Diurnal cycle of upper-air temperature estimated from radiosondes

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[1] This study estimates the amplitude and phase of the climatological diurnal cycle of temperature, from the surface to 10 hPa. The analysis is based on four-times-daily radiosonde data from 53 stations in four regions in the Northern Hemisphere, equatorial soundings from the Tropical Ocean Global Atmosphere/Coupled Ocean Atmosphere Response Experiment, and more recent eight-times-daily radiosonde data from the Atmospheric Radiation Measurement program's Central Facility in Oklahoma. Our results are in general qualitative agreement with earlier studies, with some quantitative differences, but provide more detail about vertical, seasonal, and geographic variations. The amplitude of the diurnal cycle (half the diurnal temperature range) is largest (1 to 4 K) at the surface. At 850 hPa and above, the regional-average amplitudes are <1 K throughout the troposphere and stratosphere. The amplitude of the diurnal cycle in the boundary layer is larger over land than over ocean, and generally larger in summer than winter (except for monsoon regions, where it is larger in the dry season). In the upper-troposphere and stratosphere, land-sea and seasonal differences are not prominent. The diurnal cycle peaks a few hours after local noon at the surface, a few hours later at 850 hPa, and somewhat earlier in the upper troposphere. The timing of the diurnal cycle peak in the stratosphere is more uncertain. Radiosonde data are also used to simulate deep-layer mean temperatures that would be observed by the satellite-borne microwave sounding unit, and the amplitude and phase of their diurnal cycles are estimated. An evaluation is made of the uncertainty in these results due to the temporal resolution of the sounding data, which is only barely adequate for resolving the first harmonic of the diurnal cycle, the precision of radiosonde temperature data, and potential biases in daytime stratospheric temperature observations.

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1. Introduction

[2] Diurnal variations in upper-air temperature result from atmospheric absorption of solar and long-wave radiation, latent and sensible heat fluxes from the surface, and latent heat exchange within the atmosphere, all of which vary diurnally, and from atmospheric tidal effects, with both diurnal and semidiurnal components [*Chapman and Lindzen*, 1970; *Sherwood*, 2000]. Air temperature at different elevations can respond differently to each of these factors, which leads to vertical variations in the diurnal cycle. Although atmospheric temperature profiles have been measured, using a variety of techniques, for close to a century, the diurnal cycle in upper-air temperature has not been fully characterized. This gap is probably attributable to a dearth of data of sufficiently high frequency to resolve the diurnal cycle over a wide range of altitudes, geographic regions, and seasons.

[3] This paper attempts to characterize the diurnal cycle of temperature, and its seasonal variations, from the surface to the lower stratosphere, using archived radiosonde data covering as much of the globe as possible. The motivation for this study is twofold. The first goal is to link surface temperature diurnal variations and long-term trends with those in the upper air. At the surface, differences in daytime and nighttime temperature trends, with more warming at night than during the day, have been documented using daily maximum and minimum temperatures [*Karl et al.*, 1991], and the diurnal cycle of temperature can be relatively well characterized using synoptic observations at 3-hourly intervals [e.g., *Dai and Trenberth*, 2004]. Investigations of long-term changes in upper-air diurnal temperature range (DTR) have been attempted by *Ross et al.* [1996] using twice-daily radiosonde data for 1973–93 from Russia and Canada, where soundings are made near times of day assumed to be close to the daily maximum and minimum,

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and by *Balling and Cerveny* [2003] using twice-daily soundings from 28 stations in the central United States for 1957–2002. The lack of detailed contextual information on the nature of the climatological diurnal cycle in upper-air temperature makes it difficult to interpret possible long-term changes. For example, it is reasonable to ask, but difficult to answer, how a reported trend in tropospheric or stratospheric DTR compares with climatological-average DTR. The climatology of the diurnal cycle of upper-air temperature, at particular locations for limited periods of observation, has been addressed by previous investigators [*Harris et al.*, 1962; *Finger and McInturff*, 1968; *Wallace and Patton*, 1970; *Balling and Christy*, 1996; *Tsuda et al.*, 1997]. This paper extends earlier work by examining a much more spatially and temporally comprehensive set of observations, and by incorporating more recent observations that provide a perspective on potential effects of observational error in the earlier studies.

[4] Our second motivation is to contribute to efforts to remove spurious diurnal signals in deep-layer mean upper-air temperature observations from satellite-borne Microwave Sounding Units (MSU). Historically, the satellites' equatorial crossing times have drifted, so that observations for any particular point on Earth have not be made at the same local time of day, which introduces aliasing of the diurnal cycle into long-term trends. Removal of this spurious signal is challenging and may contribute to differences in MSU trends obtained in different studies [*Mears et al.*, 2003]. *Christy et al.* [2003] use a method based on comparing observations from different view angles, at different locations, to obtain an MSU-based estimate of the diurnal cycle, while *Mears et al.* [2003] employ output from a global climate model, in conjunction with a radiative transfer model, to estimate the diurnal cycle in MSU temperatures. *Vinnikov and Grody* [2003] do not attempt to remove a spurious diurnal signal from spatially- and temporally-averaged MSU data, but instead assess global trends as a function of month and time of day. In so doing, they obtain estimates of the climatological diurnal and seasonal variation of MSU temperatures. Here we use radiosonde observations to simulate MSU observations and estimate their expected manifestation of the diurnal cycle.

[5] The next two sections describe the data and methodology employed. Section 4 presents results for the annual mean and seasonal variations in the amplitude and phase of the diurnal cycle, and compares our findings with those of previous investigations. The final section summarizes our main findings.

2. Data

[6] Ideally, to estimate the amplitude and phase of the diurnal cycle of upper-air temperature, we would like temperature observations with good vertical resolution throughout the troposphere and stratosphere; adequate temporal resolution of both the diurnal and the semi-diurnal cycles (i.e., eight or more observations per day); global coverage; and long-term (multi-year) records for all months of the year. Furthermore, the precision of the temperature data should be substantially finer than the amplitude of the diurnal cycle, and the data should be free of diurnally-varying errors, so that the amplitude is not under- or overestimated.

[7] In the absence of an ideal data set, we have mined from the archive of global radiosonde data a set of soundings with some of these characteristics. We have identified 53 Northern Hemisphere radiosonde stations, listed in Table 1 and shown in Figure 1, at which observations were made four times daily, for at least one year. We selected data from the most recent period, lasting up to four years, of four-times-daily observations. Of the 53 stations, 21 had four years of data, 8 had three years, 14 had two years, and 10 had one year of four-times-daily observations. Because few stations currently take such frequent observations, much of the data are several decades old. The stations include 16 in Western Europe (most of which had four years of data) with data from the 1990's, 10 in the Former Soviet Union (FSU) and Asia with data mainly from the 1980's, and 21 in North America with data dating from the 1950's and 60's (most of which had fewer than four years of data). In the Tropics, we found only six stations with four-times-daily data for at least one year, with data from the same decades as the North American stations. To supplement this small set of tropical observations from the early years, we also used four-times-daily data for November 1992 through February 1993 from 13 equatorial western Pacific island sites and research vessels participating in the Tropical Ocean Global Atmosphere/Coupled Ocean Atmosphere Response Experiment (TOGA/COARE). Although a full year of data would have been desirable, seasonal variations both of temperature and of its diurnal cycle are likely to be small in this region.

[8] These data allow analysis of the first harmonic of the diurnal cycle, assuming a simple sine wave, at 16 levels from the surface to 10 hPa, except for the TOGA/COARE data, which extend only to 50 hPa. Using weighting functions applied to the sounding data, we are also able to simulate deep-layer mean temperatures that would be measured by the MSU channels 2 and 4 and examine their diurnal cycles. There are sufficient data at the midlatitude stations and a few tropical stations for analysis of seasonal variations in the diurnal cycle.

[9] One potential problem with these observations is that, because they span several decades and come from many nations, they likely contain a variety of different error characteristics. The precision of radiosonde data has, in general, improved over time, and the temperature measurements from more recent models have estimated precision and accuracy of approximately 0.2 to 0.5 K from the surface to 30 hPa [*WMO*, 1996]. More important, the accuracy of all sondes is greater for nighttime observations than for daytime, when solar radiation causes heating of the temperature sensor. This problem is most severe at low pressure, where the sensor is more poorly ventilated. Daytime temperature errors at 300 to 30 hPa range from 0.3 to 3.4 K [*WMO*, 1996]. At most stations, the observations are adjusted to remove this error source, but if the correction is not perfect, our diurnal cycle estimates will be influenced by the errors.

