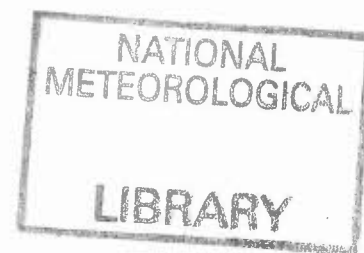


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Initial results from experiments assimilating satellite altimeter sea surface height data into a tropical Pacific ocean model.

by

R. M. Forbes

Met Office

FitzRoy Road, Exeter, Devon. EX1 3PB

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Initial results from experiments assimilating satellite altimeter sea surface height data into a tropical Pacific ocean model

R. M. Forbes

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Summary

This report presents a preliminary assessment of the impact of assimilating satellite altimeter sea surface height data into a primitive equation model of the tropical Pacific Ocean. The sea surface height differences between observation and model are translated into subsurface temperature and salinity changes using a dynamical method conserving water mass properties on subsurface isopycnals. A series of one year integrations of the model with and without assimilation are compared against independent observations, and the effects on the model mean field and variability are investigated. Assimilating altimeter data is found to increase the variability in the model and improve the representation of equatorial Kelvin waves. Problems with the altimeter assimilation in some areas of the model need further investigation, and priorities for future development of the altimeter assimilation scheme are suggested.

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1. Introduction

Observations of the ocean from ships and buoys provide information on the temperature, salinity and current structure in the upper layers of the ocean, but such measurements are rather sparsely distributed over the globe. Satellites, however, can provide a global data set at regular intervals, vastly increasing the number of observations of the ocean surface. Two of the most important satellite instruments for oceanographic studies are the infrared radiometer, which measures sea surface temperature, and the radar altimeter, which measures sea surface height. Although satellite instruments only measure surface properties of the ocean, with additional dynamic or thermodynamic information details of the subsurface structure can be inferred.

Variations in the height of the sea surface are related to variations in the subsurface density and pressure distributions throughout the depth of the ocean. Although knowledge of the sea level alone will not allow a unique determination of the deep ocean state, subsurface information can be inferred by combining the altimeter data with knowledge of the ocean dynamics in the form of a numerical ocean model. Satellite altimeter sea surface height data is thus potentially an extremely useful data set for assimilation into ocean models; more useful perhaps than sea surface temperature data which is in general only correlated with subsurface temperatures in the mixed layer.

There are currently two satellite altimeters in operation, TOPEX/POSEIDON and ERS-2, and the accuracy of the sea level measurements and geophysical corrections now enables determination of the ocean dynamic topography to within a few centimetres. There is also the prospect of sufficiently accurate satellite altimeter surface height measurements available within 2 days of real time and continuing satellite altimeter missions for many years ahead.

Previous altimeter assimilation studies using idealised data have shown that relatively simple two or three layer ocean models can be constrained by assimilating surface height data (Hurlburt, 1986; Berry and Marshall, 1989; Verron, 1992). However, more realistic ocean models with higher vertical resolution require additional constraints to explicitly translate sea surface height changes into subsurface temperature, salinity and velocity changes. Both statistical correlations (Mellor and Ezer, 1991; Oschlies and Willebrand, 1995; Carton et al., 1996) and dynamical constraints (Cooper and Haines, 1996) have been used for the vertical projection of altimeter data in multi-level primitive equation ocean models.

An ocean data assimilation system for a primitive equation ocean model has been developed at the U.K. Met. Office as part of the Forecasting Ocean-Atmosphere Model (FOAM) (Alves et al., 1995). Previous studies have investigated the assimilation of XBT thermal profiles (Bell, 1994a,b) and sea surface temperature data (Forbes, 1995) into a North Atlantic version of FOAM, and both data sets are now routinely assimilated into a global $1^\circ \times 1^\circ$ resolution model (Alves et al., 1995). This report describes an extension to the assimilation scheme to include altimeter sea surface height data. Surface height changes

observed by the altimeter are translated to temperature and salinity changes in the model using a constraint conserving water mass properties on subsurface isopycnals (Cooper and Haines, 1996).

Altimeter sea surface height data is well suited to observing the mesoscale variability in the ocean and a model which resolves these scales will gain the greatest benefit from altimeter data assimilation. A high resolution tropical Pacific ocean model is used for the assimilation experiments described in this report. The reasons for the choice of model are as follows:

- the model resolves the dominant dynamics of the region (equatorial currents, Kelvin waves, Rossby waves) and has a similar formulation to the ocean model used in FOAM.
- the Hadley Centre TOGA (Tropical-Ocean Global-Atmosphere) group have considerable experience using the model for tropical analyses and seasonal forecasting.
- there is relatively good coverage of thermal profile observations in the region from the TOGA-TAO array and the Volunteer Observing Ship (VOS) program for assimilation and comparison.
- other assimilation studies have been performed for the tropical Pacific region (Smith, 1995; Ji et al., 1995; Carton et al., 1996) for comparison.

The ocean model, the assimilation scheme and the observation data sets used in the assimilation experiments are described in section 2. The results from a series of integrations assimilating altimeter sea surface height and thermal profile data are discussed in section 3. Section 4 contains a concluding summary with suggested priorities for future work.

2. Description of the system

2.1 Ocean model and forcing fields

The ocean model is based on the primitive equation formulation developed by Bryan (1969) and Cox (1984). The model domain covers the tropical Pacific from 30°N to 30°S, and 126°E to 78°W with open boundaries to the north and south and closed western and eastern boundaries. Temperature and salinity at the open boundaries are kept close to their seasonally varying climatological values taken from the Levitus (1982) climatology. The model grid has 16 levels in the vertical, with a 10m resolution near the surface and a constant ocean depth of 4000m. The horizontal resolution varies over the domain. In the meridional direction the resolution increases from $\frac{1}{3}^\circ$ at the equator to 1° at the northern and southern boundaries. The zonal spacing is 1.5° over most of the domain, decreasing to 0.5° near the eastern and western boundaries. The horizontal eddy viscosity decreases as the grid spacing decreases, with a minimum value of $2 \times 10^3 \text{ m}^2 \text{ s}^{-1}$. Horizontal eddy diffusivity for temperature and salinity is constant at $2 \times 10^3 \text{ m}^2 \text{ s}^{-1}$ over most of the domain, increasing to $3 \times 10^4 \text{ m}^2 \text{ s}^{-1}$ near the open northern and southern boundaries. Richardson number dependent vertical diffusion (Pacanowski and Philander, 1981) is also applied. Additional schemes are included to represent mixed layer processes (Kraus and Turner, 1967) and solar radiation penetration below the first ocean layer (Jerlov, 1968). Further details may be found in Davey et al. (1995).

The model is designed for studying variations in the thermal structure of the upper ocean, and previous tests have shown the barotropic current to be typically an order of magnitude less than the near-surface baroclinic current over much of the domain. The model does not include a barotropic mode as it will not contribute significantly to the near surface advection of heat.

The ocean model is forced with the Florida State University (FSU) analysis of observed winds (Goldenberg and O'Brien, 1981), and climatological estimates of heat (Oberhuber, 1988), evaporation (Esbensen and Kushnir, 1981) and precipitation (Jaeger, 1983). Surface temperature and salinity are relaxed back to climatology at a rate of $35 \text{ W m}^{-2} \text{ K}^{-1}$. The model has been previously spun up for many decades using these forcing fields.

2.2 Data assimilation scheme

2.2.1 Horizontal analysis

The assimilation method is the analysis correction scheme of Lorenc et al. (1991) used in previous studies by Bell (1994a,b) and Forbes (1995). In this technique assimilation steps are interleaved with forecast steps and the model adjusts to the small changes imposed by the data at every timestep. The prior knowledge that the ocean is slowly varying is taken into account by nudging the data over a period of time defined by the observation time window. The method also allows a multi-variate analysis with different observed quantities from different observation platforms assimilated into the model at each time step. A further advantage is the low computational cost of the assimilation scheme relative to the ocean model.

Assimilation increments (differences between the observations and the model) are interpolated horizontally using a spatial filter which represents the way in which the model forecast errors are estimated to be correlated. The forecast error correlation scales depend on the quality of the forecast field and can be difficult to estimate. There is evidence to suggest that subsurface temperature variability in the tropical Pacific has larger correlation scales in the zonal direction than in the meridional direction (Meyers et al., 1991). Carton et al. (1996) use a similar ocean model to the one used in this study and find zonal and meridional scales for the model temperature error of 500 km and 250 km respectively. Previous investigations with the UKMO tropical Pacific model assimilating thermal profile data have suggested that a longer zonal scale (1500km) is appropriate when assimilating data from the TAO array. Further work to determine the best forecast error correlation scales is required.

Observation increments are nudged into the model over a period of time with weight increasing linearly either side of the time of validity. There is approximately a 3 day time difference between the nearest neighbour ground tracks of TOPEX/POSEIDON and it is desirable to have a time window which includes these nearest neighbour tracks. The time window is chosen to be 10 days for the altimeter surface height data (5 days either side of the observation validity time) and 20 days for the thermal profile observations (10 days either side of the observation validity time). Carton et al. (1996) use similar values for the observation time windows in their assimilation study.

The spatial correlation scale, time windows and relative weighting of model and data for each experiment are shown in Table 1.

2.2.2 Surface height vertical projection method

Many previous altimeter assimilation studies have used statistical correlations for the vertical projection of sea level anomalies onto subsurface density or pressure anomalies. Statistics can be taken from a numerical ocean model or from observational data. However, both these sources have limitations; the model may have significant systematic errors resulting in incorrect statistics, and observations are often sparsely distributed in space and time. Mellor and Ezer (1991) calculate statistics from their model relating sea surface height anomalies to temperature and salinity anomalies at fixed depths below the surface. Carton et al. (1996) suggest a better statistical model for the tropics is to relate sea level changes to changes in the depth of the thermocline. They calculate statistical correlations using data from the TOGA-TAO array in the Pacific Ocean (within 8° of the Equator), and find that a 1 cm change in sea level roughly corresponds to a 2 m change in thermocline depth.

The dynamical method of Cooper and Haines (1996) is used here to translate surface height increments into subsurface temperature and salinity increments. The method adjusts the model density profiles so they are consistent with changes in sea surface height, conserving water mass properties (temperature and salinity) on subsurface isopycnals during the process.

The projection method uses two sets of constraints. The first is described by the hydrostatic relation,

$$\Delta p_s + g \int_{z_b} \Delta \rho(z) dz = \Delta p_b \quad (1)$$

where Δp_s is the surface pressure change at the rigid lid ($z=0$) due to the altimeter data, $\Delta \rho(z)$ is the change in density at level z , and Δp_b is the change in the pressure at the bottom of the water column ($z=z_b$). Since the barotropic mode is weak in the tropical Pacific a condition of zero bottom pressure change is valid ($\Delta p_b=0$). The two terms on the left hand side of (1) must then equate; the vertically integrated density change must compensate entirely for the change in sea surface pressure/height.

