Diurnal and Semidiurnal Tides in Global Surface Pressure Fields

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ABSTRACT

Global surface pressure data from 1976 to 1997 from over 7500 land stations and the Comprehensive Ocean–Atmosphere Data Set have been analyzed using harmonic and zonal harmonic methods. It is found that the diurnal pressure oscillation \( S_1 \) is comparable to the semidiurnal pressure oscillation \( S_2 \) in magnitude over much of the globe except for the low-latitude open oceans, where \( S_2 \) is about twice as strong as \( S_1 \). Over many land areas, such as the western United States, the Tibetan Plateau, and eastern Africa, \( S_1 \) is even stronger than \( S_2 \). This is in contrast to the conventional notion that \( S_2 \) predominates over much of the globe. The highest amplitudes \((~1.3 \text{ mb})\) of \( S_1 \) are found over northern South America and eastern Africa close to the equator. Here \( S_2 \) is also strong \((~1.1 \text{ mb})\) over high terrain such as the Rockies and the Tibetan Plateau. The largest amplitudes of \( S_1 \) \((~1.0–1.3 \text{ mb})\) are in the Tropics over South America, the eastern and western Pacific, and the Indian Ocean. Here \( S_2 \) peaks around 0600–0800 LST at low latitudes and around 1000–1200 LST over most of midlatitudes, while \( S_1 \) peaks around 1000 and 2200 LST over low- and midlatitudes. Here \( S_1 \) is much stronger over the land than over the ocean and its amplitude distribution is strongly influenced by landmasses, while the land–sea differences of \( S_2 \) are small. The spatial variations of \( S_1 \) correlate significantly with spatial variations in the diurnal temperature range at the surface, suggesting that sensible heating from the ground is a major forcing for \( S_1 \). Although \( S_2 \) is much more homogeneous zonally than \( S_1 \), there are considerable zonal variations in the amplitude of \( S_2 \), which cannot be explained by zonal variations in ozone and water vapor. Other forcings such as those through clouds’ reflection and absorption of solar radiation and latent heating in convective precipitation are needed to explain the observed regional and zonal variations in \( S_2 \). The migrating tides \( S_1 \) and \( S_2 \) predominate over other zonal wave components. However, the nonmigrating tides are substantially stronger than previously reported. The amplitudes of both the migrating and nonmigrating tides decrease rapidly poleward with a slower pace at middle and high latitudes.

1. Introduction

Of the 342 W m\(^{-2}\) of solar radiation reaching the top of the atmosphere, about 168 W m\(^{-2}\) are absorbed by the earth’s surface and 67 W m\(^{-2}\) are absorbed by the atmosphere (43 W m\(^{-2}\) by water vapor, 14 W m\(^{-2}\) by ozone, 7 W m\(^{-2}\) by clouds, and 3 W m\(^{-2}\) by \( O_3 \) and \( CO_2 \) ) (Kiehl and Trenberth 1997). This atmospheric solar heating, combined with upward eddy conduction of heat from the ground, generates internal gravity waves in the atmosphere at periods of the integral fractions of a solar day (primarily at the diurnal and semidiurnal periods). These waves cause regular oscillations in atmospheric wind, temperature, and pressure fields, which are often referred to as atmospheric tides (Wallace and Hartranft 1969; Chapman and Lindzen 1970; Haurwitz and Cowley 1973; Hsu and Hoskins 1989; Whiteman and Bian 1996). Due to the fact that 24 hours are longer than the local pendulum day (the period corresponding to the local Coriolis parameter) poleward of 30° lat, the diurnal tide is incapable of propagating vertically over these regions to reach the ground (Lindzen 1967). Although the diurnal tide is often suppressed at the ground, its amplitude in the upper atmosphere is comparable with, and may be much larger than, the semidiurnal tide. In the surface pressure field, the semidiurnal oscillation \( S_2 \) is thought to predominate over much of the globe, and is regularly distributed in its amplitude (which is about 1 mb in the Tropics and decreases poleward) and phase \((S_2 \text{ usually peaks 2–3 h before noon})\).
and midnight). The classic tidal theory (Chapman and Lindzen 1970) predicts that solar heating through ozone explains about two-thirds of $S_1$'s amplitude while water vapor and heating from the ground account for the rest. Oscillation $S_1$ is dominated by its wavenumber 2 mode $S_1^2$ (moving westward at the speed of the mean sun) (Haurwitz and Cowley 1973). In contrast to $S_2$, the diurnal oscillation $S_1$ in the surface pressure field is very irregularly distributed and is influenced strongly by landmasses. Water vapor heating provides a much larger contribution to $S_1$ than ozone heating (Groves and Wilson 1982). Locally, diurnal temperature and wind variations can greatly increase the amplitude of $S_1$.

Model calculations with more recent ozone and water vapor heating profiles suggest that additional heating is needed in order to explain the observed amplitude of $S_1$ and $S_2$ (Groves and Wilson 1982; Braswell and Lindzen 1998). Forbes and Garrett (1979) suggested that nonmigrating tides (which depend on both local time and longitude) could be excited by orographic features and longitudinal variations in water vapor and ozone. Model simulations suggest that the upward sensible heat flux from the ground due to solar heating contributes significantly to the nonmigrating components of $S_1$ (Tsuda and Kato 1989). The migrating component (which is a function of local time) of $S_1$ is underestimated by more than one-third by the classic tide theory even with the updated ozone and water vapor heating (Braswell and Lindzen 1998). The latent heat associated with convective precipitation, which has a strong diurnal cycle (Dai et al. 1999a), was found to be important mostly for $S_2$ (Lindzen 1978). It is suggested that the recently debated anomalous solar absorption by clouds or water vapor, which is not included in the radiation fluxes from Kiehl and Trenberth (1997) cited above, could significantly reduce this gap between the theory-predicted and the observed $S_1$ (Braswell and Lindzen 1998).