[10] Archived operational radiosonde data from the U.S. are not adjusted for this radiation problem. Instead, corrections are applied later at numerical weather prediction

Table 1. List of Radiosonde Stations for Each Region, Including Their WMO Identifications Numbers, Latitude and Longitude, the Earliest Year of Data Used, and the Total Number of Years Used[a]

Name	Id. Number	Year	Number of Years	Lat.	Lon.	Region
Aberporth	03502	1997	2	52.1	−4.6	W. Europe
Boulmer	03240	1995	4	55.4	−1.6	W. Europe
Brindisi	16320	1995	4	40.7	18.0	W. Europe
Budapest	12843	1982	4	47.4	19.2	W. Europe
Camborne	03808	1996	4	50.2	−5.3	W. Europe
Goteborg	02527	1998	2	57.7	12.3	W. Europe
Griefswald	10184	1993	4	54.1	13.4	W. Europe
Lerwick	03005	1994	4	60.1	−1.2	W. Europe
Herstmonceux	03882	1996	4	50.0	0.0	W. Europe
Lindenberg	10393	1997	4	52.2	14.1	W. Europe
Milano	16080	1997	4	45.4	9.3	W. Europe
Pratica Di Mare	16245	1995	4	41.7	12.4	W. Europe
Stornoway	03026	1997	4	58.2	−6.3	W. Europe
Sundsvall	02365	1996	2	62.5	17.5	W. Europe
Trapani/Birgi	16429	1999	2	37.9	12.5	W. Europe
Udine	16044	1996	4	46.0	13.2	W. Europe
Alma-Ata	36870	1978	3	43.4	77.0	FSU/Asia
Arhangel’sk	22550	1979	4	64.5	40.6	FSU/Asia
Chita	30758	1985	2	52.0	113.5	FSU/Asia
Frunze/Bishkek	38353	1991	1	42.8	74.6	FSU/Asia
Gasan-Kuli	38750	1988	2	37.5	54.0	FSU/Asia
Novosibirsk	29634	1982	2	55.0	82.9	FSU/Asia
Osan	47122	1997	4	37.1	127.0	FSU/Asia
Petropavlovsk	32540	1982	4	53.1	158.6	FSU/Asia
Sverdlovsk	28440	1989	2	56.7	61.1	FSU/Asia
Tashkent	38457	1982	4	41.4	69.4	FSU/Asia
Chuuk	91334	1992		7.4	151.8	TOGA-COARE
Honiara	91517	1992		−9.4	159.9	TOGA-COARE
Kapingamarangi	91434	1992		1.1	154.8	TOGA-COARE
Kavieng	94076	1992		−2.5	150.8	TOGA-COARE
Manus	94044	1992		−2.1	147.0	TOGA-COARE
Misima	94087	1992		−10.6	152.8	TOGA-COARE
Nauru	91530	1992		−0.5	166.9	TOGA-COARE
Pohnpei	91348	1992		7.0	158.1	TOGA-COARE
Xiangyanghong 5		1992		−2.1	155.0	TOGA-COARE
R/V Hakuho-Maru		1992		0.0	143.2	TOGA-COARE
R/V Moana Wave		1992		0.1	155.9	TOGA-COARE
Santa Cruz		1992		−4.1	156.4	TOGA-COARE
XP3		1992		−2.4	158.2	TOGA-COARE
Balboa/Howard AFB	78806	1967	2	9.0	−79.6	Tropics
Clark AFB	98327	1967	3	15.2	120.6	Tropics
Guam	91217	1953	1	13.6	144.8	Tropics
Ubon Ratchathani	48407	1968	3	15.3	104.9	Tropics
Udorn	48354	1968	3	17.4	102.8	Tropics
Wake Island	91245	1953	1	19.3	166.6	Tropics
Albany	72518	1956	1	42.8	−73.8	North America
Bermuda	78016	1965	4	32.4	−64.7	North America
Buffalo	72528	1956	1	42.9	−78.7	North America
Cape Kennedy	74794	1962	3	28.5	−80.6	North America
Dayton	72429	1957	1	39.9	−84.1	North America
Fort Worth	72259	1953	4	32.8	−97.4	North America
Goose	72816	1957	3	53.3	−60.4	North America
Mt Clemens	72537	1955	1	42.6	−82.8	North America
Norfolk	72308	1953	4	36.9	−76.2	North America
Oakland	72493	1956	1	37.8	−122.2	North America
Oklahoma City	72354	1968	1	35.4	−97.4	North America
Pittsburgh	72520	1955	2	40.5	−80.2	North America
Rantoul	72531	1953	2	40.3	−88.2	North America
Sault Ste. Marie	72734	1955	4	46.5	−84.4	North America
Seattle	72793	1955	2	47.7	−122.3	North America
Shreveport	72248	1954	3	32.5	−93.8	North America
Silver Hill	72405	1954	2	38.8	−76.9	North America
Topeka	72456	1956	1	39.1	−95.6	North America
Tucson	72274	1955	2	32.1	−110.9	North America
Valparaiso	72221	1966	4	30.5	−86.6	North America
Vandenberg AFB	72393	1966	3	34.5	−120.5	North America

[a]The stations and regions are shown in Figure 1. Positive (negative) longitudes are east (west) of the Greenwich meridian. FSU designates the Former Soviet Union. For TOGA-COARE research vessels only four months of data were available, no identification number is listed, the coordinates are nominal, and soundings within 5 degrees latitude of the equator (at the given longitude) were used in the analysis.

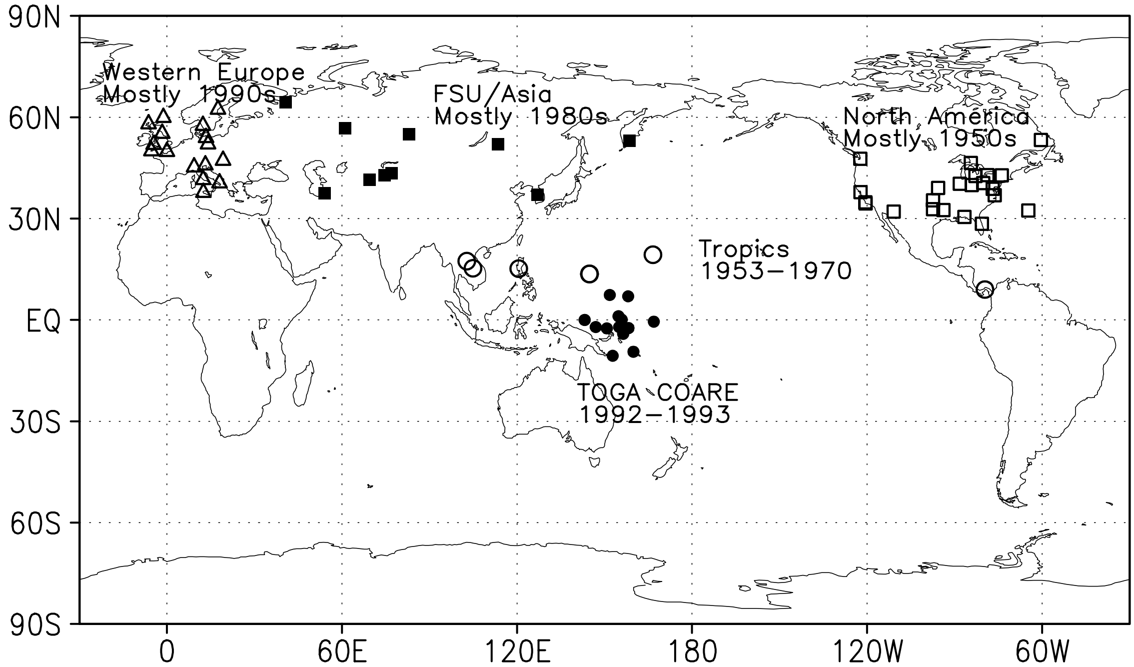

Figure 1. Radiosonde stations used in this study, with symbols indicating regional groupings, and showing the years for which data were available. Station names and locations are listed in Table 1.

centers. It is well established that U.S. radiosonde temperatures from the 1950's and 1960's, made with VIZ radiosondes, are too high for daytime observations in the stratosphere. Indeed, some early studies of the diurnal cycle of upper-air temperature were motivated by a desire to develop corrections for these daytime solar radiation errors [*Teweles and Finger*, 1960; *Harris et al.*, 1962; *Finger and McInturff*, 1968]. The majority of stations in our North America and Tropics regions are affected by this problem (Table 1). We have not applied any corrections to these U.S. soundings because of the possibility that the corrections are not completely accurate. Instead we rely on comparison with more recent, corrected data from other regions (Table 1), and from one experimental site in the U.S., to determine the reliability of the older U.S. stratospheric data.

