequency within the 1-2 month band is revealed.

In the Simmons et al. (1983) model, the most rapidly growing barotropic instability mode in the absence of damping had an e-folding
Figure 4. Plots of coherence and coherence-phase statistics. (a) Coherence between the region D correlation reference point of Figure 3 (used here as coherence reference) and other 200 hPa points along the equatorial Indian Ocean-Western Pacific path. Coherence is plotted vs. frequency, with oscillation periods in days indicated. A running mean of 21 points was applied as a spectral estimator, yielding a bandwidth of 0.0072 day$^{-1}$ and an approximate 95% significance level of coherence equaling 0.37, shown as a long horizontal line segment in each plot. (b) Phase of coherence in Figure 4a, using the same spectral estimator. Horizontal lines are 0, $\pi$, and $2\pi$ radians.
COHERENCE BETWEEN POINT D AND THE INDIAN OCEAN/WESTERN PACIFIC TROPICS

(a)
Figure 4 (Continued)
time of approximately one week and a period near 50 days. To test for dominance of such a mode, we calculated coherence between regions along the arrowed wavetrain path in Fig. 2, with region D as reference. The resulting plots (not shown), particularly for region F, indicated large sporadic statistical significance across the full spectrum from 15 to 60 day periods, implying that the observed wavetrain is responsive to a broader band of frequencies than just 1-2 month periods. This implies that the wavetrain may be triggered by means other than just a 1-2 month tropical forcing.

In conclusion, it appears likely that the SH tropospheric wavetrain pattern is triggered at times by an Indian Ocean-Western Pacific tropical forcing; although sensitive to a broad band of frequencies, the connection favors 1-2 month periods.

2. Extratropical temperature response from tropical heating

In a previous study using MSU4 and SSU stratospheric brightness temperatures, Ziemke and Stanford (1990) observed large correlation and coherence between the tropical Indian Ocean region at 90 hPa and much of the extratropical southern stratosphere. Their study indicated that the observed extratropical patterns in the southern winter stratosphere were statistically connected to the tropics, likely the result of tropical heating in the troposphere. We include here a similar analysis, but with troposphere and stratosphere combined, and using temperatures derived from the geopotential heights as discussed in III.C.
A reference point for correlation was chosen along the equator at 90°E and at pressure level 500 hPa, close to the maximum heating level in the troposphere. The choice of longitude for the reference point was based both on significant spectral power for 1-2 month oscillations, and large correlations with the extratropical upper stratosphere. Global correlation plots for the levels 500 and 100 hPa for this reference point (marked "X") are shown in Fig. 5. Markings such as the letters and the arrow relate to a vertical cross-section which will be discussed shortly.

In Fig. 5 we first note that 500 and 100 hPa temperatures appear oppositely correlated from the tropics outward to at least the midlatitudes in both hemispheres. The correlation is calculated over eight years of 1-2 month band-passed data sets, and captures average long-term effects from global-scale, sporadic upper and lower level divergence cells in which 100 and 500 hPa are anticorrelated in varying amounts.

Figure 5 indicates an apparent equatorial dipole of correlation similar to that observed by Gao and Stanford (1988a); in the lag=0 plot at 500 hPa we see positive values of correlation about the reference point region, and negative values along the equatorial central Pacific. As noted earlier in III.D.1, the equatorial dipole pattern is likely associated with the well-known dipole in temperature, winds, and pressure related to the MJO. A similar dipole in outgoing longwave radiation was found by Lau and Chan (1985), and Weickmann et al. (1985). The equatorial dipole in Fig. 5 also exhibits an initially slow eastward phase
TEMPERATURE CORRELATIONS WITH 500 hPa INDIAN OCEAN REFERENCE

LAG: 0 DAYS

LAG: 6 DAYS

LAG: 12 DAYS
Figure 5. Global correlations of 1–2 month band-passed (see filter, Figure 1b) temperatures at 500 and 100 hPa, with an equatorial reference point (marked "X") at 500 hPa, 90°E. Time lags are indicated in each plot, and the correlation contouring and significance levels are the same as in Figure 3. Global significance is satisfied at the 95% level in the 500 hPa plots when correlation is greater than (less than) 0.33 (-0.33) over 4.5% (4.4%) of total area; critical area percentages at 100 hPa for both positive and negative correlation tails is 4.4%. All plots shown for both 100 and 500 hPa pass global significance.
propagation along the Indian Ocean-Western Pacific path. In this regard, from lag=0 to 12 days the equatorial reference-point region has propagated eastward approximately 60°, only 5° longitude per day. Comparing our observed slow-down of Indonesian temperature correlation patterns with a shallow water model by Gill (1982), this slow-down can be explained as the effect of latent heat release partly compensating the cooling due to upward motion, which reduces buoyancy effects and causes a slower eastward propagation.