Besides heating, there is also a mass forcing on surface pressure tides resulting from the imbalance between evaporation and precipitation, which is significant globally on seasonal timescales (about 0.2 mb) (van den Dool and Saha 1993; Trenberth and Guillemot 1994). We know that evaporation peaks during the day (at least over the land), while precipitation occurs more frequently during early morning over the ocean (Janowiak et al. 1994) and in the afternoon over many land areas (Dai et al. 1999a). As the sun moves over the oceans (land), global evaporation is likely to increase (decrease). These diurnal variations are likely to induce a diurnal cycle of net water flux at the surface, which could provide an additional forcing for surface pressure tides. However, we are unaware of any studies addressing this mass forcing.

Because the longitude-dependent nonmigrating diurnal tides are nonnegligible at the surface and mixed up with the migrating tides, the migrating tides can be determined only from data around a latitude circle (Lindzen 1979). Most of our observational knowledge of $S_1$ and $S_2$ on a global scale comes from the analyses of surface pressure data from about 250 stations done by Haurwitz et al. from the 1950s to the early 1970s (Haurwitz 1956; Haurwitz 1965; Haurwitz and Cowley 1973). A majority of these stations were located in western Europe and North America while only about 50 of them were in the Southern Hemisphere. Most of the open oceans were not covered at all in these analyses. Obviously, the global distributions of $S_1$ and $S_2$ and their seasonal variations derived from such a limited spatial coverage should be interpreted with caution. Furthermore, the sparse spatial sampling and coarse grid resolution (15° long by 10° lat) used by Haurwitz and Cowley (1973) make their results of wave components likely to be unreliable, especially at high wavenumbers. Nevertheless, the $S_1$ and $S_2$ maps and their main wave components from these analyses have been widely cited and applied in the literature (e.g., Tsuda and Kato 1989; Lindzen 1990; Whiteman and Bian 1996; Deser and Smith 1998; Braswell and Lindzen 1998). Hamilton (1980a) updated Haurwitz's dataset by adding 35 new stations (only two of them in the Southern Hemisphere). Regional analyses of $S_1$ and $S_2$ (e.g., Trenberth 1977; Mass et al. 1991; Kong 1995) revealed more small-scale features. More recent efforts to document global variations of $S_1$ and $S_2$ by analyzing the European Centre for Medium-Range Weather Forecasts analysis (Hsu and Hoskins 1989) and National Centers for Environmental Prediction (NCEP) reanalysis (van den Dool et al. 1997) 6-hourly data were hampered by the coarse temporal resolution of the data as well as the deficiencies of the models.

In this study, we update the earlier analyses and document $S_1$ and $S_2$ on a global scale by analyzing 3-hourly surface pressure data from 1976 to 1997 from all the land and ocean weather stations included in the Global Telecommunication System (GTS) and the marine reports from the Comprehensive Ocean–Atmosphere Data Set (COADS). There are about 15 000 stations included in GTS, but only 4000–7000 stations report at any given time, which still provides good spatial coverage over all the continents and islands except the Antarctic. The COADS data include most of the reports from commercial ships and various kinds of buoys and provide fairly good coverage of the global oceans during the 1976–97 period. We also analyzed the 3-hourly surface pressure data from 1980 to 1994 from the reanalysis with version 1 of the Goddard Earth Observing System (GEOS-1) Data Assimilation System (DAS) and found that the amplitudes of $S_1$ and $S_2$ of the reanalysis data tend to be smaller in high latitudes and larger in low latitudes than observed. We applied harmonic analysis to derive the amplitudes and phases of $S_1$ and $S_2$, and zonal harmonic analysis (Haurwitz and Cowley 1973) to decompose $S_1$ and $S_2$ into various zonal wave components. We also compared the geographical and seasonal patterns of $S_1$ and $S_2$ with those of atmospheric total column ozone, atmospheric precipitable water, and...
sensible heat flux from the earth’s surface [which is approximated by the mean diurnal range of surface air temperature (DTR)]. We find that spatial variations in the amplitude of \( S_1 \) are strongly correlated with DTR, suggesting that sensible heat flux is a major forcing for \( S_1 \) over land areas.

In section 2, we describe the datasets used in this study. Harmonic and zonal harmonic analysis methods are described in section 3. The global distributions of \( S_1 \) and \( S_2 \), their seasonal variations, and zonal wave components are presented and compared with earlier studies in section 4. In section 5 we compare the seasonal and spatial patterns of \( S_1 \) and \( S_2 \) with those of atmospheric total column ozone, atmospheric precipitable water, and DTR. A summary is given in section 6.

2. Data

The 3-hourly surface pressure data were extracted from the GTS synoptic weather reports archived at the National Center for Atmospheric Research (NCAR) (DS464.0; http://www.scd.ucar.edu/dss/datasets/ds464.0.html). This surface dataset, which covers the time period from July 1976 to April 1997 and has a volume of about 2.5 GB per year, contains 3-hourly (0000, 0300, 0600 UTC, etc.) surface pressure measurements from about 15,000 land and ocean stations and 6-hourly marine reports from commercial ships and buoys. Because the spatial coverage of this dataset is poor over the equatorial Pacific and the southern oceans, we also processed individual marine reports from the COADS dataset (Woodruff et al. 1993) from January 1976 to December 1995 (data after 1995 had not been released at the time of analysis). The COADS reports include hourly data from a small number of buoys and 6-hourly and 3-hourly data from ships and buoys. We used the COADS reports at the GTS 3-hourly reporting times (i.e., 0000, 0300, 0600 UTC, etc.). The number of reports of surface pressure at 0300, 0900, 1500, and 2100 UTC is generally less than that at 0000, 0600, 1200, and 1800 UTC for both the GTS and COADS datasets, especially over the southern oceans in the COADS data.

