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Temporal scaling of temperature variability from land to oceans

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ABSTRACT

Recent theoretical models show that the scaling of environmental variability affects the dynamics and persistence of populations. These models explore the effect of different noise colours, without much evidence as to the actual scaling of environmental variability in nature. Here we revisit the assertion of Steele (1985) that temperature scales differently on land than in the ocean, and we test whether these results can be extrapolated to aquatic systems in general. We compare spectra of temperature variability at 57 sites in air, rivers, lakes, the North American Great Lakes and oceans. The slopes of temperature spectra are only slightly negative on land (~ white noise) and become systematically steeper (reddened) in rivers, lakes, the Great Lakes and oceans. Coastal sites in the Great Lakes and the oceans are most similar to smaller lakes. We report plateaux in temperature spectra that differ markedly from the structure of environmental variability currently used in population dynamics models.

Keywords: aquatic systems, environmental variability, noise colour, power spectra, scaling, temperature, temporal dynamics.

INTRODUCTION

Recent theoretical models show that the scaling of environmental variability can affect the dynamics and persistence of populations (e.g. Kaitala *et al.*, 1997; Ripa *et al.*, 1998; Cuddington and Yodzis, 1999; Halley and Kunin, 1999). Empirical evidence exists to show that many environmental variables, such as precipitation or river flow, are autocorrelated in time (e.g. Mandelbrot and Wallis, 1969) and show increasing variability at longer time-scales (Pelletier, 1997, 2002; Koscielny-Bunde *et al.*, 1998). This type of variability is called reddened noise (by analogy to the spectral composition of light; Halley, 1996) and is found across an amazingly broad range of natural phenomena, from the sequence of base pairs in DNA molecules to heart beat rates in humans to climatic variables (Havlin *et al.*,

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1999). However, it has been suggested that the structure of environmental variability ranges from white to black noise for different environmental variables measured in different ecosystems (e.g. Steele, 1985; Cuddington and Yodzis, 1999; Cyr *et al.*, 2003; Vasseur and Yodzis, in press). A better understanding of the scaling of environmental variability in nature would not only provide more realistic parameters for theoretical models, but could be used to predict when different results are likely to apply.

Temperature is more variable on land than in aquatic ecosystems (Linacre, 1969; Straškraba, 1980), and the temporal scaling of this variability, or noise colour, is thought to differ markedly between land and oceans (Steele, 1985). It has been shown that the variability in air temperature is approximately constant (i.e. white noise) over 'ecological' time-scales (1 to 50–100 years; Steele, 1985; Pelletier, 1997), while sea level, a surrogate for whole ocean temperature, becomes more variable at longer time-scales (i.e. reddened noise; Steele, 1985). Here we test whether these results can be extrapolated to other aquatic ecosystems by comparing spectra of temperature variability at 57 sites in air, rivers, lakes, the North American Great Lakes and oceans. We hypothesize that the scaling of temperature variability in rivers and small lakes should be most similar to that found in air, and should get progressively more reddened (and more similar to the oceans) with increasing lake size.

In this study, we focus on ambient temperature because long-term temperature data sets are most readily available from a wide range of ecosystems. Temperature plays a crucial role in all aspects of the lives of organisms (e.g. energy use, growth, reproduction), especially aquatic organisms, which are mostly ectothermic. Ambient temperature, of course, is only one factor limiting the growth and reproduction of organisms, but the importance of water temperature in determining the physical structure of aquatic ecosystems suggests that other important environmental variables may scale in a similar way (e.g. oxygen concentration, nutrient availability; Cyr *et al.*, 2003).

METHODS

We gathered long-term (7–58 consecutive years, median = 18 years) monthly temperature data sets at 10 terrestrial sites, 11 rivers, 11 lakes of different sizes (surface area = 0.01–500 km^2, mean depth = 1.2–248 m), 8 coastal (< 3 km from shore) and 8 offshore sites on the North American Great Lakes, and 4 coastal (depth < 200 m) and 5 offshore (depth > 800 m) ocean sites (see Appendix). We used untransformed temperature data (i.e. temperature on a given day of the month), except at two inshore sites in the Great Lakes where only mean monthly temperatures were available, because temperature is only measured a few days per month in most inland lakes. Sporadically missing temperatures were interpolated linearly.

All stations had year-round temperature recordings, except offshore sites on the Great Lakes. The NOAA's buoys on the Great Lakes are retrieved from November/December (October in Lake Superior) to March/May (June in Lake Superior) to avoid ice damage, so the offshore data sets have several months of missing water temperature each year. We interpolated these missing data by calculating the trend in daily temperatures each spring and each fall, from the first (spring) or last (fall) recorded date to the date when the annual mean temperature of the site was reached (in early or late summer, respectively). In the few years when less than one month of data were available to calculate these trends, we used the mean spring or fall trend calculated in other years for the interpolations. Interpolated surface water temperatures (1 m depth) were not allowed to drop below 0.1°C. These interpolations at a time of the year when temperatures are relatively constant had very little effect on the slope and shape of the power spectra we calculated. We tested this by applying the interpolation procedure to three inshore stations, where water temperature was recorded continuously, and comparing the slopes of the power spectra for the interpolated and original data sets. The slopes calculated on the interpolated data sets were only slightly steeper (0.2–3.0% difference) than the slopes calculated on the real data sets.

