Chlorophyll Variability in Hong Kong Coastal Waters: Spatial Coherencies and Relations to Large-Scale Climate Variability

Emily C. Shaw[1,3,*], Albert J. Gabric[1] , Arthur J. Miller[2] and G. Anand Tularam[1]

[1] Griffith School of Environment, Griffith University, Nathan, Queensland 4111, Australia
[2] Scripps Institution of Oceanography, UCSD, La Jolla, CA 92093-0224
[3] Present address: Climate Change Research Centre, The University of New South Wales, Sydney, NSW 2052, Australia
*Corresponding author: Email: e.shaw@student.unsw.edu.au

Abstract

Discerning the influence of climatic variability on phytoplankton dynamics within coastal ecosystems is complex due to anthropogenic influences that also impact phytoplankton growth. We analyzed a 17-year time series of water quality monitoring data from 1988-2004 in the coastal waters of Hong Kong to determine if climatic variability was an important process driving phytoplankton variability. The relationship between chlorophyll *a* concentration (CHL) and three major climatic modes (El Niño-Southern Oscillation, Pacific Decadal Oscillation and North Pacific Gyre Oscillation (NPGO)) was examined using empirical orthogonal function and correlation analyses. CHL variability was dominated by an in-phase pattern across the whole study area suggesting that a large-scale forcing, such as climate, that acts on the entire area may be driving CHL variability. CHL was strongly correlated with the NPGO index (NPGOI), however a much longer time series will be

required to unequivocally determine if the NPGO is driving phytoplankton dynamics in Hong Kong coastal waters. We suggest that the negative relationship between wind speed and NPGOI may be a mechanism driving the positive relationship between the NPGOI and CHL. Our findings show that climatic variability can be an important factor in determining phytoplankton dynamics in coastal waters, even where they have been strongly influenced by anthropogenic factors, such as cultural eutrophication.

1. Introduction

Phytoplankton biomass and the frequency of harmful algal blooms increased markedly in the coastal waters of Hong Kong during the 1970s and 1980s [*EPD*, 2006; *Hodgkiss and Ho*, 1997]. These changes have been attributed to increased nutrient loads and changes to nutrient ratios that occurred during this period [*EPD*, 2006; *Hodgkiss and Ho*, 1997]. In response to declining water quality, the Hong Kong Environmental Protection Department (EPD) implemented a comprehensive water quality monitoring program in 1986. One of the aims of this program was to determine the relationship between nutrients and phytoplankton abundance [*EPD*, 2006]. There has been a large amount of research focused on the link between phytoplankton and nutrients in Hong Kong [e.g. *Hodgkiss and Lu*, 2004; *Yin et al.*, 2000; *Yin et al.*, 2001]. Little is known, however, on whether climatic variability also affects local phytoplankton dynamics.

An understanding of the relative importance of climatic variability versus anthropogenic influence in coastal ecosystems is critical for the future management of coastal water quality. Although the impacts of cultural eutrophication have been recognized for some time [*Nixon*, 1995], the role of climate variability in shaping coastal marine ecosystems is relatively poorly understood. An example of a climate change-induced shift in biological communities was reported by Cloern et al. [2007] for San Francisco Bay, where climate-driven variability in the annual recruitment and immigration of predators to the Bay induced increasing phytoplankton biomass and the occurrences of new seasonal blooms, despite concurrent efforts to control the input of nutrients to the Bay.

Phytoplankton biomass is determined by temperature and the availability of light and nutrients, all of which are largely controlled by physical processes in oceanic ecosystems [*Behrenfeld et al.*, 2006]. These physical processes, such as stratification and upwelling, are controlled by climatic variations in the ocean-atmosphere system [*Miller et al.*, 2004]. Climate variability affects phytoplankton dynamics at seasonal time scales, but lower frequency climate forcings also operate on interannual to decadal time scales. These low-frequency forcings include, *inter alia*, El Niño-Southern Oscillation (ENSO) and Pacific decadal variability. Behrenfeld et al. [2006] found global-scale trends in oceanic primary productivity over the past decade are tightly coupled to climatic variability.

However, our understanding of how large-scale climatic variability affects coastal ecosystems and how phytoplankton fluctuations are related to variability in physical forcings is much less clear. Kim *et al*. [2009] find no strong relation between climate forcing and phytoplankton blooms in the coastal region of the Southern California Bight, while McPhee-Shaw [2011] suggest that surface gravity-wave processes can drive some coastal blooms off the northern California coast. Many coastal ecosystems are already heavily impacted by stressors such as increased nutrient loading and loss of water clarity due to catchment runoff

[*Gabric and Bell*, 1993], which can mask effects due to climate variability. Although nutrient concentrations in some coastal waters have declined substantially in recent decades, after improved wastewater treatment and reduction of agricultural runoff [*Smetacek and Cloern*, 2008], coherent phytoplankton responses were not apparent, either as synchronous reductions in biomass or shifts to communities characteristic of low-nutrient habitats. Thus, it appears that physicochemical environmental factors, such as temperature, light, and nutrients, which are climate-related, set the upper limits to biomass, but cannot explain why different phytoplankton groups replace each other or why their annual maxima occur when and where they do [*Smetacek and Cloern*, 2008].

In the Hong Kong region, ENSO variability leads to changes in temperature and rainfall patterns and can influence the monsoon [*Leung and Wu*, 2004]. El Niño onset years and those immediately following are generally warmer than average and have high rainfall, whereas the effects of La Niña are relatively less pronounced [*Chang*, 1999]. Therefore El Niño years may be expected to have higher phytoplankton biomass due to increased water column temperatures and higher nutrient loads from increased runoff. It has also been suggested by Yin et al [2000] that dilution by freshwater outflow was a controlling factor in determining the distribution of nutrients and phytoplankton biomass in the Pearl River estuary due to high discharge during June and July of 1998, a strong El Nino year.

On decadal time scales, the North Pacific is characterized by the Pacific Decadal Oscillation (PDO) [*Mantua and Hare*, 2002] and the recently identified North Pacific Gyre Oscillation (NPGO) [*Di Lorenzo et al.*, 2008]. The NPGO drives low frequency fluctuations of upper ocean salinity and nutrients observed in long-term records of the Northeast Pacific. The PDO includes low-frequency components driven by ENSO and is associated with similar, but less extreme, climatic variability [*Mantua and Hare*, 2002]. The PDO is often described as being in a warm or cool phase, with warm phases of the PDO associated with dry conditions in Hong Kong and anomalously cool air temperatures throughout eastern China [*Chan and Zhou*, 2005; *Leung and Wu*, 2005]. The influence of the PDO on regional temperature and rainfall may provide an indirect mechanism affecting phytoplankton dynamics in Hong Kong waters.