[11] The experimental site is the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) program's Central Facility, near Lamont, Oklahoma. Radiosonde observations there are made with Vaisala RS80 radiosondes, to which the Vaisala RSN93 radiation adjustments [*Antikainen and Turtiainen*, 1992; *Turtiainen*, 1993] have been applied. The RSN93 adjustments involve subtracting predetermined temperature increments from the sounding data, all the way from the surface to 3 hPa, to remove a positive temperature bias due to the heating from solar radiation absorbed by the sensor during daytime conditions. These increments increase with altitude and with solar elevation angle, and vary from 0 to 0.5 K below 500 hPa, to ~0.3–0.8 K at 100 hPa, and can exceed 3.0 K at 3 hPa at solar angles >50 degrees. The RSN93 scheme has small nighttime corrections for the cooling effect of infrared radiation emitted from the sensor. Many of the stations in the Western Europe and TOGA/COARE regions also employ Vaisala sondes, and these data have also been adjusted for radiation errors. For data from before 1993, an earlier version of the adjustment was probably used, and we are not certain which version was used to adjust the more recent data from the 1990's.

[12] The ARM Central Facility data are distinctly well-suited to analysis of the diurnal cycle. For 315 days in the period 1994–2000, soundings were taken at three-hour intervals (eight observations per day), which allows us to estimate the uncertainty in diurnal cycle amplitude and phase estimates based on only four observations per day. The ARM data set, described by *Dai et al.* [2002], is available at 2 s vertical resolution, much finer than the archived radiosonde data discussed above, which are available only at the mandatory reporting levels and any identified significant levels. Although there are not enough ARM soundings to determine diurnal cycles on a monthly basis, particularly in winter, there are sufficient data to do so on a seasonal basis. The more modern technology, combined with the high vertical and temporal resolution of the sounding data, provides an excellent basis for comparison with the older operational data.

3. Methodology

[13] We estimate the diurnal cycle for each station, for each calendar month, using soundings from at least one and as many as four years of four-times-daily data. (The ARM and TOGA/COARE data have more limited periods of availability, and the ARM data are eight-times-daily, as discussed above.) For each station, pressure level, and day, we compute the mean temperature, based on data at all available times of day, and then calculate available hourly departures from the mean daily temperature value. These hourly departures are averaged for each calendar month, yielding a monthly mean diurnal cycle, at each station, for each pressure level, from which the effects of

synoptic variability (as represented by the day-to-day changes in daily-average temperature) have been largely removed.

[14] For each station, pressure level, and month, we fit the available hourly departures to a single sinusoid (the sum of a sine and a cosine term) using singular value decomposition, and then compute the amplitude ($\sim\frac{1}{2}$ DTR) and phase (hour of maximum temperature, converted to LST). We do not attempt to adjust the observation time for the difference between the launch time and the time at which the sonde reaches any given elevation, because launch times are often nominal, and exact launch times are not generally known. In addition, the elapsed time between launch and termination is only about 1–1.5 hours, and we expect larger errors in our phase estimates due to the six-hour gap between soundings. Another limitation of this temporal sampling is that we cannot resolve any higher frequency harmonics in the diurnal cycle or evaluate its asymmetry.

[15] From the station results, we calculate regional averages of the monthly amplitude values, and annual regional averages. For phases, we used modes, rather than averages, for two reasons. First, in a few cases (discussed below) when the amplitude is small, the phase is ill-defined, and the distribution of phase values is broad, making the mean meaningless. Second, values near midnight (e.g., 2000 to 0400 LST) cannot be arithmetically averaged in a straightforward fashion. Use of the modal values, based on binning the data into one-hour bins, avoids these problems. The purposes of examining regional averages are (1) to reduce errors in amplitude estimates by using a larger sample, and (2) to compensate partially for the limitations of the four-times-daily observations. Because stations in a given region span $\sim$30 to 120 degrees of longitude (Figure 1), observations made at standard synoptic times (0000, 0600, 1200, and 1800 UTC) are made at different local times at different stations within a region. By aggregating the stations within a region, and expressing result in terms of LST, we obtain a more realistic estimate of the hour of maximum temperature.

[16] We process the data from the ARM Central Facility slightly differently, due to the different spatial and temporal resolution of the data. Because there are not enough soundings to allow separate analyses for each month, we computed seasonal (DJF, MAM, JJA, SON) averages of the diurnal cycle. Taking advantage of the high vertical resolution of the soundings, we estimate the amplitudes and phases at 10 hPa vertical resolution from 1000 hPa to 50 hPa, where the first layer (1000–990 hPa) represents surface values. Finally, because there is only a single station, there is no regional averaging.

4. Results

[17] In this section we present estimates of the vertical profiles of the amplitude and phase of the diurnal cycle for each region of the globe, first as annual climatological averages. We then examine seasonal variations of the amplitude and phase estimates at specified pressure levels. Next we present comparable results for simulated deep-layer average temperature that would be observed by the Microwave Sounding Unit. We then compare our results to those of previous investigators.

4.1. Mean Vertical Profiles of the Amplitude and Phase of the Diurnal Cycle

[18] Figure 2 depicts the vertical profiles of the regional and annual average amplitudes (left panel) and phases (right panel) of the diurnal cycle of temperature, from the surface to 10 hPa (50 hPa for TOGA/COARE), for each of the five regions in Figure 1.

[19] For each region, the largest annual-average amplitudes ($\sim$1 to 4 K) are at the surface. The amplitude of the near-surface diurnal cycle is smallest over the TOGA-COARE (tropical Western Pacific) region, probably due to the larger heat capacity of water vs. land, which moderates maritime air temperature variations. Here it is useful to note that our Tropics region includes two stations in Thailand and four island stations, so the Tropics soundings are more influenced by land than the TOGA-COARE data, which come from ships and atolls. The largest diurnal cycle amplitudes are at the surface in continental regions (FSU/Asia and North America).

[20] It is important to note that these surface values are for surface air temperature, not skin temperature. As shown by *Aires et al.* [2004], the diurnal amplitude of surface skin temperature over land can range from $\sim$2 to $\sim$20 K, with larger values over desert, shrubland, and grassland (compared with woodland and forest regions), and with larger values in summer than winter [see also *Jin*, 2004]. Thus it appears that the amplitude of the diurnal temperature wave can diminish by about a factor of five between the Earth's surface and the overlying atmosphere. (However, the larger diurnal cycle of skin temperature exerts a noticeable effect on brightness temperatures observed by microwave radiometers, so MSU diurnal cycles would be expected to be larger than those computed from atmospheric temperatures alone.)

[21] At 850 hPa and at higher altitudes in all regions, the annual-average amplitudes are generally <1 K, and they remain small through the troposphere and lower stratosphere. At levels above 200 hPa, the early (1950's and 1960's) North American and Tropical data (open squares and circles in Figure 2) yield larger amplitudes than found in more recent data in other regions. The TOGA/COARE data, although only available for four months, also show larger amplitudes. This feature is likely due to uncorrected radiation and lag errors affecting the daytime data [*Finger and McInturff*, 1968; *Teweles and Finger*, 1960]. The smallest amplitudes, generally <0.5 K from 850 hPa to 10 hPa, are in Western Europe. These soundings were mainly from the 1990's and were made with Vaisala instruments (at all stations except Budapest), and radiation adjustments were applied. These small estimated amplitudes are comparable to the published estimates of the typical precision of radiosonde temperature data [*WMO*, 1996]. By aggregating $\sim$30 to 120 soundings for each calendar month and station, we hope to overcome random error. However, any uncorrected (or possibly overcorrected) daytime radiation error contributes to uncertainty in estimated amplitudes.