The second constraint ensures conservation of water mass properties on subsurface isopycnals and is satisfied by arbitrary vertical displacements of the model density profile (derived from the temperature and salinity fields). The vertical displacement required to fit the surface pressure increment is then determined from equation (1). Water with the same properties as the top/bottom layer is added at the top/bottom of the ocean model when the water column is lowered/raised. For example, a positive sea level anomaly ($\Delta p_s > 0$) means the integral of $\Delta \rho(z)$ must be negative and the model density profile must be raised; warm low density water is added to top of the profile and cold high density water is removed from the bottom. This example is shown schematically in Figure 1.

Some advantages of the technique are:

- spurious water masses are not introduced into the model by the assimilation scheme.
- the method is model independent and does not require any pre-processing steps or statistical calculations.
- the method relies on the model dynamics for *a-priori* information rather than statistics that are fixed at the start of the assimilation and is therefore more adaptable to the particular model state at any one time.
- there is a strong correlation between surface height and the depth of the thermocline in the tropical Pacific and vertical displacement of the thermocline is a realistic feature of tropical wave dynamics.

Some disadvantages and limitations of the present implementation are:

- the method is based on a local adjustment of the existing water column in the vertical and such a displacement does not necessarily represent a realistic physical process. In reality water masses are often displaced horizontally.
- if the stratification or the T-S characteristics in the model are initially incorrect, the method cannot explicitly correct them.
- the zero bottom pressure constraint which provides a unique solution for the vertical adjustment process is not completely satisfactory, because it does not allow for any barotropic changes. Although the assumption is thought to be valid for the equatorial region, there can be significant barotropic signals at higher latitudes.
- there is no constraint on the magnitude of the vertical displacement.
- when a water column is raised/lowered, the zero density stratification imposed by the method at the base/top of the model can be unrealistic
- there is a potential cooling bias at the surface layer. The surface mixed layer can be quite shallow in some regions and lifting the model profile can bring colder water to the surface (a realistic feature in mid-latitude cold core eddies). Following on from the previous point, if the density profile is then lowered the T-S characteristics of the water added at the top of the profile are chosen to be the same as the surface water characteristics before assimilation, i.e. cooler than before. This may not always be the correct assumption to make.

Cooper and Haines (1996) found the assimilation method produced significant errors at depths close to the seasonal thermocline if the temperature of the mixed layer was incorrect. The performance of the method improved when knowledge of the mixed layer temperature was assumed. It is therefore important in certain regions to assimilate surface temperature data as well as the altimeter surface height data. Combining sea level and temperature data in the nudging assimilation scheme therefore has the potential to overcome the final disadvantage outlined above.

Expt ID	Assim Thermal Profiles	Assim Altimeter	Mean Sea Surface	Correlation Scale (km)				Relative Weight	
				Thermal		Altimeter		Obs/Model	
				E-W	N-S	E-W	N-S	Thermal	Altimeter
UKM	-	-	-	-	-	-	-	-	-
UKA	-	Yes	RA6	-	-	300	150	1	1
UKB	Yes	-	-	1500	300	-	-	1	1
UKC	Yes	Yes	UKM	600	300	600	300	1	0.5
UKD	-	Yes	UKM	-	-	300	150	1	1
RA6	Yes	-	-	450-1200	450	-	-		

Table 1. Assimilation experiment details.

2.3 Observational data

TOPEX/POSEIDON Sea Level Anomaly data

The CLS Space Oceanography Group in France produce high level altimeter products from AVISO/Altimetry, a multi-satellite databank dedicated to space oceanography. The Sea Level Anomaly product (AVISO, 1995) contains surface height data relative to a mean and is processed with the best geophysical corrections available at the time. Data from the TOPEX/POSEIDON (T/P) Sea Level Anomaly product for the first two years of the satellite mission (cycle 2 to cycle 75; October 1992 to September 1994) are used in this study.

The tide correction is from version 1.2 of the University of Texas tidal model (Ma et al., 1994) and the electromagnetic bias correction from Gaspar et al. (1994). Ionospheric effects were derived from the TOPEX dual frequency altimeter and the wet tropospheric correction from the onboard TMR radiometer. Dry tropospheric and inverse barometer effects were calculated using data from the European Center for Medium-Range Weather Forecasting (ECMWF). No orbit error correction is applied because of the high accuracy of T/P orbits. The data is quality controlled to remove bad height measurements (e.g. due to land, ice, rain contamination) and also spikes that occasionally occur in the observations (Le Traon et al., 1994). A repeat track analysis method is then applied to calculate the sea level anomalies. For a given track and for each cycle, data are resampled every 7 km using cubic splines. Differences relative to the mean over all available cycles (two year period) are then calculated. The along-track resolution is considerably higher than the tropical Pacific model resolution, and there is therefore some redundancy of data. For this study, the altimeter observations were further averaged along-track into bins dependent on the resolution of the grid (along track spatial resolution varies from 30 km to 110 km).

TOPEX/POSEIDON is on a 10-day repeat cycle with a cross-track spatial resolution at the Equator of 316 km. Mitchum (1994) has compared TOPEX sea level anomaly data (processed with all the geophysical corrections) with sea level measurements from 71 tide gauges around the globe and found a correlation of 0.66 and an RMS difference of 4.3 cm on a 10-day timescale. The spatial distribution of TOPEX/POSEIDON data for a particular 10 day period is shown in Figure 2(b).

Thermal profile data

Subsurface temperature profile observations have been provided by the NOAA National Center for Environmental Prediction (NCEP) via anonymous ftp. The data set includes data from the TOGA TAO array moorings as well as expendable bathythermographs (XBTs) from the Volunteer Observing Ship program and other data transmitted over the Global Telecommunications System. All the data has been quality controlled with a gross error check against climatology and a check on the static stability of the profiles (Ji et al., 1995). In contrast to the density of satellite altimeter observations, the spatial and temporal distribution of thermal profile observations is rather sparse (Figure 2a).

Tide gauge data

Sea level data from Pacific island tide gauge stations (Wyrski, 1979) has been provided by the University of Hawaii Sea Level Center via anonymous ftp. The data have had data spikes and time shifts corrected, and the tidal signal has been filtered out. Timeseries of daily averages are further smoothed with a 9-day running mean filter for comparison with the model integrations.

3. Comparison between model and assimilation integrations

Results from a series of model integrations assimilating different sets of observations are compared in this section. Details of the integrations can be found in Table 1. All integrations started at the beginning of October 1992 and ran for either one or two years. The period of study includes the latter part of the 1991-1993 El Nino with associated strong equatorial Kelvin wave activity generated by intense wind bursts west of the date line (Boulangier and Menkes, 1995). There is also much Rossby wave activity away from the Equator.

This section is divided into two parts. The first part looks at the time-mean ocean state and whether systematic errors in the model can be improved by assimilating data. The second part concentrates on the variability in the model.

3.1 Mean state of the model

The determination of the ocean dynamic topography from a satellite altimeter is limited at present by inaccuracies in the geoid correction. The geoid is essentially a stationary field on the timescales of interest in this study and the uncertainty can therefore be removed by subtracting the time mean surface height field from the data. The resulting sea level anomalies provide information on the variability of the ocean dynamics.

The assimilation scheme uses instantaneous sea level anomaly data rather than sea level tendency, and so a suitable time-mean surface height field needs to be removed from the model (or equivalently added to the altimeter sea level anomaly data) for a direct comparison of model and data. The most obvious choice is the time-mean surface height field derived from the model for the same period as the altimeter time-mean (i.e. two years from the beginning of October 1992 to the end of September 1993). In this case one expects the altimeter data assimilation to change only the variability in the model, leaving the mean unchanged. Changing the variability in the model could however lead indirectly to changes in the model mean.

Although the time-mean estimate from the ocean model is possibly a better estimate of the true time-mean field than that provided in the geoid contaminated altimeter data, the ocean model does have significant systematic errors. There is a question as to whether a more accurate mean surface height field can lead to direct improvements in the model mean state. Assimilating thermal profile data into the model should yield a more accurate thermal structure in the upper layers of the ocean and a correspondingly improved mean sea surface height field.

The two-year mean sea surface height fields are shown in Figure 3 for the UKMO model with no data assimilation (UKM), the UKMO model with thermal profile assimilation

(UKB), and the NCEP model with thermal profile assimilation (RA6). The area-weighted mean over the model domain has been removed for each field. The sea surface height over most of the equatorial region increases from east to west. This is due mainly to the slope of the thermocline in the eastern half of the basin and increasing temperatures in the upper ocean in the west. There is a deep trough between 5°N and 10°N associated with the eastward flowing North Equatorial Countercurrent (NECC). Other major currents in the tropical Pacific Ocean include the westward flowing South Equatorial Current (SEC) between 10°S and 5°N, and the North Equatorial Current (NEC) between 10°N and 20°N. Below the surface and within a few degrees of the equator there is also an eastward flowing Equatorial Undercurrent (EUC) which follows the sloping subsurface isopycnal surfaces.

The first point to note from Figure 3 is the large scale similarity between the two models assimilating thermal profile data (UKB and RA6). This is perhaps to be expected since both models are assimilating essentially the same data. There are still differences, however, particularly in the north-west corner of the domain and in the NECC trough. The differences in the north-west can be explained by the fact that the RA6 model domain extends to 60°N and includes the Kuroshio current system. The UKMO model does not extend beyond 30°N, does not include a barotropic mode and is relaxed to Levitus climatology near the boundary. It is therefore not expected to accurately reproduce the dynamics in this area.

The second point to note is the difference between the UKMO model (UKM) and the thermal profile assimilations (UKB and RA6). Although the general characteristics of the surface height field are similar, there are large differences within 10°N of the north and south boundaries, the NECC trough is shallower in UKM, and the general west-east slope is weaker.

Integration UKA assimilates T/P data with the RA6 mean sea surface, and UKD is the equivalent integration assimilating T/P data with the UKM mean sea surface. When altimeter data is assimilated in UKA over the whole of the model domain, the sea surface height field adjusts to look like the RA6 mean within a few weeks. However, the large changes imposed by the data near the model boundaries initiates spurious large scale waves which dominate the analysis after a couple of months (not shown). The assimilation is improved by assimilating data with full weight into a domain bounded by 15°S, 15°N, 150°E and 90°W, and reduced weight outside this domain. However, an unrealistic wave still develops in the north-west, and integration UKM which uses a surface height mean consistent with the model also suffers from an instability in this region. It is not yet clear why this is the case, although it may be that the data is weighted too high and nudged into the model too hard, or that the temperature and salinity characteristics in this region are not well represented in the model (the barotropic component might be significant in this region). The problem did not occur in experiment UKC which assimilated both thermal profiles and T/P data and gave a lower weight to the altimeter data.