Spectral analyses were performed using fast Fourier transform on the seasonally detrended time-series (Chatfield, 1989). Each time-series was detrended by subtracting from each observation the deviation from the overall average measured for that month over the whole sampling period (e.g. deviation from the mean value of all January samples). All power spectra were smoothed using a Parzen window with a truncation point (*M*) of 7 (Chatfield, 1989). The choice of *M* had a minimal effect on the slopes of power spectra we calculated (e.g. the slopes of power spectra changed from −0.10 to −0.13 when *M* was increased from 7 to 87 in the full Toronto air temperature data set, from −0.410 to −0.414 when *M* was increased to 61 in the Erie inshore data, and from −1.19 to −1.12 when *M* was increased to 19 in the offshore data collected by NOAA buoy 46003 in the Pacific Ocean). The slopes of log-transformed power spectra were calculated using simple linear regression analysis, which effectively weighs the slopes towards short-term variability, since there are more points at the high-frequency end of the spectrum. We did not weigh the log(frequency) axis evenly because the plateaux observed in these spectra (see below) and analytical bias (levelling off) at the low-frequency end of the spectrum would bias such estimates. The slopes of the power spectra we measured are equivalent to the exponent ($-\gamma$) in $1/f$-noise relationships [$S(f) \propto f^{-\gamma}$, where $S(f)$ is a spectral density function] that indicates the 'colour' of the noise (Halley, 1996). A slope of zero suggests equal variability at all frequencies (white noise), whereas steeper negative slopes suggest progressively less variability at high frequencies relative to low frequencies (slopes of −1, −2 and < -2 for pink, brown and black noise, respectively).

Ideally we would compare spectra from time-series of equal lengths, but this would limit even more severely the number of sites or the length of series that could be used for each type of aquatic ecosystem. The shortest time-series we analysed covers 7 consecutive years of monthly data ($n = 84$) and is shorter than the minimum generally recommended for spectral analysis ($n = 100$–200; e.g. Chatfield, 1989). This limits our ability to distinguish peaks in the power spectra (Jenkins and Watts, 1968; Chatfield, 1989), but has little effect on the slope of the power spectrum, especially over short time-scales. We tested the effect of using time-series of different lengths by comparing slopes of power spectra measured on short non-overlapping portions of our longest time-series (full Toronto air temperature series, 155 years). Series that were 7 years long yielded slopes between −0.188 and 0.171 ($n = 7$, median $= -0.015$), 14-year series yielded slopes between −0.164 and 0.184 ($n = 7$, median $= -0.069$), 55-year series (used in this study) yielded a slope of −0.070 and the full 155-year series yielded a slope of −0.103. Short data series add variability and tend to overestimate slightly the power spectrum slope, but these overestimations are slight compared with the differences we found among types of ecosystems (see below).

To display the average power spectra more clearly, we averaged all spectral densities in intervals of 0.1 on the log(frequency) axis. However, the regression analyses used to determine the slopes of power spectra were performed on the original unsmoothed power spectra. Slopes of power spectra were compared among types of ecosytems using a Kruskal-Wallis test with multiple comparisons (Conover, 1980). All analyses were performed using Statistica for Windows, version 5.

RESULTS

Temperature variability (or spectral density) is much higher, at any given time-scale, in terrestrial than in aquatic ecosystems (Fig. 1). Temperature variability in air and rivers is slightly higher at long time-scales (low frequencies) and declines in a roughly log-linear fashion towards shorter time-scales (high frequencies). A different pattern of variability is found in lakes and surface oceans (Fig. 1). In the Great Lakes, temperature variability