A prominent feature of the temperature fluctuations appears in the 500 hPa patterns at lag=6 days: a region of positive correlation about the reference point has formed into two distinct parts which propagate outward into both hemispheres. Both parts also appear to propagate westward, appearing more distinct at lag=12 days in the Northern Hemisphere (NH). The larger correlations of the NH part may result from easterly zonal winds in the NH stratosphere which trap planetary waves in the troposphere (see, for example, Holton 1975). We note that by lag=12 days the NH lobe has effectively moved westward and northward by 15°, indicating both a northward and westward propagation approximately equal to 0.8 m s⁻¹. For later lags (not shown), this lobe slowly continues its propagation slightly northwestward across India over Pakistan and eventually dissipates there at approximately lag=24 days. This northward propagating lobe of temperature correlation may be associated with summer monsoon rainfall in India, which begins from the southeast part of the peninsula and then spreads northward (Hartmann and Michelsen, 1989). In a
related investigation, combining 30–60 day filtered data sets of NMC analyzed winds and OLR (outgoing longwave radiation), Knutson and Weickmann (1987) found that, during NH summer, a northward propagation of cyclonic circulation over the Indian monsoon region generally coincided with a northward propagating convective activity, indicating a 30–60 day modulation of the Indian monsoon. The model by Garcia and Salby (1987), involving randomly evolving tropical heating, indicated similar subtropical lobes at one scale height (approximately 370 hPa) in both hemispheres; the lobes' location was west of an equatorial Indonesian forcing in the troposphere, as seen in their Fig. 23. This was for their case II.1 result for the northern, rather than the southern winter studied here, and only during the easterly phase of the quasi-biennial oscillation. Although the comparison of the above correlations with their model patterns is for opposite winter hemispheres, a comparison can still be made and suggests that tropical heating is responsible for the observed behavior of correlation patterns.

We next present evidence that the lobed feature discussed above leads to vertical and latitudinal propagation out of the tropics. To facilitate tracing 1–2 month temperature correlations out of the tropics and into the stratosphere, we present Fig. 6a which is a vertical cross-section of correlation through the path AA' in Fig. 5. In the lag=6 day plot the region which surrounds the reference point is seen splitting into the two subtropical lobes previously discussed. A small region of positive correlation (see small arrow) grows in magnitude, and coalesces with the
Figure 6. Pressure vs. latitude vertical cross-section plots. (a) Vertical cross-section through path AA' of Figure 5, with the same plotting parameters. Global significance is satisfied at the 95% level when correlation is greater than (less than) 0.33 (-0.33) over 6.1% (6.2%) of the vertical cross-section region (grid points weighted by cosine of latitude). All plots shown pass global significance. (b) Conceptual model showing propagation of 1-2 month signals from the troposphere, upward into the stratosphere.
Figure 6 (Continued)
lower subtropical lobe by lag=12 days. In subsequent time lags this correlation appears to propagate both southward and upward, well into the stratosphere. The small growing positive correlation at lag=6 days (see arrow) at 100 hPa is also indicated by a small arrow in the horizontal plots of Fig. 5. The growing correlation region develops at 100 hPa, and its ensuing correlation path may be described as wave-packet-like, moving out of the subtropical troposphere and up into the stratosphere at 100 hPa near 35°S. Note that negative correlation patterns in the high stratosphere appear to propagate equatorward in subsequent lags. Figure 6b shows a conceptual model for the propagation of the 1-2 month signal from the tropical upper troposphere, passing through the midlatitude middle stratosphere, and eventually reaching great heights in the upper stratosphere as it moves back into the tropics. In conclusion, 1-2 month signals over the 6-month southern winters appear to propagate quasi-barotropically from the equatorial Indian Ocean troposphere near 90°E, out to the winter midlatitudes near 35°S, and then upward into the stratosphere.

There are several other regions of high correlations present in Fig. 6a, such as the positive correlation region centered in the summer hemisphere near 30°N, 20 hPa at lag=0 days. On the basis of elementary dynamics, we expect vertical propagation of planetary waves only in the winter hemisphere where the winds are westerly, so that this positive correlation region is likely due to waves already in the stratosphere, and not due to waves propagating directly upward from the equatorial reference
point region. Consistent with this, Ziemke and Stanford (1990), while analyzing MSU4 and SSU temperature data sets, found little evidence for direct vertical propagation of 1-2 month signals in the equatorial stratosphere.

E. Results: 1-2 Month EP Flux in the SH Winter Stratosphere

We present here a short analysis of the Eliassen-Palm (EP) flux diagnostic over the eight years of 6-month southern winters, with and without the 1-2 month band-pass filter, using the 3-dimensional winds and temperatures as described in III.C. All wind and temperature time series were filtered in frequency space via the band-pass filter in Fig. 1b prior to calculating 1-2 month band EP fluxes. For the calculations presented in Fig. 7, the transformed Eulerian mean (TEM) equations given by Andrews et al. (1987) were implemented. The EP flux vector \( \vec{F} \) is

\[
\begin{bmatrix}
F^\phi \\
F^z
\end{bmatrix} = \rho_0 \mu \phi \begin{bmatrix}
\frac{v_z v' \theta' / \theta_z - u' \nu'}{\mu} \\
[f - (\mu \phi)^{-1}(u \cos \phi)] \nu' \theta' / \theta_z - \nu' u'
\end{bmatrix}
\]

(1)

and an EP flux divergence term denoted DF is given by

\[
DF = \frac{\nabla \cdot \vec{F}}{\rho_0 \mu \phi} = \frac{1}{\rho_0 \mu \phi} \left[ \frac{1}{\cos \phi} \frac{\partial (F^\phi \cos \phi)}{\partial \phi} + \frac{\partial (F^z)}{\partial z} \right].
\]

(2)