[22] As seen in Figure 2 (right panel), the four-times-daily radiosonde data suggest that the diurnal cycle tends to peak after noon local time in the troposphere, and near noon in

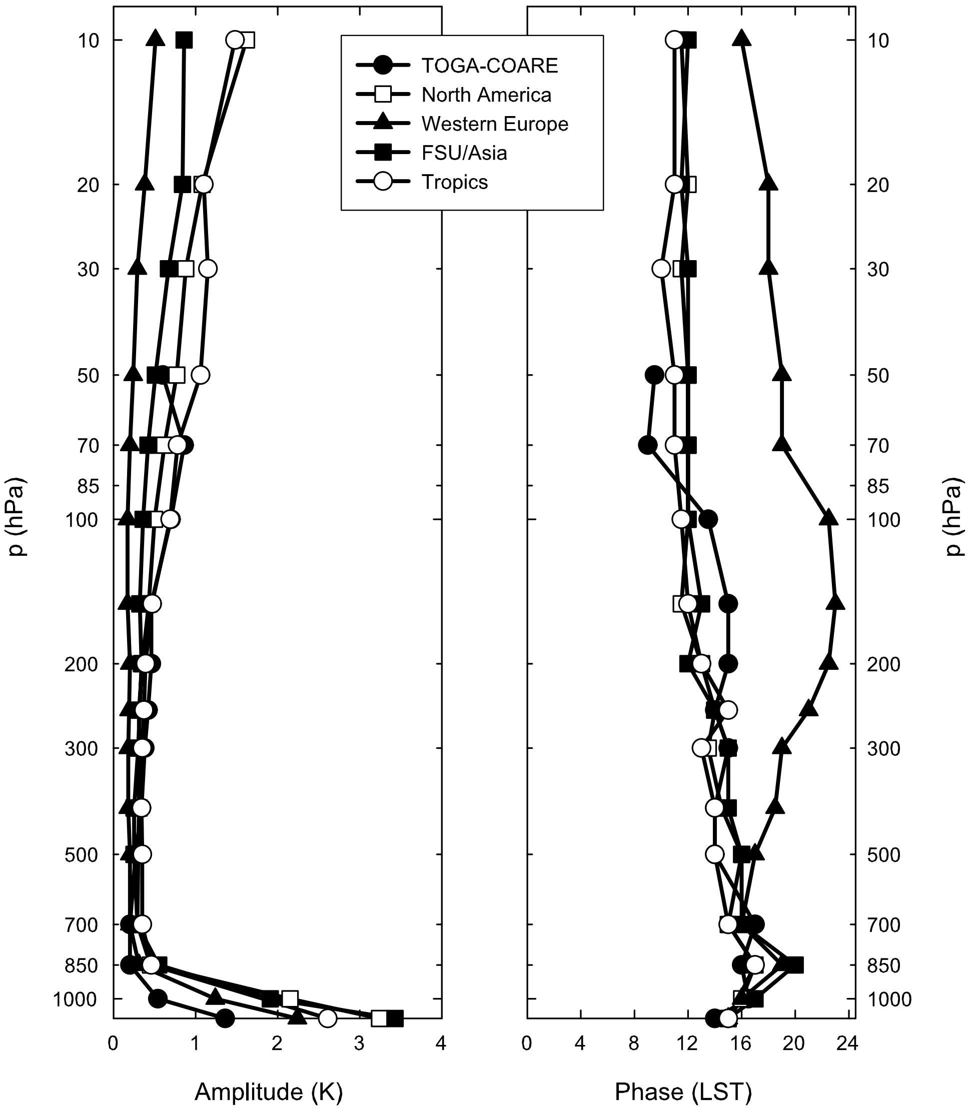

Figure 2. Vertical profiles of the annual- and regional-average amplitude (left) and phase (right) of the diurnal cycle of upper-air temperature. The amplitude is one-half the diurnal temperature range, and the phase is shown as the hour (local standard time) of maximum temperature.

the stratosphere. For each region, the annual-average phase peak occurs near 1500 LST at the surface, later (between 1600 and 2000 LST) at 850 hPa, and somewhat earlier above 850 hPa.

[23] The exception is the Western Europe region, where the modal phase peak above 500 hPa is later in the afternoon or in the evening. However, the small amplitude of the diurnal cycles in this region (Figure 2, left panel) means that the cycles are not well-defined, and the phase can be ambiguous, particularly with such limited temporal resolution of the diurnal cycle. In these cases, the regional modal phase values shown in Figure 2 and subsequent figures for upper-tropospheric and stratospheric levels are based on individual station values with substantial spread about the modes.

4.2. Seasonal Variations in the Diurnal Cycle

[24] Figure 3 shows the annual cycles of regional-average amplitudes and phases at the surface and at the 850, 500, 300, 100, and 30 hPa levels. At midlatitudes, in the lower troposphere, the amplitude of the diurnal cycle has a strong seasonal cycle. At the surface and at 850 hPa, summertime amplitudes are about double those in winter, in accord with the skin temperature findings of *Aires et al.* [2004] discussed above.

[25] The exception is in the Tropics region, where surface and 850 hPa temperatures have their largest diurnal amplitudes in the period from November to May. This result is influenced mainly by the two Thai stations. We speculate that summertime increases in cloud cover, associated with June–October monsoon season, lead to smaller diurnal cycle amplitudes. The other, more maritime, stations in that region show less seasonal variability. For the TOGA/COARE region, we are unable to discern the seasonal variability of the diurnal cycle due to lack of data during March–October.

[26] In general, there is little seasonal structure to the phase of the diurnal cycle at the surface, which peaks

