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DIURNAL TEMPERATURE VARIATIONS: SURFACE TO 25 KILOMETERS [1]

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ABSTRACT

Vertical profiles of 12-hr temperature difference are examined for evidence of structure related to the topographically forced diurnal wind variations. Wavelike features are found with amplitude of the order of 1°C and wavelengths of the order of 5–15 km. These values agree with estimates inferred from the tidal wind field on the basis of continuity considerations.

The diurnal temperature range in the planetary boundary layer decreases exponentially with height, with the decay rate varying markedly from one geographical region to another.

1. INTRODUCTION

Studies of diurnal wind variability in the troposphere and lower stratosphere by Hering and Borden (1962) and Wallace and Hartranft (1969) have revealed the existence of broad scale "tidal" wind patterns that bear a strong relation to the underlying topography. These have amplitudes of the order of 1–2 m sec^{-1}, with largest values in the Tropics and over middle-latitude land areas during summer. Their horizontal scale appears to be governed by the local topography at the lower levels and by the continent-ocean distribution at the tropopause and above.

This tidal wind field is observed to be highly divergent at certain times of the day. The observed amplitudes and horizontal scales imply divergences generally of the order of 10^{-6} sec^{-1} and locally as large as 10^{-5} sec^{-1} in the lower troposphere. The associated vertical structure consists of downward propagating waves. A survey of vertical profiles such as that shown in figure 1 suggests a vertical scale (wavelength/2π) between 1 and 5 km. On the basis of these estimates, we can infer from continuity considerations that the diurnal oscillation in vertical motion should have an amplitude of the order of tenths of cm sec^{-1}, with locally higher values in the lower troposphere. This is within an order of magnitude of the size of the vertical motions associated with the weak synoptic systems that prevail in the Tropics and over middle latitudes during the summer season.

If the vertical motions inferred from the wind data are correct, we should expect to find diurnal temperature fluctuations with comparable space scales. A diurnal oscillation in vertical motion with amplitude w^* would produce, by adiabatic heating and cooling, a temperature oscillation with amplitude T^* given by

$$T^*=\frac{1 \text{ day}}{2\pi}\left(\frac{g}{c_p}+\frac{\partial T}{\partial z}\right) w^*$$

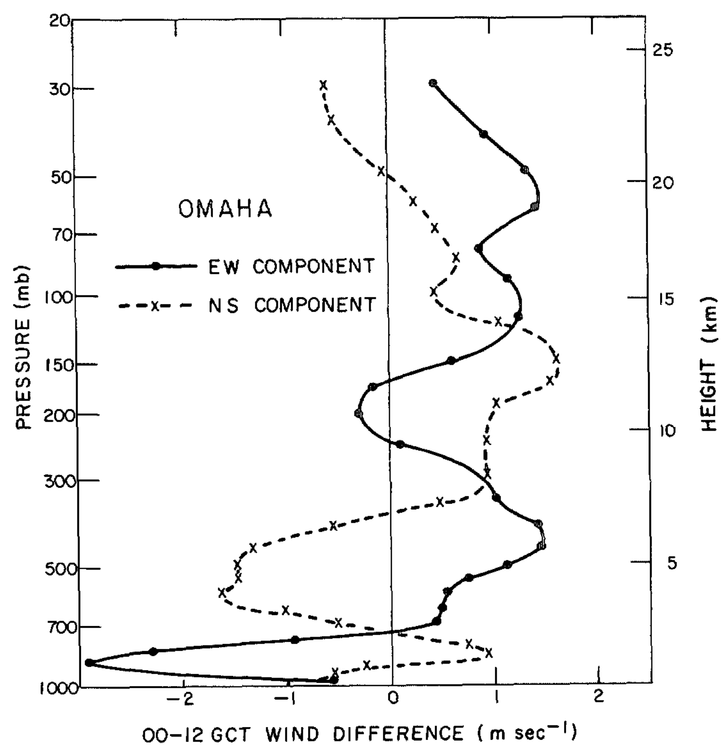

FIGURE 1.—Vertical profile of mean 12-hr wind difference at Omaha.

where g is the acceleration due to gravity, c_p is the specific heat of air, T is temperature, and z is height. The static stability factor $[(g/c_p)+(\partial T/\partial z)]$ averages near 3°–4°C km^{-1} in the troposphere and 10°–15°C km^{-1} in the stratosphere. The tidal vertical motions inferred from continuity considerations imply 12-hr temperature differences of the order of 1°C in both regions if adiabatic motion can be assumed. This is at least three times as large as the diurnal temperature range predicted by classical tidal theory, which neglects topography (Lindzen 1967).