All variables are standard, and subscripts denote partial differentiation; superscripts are used for the components of \( \vec{F} \). Physically, \( F^\phi \) represents a form of eddy momentum flux per unit mass, while \( F^z \) represents a corresponding heat flux. For linear disturbances localized in wavenumber in a slowly-varying background flow, the direction of \( \vec{F} \) gives an
Figure 7. Vertical cross-sections with \( Z= \) number of scale heights \( H \) (\( H=7 \text{km} \)) vs. SH latitude during year 1986. First column of plots: 1-2 month band-passed temperatures (°C) at 90°E which includes wavenumbers 1-10. Positive (negative) temperatures, indicated by the solid (dashed) contours, begin at 0.5 (-0.5) and increment by 0.5. Temperatures greater than or equal to 1.5°C are shaded. Second column: 1-2 month EP flux vectors \( \vec{F} = (F^\phi, F^z) \), and contours of divergence term \( DF \) (see text). \( F^z \) has been multiplied by a factor 250; note reference EP flux vector 100000 kg s\(^{-2}\) above top plot, applicable to both \( F^z \) and \( F^\phi \). Dashed contours of \( DF \) (units: m s\(^{-1}\) day\(^{-1}\)) are -0.5, -1.0, ... Solid contours of \( DF \) are 0(dark), 0.5, ... Third column: Local time rate of change of zonally averaged zonal wind without 1-2 month band-pass filter. Contouring is the same as in the second column.
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approximate direction of wave group velocity. DF is an effective measure of the influence of eddies in changing the mean zonal flow: positive (negative) DF tends to increase (decrease) the time rate of change of the zonally averaged zonal wind.

Part of our EP flux analysis was done to compare results with Graves and Stanford (1989). In an effort to make comparisons with their study, as well as to simplify calculations for 8-year ensemble analyses, in these special cases we have chosen their use of quasi-geostrophic scaling. The EP flux vector and term DF under such scaling are the same as above, except that we ignore terms involving either the vertical wind or the zonally-averaged zonal wind.

1. 1-2 month eddy effects on the mean flow

In addition to vertical propagation of $T'$ in Fig. 7 (following shaded regions), the May 11 and June 4 plots indicate a vertical span approximately equal to 3 scale heights ($Z=3$ to $Z=6$) between minimum and maximum temperature extrema (vertical half-wavelength). The peak amplitude of $T'$ also approximately doubles during vertical propagation. As $T'$ propagates vertically upward toward the mesosphere, it propagates northward and spreads out latitudinally. This northward propagation explains large equatorial correlations of $T'$ found in the high stratosphere in some of our plots (not shown), when the reference point is at some lower height along the equator.

As evident in the second and third columns of Fig. 7, eddy effects
from the 1-2 month band produce significant changes in the mean flow in the southern winter middle stratosphere. Over the time period shown in Fig. 8, the 1-2 month divergence term DF is inphase with the time rate of change of $\bar{U}$. Figure 9 shows the 8-year ensemble mean EP flux and divergence term DF diagnostics, with and without the 1-2 month band-pass filter. The seasonally averaged 1-2 month oscillations contribute (at most) approximately 10% to the total eddy divergence term DF, indicating an observable, but small forcing of the zonal mean wind.

2. Reduced stratospheric EP flux divergence "dipole"

The study by Graves and Stanford (1989) indicated questionably strong negative values of the quasi-geostrophically scaled divergence term DF in the high stratosphere midlatitudes during the ENSO years 1982 and 1983. This resulted in a latitudinal "dipole" of divergence, with small positive values toward the pole. In their calculations, they used linear winds (Robinson, 1986; Randel, 1987a), while we here used iterative winds (Marks, 1989). For brevity we will only state that the strong negative divergence and dipole have been greatly reduced in our results for the ENSO years, as well as the other years considered in this study. We also mention that of the eight years studied here (1980-1987), the 1983 ENSO year gave the strongest quasi-geostrophically scaled EP flux in the SH mid-to-upper stratosphere; Graves and Stanford (1989), using a different wind evaluation scheme, found the same result.
Figure 8. Terms $\frac{\partial U}{\partial t}$ and $DF$ (see equations 1 and 2) in middle stratosphere of Figure 7, plotted in units of $m \cdot s^{-1} \cdot day^{-1}$ vs. time (days) for May, June, and July 1986. Tick marks are at 4-day increments, with arrows indicating the days in Figure 7.
Figure 9. Eight-year averages of seasonal (April-September) quasi-geostrophic EP flux vector $\vec{F}$ and divergence term $DF$ in the Southern Hemisphere, plotted as $Z$ (scale heights) vs. latitude. (a) represents 1–2 month band-passed data, while the calculations in (b) were made without this frequency filtering. Vertical component of EP flux vector has been multiplied by 100 in both plots; note arrow in upper left indicating EP flux strength (units: kg s$^{-2}$), applicable to both components of the EP flux vector. Dashed contours of $DF$ (units: m s$^{-1}$ day$^{-1}$) in (a) are $-0.02, -0.04, \ldots$ Solid: 0(dark), 0.02, 0.04, $\ldots$ Contours of $DF$ in (b) are the same as in (a), except multiplied by the factor 10
8-YEAR AVERAGE EP FLUX

(a) BAND-PASS FILTERED

(b) WITHOUT BAND-PASS
3. **Quasi-biennial oscillation effects**

Dynamical effects from the stratospheric quasi-biennial oscillation (QBO) of tropical zonal wind could influence the global extratropical response from 1-2 month tropical forcing. To investigate the relationship of the QBO, we used the 50 hPa zonal winds from Singapore (1.3° N) given in Lait et al. (1989). Over the span of 6-month seasons defined here, there were some years in which the Singapore wind was purely eastward or purely westward, and some years which indicated a transition between eastward and westward. Our SH analysis of the QBO showed little observable difference between eastward and westward 50 hPa QBO phases; however, the analyses did suggest that relatively smaller EP flux vectors, particularly in the mid-to-upper stratosphere, occurred during the transition seasons.

