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Sea-level-rise trends off the Indian coasts during the last two decades

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The present communication discusses sea-level-rise trends in the north Indian Ocean, particularly off the Indian coasts, based on estimates derived from satellite altimeter and tide-gauge data. Altimeter data analysis over the 1993–2012 period reveals that the rate of sea-level rise is rather spatially homogeneous over most of the north Indian Ocean, reaching values close to global mean sea-level-rise trend (3.2 mm yr^{-1}) estimated over the same period. The only notable exception lies in the northern and eastern coasts of the Bay of Bengal, which experience larger trends (5 mm yr^{-1} and more). These recent trends derived from altimeter data are higher than those estimated from tide-gauge records over longer periods during the 20th century. This communication calls for an improved understanding of the mechanisms behind this accelerated sea-level-rise recorded over the past two decades, that could either be a direct response to global warming or a result from an aliasing by the natural variability.

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A large body of literature provides global and regional sea-level-rise trends estimated from coastal tide-gauge analysis. The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) initially reported a sea-level-rise trend ranging from 1.0 to 2.0 mm yr^{-1}, depending on the region[1]. The fourth and recently released fifth IPCC reports further provided a global mean sea-level-rise trend to be close to 1.8 mm yr^{-1} over the 1961–2003 period[2] and 1.7 mm yr^{-1} over the 1901–2010 period[3] respectively. In broad agreement with sea-level reconstruction estimates[4], analysis of past tide-gauge records along the coasts of the north Indian Ocean reported[5] an average sea-level-rise trend of 1.3 mm yr^{-1}, except at Diamond Harbour, Kolkata, in the deltaic region of the northern coast of the Bay of Bengal, where large sea-level-rise trends have been reported[5,6].

A natural limitation of the tide-gauge records lies in their sparse and uneven geographical distribution, most of them being located along the coastlines of continents and islands. Whether the sea-level-rise trends estimated from tide-gauge records are representative of the mean sea-level change experienced in open ocean is an important issue in the sea-level research. Such an issue can now be tackled owing to the availability of sea-level data since 1992 from the satellite altimeter measurements. In recent years, the good spatial and temporal coverage of altimeter data has led an increasing number of studies to use these data in conjunction with coastal tide-gauge records to discuss observed sea-level variability[7]. The present communication contributes to such a discussion for the specific case of the observed sea-level-rise trend in the north Indian Ocean.

Altimeter data from TOPEX/Poseidon, Jason-1 and 2 combined observations were processed and redistributed as monthly mean sea-level anomalies with respect to the seasonal cycle by Commonwealth Scientific and Industrial Research Organization (CSIRO) on a 1° × 1° near-global grid (http://www.cmar.csiro.au/sealevel/sl_data_cmar.html). In this study, we used two types of sea-level data: (i) the data corrected for two major land and environmental effects, namely GIA (glacial isostatic adjustment) and IB (inverse barometer effect), and (ii) the uncorrected data. We also made use of four tide-gauge records at Mumbai, Kochi, Visakhapatnam and Diamond Harbour (Figure 1), which are the longest records available along the Indian coast. We used both monthly mean and annual mean data obtained from the archives of Permanent Service for Mean Sea Level (PSMSL, http://www.psmsl.org)[8]. Monthly mean sea-level anomalies were calculated for these tide-gauge records by removing the mean seasonal cycle over the period considered. Since past tide-gauge records often do not have GPS measurements to account for the temporal evolution of land movements, GIA uncorrected altimeter data were used for a fair comparison of sea-level evolution between altimeter and tide-gauge data. However, the spatial map of net sea-level-rise trend in the north Indian Ocean, derived from altimeter data uses GIA and IB-corrected sea-level data. Also, the predicted present-day rate of sea-level change at the tide-gauge stations due to GIA, estimated from the ICE-5G model[9], was made available by PSMSL. We used these estimates to obtain the net sea-level rise trends from tide-gauge records shown in Table 1.

