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SEA SURFACE TEMPERATURE TRENDS IN THE COASTAL OCEAN

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Abstract

Sea surface temperature (SST) trends in the coastal zone are shown to be increasing at rates that exceed the global trends by up to an order of magnitude. This paper compiles some of the evidence of the trends published in the literature. The evidence suggests that urbanization in the coastal hinterland is having a direct effect on SST through increased temperatures of river and lake waters, as well as through heated run-off and thermal effluent discharges from coastal infrastructure. These local drivers of SST are compounded by regional drivers manifest as changing weather patterns (latent heat exchange) and direct radiative heating of shallow coastal waters (particularly in restricted embayments and seas). Thus the impact of urbanization on SST may extend well beyond the much-popularised impact of "greenhouse gasses". The Marine Climate Change Impacts Partnership Report [37] stated that our capacity to define and predict long-term coastal changes due to anthropogenic causes is "unknown" and confidence in results is "low". This is a major barrier to planning for inevitable changes in coastal climate that are likely to take place over the coming decades.

1. Introduction

Recent warming of global sea surface temperature (SST) is reported to be "beyond doubt" human-induced [7, 8, 44, 45]. Such effects have been eliminated from global data sets to derive "corrected, homogenized" long-term SST anomalies related to climate change [21]. The predicted global rise in sea surface temperature (SST) over the last 3 decades is 0.13°C/decade [10, 24]. This trend is lower than the growing body of literature that reports on direct measurements of SST in the coastal zone [2, 4, 28, 30, 38]. Much of this rise is linked to coastal urban developments which are subject to upward trends in air temperature ("the heat island effect") [19] that are well in excess of the global trends [27]. The contribution of the urban heat island effect is considered to be small at the global level (less than 0.1°C increase in the last century) [42], yet the literature shows evidence of direct warming of nearshore seawater (and fresh water) from coastal anthropogenic development. This warming trend is documented to be up to 10 times greater than the global trend. As a result, the urban influence on temperature may be expanding into the coastal ocean. If this is true, then global models of SST are likely to under-predict in the coastal zone.

In order to understand the possible warming effect in surface coastal waters, it is worth revisiting the heat budget equation of Sverdrup [54] which takes the form: $\Delta Q = Q_s - Q_b - Q_h - Q_e$, where the incoming solar radiation (Q_s) is balanced by re-radiation (Q_b), convection of sensible heat (Q_h), and condensation/evaporation (latent heat) effects. Whereas the first two terms are dominant globally, the second two are highly dependent on local conditions of air temperature, wind speed and relative humidity (amongst others). This heat budget then contributes to the observed changes in temperature (*T*) through the 2-dimensional partial derivative in time (*t*), simplified from Qu [47]:

$$\frac{\delta T}{\delta t} = \frac{\Delta Q}{\rho C_p h} - U\frac{\delta T}{\delta x},$$

where U is the mean flow in the horizontal, h is water depth, C_p is the thermal capacity of seawater and ρ is the seawater density. Note that in the case of coastal waters, the mixing depth (h) decreases shorewards resulting in proportionate warming for a constant ΔQ. Also, notice that there is a horizontal advective term, where both U and $\frac{\delta T}{\delta x}$ can be large as well as variable in coastal settings [51]. As a result, measurements of coastal SST should show evidence of a faster and greater response to global warming that would the ocean. This evidence appears in the global comparison of NOAA AVHRR satellite night-time SST observations with the night-time Hadley Centre (HADSST2) SST anomalies (courtesy: www.nodc.noaa.gov/SatelliteData/ghrsst) shown in Figure 1: Notice that differences are greatest in the coastal zone and appear to be greatest in mid-latitudes of both northern and southern hemispheres: A trend also reported by Dommenget [15]. The accuracy of the AVHRR satellite in the coastal zone has been shown to be order ±0.1°C [2], thus differences appear to be in the homogenization of the HADSST2 data set that may be under-predicting in places coastal SST by up to 1°C. This under-prediction is greater than the temperature anomaly attributed to human effects over the entire 20th Century. The regions that show the largest coastal SST anomalies are those of highest coastal urban densities and altered shorelines as defined by Harrison and Pearce [20]. These include North and South America, the Mediterranean, S. Africa, and the Far East. Anomalies are greatest where coastal cities larger than 1 million are most abundant. The inference of this is that in coastal regions of high urban development, human activity is directly warming adjacent coastal waters [31, 58] and that this contribution is equal or greater than that due to greenhouse gasses or advection/mixing by surface currents [51]. This is clear in the work of Van Aken [59] who showed a correlation between SST in the Wadden Sea, the Netherlands and winds blowing off heated urban centres. In this case, future impacts of SST in the coastal zone are likely to be poorly predicted by global trends: Whilst coastal impacts have been included in IPCC report, the emphasis has been on coastal flooding and coastal erosion. Thus there appears to be a blind-spot in our understanding of future coastal vulnerability that could be mitigated by a synthesis of SST change in our coastal ocean.

