Origin of intraseasonal variability in Lake Tanganyika

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[1] Intraseasonal thermocline oscillations in Lake Tanganyika are analysed using observations near Mpulungu and simple analytical/numerical models, in order to understand their origin. The region around the lake is characterised by strong and persistent southeast winds during the four months dry season, lasting from May to August. The associated wind-stress causes the tilting of the thermocline which oscillates for the whole year. The wavelet transform spectra of temperature at 30 m depth of the lake near Mpulungu indicates the presence of various scales of motion, localised in frequency and time. The dominant modes of thermocline oscillations are intraseasonal variability with 3–4 weeks periods. Similar results are obtained from a reduced-gravity model with various wind forcing, including the observed forcing, and a simple analytical solution. In addition, the model results indicates that the dominant mode of oscillation exhibits one node only. From the study, it is inferred that the free modes of oscillations of the lake are in resonance with wind pulses. *INDEX TERMS:* 4239 Oceanography: General: Limnology; 4544 Oceanography: Physical: Internal and inertial waves; 9305 Information Related to Geographic Region: Africa. **Citation:** Naithani, J., E. Deleersnijder, and P.-D. Plisnier, Origin of intraseasonal variability in Lake Tanganyika, *Geophys. Res. Lett.*, *29*(23), 2093, doi:10.1029/2002GL015843, 2002.

1. Introduction

[2] Lake Tanganyika is situated near the equator (3°20′ to 8°45′ S and 29°05′ to 31°15′ E), with the length oriented along the south-north direction (Figure 1a). It is a relatively long and deep lake, with an average width of about 50 km (around 650 km long, 570 m average depth and maximum width of around 80 km, Figure 1b). The region around the lake experiences strong and persistent southeast winds for about four months from May to August, the dry season. Under the influence of the associated wind-stress, the thermocline gets tilted downwind towards the north and oscillates back and forth for the whole year. An upwelling occurs at the southern end of the lake to replace the loss of water pushed northwards by the continuous wind-stress. Internal seiches or thermocline oscillations in Lake Tanganyika have been described earlier to be of 3–4 weeks period using observations and model simulations [*Coulter and Spigel*, 1991 and *Naithani et al.*, 2002a, 2002b]. *Naithani et al.* [2002a, 2002b] have simulated periods of oscillations of around 24 days using an analytical solution and a reduced-gravity model. In both works a constant wind-stress was applied over the whole length of the lake for four months. However, no efforts were made to correlate the model simulations with observations.

[3] The intraseasonal variability (ISV) in the equatorial atmosphere are mainly due to the eastward-propagating low-frequency large-scale convection and circulation cells, which get their energy from the seasonally migrating intertropical convergence zone (ITCZ) [*Madden and Julian*, 1971, 1994]. Although, initially suggested to be around 40–50 day period, they were reported to be of 15 day by *Krishnamurti and Bhalme* [1976] due to cloud-radiation feedback processes, 20–40 day oscillations by *Goswami and Shukla* [1984] due to the interactions between moist convective and dynamical processes. *Neelin et al.* [1987] and *Lin et al.* [2000] reported that the ISV of 20–80 day oscillations are maintained by evaporation wind-feedback processes. The issue addressed here is, if the ISV of wind driving the ISV of the lake/thermocline, or the free oscillations of the thermocline are mainly responsible for these periodicities in the lake, or the ISV of lake and ISV of winds are in resonance with each other. In this work we focus on this question directly and more precisely, and try to find the origin of these oscillations using time series observations at Mpulungu, a reduced-gravity model with various wind forcings and a simple analytical solution provided with a periodic wind forcing.