Monthly mean sea-level anomalies of tide-gauge and altimeter data were compared using a linear correlation analysis. The significance of this correlation was assessed on the basis of a two-sided *t*-distribution of linear correlation coefficients with effective degrees of freedom taken as the number of maximum yearly values that exist in each tide-gauge record reduced by 2. We did not consider the total number of months as the number of degrees of freedom due to the possible auto-correlation of the time series; rather we assumed that yearly values are independent of each other. Tide-gauge and altimeter sea-level-rise trends were estimated using a linear regression analysis and the sea-level-trend uncertainty was based on a two-sided Student's *t*-test with the degrees of freedom being equal to the number of yearly values reduced by 2.

The extent to which tide-gauge measurements adequately represent large-scale sea-level changes observed by satellites during the recent period was assessed through a linear correlation analysis of tide-gauge data with uncorrected altimeter data. Among the four selected tide gauges, two (Mumbai and Visakhapatnam) did not provide data during most of the period of satellite altimetry, which does not allow to make a comparison with altimeter data for these stations. Hence, we performed this comparison only for Kochi and Diamond Harbour records, as these two stations have at least 10 years of data

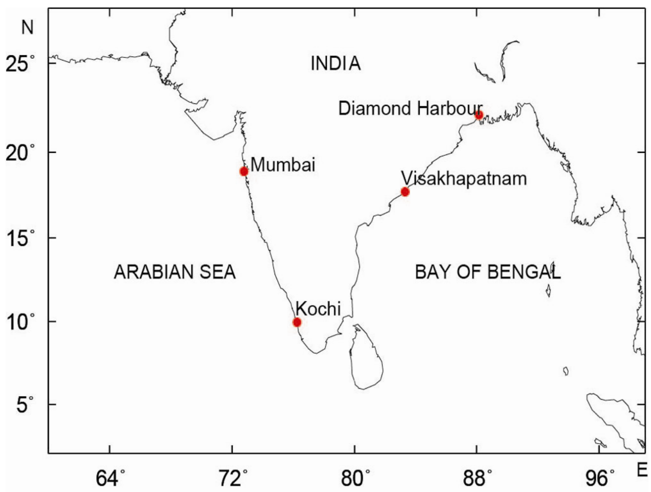

Figure 1. Geographical location of tide gauges whose records were analysed in the present study.

Table 1. Sea-level-rise trends at selected tide-gauge locations (Mumbai, Kochi, Visakhapatnam and Diamond Harbour). The trend estimation period for Mumbai and Visakhapatnam was restricted up to 1993 and 2000 respectively, due to extensive data gaps at the end of the records

Station	Period of analysis	Number of years of data availability	Trends in relative sea-level-rise (mm yr^{-1})	GIA correction (mm yr^{-1})	Net sea-level-rise trend (mm yr^{-1})
Mumbai	1878–1993	113	0.77 ± 0.08	–0.31	1.08
Kochi	1939–2007	56	1.45 ± 0.22	–0.36	1.81
Visakhapatnam	1937–2000	53	0.69 ± 0.28	–0.24	0.93
Diamond Harbour (Kolkata)	1948–2010	61	4.61 ± 0.37	–0.35	4.96

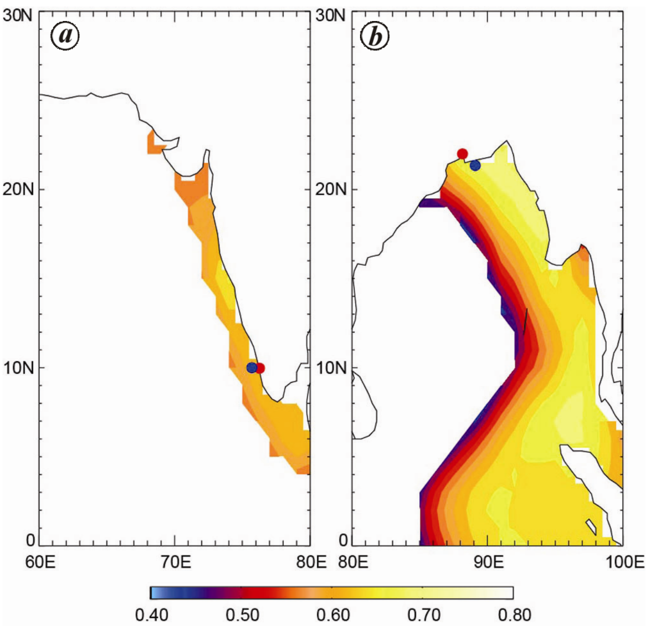

Figure 2. Linear correlation coefficients between the tide-gauge data and altimeter data in the north Indian Ocean for (***a***) Kochi and (***b***) Diamond Harbour, Kolkata. Only those correlation coefficients which are statistically significant at the 90% confidence level are shown for both (***a***) and (***b***). The original location of tide gauge (red dot) and the location where altimeter time series was extracted (blue dot) are also shown.