The diurnally dependent radiation error in the temperature sensor, which may be as large as several degrees Celsius at 30 mb and above, may be distinguished from

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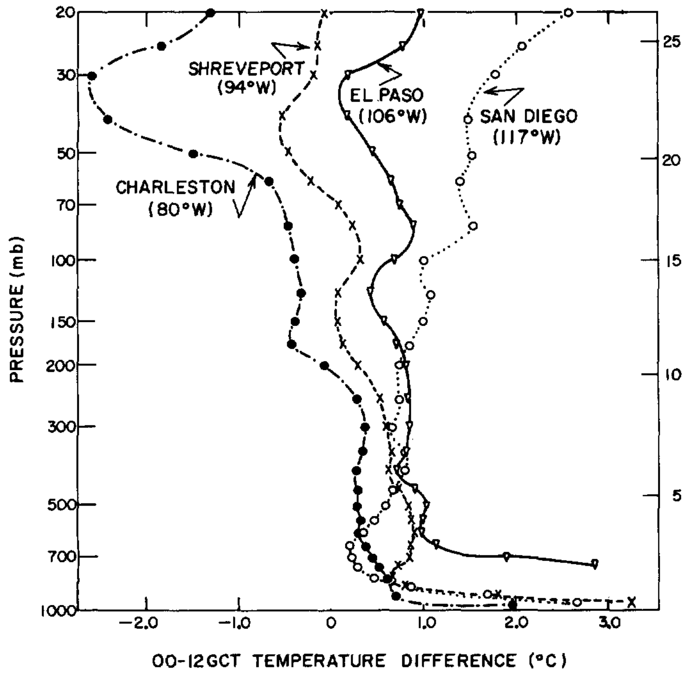

FIGURE 2.—Vertical profiles of observed 12-hr temperature differences.

the topographically induced tidal oscillation by virtue of the difference in vertical structures. The vertical profiles of the true 12-hr temperature differences should exhibit an oscillatory height dependence, whereas the bias inherent in the instrument should increase monotonically with height.

Thus, the temperature oscillation associated with the topographically induced component of the diurnal tide should be detectable in radiosonde data. The main purpose of this study is to verify its existence by presenting vertical profiles of seasonal mean 12-hr temperature differences. The data source and data-processing procedures are identical to those described in Wallace and Hartranft (1969). Unless otherwise specified, the temperature differences represent summer (June–August) averages over the period July 1957–August 1964.

2. RESULTS

Figure 2 shows the vertical profiles of the 00–12 GMT temperature differences for four stations that lie in an east-west line close to 30° N. This sequence of profiles serves to demonstrate three distinct features of the observed 12-hr temperature differences:

1) Above the lowest few kilometers, the most pronounced feature of the profiles is the tendency for the absolute value of the temperature difference to increase monotonically with height at some stations. East of 90° W., where the 00–12 GMT difference represents evening (darkness) minus early morning (daylight), the values become more negative with height, while west of that longitude, the opposite trend is observed. This pattern reflects the fact that the daylight soundings tend to be warmer, particularly at high levels. This is mainly a reflection of the instrument error.

2) Superimposed upon this trend are fluctuations with amplitudes as large as 1°C and wavelengths of the order of 5–10 km. It is these that we identify with the "tidal" vertical motion field.

3) The temperature differences in the lower portion of the curves are much too large to be ascribed to vertical motions. These reflect the effect of diabatic processes operating within the planetary boundary layer.

