Annual sea surface temperature lag as an indicator of regional climate variability

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ABSTRACT: The annual SST lag for the world ocean is obtained from a Fourier analysis of the HadISST (1870–2008) and NOAA WOA05 (1900–2005) monthly SST data series. The main properties are a mean of 73 days and a standard deviation of 16 days, with tongues of high SST lag extending poleward and eastward from the equatorial regions where a maximum in lag of about 110 days occurs. The SST lag is the sum of an atmospheric surface heat flux lag and an ocean heat storage lag which is the dominant contributor and provides direct estimates of the damping time for air/sea heat exchange, which are in good agreement with observations in the eastern North Atlantic Ocean, and also predictions of the phase lag of the mid-latitude ocean surface temperature field to El Nino-Southern Oscillation (ENSO) forcing. Hence, SST lag can be used to diagnose global climate variability. Local differences in lag of up to about 15 days occur between the 1991–2005 and 1976–1990 periods, which are accompanied by significant changes in regional climate. The lag time series for grid points in the eastern Indian Ocean, North Pacific Ocean and North Atlantic Ocean show that the variability can be interpreted in terms of bounded random walks of length about 20 years. The CSIRO Mk. 3.5 run for Scenario A2 over the period 1871–2100 has a similar random structure and also shows a secular increase in SST lag in the temperate oceans which is attributable to an expansion of the tropical belt. Copyright © 2012 Royal Meteorological Society

KEY WORDS sea surface temperature lag; damping time; ocean mixed layer; random processes; climate change

Received 4 September 2009; Revised 29 June 2012; Accepted 11 August 2012

1. Introduction

The lag in air temperatures (AT), and sea surface temperatures (SST), behind solar radiation is known as the lag of the seasons (Byers, 1974; Prescott and Collins, 1951). These lags show strong interannual variability due to the vagaries of weather which may act differentially throughout the year, but the net effect can be represented by a phase lag of the annual temperature cycle over the radiation cycle.

We extract the SST lag, which is one part of the annual harmonic signal (consisting of a mean, range and lag) via the Fourier method described in Section 2, and interpret it using a simple one-dimensional mixed layer model to consider the harmonic response (Section 3) due to surface heat flux forcing.

An analysis for the world ocean of the climatology of SST lag is presented in Section 4, and in Section 5 two pairs of periods are selected for anomaly comparisons (a) 1991–2005 and 1976–1990, which are representative of contemporary interdecadal variability; and (b) 1951–2000 and 1901–1950 which encompass the centennial variability during the 20th century.

The main aim of the study is to show that SST lag is an indicator of regional climate variability, which occurs through the changes in air/sea feedback that are directly related to the SST lag. SST lag was not discussed in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) though in our work, the focus is not on global climate change, but rather on the underlying randomness of the heat exchange between the atmosphere and the ocean which affects regional climates. Section 6 provides an interpretation of the lag results from this perspective, and Section 7 is a brief discussion of the results in a broader context.

2. Lag analysis methods

We have processed the updated HadISST (Rayner et al., 2003), and the NOAA WOA05 (Locarnini et al., 2006) 1° resolution climatology data by fitting an annual Fourier mode to the monthly values of SST and surface (air-sea) heat flux data (Josey et al., 1999), and daily values of AT data and obtaining, by multiple regression, least squares estimates of the mean, and the coefficients of \( \cos(\sigma t) \) and \( \sin(\sigma t) \), where \( \sigma \) is the annual frequency. This procedure, which evaluates the range, the mean and the phase lag of the cycle and also the regression coefficient \( r \) of the fit (Alexander et al., 2005), averages over all the variability in the monthly and daily records of each year, and produces a good first order representation of SST and AT lag variability. The lag is referenced to the time of
the maximum in daily insolation in the subtropics in each hemisphere (22nd December in the Northern Hemisphere and 21st June in the Southern Hemisphere), even though in the tropics the sun passes directly overhead twice annually. Lag estimates are however omitted if \( r < 0.9 \), which occurs mainly in the tropics (Figure 1(a) and (b)). Outside of the tropics the higher correlations \( (r > 0.9) \) are the result of the dominance of the annual harmonic in the monthly temperature series (Li, 2009). The main features are similar in both products, although the period of averaging for HadISST (1870–2008) is longer than for NOAA WOA05 (1900–2005). The Hadley Centre data have better regressions in the Southern Ocean and in the Arctic Ocean, presumably due to a more complete reconstruction of the monthly SST data.