during the period considered (1993–2012). Figure 2 *a* and *b* shows the spatial map of correlation of monthly mean sea-level anomalies from tide-gauge data at Kochi and Diamond Harbour respectively, with gridded altimeter time series for the entire north Indian Ocean region, following a recent study[10]. We then compared in Figure 3 the tide-gauge sea-level evolution with the altimeter time series extracted from the nearby altimeter grid point (blue dot, Figure 2), selected for its maximum linear correlation coefficient with the tide gauge record (red dot, Figure 2). Apart from showing the best-matching grid point in the tide-gauge vicinity, Figure 2 also illustrates how these tide-gauge measurements are representative of the offshore variability. While Kochi tide-gauge data show significant correlations with sea-level variability in a very narrow region off the west coast, Diamond Harbour data exhibit significant correlations over a broader region extending along the northeast coast of the Bay of Bengal to the eastern equatorial Indian Ocean. Sea-level signals originating from the equatorial Indian Ocean (both interannual variability related to ENSO – El Niño Southern Oscillation and IOD – Indian Ocean Dipole and decadal variability)[11–13] are expected to force considerable sea-level variations in the eastern equatorial Indian ocean. A part of these signals is transmitted as coastally trapped Kelvin waves which propagate northward along the eastern coast of the Bay of Bengal and continuing westward at the head Bay.

The extracted altimeter time series at Kochi and Diamond Harbour shows correlation coefficients of 0.63 and 0.69 respectively, with corresponding tide-gauge data (Figure 3). There are several reasons that could account for the unexplained variance between satellite and tide-gauge time series. Basically, while satellite measures sea level from space, tide gauge measures sea level relative to the land surface on which it is located. The land movements as well as local sedimentation can affect tide-gauge readings. On the other hand, altimeter gridded products may not fully retrieve highly localized coastal sea-level fluctuations due to signal contamination close to the coasts and to the gridding process, which may smoothen out the small-scale coastal features. The consistency of our analysis to the grid size was assessed by repeating the same correlation analysis using 1/3° × 1/3° resolution sea-level data from AVISO (http://www.aviso.altimetry.fr) and found the results to be identical. We therefore used the 1° × 1° gridded data for the rest of the analysis.

Figure 4 provides a spatial map of net altimeter sea-level-rise trend in the north Indian Ocean estimated over the period 1993–2012 (Figure 4 *a*) with related trend uncertainties (Figure 4 *b*). The monthly mean sea-level anomalies were averaged to obtain annual mean sea-level anomalies and these annual mean sea-level anomalies were used in the trend estimation. This analysis used GIA-corrected data so that trends obtained reflect the net sea-level rise in the region. Figure 4 *a* shows a rise of sea level everywhere in the north Indian Ocean during the last two decades. The spatial pattern is nearly uniform over most of the region. The average trend in the north Indian Ocean (3.28 mm yr^{-1} for the entire basin) is also close to the global mean sea-level rise[14] trend of 3.2 mm yr^{-1} (with an uncertainty of 0.4 mm yr^{-1}) during 1993–2012. The only notable exception lies along the northern and eastern coasts of the Bay of Bengal that experience considerably larger trends (more than 5 mm yr^{-1}) compared to other regions. The pattern of these large trends in the eastern equatorial Indian Ocean extending towards the northeastern coast of the Bay is reminiscent of the correlation pattern discussed in Figure 2 *b*, where sea-level changes observed in Diamond Harbour are strongly related to the eastern equatorial Indian Ocean, suggesting a possible transmission of sea-level signals at interannual and decadal periods along the northeastern coast of the Bay as coastally trapped Kelvin waves[12,13].