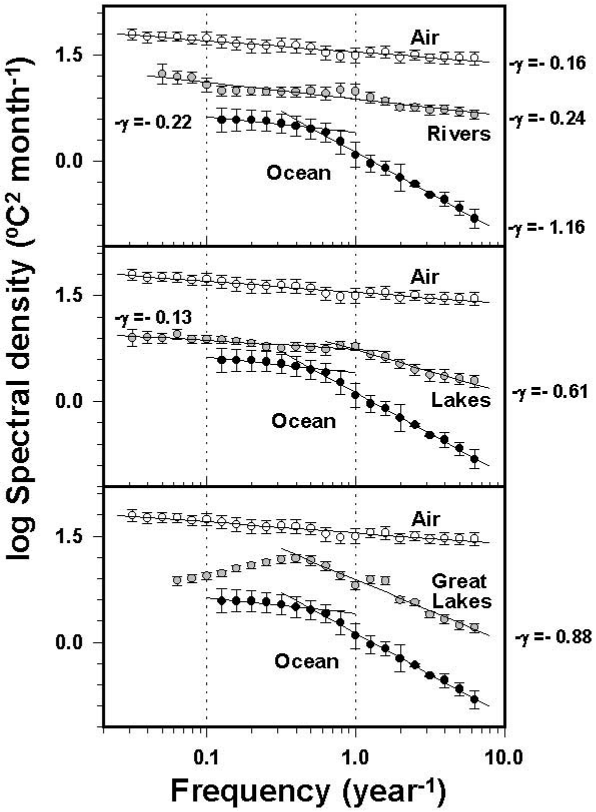

Fig. 1. Mean power spectra of ambient temperature in air (open circles, $n = 10$), Pacific oceanic sites (solid circles, $n = 3$) and rivers ($n = 11$) in the upper panel, lakes ($n = 11$) in the middle panel and offshore Great Lakes ($n = 8$) in the lower panel. Power spectra indicate the relative magnitude of temperature variability (spectral density) from long time-scales (low frequencies) to short time-scales (high frequencies). Each point is the among-site mean spectral density in log(frequency) categories of 0.1. The spectrogram was simplified to these frequency classes to facilitate display. Error bars are standard errors in log(spectral density) among sites. The lines and exponents describing each spectrum are calculated from among-site mean spectral densities and are only shown for reference. Spectral slopes for individual sites are shown in Fig. 2. Vertical dotted lines highlight the 10 year [log(frequency) $= -1$ year^{-1}] and 1 year [log(frequency) $= 0$ year^{-1}] time-scales.

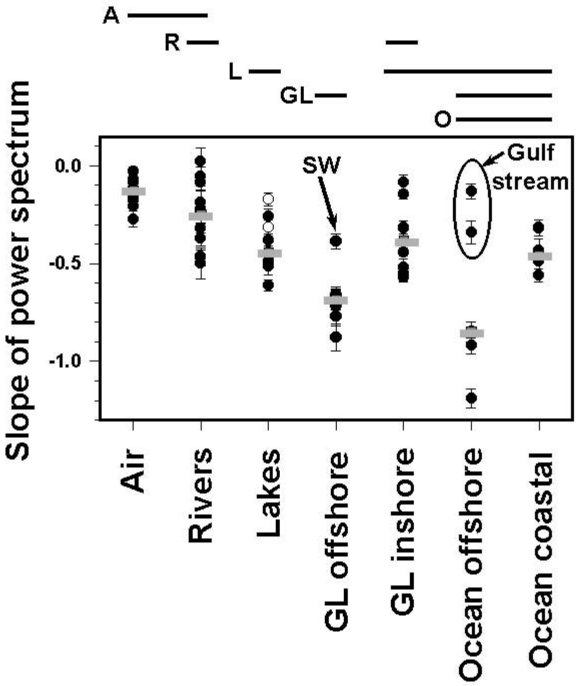

Fig. 2. Slopes (± standard error) of temperature power spectra in different types of ecosystem. Each point is a site and the grey rectangle represents the median slope in each type of ecosystem. Open circles are polymictic lakes. SW is a site in the western basin of Lake Superior. The two least negative slopes for offshore oceanic sites are located close to the Gulf Stream. Error bars are standard errors on the slopes. The horizontal lines above the graph join types of ecosystems with slopes that are not statistically different from each other ($P > 0.05$), based on the results from *post-hoc* multiple comparisons. From top to bottom, these lines represent five series of comparisons between air (A), rivers (R), lakes (L), Great Lakes offshore (GL), ocean offshore (O) and other types of ecosystems.

at offshore sites peaks around a < 1–3 year time-scale. In smaller lakes and in oceans, surface temperature variability is relatively constant at long time-scales (≥1 year in lakes, >2–5 years in oceans) and drops more rapidly at sub-annual time-scales.

The slopes of power spectra range from −0.07 to −1.19 and, as hypothesized, become steeper from air to rivers, lakes, the Great Lakes and the oceans (Kruskal-Wallis test, $P < 0.001$; Fig. 2). The slopes of power spectra at inshore sites in the Great Lakes and in the oceans did not differ significantly from those found in rivers and lakes (*post-hoc* multiple comparisons, $P > 0.05$; Fig. 2). These slopes are calculated from unweighted spectral densities and are minimally affected by low-frequency non-linearities in the spectra (correlations between overall slopes and slopes calculated over sub-annual time-scales only: $r = 0.82$ in lakes, $r = 0.92$ in Great Lakes, $r = 0.99$ in oceans). As the slopes of power spectra become more negative, the importance of short-term temperature variability decreases relative to long-term variability.