2. Wavelet Spectral Analysis of Observations

[4] In order to see various scales present in the time series and their respective localisation in time, Morlet wavelets have been used. Wavelet transform (WT) is used instead of the classical Fourier transform, since it allows the visualisation of the time evolution of various scales present in the multiscale time series. The description of these wavelets can be found in *Foufoula-Georgiou and Kumar* [1994], *Meyers et al.* [1993] and *Naithani et al.* [2002b]. Figure 2 presents time series of horizontal wind speed, along lake component wind-stress, temperature at 30 m depth in the Lake and the real part of the complex Morlet wavelet coefficients of the respective time series, from April 1993 to March 1994. Winds are high from May to early September, i.e. during the dry season (Figure 2a). During the rest of the year, from October to April, i.e. the wet season, the winds are low and variable. The WT spectra of the time series of horizontal wind show various variabilities including the ISV (around 11, 22, 33 and 64 days). The periods around 11, 22 and 64 days are prominent in the dry season. A noticeable feature in the spectra of wind is the frequency modulation gradually from a 64 day scale in April 1993 to around 33 day scale in

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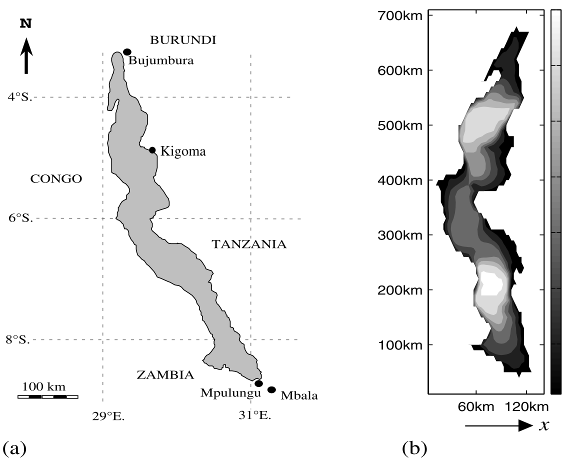

Figure 1. Map of Lake Tanganyika (a) and the bathymetry (b). The graybar shows depth in metre.

October 1993. The variabilities around 22 and 64 days are punctuated by several singularities indicated by the sharp converging WT phase lines onto the 2–4 days, especially around April, August and December 1993. This convergence of phase lines indicates the time when the frequency shifted, indicating the singularities in the signal. The scale around 33 day has maximum intensity in the wet season. The 22 day scale is present in the wind spectra again with very low intensity in February and March 1994. Since, the oscillations in the lake are induced by wind-stress acting on the water surface due to strong SE winds, the WT spectra of wind-stress is also presented. The resulting wind-stress and the real part of its WT coefficients are given in Figure 2b. The wind-stress is calculated for the y component of wind aligned parallel to 160°, i.e. along lake length, which is the main flow direction in the dry season. It is seen that most of the wind gusts are from around this direction. The WT spectra of wind-stress show scales around 22, 33 and 64 days present at similar times as in the wind spectra. The 22 and 64 day oscillations are present with maximum intensity during the early part of the time series. The scale around 33 day is present from the last week of September onwards as in the WT spectra of wind, with greater intensity from October to December months. The scale around 22 day is present again from December 1993 to March 1994, however with much less intensity than in the dry season.

[5] The time series of temperature at 30 m depth shows lower temperatures during the dry season (Figure 2c). The temperature starts decreasing as the wind increases in May and stays low for the whole dry season, due to wind driven mixing, evaporative cooling and convective mixing. The temperature starts building up back to normal as the dry season wind stops at the end of August. In the WT spectra of temperature at 30 m depth (Figure 2c) the convergence of phase lines from 64 day scale to 33 and 16 day scales at the end of the dry season are due to the building up of the temperature in the lake after the dry season wind ceases. The 22 day scale is present from April to August and again from December to February, while the 33 day scale is present in October–November and again in March. The 22 day ISV in the lake during the dry season can be considered to be the forced oscillations present in the wind-stress. The variation of 33 day ISV in the wet season is similar to that in wind stress spectra, with maximum intensity in October and November and low intensity for the rest of the season. The 22 day ISV is again present from December to February, but with higher intensity than the variability around 33 day at the same duration. The variabilities in the wet season too are similar to variabilities in the wind-stress spectra. Besides these main oscillation periods, the WT spectra at 30 m depth also show peaks around 3, 6 and 12 days being more prominent in the wet season.