The NPGO reflects changes in strength of the central and eastern branches of the subtropical gyre and is driven by wind anomalies consistent with the North Pacific Oscillation (NPO), which is the second dominant mode of sea level pressure (SLP) variability [*Di Lorenzo et al.*, 2008]. Indeed, in the eastern Pacific, interannual and decadal variations in salinity, surface chlorophyll *a* concentration (CHL) and nutrient concentration that cannot be explained by the PDO have been found to be associated with the NPGO. Fluctuations in the NPGO reflect changes in the north Pacific gyre circulation and can affect marine ecosystems through changes in nutrient upwelling and primary productivity [*Di Lorenzo et al.*, 2008]. Similarly, the NPGO has been shown to affect parts of the western boundary of the Pacific Ocean, but with a time lag of 2-3 years [*Ceballos et al.*, 2009]. Therefore the coastal waters of Hong Kong may experience changes to nutrient and phytoplankton dynamics that result from changes in upwelling driven by the NPGO.

In this study, we focus on the CHL variability observed in the Hong Kong coastal ocean, which has been monitored for 17 years during 1988-2004. We first characterize the spatial coherences to determine if there are broad-scale patterns of variability in this region. We then attempt to link these regional patterns to basin-scale climate fluctuations and regional-scale meteorological variations. This study is a first step towards investigating the effects of climatic variability, such as described by ENSO, PDO and NPGO indices, on physicochemical parameters and phytoplankton dynamics in Hong Kong coastal waters over interannual and decadal timescales.

2. Data and Methods

2.1. Study Area

The hydrological characteristics of Hong Kong coastal waters (Figure 1) are important in influencing the biological processes and habitat types. Hong Kong is located on the southern coast of China and opens to the northern South China Sea. Its coastal waters are influenced by four main water masses: the Pearl River estuarine plume, South China Sea water, the China Coastal Current and the Kuroshio Current [*Yin et al.*, 1999]. The relative impact of these water masses on the coastal waters of Hong Kong is driven by the East Asian Monsoon [*Hu et al.*, 2000]. Due to the monsoonal influence, the winter climate is cool, dry and dominated by north-easterly winds, whereas summer conditions are warm and wet with weaker south-westerly winds prevailing [*Hu et al.*, 2000]. As a result, oceanographic processes often have a marked seasonal variability.

During the summer wet season, the Pearl River discharge has a dominant influence on Hong Kong coastal waters. In terms of discharge volume, the Pearl River is the second largest river in China, with a discharge volume of 350 x 10^9 m^3 yr^{-1}, where 80% of the discharge occurs in the wet season (April-September) and only 20% during the dry season (October-March) [*Jilan*, 2004; *Zhang*, 2000]. The Pearl River estuarine plume flows out the western side of the estuary, to the west of Hong Kong. It then moves east, driven by the southwest monsoon, where it may influence the entire Hong Kong coastal zone, especially the western and southern regions [*K D Yin et al.*, 2001].

2.2. Data sets

2.2.1. Water quality monitoring data

This study used water quality data collected by the Hong Kong EPD at 75 sites (Figure 1), at monthly or bimonthly intervals over a 17-year period from 1988-2004. The sites were located within ten defined water quality monitoring zones, namely Deep Bay, Eastern Buffer, Junk Bay, Mirs Bay, North Western, Port Shelter, Southern, Tolo Harbour, Victoria Harbour and Western Buffer. Sampling was conducted aboard the research vessel the *Dr. Catherine Lam* using a rosette water sampler with a linked conductivity-temperature-depth profiler [*EPD*, 2006]. Physicochemical and biological analyses were conducted at the EPD laboratories or the Government Laboratory in Hong Kong.

2.2.2. Climatic indices

Climatic indices were used to describe each of the three modes of climatic variability examined in this study. The PDO and NPGO were described by the PDO Index (PDOI) and the NPGO Index (NPGOI), respectively. The PDOI is defined as the first empirical orthogonal function (EOF) of sea surface temperature (SST) variability north of 20°N in the north Pacific [*Mantua et al.*, 1997] and monthly values of this index were obtained from the Joint Institute for the Study of the Atmosphere and Ocean (http://jisao.washington.edu/pdo/). Positive values of the PDOI indicate that the PDO is in the warm phase, whereas negative values indicate that PDO is in the cool phase. The NPGO is defined as the second dominant mode of sea surface height (SSH) anomaly variability in the Northeast Pacific (180°–110°W; 25°N–62°N), which very closely tracks the second mode of North Pacific SST anomalies, and monthly index values were obtained from Di Lorenzo *et al*. [2008]. ENSO was described using the Multivariate ENSO Index (MEI). The MEI is a weighted average of SLP, surface wind direction, SST, surface air temperature and cloudiness. Monthly MEI values were obtained from the National Oceanic and Atmospheric Administration (NOAA, http://www.cdc.noaa.gov/ENSO/).

2.3. Data analysis

The data analysis proceeded in two stages, with analysis of spatio-temporal variability across the whole region done first using EOF analysis, followed by a more detailed examination of a smaller subset of sites selected based on the coherencies uncovered by the EOF study. In the first stage we examined the leading patterns or modes of spatial and temporal variability in CHL anomalies, for the seasonally adjusted data, over the Hong Kong region. The EOF method decomposes the time-series data into an independent set of spatial modes (EOFs) and temporal fluctuations described by the principal components (PCs). The first mode explains the highest amount variance within the data, with each subsequent mode explaining less variance. The EOF analysis was carried out using only those sampling sites (37 of the 75 sites) that included complete monthly CHL data (204 months) for the period 1988-2004. The leading PCs were then correlated with the climate indices that described each of the potential climatic forcings and the spectral characteristics of the leading EOF and climate index time series were compared.

In the second stage of analysis, a subset of twelve water quality monitoring sites representative of the different water quality zones was selected for more detailed scrutiny. The chosen sites (DM2, NM1, NM5, SM1, SM12, WM1, VM12, JM4, EM3, PM1, TM4 and MM17) span a range of hydrological characteristics and incorporated at least one station from each water quality monitoring zone (Figure 1). For each of the 12 selected water quality sites, each climatic index was correlated with CHL concentration, temperature, salinity, turbidity, total phosphorus (TP) and total nitrogen (TN) using bivariate Pearson correlation analyses. CHL concentration and turbidity were transformed using a $\log_{10}(x+1)$ transformation and TN and TP were transformed using a fourth-root transformation to normalize the data. Because the climatic indices did not display a seasonal component, the water quality parameters were transformed using a 12-point moving average (12MA) smoother, to remove the seasonal component of the time series, so that only the low-frequency component was analyzed. By removing the seasonal component of the time series, the influence of the climatic indices on interannual through interdecadal variability in the water quality parameters could be examined.

Each climatic index was also correlated with meteorological data obtained from the Hong Kong Observatory (http://www.hko.hk/). The meteorological data analyzed were wind speed, rainfall, mean temperature and SLP. Each parameter was measured daily and averaged over a period of one month, except for rainfall, which was presented as the total monthly amount. The meteorological parameters were also transformed using a 12MA smoother to remove seasonality.