In contrast to the fixed land stations, the ships and many of the buoys are moving and thus their reports do not have a fixed long–lat location. Thus, we averaged individual marine reports within each 2.5° long by 2° lat box to obtain a mean value for each grid box at each reporting time. Land and fixed ocean stations were analyzed individually for the amplitude and phase of \( S_1 \) and \( S_2 \), which were then combined with those from the gridded marine data. The amplitude and phase were further gridded onto a 5° long \( \times 4° \) lat grid using the natural neighbor interpolation method (Watson 1994). The gridded amplitudes and phases were then used in the plotting and zonal harmonic analysis.

Over the southern oceans (i.e., south of about 50° S) and some parts of the central equatorial Pacific, surface pressure data are available only at 0000, 0600, 1200, and 1800 UTC. These 6-hourly marine reports are not sufficient for sampling the semidiurnal cycle. Previous analyses (e.g., Haurwitz and Cowley 1973) and the 3-hourly GEOS-1 reanalysis data (which have a global coverage) indicated that relative to local time the semidiurnal cycle does not change rapidly in the longitudinal direction over the oceans. This allowed us to use reports (after the daily mean is removed) 10° to the east (40 min later) and to the west (40 min earlier) to supplement the 6-hourly data at some (~15%) of the ocean grid boxes (away from coastlines). This resulted in 12 reports per day (0000, 0040, 0520, 0600, 0640 UTC, etc.) at these ocean boxes. Sampling tests with given diurnal and semidiurnal harmonics showed that the 3-hourly even sampling (i.e., 0000, 0300, 0600 UTC, etc.) and the supplemented 12 reports day$^{-1}$ sampling are sufficient to exactly reproduce the original harmonics.

The individual observations at each synoptic hour were averaged over each season (DJF = December–February, MAM = March–May, JJA = June–August, and SON = September–November) for each year. For the seasonally averaged values to be used in our harmonic analysis, we required at least seven of the eight synoptic hours to have data for the land stations and eleven of the twelve supplemented synoptic hours to have data for the marine boxes. About 7500 GTS stations meet this requirement with 4 or more yr of data during the 1976–97 period. Of the stations, about 4500 stations have at least 10 yr of data during the period. GTS stations and the ocean grid boxes with less than 4 yr of data were excluded from our analysis. Mass et al. (1991) showed that over the United States using more than 4 yr of data did not change the results of \( S_1 \) and \( S_2 \). The stations and ocean boxes with sufficient data that were used in our analysis are shown in Fig. 1. It can be seen that the station and marine observations provide good coverage over the globe except for the Antarctic, the Arctic Ocean, and the southern Pacific (south of 52° S and 70°–180° W) where the data are sparse. Given the relatively large-scale nature of \( S_1 \) and \( S_2 \), the spatial coverage of Fig. 1 should be sufficient for capturing the large-scale (>500 km) features of \( S_1 \) and \( S_2 \), especially over the Northern Hemisphere.

The annual-mean surface pressure data (expressed as anomalies relative to daily mean values) used to derived annual \( S_1 \) and \( S_2 \) are shown in Fig. 2. It can be seen that the westward-propagating wavenumber 2 mode predominates over low and middle latitudes but becomes less evident at high latitudes. The anomalies are largest over South America and Africa. Figure 2 is qualitatively consistent with the global patterns in the semidiurnal component of atmospheric pressure velocity \( \omega \) (Trenberth et al. 1995), assuming that \( \omega \) represents vertical motion of the air.

The station and marine data of surface pressure potentially contain various errors. For example, the surface pressure data are resolved to the nearest 0.1 mb, which is a substantial fraction of the amplitudes of \( S_1 \) and \( S_2 \).
(about 1 mb at low latitudes and 0.2–0.5 mb at high latitudes). However, the measurement errors are likely to be random and thus are significantly reduced after averaging over the seasons and the 22-yr period. Another error may result from changes in barometers. Cooper (1984) shows that the amplitudes of the pressure tides may change by up to 20% due to changes in mercury barometers mainly because different barometers have different temperature corrections. Both mercury and aneroid barometers are used at land stations and on ships. It will be very difficult, if possible at all, to quantify the systematic errors associated with various types of barometers in all the station and marine records. We will compare our results to those based on the data before the 1970s when mercury barometers were often used. Furthermore, the phase estimated from the relatively coarse temporal sampling (3-h interval) will have an uncertainty up to ±1.5 h. In our analysis temporal averaging and spatial smoothing were applied to emphasize the mean large-scale features. It is likely that the maximum amplitudes shown in this study may be lower than those at individual stations because of the smoothing used in contouring.

Because of its global coverage, especially over the oceans, we also analyzed the 3-hourly averaged surface pressure dataset from the reanalysis with the GEOS-1 DAS (Wu et al. 1997). This monthly dataset covers the period from 1980 to 1994 and is on a 2.5° × 2° global grid. While the data assimilation model incorporates surface observations, the model itself has a significant influence on the assimilated surface pressure field. Since the pressure data are averaged over a 3-h period, the calculated amplitudes of $S_1$ and $S_2$ need to be multiplied by a factor ($F$) to obtain the real amplitudes that one would get from using instantaneous values (such as from the station data). The factor $F = \frac{\omega \Delta t}{2 \sin(\omega \Delta t/2)}$ where $\omega$ is the angular frequency and $\Delta t$ is the averaging time period (3 h), can be easily derived by averaging a sine function over a given period. Here $F = 1.0262$ for $S_1$ and 1.1107 for $S_2$, with $\omega = \frac{2 \pi}{24}$ for $S_1$ and $\frac{2 \pi}{12}$ for $S_2$.