**F. Summary and Discussion**

We have presented an extended analysis of a previously observed 35-60 day SH wavetrain in 200 hPa geopotential heights. Correlation and coherence statistics imply that a plausible excitation mechanism for the wavetrain pattern is 1-2 month tropical forcing lying along the Indian Ocean–Western Pacific Ocean path. Between this path and the wavetrain midlatitude region D (see Fig. 2), both correlation and coherence showed large out-of-phase statistical significance; in addition, coherence indicated a connection favoring 1-2 month periods over other frequency bands.
We have also presented evidence for propagation of temperature fluctuations out of the Indonesian tropics into the southern winter stratosphere. With a 500 hPa equatorial reference point at 90°E, the correlation statistic revealed poleward and westward propagation of 1-2 month temperature perturbations into both hemispheres, as well as evidence for a connection with temperatures in the high winter stratosphere via vertical propagation. One feature observed was a latitude pulse which splits into two westward propagating parts; one part moves southward into the winter subtropics, and the other propagates northward. The latter feature, because of easterly NH stratospheric winds, is trapped and limited mostly to the troposphere. It propagates slowly across India and may be associated with the Indian monsoon. In contrast, the southward propagating part moved south and west to near 35°S, where westerly SH winds in the stratosphere permitted vertical propagation of the long planetary waves upward into the high stratosphere. This propagation route explains the 1-2 month oscillation features observed in recent studies throughout the SH extratropical stratosphere.

Finally, we have presented a brief analysis of the EP flux diagnostic in the SH stratosphere during wintertime. A case study showed vertical and equatorward propagation of 1-2 month eddy temperature waves, their characteristic scales, and effects on the mean zonal wind. The 1-2 month perturbations may at times be responsible for much of the observed mean flow changes in the middle stratosphere, but on the long term average (8 years), the direct influence from 1-2 month eddy divergence is of order
G. Acknowledgements

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H. Appendix: Method of Time Series Projection

In the following, we present a generalization of the seasonal projection method which was previously described for a special case by Gao and Stanford (1988b). This frequency domain technique can result in significantly increased computational efficiency with analyses of large, digitally filtered data sets.

We begin with the harmonic expansion of a time series \( x(t; t=1,2,\ldots,N) \) involving real number Fourier cosine \( c(p) \) and sine \( s(p) \) coefficients (Chatfield 1980):

\[
\begin{align*}
N/2-1 \\
x(t) &= c(0) + \sum_{p=1}^{N/2-1} \left[ c(p)\cos\left(\frac{2\pi pt}{N}\right) + s(p)\sin\left(\frac{2\pi pt}{N}\right) \right] + c(N/2)(-1)^t \quad (A1)
\end{align*}
\]

where
\[ c(0) = \sum_{t=1}^{N} \frac{x(t)}{N} \quad \text{and} \quad c(N/2) = \sum_{t=1}^{N} \frac{x(t)(-1)^t}{N} \quad \text{(A2)} \]

The central theme of the time series projection method is to multiply the original time series \( x(t) \) by the following infinitely long periodic step function \( g_{\pm}(t) \), truncated at \( m=M \):

\[ g_{\pm}(t) = \frac{1}{2 \pi} \sum_{m=1, 3, 5, \ldots}^{N} \frac{1}{m} \sin(2\pi mt/T) \quad \text{(A4)} \]

For either sign chosen in (A4), as \( M \) approaches infinity \( g_{\pm}(t) \) will approach an infinitely long periodic boxcar function of unit height.

Figure 10 shows two functions corresponding to the positive sign in (A4); one function shown is the ideal boxcar and the other corresponds to a truncation of \( m \) at \( M=7 \). The negative sign in (A4) will give the same function as the positive sign, except shifted to the right by \( T/2 \).

An added constraint in the above method is that \( N = YT \), where \( Y \) must be a positive integer; note that this defines \( T \) as a rational number, since \( N \) is an integer. With the special seasonal projection used for all correlation analyses in this study, \( T \) equals one year, resulting in 6-month seasons. (Other time segment projections can be obtained, as noted later.)

The above multiplication yields a product function

\[ x'(t) = g_{\pm}(t)x(t) \quad \text{(A5)} \]

which is a projection of \( x(t) \) onto the partitions in time where the
Figure 10. Infinite periodic step function $g_+(t)$ for the time series projection method discussed in III.H. Both ideal and truncated ($M=7$) functions are shown for comparison. Truncation at $M=7$ is used in this study for all correlation analyses of 6-month seasonally projected time series.
truncated expression \( g(t) \) is approximately 1. We now write \( x'(t) \) as in (A1), but with primed harmonic coefficients \( c'(p) \) and \( s'(p) \). Substituting (A4) and (A5) into (A2) and (A3), and with the use of trigonometric identities, we obtain the following projected harmonic coefficients \( c'(p) \) and \( s'(p) \), truncated at \( m=M \):