[6] The slow frequency modulation in wind speed and wind-stress spectra might be due to the increase in moisture content of air in dry season because of strong winds, while

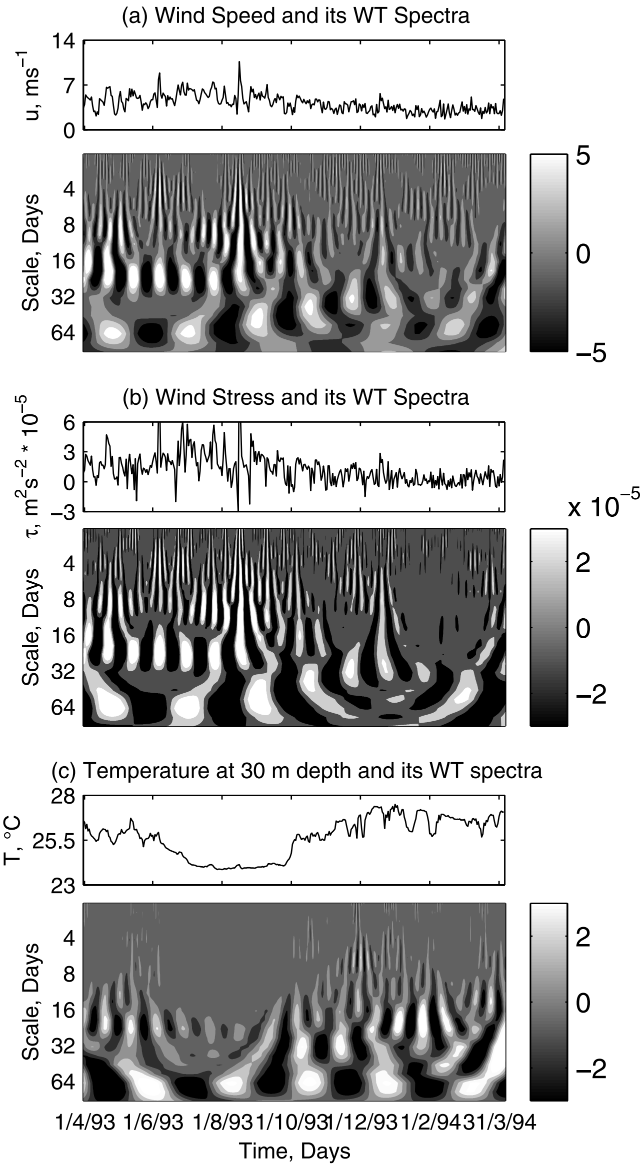

Figure 2. Time series and the time-scale representation of the real part of the complex Morlet wavelet coefficients based on 3-hourly averaged (a) horizontal wind, (b) along lake component of the wind-stress, and (c) temperature at the depth of 30 m from April 1993 to March 1994 near Mpulungu.

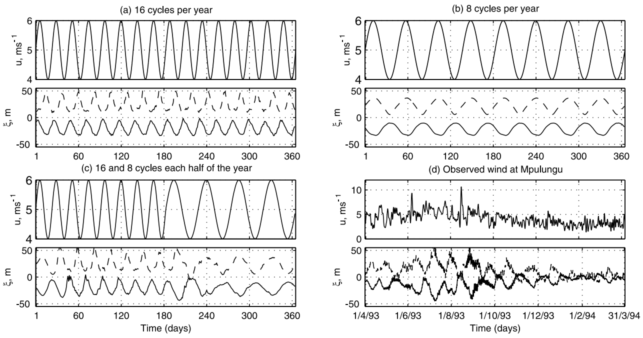

Figure 3. Wind speed forcing (u) and the downward displacement of the thermocline (ξ) 30 kms from the southern (solid line) and the northern (dashed line) ends of the lake simulated by the two-layer reduced-gravity model for (a) 16 cycles per year, (b) 8 cycles per year, (c) 16 and 8 cycles each half of the year and (d) the observed wind at Mpulungu from April 1993 to March 1994.

