

4.3 Atmospheric tides

The atmosphere also has tides, if by “tides” one means motions that fluctuate with diurnal, semidiurnal (terdiurnal, ...) period. Fig. 4.11 shows surface

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pressure at a tropical location and a northern midlatitude location. There is little evidence for a diurnal and semidiurnal component in middle latitudes, for two reasons: the signal (which can, in fact, be extracted by analysis of long time series) is weak there, and there is a large “synoptic” variability of pressure associated with day-to-day weather events, which masks the tidal signal. In the tropics, conversely, the day-to-day variability is small (for reasons we shall see later), and the tidal signal is stronger. Fig. 4.11 shows a tidal range of about 5mm Hg (\simeq 7hPa) at Batavia. This rather small amplitude makes the atmospheric tide a curiosity, rather than an important

phenomenon, at the surface, though its amplitude is much larger in the upper atmosphere.

Like the ocean tide, the atmospheric tidal signal (at the surface) is predominantly semidiurnal but, unlike the ocean tide, it is *solar* semidiurnal: its phase remains fixed with respect to the (solar) clock. [This is just evident in Fig. 4.11, and more clear with a longer time series.] Since we deduced from eq. (4.3) that the lunar gravitational forcing dominates the solar, this seems curious. Moreover, calculations show that the atmospheric tide to be expected from gravitational forcing—lunar or solar—is much weaker than observed. Something else must be forcing the “tide.”

That “something else” is heating. The atmosphere is of course subject to diurnally-varying solar heating, whose effects in driving large-scale motions far outweigh gravitational forcing. Even though the thermal forcing is “diurnal” it is not a single harmonic (since, for example, nighttime cooling via IR radiation varies much less through the night than does solar forcing during the day). The diurnal variation of net heating is shown schematically in Fig. 4.12. We could expand the heating $J(\lambda - \Omega_s t)$ (the whole heating pattern, to

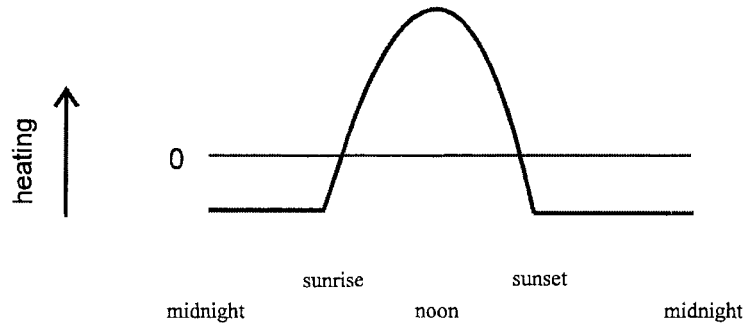


Figure 4.12:

a first approximation, it propagates around the world at the angular speed Ω_s of the subsolar point) as a series

$$J(\lambda - \Omega_s t) = \sum_{n=1}^{\infty} J_n \cos [n (\lambda - \Omega_s t)] ,$$

where $n = 1, 2, 3, \dots$ corresponds to the diurnal, semidiurnal, terdiurnal, ... components, all of which will be nonzero. Nevertheless, this does not

solve our problem as, with any reasonable representation of J , the diurnal component is the largest. So why is the observed tide semidiurnal?

For many decades, it was thought that the answer had to lie in the resonance of the atmosphere at the semidiurnal period⁵. This was hard to prove, as in order to calculate the atmosphere's resonant frequencies, it is necessary to know its thermal structure, and little was known above altitudes of about 15km until the 1940s. Calculations then showed the resonance hypothesis to be untenable.

So what is happening? It turns out that the most important region of forcing of the thermal tide is in the stratosphere, at altitudes above around 30km, through absorption of insolation by ozone. At these altitudes, the diurnal component is larger than the semidiurnal. However, in order to reach the surface, the tide must *propagate* there—the tide is a wave motion, albeit a forced one. Now, we saw from (3.2) that internal gravity waves must satisfy

$$\omega^2 = \frac{N^2 k^2}{k^2 + m^2},$$

from which we deduced that ω^2 cannot exceed N^2 . In the tidal case, ω and k are given by the forcing; the only free parameter is the vertical wavenumber m , which satisfies:

$$m^2 = k^2 \left(\frac{N^2 - \omega^2}{\omega^2} \right). \quad (4.11)$$

So we can now be more specific and state, not that ω cannot exceed N , but that the vertical wavenumber is real—and hence vertical propagation can occur—only if $\omega^2 < N^2$. Otherwise, the wave is trapped in the vertical.

Now, this criterion is no problem for tides—their frequencies are very much less than N . However, we noted earlier that the effects of the Earth's rotation are important for tides; when rotation is included, (4.11) becomes

$$m^2 = k^2 \left(\frac{N^2 - \omega^2}{\omega^2 - f^2} \right), \quad (4.12)$$

where $f = 2\Omega \sin \varphi$ (Ω = Earth rotation rate, φ = latitude) is the Coriolis parameter. Thus, vertical propagation requires

$$f^2 < \omega^2 < N^2. \quad (4.13)$$

⁵ Atmospheric tides have, in fact, aroused the interest of some powerful minds. It was Laplace who suggested that they are thermally forced; Lord Kelvin put forward the resonance hypothesis.

Since $\omega = n\Omega$ (with an error of $1/365$, because of the Earth's orbit of the sun), and since f reaches its maximum value of 2Ω at the poles, $f^2 \leq N^2$ everywhere for the semidiurnal and higher components. For the diurnal component, however, $f < N$ only within 30° of the equator; at higher latitudes, the tide cannot propagate downward. For this reason, much of diurnal forcing is extremely inefficient at producing a surface response, and the semidiurnal component dominates there.

4.4 Further reading

An elementary discussion of ocean tides is given in:

Waves, tides and shallow-water processes, by the Open University Course Team, The Open University, Pergamon Press, 1989.

A comprehensive discussion of the mathematical theory of tides on a global ocean is given in the classical text:

Hydrodynamics, H. Lamb, Cambridge U.P., 1916.

For a discussion of atmospheric tides (including an historical account of the resonance theory) see Chapter 9 of:

Dynamics in Atmospheric Physics, R.S. Lindzen, Cambridge U.P., 1990.