The slopes of power spectra differ among lakes of different sizes, but the data can be interpreted in two ways (dashed and solid lines in Fig. 3). The data could be interpreted as showing a steepening of spectrum slopes in lakes of increasing size (dashed line in Fig. 3),

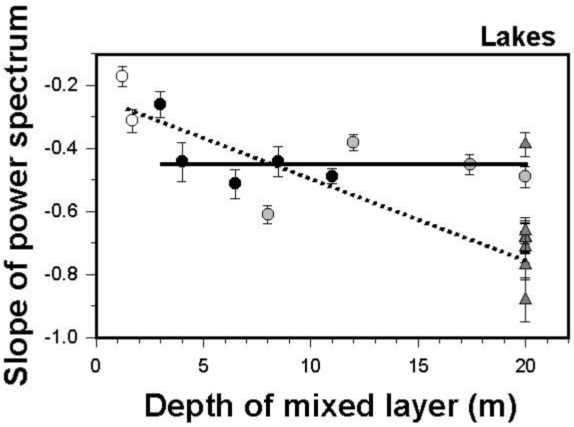

Fig. 3. Relationships between the slopes (± standard error) of temperature power spectra and depths of the surface mixed layers (epilimnia) in lakes. Open circles are polymictic lakes, solid circles are dimictic temperate lakes, grey circles are warm monomictic lakes and triangles are Great Lakes offshore sites. Solid line represents the median slope (–0.45) for stratified lakes (dimictic and monomictic). Dotted line indicates a possible relationship for temperate lakes and the Great Lakes (dashed line; $r^2 = 0.68$, $P < 0.0001$, $n = 15$), distinct from the relatively constant slope observed in warm monomictic lakes. Our data set cannot distinguish unambiguously between these two possibilities (see text).

from small polymictic lakes (i.e. lakes that do not develop a stable stratification, where the water column mixes intermittently; shown as open circles) to dimictic lakes (i.e. lakes that develop a stable stratification during summer and that mix only twice a year, in the spring and fall; shown as solid circles) to offshore sites in the Great Lakes (shown as grey triangles). This interpretation is consistent with our original hypothesis that short-term variability is dampened in large water masses. Interestingly, if this interpretation is correct, it suggests a qualitatively different relationship (more constant spectrum slopes) in warm monomictic lakes (i.e. lakes that do not freeze and that mix only once a year; grey circles in Fig. 3). Alternatively, a more parsimonious interpretation of the data (shown by a solid line in Fig. 3) is that the slopes of power spectra are similar in stratified lakes up to 500 km^2 surface area (solid and grey circles), regardless of the depth of the surface mixing layer (3–20 m), and are qualitatively different from most offshore sites in the Great Lakes (triangles). Insufficient data are currently available to distinguish between these two possible interpretations.

The pattern of temperature variability differs markedly between strata in lakes (Fig. 4). Water temperature at the bottom of lakes (in the hypolimnion) is generally more stable over sub-annual time-scales than temperatures at the lake surface, except in shallow lakes where the whole water column is mixed intermittently during large storm events (e.g. Allequash, compare open and solid circles in top panel in Fig. 4). The difference observed between strata disappears beyond a yearly time-scale in lakes that mix completely every year (Crystal, Trout), but is maintained over the time-scale of our analysis (~ 30 years) in larger and deeper lakes that mix to different depths depending on local meterological conditions (Maggiore, Tahoe; Barbanti and Ambrosetti, 1989; Jassby *et al.*, 1999; two bottom panels in Fig. 4).

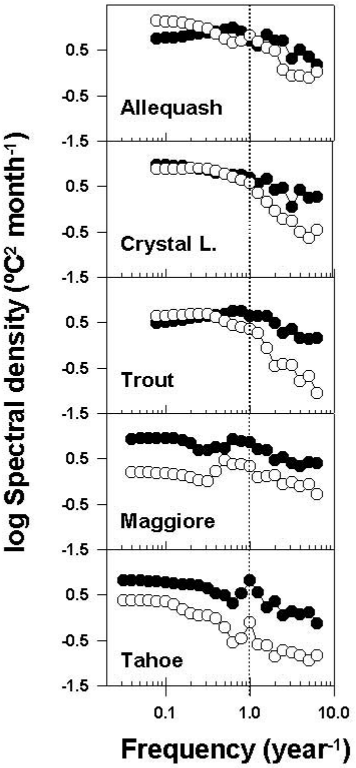

Fig. 4. Power spectra comparing temperature variability at the surface (solid circles) and in bottom water (open circles) of five lakes are presented in order of increasing depth of the surface mixed layer. Bottom (hypolimnetic) temperature was measured at 7 m depth in Allequash, 15 m in Crystal, 20 m in Trout, 19.5 m in Maggiore and 90 m in Tahoe. Spectral densities were averaged in 0.1 log(frequency) classes for clearer display. Vertical dotted lines highlight the 1 year [log(frequency) = 0 year^{-1}] time-scale.