the abrupt frequency change in the lake is due to the abrupt change in the speed and direction of wind in August–September at the end of dry season. The shift in the oscillation frequency (33 to 22 day scale) at the end of December might be due to the fact that the oscillations tend to have higher frequency during high temperature periods. Amplitude modulation at various scales are due to the nonlinear interactions between various scales and also due to the interference of a frequency component from its sidebands. The latter is depicted by the tilt in the WT phase lines. In the observations the 33 day scale has more intensity in the wet season at approximately the same time as in the wind-stress spectra, this indicates that these oscillations in the wet season too are inherited by the wind-stress and the free oscillations in the lake are indeed influenced by the ISV in its forcing mechanism. However, this is still not very clear since in the earlier studies [*Naithani et al.*, 2002a, 2002b], the authors have found similar period of oscillation while providing a continuous wind forcing for the four months dry season. This implies that the ISV in the lake is independent of the ISV in the wind and that these periods can still be there even if the wind had no imbedded oscillations. The question arises, to what extent the free oscillations of the lake (after the strong wind-stress ceases) are influenced by the winds. In order to have more justification to this statement, we did some tests with the numerical and analytical models.

3. Numerical/Analytical Tests

[7] Figure 3 shows some tests with a two-layer reduced-gravity model where different wind forcings were provided. Model details can be found in *Naithani et al.* [2002b]. In the model the heat flux at the lake surface and the exchange of heat and matter across the thermocline are considered zero, and the bathymetry is ignored as the bottom layer is assumed inactive. Thermocline displacement some 30 kms from the southern and northen ends of the lake are also presented in Figure 3 along with the wind forcing. In the first two model runs, the model was forced with a wind with 16 and 8 cycles per year, respectively and the thermocline also presented similar oscillations (Figures 3a and 3b). In the next run, 16 and 8 cycles were provided each half of the year and the model thermocline responded with similar oscillation periods (Figure 3c). In the last run, the model was forced with the observed winds at Mpulungu for April 1993 to March 1994 (Figure 3d). Once again the thermocline oscillations matched with the frequency of the observed wind pulses, while the amplitude of the response depends on the frequency. These tests indicates that the thermocline oscillations in the lake are indeed influenced by the oscillations in wind forcing. Figure 4 presents the real part of WT coefficients of model simulated thermocline oscillations for the last model run. The figure shows the 22 day scale being prominent in the dry season, 33 day scale in October to December and again 22 day scale from February onwards as in the wind spectra (Figure 2a).

[8] Next a simple analytical solution of the periodic response of the lake to a periodic wind forcing is analysed. The simplified, one-dimensional, linearised equations of *Naithani et al.* [2002a] used for the purpose are: $\frac{\partial \xi}{\partial t} + h\frac{\partial v}{\partial y} = 0$, and $\frac{\partial v}{\partial t} = -\varepsilon g\frac{\partial \xi}{\partial y} - \gamma v + \frac{t_y}{\rho h}$, where ξ is the downward displacement of the thermocline, h is the unperturbed depth of the upper layer, v is the along lake velocity, γ is the damping coefficient, t_y is the along lake component of wind-stress and ρ is the water density. The wind forcing used is homogeneous in space and periodic in time, i.e. $t_y/\rho = \mathrm{Re}(\tau e^{i\omega t})$, where $i = \sqrt{-1}$, τ is a real constant and $T = 2\pi/\omega$ denotes the period of the wind-stress. Series expansion of the forcing is, $\tau = \sum_{n=1}^{\infty} \tau_n \sin(k_n y)$, with $\tau_n = 4\tau/(Lk_n)$ and $k_n = (2n - 1)\pi/L$. We looked for a solution of the form: $\xi(t, y) = \mathrm{Re}\left[\sum_{n=1}^{\infty} E_n e^{i\omega t}\cos(k_n y)\right]$, and $v(t, y) = \mathrm{Re}\left[\sum_{n=1}^{\infty} V_n e^{i\omega t}\sin(k_n y)\right]$, where E_n and V_n are the complex amplitudes of the *n*-th mode. The impermeability of the ends of the lake requires $v(t, y = 0, L) = 0$. The *n*-th mode resonance frequency: $\mu_n = (\varepsilon g h)^{1/2} k_n = \frac{\pi(\varepsilon g h)^{1/2}}{L}(2n - 1)$, or resonance period: $R_n = \frac{2L}{(\varepsilon g h)^{1/2}}\frac{1}{2n-1}$. The response is: $E_n = \frac{4\tau}{L\left(\omega^2 - \mu_n^2 - i\gamma\omega\right)}$, and $V_n = -\frac{i\omega}{hk_n}E_n$, finally $|E_n| = \frac{4\tau}{L\left[\gamma^2\omega^2 + \left(\omega^2 - \mu_n^2\right)^2\right]^{1/2}}$.