3. Analysis methods

We applied harmonic and zonal harmonic analyses to extract the solar diurnal and semidiurnal oscillations from the surface pressure data. We followed the analysis procedure described by Haurwitz and Cowley (1973). The surface pressure data at each location are represented by

$$P(t') = P_0 + S_1(t') + S_2(t') + \text{residual}$$

$$S_n(t') = A_n \sin(n't' + \sigma_n) = a_n \cos(n't') + b_n \sin(n't'),$$

where $P_0$ is the daily mean pressure, $A_n$ is the amplitude (note: the peak-to-peak amplitude is $2A_n$), $\sigma_n$ the phase, $t'$ local mean solar time (LST) expressed in degrees or radians (i.e., $t' = 2\pi t'/24$, where $t$ is LST in hours). The 3-hourly station data and the supplemented marine data are insufficient for resolving harmonics with periods shorter than 12 h. Although accurate estimates of these high-order harmonics are not available over most of the globe, some analyses of hourly data showed that these high-order harmonics (primarily $S_3$) are much (at least a factor of 4–5) smaller than $S_1$ or $S_2$ (Trenberth...
FIG. 2. Annual-mean surface pressure anomalies (mb) relative to daily mean values at the 3-hourly observation times derived by averaging and gridding the station and marine pressure data of the 1976–97 period. Negative values are hatched. Contour interval is 0.4 mb. Plots for seasonal mean pressure are similar.
which effectively smooths out variations on scales less
than 5°. Substituting Eqs. (3) and (4) into (2), replacing \( t \) with \( t' - \lambda \), after some trigonometric
transformations (2) becomes (Haurwitz and Cowley 1973)

\[
S_n(t) = \sum_{\lambda=-\infty}^{\infty} \left[ a_n^s \cos(nt + s\lambda) + b_n^s \sin(nt + s\lambda) \right]
\]

where the \( k_n^s \), \( l_n^s \), \( q_n^s \), and \( r_n^s \) depend on \( \theta \). The differences between the DJF and JJA amplitudes
of \( S_1 \) are large over many land areas. For example, the
amplitude over central Australia is about 0.9–1.1 mb in
DJF compared with about 0.6–0.7 mb in JJA. The geo-
graphic distribution of the JJA minus DJF amplitude
difference suggests that the seasonal, meridional move-
ment of the maximum solar heating zone or the inter-
tropical convergence zone (ITCZ) is the main cause for
seasonal variations of \( S_1 \). For example, as the ITCZ
moves into the Northern Hemisphere in JJA over the
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of \( S_1 \) in northern subtropics and midlatitudes increases
to about 0.6 mb and does not decrease monotonically pole-
to the equator. The next largest amplitudes (~1.1 mb)
are in the Rocky Mountains and the Tibetan Plateau.
Over the open oceans, the amplitude ranges from 0.3
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substantially from Fig. 3. For example, the high-amplitude center over North America extends from the southwestern United States to northern Mexico in Haurwitz and Cowley’s (1973) results, while it is confined mostly to the western United States in Fig. 3. These differences likely result from the poor station coverage over these regions in Haurwitz and Cowley’s (1973) work (e.g., there were only 5–6 stations from the Rockies to Mexico and no stations in northern and central South America except a few on the eastern coast). The magnitude and regional patterns of the amplitudes shown in Fig. 3 are consistent with (although slightly lower due to smoothing than) those of Trenberth (1977) over New Zealand, Mass et al. (1991) over the United States, and Kong (1995) over Australia.

Figure 4 shows the phase (reported as $T_{\text{max}}$, the local time when the $S_1$ maximum occurs) of $S_1$ for annual surface pressure; plots for seasonal $S_1$ are similar. It can be seen that the land–sea differences in the phase are small, in contrast to the distribution of the amplitudes. Over low latitudes ($30^\circ S$–$30^\circ N$), $S_1$ reaches maxima in the morning around 0600–0800 LST (phase $\sigma_1 = 0^\circ$–$30^\circ$). In both northern and southern midlatitudes, $S_1$ peaks in the late morning around 1000–1200 LST ($\sigma_1 = 300^\circ$–$270^\circ$), except in eastern Asia and the North Pacific where $T_{\text{max}}$ is around 0600–0800 LST. This is in
Fig. 4. Local solar time $T_{max}$ (h) when the diurnal oscillation, $S_1$, of annual surface pressure reaches its maximum. Here $S_1$ is represented by $S_1 = A_1 \sin(2\pi t/24)$, where $A_1$ is the amplitude shown in Fig. 3, $t$ local solar time in hours, and phase $\sigma_1 = \pi/2 - 2\pi T_{max}/24$.