3. A simple mixed layer model

The phase of the SST lag is the sum of two components: (1) the surface heat flux phase lag \( (f) \), which is the lag of the air-sea heat flux cycle over the insolation cycle, and is zero in a radiative atmosphere transparent to insolation and (2) the oceanic heat storage phase lag \( (g) \), which is the lag of the SST cycle over the air-sea heat flux cycle. Figure 2, derived from the Southampton Oceanography Centre 1° net heat flux data set (Josey et al., 1999), shows that the surface heat flux lag may take either sign. The global mean (5 days) and standard deviation (9 days) of the heat flux lag are much less than the global mean (73 days) and standard deviation (16 days) of the SST lag (Figure 1(a)); therefore, the ocean heat storage lag is the main cause of the SST lag.

In the simplest situation in which the effect of ocean currents can be neglected, the ocean heat storage lag can be predicted using the one-dimensional relation (Frankignoul et al., 1998),

\[
\frac{dT_s}{dt} + BT_s = q
\]

where \( t \) is time, \( T_s \) is the SST (assumed to be a vertically uniform mixed layer anomaly), and \( q = Q/(\rho C_p H) \) is a normalized surface heat flux in which \( Q \) is the downward surface heat flux and \( \rho \) and \( C_p \) are the density and specific heat at constant pressure of seawater, respectively, and
\( B > 0 \) for a negative feedback and \( B < 0 \) for a positive feedback. The solution of (1) for an annual harmonic of heat flux, \( q = q_0 \cos(\sigma t - f) \), in which \( \sigma \) is the annual frequency and \( q_0 \) is the amplitude and \( f \) is the phase of the cycle, is \( T_s = T_0 \cos(\sigma t - f - g) \), where the amplitude,

\[
T_0 = q_0/(\sigma^2 + B^2)^{1/2}
\]

and the phase,

\[
g = \tan^{-1}(\sigma/B)
\]

Thus, \( g \) provides a direct estimate of \( B \), or alternatively the damping time \( (B^{-1}) \) applicable for the annual temperature cycle. This quantity can be diagnosed from coupled general circulation models (CGCMs), e.g., Kleeman and Power (1995), and has also been measured in the North Atlantic Ocean using the Comprehensive Ocean-Atmosphere Data Set on a 5° \( \times \) 5° grid during the period 1952–1992 (Frankignoul et al., 1998).

The results from these observations which were conducted in a region of small currents between about 20°N and 50°N in the eastern Atlantic Ocean indicate that the damping time \( (B^{-1}) \) decreases from about 4 months at 20°N to 1.5 months at 50°N. An inspection of Figure 1(a) to obtain \((f + g)\) and Figure 2 to obtain \( f \) shows that over the same range of latitudes \( g \) decreases from about 65° to about 40°, which from Equation (2b) corresponds with an almost identical decrease in damping time from 4.1 to 1.6 months. Over the same range of latitudes the estimates of the feedback factor \((\rho C_pHB)\) ranged from 10 to 30 Wm\(^{-2}\) K\(^{-1}\), which are all less than the Haney constant \((\lambda \approx 40\) Wm\(^{-2}\) K\(^{-1}\)) (Haney, 1971).

We conclude, on the assumption that \( f \) is due to atmospheric processes, (see Section 4.2), that \( g \) is a good estimator of \( B \). The observations in the North Atlantic Ocean indicate that \( B \), which takes account of the local negative feedback and also the adjustment in air temperature to the SST anomaly, is not a strongly scale dependent quantity. The importance of this latter positive feedback effect, which was first recognised by Bretherton (1982), is well known to ocean modellers, e.g., Kleeman and Power (1995).