\[
c'(0) = \frac{1}{2} c(0) \pm \frac{1}{\pi} \sum_{m=1, 3, 5, \ldots}^{M} \frac{1}{m} s(mY) \tag{A6}
\]

\[
c'(N/2) = \frac{1}{2} c(N/2) \pm \frac{1}{2\pi} \sum_{m=1, 3, 5, \ldots}^{M} \left[ s(N/2+mY) - s(N/2-mY) \right] \tag{A7}
\]

\[
c'(p;p=1, 2, \ldots, N/2-1) = \frac{1}{2} c(p) \pm \frac{1}{\pi} \sum_{m=1, 3, 5, \ldots}^{M} \frac{1}{m} \left[ s(p+mY) - s(p-mY) \right]/m \tag{A8}
\]

\[
s'(p;p=1, 2, \ldots, N/2-1) = \frac{1}{2} s(p) \pm \frac{1}{\pi} \sum_{m=1, 3, 5, \ldots}^{M} \left[ c(p-mY) - c(p+mY) \right] + c(0)\delta(p,mY)/m \tag{A9}
\]

Expression \( \delta(p,mY) \) is the Kronecker delta function which equals 1 when \( p=mY \) and 0 otherwise. The truncation of \( m \) in the above expressions assumes \( MY<N/2 \), so that harmonic terms, including a delta function \( \delta(p,mY-N/2) \) in (A9) can be ignored. Note also that the number of terms in the summations may be reduced even further when these original coefficients have been filtered in frequency.

An example showing the accuracy of the above method for 1-2 month band-passed coefficients (see filter, Fig. 1b) is shown in Fig. 11; this represents a time series reconstruction of a seasonal projection, by choosing \( Y=8 \) (\( T=365.0 \) days) where \( N=2920 \) days in the time series. In this
figure, we truncated the summations in (A6)-(A9) by choosing the largest value of \( m \) to be 7; truncation is always a matter of choice, weighing computational efficiency against accuracy. Figure 11, being one of the equatorial geopotential height time series in III.D.1, represents exactly the 6-month seasonal projection method with \( M=7 \) used on all time series in this study for correlations, which we now discuss.

To illustrate the usefulness of the method, consider the statistic of time-lag correlation, given in time by

\[
R = \sum_{t=1}^{N} \frac{[x_1(t+r)-\bar{x}_1(t+r)][x_2(t)-\bar{x}_2(t)]}{\sigma_1 \sigma_2}
\]

(A10)

where

\[
\sigma_1 = \left[ \sum_{t=1}^{N} [x_1(t+r)-\bar{x}_1(t+r)]^2 \right]^{1/2}
\]

(A11)

\[
\sigma_2 = \left[ \sum_{t=1}^{N} [x_2(t)-\bar{x}_2(t)]^2 \right]^{1/2}
\]

(A12)

\[
\bar{x}_j = \frac{\sum_{t=1}^{N} x_j(t)}{N}
\]

(A13)

Using (A1) and trigonometric identities, it follows that with our band-pass filtered time series an equivalent form for \( R \) written in frequency is

\[
R = \sum_p \left[ \left[ c_1(p)c_2(p) + s_1(p)s_2(p) \right] \cos(2\pi pr/N) \right. \\
\left. + \left[ c_2(p)s_1(p) - s_2(p)c_1(p) \right] \sin(2\pi pr/N) \right] \\
\left[ \sum_p \left[ c_1^2(p) + s_1^2(p) \right] \Sigma_p \left[ c_2^2(p) + s_2^2(p) \right] \right]^{1/2}
\]

(A14)

(A14) was used in this study for all 6-month seasonally projected correlation analyses, with the harmonic coefficients in (A14) being the
Figure 11. All plots: geopotential height (m) vs. time (days) with wavenumbers 1-10 and 2920 (daily) values in the time series. Top: Original 200 hPa 135°E, equatorial geopotential height time series. Middle: Reconstruction of the original time series following band-pass filtering (see filter, Figure 1b) of harmonic coefficients. Bottom: Same as middle plot, except with the inclusion of a seasonal projection modification of the harmonic coefficients (see III.H) after band-pass filtering.
primed quantities (A6)-(A9). Note that (A14), although very accurate, will be an approximation to $R$ for the seasonal projection case, particularly since it involves multiplying the original data sets $x(t)$ by $g_\pm(t)$ which only approximates the ideal boxcar.

If it is desired to calculate correlations for band-passed data during only 6-month summers or winters, the above time series projection method is an improvement over conventional methods in both computer time and data handling. With or without seasonal projection, band-passed data usually requires only a small number of terms in (A14), and this naturally represents a vast improvement in computer time and data storage over calculating correlation from (A10). Furthermore, in the above time series projection scheme, all data remain as band-passed Fourier harmonic coefficients without requiring an additional inverse transformation back to time.

The general time series projection method is not limited to 6-month seasons. For example, in our study of 8-year time series, choosing the integer $Y$ in (A6)-(A9) as 16, 8, 4, 2, or 1 would result in 3-month, seasonal, annual, 2-year, and 4-year time series projections, respectively.