2. Why is SST Important in the Coastal Zone?

The coastal zone occupies 18% of the world's land mass and is over 842,000 km long [53]. SST influences and is influenced by natural drivers and human activities that extend from the freshwater headwaters to the continental margin [48, 33, 28]. Land-sea (air) temperature contrasts tend to be in equilibrium (order 1.5 ± 0.3) and form a coupled system of heat transfer to coastal waters [15], though there are notable exceptions where longshore currents are strong [34]. The coupled coastal system delivers heat to the coastal ocean in part through down-wind advection of urban heat from major cities [26]. It is estimated that 1.6 billion people live on the coast worldwide [14]. The coastal population is three times the global average and is estimated to increase 30% by 2025 [52]. Coastal development/impact accounts for up to 85% of some shorelines (Belgium and the Netherlands) increasing the coastal urban footprint proportionately [11]. Trade and infrastructure at the coast (and hence the heat island effect) are also increasing steadily and thus coastal impacts are likely to increase in the future [36].

The poleward migration of species due to increasing coastal SST anomalies is documented [56, 22, 28] as well as impacts on ecosystem functioning [33]. SST rise in the coastal zone influences salt marsh germination [16] and salt marsh growth [55]; it is a main cause of coral bleaching [35] and coralline diseases with resulting increasing reefal mortality [12, 49]; it results in poleward migration of benthic (rocky and infauna) species [28], displaces marine fish and associated nursery grounds [17] and results in increases in anoxia or eutrophication [50]. It is attributed to losses of seagrasses worldwide [9], and for increases in fish kill phenomena, such as the recent catastrophic events in the Arabian Gulf [49]. The result of these effects is coastal habitat change as well as habitat loss: Habitat destruction in the coastal zone at the turn of the Century was equivalent to forest clear-cutting on land but 150 times more prevalent [48]. The predicted future coastal impact is continued habitat loss and increased risk to the coastal built environment [58].

3. What is the Evidence for SST Changes in the Coastal Zone?

Coastal SST adjacent to urban areas has shown rapid increases in the last three decades [40, 60, 38]. The rate of SST rise appears in proportion to the size of the coastal urban area [38]. Chesapeake Bay (a region of considerable urban development) is a good example of urban heating of seawater where rises of up to 0.8°C/decade have been measured [46]. Similarly, Nixon et al.

[40] have analyzed a 118 year temperature record from Woods Hole and found a significant warming of 0.4°C/decade since 1965, with a long-term cooling trend prior to this date.

Temperature measurements collected at 11 sites since 1920 by the Canadian, British Columbia Lighthouse network (www.dfo-mpo.gc.ca) show a pattern similar to the USA. That is, no trends prior to around 1973, then a steady rise in SST at rates up to 0.7°C/decade [4]: The rates of SST rise in the sheltered Strait of Georgia (where most of the population of BC live) are three times those found along the open coast north of Vancouver Island.

In the UK, the rise in coastal SST measured at 39 sites since 1966 or earlier is on average 0.51°C/decade [29]; this is proportional to rises in air temperature measured in Central England [25] and throughout Europe, which are well above the global averages. The general pattern is similar to those of USA and Canada. That is, there was no trend in SST in early records (i.e., till 1985), then a steady rise at all but four of the 39 stations. Note that the onset of rising coastal temperatures was 10-15 years later in Europe than it was in N. America; perhaps a reflection of trends in economic prosperity. The greatest rise was found along the SE English coast (down-wind of the largest urban centres) whilst those stations showing no trend were clustered around the (upwind) Cornish peninsula. Part of the warming trend may be explained by the predominately-positive North Atlantic Oscillation in the 21st century [46], but only in part, as it cannot explain the change that began in 1985. Recent trends in SST around the UK are highly variable. They suggest strong local variability driven by local drivers such as urban centres, fresh water discharge, wind speed and direction, and power plant effluents. Jenkins et al. [25] predicted a further rise of 4°C in the southern North Sea in the coming Century, which is only marginally lower then present rates, and that these rises will be greatest in the southern North Sea and approaches, though rapid warming of the northern North Sea is also evident [57]. Indeed, Koutsikopoulos et al. [32] documented an increase in SST of 0.67°C/decade between 1972 and 1993 in the Bay of Biscay. Goikoetxea et al. [18] showed continued increases in SST of 0.61°C/decade through to 2007, concluding that "*air temperature is the most direct and influential parameter in the relation to SST variations*". Similar rates of SST warming have been measured off the Gulf of Oman and in the northern Arabian Gulf [2] which reached 0.6°C/decade over the last 25 years. Al Rashidi et al. [3] attributed 50% of this trend to regional and local drivers of heat transfer: Power and desalination plants generate thermal plumes in the coastal zone that contribute 0.1°C/decade to the temperature trends in the northern Arabian Gulf. Urban storm drain runoff, and treated sewage discharge (which is untreated in regards to temperature) are also contributing to SST rises particularly in restricted embayments such as Kuwait Bay [1]. Arrol [5] has measured a heat halo around the Palm Jumeirah, Dubai which is consistently 3-4°C warmer than the adjacent waters 1 km offshore where peak summertime temperatures approach 37°C. This warming effect is not related to heat transfer from a shallow seabed, which undoubtedly takes place in wide shallow shoals or intertidal regions [44], as the warming is restricted to the palm island.