INSTRUMENT ERROR

Badgley's (1967) finding that instrument error is inversely proportional to the square root of air density (a result based on dimensional analysis and laboratory tests in a vacuum chamber) suggested that it might be possible to estimate the contribution of this effect to the observed temperature difference profiles by means of a simple curve-fitting procedure. We approximated the density dependence by the pressure dependence and assumed that

$$\Delta T_e = \beta \left(\frac{p}{1000 \text{ mb}}\right)^{-1/2}$$

where ΔT_e is the instrument error, p is pressure, and β is the "error coefficient" to be determined by fitting this function to the observed temperature-difference profiles by the method of least squares. A coefficient was determined independently for each station. In the fitting procedure, only data above the planetary boundary layer were used. We note that β is numerically equal to the estimated temperature error at 1000 mb and to one-tenth of the estimated error at 10 mb.

Figure 3 shows the values of the "error coefficient" for the summer data for stations between 10° N. and 50° N. as a function of longitude. The points fall close to a smooth curve that crosses the origin near 90° W. The curve slopes steeply near this longitude, which is evidence of the high sensitivity of instrument error to solar elevation angle at low angles. The functional dependence upon solar angle and the typical magnitudes of the computed temperature error are in reasonably close agreement with previous studies, for example, Finger and McInturff (1968).[3]

It should be noted that the instrument error as computed by this method contains a small contribution from that component of the true diurnal temperature variation which increases monotonically with height. We made no attempt to isolate this component in the present study.

THE TRUE DIURNAL TEMPERATURE VARIATION

We subtracted the instrument error, as computed above, from the vertical profiles of the observed 00–12 GMT temperature differences and obtained, as a residual, an esti-

[3] An exact comparison cannot be made because the data used in the present study contain observations made with both the duct and outrigger type radiosondes. Most stations changed to the latter type about 1960–61.

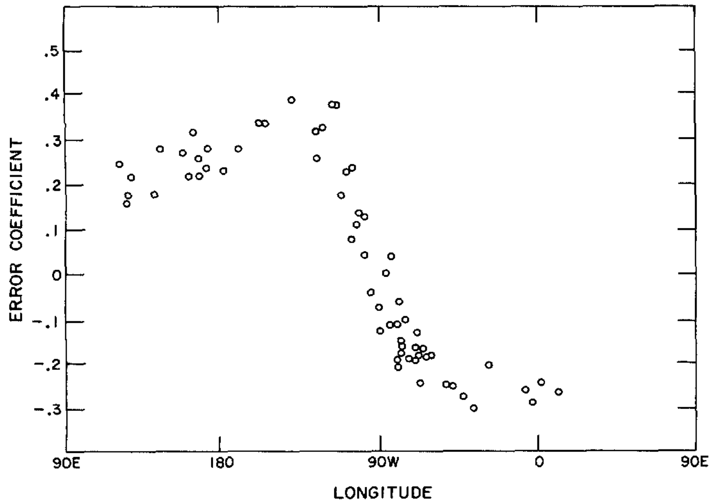

FIGURE 3.—"Error coefficient" plotted as a function of longitude for stations between 10° and 50° N. See text for explanation.

mate of the true diurnal temperature variation. In these corrected profiles, the wavelike fluctuations pointed out above are much more prominent. Three examples are shown.

Figure 4 shows, on an expanded scale, the corrected summer profiles for three stations in the central United States. The features to be emphasized are the oscillations that appear with similar phases at the three stations. Comparison of figures 1 and 4 reveals that the wind and temperature fluctuations have the same vertical scale. The similarity of the three profiles attests to the reality of these features. The apparent linear trend with height may be a real feature, or it may be a reflection of instrument error not removed by the curve-fitting procedure.

A stronger similarity can be seen in the summer profiles for three adjacent Caribbean stations shown in figure 5. The amplitudes are in excess of 1°C, which is typical for tropical stations during all seasons.