DISCUSSION

The scaling of temperature variability in different ecosystems

Temperature variability on land increases only slightly with increasing time-scales (Fig. 1). This result is generally consistent with Steele's (1985) original conclusion and with more recent and more exhaustive analyses of the numerous air temperature data sets currently available (e.g. Pelletier, 1997; Koscielny-Bunde *et al.*, 1998; Vasseur and Yodzis, in press). The slopes we measured (–0.07 to –0.27, $n = 10$) are slightly less negative than the slopes reported for power spectra of monthly mean air temperature time-series (slope of average power spectrum = –0.43, $n = 94$, Pelletier, 1997; median slope at inland sites = –0.3, $n = 37$, Vasseur and Yodzis, in press). This discrepancy can easily be explained by our use of untransformed temperature measurements, as opposed to monthly mean temperatures. The slopes at three of our sites (Balaton, Maggiore, Toronto) become –0.29 to –0.44 when based on monthly mean temperatures. The spectral slopes we measured are also consistent with the exponents of the 'universal persistence law' reported by atmospheric physicists (spectral slopes approximately −0.3; Koscielny-Bunde *et al.*, 1998; spectral slopes calculated from exponents of detrended fluctuation analysis or wavelet analysis according to Talkner and Weber, 2000).

The magnitude of temperature variability is much lower in rivers than on land, but the temporal scaling of this variability is similar in both systems (compare intercepts and slopes in the top panel of Fig. 1). The slopes of power spectra were not statistically different in rivers and air (Fig. 2). This similarity is not surprising, since rivers are connected hydrologically to the surrounding landscape, are in close contact with the atmosphere and are well mixed.

In contrast, temperature variability in lakes is dampened at sub-annual time-scales (middle panel in Fig. 1). The slopes of power spectra in lakes range from −0.17 to −0.88 (Fig. 3). The shallowest slopes are found in polymictic lakes that do not develop a stable stratification (i.e. the whole water column mixes intermittently; open circles in Fig. 3) and in small lakes with shallow mixing zones (thin epilimnia; Fig. 3). These small lakes have spectrum slopes similar to those found in rivers (Fig. 2). The slopes of power spectra are steepest at offshore sites in the Great Lakes, except for one site in the western basin of Lake Superior (SW) that has a spectral slope similar to those measured in smaller lakes (Figs 2, 3). Very little is known about water circulation in Lake Superior, but the best data available suggest that the northern shore of the western basin is an area of frequent upwellings that may be responsible for the intense eddies (characterized by large temperature anomalies) found throughout this basin (Ralph, 2002). Site SW is also close to the edge of a gyre that originates in warmer coastal waters during the summer (Beletsky *et al.*, 1999). The movement of water masses with different temperatures could explain the relatively large component of short-term (mostly sub-annual) variability in water temperature observed at site SW compared with other offshore sites in the Great Lakes.

As hypothesized, the slopes of power spectra become steeper (redder noise) in larger lakes. If we interpret Fig. 3 as showing a steepening of the slopes of power spectra with increasing lake size in polymictic and dimictic lakes (dashed line), we also have to conclude that a small range of power spectra slopes are found in warm monomictic lakes, regardless of their size (grey circles). Warm monomictic lakes develop deeper surface mixing layers than dimictic lakes of similar morphometry, and the actual depth of mixing on any given day varies depending on wind and precipitation events (Serruya and Pollingher, 1983). Therefore, warm monomictic lakes could have higher short-term temperature variability (and shallower spectral slope) than dimictic lakes of similar surface areas. Alternatively, Fig. 3 could be interpreted as showing a difference in slopes between lakes with a surface area < 500 km^2 and the Great Lakes (solid line). This interpretation is consistent with suggestions that mixing of the surface layer is qualitatively different between small lakes and lakes longer than ~ 25 km (Patalas, 1984; Gorham and Boyce, 1989). Lake Tahoe, the largest lake in our data set, is very close to this cut-off size. In larger lakes, such as the Great Lakes, the Coriolis effect plays an important role in limiting the surface mixing depth (Gorham and Boyce, 1989). This latter interpretation of the data suggests similar scaling of temperature variability in dimictic and in warm monomictic lakes. Unfortunately, the data available do not distinguish clearly between these two possibilities. More long-term data sets are needed for large temperate dimictic lakes and for small tropical and sub-tropical monomictic lakes to test these hypotheses.

Offshore oceanic sites cluster in two groups, with steep slopes at three sites in the Pacific and much shallower slopes in the Atlantic (Fig. 2). Both Atlantic sites are located at the boundary of the Gulf Stream (NOAA buoy 44004: 38°27′N, 70°41′W; buoy 41010: 28°53′N, 78°32′W), where current shifts and warm-core and cold-core rings that break off from the main current (Knauss, 1997) would add short-term variability in water temperature. Changes in the position of the Gulf Stream and in the frequency of rings affect the recruitment success of demersal fish in this region, possibly through differential entrainment of fish larvae (Myers and Drinkwater, 1989). Not surprisingly, the scaling of temperature variability is not uniform across the ocean, and the proximity to physical fronts can add significant short-term variability.