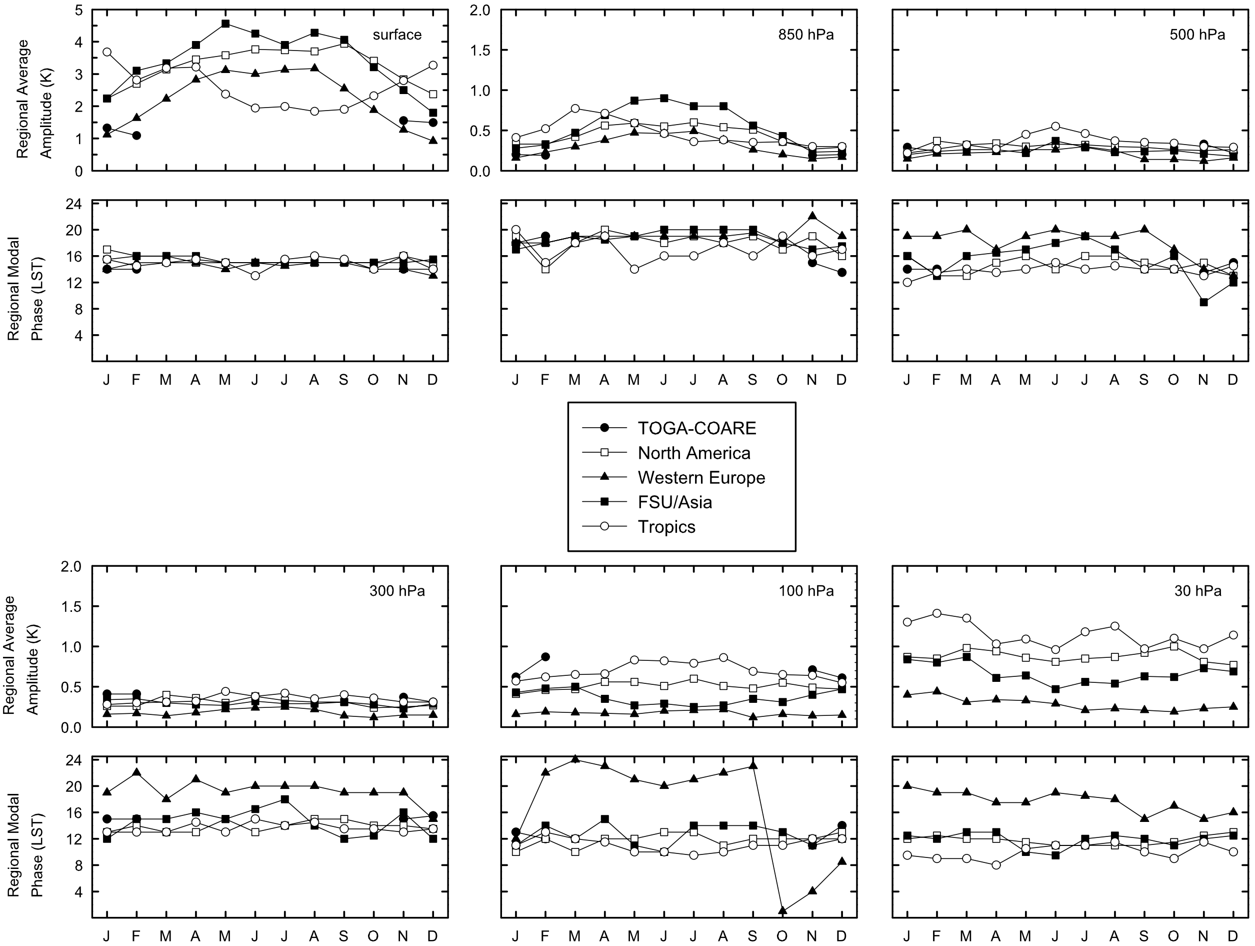

Figure 3. Regional averages of the annual cycle of the amplitude (top of each pair) and phase (bottom of each pair) of the diurnal cycle of temperature at the surface, and the 850 and 500 hPa levels (top row) and the 300, 100, and 30 hPa levels (bottom row). Note the different vertical scale for the surface amplitude and the amplitude at other levels.

between 1400 and 1600 LST. At 850 hPa, when the monthly- regional-average amplitude exceeds ~0.3 K, the phase peak occurs at ~1700 to 1900 LST. For smaller amplitudes, there is more variability in the phase times, which can be interpreted as more uncertainty as the amplitude approaches measurement precision.

[27] At 500 hPa and above, the seasonal variability of the diurnal cycle is very small compared with the levels nearer the surface. The smaller amplitudes lead to uncertainty in the phases, which is particularly notable at 100 hPa. The 100 hPa data from Western Europe show monthly-average amplitudes <0.2 K (Figure 3). The corresponding phases are poorly estimated, and there is considerable spread among the station values, as seen in Figure 4 (triangles). The nighttime phase peaks we obtain for some stations in Western Europe seem counterintuitive and may suggest inappropriate lag or radiation error correction schemes applied to the Vaisala sounding data. This inference is consistent with the change in the Vaisala radiation adjustments [*Turtiainen*, 1993], which only affected data at pressures at 100 hPa or less, and involved a reduction of the magnitude of the nighttime adjustment and an increase in the magnitude of the daytime adjustment, at low elevation angles. The spread in phase estimates among stations at stratospheric levels in this region could be due to the use of different versions of the radiation correction algorithm at different stations.

[28] These small amplitudes and erratic times of phase maximum in Western Europe contrast markedly with the situation for North America, where the 100 hPa amplitudes are ~0.5 K and the phase peaks occur within a few hours of local noon at all stations (Figure 4, open squares). As mentioned above, however, it is likely that the North American data overestimate the diurnal cycle amplitude due to daytime high biases in temperature observations associated with radiation effects on the radiosonde sensors.

[29] Given this uncertainty in phase times and amplitudes, attributable to data problems, insufficient temporal sampling, or both, we turn to the ARM Central Facility data, with 8 soundings per day, for a more detailed picture. Figure 5 shows the mean seasonal temperature anomalies (departure from the daily mean) as a function of altitude (surface to 50 hPa) and time of day, for each season. To more clearly depict the much smaller diurnal cycles above 500 hPa, the same data, with different contouring, are shown in Figure 6. Figure 7 shows the seasonal-average vertical profiles of mean amplitude (left panel) and phase (right panel) derived from these soundings.

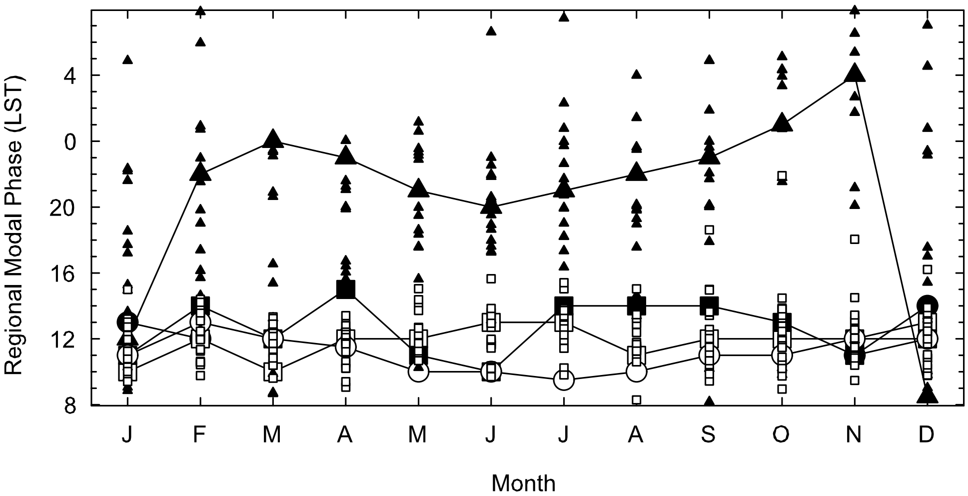

Figure 4. Annual cycle of regional modal values of the phase peak of the diurnal cycle of temperature at 100 hPa. The small symbols represent station values for the Western Europe (filled triangles) and North America regions (open squares) used to obtain the regional modal phase values. Other symbols are as in Figures 2 and 3. Note the vertical axis is different from those in Figure 3.

[30] Many of the features found in the global, four-times-daily sounding data are supported by the ARM soundings. Figures 5 and 7 show clearly the afternoon peak in temperature, the much stronger diurnal cycle below 850 hPa than above, the larger amplitude diurnal cycle in JJA than in other seasons, and the earlier phase peak at the surface than higher in the planetary boundary layer. The amplitude results from this site are in good agreement with the lower-tropospheric results from the much older North American data presented above, but the phase peak times are later in the ARM data than in the older North American data. The erratic vertical profile of phases for DJF (Figure 7) is probably due to the poorer sampling of this season (37 profiles over 1994–2000) compared with the other three (about 90 profiles each). The decrease in amplitudes from the surface through the boundary layer is consistent with the results of *Wallace and Patton* [1970].

[31] The results for the upper-troposphere and lower stratosphere, shown in Figures 6 and 7, differ somewhat from those obtained with the four-times-daily samples. The ARM data show diurnal amplitudes <0.5 K, which is in better agreement with the results from the recent Western European data than the older North American data. Note that the ARM soundings are from Vaisala observations with radiation corrections applied, like those from Western Europe, and unlike those from North America. The phase peak is well after local noontime, 1700 to 2200 LST, up to 200 hPa, which is several hours later than shown in Figure 2, except for Western Europe, where phases are in better agreement. In contrast, above 200 hPa the phase peaks are closer to noon, which disagrees with the Western European results but supports the results from the other regions in Figure 2. However, the ARM phase estimates vary erratically in the vertical (Figure 7), particularly for DJF and particularly above 200 hPa.

[32] For a perspective on the disparities between the results from the ARM data and those from the operational radiosonde network, and to gain a better overall understanding of the uncertainty in our results associated with the temporal resolution of the observations, we performed a subsampling analysis of the ARM data. For comparison with the results based on eight observations per day, we performed two additional analyses based on four-times-daily observations, sampling first at 0200, 0800, 1400, and 2000 LST (Experiment I) and then at 0500, 1100, 1700, and 2300 LST (Experiment II). The results (not shown) reveal the following:

[33] 1. Phase and amplitude estimates based on the full 3-hourly data set are generally closer to those based on Experiment I than Experiment II. Since the Experiment I sampling is closer to the sampling of the older operational data, this result enhances our confidence in our findings based on four observations per day.

[34] 2. Near-surface amplitudes are from ~0.3 to 1 K larger in Experiment II than in Experiment I, with the largest difference in summertime. This is probably because Experiment II better captures late-afternoon/evening maximum temperatures.