3. Results

3.1. EOF analysis

The three largest PCs explain over 50% of the variability and serve to isolate dominant space/time features of the interannual variability (Table 1). The spatial patterns associated with these main modes of variability are shown in Figure 2. The spatial variability in the leading mode (EOF1, 28%) displays a surprisingly uniform pattern across the study region. This suggests that CHL variability is determined by a forcing which is independent of location and thus possibly exogenous to the system. The second mode (EOF2, 17%) exhibits oppositely signed loadings between Tolo Harbour and Victoria Harbour. This suggests that regional phytoplankton controls may differ between these locations. For example, Tolo Harbour is weakly flushed, whereas phytoplankton biomass in Victoria Harbour is limited by strong flushing and mixing [*Thompson and Ho*, 1981; *K Yin and Harrison*, 2007]. EOF3 (12%) has opposite signed loadings between Deep Bay and the eastern side of Hong Kong, again suggesting a spatial variation in local forcings, such as the seasonal Pearl River discharge, which strongly affects Deep Bay, but has limited impact on the eastern waters [*Yin*, 2002]. Further analysis on these regional differences is needed, but is beyond the scope of this study.

Relationships between climate indices and regional CHL response were tested by computing the temporal correlation of each of the leading EOFs with the three climate indices (Table 2). The leading mode of CHL variability (PC1) is significantly positively correlated with the NPGOI and significantly negatively correlated with both the PDOI and MEI, where the strongest correlation exists with the NPGOI (Figure 3). Spectral analysis revealed that the NPGO and PC1 time series had very similar characteristics, with both power spectra having maxima at frequencies of 17 years and smaller peaks at 8.5 and 5.7 years.

3.2. Correlations between climate indices and physicochemical and meteorological parameters

3.2.1. Pacific Decadal Oscillation

When the subset of stations was analyzed, the PDOI was significantly negatively correlated with CHL concentration in each of the stations except SM12 (Supplementary material). However, the correlation coefficient was small in most stations, the largest value of magnitude being -0.37, indicating that there is only a weak relationship between these variables (Supplementary material). There was also a significant negative correlation between the monthly PDOI values and the mean monthly air temperature of Hong Kong (Table 3). However, the correlation between PDOI and water temperature at the monitoring stations was not significant. Rainfall was positively correlated with the PDOI, as was TN in most stations. The PDOI was negatively correlated with turbidity and positively correlated with TP in some stations (Supplementary material).

3.2.2. North Pacific Gyre Oscillation

There was a significant positive correlation between the NPGOI and CHL in all stations. The strength of the correlation varied between the stations (Figure 4), where the lowest correlation coefficient was 0.28 at site TM4 and the highest was 0.74 at VM12, in which there was a strong correlation. In a number of stations, particularly NM1, NM5, SM1, VM12 and WM1, the low-frequency variation in CHL closely matched the variation in the NPGOI (Figure 4). The bulk of the correlation is associated with a single large-amplitude, sinusoidal oscillation in both the NPGOI and the CHL time series during this time period. Higher frequency variations in these variables did not appear to be correlated.

The NPGOI was also correlated with a number of other water quality and meteorological parameters. There were significant positive correlations between NPGOI and turbidity at all sites. This correlation was generally strong, with correlation coefficients exceeding 0.6 at most stations (Supplementary material). A significant negative correlation between the NPGOI and TP also existed at all of the monitoring stations, with the correlation coefficients lower than -0.6 (i.e. has an absolute value exceeding 0.6) in most stations (Supplementary material). When the NPGOI was correlated with the meteorological data, a significant negative correlation existed between the NPGOI and both wind speed (correlation coefficient = -0.55) and SLP (correlation coefficient = -0.56) (Table 3). A weaker significant positive correlation (correlation coefficient = 0.34) also existed between the NPGOI and air temperature, and there was a positive correlation between water temperature and NPGOI in some stations. In a majority of stations there was a negative correlation between TN and NPGOI.

3.2.3. El Niño-Southern Oscillation

CHL concentration was significantly negatively correlated with MEI at all stations except SM12, such that CHL concentrations are highest during La Niña conditions and lowest during El Niño conditions. The strength of the correlations between these indices and CHL was lower than the strength of the correlations between CHL and the NPGOI (Supplementary material). The coefficients of correlation for significant correlations between CHL and MEI ranged from -0.29 (at JM4) to -0.45 (at DM2) (Supplementary material).

Similarly, significant positive correlations were found between MEI and both rainfall and SLP (Table 3), indicating that rainfall and SLP are highest during El Niño conditions and lowest in La Niña conditions. Turbidity and salinity were negatively correlated with the MEI at a number of the study sites (Supplementary material). Conversely, TN was significantly positively correlated with the MEI at all sites except DM2 (Supplementary material). TP was also positively correlated with MEI in a number of sites (Supplementary material).

4. Discussion

Patterns of CHL variability in the Hong Kong region exhibit regional-scale coherencies. The first mode, in particular, describes a coherent uni-signed pattern of regional-scale response. The temporal correlation between this leading mode of CHL variability (PC1) and NPGOI is strong over the time period and suggests that the regional impact of this climate forcing may be shaping the interdecadal variability in CHL in Hong Kong waters. The uniformity of this pattern across the study area, along with the significant correlations at all of the subset of study sites, is indicative that a large-scale forcing, such as climatic variability, is driving this part of the response. Conversely, changes in nutrient loads, for example, have had different temporal patterns at each of the study zones, due to changes in catchment land management and sewage treatment processes and discharge locations. For example, 70% of Hong Kong's sewage was discharged into Victoria Harbour, receiving only preliminary treatment, until 2001 when the Harbour Area Treatment Scheme was introduced and chemically-enhanced treatment commenced and the sewage discharge location changed [*EPD*, 2006; *K Yin and Harrison*, 2007]. Whereas the nutrient loads in Tolo Harbour have been decreasing since 1987 with the implementation of the Tolo Harbour Action Plan, which resulted in a decrease in total nitrogen load from approximately 6000 kg total N d^{-1} to <1000 kg total N d^{-1} from 1987-2000 [*EPD*, 2006; *K Yin and Harrison*, 2007].

The EOF analysis results are consistent with the finding that CHL at individual stations were significantly correlated with each of the climatic indices examined. This indicates that variability in climatic forcings on interannual to decadal time scales may influence phytoplankton dynamics in Hong Kong coastal waters. This is a surprising result, as the relative influence of climatic variability on phytoplankton dynamics in Hong Kong coastal waters was previously thought to be low, since phytoplankton populations were assumed to be predominantly influenced by other local factors, especially cultural eutrophication. Although the PDO and ENSO were found to describe only limited variability in phytoplankton standing stock trends, the low-frequency component of the NPGO was strongly correlated with CHL at a number of sites. The higher EOF modes exhibited regional signatures that will require further analysis to be properly linked with climatic processes.