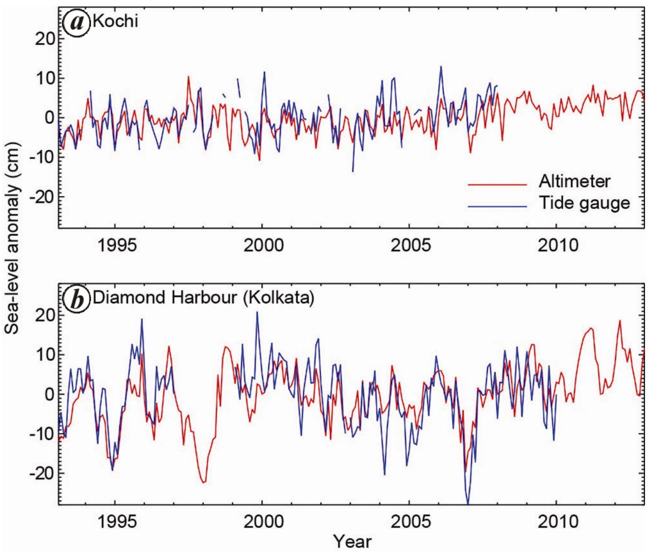

Figure 3. Comparison between altimeter (red) and tide gauge (blue) monthly mean sea-level anomalies (seasonal cycle removed) at (***a***) Kochi and (***b***) Diamond Harbour.

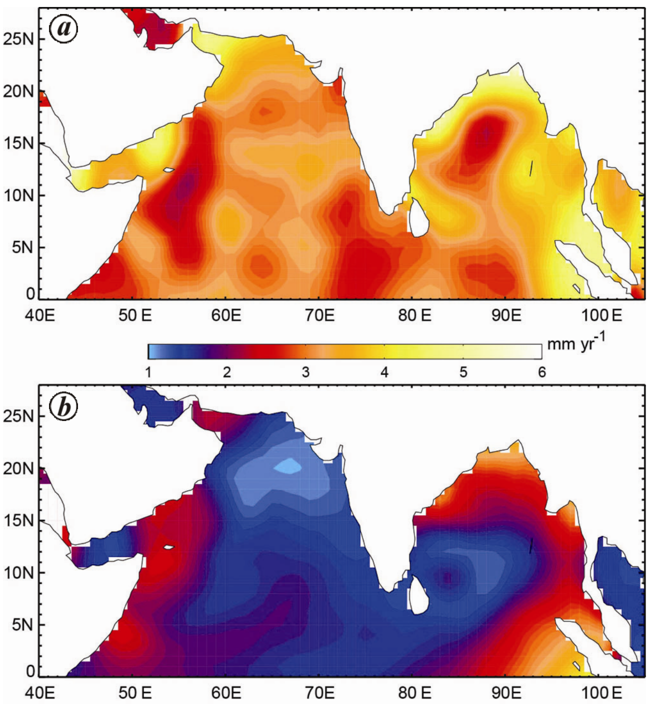

Figure 4. ***a***, Spatial map of sea-level-rise trend (1993–2012) estimated from satellite measurements of annual mean sea-level anomalies over the north Indian Ocean (monthly mean sea-level anomalies are averaged over each calendar year to get annual means). ***b***, Sea-level-rise trend uncertainty at the 95% confidence level based on a two-sided student's *t*-test with the degrees of freedom = $N - 2$, where $N = 20$ (total number of years).

Figure 4 *b* shows that estimates of these large sea-level trends in the eastern and northern Bay of Bengal are also associated with large uncertainties (about 3 mm yr^{-1}). As reported ealier[12,13], interannual and decadal variability along the eastern and northern rims of the Bay of Bengal (as shown in Figure 3 *b* for Diamond Harbour) is known to be larger compared to other regions in the north Indian Ocean (Figure 3 *a* for Kochi). This largely explains the increased level of uncertainty in observed sea-level trend along the northeastern part of the Bay of Bengal, as large interannual to decadal variability in the sea-level time series in a given region will reduce the goodness of a linear fit in time and bring more uncertainties in the trend estimation. Accordingly, the weaker trend uncertainties found in the central equatorial Indian Ocean, the west coast of India and the southwest of Bay of Bengal (up to about 15°N) are consistent with the minimum sea-level variability reported[11] in these regions at interannual timescales. Strong climatic signals with periods ranging from interannual to decadal can obscure the underlying sea-level-rise trends, by aliasing the low-frequency sea-level variability into the trend. A more accurate assessment of the trend estimation therefore requires a better identification and understanding of the sea-level signals associated with natural climate variability at both interannual and decadal timescales in the northeastern part of the Bay of Bengal.