I. References


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IV. SUMMARY

Low-frequency oscillations on time scales of 1-2 months have been studied throughout the atmosphere, with special emphasis on the stratosphere. Statistically significant 1-2 month oscillations were found to exist throughout the stratosphere, extending from the tropics to the high latitudes in both hemispheres. This study showed that the largest statistical significance of these oscillations in the high stratosphere occurs in the extratropics, due to vertically propagating extratropical planetary waves during winter. A westward tilt with height was observed in the brightness temperature correlation patterns in the mid-to-high southern latitudes, and is consistent with baroclinic processes or vertically propagating Rossby waves. In contrast, the tropical latitudes exhibited small statistical significance in the high stratosphere, and no evidence of direct vertical propagation or tilt of correlation patterns with height.

Statistics calculated from globally gridded 90 hPa brightness temperatures exhibited a connection between the Indian Ocean tropics and SH extratropics. Time-lag correlation plots calculated for 6-month SH winters (April through September) displayed a strong connection between this tropical region and the SH latitudes extending to 80°S. Coherence between the Indian Ocean region and the high SH latitudes showed dominance of a 50-day oscillation over other periods in the LFO spectrum (12.8 to 95 day periods). From observations and model comparisons it was surmised
that the connection is the result of a tropical forcing of the extratropical wave patterns.

A previously discovered 35-60 day 200 hPa SH wavetrain in geopotential heights was also found to be statistically connected to the Indian Ocean tropics. Time-lag correlation plots calculated for 6-month SH winters showed that this wavetrain is likely forced by a source lying along the equatorial Indian Ocean-western Pacific Ocean. Coherence between points along this path and the wavetrain exhibited a dominance of 1-2 month over other periods of the spectrum.

With a 500 hPa equatorial reference point in the Indian Ocean, the correlation statistic revealed poleward and westward propagation of 1-2 month temperature perturbations into both hemispheres, as well as evidence for a connection with temperatures in the high winter stratosphere via vertical propagation of planetary waves. One feature observed was a pulse which split latitudinally into two westward propagating parts; one part moved southward into the winter subtropics, while the other propagated northward. The latter feature, because of easterly NH stratospheric winds, appeared trapped and limited to the troposphere. It was also observed to propagate slowly across India and may be associated with the Indian monsoon. In contrast, the southward propagating part moved west and south to near 35°S, where westerly SH winds in the stratosphere permitted vertical propagation of the long planetary waves upward into the high stratosphere. Thus, the propagation route in the SH winter hemisphere exhibits an "out-then-up" behavior: temperature fluctuations
initially propagate quasi-horizontally out of the Indian Ocean source region into the SH midlatitudes, and then upward.

The Eliassen-Palm flux diagnostic in the stratosphere was calculated for 6-month SH winters; results for both a case study and an 8-year ensemble average were presented. The case study showed that 1-2 month perturbations may at times be responsible for much of the observed changes in the mean flow of the middle stratosphere; however, on the long-term average (eight years), the direct influence from 1-2 month eddy divergence is only of order 10%.
### V. APPENDIX: GLOSSARY

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomaly</td>
<td>The departure of an element from its time-averaged (or spatially-averaged) value.</td>
</tr>
<tr>
<td>Baroclinic</td>
<td>A baroclinic atmosphere is one in which surfaces of constant pressure and constant mass density intersect.</td>
</tr>
<tr>
<td>Barotropic</td>
<td>A barotropic atmosphere is one in which surfaces of constant pressure and constant mass density do not intersect.</td>
</tr>
<tr>
<td>Beta (β) plane</td>
<td>Originating in a model by C. G. Rossby, this is a truncated Taylor series approximation to the Coriolis parameter $f$ (see CORIOLIS PARAMETER) on the spherical earth's surface given by $f = f_0 + \beta(y-y_0)$, where $\beta =$ Rossby parameter (constant), $y =$ northward displacement, and $f_0 =$ constant coriolis parameter at fixed latitude.</td>
</tr>
<tr>
<td>Brightness temperature</td>
<td>Temperature derived directly from radiance. Brightness, luminance, and radiance are often used synonymously.</td>
</tr>
<tr>
<td>Circulation</td>
<td>The flow of a fluid in or through a given area or volume.</td>
</tr>
<tr>
<td>CISK</td>
<td>Conditional Instability of the Second Kind. Cisk occurs when cumulus convection supplies the heat necessary to drive a large-scale disturbance, and the large-scale disturbance produces the moisture convergence necessary to drive the cumulus convection.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Climate</td>
<td>This is the synthesis of the day-to-day values of the meteorological elements that affect the locality.</td>
</tr>
<tr>
<td>Climatology</td>
<td>The study of climate.</td>
</tr>
<tr>
<td>Constituent</td>
<td>One part of the whole, as oxygen is a constituent of the atmosphere.</td>
</tr>
<tr>
<td>Convection</td>
<td>In general, mass motions within a fluid resulting in transport and mixing of the properties of that fluid.</td>
</tr>
<tr>
<td>Coriolis parameter</td>
<td>Defined as $f = 2\Omega \sin \phi$ where $\Omega$ = angular speed of earth $= 7.27 \times 10^{-5}$ rad s$^{-1}$, and $\phi$ = latitude.</td>
</tr>
<tr>
<td>Cumulus</td>
<td>Detached clouds, generally dense and with sharp outlines, developing vertically in the form of rising mounds, domes or towers, of which the bulging upper part often resembles a cauliflower.</td>
</tr>
<tr>
<td>Cyclone</td>
<td>Atmospheric pressure distribution in which there is a low central pressure relative to the surroundings.</td>
</tr>
<tr>
<td>Easterlies</td>
<td>In general, any winds blowing from the east.</td>
</tr>
<tr>
<td>Easterly</td>
<td>An easterly wave is one which propagates from east to west.</td>
</tr>
<tr>
<td>External wave</td>
<td>A wave in fluid motion having its maximum amplitude at an external boundary such as a free surface.</td>
</tr>
<tr>
<td>Extratropics</td>
<td>Denotes latitudes poleward of the tropics ($23^\circ 27'$) in</td>
</tr>
</tbody>
</table>
both hemispheres.