4.1. North Pacific Gyre Oscillation

The correlation between CHL and the NPGOI was highly significant in all stations, but was dominated by a single Fourier harmonic with an approximately 17-year time scale during this period. In eight of the twelve sampling stations the correlation coefficients were above 0.5 and as high as 0.74, indicating that a large amount of the interannual variation in phytoplankton biomass can be explained by variations in the NPGO. There were also strong positive correlations between the NPGOI and turbidity, and this may be because high levels of phytoplankton are associated with an increase in water column turbidity.

There was a strong negative correlation of (-0.55) between NPGOI and local wind speed over this time period. Wind-driven vertical mixing and temperature have been suggested as controls on phytoplankton growth in Hong Kong waters during winter, even though nutrient levels are relatively low at this time of year [*Ho et al.*, 2008]. This is because in a number of zones in Hong Kong waters, the input of NH_4 and PO_4 from sewage discharge is sufficient to support phytoplankton growth [*Ho et al.*, 2008]. Wind speeds associated with the seasonal monsoon are higher in winter and spring than in summer and autumn and these high wind speeds are believed to be responsible for the relatively low CHL, which persist into spring despite an increase in water temperature [*Ho et al.*, 2008]. Turbulence and vertical mixing caused by high wind speed may have also increased the surface TP and be responsible for the observed negative correlation between TP and NPGOI.

Based on the results presented here, it is hypothesised that the dominant mechanism through which the NPGO may influence interannual variability in phytoplankton dynamics in Hong Kong coastal waters is by variability in wind speed. Indeed this may also explain why the strength of the correlation between NPGOI and CHL varied spatially throughout the study area. Station VM12 in Victoria Harbour had the strongest correlation between NPGOI and CHL. Previous studies of Victoria Harbour have shown that phytoplankton biomass is lower than expected from the ambient nutrient concentrations and this is believed to be due to strong vertical mixing from wind and tidal forces [*Yin and Harrison*, 2007]. Therefore, if phytoplankton growth is constrained by wind induced mixing in Victoria Harbour, this may explain why the correlation between NPGOI and CHL is the highest at VM12. Conversely, the correlations between the NPGOI and CHL were comparatively weak in the stations within Mirs Bay and Deep Bay. This may be because the relative influence of wind speed is less important in these stations, where phytoplankton may be limited by low nutrient concentrations in Mirs Bay and by dilution or light availability in Deep Bay [*Yin*, 2002; *Yin et al.*, 2004]. It should be noted that although variation in wind speed is believed to be the dominant mechanism driving the relationship between the NPGO and phytoplankton dynamics, other factors, such as the positive relationship between NPGOI and temperature, might also have an influence.

Studies on the ecosystem effects of the NPGO in the eastern Pacific show that there is a strong positive correlation between the NPGOI and both nutrients and CHL in the California Current System [*Di Lorenzo et al.*, 2008]. This occurs because the wind-driven upwelling, associated with the NPGO, is the dominant process controlling nutrient concentrations, which in turn control phytoplankton dynamics [*Di Lorenzo et al.*, 2008]. The NPGO has similarly been found to influence the ocean dynamics in the western Pacific through Rossby wave propagation, but the observed correlations are lagged by approximately three years [*Ceballos et al.*, 2009]. However, the results presented here show strong positive correlations between the NPGO and CHL with no strong time lag. Therefore, with the limited time series of 17 years, which here only shows a single oscillation in the NPGO, we cannot conclude that the strong correlation between NPGOI and CHL implies that NPGO is causing the observed CHL pattern.

4.2. Pacific Decadal Oscillation and El Niño-Southern Oscillation

CHL was negatively correlated with the PDOI, indicating that phytoplankton biomass tends to be higher when the PDO is in the cool phase than in the warm phase. The trend in CHL concentration was also negatively correlated with the MEI, indicating that phytoplankton biomass is generally higher in La Niña conditions and lower in El Niño conditions. The physicochemical conditions associated with El Niño (La Niña) and PDO warm (cool) phase also tend to be similar. This is in agreement with findings that ENSO and PDO are not independent and that they are in phase during El Niño (La Niña) and PDO warm (cool) phase [*Chan and Zhou*, 2005].

There were significant positive correlations between rainfall and both the PDOI and MEI, indicating that rainfall is highest during PDO warm phase and El Niño conditions. This supports findings by Leung and Wu [2004] and Chang [1999], which show that rainfall is higher during El Niño conditions. Rainfall in southern China underwent a regime shift from wet to dry in the mid 1970s when the PDO switched from the cool phase to the warm phase [*Leung and Wu*, 2005; *Zhou et al.*, 2007]. This is in disagreement with the results presented here that show that the PDOI is positively correlated with rainfall (during this time interval). However, changes associated with the PDO tend to occur as regime shifts and the PDO did not undergo such a regime shift during the period examined here from 1988-2004 [*Mantua et al.*, 1997]. This suggests that under a constant PDO regime, the dependency of PDO on ENSO drives the positive correlation between PDOI and rainfall.

The reason for the negative relationship between phytoplankton biomass and both the PDOI and MEI is unclear. The correlation analysis shows that during La Niña/PDO cool phase, when CHL is at its highest, there is low rainfall and TN, and high turbidity, TP and salinity. The correlations between the PDOI and MEI with TN and salinity are likely to result from the relationship between rainfall and these indices, where rainfall is associated with increases in TN and a decrease in salinity. The high turbidity during La Niña/PDO cool phase is likely to result from high phytoplankton biomass, as rainfall and sediment runoff are low during these climate states. High TP concentrations would not be expected to have a major effect on phytoplankton biomass due to the high background levels of nutrients in Hong Kong coastal waters [*Harrison et al.*, 2008]. The correlations between CHL and both the PDOI and MEI, which were relatively weak compared with the correlation with the NPGOI, could be a result of the interdependencies between the climatic indices, where both the PDOI and MEI are significantly negatively correlated with the NPGOI (Table 4).

4.3. Future importance of climatic variability in determining phytoplankton dynamics

Although the results here suggest that climatic forcings can explain large amounts of the variation in phytoplankton standing stock, this does not imply that the effects of nutrient loading and cultural eutrophication are unimportant. We hypothesise that the mechanism driving the NPGO-CHL relationship is through physical processes, primarily wind-driven mixing. In zones where phytoplankton growth is light-limited due to strong vertical mixing, such as Victoria Harbour [*Yin and Harrison*, 2007], the correlation between the NPGOI and CHL was high (0.74). Whereas in Mirs Bay, where nutrients may limit phytoplankton growth (Yin 2002), the correlation was weaker (0.42). Therefore, if nutrients were to be reduced in Hong Kong coastal waters, the relative influence of the NPGO on phytoplankton biomass may decrease, as nutrient concentrations become more influential and physical factors become relatively less influential in determining phytoplankton dynamics. Indeed, previous studies of Tolo Harbour show that there was an 8.5 fold increase in phytoplankton biomass from 1978-1985, coincident with large increases in nitrate and phosphate levels [*Hodgkiss and Ho*, 1997]. This suggests that if nutrient concentrations are lowered to levels similar to those in the 1970s, then ambient nutrient concentration may once again become the dominant factor controlling phytoplankton growth.