On substituting the annual cycle frequency, \( \sigma = 2 \times 10^{-7} \) s\(^{-1}\), we obtain from (2b) for \( g = 40°, 60°, 80° \) that the respective damping times \( (B^{-1}) \) are 1.6, 3.3 and 10.9 months, and also for a Haney exchange process in which \( B = \lambda/[(\rho C_pH)] \), assuming that \( \lambda = 40\) Wm\(^{-2}\) K\(^{-1}\), \( \rho = 10^3 \) kg m\(^{-3}\), \( C_p = 4 \times 10^3 \) J kg\(^{-1}\) K\(^{-1}\) and \( H = 50 \) m, we have \( B^{-1} = 1.9 \) months and hence \( g = 45° \). These results give a framework to interpret the global lag patterns. They can also be used to estimate the response of the surface temperature field to ENSO forcing. On assuming an ENSO period of 4 year, we find that for \( g = 50° \), which occurs in the mid-latitudes (Figures 1(a) and 2), the damping time is 2.3 months, and hence from Equation (2b) the phase lag is 2.2 months, which lends support to the theoretical phase lag of 2.5 months for a mixed layer depth range of 25–100 m obtained in numerical experiments with a Quasi-Equilibrium Tropical Circulation Model coupled to a slab mixed layer ocean model (Su et al., 2005).

### 4. World ocean lag patterns

#### 4.1. The SST lag

Figure 1(a) and (b) highlight the asymmetry of SST lag across the continents, in particular the zonal contrast between the Indian and Pacific Oceans for Australia, and the south-west/north-east contrasts between the Pacific and Atlantic Oceans for North America, and the Atlantic Ocean and the Mediterranean Sea for Europe (Stine et al., 2009). The SST lag shows three interesting features:

(i) Three subtropical high SST lag tongues originate in the equatorial regions of the southern ocean basins and extend south-eastward to continental coastlines and two tongues originate in the North Atlantic and Pacific Oceans extending to the African and American coastlines. The tropical Atlantic Ocean tongues are implicit in the analysis of Carton and

![ANNUAL SEA SURFACE TEMPERATURE LAG](Image)
Zhou (1997), but are not mentioned. The high SST lag tongues, which appear to coincide with the trade wind circulations, are due to the combined effect of the two lag components \( f \) and \( g \), and an inspection of Figures 1(a) and 2 shows that in the centre of the tongues, \( g \) is greater than about 80°, but less than 90° (except possibly in the North Atlantic tongue). Thus in these regions the ocean/atmosphere damping time has a maximum and \( B \) has a minimum, and in the event that \( g > 90°, B < 0 \), that is, the feedback becomes positive, in effect producing conditions suitable for tropical cyclone development.

(ii) In the Southern Ocean, an SST lag maximum is present at around 50°S in the Indian Ocean sector. This maximum is absent in other sectors. This feature reflects the influence of the relatively warm water of the Agulhas Current laterally mixing with the Antarctic Circumpolar Current, which enhances the non-local damping process through the resultant meso-scale eddy production. Elsewhere, as the higher latitudes are approached the SST lag becomes smaller indicating a more local damping.

(iii) The smallest open sea SST lags occur in the Indonesian and South China Seas, which suggest that here, \( g < 45° \). This would imply an enhanced negative feedback in this Monsoonal region, which appears to be associated with the cloud formation that causes the maximum temperatures to occur early in the season.

4.2. The surface heat flux

The surface heat flux lag (Figure 2) is mainly positive, indicating a local export of heat by the atmospheric general circulation (atmospheric heat divergence), which in particular occurs in the tongues of higher SST lag in the subtropics and in areas of higher lag in the Southern Ocean south of Africa extending eastwards to Australia, and in the northern Atlantic and Pacific Oceans (Figure 1(a)). In contrast, there are large regions of negative surface heat flux lag in the temperate parts of the Southern Hemisphere and the northern Pacific Ocean, which are due to the local import of heat by the atmospheric general circulation (atmospheric heat convergence) from the subtropical regions, and also in the European seas, the Asian shelf seas and the Gulf of Mexico, which are of continental origin.