Figure 4 compares temperature cross-sections along the Equator in the top 300 metres of the model. The cross-sections are all monthly means valid for December 1992, three months into the integrations. The thermocline is too diffuse when no data is assimilated (UKM), particularly in the east (Figure 4a). Assimilating thermal profile data into the model

(UKB) tightens the thermocline considerably and raises the isotherms in the east (Figure 4b). Experiment UKD assimilating T/P data with the UKM mean results in a cross-section (not shown) which is very similar to that produced by the model with no data assimilation (Figure 4a). In contrast, experiment UKA which assimilates T/P data with the RA6 mean does raise the isotherms and tighten the thermocline in the east (Figure 4c), even though the assimilation method explicitly conserves the interior stratification.

3.2 Variability in the model

Altimeter data is most suited to observing the variability of the ocean, and the high variability in the tropical Pacific ocean includes Kelvin and Rossby waves as well as the inter-annual El Nino signal. The wave activity along the Equator can be seen in time-longitude plots of the sea surface height anomalies derived from TOPEX and from the TOGA-TAO array (Figure 5). The two data sets show essentially the same eastward propagating features with similar amplitudes of the variability. For example, note the two downwelling Kelvin waves propagating eastward in late 1992/early 1993. The TOPEX data has a greater spatial resolution than the TOGA-TAO array which probably explains the smaller scale structures apparent in the altimeter data.

Figure 6 shows equivalent time-longitude plots of sea level anomalies for various model integrations. The model with no data assimilation (UKM) reproduces some of the large scale undulations along the Equator but many of the propagating features seen in the data are not apparent or have an incorrect magnitude. Assimilating the thermal profile data (UKB) improves the model considerably, increasing smaller scale variability. Many of the propagating features can be identified with features seen in the TOPEX and TAO data (Figure 5) and there is some evidence of the two distinct Kelvin waves in the early part of the period. The third plot shows the T/P assimilation (UKD), in which the small scale variability has increased dramatically and the two Kelvin waves are well represented. The evolution of the sea level anomaly field along the Equator is significantly improved by assimilating altimeter data into the model.

Does the model variability below the surface also improve when altimeter data is assimilated? One useful diagnostic in the tropical Pacific is the depth of the thermocline characterised by the 20°C isotherm. Figure 7 shows time-longitude plots along the Equator of the 20°C isotherm anomaly (in metres) for the model (UKM) and altimeter assimilation (UKD). A timeseries of observed anomalies based on TAO buoy data between 2°N and 2°S is also shown. The TAO data is smoothed to 5-day averages and differenced from an XBT climatology. Again, UKD has higher variability and smaller scale features than UKM. Although a comparison with the TAO timeseries is difficult because a different climatology has been subtracted from the observed data, many of the eastward propagating features can be seen in all three plots with the altimeter assimilation resolving some of the finer detail. There is however a low anomaly in the altimeter assimilation (eastern Pacific, February /March 1993) that is much more pronounced than in either the model or the observed anomalies.

A further source of independent data for validating the model is the network of tide gauge stations in the tropical Pacific. The tide gauges chosen for comparison in this report are shown in Figure 8. The stations are grouped according to their location with reference to the dominant ocean dynamics of the tropical Pacific. Area 1 is the eastern Pacific on the Equator; there is only one island tide gauge station in this region. Area 2 contains stations on the Equator in the central and western Pacific. Off equatorial stations in the central region are associated with areas 3 and 4, and in the western region with areas 5 and 6. Area 7 contains two stations north of the Equator in the far west Pacific.

Table 2 shows the fraction of the variance of the tide gauge data accounted for by different model integrations. The mean over all eighteen stations indicates the surface height variability in the model is closer to the tide gauge data when thermal profile data is assimilated. A further improvement of about the same magnitude is seen when T/P data is additionally assimilated.

An analysis by area shows the greatest improvement along the Equator in the central and western regions (Area 2, except for Kapingamarangi), in the central region between the Equator and 15°S (Area 3), and in the western region between the Equator and 15°N (Areas 6 and 7). At all of these stations there is an improvement when thermal profile data is assimilated, and at most stations there is a further improvement when additionally assimilating T/P data.

The actual timeseries of surface height variability at a sample of tide gauge stations (one for each area) are shown in Figure 9 for the integrations UKM, UKB, and UKC. The most striking feature apparent in the timeseries is the much higher frequency variability in the tide gauge data (even after applying a 9-day running mean filter) when compared to the variability in the model integrations. The altimeter data has a large impact in some regions, and very little impact in others. Along the equator (areas 1 and 2) some of the higher frequency variability is captured by the altimeter and thermal profile assimilation (UKC), although the amplitude is on the low side. The two equatorial Kelvin waves described earlier can be seen passing through Christmas Island in December 1992 and January 1993. The Kelvin wave signals in the thermal profile assimilation (UKB) are present but weaker still, and the model with no assimilation (UKM) fails to capture the individual peaks associated with either wave. In the off equatorial central regions (areas 3 and 4) there is little to distinguish between the three integrations and much of the variability in the tide gauge data is not captured. In particular there is very little variability in any of the model integrations at Johnston, but large variations are apparent in the tide gauge data. The altimeter data has a low weight in this area (it is above 15°N - see section 3.1), and may have little impact on the model. It is also possible that the signals are not present in the altimeter data and this needs to be investigated further. In areas 6 and 7 in the north western region, the combined altimeter and thermal profile assimilation (UKC) fits the longer timescale variability in the tide gauge data better than UKB or UKM.

Area	Station	Lat/Long	Fraction of the variance accounted for by:		
			Model	XBT Assim	XBT+ ALT Assim
1	Santa-Cruz	(00-45S,090-19W)	0.47	0.46	0.32
2	Christmas	(01-59N,157-29W)	0.15	0.52	0.64
2	Kanton	(02-49S,171-43W)	0.08	0.28	0.62
2	Tarawa	(01-22N,172-56E)	0.13	0.19	0.46
2	Nauru	(00-32S,166-54E)	0.26	0.30	0.37
2	Kapingamarangi	(01-06N,154-47E)	0.45	0.34	0.24
3	Penrhyn	(08-59S,158-03W)	0.01	0.04	0.32
3	Pago-Pago	(14-17S,170-41W)	0.00	0.11	0.25
3	Funafuti	(08-32S,179-13E)	0.19	0.35	0.37
4	Honolulu	(21-18N,157-52W)	0.06	0.17	0.13
4	Johnston	(16-45N,169-31W)	0.41	0.30	0.27
5	Honiara	(09-26S,159-57E)	0.28	0.44	0.18
5	Rabaul	(04-12S,152-11E)	0.70	0.60	0.44
6	Mauro	(07-06N,171-22E)	0.28	0.32	0.47
6	Kwajalein	(08-44N,167-44E)	0.22	0.27	0.59
6	Pohnpei	(06-59N,158-15E)	0.22	0.39	0.39
7	Guam	(13-26N,144-39E)	0.44	0.63	0.63
7	Yap	(09-31N,138-08E)	0.00	0.17	0.52
		Mean value	0.24	0.33	0.40

Table 2. Fraction of the variance in the tide gauge sea level data accounted for by the model (UKM) and assimilations (UKB and UKC). Data for the first year of integration (October 1992 to September 1993) are used to form the statistics.

4. Concluding summary

This report presents a preliminary assessment of the impact of assimilating TOPEX/POSEIDON altimeter data into a tropical Pacific Ocean model. Overall, the results are encouraging, but further work is necessary to gain a clearer and more detailed understanding of the effects of assimilating altimeter data.

The main points to come out of this study are:

- as expected, the choice of time-mean surface height field for the altimeter assimilation has a large impact on the model mean.
- model instabilities were encountered in the north-west tropical Pacific in the integrations assimilating only altimeter data. There were no such problems when the weight given to the altimeter data was reduced and thermal profile data was additionally assimilated.
- there is increased variability in the model when altimeter data is assimilated.
- equatorial Kelvin waves which are not present or weak in the model integration are well represented when altimeter data is assimilated.

Further work to conclude the investigation with this model is required. Priorities are to:

- obtain a quantitative verification of the evolution of the model temperature field by calculating statistics from a direct comparison with thermal profile data.
- assimilate sea surface temperature observations in combination with the thermal profile and altimeter data.
- determine the sensitivity of the results to changes in the assimilation parameters (background error correlation scales, time window, observation weights)
- understand why there were unrealistic waves initiated in certain areas in the model when assimilating only the altimeter data.

Further work towards an altimeter assimilation scheme suitable for operational implementation in other regions of the ocean:

- arrange for transmission of near real-time altimeter data from NOAA/NavOceano to the U.K. Met. Office.
- apply an along-track filter to the altimeter data to remove residual orbit errors.
- extend the surface height projection technique to allow some bottom pressure variation and include a further constraint to limit the vertical displacement of isopycnals.
- assimilate ERS-1/ERS-2 data (which has a repeat cycle of 35 days and a higher cross-track spatial resolution than TOPEX/POSEIDON).

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References

- Alves, J. O. S., Bell, M. J., Brooks, N., Cooper, A. L., Foreman, S. J., Forbes, R. M., Sherlock, C.G., (1995). Performance review of the prototype FOAM system. Forecasting Research Division Technical Report No. 159, Meteorological Office, Bracknell.
- AVISO, (1995). AVISO User Handbook: Sea Level Anomaly files. AVI-NT-011-312-CN, Edition 1.
- Bell, M. J., (1994a). Results from initial experiments with the assimilation of thermal profiles into a dynamical model of the Atlantic Ocean. Forecasting Research Division Technical Report No. 98, Meteorological Office, Bracknell.
- Bell, M. J., (1994b). Experiments with the assimilation of thermal profile data into a dynamical model of the Atlantic Ocean. Forecasting Research Division Technical Report No. 134, Meteorological Office, Bracknell.
- Berry, P., Marshall, J., (1989). Ocean modelling studies in support of altimetry. *Dyn. Atmos. Oceans*, **13**, 269-300.
- Bryan, K., (1969). A numerical method for the study of the circulation of the world ocean, *J. Comput. Phys.*, **4**, 347-376.
- Boulanger, J-P., Menkes, C., (1995). Propagation and reflection of long equatorial wave in the Pacific Ocean during the 1992-1993 El Nino. *J. Geophys. Res.*, **100**, 25041-25059.
- Busalacchi, A. J., McPhaden, M. J., Picaut, J., (1994). Variability in equatorial Pacific sea surface topography during the verification phase of the TOPEX/POSEIDON mission. *J. Geophys. Res.*, **99**, 24725-24738.
- Carton, J. A., Giese, B. S., Cao, X., Miller, L., (1996). Impact of altimeter, thermistor, and expendable bathythermograph data on retrospective analyses of the tropical Pacific Ocean. *J. Geophys. Res.*, **101**, 14147-14159.
- Cooper, M., Haines, K., (1996). Altimetric assimilation with water property conservation. *J. Geophys. Res.*, **101**, C1, 1059-1077.
- Cox, M. D., 1984, A primitive equation 3-dimensional model of the ocean. GFDL Ocean Group Tech. Report No. 1.