The steepening of power spectra from air to rivers to lakes to the Great Lakes to the oceans (Fig. 2) is easily understood. Water conducts heat 10,000 times more efficiently than air and has four times the heat capacity of air, so we expect short-term temperature variability to be dampened in water, especially in large water masses. Our results support these expectations, but also suggest that the physical structure of aquatic systems, and the extent to which their water column mixes, is crucial in determining the temporal scaling of temperature variability (Figs 3, 4). Three apparently anomalous sites were located in areas with intense eddies or with strong physical fronts (SW in Lake Superior and two sites in the Atlantic beside the Gulf Stream; Fig. 2). The temperature variability at these sites is more likely to reflect differences in temperature among water masses that pass over a sensor that is held at a fixed location.

The slopes of inshore temperature spectra in the Great Lakes and in the oceans depart strikingly from those at offshore sites, and are more similar to slopes measured in smaller lakes (Fig. 2). Inshore currents, upwellings, and more rapid warming and cooling of shallow areas would increase short-term temperature variability at these sites.

Our results show clear differences in the scaling of temperature variability across different types of aquatic systems, and between different parts of these ecosytems (e.g. surface and deep water in inland lakes, areas around physical fronts in the oceans). Scaling differences are also found on land, with redder noise (i.e. steeper spectral slope) in mean air temperature at maritime than at continental sites (Pelletier, 1997; Vasseur and Yodzis, in press). Vasseur and Yodzis (in press) also report a tendency to find whiter noise in maximum air temperature at temperate latitudes compared with high or low latitudes.

Departure from log-linear power spectra

The plateaux we observe in lakes and oceans (Fig. 1) have been predicted by theoretical models (Frankignoul and Hasselmann, 1977) and have been described, over different time frames, in the ocean (e.g. Wunsch, 1981; Steele, 1985; Monetti *et al.*, 2003) and on land (e.g. Pelletier, 1997; Weber and Talkner, 2001). These plateaux are possibly the result of heat exchanges with the atmosphere during the period(s) of water column mixing that occur every year (Frankignoul and Hasselmann, 1977; Steele and Henderson, 1994; Monetti *et al.*, 2003). The cause for the peak in variability at a 2–3 year time-scale in the Great Lakes is unknown (Fig. 1). Inter-annual variability in the dynamics of the Great Lakes (e.g. circulation patterns, extent and duration of ice cover) have been described (e.g. Assel and Rodionov, 1998; Ullman *et al.*, 1998; Beletsky *et al.*, 1999), but the data are still too sparse to test for periodicity in these phenomena. The plateaux in power spectra suggest that in many aquatic systems temperature variability scales differently across different ranges of temporal scales, and the use of simple log-linear ($1/f$) relationships to describe spectra of environmental variability is likely to overestimate multi-annual and decadal variability. All current theoretical models are either based on autoregressive models, which assume an exponential decrease in temporal correlation beyond a characteristic time-scale (e.g. Kaitala *et al.*, 1997; Petchey *et al.*, 1997; Heino *et al.*, 2000), or on single values of γ (spectrum slope, see Methods; e.g. Cuddington and Yodzis, 1999; Halley and Kunin, 1999; Morales, 1999). These assumptions about the structure of environmental variability may seriously bias the predictions of population dynamics and of probabilities of extinction.

Ecological implications

Recent theoretical models suggest that population dynamics and the probability of population extinction are affected by the structure of environmental variability (Kaitala *et al.*, 1997; Cuddington and Yodzis, 1999; Morales, 1999). The gradient of noise colour we report for different types of ecosystems could be used to guide the choice of parameters in these models. However, the theoretical implications of the plateaux we found in lake and ocean power spectra (Fig. 1) should be evaluated.

The gradient we observed in the scaling of temperature variability from land to rivers to lakes to oceans provides a framework for testing the importance of environmental variability in natural populations. The dynamics of natural populations are clearly reddened (Ariño and Pimm, 1995; Cyr, 1997; Inchausti and Halley, 2002), and this type of variability could result from external forcing (i.e. environmental variability) and/or from biological interactions (e.g. density dependence, trophic interactions; Pimm and Redfearn, 1988; Ripa *et al.*, 1998; Ranta *et al.*, 2000). There is clear evidence that the scaling of environmental variability differs among types of ecosystems, but it is still unclear whether population dynamics also scale differently among ecosystems (Ariño and Pimm, 1995; Cyr, 1997; Inchausti and Halley, 2002). The effects of environmental variability on organisms may be dampened by physiological filters (Petchey, 2000; Laakso *et al.*, 2001) or by shifts in the composition and interactions of organisms in natural communities (Ripa *et al.*, 1998; Beisner, 2001). The impact of environmental variability on biological processes is complex and difficult to disentangle, but a necessary first step in this endeavour is to understand natural environmental variability.