5. Recent changes in SST lag: effects on regional climate

Two period pairs have been selected for the anomaly computations using the HadISST data: 1991–2005 and 1976–1990 which are representative of contemporary interdecadal variability (Figure 3(a)), and 1951–2000 and 1901–1950 which encompass the centennial variability during the 20th century (Figure 3(b)).

5.1. Interdecadal scale changes (SST lag \( 1991–2005 –\) SST lag \( 1976–1990 \))

(i) In the Southern Hemisphere a positive anomaly in the Indian Ocean has moved down the west coast and along the south coast of Australia. A positive anomaly has also developed in the Southern Ocean south of Australia, extending the region of high SST lag south-east of Africa further eastward, and another positive anomaly has occurred in the South Atlantic Ocean that extends the high SST lag tongue further to the south.

(ii) In the Northern Hemisphere, the enhanced propagation of a high SST lag tongue in the North Atlantic Ocean causes a strong positive anomaly off Newfoundland and the west coast of Greenland on the western coast of the ocean (producing an SST lag region in the northern part of the ocean that is similar to the North Pacific Ocean). This change is associated with a strong negative anomaly north of the equator, in the Pacific Ocean (with a smaller positive anomaly south of the Equator). Therefore, in the last 30 years the south-west/north-east lag contrast across the North American continent has reduced due to a positive anomaly difference.

The changes in regional climate over the last 30 years appear to be due basically to changes in location of the regions of strong and weak interaction between the atmosphere and ocean arising from these anomalies. In the Southern Hemisphere the expansion of a high SST lag anomaly along the western coast of Australia has coincided with a period of change in tropical cyclone occurrence and an extension in summer conditions and a reduction in autumn rains (Hendon et al., 2007; Landvoigt et al., 2008), and in the Southern Ocean, the greater SST lags around 50°S (Figure 3(a)), appear to be associated with the poleward shift in the westerly wind belt (Simmonds and Keay, 2000). In the Northern Hemisphere, the positive SST lag anomaly in the north-western Atlantic Ocean would be expected to enhance late summer north-eastward advection of heat from the subtropical continental (Wang et al., 2006), possibly leading to increased ice melting in the Canadian Arctic. The positive SST lag anomaly in the North Atlantic Ocean has also been accompanied by a poleward shift in the storm belt (Wang et al., 2006), similar to the Southern Ocean. Associated with the positive SST lag anomaly in the north-western Atlantic Ocean is a corresponding negative SST lag anomaly in the North Pacific Ocean consistent with a reduction in the strength of the north-east trades which tends to produce permanent El Niño conditions (Power and Smith, 2007).

5.2. Centennial scale SST lag changes (SST lag \( 1951–2000 –\) SST lag \( 1901–1950 \))

We have also evaluated the trends in lag anomalies over the last century (SST lag \( 1951–2000 –\) SST lag \( 1901–1950 \)) (Figure 3(b)) over which it is probable that the effects of anthropogenic warming have become significant. An
ANNUAL SEA SURFACE TEMPERATURE LAG

Figure 3. (a) Interdecadal scale SST lag anomaly (SST lag 1991–2005 – SST lag 1976–1990) from HadISST. (b) Centennial scale SST lag anomaly (SST lag 1951–2000 – SST lag 1901–1950) from HadISST.

anomaly pattern of basin scale characterises the world ocean, in which there is no evidence (except in the North Pacific Ocean) of the existence of anomalies associated with the high SST lag tongues. Positive SST lag anomalies occur on the eastern and south-eastern coasts of Australia which reduce the continental asymmetry, and may give rise to the distinctive trends in the summer maximum lag which have increased by 6 days in Melbourne and 11 days in Sydney from 1900 to 2001 (Alexander et al., 2005). There is also a negative south-west/north-east SST anomaly difference across North America, which increases the continental asymmetry.