The relative importance of each mode of climatic variability and its relationship to CHL may also change in the future if nutrient loads were to decrease. For example, if nutrient limitation were to be the dominant control over phytoplankton growth in Hong Kong coastal waters then the positive relationship between CHL and NPGOI may cease to exist, as TP and TN are both negatively correlated with the NPGOI. ENSO may also become more influential on phytoplankton standing stock, where large amounts of nutrients can be introduced into the coastal zone from the Pearl River with the high rainfall associated with El Niño.

5. Conclusions

The interannual variability in CHL in the coastal waters of Hong Kong from 1988 to 2004 exhibits a dominant in-phase pattern at all of the monitoring sites. Since localized perturbations to the coastal ecosystem, such as enhanced nutrient loads, have occurred at different times and to different extents between the sites, this may indicate that a large-scale external factor, such as climatic variability, may be driving the observed CHL variability. The dominant mode of CHL variability was strongly positively correlated with the NPGOI, although the 17-year time series was not long enough to provide a conclusive link between the NPGO and phytoplankton dynamics. We suggest that the negative relationship between wind speed and the NPGOI may be a possible mechanism driving the relationship between the NPGOI and CHL.

The results reported here suggest that climatic variability can be an important factor in controlling phytoplankton dynamics even in coastal waters that are impacted by a number of anthropogenic stressors. However, this does not imply that anthropogenic factors, such as cultural eutrophication, are not important in determining phytoplankton dynamics. If nutrient concentrations were to be reduced to an extent where they were the dominant factor limiting phytoplankton growth, then physical controls such as wind-induced mixing may become less important and nutrient loads may become more important in determining phytoplankton biomass.

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References

Behrenfeld, M. J., R. T. O'Malley, D. A. Siegel, C. R. McClain, J. L. Sarmiento, G. C. Feldman, A. J. Milligan, P. G. Falkowski, R. M. Letelier, and E. S. Boss (2006), Climate-driven trends in contemporary ocean productivity, *Nature*, *444*(7120), 752-755.

Ceballos, L. I., E. Di Lorenzo, C. D. Hoyos, N. Schneider, and B. Taguchi (2009), North Pacific Gyre Oscillation Synchronizes Climate Fluctuations in the Eastern and Western Boundary Systems, *Journal of Climate*, *22*(19), 5163-5174.

Chan, J. C. L., and W. Zhou (2005), PDO, ENSO and the early summer monsoon rainfall over south China, *Geophysical Research Letters*, *32*(8).

Chang, W. L. (1999), Some Impacts of El Niño and La Niña Events on the Weather of Hong Kong, paper presented at Workshop on the Impact of the El Niño Southern Oscillation (ENSO) / La Niña on Meteorology and Hydrology in the Typhoon Committee Area, Macau, 29 June - 1 July.

Cloern, J. E., A. D. Jassby, J. K. Thompson, and K. A. Hieb (2007), A cold phase of the East Pacific triggers new phytoplankton blooms in San Francisco Bay, *Proceedings of the National Academy of Sciences of the United States of America*, *104*(47), 18561-18565.

Di Lorenzo, E., et al. (2008), North Pacific Gyre Oscillation links ocean climate and ecosystem change, *Geophysical Research Letters*, *35*(L08607), doi:10.1029/2007GL032838

EPD (2006), 20 Years of Marine Water Quality Monitoring in Hong Kong, Environmental Protection Department, Government of the Hong Kong Special Administrative Region.

Gabric, A. J., and P. R. F. Bell (1993), Review of the Effects of Nonpoint Nutrient Loading on Coastal Ecosystems, *Australian Journal of Marine and Freshwater Research*, *44*(2), 261-283.

Harrison, P. J., K. D. Yin, J. H. W. Lee, J. P. Gan, and H. B. Liu (2008), Physical-biological coupling in the Pearl River Estuary, *Continental Shelf Research*, 1405-1415.

Ho, A. Y. T., J. Xu, K. D. Yin, X. C. Yuan, L. He, Y. L. Jiang, J. H. W. Lee, D. M. Anderson, and P. J. Harrison (2008), Seasonal and spatial dynamics of nutrients and phytoplankton biomass in Victoria Harbour and its vicinity before and after sewage abatement, *Marine Pollution Bulletin*, *57*(6-12), 313-324.

Hodgkiss, I. J., and K. C. Ho (1997), Are changes in N:P ratios in coastal waters the key to increased red tide blooms?, *Hydrobiologia*, *352*, 141-147.

Hodgkiss, I. J., and S. H. Lu (2004), The effects of nutrients and their ratios on phytoplankton abundance in Junk Bay, Hong Kong, *Hydrobiologia*, *512*(1-3), 215-229.

Hu, J., H. Kawamura, H. Hong, and Y. Qi (2000), A Review of the Currents in the South China Sea: Seasonal Circulation, South China Sea Warm Current and Kuroshio Intrusion, *Journal of Oceanography*, *56*, 607-624.

Jilan, S. (2004), Overview of the South China Sea circulation and its influence on the coastal physical oceanography outside the Pearl River Estuary, *Continental Shelf Research*, *24*(16), 1745-1760.

Kim, H.-J., A. J. Miller, J. McGowan, and M. L. Carter (2009), Coastal phytoplankton blooms in the Southern California Bight, *Progress In Oceanography*, *82*(2), 137-147.

Leung, Y. K., and M. C. Wu (2004), The Effect of ENSO and East Asian Monsoon on the Annual Rainfall in Hong Kong, China, paper presented at Sixth Joint Meeting of Seasonal Prediction on East Asian Summer Monsoon, Guilin, China, 11-13 May, 2004.

Leung, Y. K., and M. C. Wu (2005), Regime Shift in Summer Rainfall in Southern China, paper presented at Seventh Joint Meeting of Seasonal Prediction on Eastern Asian Summer Monsoon, Nanjing, China, 11-13 May, 2005.

Mantua, N. J., and S. R. Hare (2002), The Pacific decadal oscillation, *Journal of Oceanography*, *58*(1), 35-44.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bulletin of the American Meteorological Society*, *78*(6), 1069-1079.

McPhee-Shaw, E. E., K. J. Nielsen, J. L. Largier, and B. A. Menge (2011), Nearshore chlorophyll-a events and wave-driven transport, *Geophysical Research Letters*, *38*.

Miller, A. J., F. Chai, S. Chiba, J. R. Moisan, and D. J. Neilson (2004), Decadal-scale climate and ecosystem interactions in the North Pacific Ocean, *Journal of Oceanography*, *60*(1), 163-188.

Nixon, S. W. (1995), Coastal Marine Eutrophication - a Definition, Social Causes, and Future Concerns, *Ophelia*, *41*, 199-219.

Smetacek, V., and J. E. Cloern (2008), Oceans - On phytoplankton trends, *Science*, *319*(5868), 1346-1348.

Thompson, G. B., and J. Ho (1981), Some Effects of Sewage Discharge Upon Phytoplankton in Hong-Kong, *Marine Pollution Bulletin*, *12*(5), 168-173.