A strong seasonal dependence can be noted by contrasting the summer and winter profiles for Ascension Island (fig. 6). This confirms earlier results of Sparrow (1967). When a Student's *t*-test is applied to the seasonal differences, even the small difference at 20 mb is significant at the 0.1 percent level.[4] In the Tropics, the seasonal dependence is manifested by a change in the shape of the profiles; whereas in middle latitudes, it appears as a change in amplitude, with the summer values being larger.

THE DIURNAL TEMPERATURE RANGE IN THE PLANETARY BOUNDARY LAYER

Within the lowest few kilometers above the ground, the vertical profiles for land stations exhibit large temperature ranges with afternoon maxima. This is the layer in which diabatic processes (that is, eddy fluxes of sensible heat and longwave emission) operate on a time scale suffi-

[4] The seasonal samples at each level comprise 21 individual monthly means. The standard deviation of the monthly mean values about the seasonal mean is generally less than 0.8°C.

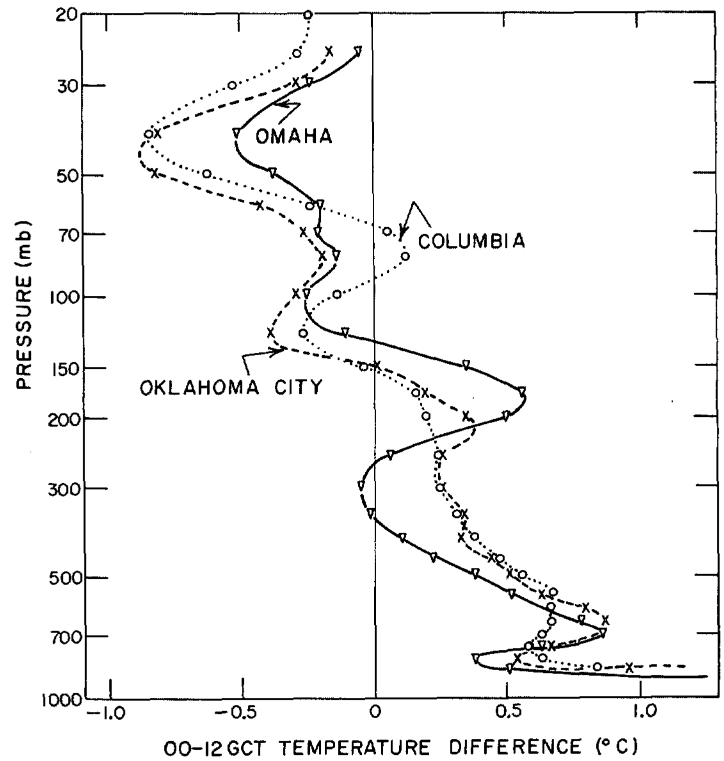

FIGURE 4.—Vertical profiles of corrected 12-hr temperature differences.