- Davey M.K., Ineson S., Balmaseda M.A., (1994). Simulation and hindcasts of tropical Pacific Ocean interannual variability. *Tellus*, **46A**, 4.
- Esbensen, S. K. and Kushnir, Y., 1981, The heat budget of the global ocean: an atlas based on estimates from surface marine observations. Climate Research Institute, Oregon State Univ., Corvallis, Report No. 69.
- Forbes, R. M., (1995). Experiments with the assimilation of surface temperature and thermal profile observations into a dynamical model of the Atlantic Ocean. Forecasting Research Tech. Report No. 167, Meteorological Office, Bracknell.
- Gaspar P., Ogor, F., Le Traon, P-Y., Zanife, O-Z., (1994). Estimating the sea state bias of the TOPEX and POSEIDON altimeters from crossover differences. *J. Geophys. Res.*, **99**, 24981-24994.
- Goldenburg, S. B., O'Brien, J. J., (1981). Time and space variability of tropical Pacific wind stress. *Mon. Wea. Rev.*, **109**, 1190-1207.
- Hurlburt, H. E., (1986). Dynamic transfer of simulated altimeter data into subsurface information by a numerical ocean model. *J. Geophys. Res.*, **91**, 2372-2400.
- Jaeger, L., 1983, Monthly and areal mean patterns of global precipitation. pp 129-140 in Street-Perrott, A., Beran, M., and Ratcliffe, R. (eds) Variations in the global water budget. Dordrecht, Reidel.
- Jerlov, N. G., (1976). Marine Optics. Elsevier Oceanogr. Ser., Vol.14, 231pp, Elsevier, New York.
- Ji, M., Leetma, A., Derber, J., (1995). An ocean analysis system for seasonal to interannual climate studies. *Mon. Weather Rev.*, **123**, 460-481.
- Kessler, W. S., (1990). Observations of long Rossby waves in the northern tropical Pacific. *J. Geophys. Res.*, **95**, 5183-5217.
- Kraus, E. B., Turner, J. S., (1967). A one-dimensional model of the seasonal thermocline. *Tellus*, **19**, 98-105.
- Le Traon, P. Y., Stum, J., Dorandeu, J., Gaspar, P., Vincent, P., (1994). Global statistical analysis of TOPEX/POSEIDON data. *J. Geophys. Res.*, **99**, 24619-24631.
- Levitus, S., (1982). Climatological atlas of the world ocean. NOAA Professional Paper 13.
- Lorenc, A. C., Bell, R. S., MacPherson, B., (1991). The Meteorological Office analysis correction data assimilation scheme". *Quart. J. Roy. Meteor. Soc.*, **117**, 59-89.

- Ma, X. C., Shum, C. K., Eanes, R. J., Tapley, B. D., (1994). Determination of ocean tides from the first year of TOPEX/POSEIDON altimeter measurements. *J. Geophys. Res.*, **99**, 24809-24820.
- Mellor, G. L., Ezer, T., (1991). A Gulf Stream model and an altimetry assimilation scheme. *J. Geophys. Res.*, **96**, 8779-8795.
- Meyers, G., Phillips, G. H., Smith, N. R., Sprintall, J., (1991). Space and time scales for optimum interpolation of temperature - Tropical Pacific Ocean. *Progr. Oceanogr.*, **28**, 189-219.
- Mitchum, G. T., (1994). Comparison of TOPEX sea surface heights and tide gauge sea levels. *J. Geophys. Res.*, **99**, 24541-24553.
- Oberhuber, J. M., (1988). An atlas based on the "COADS" data set: The budgets of heat, buoyancy and turbulent kinetic energy at the surface of the global ocean. Rep. No. 15, Max Planck Institut fur Meteorologie, 20 pp.
- Oschlies, A., Willebrand, J., (1996). Assimilation of Geosat altimeter data into an eddy-resolving primitive equation model of the North Atlantic Ocean. *J. Geophys. Res.*, **101**, C6, 14175-14190.
- Packanowski, R. C., Philander, S. G. H., (1981). Parameterisation of vertical mixing in numerical models of tropical oceans. *J. Phys. Oceanogr.*, **11**, 1443-1451.
- Smith, N. R., (1995). An improved system for tropical ocean subsurface temperature analyses. *J. Atm. Ocean. Tech.*, **12**, 850-870.
- Verron, J., (1992). Nudging satellite altimeter data into quasi-geostrophic ocean models. *J. Geophys. Res.*, **97**, 7479-7491.
- Wyrski, K., (1979). Sea level variations: Monitoring the breath of the Pacific. *Eos*, **60**, 25-27.

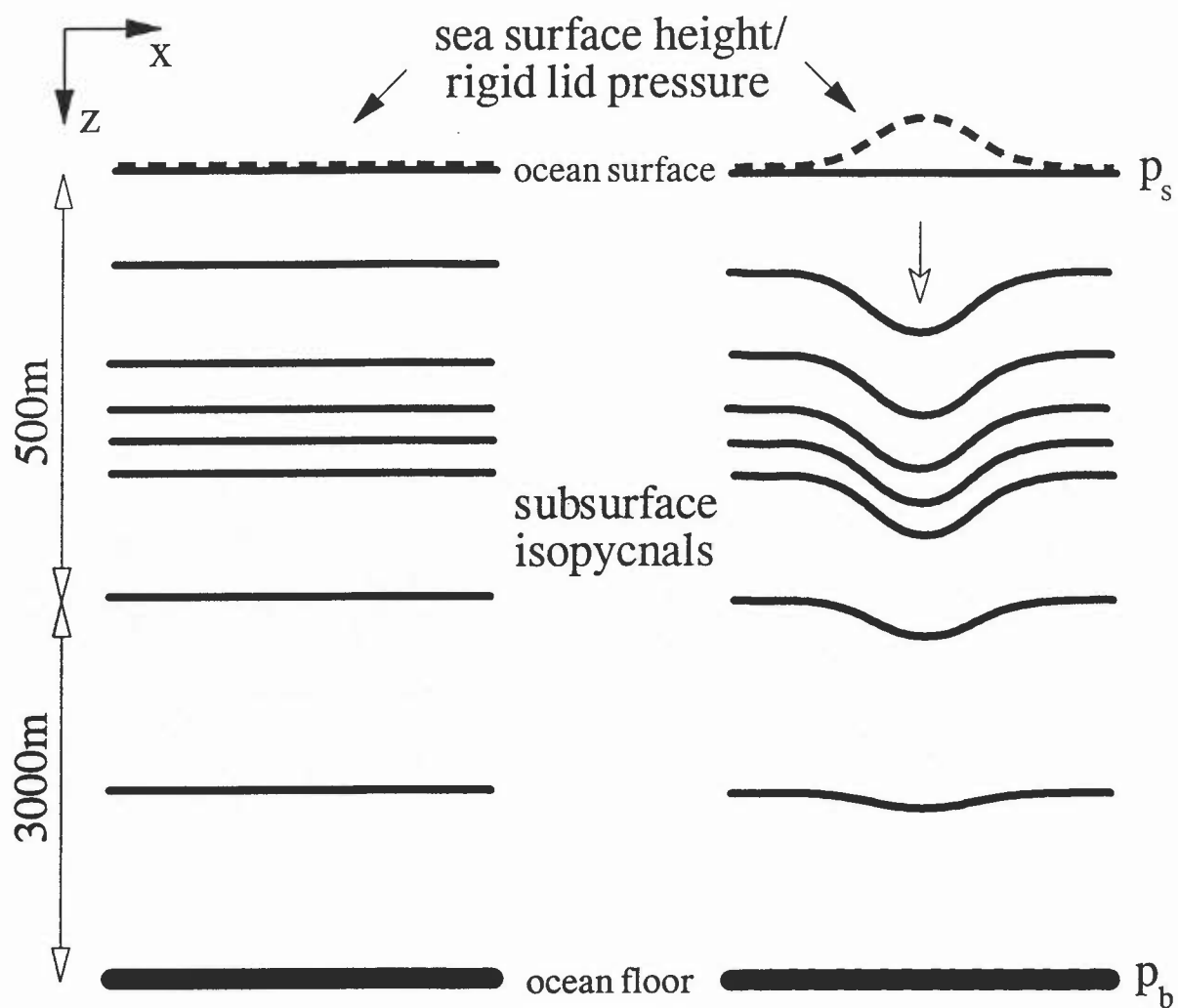
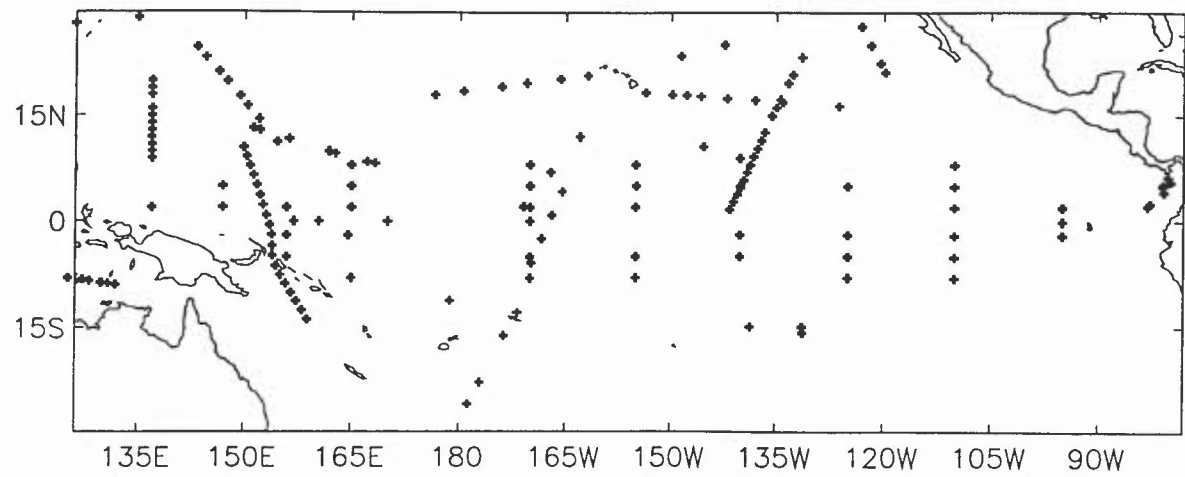
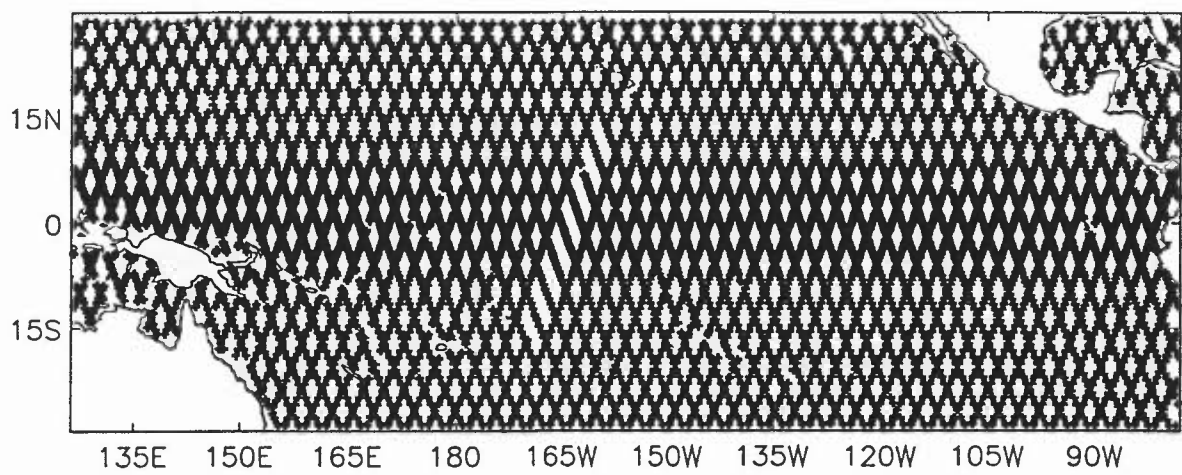