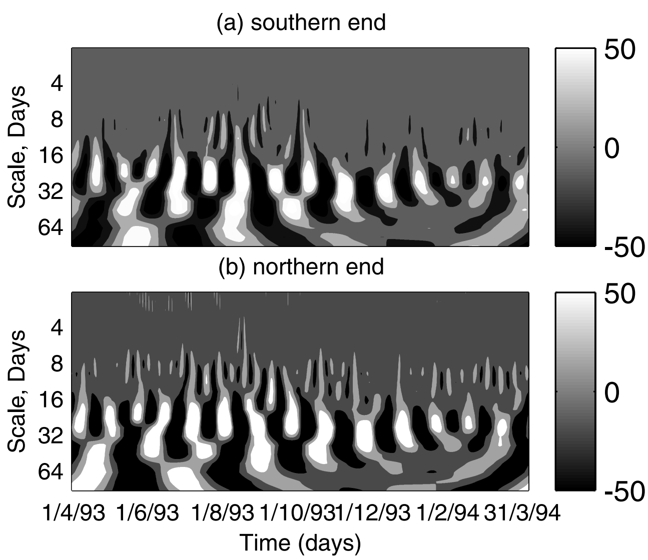

Figure 4. Real part of the complex Morlet wavelet coefficients for the model simulated downward displacement of the thermocline shown in Figure 3c for (a) the southern end and (b) the northern end of the Lake.

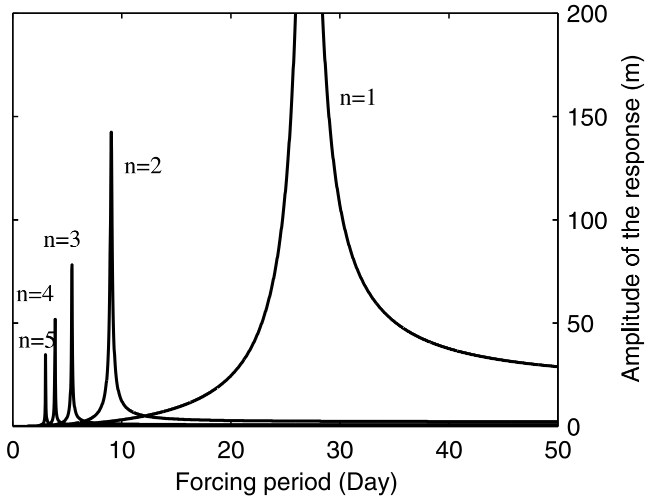

Figure 5. Plot of amplitude of response of the thermocline oscillations to periodic forcing for v_a = 5 m s^{-1}, h = 50 m, L = 650 km, γ = 4 $year^{-1}$ and $\varepsilon = 6.3 \times 10^{-4}$.

[9] This clearly indicates that, the maximum of $|E_n|$ is achieved for $\omega = \mu_n$. Figure 5 presents the amplitude of the response as a function of the forcing period and indicates that for n = 1 mode, the most probable amplitude is around 15 to 40 meters for the periods 20 to 35 days. It can be easily seen, from the figure that it is much easier to excite n = 1 mode because of its much wider window. Exciting the other modes is much more difficult, because of the sharpness of their response curves. This figure indicates that the free oscillations in the lake are indeed in the same range as in the observed winds. This implies that the free oscillations are in resonance with the wind pulses.

4. Conclusions

[10] The response of the lake to the applied wind-stress consists of the directly forced motion and the free oscillations or seiches. The amplitude of oscillations depends upon the lake geometry and wind-stress, while the period depends upon the lake-length and the wind forcing period. From earlier studies [*Coulter*, 1968; *Coulter and Spigel*, 1991; *Naithani et al.*, 2002a, 2002b] and this study, it is clear that the geometry, and particularly the length, of the lake is such that the free-oscillations in the lake are of the order 3–4 weeks. Therefore, it is concluded that the free oscillations in the lake similar to the ISV of wind pulses are being excited and are in resonance with each other.

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