Coastal seawater temperature has been measured in Korea since 1968 (a period of rapid industrial expansion in the region). Jung [30] has analyzed these data and shown that SST is rising up to 0.26°C/decade and that 66% is explained by local air temperature which is largely driven by the local heat island effect. Similar trends were found the Seto Island Sea, Japan [38]: a heavily populated region in excess of 30 million people. Here, the SST anomaly is 4°C adjacent to the largest cities of Osaka and Kobe: this anomaly diminishes in proportion to coastal city population. SST rise in the sheltered Tokyo Bay (which is surrounded by the city of Tokyo with a population of over 8 million) from 1976-1997 was a massive 1.5°C/decade [60].

SST of restricted coastal water bodies appears to be rising faster than those of open coasts. The effect of restriction is perhaps best illustrated in the

Great Lakes. Here, water temperature appears to be rising even faster than coastal marine counterparts. Lake Superior, for example has warmed at a rate of 2°C/decade since about 1970 [6]. Unpublished data from the National Data Buoy Center (http://www.ndbc.noaa.gov/) show that Lake Ontario is also warming at this rate. The mean annual water temperature prior to 1960 was 5°C; it is now in excess of 15°C.

4. Needs for the Future

The accurate prediction of coastal impacts by humans over a 100 year time scale is a growing requirement of government, administrators and industry [23, 13]. Global vulnerability analyses undertaken by Nicholls et al. [39] have identified high risks and grave vulnerability of the coastal zone to sea level rise, increased storminess and climate change. Curiously, SST has not figured highly in terms of future coastal impacts of climate change in the IPCC Fourth Assessment Report [24]. The Marine Climate Change Impacts Partnership Report [37] stated that our capacity to define and predict long-term coastal changes due to anthropogenic causes is "*unknown*" and confidence in results is "*low*". This is a major barrier to planning for inevitable changes in coastal climate. According to Carter and Woodroffe [9], coastal change is the greatest unknown in coastal management, yet coastal management is now expected to achieve multiple goals in terms of maintaining human safety, and sustaining healthy coastal ecosystems (the EU habitats directive) which will depend on understanding coastal vulnerability and potential countermeasures to impact. These goals cannot be met without a joined-up approach to the monitoring and reporting of SST of our coastal waters and without a re-focussing of our concerns to the coastal ocean.

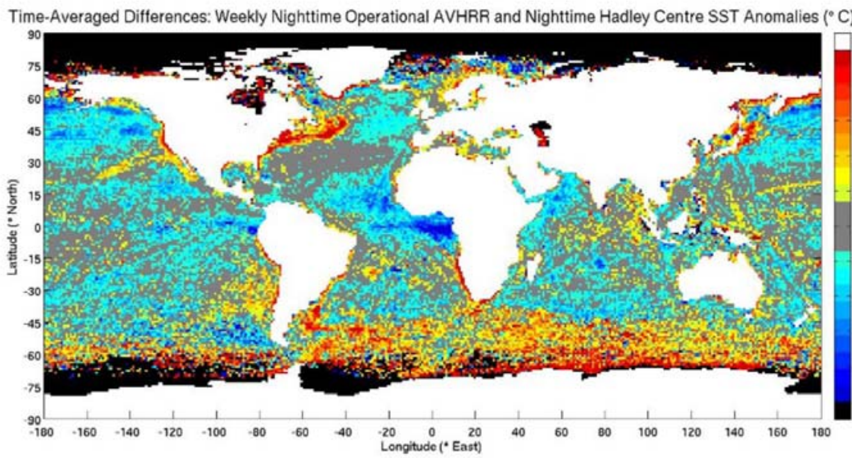

Figure 1. A comparison of the Global Climate Observing System (GCOS) SST data and the night-time sea surface temperature anomalies of the Hadley Centre HadSST2 data set for the weekly-averaged, nighttime SST (Courtesy NOAA; www.nodc.noaa.gov/SatelliteData/ghrsst). The GCOS data set is derived from the AVHRR Pathfinder V5 satellite and is averaged over 1x1 degree from 1985-2007. The HadSST2 is similarly averaged over the period 1961-1990 and derived from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). The comparison shows close agreement in mid-ocean, equatorial regions, but shows divergences in polar regions, in the vicinity of strong ocean currents and in the coastal zone of N. and S. America, S. and SW. Africa, the Mediterranean and the Far East.

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