Contrast to Haurwitz and Cowley’s (1973) findings where the maximum of $S_1$ tends to occur in midlatitudes about 90 min earlier in the Southern Hemisphere than in the Northern Hemisphere. Trenberth (1977) reported a phase of about +30° to −30° (or $T_{max} = 0400$–0800 LST) over New Zealand for annual $S_1$, which is similar to that shown in Fig. 4. Mass et al. (1991) found a $T_{max}$ of about 0700 LST for $S_1$ over the United States, which is about 1–2 h earlier than that shown in Fig. 4. Kong (1995) showed a phase of 360°–320° (or $T_{max} = 0600$–0840 LST) over Australia, which is in good agreement with Fig. 4. Van den Dool (1997) found a $T_{max}$ of 0500–0600 LST around the equator, which is consistent with Fig. 4, although there are more zonal variations in Fig. 4. It should be pointed out that the phase estimated from station data can vary considerably from one station to another on small scales (Trenberth 1977) and the error bars are likely to be large [note that $\sigma_1$ is estimated based on $\tan^{-1}(a_1/b_1)$ from Eq. (2)]. Figure 4 shows only the large-scale patterns of the phase.

2) ZONAL WAVE COMPONENTS

Figure 5 shows the globally averaged amplitudes for wave components at wavenumber $s = −14$ to +15 for DJF, JJA, and annual $S_1$. The wavenumber 1 component, $S_1^1$, has a global mean amplitude of about 370 μb (1 μb = 10−3 mb), whereas the next closest amplitude ($S_1^2$) is about 100 μb. The amplitudes at higher wavenumbers decrease very slowly. We found that low grid resolution and smoothing used in deriving $S_1$ can significantly reduce the high wavenumber components and enhance $S_1^1$ (same is true for $S_2$ where the main component is $S_2^1$). The seasonal differences in the wave components are small.

Haurwitz and Cowley (1973) showed a global mean amplitude of about 410 μb for annual $S_1$ and much lower amplitudes ($≈20$–30 μb) at the high ($s \leq −4$ and $s >$
6) wavenumbers. Also, $S_{1}^{3}$ is not much stronger than the adjacent ones, in contrast to Haurwitz and Cowley’s (1973) findings. These differences are expected because Haurwitz and Cowley (1973) used a much coarser grid (15° long by 10° lat), which cannot adequately resolve the higher components.

The amplitude of the main wave $S_{1}^{1}$ for annual pressure is about 626 $\mu$b at about 4°S and decreases rapidly to the north and south (Fig. 6), with a slower pace in northern subtropics and a secondary peak around 48°S. Oscillation $S_{1}^{1}$ is weaker in JJA than in DJF over low latitudes and southern midlatitudes, but stronger in JJA than in DJF north of about 20°N, which is consistent with the seasonal differences shown in Fig. 3.

Haurwitz and Cowley (1973) used $\cos^{3}\theta$ to represent the latitudinal dependence of the amplitude of $S_{1}^{1}$. We found that $\cos^{3}\theta$ or higher-order polynomials of $\cos\theta$ do not represent well the dependence of $S_{1}^{1}$ on latitude. It is interesting to note that classic tidal theory also predicts slow decreases or secondary peaks of $S_{1}^{1}$ over the subtropics (Braswell and Lindzen 1998).

The amplitudes of waves at higher wavenumbers also decrease poleward but at a slower pace than that for $S_{1}^{1}$ (Fig. 7). Figure 7 shows that besides $S_{1}^{1}$ other westward propagating waves ($s > 1$) are stronger than the eastward propagating waves ($s < 0$) in the 20°–50°N zone, whereas waves at $s = -2$–$-4$ are slightly stronger than waves at $s = 3$–5 over southern low latitudes (0°–30°S).

b. The solar semidiurnal oscillation, $S_{2}$

1) Global distributions of amplitude and phase

The amplitude of $S_{2}$ (Fig. 8) is more homogeneous zonally than that of $S_{1}^{1}$ (cf. Fig. 3) and is largest (~1.0–1.3 mb) in the Tropics over South America, the eastern and western Pacific, and the Indian Ocean. Here $S_{2}$ generally decreases poleward with largest gradients in the subtropics. The amplitude is about 0.3–0.6 mb over middle and high latitudes. The land–sea differences at a given latitude are relatively small compared with $S_{1}^{1}$.

Figure 8 shows that the zone of maximum amplitude (≥1.0 mb) of $S_{2}$ extends northward to about 20°N in DJF. This is in contrast to $S_{1}^{1}$ whose maximum-amplitude zone moves northward and southward in phase with the ITCZ. The amplitude is about 0.1–0.3 mb smaller in JJA than in DJF over the Tropics. Over midlatitudes, seasonal variations of $S_{2}$ are small, although $S_{2}$ is slightly weaker in JJA than in DJF over northern midlatitudes.

Compared with Haurwitz and Cowley (1973), Fig. 8 reveals more regional and zonal variations, although the magnitude of the amplitude is comparable over most of the areas. Figure 8 also shows maximum amplitudes of $S_{2}$ over the eastern tropical Pacific, where Haurwitz and Cowley (1973) had no data. Figure 8 is also consistent with the regional analyses of Trenberth (1977), Mass et al. (1991), and Kong (1995).

Figures 9, 3, and 8 show that although $S_{2}$ is generally stronger than $S_{1}^{1}$ over the oceans, $S_{2}$ is comparable to or stronger than $S_{2}$ over most land areas, especially in summer and over high terrain such as the western United States and the Tibetan Plateau. During JJA, $S_{2}$ is substantially stronger than $S_{2}$ over all Northern Hemisphere land areas. This is in contrast to the conventional notion (based on analyses of limited data before the 1970s) that $S_{2}$ predominates over much of the globe, a paradox that the classic theory of atmospheric tides was developed to solve (Chapman and Lindzen 1970; Lindzen 1990).