Figure 1 Schematic diagram illustrating the vertical adjustment of subsurface isopycnals in the surface height assimilation scheme for a positive surface height anomaly. The temperature and salinity profiles are lowered so there is no change in the bottom pressure.



(a)



(b)

Figure 2 Spatial distribution of data in a 10 day period for (a) thermal profiles (XBTs and TOGA-TAO array), (b) TOPEX/POSEIDON sea surface height.

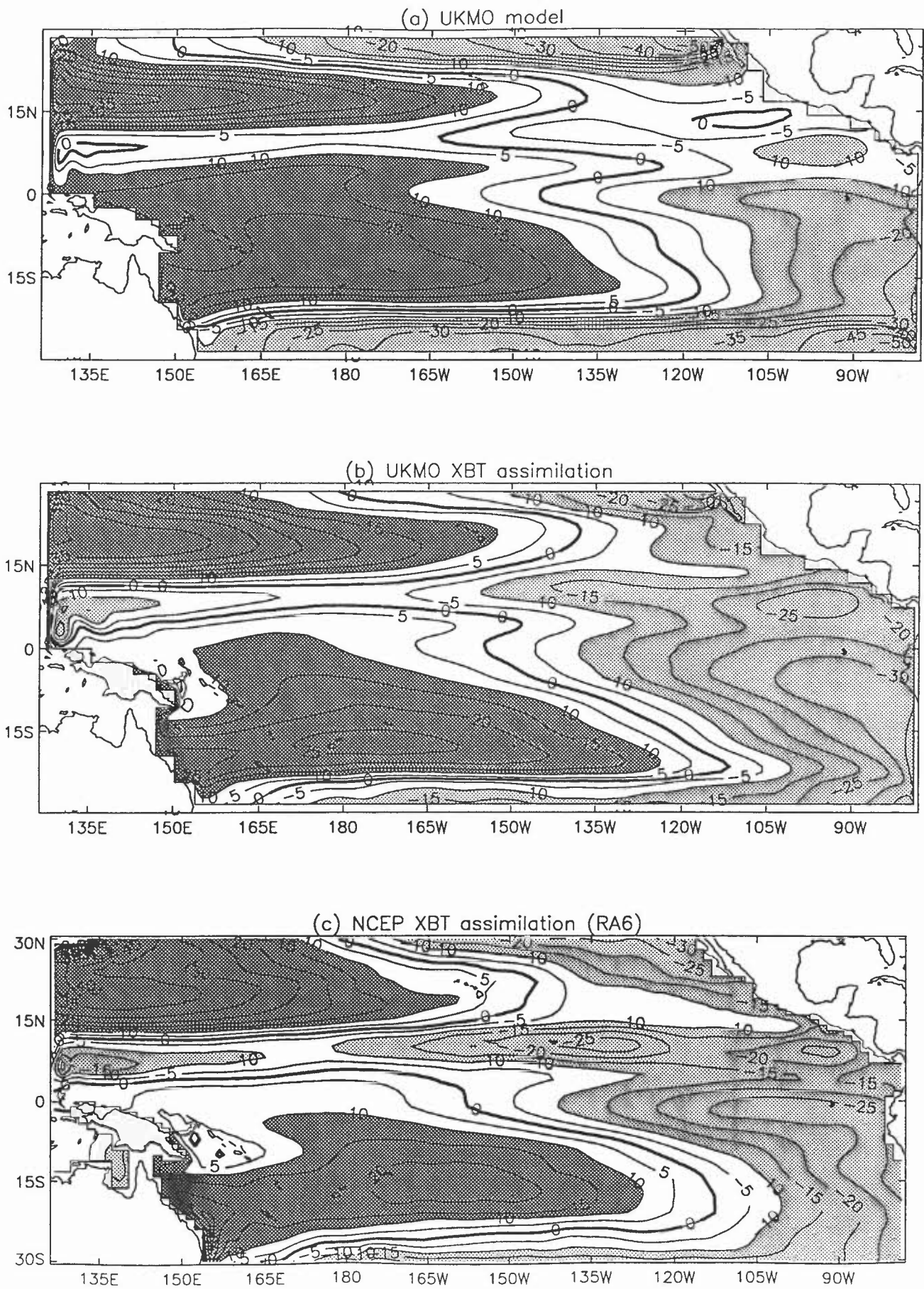


Figure 3 Comparison of different mean sea surface height fields for the period October 1992 to September 1994 for (a) UKMO model (UKM), (b) UKMO model with thermal profile assimilation (UKB), (c) NCEP model with thermal profile assimilation (RA6)

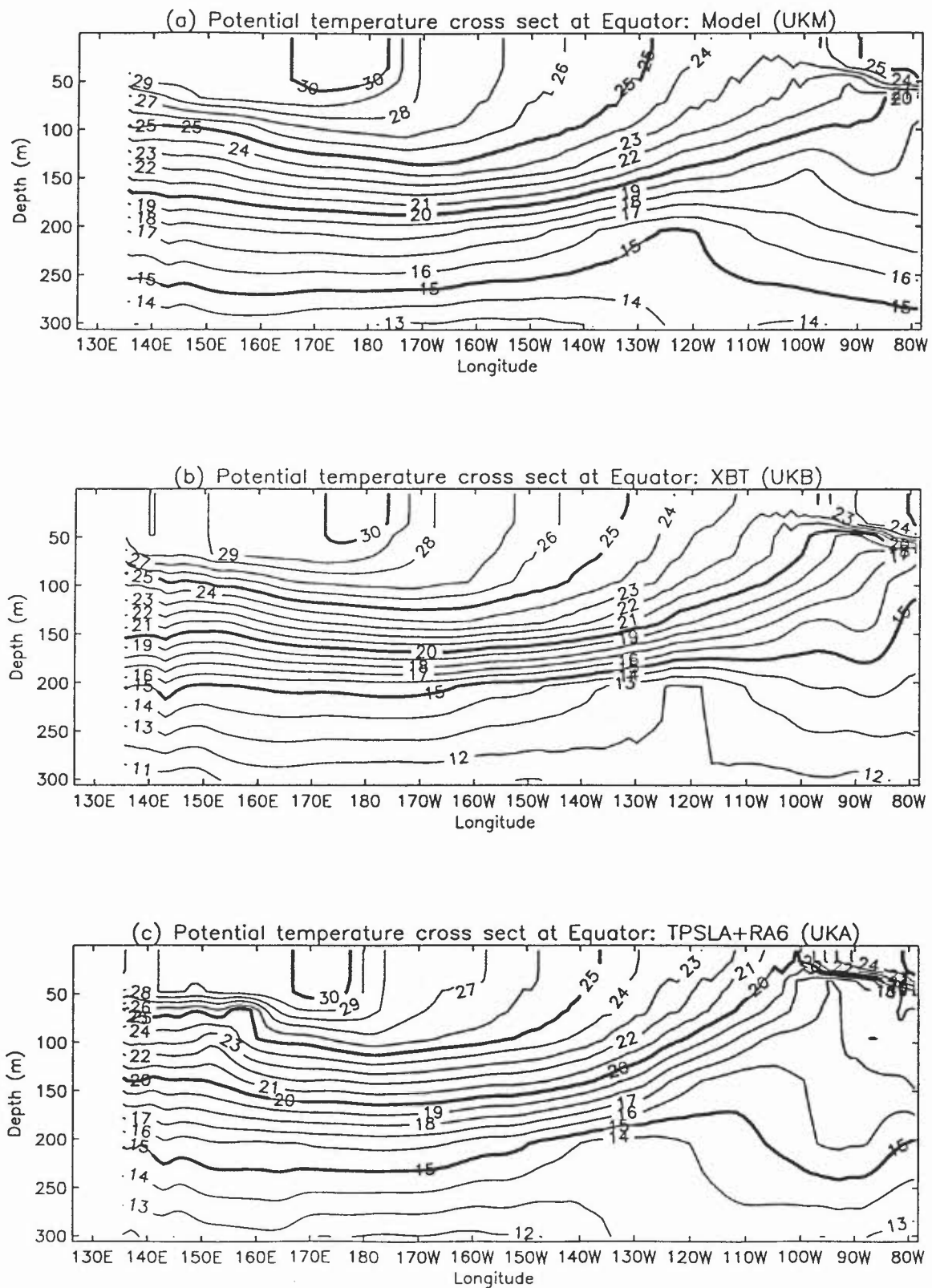


Figure 4 Potential temperature cross-sections along the Equator showing stratification and thermocline slope for (a) the model with no assimilation (UKM), (b) the thermal profile assimilation (UKB), and (c) the altimeter assimilation with RA6 as a mean surface height field (UKA).