Yin, K., and P. J. Harrison (2007), Influence of the Pearl River estuary and vertical mixing in Victoria Harboron water quality in relation to eutrophication impacts in Hong Kong waters, *Marine Pollution Bulletin*, *54*(6), 646-656.

Yin, K. D. (2002), Monsoonal influence on seasonal variations in nutrients and phytoplankton biomass in coastal waters of Hong Kong in the vicinity of the Pearl River estuary, *Marine Ecology-Progress Series*, *245*, 111-122.

Yin, K. D., P. J. Harrison, J. Chen, W. Huang, and P. Y. Qian (1999), Red tides during spring 1998 in Hong Kong: is El Nino responsible?, *Marine Ecology-Progress Series*, *187*, 289-294.

Yin, K. D., P. Y. Qian, J. C. Chen, D. P. H. Hsieh, and P. J. Harrison (2000), Dynamics of nutrients and phytoplankton biomass in the Pearl River estuary and adjacent waters of Hong Kong during summer: preliminary evidence for phosphorus and silicon limitation, *Marine Ecology-Progress Series*, *194*, 295-305.

Yin, K. D., P. Y. Qian, M. C. S. Wu, J. C. Chen, L. M. Huang, X. Y. Song, and W. J. Jian (2001), Shift from P to N limitation of phytoplankton growth across the Pearl River estuarine plume during summer, *Marine Ecology-Progress Series*, *221*, 17-28.

Yin, K. D., J. L. Zhang, P. Y. Qian, W. J. Jian, L. M. Huang, J. F. Chen, and M. C. S. Wu (2004), Effect of wind events on phytoplankton blooms in the Pearl River estuary during summer, *Continental Shelf Research*, *24*(16), 1909-1923.

Zhang, J. (2000), Evidence of trace metal limited photosynthesis in eutrophic estuarine and coastal waters, *Limnology and Oceanography*, *45*(8), 1871-1878.

Zhou, W., X. Wang, T. J. Zhou, and J. C. L. Chan (2007), Interdecadal variability of the relationship between the East Asian winter monsoon and ENSO, *Meteorology and Atmospheric Physics*, *98*(3-4), 283-293.

Tables:

Table 1. Percent variance explained (PVE) for the first 8 modes of the EOF analysis

Mode	PVE (%)	Cumulative PVE (%)
1	27.8	27.8
2	16.6	44.4
3	12.2	56.6
4	7.0	63.6
5	6.5	70.1
6	5.4	75.5
7	4.0	79.5
8	2.2	81.7

Table 2. Correlations of leading PCs with climate indices (N=204)

	PC1	PC2	PC3	PC4
NPGOI	0.472[a]	0.117	0.003	-0.009
PDOI	-0.238[a]	-0.071	-0.026	0.072
MEI	-0.399[a]	-0.001	-0.132	-0.034

[a]Correlation is significant at the 0.01 level

Table 3. Correlations between climatic indices and weather parameters

	PDOI	NPGOI	MEI
Wind Speed	-0.100	-0.548[b]	-0.106
Rainfall	0.141[a]	0.016	0.220[b]
Temperature	-0.246[b]	0.336[b]	-0.016
SLP	0.499[b]	-0.560[b]	0.531[b]

[a]Correlation is significant at the 0.05 level (2-tailed)

[b]Correlation is significant at the 0.01 level (2-tailed)

Table 4. Correlations between the climatic indices

	PDO Index	NPGO Index	Multivariate ENSO Index
PDO Index	1	-0.259[a]	0.520[a]
NPGO Index	-0.259[a]	1	-0.319[a]
Multivariate ENSO Index	0.520[a]	-0.319[a]	1

[a]Correlation is significant at the 0.01 significance level

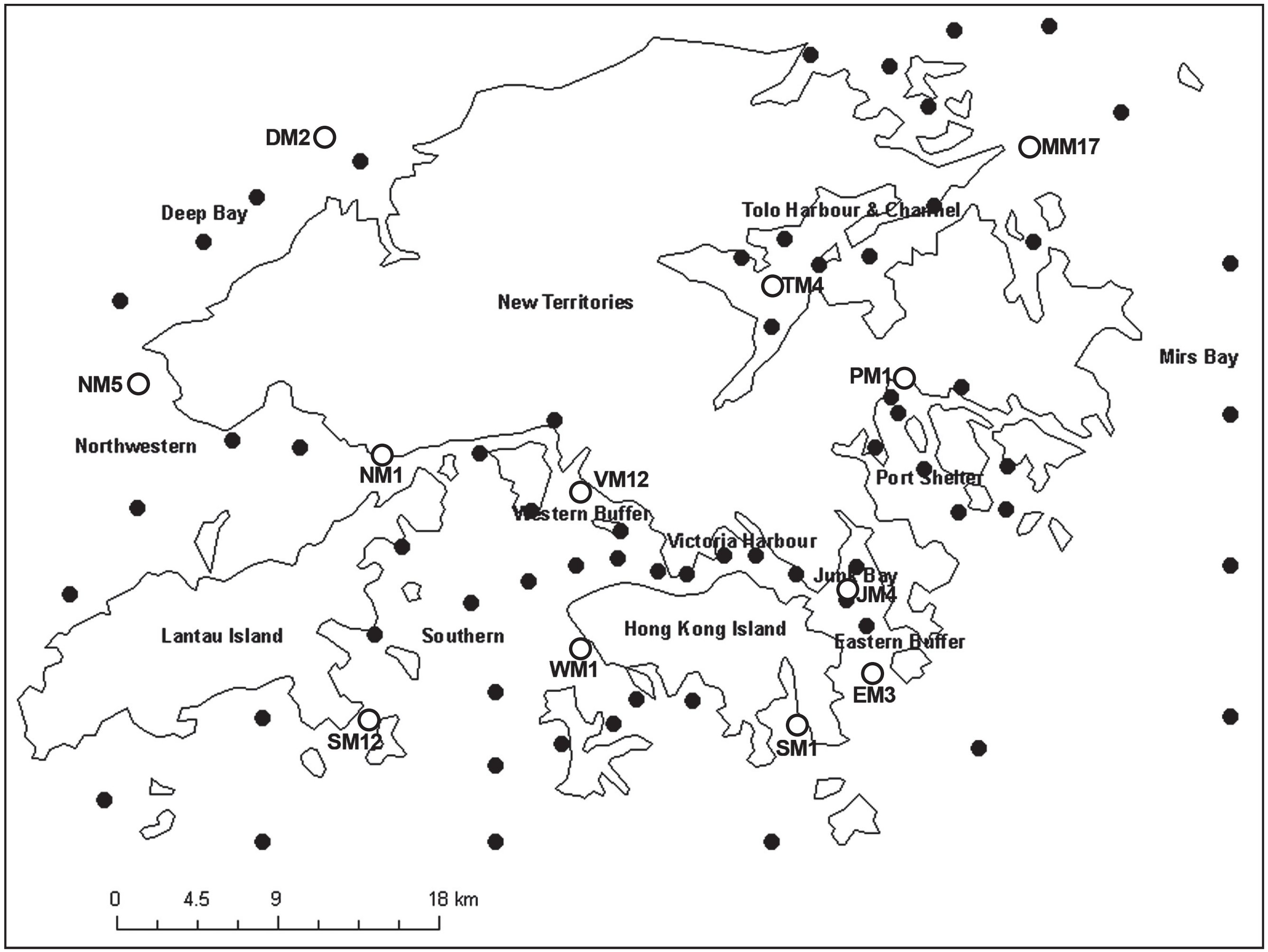
Figure Captions:

Figure 1. Location of the 75 sampling sites. Stations that are labeled were used in the subset of stations for the correlation analyses.