6. Interpretation

6.1. The random structure of the SST lag time series

Figure 3(a) indicates that regions of large interdecadal SST lag anomaly occur in the eastern Indian Ocean (IND), the North Atlantic Ocean (ATL) and the North Pacific Ocean (PAC). We have extracted interannual and 5 year running mean time series for a representative grid point in each region (Figure 4(a)). The standard deviations (σ) of the interannual/five year running mean time series are: IND 13.5/3.7 days, ATL 8.6/6.0 days, PAC 11.0/4.2 days, and the correlation coefficients (r) are: IND-ATL 0.02/0.13, IND-PAC -0.11/-0.31, ATL-PAC -0.02/-0.15, indicating that the 5 year running mean time series, although less energetic, are more highly correlated than the interannual time series, although only explaining less than 10% of the variance.

We interpret the three time series as being due to a bounded random walk structure in which the non-dimensional lengths of the random walks can be estimated from the expression,

$$T_{rw} = \pi / 2 \left( \frac{M_{rw}}{\sigma} \right)^2$$  \hspace{1cm} (3)

where σ is the standard deviation of the time series and $M_{rw}$ is the mean of the expected values of the maximum excursion (Feller, 1962), and the random walk length ($T_{rw}$) can be interpreted as the period over which the full extent of the natural variability may on average be expected to occur.

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An inspection of Figure 4(a) shows that the maximum excursions of the three series are: IND 15 days, ATL 20 days and PAC 15 days. On substituting these values together with the corresponding standard deviations into Equation (3) we obtain, respectively, $T_{rw} = 26, 20$ and 17 years suggesting that over the period 1870–2008 the random walk length is approximately 21 years. This result is consistent with that obtained from the global temperature series over a period of similar length (Bye et al., 2011).

6.2. The spatial correlations

Figure 4(a) shows that around 1990 the 5 year running mean PAC lags were decreasing, whereas the IND and ATL lags were increasing, giving rise to the anomaly patterns of Figure 3(a). The effects are reflected in the changes in regional climates discussed in Section 5. At other periods the trends are relatively different, and over the period 1870–2008, the changes in lag are only weakly correlated, as illustrated by the correlations between the IND, PAC and ATL time series.

The important question is whether the correlations are due primarily to the existence of identifiable interdecadal coupled climate modes or whether they are a property of the random structure of the individual time series, which would not be sustained if a longer record were available. In order to address this question, noting that the correlations for the interannual lag series (which effectively is a longer sample than the 5 year running mean lag series) are much smaller, we divided the interannual lag series into 5 20 year time series (Table I). It is clear that over the shorter time series the correlations are variable and generally greater than the correlation for the complete record. The standard deviations of the shorter time series, however, are similar to that of the complete record.

The obvious conclusion is that the randomness of the individual time series is responsible for the shorter term variability in correlation, and that by inference

<table>
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<tr>
<th>Year</th>
<th>$r$</th>
<th>$\sigma$ (days)</th>
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<tbody>
<tr>
<td>IND-PAC</td>
<td>-0.51</td>
<td>11.9</td>
</tr>
<tr>
<td>PAC-ATL</td>
<td>0.22</td>
<td>12.2</td>
</tr>
<tr>
<td>IND-ATL</td>
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<td>8.3</td>
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<table>
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<tr>
<th>Year</th>
<th>$r$</th>
<th>$\sigma$ (days)</th>
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</thead>
<tbody>
<tr>
<td>1901–1920</td>
<td>-0.23</td>
<td>15.6</td>
</tr>
<tr>
<td>1921–1940</td>
<td>-0.04</td>
<td>16.5</td>
</tr>
<tr>
<td>1941–1960</td>
<td>-0.13</td>
<td>13.4</td>
</tr>
<tr>
<td>1961–1980</td>
<td>0.37</td>
<td>10.9</td>
</tr>
<tr>
<td>1870–2008</td>
<td>-0.11</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Table I. Correlations ($r$) and standard deviations ($\sigma$) for 5 20 year interannual time series for IND, PAC and ATL.
the correlations exhibited by the 5 year running mean time series (although higher than for the corresponding interannual time series) probably reflect a similar random process.