Figure 5 shows sea-level evolution from the four selected tide-gauge stations over the longest available period. Table 1 shows for these four tide-gauge records the associated relative sea-level-rise trends along with GIA-corrected net sea-level trends. The net sea-level-rise trends for different records range between 0.93 and 1.8 mm yr^{-1}, except for Diamond Harbour, where this trend reaches almost 5.0 mm yr^{-1}. The large trend at Diamond Harbour was reported in earlier studies[5,6] and has been partly attributed to subsidence in the deltaic region[5]. Altimeter data analysis shows higher sea-level-rise trends in the north Indian Ocean during the last two decades (Figures 4 and 5) compared to the trends derived from the tide-gauge records over the entire period (Table 1 and Figure 5). However, estimation of the sea-level-rise trend over the recent 1992–2007 period at Kochi, where sufficient tide-gauge data are available, reveals a larger trend (3.7 mm yr^{-1}) than over the entire available period (1.45 mm yr^{-1}). Trend for the Diamond Harbour record is not statistically significant for the altimeter period because of the data gaps and large internannual variability observed at this station, while trends for the recent period could not be calculated for Mumbai and Visakhapatnam records because of the lack of data during the altimeter period.

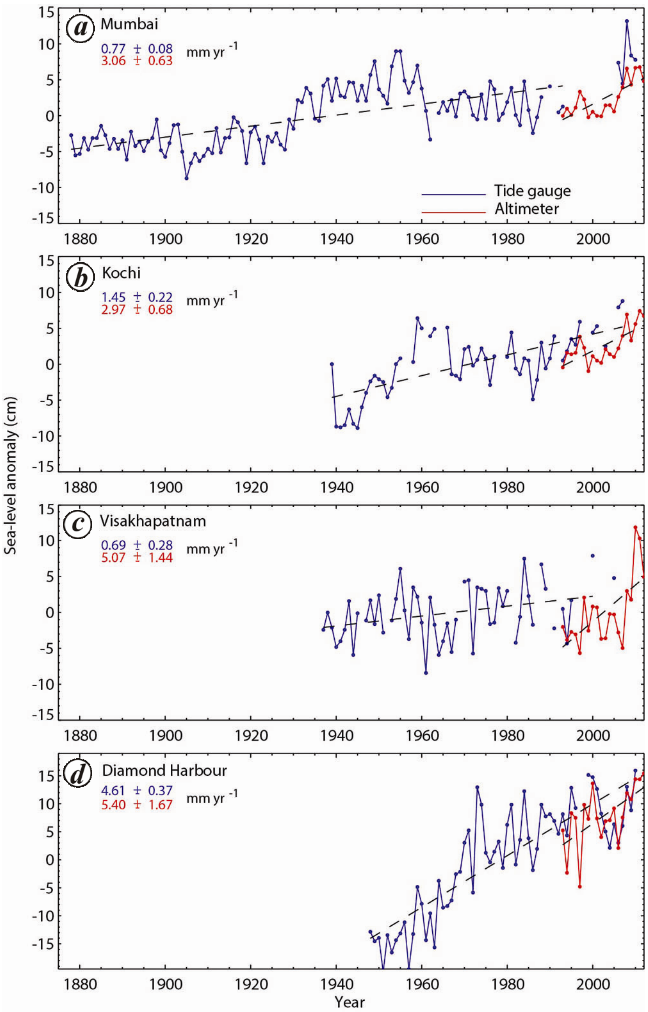

Figure 5. Time series of annual mean sea-level anomalies at the selected tide-gauge stations in (***a***) Mumbai, (***b***) Kochi, (***c***) Visakhapatnam and (***d***) Diamond Harbour. Tide-gauge data are shown as blue line, while red line shows altimeter annual mean sea-level anomalies extracted at an offshore point close to each tide-gauge location. Slope of the sea-level-rise trend line (black dashed line) with its standard error, estimated from both tide-gauge and altimeter data is shown on the top left of each panel.