FGGE  
**First GARP Global Experiment.** Extensive measurements of many important variables over the entire globe, from 1978-1979.

**Free surface**  
Generally the upper level of a liquid at which the pressure on the liquid is equal to the external atmospheric pressure, assumed constant.

**GARP**  
Global Atmospheric Research Project.

**Geopotential**  
The potential energy per unit mass of a body due to the earth's gravitational field, and is given by $\Phi = \int g(z') dz'$ integrated from geometric height $z' = 0$ (mean sea level) to $z' = z$. $g(z)$ is the acceleration of gravity, a function of geometric height $z$.

**Geopotential height**  
Equals geopotential/$g_0$, where $g_0 = 9.80665 \text{ ms}^{-2}$ = average acceleration of gravity at mean sea level.

**Geostrophic**  
Referring to the balance, in the atmosphere, between the horizontal coriolis forces and horizontal pressure forces. Denoting the zonal (meridional) geostrophic velocity by $U$ ($V$), $\Phi$ as geopotential, $f$ as the coriolis parameter, and subscripts $x$ and $y$ as zonal and meridional partial differentiations, respectively, it follows from the primitive equations that $U = -\Phi_y/f$, and $V = \Phi_x/f$.

**Gravity wave**  
A wave disturbance in which buoyancy acts as the restoring force on parcels displaced from hydrostatic
equilibrium. Waves may combine longitudinal and transverse displacements of parcels relative to the direction of propagation. Typical period: minutes to hours. Typical horizontal (vertical) wavelength: 100 km (10 km).

**Internal wave**
A wave in fluid motion which has its maximum amplitude inside the fluid, or at an internal boundary.

**Kelvin wave**
An eastward propagating tropical wave in which the zonal velocity and meridional pressure fields are in exact geostrophic balance so that on the equatorial $\beta$ plane the meridional velocity is identically zero and the wave can propagate as an ordinary two-dimensional internal gravity wave. Typical period: 10–20 days. Typical zonal wavenumber: 1–2. Typical vertical wavelength: 6–10 km.

**Log-pressure vertical coordinate $z$**
Vertical coordinate $z = -H \log(p/p_0)$ where $H$ = scale height (constant), $p$ = pressure, $p_0$ = constant standard reference pressure (usually taken as 1000 hPa), and log denotes natural logarithm.

**Meridional**
In meteorology, this refers to the northward or southward directions. The meridional cartesian coordinate (velocity) is usually denoted by "y" ("v") and points northward toward the pole.

**Mesosphere**
Part of the atmosphere between the stratopause (near 50 km) and the mesopause (near 80 km), in which temperature generally falls with increasing height.
Monsoon

A name for seasonal winds. It was first applied to the winds over the Arabian Sea, which blow for six months from northeast and for six months from the southwest, but it has been extended to similar winds in other parts of the world.

MSU4

Microwave Sounding Unit channel 4. This is a satellite instrument which measures the 5.5 μm oxygen band, effectively "seeing" a portion of the atmosphere from 30-150 hPa centered near 90 hPa (approximately 17 km altitude).

NMC

National Meteorological Center, Washington D.C.

OLR

Outgoing Longwave Radiation. Radiation emitted from the earth in the infrared, used to identify regions of convection. Large (small) OLR means small (large) convection.

Potential temperature $\theta$

$\theta$ is defined by $\theta = T(p_0/p)^\kappa$ where $p$ = pressure, $p_0$ is a constant pressure (usually taken as 1000 hPa), $T$ is absolute temperature, and $\kappa$ is a dimensionless parameter (see PRIMITIVE EQUATIONS). $\theta$ is the temperature which a parcel of dry air at pressure $p$ and temperature $T$ would have if it were compressed or expanded adiabatically to the pressure $p_0$.

Primitive equations

As shown by Andrews et al. (1987), the spherical set of equations with log-pressure coordinate $z$ in the vertical is as follows:
\[
\frac{Du}{Dt} = -\frac{\Phi}{a \cos(\phi)} + \left[ f + \frac{u \tan \phi}{a} \right] v + X \text{ zonal momentum balance}
\]

\[
\frac{Dv}{Dt} = -\frac{\Phi}{a} - \left[ f + \frac{u \tan \phi}{a} \right] u + Y \text{ meridional momentum balance}
\]

\[
\Phi_z = H^{-1} \mu^{-1} R \theta \exp(\kappa z/H) \quad \text{vertical hydrostatic balance}
\]

\[
\frac{u}{a \cos \phi} + \frac{(\rho\omega)^2}{\rho_0} = 0 \quad \text{continuity of mass balance}
\]

\[
\frac{D\theta}{Dt} = Q = \left( J/c_p \right) \exp(\kappa z/H) \quad \text{thermodynamic equation with diabatic heating Q}
\]