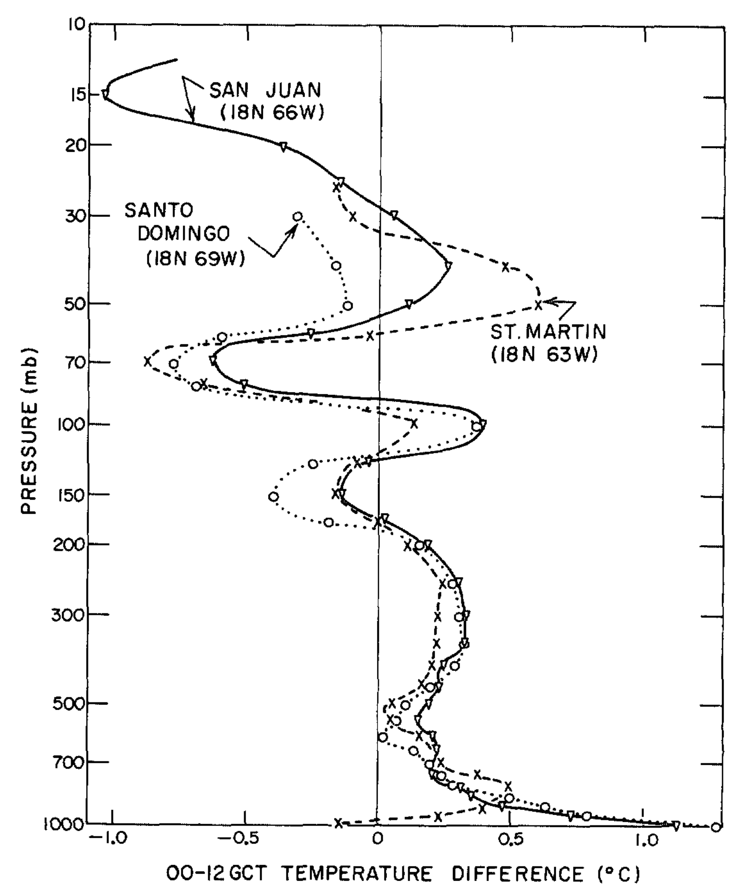

FIGURE 5.—Vertical profiles of corrected 12-hr temperature differences.

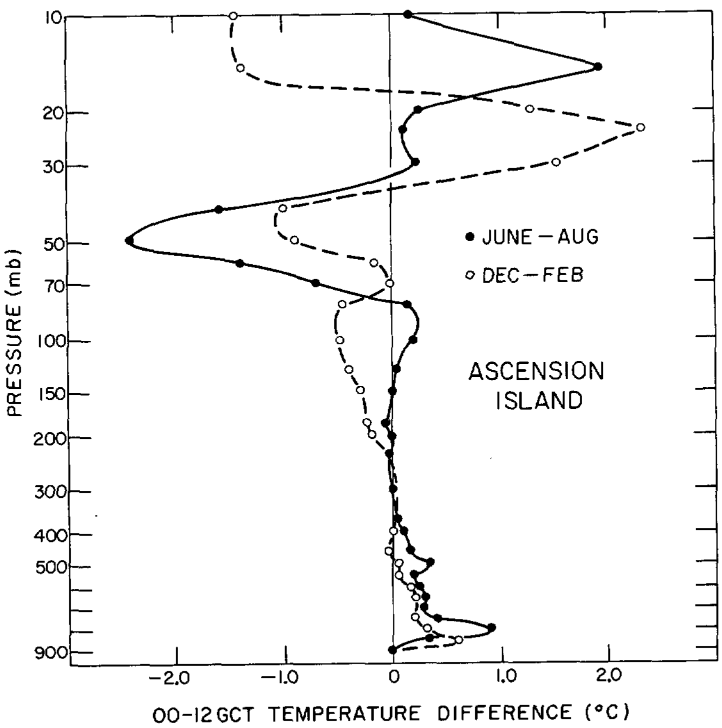

FIGURE 6.—Vertical profiles of corrected 12-hr temperature differences for summer and winter at Ascension Island.

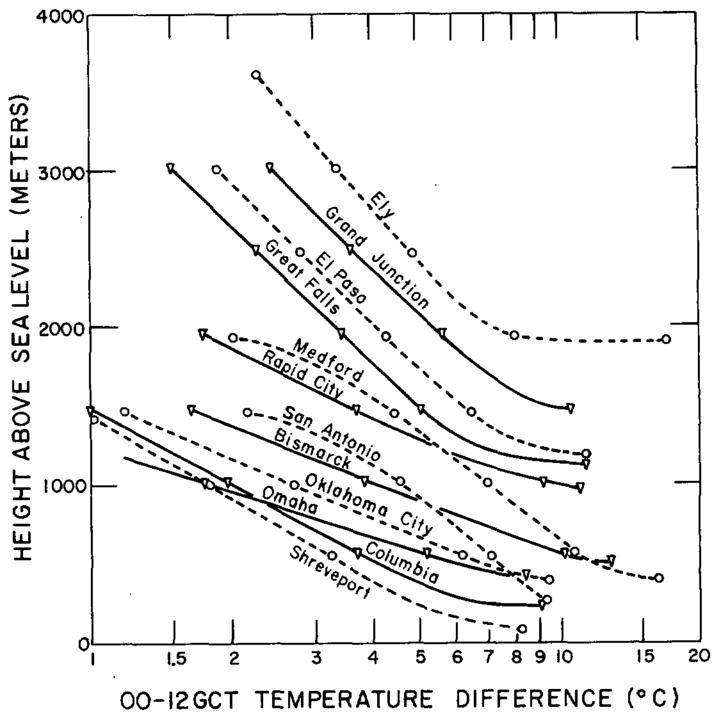

FIGURE 7.—Vertical profiles of observed 12-hr temperature differences for inland stations in the western United States.