[35] 3. Above 850 hPa, the differences in amplitude estimates among the sampling experiments are generally within ~0.05 to 0.2 K.

[36] 4. The vertical profile of phase estimates in the lower troposphere, with later maximum temperatures at ~850 hPa than at the surface and than above 850 hPa, is a robust result.

[37] 5. Phase estimates in Experiments I and II are within two and four hours, respectively, of the estimates from the fully sampled data below 200 hPa, except for the DJF results. The lack of consistency in the DJF phase results suggests that they are unreliable, probably because of the smaller sample size for that season.

[38] In short, the high resolution ARM data tend to yield amplitude results consistent with the lower resolution data from other regions, and from North America, for the lower troposphere, enhancing our confidence in those results. The mixed areas of agreement and disparity with the lower resolution data for the region above 200 hPa suggest greater uncertainty in our ability to discern the details of the diurnal

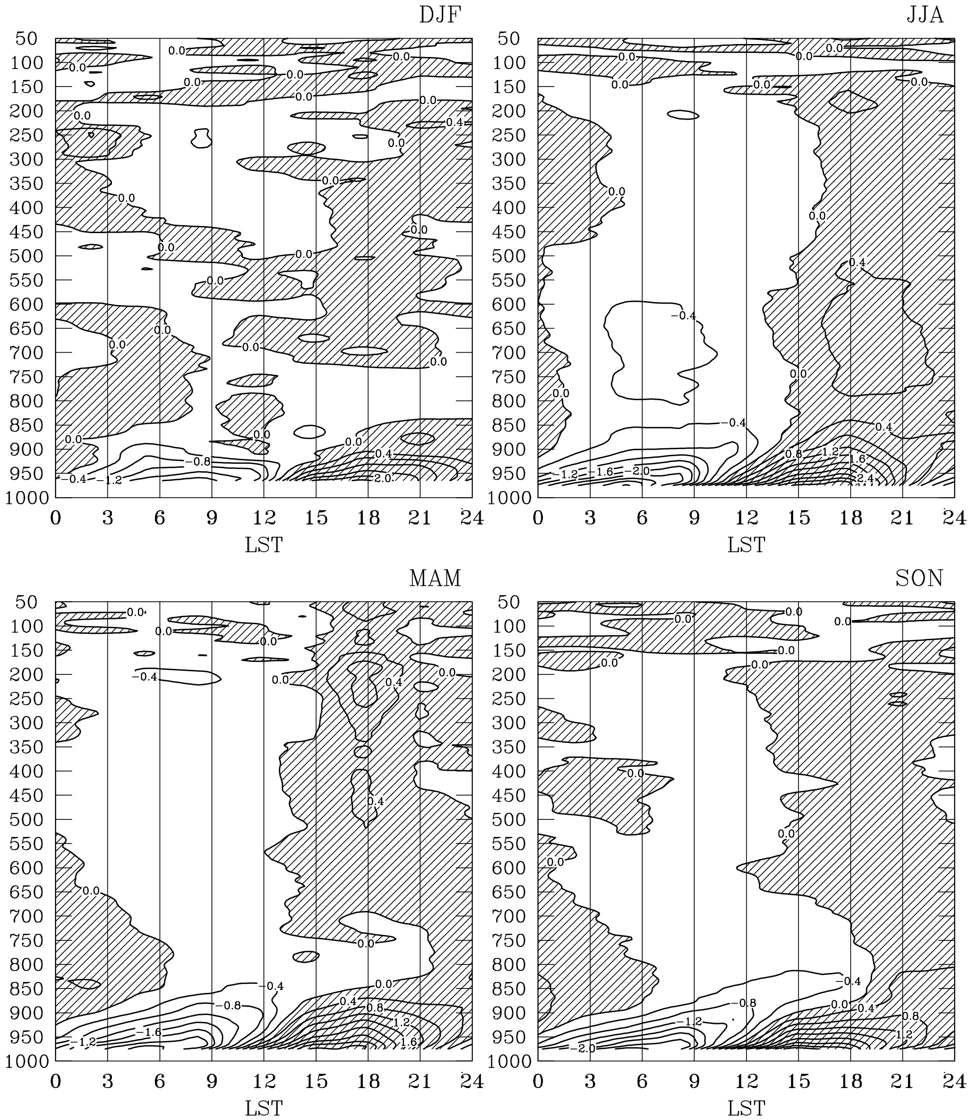

Figure 5. Contour plots depicting mean vertical structure, from the surface to 50 hPa, of diurnal variations of temperature anomalies (departures from the daily average) at the ARM Central Facility, for each of the four seasons.

temperature wave there. From the subsampling experiments, we estimate an uncertainty in amplitude estimates of up to 1 K near the surface, and <0.2 K above 850 hPa, and an uncertainty in phase estimates of 2 to 4 hours between the surface and 200 hPa, with higher uncertainty in phase at higher elevation.

4.3. Estimates of the Diurnal Cycle in Deep-Layer Mean Temperatures

[39] As discussed in the Introduction, one motivation for this study is to provide an independent estimate of the diurnal cycle of upper-air temperature for use in removing potential aliasing effects of the diurnal cycle in analysis of long-term trends in Microwave Sounding Unit observations. For this purpose, we use radiosonde data to simulate deep-layer mean temperatures for the mainly tropospheric MSU Channel 2 and the mainly stratospheric Channel 4, by employing static weighting functions, shown in Figure 8, to the radiosonde pressure-level data [*Seidel et al.*, 2004]. For MSU Channel 2, different weighting functions are used for land and ocean (TOGA/COARE) soundings; for land, the contribution of the surface is larger.

[40] Figure 9 depicts the seasonal variations of the diurnal cycle amplitudes and phases, for each region, of deep-layer mean temperatures for Channels 2 and 4. For Channel 2, the regionally-averaged amplitudes range from ∼0.2 K in winter in Western Europe to ∼0.9 K in the Tropics region during the dry season. The seasonal variability noted in the diurnal cycle amplitude at the surface and at 850 hPa (Figure 3) is evident in the Channel 2 results, but it is less pronounced, because those lowest levels account for <25% of the deep-layer mean. The phase peak occurs within a few hours of 1600 LST.

[41] For Channel 4, we obtain a wide range of amplitudes (Figure 9), with smallest values (∼0.2 K) in Western Europe and largest values (∼0.8 K) in the much older data from the tropics. The phase peak is estimated to occur between ∼1000 and 1400 LST for all regions except Western