Figure 10 shows that for annual pressure $S_{2}$ peaks around 1000 and 2200 LST (phase $\sigma_{2} = 150°$) at low- and midlatitudes, which is in good agreement with Haurwitz (1956). The phase is noisy at high latitudes, because of few observations and weak tidal signals there. The phase of $S_{2}$ does not change substantially from season to season. The land–sea differences in the phase are small.

To compare with earlier estimates of $S_{2}$ of North
America (Spar 1952a; Hamilton 1980a,b) and the North Atlantic Ocean (Rosenthal and Baum 1956), which were derived using the data from the 1930s to the 1950s when pressure was likely to be measured by barometers different to those of recent decades, we plotted the amplitude and $T_{\text{max}}$ of annual $S_2$ for the North Atlantic and North America domain (Fig. 11).

Comparison with Rosenthal and Baum (1956), who analyzed 3-hourly data from nine ship stations in the North Atlantic, revealed that our estimated amplitudes of $S_2$ are slightly higher (0.4 mb vs 0.3 mb) over the high-latitude Atlantic (50°–60°N) while the amplitudes are similar at the lower latitudes (35°–50°N, about 0.5–0.7 mb in winter and 0.4–0.5 in summer). However, our $S_2$ is less uniform zonally and increases slightly eastward in the North Atlantic. Rosenthal and Baum (1956) found a phase ($T_{\text{max}}$) of 0900–1100 LST for $S_2$ over the North Atlantic, which is comparable to Fig. 11. Based on the 1931–40 mean hourly pressure data from 100 U.S. stations, Spar (1952a) showed that the amplitude of annual $S_2$ decreases from about 0.8 mb at the southern border to about 0.3 mb at the northern border of the contiguous United States and the phase ($T_{\text{max}}$ of annual $S_2$) is between 0930 and 1100 LST over the United States. Both the amplitude and phase are in good agreement with Fig. 11. Our $S_2$ over Canada (Fig. 11) is also comparable to earlier results of Hamilton (1980b), who analyzed 3-hourly surface data of 1951–60 from 60 Canadian stations, although our amplitude is slightly (by about 0.05–0.1 mb) higher than that of Hamilton (1980b). The above comparison suggests that instrumental errors associated with changes in barometers are...
likely to be relatively small and that surface pressure tides determined using the data of the recent decades are comparable to those based on the data before 1960.

2) ZONAL WAVE COMPONENTS

Figure 12 shows the globally averaged amplitudes for wave components at wavenumber $s = -13$ to $+15$ for DJF, JJA, and annual $S_2$. The wavenumber 2 component, $S_2^2$, has a global mean amplitude of about 566 mb in DJF, 523 mb in JJA, and 576 mb for annual mean, whereas the next closest amplitude is about 100 mb. The amplitudes at higher wavenumbers decrease only slightly. The seasonal differences in the wave components are small.

Figure 12 differs substantially from Haurwitz and...
Cowley (1973) in that their main wave $S^2_2$ is considerably stronger ($\approx 750 \mu b$ for annual pressure) and their waves at $s \leq -1$ and $s \geq 4$ are much weaker (with amplitudes of 8–30 $\mu b$). This is expected because Haurwitz and Cowley (1973) had very limited spatial coverage, which could not resolve the higher wavenumber components and resulted in zonally homogeneous distributions.

The main wave $S^2_2$ for the annual $S_2$ has an amplitude of about 1096 $\mu b$ around 4°N and it decreases rapidly to the north and south (Fig. 13). In the Tropics and northern subtropics, the DJF $S^2_2$ is stronger than the JJA $S^2_2$. From 40°S to 55°S, the amplitude increases poleward. Because of this, polynomials of $\cos \theta$ do not fit the curves well, and a function of $\cos^3 \theta$, as used by Haurwitz and Cowley (1973), cannot represent the dependence of $S^2_2$ on latitude, especially over middle and high latitudes.

Figure 14 shows that the amplitudes at higher wave-numbers also decrease poleward but at a much slower pace than that for $S^2_2$. The wave components are fairly symmetric relative to both the equator and wavenumber 2 for annual $S_2$.

c. $S_1$ and $S_2$ in GEOS-1 reanalysis

Figure 15 shows that the amplitude of annual $S_1$ in the GEOS-1 reanalysis is generally lower than observed over much of the globe except for the high-amplitude centers over South America, Africa, Australia, southern Asia, and the central tropical Pacific where the model has a positive bias. The zonal wave components of the assimilated $S_1$ are also dominated by $S^1_1$, but with a smaller global mean amplitude at $s = 1$ ($\approx 330 \mu b$ for annual $S^1_1$) and considerably larger amplitude at $s = -3$ ($\approx 156 \mu b$) compared with the station data (cf. Fig. 5). The seasonal variations in the assimilated $S_1$ compare favorably with the station data. The assimilated $S_1$ peaks in the early morning (0400–0800 LST) over land areas and the Pacific, about 1–2 h earlier than the $S_1$ from station data (cf. Fig. 4).

The amplitude of $S_2$ in the reanalysis (Fig. 16) is more uniform zonally, about 0.2–0.5 mb larger at low latitudes, and about 0.1–0.3 mb smaller at high latitudes than observed (cf. Fig. 8). The assimilated $S_2$ is dominated by $S^2_2$, which has a global mean amplitude of 784 $\mu b$ for annual pressure. This is considerably larger than that of Fig. 12 (576 $\mu b$). On the other hand, the amplitudes at higher wavenumbers for the assimilated $S_2$ are lower than observed, as expected from their smoother distributions.