where \((u, v, w)\) is the (zonal, meridional, vertical) velocity, \(\Phi\) is geopotential, \(t\) is time, \(X\) (\(Y\)) is zonal (meridional) friction, \(\lambda\) is longitude, \(\phi\) is latitude, \(a\) is radius of earth, \(f\) is coriolis term, \(\theta = \text{potential temperature (see POTENTIAL TEMPERATURE)}\), \(c_p = \text{mass specific heat of dry air with pressure held constant} = 1004 \text{ J K}^{-1} \text{kg}^{-1}\), \(J = \text{diabatic heating rate per unit mass, } \kappa = R/(\mu c_p) = 0.286 \text{ (unitless)}\), \(\rho_0 = \rho_{00} \exp[-z/H] \quad (\rho_{00} = \text{constant = mass density at sea level})\), subscripts \(\lambda, \phi, z\) denote partial differentiation by longitude, latitude, and log-pressure coordinate, respectively, and the "material derivative" operator is defined as

\[
\frac{D}{Dt} = \frac{\partial}{\partial t} + \frac{u}{a \cos \phi} \frac{\partial}{\partial \lambda} + \frac{v}{a} \frac{\partial}{\partial \phi} + w \frac{\partial}{\partial z}.
\]

(See SCALE HEIGHT for any other parameters not defined above.)

Note the "velocity" components:

\[
(u, v, w) = \left[ \frac{D\lambda}{Dt}, \frac{D\phi}{Dt}, \frac{Dz}{Dt} \right].
\]
Quasi-Biennial Oscillation (QBO). This is predominantly an oscillation of the equatorial zonal wind in the low stratosphere with an oscillation period which varies from approximately 24 to 30 months.

Quasi-geostrophic In general, the use of the assumption of geostrophic equilibrium in certain contexts of the equations of motion, but not in others.

Rawinsonde A method of upper-air observation consisting of a balloon-borne radio transmitter which can evaluate wind speed and direction, temperature, pressure, and relative humidity.

Rossby parameter Defined by \( \beta = \frac{df}{dy} = (2\Omega/a) \cos \phi = \) northward rate of change of the coriolis parameter \( f \) (see CORIOLIS PARAMETER). Variable \( y \) is the meridional cartesian coordinate, \( \Omega \) = angular (circular) speed of earth = \( 7.27 \times 10^{-5} \) rad sec\(^{-1} \), \( a \) = radius of earth = 6.37 km, and \( \phi \) = latitude.

Rossby wave An alternate for "long wave" or "planetary wave". In synoptic meteorology, this is a smooth, wave-shaped contour pattern on an isobaric chart with a wavelength of about 2000 km. With \( U = \) mean zonal wind, \( \beta \) = Rossby parameter, and \( \lambda = \) wavelength, the eastward phase speed \( c \) is given approximately by \( c = U - \beta \lambda^2/4\pi^2 \). Typical period: days, to perhaps more than a month. Typical zonal wavenumbers: 1-5.

Scale Height This is the parameter \( H \) occurring in the definition of log-pressure coordinate (see LOG-PRESSURE COORDINATE).
In a hypothetical atmosphere in which temperature is constant, both air pressure and mass density are proportional to $\exp(-z/H)$ where $z =$ geometric height. $H$ is then given by $H = \frac{RT}{\mu g}$, where $R =$ gas constant $= 8314 \text{ J kmol}^{-1} \text{ K}^{-1}$, $T =$ absolute temperature (K), $\mu =$ mean molecular weight $\approx 29 \text{ kg kmol}^{-1}$ and $g =$ mean acceleration of gravity at sea level $= 9.80665 \text{ m sec}^{-1}$. In the troposphere or stratosphere, a mean temperature 250K yields $H \approx 7.3 \text{ km}$.

**SSU**

Stratospheric Sounding Unit. This is a satellite instrument which employs a selective absorption technique for carbon dioxide, effectively "seeing" a portion of the atmosphere centered near 28 km (15 hPa), 35 km (5 hPa), and 44 km (1.5 hPa), corresponding to the channels SSU1, SSU2, and SSU3, respectively.

**Stratosphere**

The region of the atmosphere lying above the troposphere and below the mesosphere, where, in contrast to these regions, temperature increases with increasing height. The stratosphere therefore extends from the tropopause (near 16 km in the tropics and 9 km at the poles) to the stratopause (near 50 km).

**Subtropics**

Denotes latitudes between the tropics (between latitudes $23^\circ 27'$ north and south) and the "temperate regions" whose boundaries are near $40^\circ$ in both hemispheres.

**Synoptic**

In meteorology, pertaining to an overall view at a given moment in time.
TOMS
Total Ozone Mapping Spectrometer. A satellite instrument which measures a total vertical column of ozone, downward from the position of the satellite to the surface of the earth.

Tropics
Denotes latitudes equatorward of 23° 27' north and south.

Troposphere
The lowest region of the atmosphere extending upward to the tropopause (from approximately 16 km in the tropics to 9 km at the poles).

Walker cell
In the height versus longitude plane along the equator, this is a large-scale zonal circulation cell of convection known to occur over the Pacific Ocean.

Wavenumber
The number of complete wavelengths fitting around the globe, particularly along the zonal direction (east-west).

Westerlies
In general, any winds blowing from west to east.

Westerly
A westerly wave is one which propagates from west to east.

Zonal
In meteorology this means along the eastward or westward direction. The cartesian zonal coordinate (velocity) is usually denoted by "x" ("u") and is directed eastward.
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