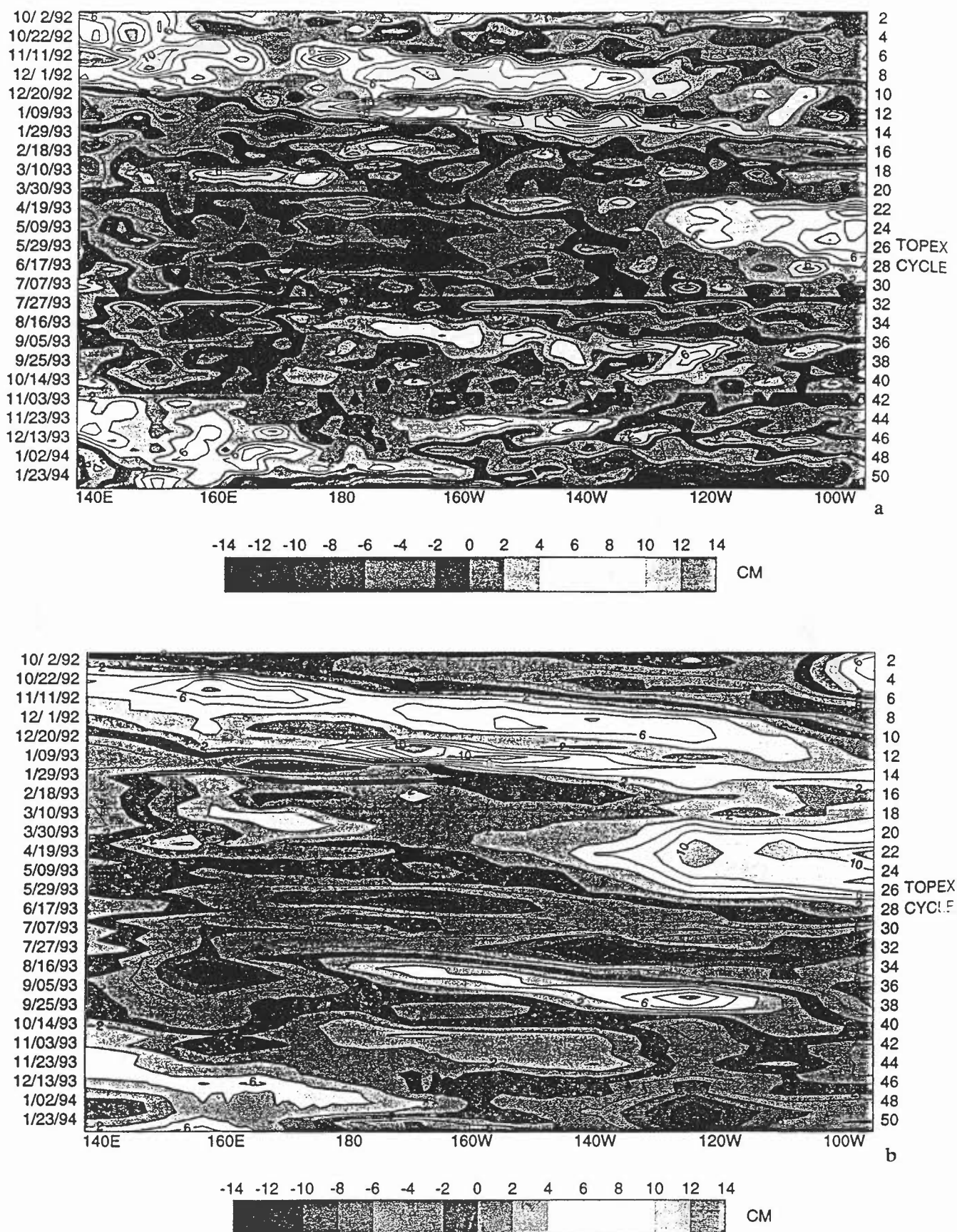
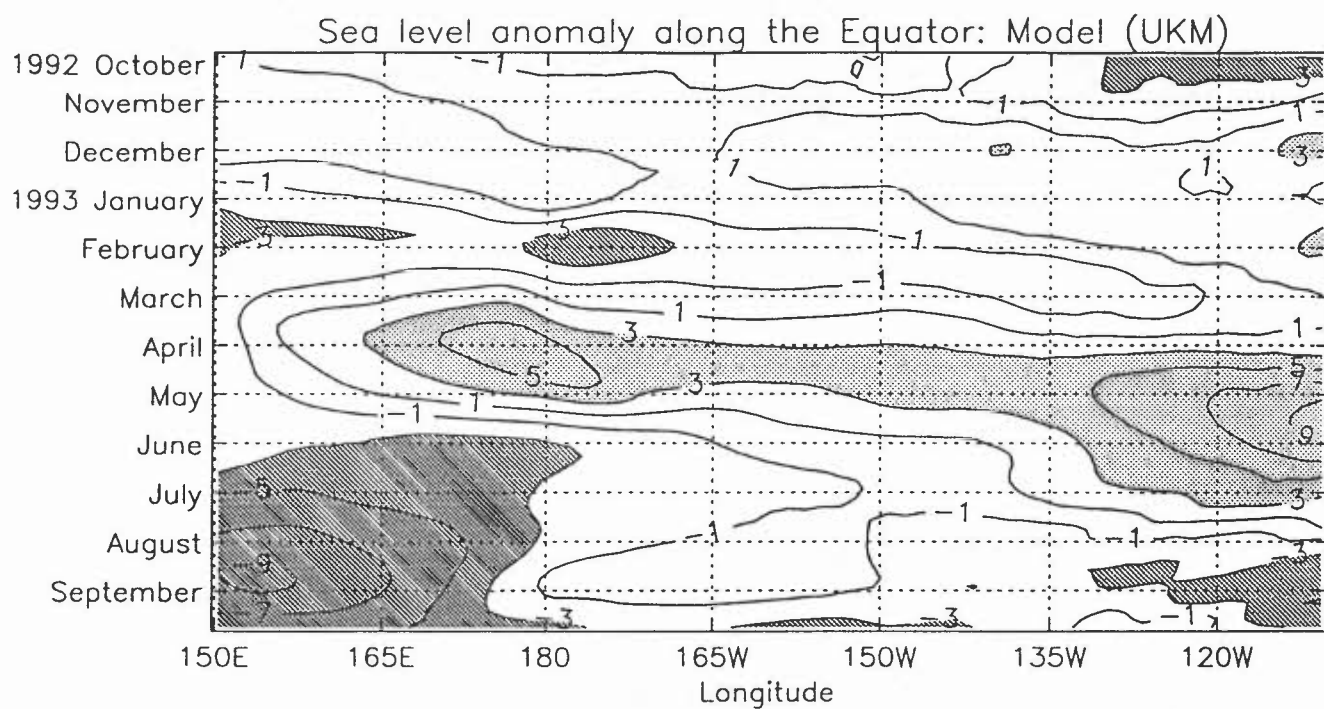


Figure 5

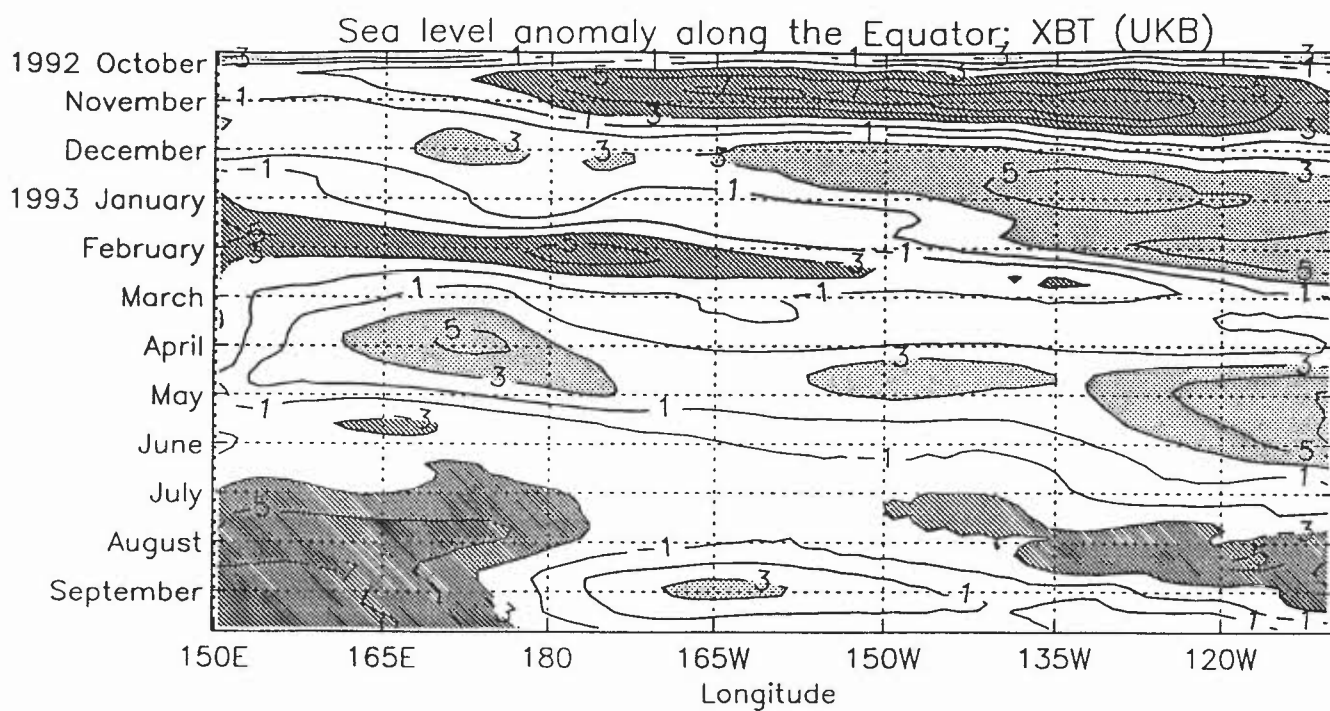
Time-longitude structure of surface topography variations along the Equator from 137°E to 95°W. The 506-day mean has been removed from both data sets. (a) TOPEX sea level. (b) TOGA-TAO dynamic height (0/500 dbar). TOPEX data were not available during cycles 20, 31, and 41, when the POSEIDON altimeter was operating. From Busalacchi et al. (1994).