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APPENDIX

Site description, time span and source of all temperature data series

Site	Latitude, longitude	Depth meas. (m)	Depth site (m)	Dist. shore (km)	Years	Source of data
Air						
Balaton, Hungary	47°00′N, 17°00′E	—	—	—	1975–1997 (23)	Balaton Water Authority, Hungary
Blagovescensk, Russia	50°18′N, 127°36′E	—	—	—	1950–1995 (46)	Federal Service of Russia[1]
Ircutsk, Russia	52°18′N, 104°18′E	—	—	—	1950–1995 (46)	Federal Service of Russia[1]
Maggiore, Italy	45°55′N, 08°33′E	—	—	—	1969–1994 (26)	Hydrobiol. Inst., Pallanza, Italy[2]
Minocqua, WI, USA	45°54′N, 89°40′W	—	—	—	1992–2002 (9)	NTL-LTER[3]
Omsk, Russia	55°00′N, 73°24′E	—	—	—	1950–1995 (46)	Federal Service of Russia[1]
Perm, Russia	58°00′N, 56°24′E	—	—	—	1950–1995 (46)	Federal Service of Russia[1]
Sevilleta, NM, USA	34°21′N, 106°41′W	—	—	—	1990–2002 (12)	Sevilleta LTER[4]
St. Petersburg, Russia	60°00′N, 30°18′E	—	—	—	1950–1995 (46)	Federal Service of Russia[1]
Toronto, ON, Canada	43°40′N, 79°14′W	—	—	—	1942–1997 (55)	Environment Canada
Rivers						
Atchafalaya, LA, USA	29°42′N, 91°12′W	—	—	—	1978–1994 (17)	USGS[5]
Bay of Quinte, ON, Canada	44°08′N, 77°24′W	4.0	—	0.5	1943–1997 (55)	Belleville Water Treatment Plant
Cuyahoga, OH, USA	41°24′N, 81°38′W	—	—	—	1974–1981 (8)	USGS[5]
Fox, WI, USA	41°40′N, 82°50′W	2.0	—	—	1947–1990 (44)	NOAA[6]
Maumee, OH, USA	41°30′N, 83°43′W	—	—	—	1973–1981 (9)	USGS[5]
Missouri, NE, USA	41°16′N, 95°55′W	—	—	—	1973–1993 (21)	USGS[5]
Russian, CA, USA	38°31′N, 122°56′W	—	—	—	1974–1986 (13)	USGS[5]
San Joaquin, CA, USA	37°41′N, 121°16′W	—	—	—	1973–1981 (9)	USGS[5]
St-Laurent, QC, Canada	46°46′N, 68°44′W	—	—	—	1986–1997 (12)	Ste-Foy Water Treatment Plant
Susquehanna, PA, USA	40°15′N, 76°53′W	—	—	—	1973–1981 (9)	USGS[5]
Zala, Hungary	47°00′N, 17°00′E	0.4	—	—	1975–1997 (23)	Balaton Water Authorities, Hungary

Appendix—*continued*

Site	Latitude, longitude	Depth meas. (m)	Depth site (m)	Dist. shore (km)	Years	Source of data
Inland lakes						
Allequash, WI, USA	46°02′N, 89°37′W	0.0	8	—	1981–1994 (14)	NTL-LTER[3]
Crystal Bog, WI, USA	46°00′N, 89°36′W	0.0	3	—	1981–1994 (14)	NTL-LTER[3]
Crystal Lake, WI, USA	46°00′N, 89°37′W	0.0	20	—	1981–1994 (14)	NTL-LTER[3]
Harp, ON, Canada	45°23′N, 79°08′W	0.1	38	—	1976–1993 (18)	P.J. Dillon, Univ. Trent, Canada
Kinneret, Israel	32°50′N, 35°30′E	0.0	40	—	1969–1997 (29)	T. Berman, Kinneret Limnol. Lab, Israel
Maggiore, Italy	45°55′N, 08°33′E	0.5	370	—	1969–1994 (26)	Meterol. Observatory, Pallanza, Italy[1]
Mendota, WI, USA	43°05′N, 89°23′W	—	25	—	1908–1930 (23)	NTL-LTER[3]
Sandusky Bay, OH, USA[7]	41°29′N, 82°52′W	1.5	3	—	1961–1976 (16)	NOAA[6]
Tahoe, CA, USA	39°06′N, 120°09′W	0.0	501	—	1967–1997 (31)	C.R. Goldman, Univ. California Davis, USA
Trout, WI, USA	46°02′N, 89°40′W	0.0	36	—	1981–1994 (14)	NTL-LTER[3]
Washington, WA, USA	47°30′N, 122°20′W	—	65	—	1961–1994 (34)	W.T. Edmondson, Univ. Washington, USA
Great Lakes littoral						
Erie, PA, USA	42°09′N, 80°09′W	8.5	—	2	1957–1992 (36)	NOAA[6]
Kingston Basin, ON, Canada	44°13′N, 76°29′W	16.0	—	0.9	1970–1996 (27)	Kingston Water Treatment Plant
Put-In-Bay, OH, USA	41°40′N, 82°50′W	1.5	—	0	1942–1984[8] (43)	NOAA[6]
Saginaw Bay, MI, USA	43°43′N, 83°54′W	3.3	—	3	1969–1993[9] (25)	NOAA[6]
Sault Ste. Marie, ON, Canada	46°30′N, 84°20′W	6.0	—	0	1906–1963 (58)	NOAA[6]
St. Joseph, MI, USA	42°06′N, 86°30′W	4.0	—	0.4	1960–1992 (33)	NOAA[6]
Toronto, ON, Canada[10]	43°40′N, 79°14′W	18.0	—	3	1988–1996 (9)	F.J. Horgan Water Treatment Plant
Thunder Bay, ON, Canada[10]	48°28′N, 89°09′W	6.1	—	1	1958–1977 (20)	Bare Point Water Treatment Plant