Based on the estimated trends from both tide-gauge records and altimeter data, it is therefore likely that the sea level rose at a faster rate during the last two decades than for the entire 20th century. A period of two decades is, however, not long enough to resolve the natural sea-level variability at interannual and decadal timescales, which aliases the trend estimate. Based on the present understanding, it is therefore, not possible to ascertain whether the increased sea-level-rise during the recent period depicts an acceleration resulting from global warming or an aliasing caused by natural variability. Han *et al.*[15] attributed the increase in sea levels in the north Indian Ocean since 1960s to changes in surface wind fields in the region. Another possible cause for this sea-level-rise acceleration may be the Himalayan glacier melt which has been reported to increase over the recent decade[16]. However, determining the respective contribution of wind changes, glacier melt and thermal expansion of the ocean due to global warming on the observed sea-level-rise in the region is beyond the scope of the present work.

The recent reporting of the hiatus in global warming during the last decade in the Synthesis Report for Policy Makers (SPM)[17] of the IPCC Working Group I resulted in a lot of debate among scientists as well as the public. Since 1998, global temperature rise has been considerably slowing down compared to the trends observed for the 20th century. *Current Science* published a guest editorial[18] on this topic, pointing out that a period of about one to two decades may not be long enough to derive meaningful trends because of the potential aliasing by natural variability in the system. It was also pointed out that it should be assessed whether other variables such as sea level or oceanic heat content also exhibit a similar behaviour over the recent period.

Our results suggest that sea-level-rise in the north Indian Ocean does not experience any slowdown, but rather an acceleration over the past two decades. A similar acceleration has also been reported at global scale in the SPM[17], with global mean sea-level rise of 1.7 mm yr^{-1} between 1901 and 2010, and of 3.2 mm yr^{-1} between 1993 and 2010. Also, the results suggest that the level of uncertainties associated with trend estimates over a short period can be very large, like in the northeastern Bay of Bengal, because of the potential aliasing by natural variability. These issues are related to two major areas of current sea-level research: the apparent acceleration in the global sea-level rise and the mechanisms behind the regional differences in sea-level-rise trends. Recent studies[11–13] have shown that natural variability in the Indian Ocean region causes considerable sea-level changes at different time scales, including interannual and decadal. Further studies are therefore required to determine whether the apparent increase in sea-level-rise trends observed during the recent period is partly a residual signature of natural variability or results from global warming.

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Distribution and molecular characterization of *Wolbachia* endosymbionts in odonata (insecta) from Central India by multigene approach

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***Wolbachia* are maternally inherited bacterial endosymbionts of arthropods distributed among a wide range of hosts. It is now well known that they induce reproductive manipulations in their arthropod hosts by various phenotypic effects. The objective of the present study was to investigate *Wolbachia* infection among the insect order Odonata comprising 16 species from 5 families. Fifteen odonate species representing five families were found to harbour *Wolbachia* with the overall infection rate of 70%, out of which fourteen species are reported for the first time. According to multilocus sequence typing (MLST) data and phylogenetic analysis, all odonate *Wolbachia* species belong to supergroup F, except *Trithemis pallindinervis*, which belongs to supergroup B. MLST data reveal 20 new, highly similar STs (99.32 ± 0.34). We found a high rate of *Wolbachia* infection in Odonata of India, which indicates importance of this association. The characterization of these *Wolbachia* strains promises to lead to a deeper insight into this interaction, which is essential for further studies based on their phenotypic effects. The study suggests that all the characterized *Wolbachia* STs are totally new and arise as a result of point mutation.**

Keywords: Multilocus sequence typing, phenotypic effects, point mutations.

THE Alphaproteobacteria *Wolbachia* are intracellular and maternally inherited bacterial symbionts found in many arthropod and filarial nematodes. Along with vertical cytoplasmic inheritance, *Wolbachia* are also known to transfer horizontally across different hosts[1]. Along with symbiotic associations like mutualism and parasitism, *Wolbachia* can influence the host population by different

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