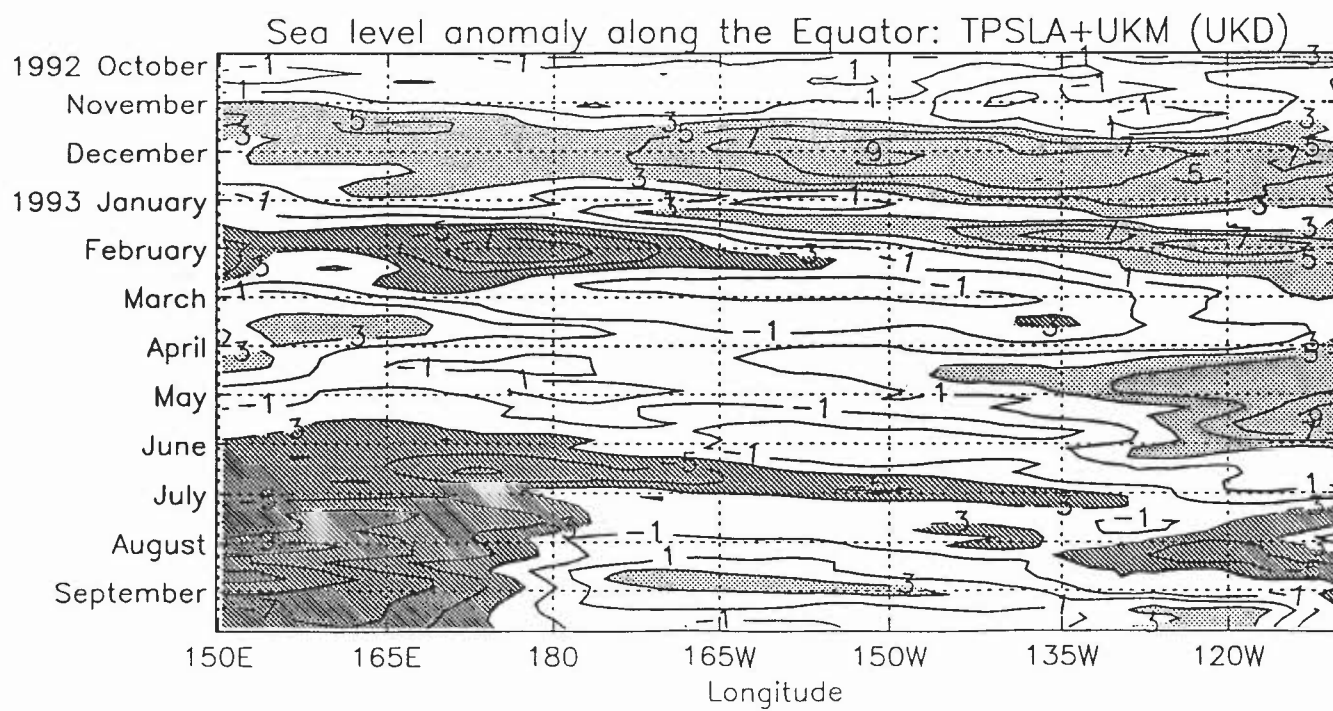
(a)

Figure 6.

Sea surface height anomaly (cm) time-longitude plots along the Equator. The two-year mean has been removed from each data set. (a) the model with no assimilation (UKM), (b) the model with thermal profile assimilation (UKB), and (c) the model with altimeter assimilation (UKD). Anomalies above 3 cm are lightly shaded and values below -3 cm are heavily shaded.

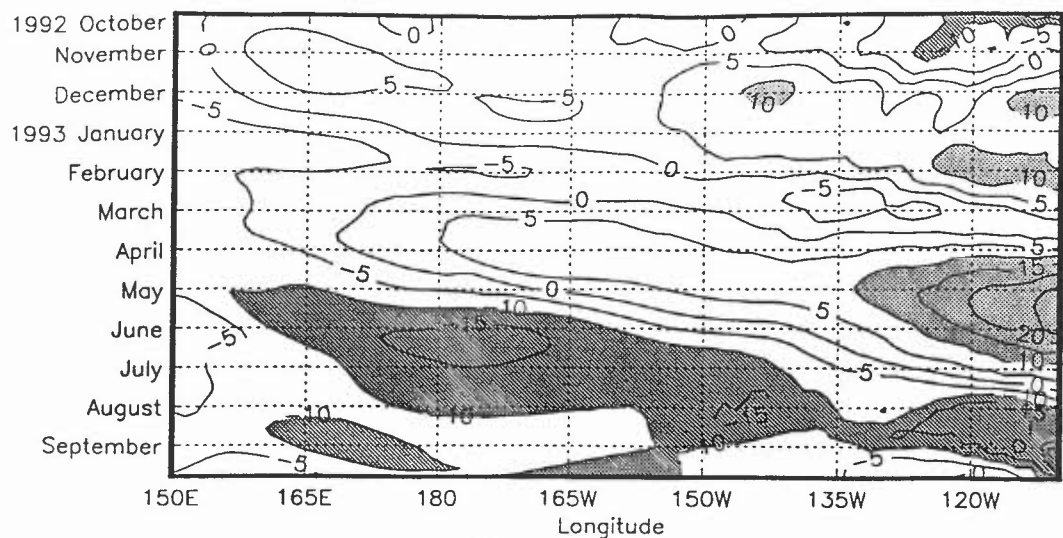


(b)

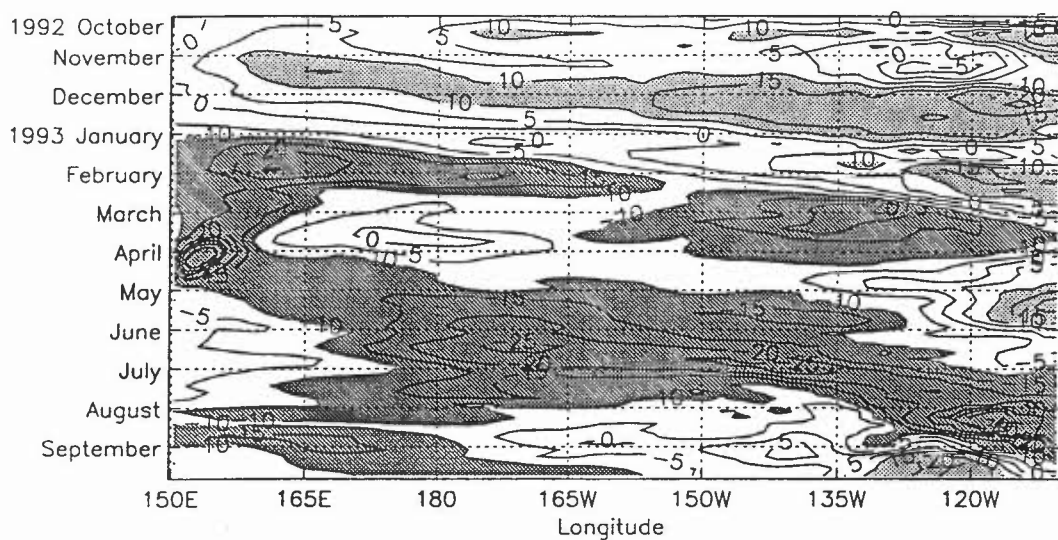


(c)

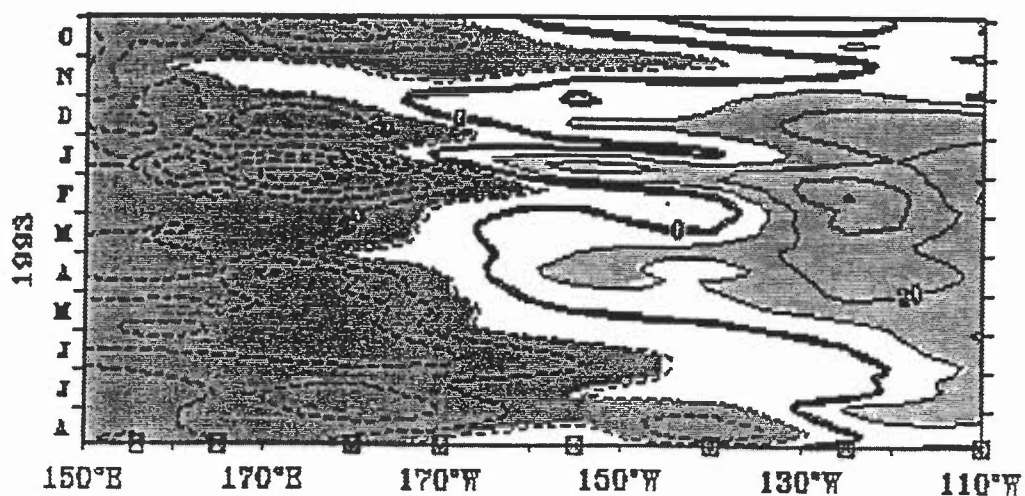
Figure 6. (Continued)



(a)



(b)



(c)

Figure 7

20°C isotherm depth anomaly (m) time-longitude plots along the Equator for (a) the model with no assimilation (UKM), (b) the model with altimeter assimilation (UKD), and (c) observed data from the TAO array (Kessler, 1990). The reference mean used to calculate the anomalies is the two-year model mean for the model derived data, and an observed climatology for the TAO data. The shading (light > 10m, dark < -10m) highlights the most significant anomalies.