Great Lakes offshore						
L. Erie, East Basin	41°41′N, 82°24′W	0.6	15	—	1980–1997 (18)	Buoy 45005, NOAA[11]
L. Huron, North	45°21′N, 82°50′W	0.6	130	—	1980–1997 (18)	Buoy 45003, NOAA[11]
L. Huron, South	44°17′N, 82°25′W	0.6	62	—	1981–1997 (17)	Buoy 45008, NOAA[11]
L. Michigan, North	45°19′N, 86°25′W	0.6	174	—	1979–1997 (19)	Buoy 45002, NOAA[11]
L. Michigan, South	42°40′N, 87°01′W	0.6	165	—	1981–1997 (17)	Buoy 45007, NOAA[11]
L. Superior, West	47°19′N, 89°52′W	1.0	162	—	1981–1997 (17)	Buoy 45006, NOAA[11]
L. Superior, Centre	48°03′N, 87°46′W	0.6	254	—	1979–1997 (19)	Buoy 45001, NOAA[11]
L. Superior, East	47°33′N, 83°33′W	0.6	218	—	1980–1997 (18)	Buoy 45004, NOAA[11]
Oceans coastal						
Atlantic, E of MA, USA	42°21′N, 70°41′W	0.6	55	—	1984–1994 (11)	Buoy 44013, NOAA[11]
Atlantic, SE of MA, USA	40°30′N, 69°26′W	0.6	62	—	1983–1998 (16)	Buoy 44008, NOAA[11]
Mediterranean, Spain	—	0.5	—	—	1968–1992 (25)	C. Duarte, IMEDEA Esporles, Spain
Pacific, W CA, USA	38°14′N, 123°20′W	0.6	123	—	1988–1997 (10)	Buoy 46013, NOAA[11]
Oceans offshore						
Atlantic, E of NJ, USA	38°27′N, 70°41′W	1.0	3164	—	1986–1999 (14)	Buoy 44004, NOAA[11]
Atlantic, E of FL, USA	28°53′N, 78°32′W	1.0	841	—	1988–1999 (12)	Buoy 41010, NOAA[11]
Pacific, S of Aleutians	51°50′N, 155°51′W	1.0	4572	—	1981–1988 (8)	Buoy 46003, NOAA[11]
Pacific, W of Hawaii	19°10′N, 160°43′W	1.0	4943	—	1984–1999 (16)	Buoy 51003, NOAA[11]
Pacific, W of OR, USA	42°32′N, 130°15′W	1.0	3420	—	1990–1998 (9)	Buoy 46002, NOAA[11]

[1] http://www.meteo.ru

[2] Air and water temperatures are published annually in *Memorie del Instituto Italiano di Idrobiologie*.

[3] North Temperate Lakes, Long Term Ecological Research Network, http://limnosun.limnology.wisc.edu

[4] Sevilleta, Long Term Ecological Research Network, http://sevilleta.unm.edu

[5] National Stream Water-Quality Monitoring Networks (WQN), US Geological Survey Digital Data Series DDS-37 (1996).

[6] See McCormick and Fahnenstiel (1999) for detailed site description.

[7] Sandusky Bay is completely enclosed and separate from L. Erie.

[8] 1974 missing.

[9] 1976 and 1979 missing.

[10] Monthly average temperatures

[11] http://www.ndbc.noaa.gov

‘Depth meas.’ is the depth at which water temperature was recorded. ‘Depth site’ is the depth at which the buoys were moored at Great Lakes offshore sites and oceanic sites, or the maximum depth in lakes (the sampling sites were not necessarily located over the deepest part of the lake). ‘Dist. shore’ is the distance at which water intakes were positioned relative to shore at river and coastal Great Lakes sites.