Table 1 lists the migrating diurnal ($S^1_1$) and semidiurnal ($S^2_2$) tides of annual mean surface pressure along the equator estimated by various sources. It can be seen that both the GEOS-1 and NCEP–NCAR reanalysis data tend to overestimate the tides at the equator. Our esti-
mates of $S_1$ and $S_2$ are similar to those of Haurwitz and Cowley (1973) around the equator, but the relative importance of $S_1$ increases at higher latitudes in our analysis.

5. Implications for the forcing of $S_1$ and $S_2$

Although sensible heating from the ground has been shown to be an important forcing for diurnal nonmigrating tides in model simulations (Tsuda and Kato 1989), it has not been included in classic tidal calculations (e.g., Chapman and Lindzen 1970; Braswell and Lindzen 1998). The fact that the amplitude of $S_1$ and its seasonal variations are much larger over the land than over the ocean suggests that over land areas $S_1$ is greatly enhanced by the sensible heating from the ground. Atmospheric total ozone concentrations are fairly uniform zonally over low and middle latitudes (McPeters et al. 1996) and water vapor contents are higher in marine air (Randel et al. 1996). Thus the solar absorption by ozone and water vapor cannot explain the land–sea differences in the amplitude of $S_1$. On average, the earth’s surface absorbs about half of the incoming solar radiation at the top of the atmosphere (Kiehl and Trenberth 1997). Over land areas, the absorbed solar

 radiation at the ground creates large sensible heating of the surface air and generates large diurnal ranges of surface air temperature (DTR) (Fig. 17; see also Dai et al. 1999b). On the other hand, because of the unlimited water for evaporation, the large specific heat of water, and the turbulence mixing in surface oceans, solar heating of the ocean surface does not provide strong sensible heating of marine surface air, resulting in much smaller DTR over the oceans than over land areas (Fig. 17). Indeed, the geographic variations of $S_1$ (Fig. 3) correlate significantly (attained significance level $p < 0.1\%$) with those of DTR (Fig. 17) (spatial correlation coefficient $r = 0.61$ for DJF, 0.67 for JJA, and 0.65 for annual mean). This is consistent with Mass et al. (1991), who found a correlation of 0.71 between summer diurnal amplitudes of surface pressure and DTR over the United States. Earlier studies also found stronger $S_1$ in clear sky and large DTR days than in cloudy and low DTR days in New York (Spar 1952b), but insignificant correlation between $S_1$ and DTR at a Bermuda maritime station (Haurwitz 1955).

Forced by the ozone and water vapor absorption of solar radiation, the classic tidal theory predicts a peak
amplitude of 381 μb at the equator for annual $S_1$ (Braswell and Lindzen 1998), which is far below the observed (626 μb) (Table 1). Even with much weaker ground sensible heating than shown in Fig. 17, Tsuda and Kato (1989) showed through model simulations that large nonmigrating diurnal tides can be excited by the differential heating between land and ocean. Our results provide further evidence suggesting that sensible heat from the ground is a major forcing for both the migrating ($S_1$) and nonmigrating ($S'_1$, $s \neq 1$) diurnal tides. Including this forcing in theoretical calculations should substantially reduce the gap between the theory-predicted and observed diurnal tides.

Although dominated by the migrating mode $S_2$, the semidiurnal tide $S_2$ exhibits considerable regional and zonal variations in its amplitude (cf. Fig. 8). For example, the amplitude of $S_2$ is smaller over the Atlantic and central Pacific than in other regions of the Tropics. Atmospheric water vapor content is comparable over the equatorial Pacific, Atlantic, and Indian Oceans and is much lower over Africa (Randel et al. 1996), while atmospheric total ozone concentration is fairly uniform over the Tropics (McPeters et al. 1996). Therefore, ozone and water vapor forcing appears unable to explain the variations of $S_2$ in the Tropics. Clouds, which can reflect (thus reducing the solar radiation reaching the lower troposphere where most of the water vapor absorption occurs) and absorb (thus providing additional forcing for $S_1$) solar radiation, are variable in space and could be a significant forcing for $S_2$. Precipitation has large diurnal variations (Dai et al. 1999a). The latent heating in convective precipitation is shown to be a significant forcing for $S_1$ in the Tropics (Lindzen 1978; Hamilton 1981). It could also induce additional zonal and regional variations in the amplitude of $S_2$. On the other hand, the sensible heating from the ground appears to have much smaller effects on $S_1$ than on $S_2$, as implied by the relatively small land–sea differences of $S_2$ (cf. Fig. 8). The signal of the influences by clouds and latent heating in $S_2$ is much weaker than that of the sensible heating in $S_1$. Therefore, a simple correlation between

Fig. 15. Upper panel, amplitude (in units of 0.1 mb) of annual $S_1$ derived from the 1980–94 mean 3-hourly surface pressure field in the NASA GEOS-1 reanalysis. Values over 1.0 mb are hatched. Lower panel, the reanalysis minus observation difference of the amplitude (in units of 0.1 mb) of $S_1$. Positive values are hatched.
Fig. 16. Same as Fig. 15 except for $S_2$.

Table 1. The amplitude (mb) of migrating diurnal ($S_1$) and semidiurnal ($S_2$) tides of annual-mean surface pressure along the equator estimated by various sources.

<table>
<thead>
<tr>
<th>Station data$^a$</th>
<th>Station &amp; marine data$^b$</th>
<th>GEOS-1 reanalysis$^c$</th>
<th>NCEP–NCAR reanalysis$^d$</th>
<th>Classic theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>0.63</td>
<td>0.63$^e$</td>
<td>0.71$^e$</td>
<td>0.67</td>
</tr>
<tr>
<td>$S_2$</td>
<td>1.16</td>
<td>1.10$^e$</td>
<td>1.41$^e$</td>
<td>1.47</td>
</tr>
</tbody>
</table>

$^a$ From Haurwitz and Cowley (1973).
$^b$ This study.
$^c$ From van den Dool et al. (1997).
$^d$ Around 4$^\circ$S.
$^e$ Around 4$^\circ$N.
$^g$ From Lindzen (1990).