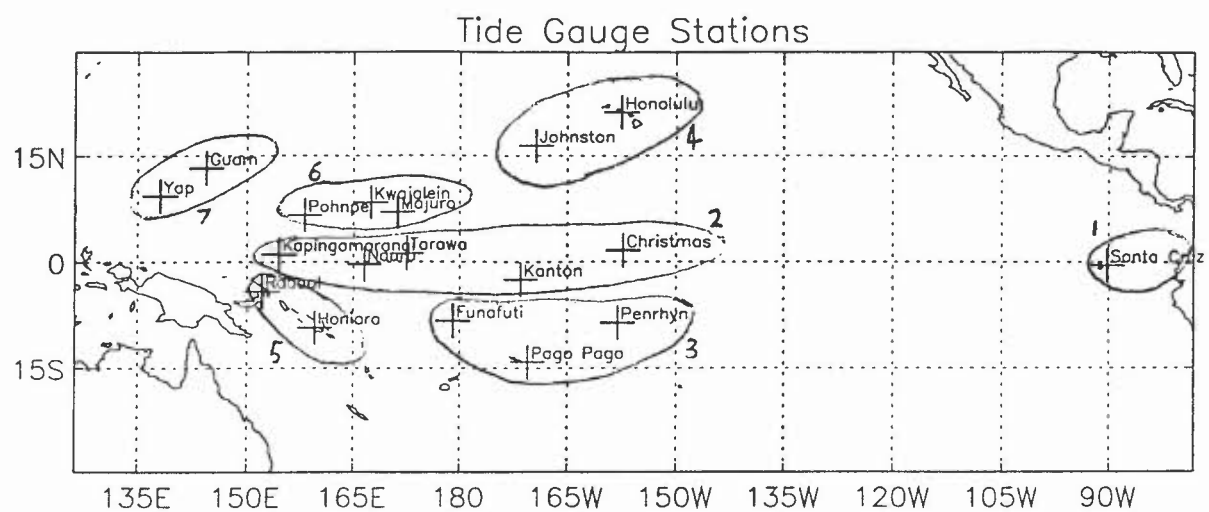
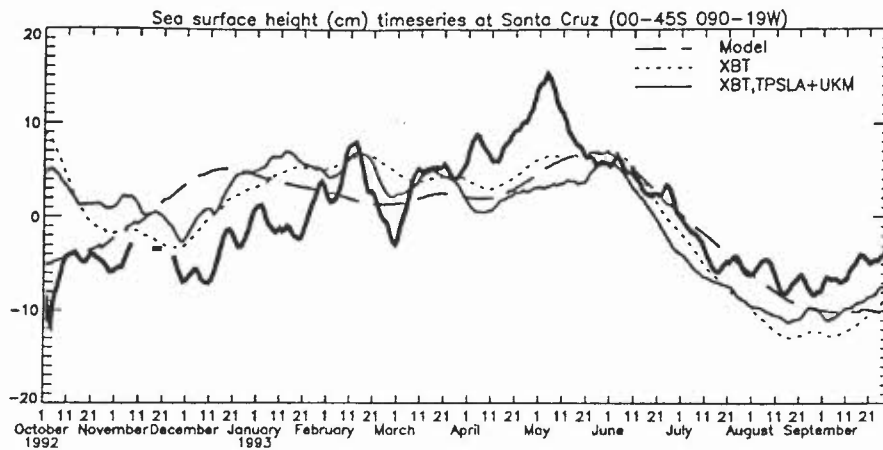
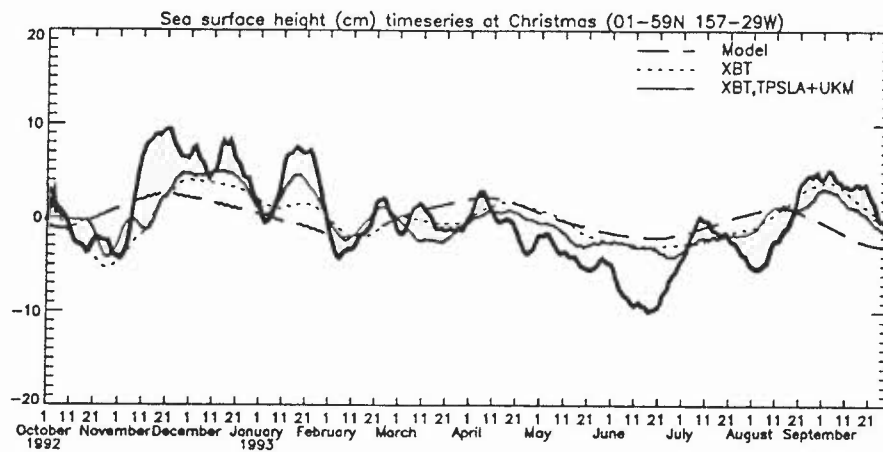


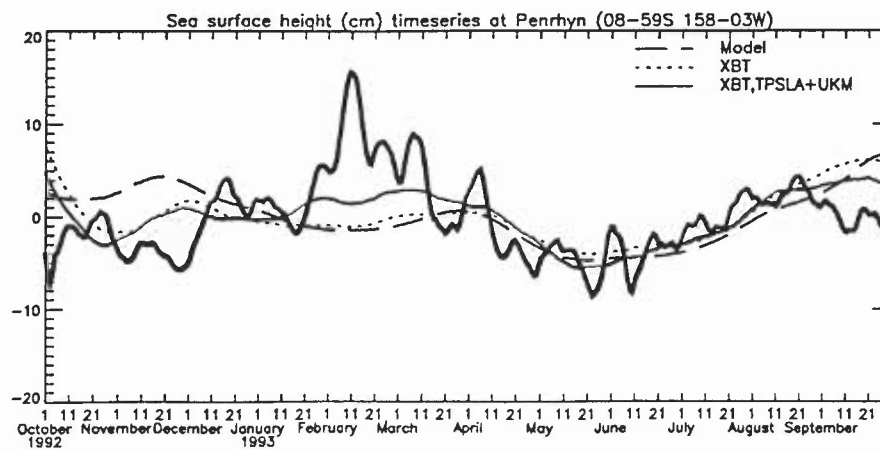
Figure 8 The model domain showing locations and groupings of tide gauge stations.



Area 1

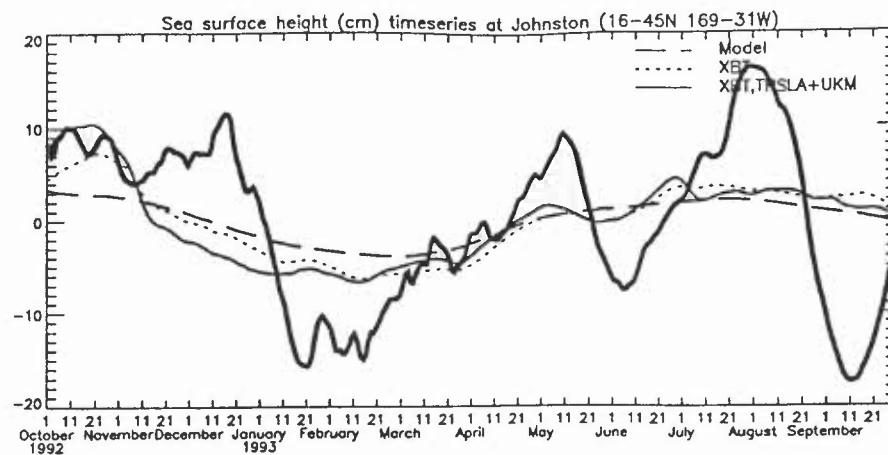


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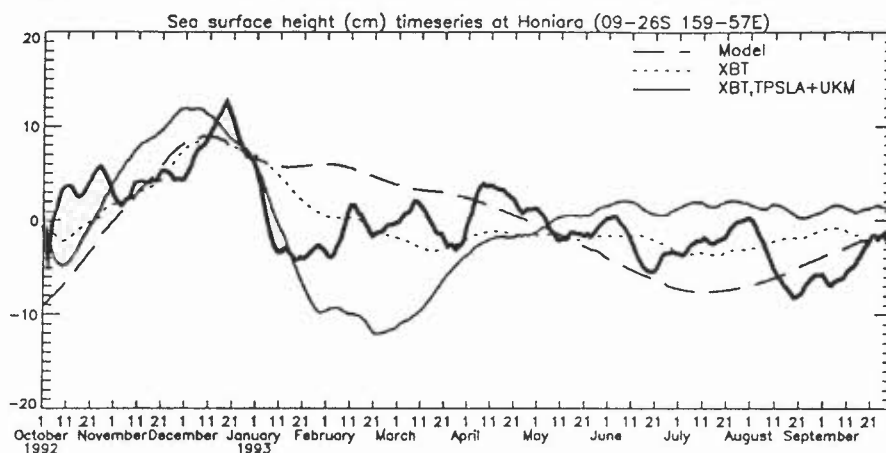


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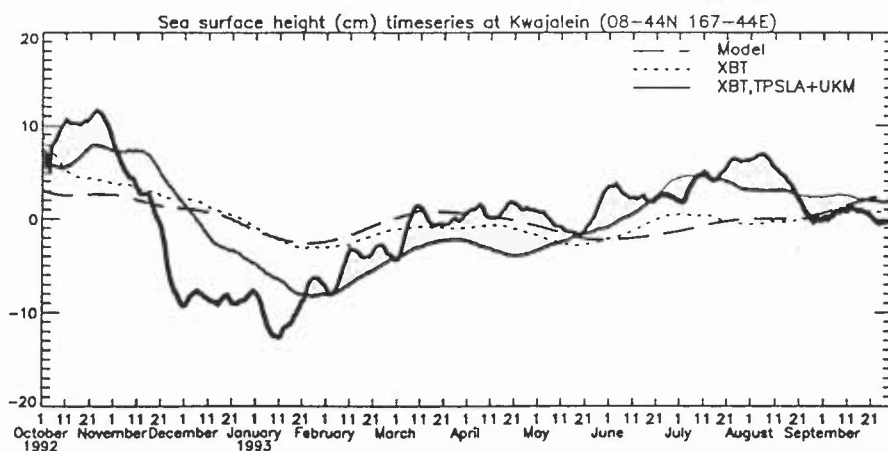
Figure 9. Time series of sea level for the period October 1992 to September 1993 from the model UKM (dashed), thermal profile assimilation UKB (dotted), combined altimeter and thermal profile assimilation UKC (thin solid), and tide gauges (thick solid). One tide gauge station is shown for each of the areas defined in Figure 8. The time-mean over the one year period has been removed from each timeseries.



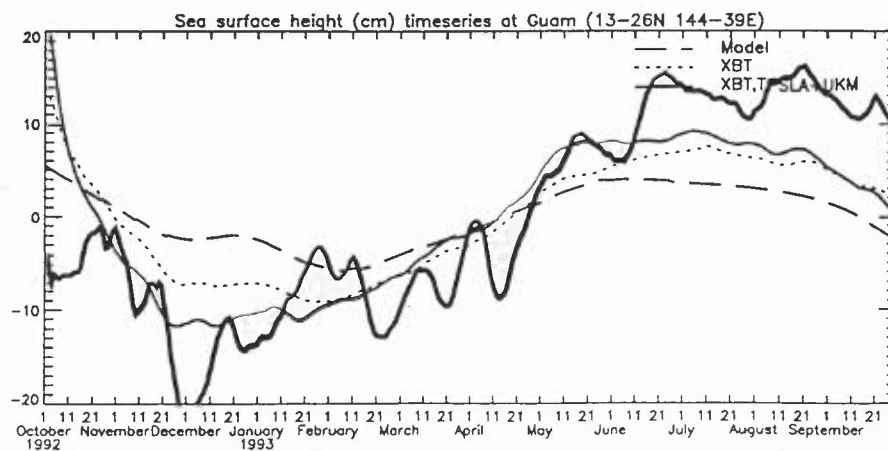
Area 4



Area 5



Area 6



Area 7

Figure 9. (Continued)