6.3. Modelling of changes in SST lag
The observational time series (Figure 4(a)) are clearly too short to establish any long period trends, which must therefore be assessed by recourse to climate models. We have processed the SST fields archived from the CSIRO Mk. 3.5 T63 coupled climate model (Gordon et al., 2002) run for the Special Report on Emission Scenarios, Scenario A2 (IPCC, 2007) in which the CO₂ concentration rises to 450 ppmv by 2020, to obtain SST lags for the three periods 1976–1990, 1991–2005 and 2006–2020 from which the modelled lag anomalies (SST lag1991–2005 − SST lag1976–1990) (Figure 5(a)), and also (SST lag2006–2020 − SST lag1976–1990) (Figure 5(b)), can be obtained. On comparing the modelled anomalies for the first 15 years (Figure 5(a)) with the observed anomalies (Figure 3(a)), it is apparent that the major regions of increase and decrease in SST lag are similar in character although the centres of the modelled anomalies differ somewhat from the observations, especially in the North Atlantic Ocean. This suggests that the physics which determines the random structure of the lag fields is well represented in the model. On this basis, we examine the modelled anomalies for the second fifteen year anomaly (Fig. 5(b)). The changes are consistent with the existence of an approximate 20 year random walk length: in the later epoch the anomaly pattern is reversed throughout almost all the world ocean. This anomaly field is of course not a prediction but rather a statistical possibility, as is clear from a comparison of the time series of SST lag anomaly between the observations (Figure 4(a)) and the model (Figure 4(b)) which indicates that the interannual

![Figure 5](image-url)
correlation coefficients \((r)\) between the observations and model are negligibly small \((r < 0.1)\), consistent with the interdecadal cycles being stochastic (IPCC, 2007).

The interdecadal variability is of similar magnitude throughout the run period (1871–2100), but with a clear upward trend in lag (Figure 4(b)) The overall linear rates of increase in SST lag [IND 7 days century\(^{-1}\) \((r = 0.35)\), ATL 15 days century\(^{-1}\) \((r = 0.63)\) and PAC 9 days century\(^{-1}\) \((r = 0.33)\)] are similar to the observed rate of increase in summer maximum temperature lag in south-eastern Australia during the 20th century (8 days century\(^{-1}\)) (Alexander et al., 2005). This suggests that there is evidence of global warming in the centennial scale record, consistent with the expansion of the tropical belt, in which poleward shifts in the westerly wind belts occur in both hemispheres (Seidel et al., 2008).

The present study has been focussed on the annual lag of the oceans. An obvious extension, in which summer and winter lags are computed both over the ocean and on land, can be used to address ocean-land lag responses. This methodology, which has been applied in Bye and Fraedrich (2012) to consider the lag response in the high latitudes under global warming, is also useful on shorter time scales in other regions, e.g., Mullan (1998).

7. Conclusion

The main result which emerges from this study is that global lag fields are subject to an interdecadal variability brought about by the existence of random walks of length about 20 years which affect all regions of the ocean differently so that no ‘permanent’ spatial correlations are in evidence for the time series chosen to be representative of the three ocean basins. In climate therefore in parallel with weather, we may have confidence in a warming trend (due to an increase in greenhouse gases) but we are unable to predict an upcoming regional climate crisis. We have also shown that the damping time for air/sea heat exchange can be estimated directly from the SST lag, and hence interannual and longer period changes in lag can be interpreted in terms of the variability of regional climate. It is also worth noting that the CSIRO climate model has a random SST lag structure, which is similar to the observations, indicating that the important processes are well represented in the model.

The interdecadal SST lag patterns, which we attribute to bounded random walks, limit regional predictability. For example, if a reversal of anomaly pattern, relative to the period (1991–2005) occurs during the period (2006–2020), the current period of extreme dryness in southern Australia and accelerating ice melting in the Arctic, e.g., Screen and Simmonds (2010), are both likely to be interrupted, although almost certainly the randomness will present new surprises and challenges.

Acknowledgements

C-LL acknowledges with thanks the Albert Shimmins Memorial Fund and CSIRO for support in completing this paper. Perceptive comments by two referees, which have led to a major restructuring of the paper, and useful discussions with Prof. Ian Simmonds, are also gratefully acknowledged.

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