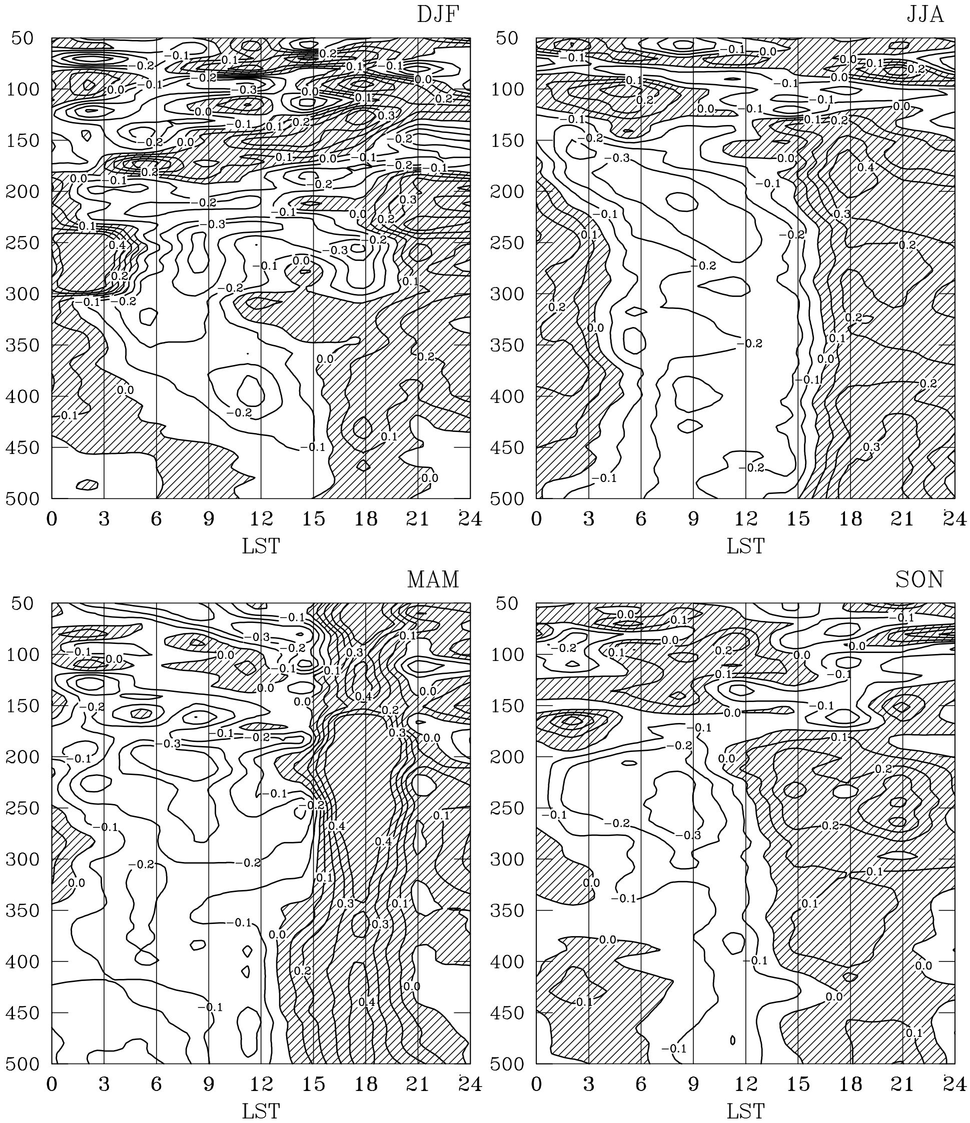

Figure 6. Same as Figure 5, but focusing on the region above 500 hPa.

Europe, where we find modal values at nighttime. The concerns we raised in the previous section about the quality of the older stratospheric data from the North American and the Tropics regions, and about the more recent Western European observations, are pertinent to the Channel 4 results.

[42] Figure 9 suggests that the amplitude of the diurnal cycle is comparable for Channels 2 and 4. However, this result is probably misleading, because of the importance of microwave emissions from the surface, particularly over land, as contributions to the Channel 2 observations. If we were able to use skin temperatures, rather than air temperatures, in estimating deep-layer means, we would most probably obtain a larger diurnal variation for Channel 2, because of the much larger skin temperature variations, discussed above. If the amplitude of the diurnal cycle of skin temperature is five time larger than that of surface air temperature as discussed above, given that the surface accounts for about 10% of the total weighting function for Channel 2 (Figure 8), and with typical surface air temperature diurnal amplitudes of about 2.5 K (Figure 3), our estimates of the amplitude of the diurnal cycle for Channel 2 are probably about 1 K too small.

4.4. Comparison With Previous Investigations

[43] Our results are, in general, in good qualitative agreement with several previous investigations of the diurnal cycle of upper-air temperature. Two earlier studies were based on four radiosonde soundings per day, as in this study, but with much more limited sets of stations. We find good agreement with the summertime results reported by *Harris et al.* [1962] for the Azores and Washington, DC. Our findings for the TOGA-COARE region are consistent with the analysis of *Tsuda et al.* [1997] of vertical profiles of amplitude and phase at Bandung, Indonesia, and at TOGA-COARE stations. That study also noted the larger amplitude diurnal cycle at the tropical tropopause, compared with nearby constant-pressure levels, which we also find in the TOGA-COARE region, but which is not further discussed in this paper.

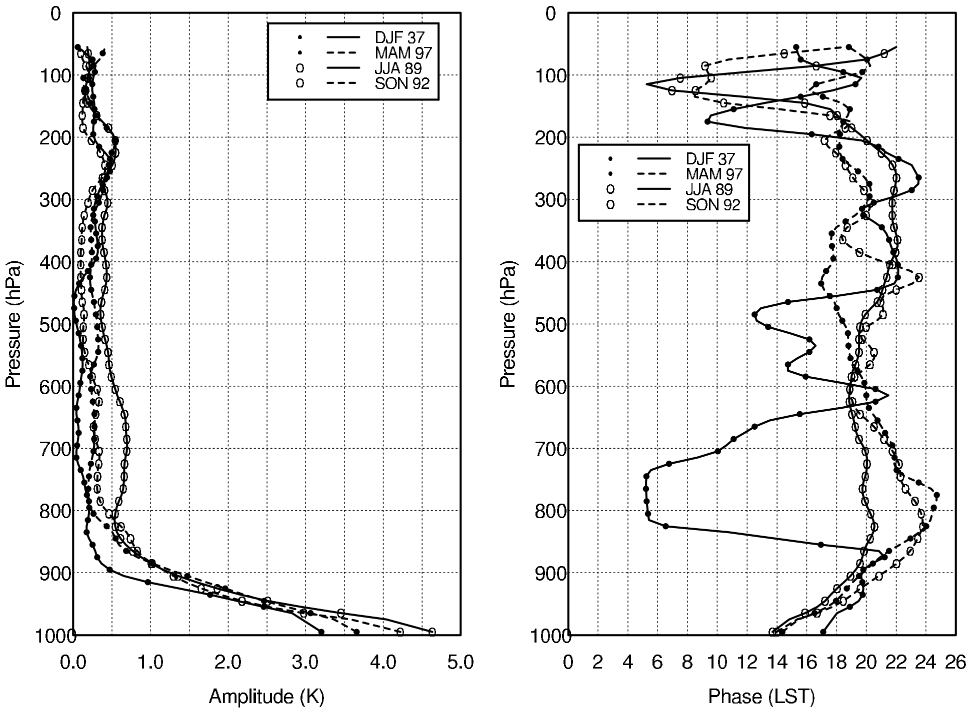

Figure 7. Vertical profiles of the seasonal mean amplitudes (left) and phases (right) of the diurnal cycle of temperature at the ARM Central Facility. The number of soundings available for each season is shown in the keys.

[44] Other studies examined the vertical structure of the diurnal cycle using two observations per day. *Wallace and Patton* [1970] employed 0000 minus 1200 UTC radiosonde temperature differences at U.S. stations to obtain vertical and seasonal variations, and our results for North America are consistent with theirs. *Balling and Cerveny* [2003] also used 0000 minus 1200 UTC radiosonde data from the central U.S. to estimate diurnal temperature range. In comparison with our amplitude estimates (which should be $^1/_2$ DTR), we obtain smaller surface and 850 hPa amplitudes, and larger amplitudes in the upper troposphere, than *Balling and Cerveny* [2003], who report DTR exceeding 8 K at the surface, exceeding 1 K at 850 hPa, and ~0.5 K at higher attitudes. These differences may be due to differences in spatial and temporal sampling. *Balling and Cerveny*'s [2003] larger lower tropospheric amplitudes may be due to their focus on the central U.S., where continental influences amplify the day-night difference compared with our North American stations, with more maritime influence (Figure 1). Our results from the ARM Central Facility, which is more representative of *Balling and Cerveny*'s [2003] region of study, support this interpretation. In the upper troposphere, our larger amplitude estimates are probably more realistic because the twice-daily soundings used by *Balling and Cerveny* [2003] do not capture the full diurnal cycle. The ARM Central Facility results show a phase peak in the evening (Figure 7), later than the 0000 UTC (1800 LST) sounding time.

[45] *Balling and Christy* [1996] employed global climatological MSU Channel 2 data, at 1930 and 0730 LST, to estimate DTR. Their results are similar to those reported in this study in terms of the pattern of seasonal variations and land vs. ocean differences. However, *Balling and Christy*

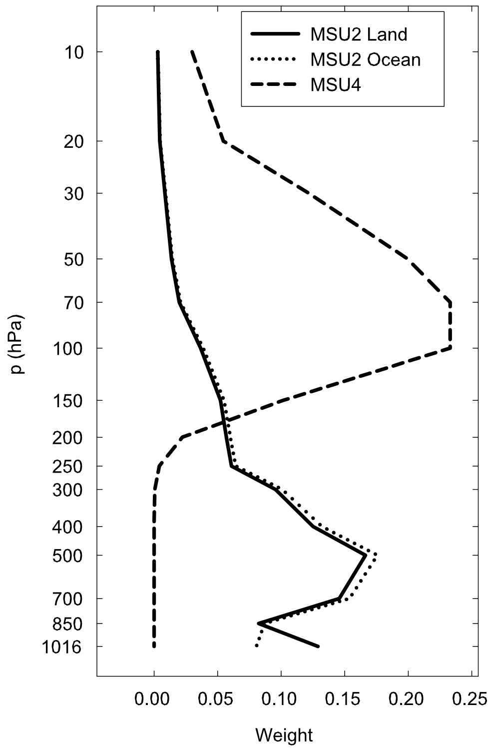

Figure 8. Static vertical weighting function used to estimate deep-layer mean temperature for MSU Channels 2 and 4 from radiosonde data. For Channel 2, different weighting functions for land and ocean stations are shown.