ciently short to create a strong diurnal temperature cycle. It is notable that this effect is entirely absent in the profiles for the weather ship stations and is quite small at island and coastal stations where local sea-breeze circulations exert a damping influence.

Figure 7 shows the lowest part of the vertical profiles for all available inland stations in the western United States, plotted on a semilog scale. These represent late afternoon minus late night differences and are thus a close approximation to the true diurnal temperature range for this particular selection of stations. In each case, the lowest point plotted represents the surface data.

Between approximately 100 and 1500 m above the ground, the temperature range at nearly all stations decreases exponentially with height, as evidenced by the straight lines in figure 7. The rate of decay, indicated by the slope of the lines, varies markedly between the Mississippi Valley and the High Plateau stations, with the latter having, in effect, a deeper penetration of the diabatic effects by about a factor of 2.

3. CONCLUDING REMARKS

The results of this study confirm the existence of temperature fluctuations related to the topographically forced component of the diurnal tide. The observed 12-hr temperature differences exhibit a vertical structure strongly suggestive of the vertically propagating modes prominent in the wind data.

Above the tropopause, the amplitudes of the temperature difference are of the order of 1°C, which is in general agreement with the estimate inferred from the wind data under the assumption of adiabatic flow. Between the planetary boundary layer and the tropopause, the observed temperature differences are generally of the order of tenths of a deg C, which is somewhat smaller than the estimate inferred from continuity considerations. This discrepancy suggests that the tidal vertical motions in the troposphere may often take place under moist adiabatic conditions, which would result in a lower effective static stability. This would tend to support the view (Bleeker and Andre 1951, Brier and Simpson 1969, and others) that the tidal wind field interacts with convective processes to a significant extent.

In previous studies, it has generally been assumed that the true diurnal temperature variation can be viewed simply as a westward propagating wave so that all stations along any latitude circle experience exactly the same variation referred to their respective local times. In light of the above results, it is clear that this is not generally the case in low and middle latitudes, where each region has its own characteristic pattern of diurnal temperature variation.

It is not clearly understood why the decay of the diurnal temperature cycle with height should be so close to exponential in the planetary boundary layer at nearly all inland stations, and why the decay rate should vary so markedly from one geographical region to another. Further investigation into these questions would appear justified by the need to model accurately the distribution of diabatic heating in the planetary boundary layer.

This crude description of the geographical dependence of the amplitude and vertical extent of the diurnal heating cycle within the planetary boundary layer provides some basis for a quantitative evaluation of the effects of topography in generating tides. McKenzie (1968) used an idealized heating distribution based on these results in his numerical model and obtained topographically dependent tidal motions with amplitudes and vertical structure similar to those observed. Further studies of this type, with more realistic models, will be needed to clarify the roles of the various tide-generating mechanisms.

The three-dimensional tidal structure is an extremely sensitive indicator of the distribution of atmospheric energy sources and sinks. The seasonal change in the monsoon circulation is strongly reflected in the tides in the Tropics, and it is not unlikely that the constant evolution of synoptic patterns causes an analogous day-to-day change in tidal structure at middle latitudes.[5] Given a sufficiently accurate model, it is conceivable that data on tidal structure might provide a convenient and useful supplement to direct measurements in monitoring the atmospheric energy budget.

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[5] The smallness of the tide during the winter season may be the effect of averaging together the tidal patterns that correspond to a variety of synoptic situations. The tides on individual days may still be quite large.

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