Figure 2. Spatial distribution of the leading seasonally adjusted EOFs of CHL (circle diameter indicates relative magnitude, such that large circles are positive numbers and small circles are negative numbers).

Figure 3. Time series of the NPGOI and PC1

Figure 4. Correlation between NPGOI and CHL. The NPGOI and CHL are shown by the dark and light lines respectively.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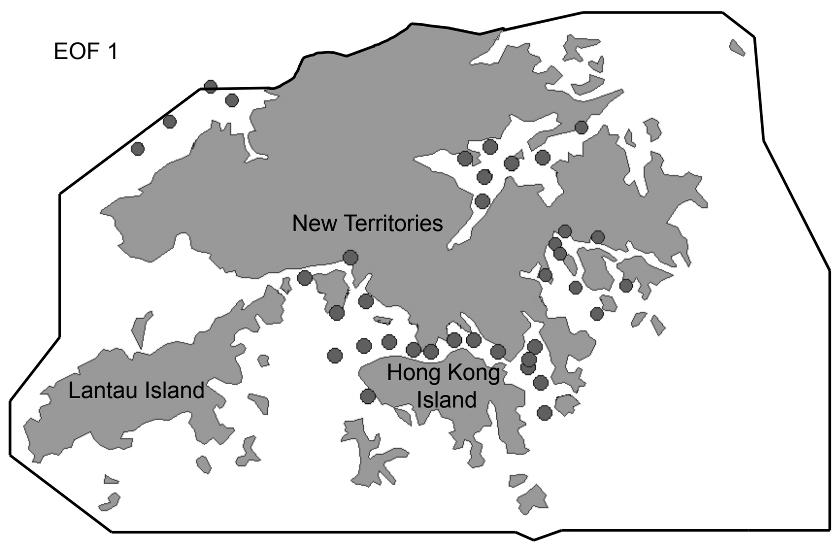
MM17
Deep Bay
Tolo Harbour & Channel
TM4
New Territories
Mirs Bay
NM5
PM1
Northwestern
NM1
VM12
Port Shelter
Western Buffer
Victoria Harbour
Junk Bay
JM4
Lantau Island
Southern
Hong Kong Island
Eastern Buffer
WM1
EM3
SM12
SM1
0
4.5
9
18 km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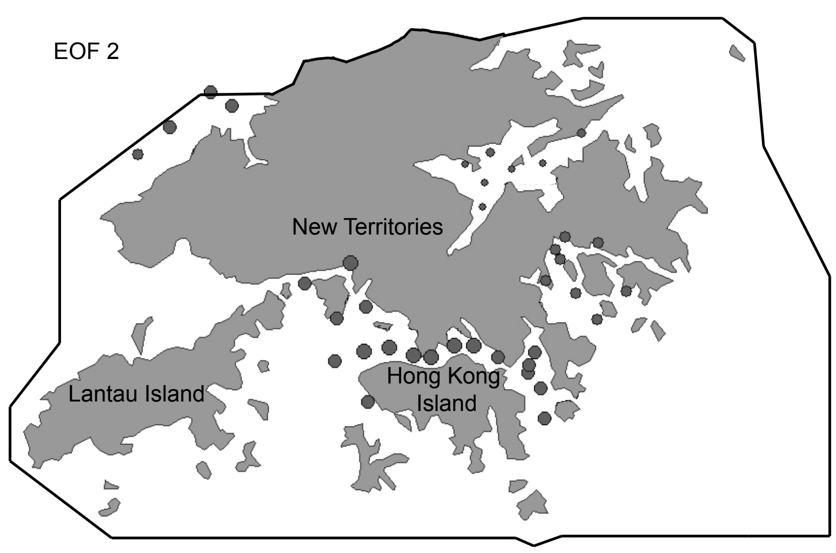