$S_2$ and cloudiness or convective precipitation is likely to result in weak relationships.

Figures 6 and 13 show that there is some asymmetry relative to the equator in the migrating tides. For example, the peak amplitude of $S_1$ is about 4$^\circ$ south of the equator. Furthermore, summer $S_1$ is substantially stronger than winter $S_1$ from about 20$^\circ$N to 50$^\circ$N. These features are not accounted for by the classic tidal theory with only ozone and water vapor heating (Braswell and Lindzen 1998).

6. Summary

Global surface pressure data of the 1976–97 period from over 7500 stations and COADS marine reports have been analyzed using harmonic and zonal harmonic methods. The spatial coverage of these data is greatly improved over previous similar analyses and is sufficient over most of the globe for capturing large-scale (>500 km) variations. However, the data are still sparse over the Antarctic, the Arctic, and the southern (south of about 50$^\circ$S) oceans, where our results are less reliable.

We find that the diurnal pressure oscillation $S_1$ is comparable to the semidiurnal pressure oscillation $S_2$ in magnitude over much of the globe except for the low-latitude open oceans, where $S_2$ is about twice as strong as $S_1$. Over Northern Hemisphere land areas, $S_1$ is even stronger than $S_2$ during summer. Our results show that
$S_1$ is more important than previously thought (e.g., Chapman and Lindzen 1970; Lindzen 1990).

Compared with previous studies (Haurwitz 1956; Haurwitz 1965; Haurwitz and Cowley 1973), we find that there is much more variation in $S_1$ and $S_2$ on regional and continental scales, and that the nonmigrating tides are considerably stronger than previously reported. Oscillation $S_1$ is greatly influenced by landmasses and is generally stronger over the land than over the ocean. The highest amplitudes (~1.3 mb) of $S_1$ are found over northern South America and eastern Africa close to the equator. Here $S_1$ is also strong (~1.1 mb) over high terrain such as the Rockies and the Tibetan Plateau. Over the open oceans, the amplitude of $S_1$ is about 0.3–0.6 mb. Over land areas, $S_1$ is strongest in local summer as the solar heating reaches a maximum, whereas its seasonal variation over the oceans is small. At low latitudes $S_1$ reaches maxima in the morning around 0600–0800 LST, while it peaks in the late morning around 1000–1200 LST at midlatitudes except for eastern Asia and the North Pacific where the maximum is around 0600–0800 LST.

The wavenumber 1 component $S_1$ of $S_1$ has a global mean amplitude of about 370 µb, compared with the next strongest wave ($S_2$) of about 100 µb. The amplitude of $S_1$ decreases poleward rapidly at low latitudes, but its dependence on latitude cannot be adequately represented by simple polynomials of the cosine of latitude.

Fig. 17. Observed annual mean range of surface air temperature (°C) averaged over the 1980–91 period. Data are not available over Australia and sparse over the open oceans (Dai et al. 1999b).
The largest amplitudes of $S_2$ ($\sim 1.0$–$1.3$ mb) are found in the Tropics over South America, the eastern and western Pacific, and the Indian Ocean. The amplitude of $S_2$ is about $0.3$–$0.5$ mb over middle and high latitudes. Land–sea differences at a given latitude in the amplitude of $S_2$ are much smaller than for $S_1$. The seasonal variations of $S_2$ appear to be out of phase with $S_1$. Specifically, the maximum-amplitude zone of $S_2$ extends northward to about $20^\circ$N in DJF while $S_1$ is weaker over low latitudes and northern midlatitudes in JJA. Here $S_2$ peaks around 1000 and 2200 LST at low- and mid-latitudes.

Oscillation $S_2$ is dominated by its migrating (wave-number 2) mode $S_2^2$, which has a global mean amplitude ranging from 523 (for JJA) to 566 (for DJF) µb, more than five times larger than the next strongest wave ($\sim 100$ µb). Here $S_2^2$ peaks in the Tropics (about 958 µb for JJA and 1081 µb for DJF) and decreases rapidly poleward with a slower pace at mid- and high latitudes.

The amplitudes of high wavenumber components decrease gradually with increasing wavenumbers. We did not find any other wave components (except $S_1$ and $S_2^2$) that are substantially stronger than their adjacent ones. Low gridding resolution of $S_1$ and $S_2$ tends to reduce the amplitudes at higher wavenumbers and enhance $S_1^1$ and $S_2^2$.

The fact that the amplitude of $S_1$ and its seasonal variations are much larger over the land than over the ocean suggests that over land areas $S_1$ is greatly enhanced by the sensible heating from the ground. The spatial variations of the amplitude of $S_1$ correlate significantly with those in the diurnal temperature range at the surface, which is a proxy of the surface sensible heating. On the other hand, the land–sea differences of $S_2$ are relatively small, suggesting that the sensible heating from the ground has a much smaller influence on $S_2$. Although the amplitude of $S_2$ generally decreases poleward with largest gradients in the subtropics, there are considerable zonal variations in atmospheric ozone and water vapor. Other forcings such as those through reflection and absorption of solar radiation by clouds and latent heating associated with convective precipitation are likely to be important for the zonal and regional variations in $S_2$. There is also some asymmetry relative to the equator in the migrating tides, especially $S_1^1$, which also implies additional forcings other than the solar heating by atmospheric ozone and water vapor.

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