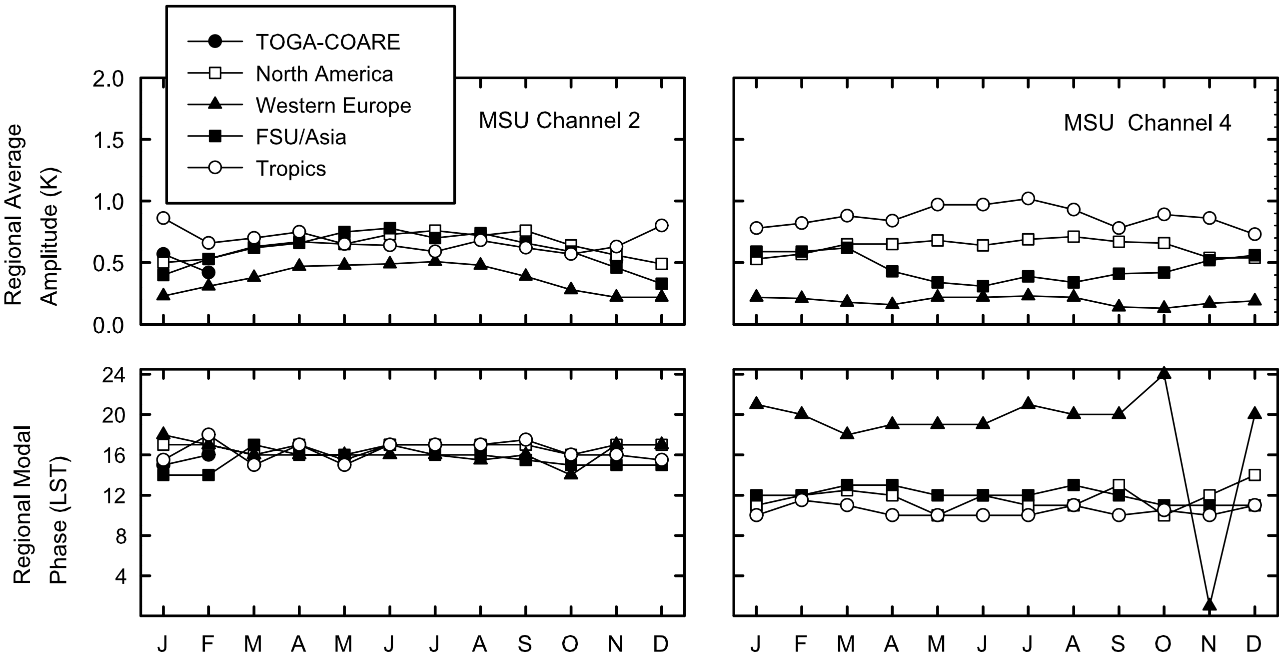

Figure 9. Same as Figure 3, but for MSU Channel 2 and Channel 4.

[1996] obtain substantially smaller amplitudes than those reported above, which may be due to any of a number of limitations in the MSU data, as they discuss, particularly the limited temporal sampling of the diurnal cycle.

[46] *Mears et al.* [2003] used hourly general circulation model results, as input to a radiative transfer model, to simulate global patterns of the amplitude and phase of the diurnal cycle in MSU Channel 2 brightness temperatures. In comparison with their estimates, we find larger amplitudes over ocean regions, smaller amplitudes over land regions, and a phase peak later in the afternoon. Our smaller amplitudes over land are likely partly due to our use of surface air temperature, rather than skin temperature, to estimate the deep-layer mean temperature from radiosonde observations, and the ~1 K correction estimated above partially narrows the discrepancy. The differences in the timing of the phase peak may be related to the relatively poorer temporal resolution of the radiosonde data, or an unrealistic model simulation of the shape of the diurnal cycle.

[47] Using methods described by *Vinnikov et al.* [2004], *Vinnikov and Grody* [2003] used MSU Channel 2 data to estimate the global average diurnal cycle of upper-air temperature, and its variability and trend, and their seasonal variations. They find amplitudes less than 0.5 to 1.0 K, and broad phase peaks sometime between 10 and 20 LST. These results are roughly consistent with our findings based on radiosonde data, but, when we add the estimated effects of microwave emissions from the surface (which should be manifested in the MSU data), we obtain larger amplitudes.

5. Summary

[48] Using climatological four-times-daily radiosonde data from 53 stations in five regions in the Northern Hemisphere, soundings in the equatorial western Pacific from TOGA/COARE, and more recent eight-times-daily radiosonde data from the ARM Central Facility in Oklahoma, we have estimated the amplitude and phase of the climatological diurnal cycle of temperature, from the surface to 10 hPa. Our results are in general qualitative agreement with earlier studies (with some quantitative differences) but provide more detail about vertical, seasonal, and geographic variations. The main findings of this study are as follows:

[49] 1. The amplitude of the diurnal cycle (half the diurnal temperature range) is largest (1 to 4 K) at the surface. At 850 hPa and above, the regional-average amplitudes are <1 K throughout the troposphere and stratosphere.

[50] 2. The amplitude of the diurnal cycle in the boundary layer is larger over land than over ocean, and generally larger in summer than winter (except for monsoon regions, where it is larger in the dry season). In the upper-troposphere and stratosphere, land-sea and seasonal differences are not prominent.

[51] 3. The diurnal cycle peaks a few hours after local noon at the surface, a few hours later at 850 hPa, and somewhat earlier in the upper troposphere. The timing of the diurnal cycle peak in the stratosphere is more uncertain.

[52] We note that our analysis has been limited to determination of the amplitude and phase of the diurnal cycle, with no consideration of its shape. Throughout we have assumed a sinusoidal variation in temperature, because of the limited temporal resolution of the radiosonde data. This limitation is one of two important deficiencies in the radiosonde data archives that are the main sources of uncertainty in these results. Although some previous studies examined twice-daily data to estimate free-air diurnal temperature range [*Wallace and Patton*, 1970; *Balling and Christy*, 1996; *Balling and Cerveny*, 2003], the resolution of even the four-times-daily observations is only barely adequate for resolving the first harmonic of the diurnal cycle. The differences in phase estimated from the ARM site, with higher resolution observations, and from the earlier North American data, suggest that our phase and

amplitude estimates may be uncertain by up to 2 hours and 1 K, respectively, near the surface, and up to 4 hours and 0.2 K, respectively, between 850 and 200 hPa, with larger uncertainties above these levels.

[53] The second major source of uncertainty, which is not independent of the temporal sampling uncertainty, is potential biases in daytime stratospheric temperature observations. It is well known that the early U.S. data have a high bias due to uncorrected daytime radiation error, which likely accounts for the larger amplitude estimates we obtain for the North America and Tropics regions. More recent data from Western Europe yield a very small amplitude stratospheric diurnal cycle, with inconsistent phase peak times and many nighttime peaks. This suggests that the data may be improperly adjusted. Thus we have less confidence in our stratospheric results than the tropospheric findings.

[54] Our estimates of the diurnal cycle in deep-layer mean temperature, as would be observed by satellite-borne MSU in two channels, are subject to these same uncertainties in the stratosphere (Channel 4). For the troposphere (Channel 2), the effects of the diurnal cycle in microwave emissions from the Earth's surface, associated with the large-amplitude diurnal cycle in skin temperature, would enhance the diurnal cycle that we estimate using air temperature only. There remain differences in estimates of the amplitude and phase of MSU deep-layer mean temperatures between our results and those of other investigators, employing different methods, that should be addressed in future research.

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