Lantau Island
Hong Kong
Island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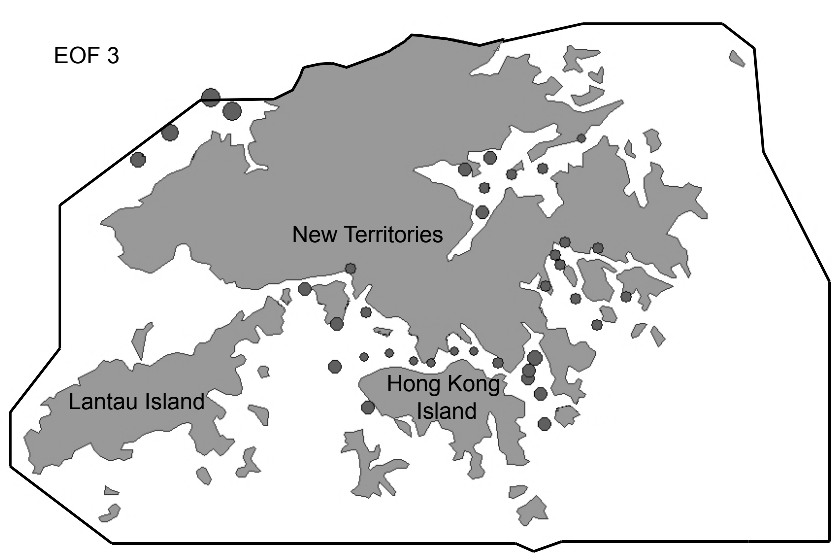
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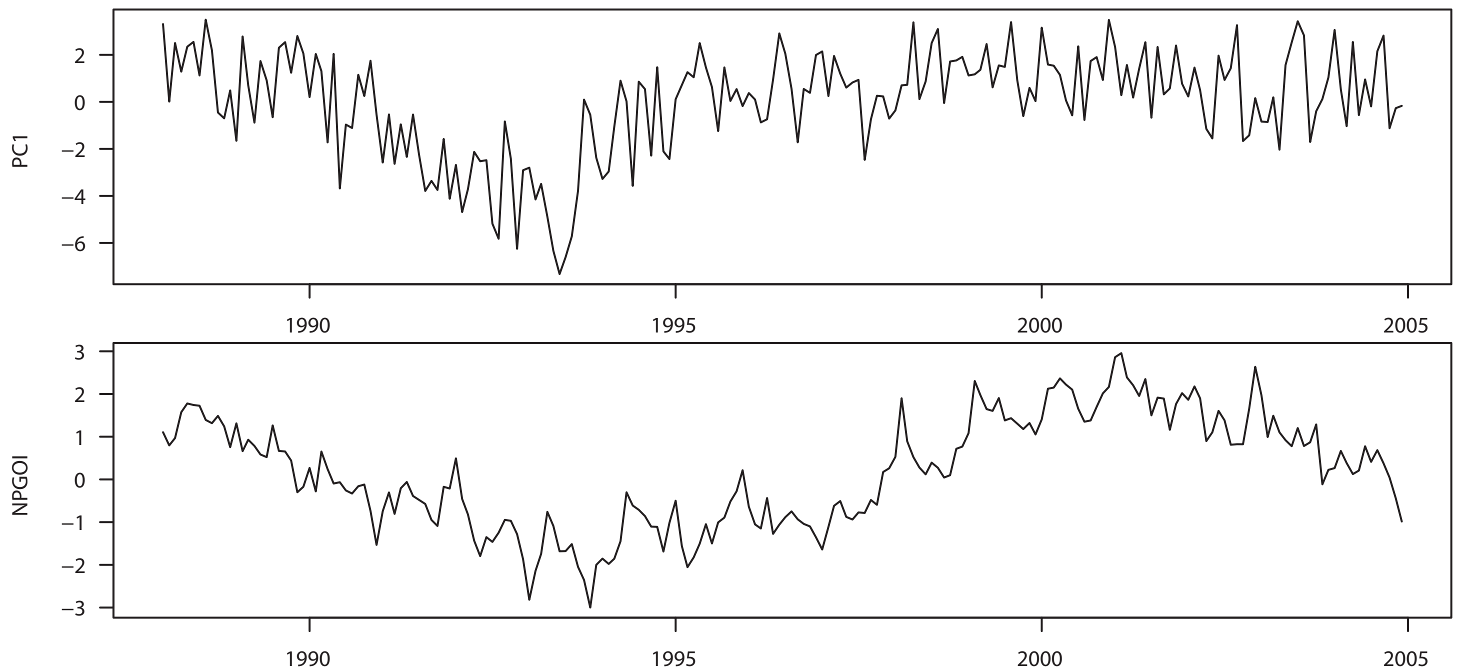
PC1
2
0
−2
−4
−6
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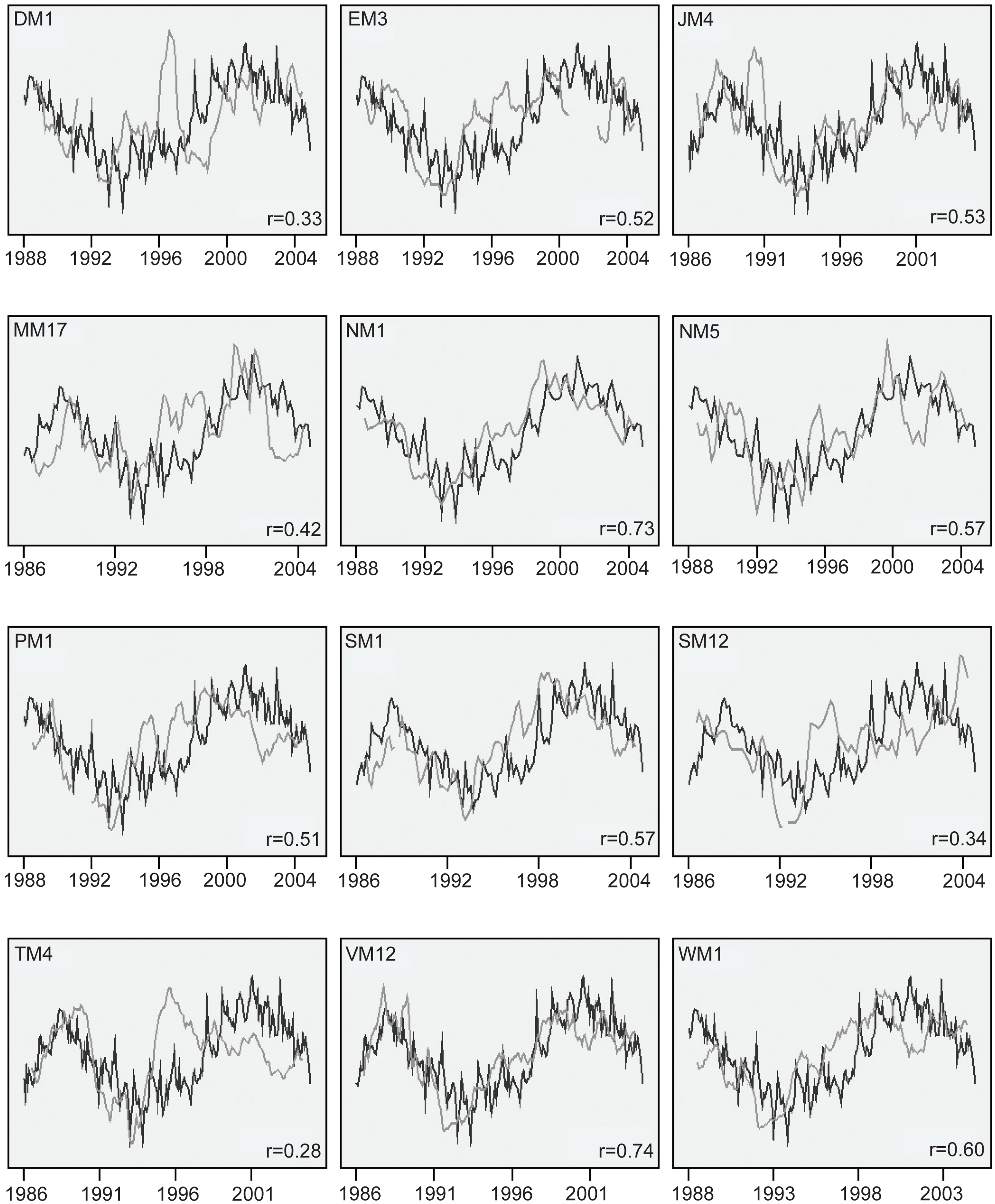
1995
2000
2005
NPGOI
3
2
1
0
−1
−2
−3
1990
1995
2000
2005


DM1
r=0.33
1988
1992
1996
2000
2004
EM3
r=0.52
1988
1992
1996
2000
2004
JM4
r=0.53
1986
1991
1996
2001
MM17
r=0.42
1986
1992
1998
2004
NM1
r=0.73
1988
1992
1996
2000
2004
NM5
r=0.57
1988
1992
1996
2000
2004
PM1
r=0.51
1988
1992
1996
2000
2004
SM1
r=0.57
1986
1992
1998
2004
SM12
r=0.34
1986
1992
1998
2004
TM4
r=0.28
1986
1991
1996
2001
VM12
r=0.74
1986
1991
1996
2001
WM1
r=0.60
1988
1993
1998
2003