NOTES AND CORRESPONDENCE

An Evaluation of the National Meteorological Center Weekly Hindcast of Upper-Ocean Temperature along the Eastern Pacific Equator in January 1992

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ABSTRACT

The upper-ocean temperature distribution along the Pacific equator from 139° to 103°W was observed in January 1992 with temperature profiles recorded from a ship and inferred from an ocean general circulation model calculation involving data assimilation (i.e., hindcast). An El Niño episode was in progress. The 100-m-thick mixed layer depth, the mixed-layer temperature, and the depth-averaged temperature below the thermocline were similar in both data products. Considerable differences occurred in the representation of the 15°–25°C thermocline, such as the depth-averaged temperatures above and below the 20°C isotherm, the east-west slope of the 20°C isotherm, and a 1000-km-wide depression. The longitudinal-averaged root-mean-square difference between the hindcast and observed depths of the center of the thermocline was 17 m. Most of the disparities could be attributed to a high wavenumber transient event that the model-based assimilation system was not intended to resolve.

1. Introduction

The interannual El Niño warming of the surface water of the eastern equatorial Pacific produces global atmospheric climate variations. Detailed analysis of the dynamics of an El Niño episode remains elusive because subsurface flow and thermal fields, especially along the eastern Pacific equator, are severely undersampled. A tenet of faith among many oceanographers is that judicious assimilation of limited in situ observations into a realistic high-resolution time-dependent, three-dimensional ocean general circulation model (OGCM) will provide simulated oceanographic data products suitable for dynamical analysis.

Since 1985, the National Oceanic and Atmospheric Administration’s (NOAA) National Meteorological Center (NMC) has routinely produced an operational monthly hindcast of the previous month's upper-ocean thermal condition in the equatorial Pacific (Leetmaa and Ji 1992). Hayes et al. (1989) demonstrated that estimation of thermocline depth at the equator needed further improvement. Since 1990, a new near–real time ocean model–based hindcast system routinely produces weekly hindcasts of Pacific Ocean thermal conditions with a delay of about 14 days (Ji and Leetmaa 1991; Leetmaa and Ji 1992). Changes included new techniques of data assimilation, use of the NMC forecast-analysis wind product instead of a wind field derived only from ship measurements, and assimilation of increased quantity of observations, such as subsurface temperature profiles recorded at moored buoys as well as from an increased number of ships. A comparison between the NMC weekly hindcast and a quasi-synoptic oceanographic survey of the upper-ocean temperature along the equator between 139° and 103°W during January 1992 is the subject of this paper.

2. Data

The University of Southern California research vessel R/V John V. Vickers transited westward along the equator from 103° to 139°W for PACFLUX II investigations of the Joint Global Ocean Flux Studies (JGOFS) program. A model T4 expendable bathythermograph (XBT), which recorded temperature at 728 sequential times or “counts” between the surface and 460 m, was launched at integral longitudes. The XBT depth, z, corresponding to a count, c, is defined by $z = 6.472 (C/10) - 0.00216 (C/10)^2$, which is the empirical formulation provided by the manufacturer. However, Hanawa and Yoritaka (1987) reported that the XBT falls through the water at a faster rate than that computed by the standard formula. Therefore, all XBT depths were increased by 5% because the
data were compared with a hindcast that assimilated depth-corrected XBT data and fixed-depth temperatures from moored buoys.

The 103°W XBT was launched on 27 December 1991, and the temperature profile at 139°W was recorded on 13 January 1992. The Vickers remained on station near 0°, 124°W for six days beginning 4 January. All XBT observations were intended to be transmitted on the Global Telecommunications System (GTS) and to be used in the NMC weekly hindcast. However, the XBT-to-GTS technique performed successfully only between 130° and 139°W or from 12–13 January. No Vickers’ XBT data were assimilated between 130° and 103°W. Fortunately, the XBT recorder on the Vickers stored all the XBT data measured from 103°–139°W.

The 12–18 January 1992 NMC hindcast temperature was created with theOGCM developed at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) by Bryan (1969) and Cox (1984) and was substantially modified for the tropical Pacific by Philander (1990). Numerous evaluations of the Philander/GFDL OGCM have proven the simulations to be reliable (Philander 1990). The geographical domain of the NMC version of the Philander/GFDL OGCM was 120°E to 70°W and 45°S to 55°N, with sponge regions poleward of 35°S and 45°N. Within the sponge layers the model temperature and salinity fields were forced to relax to the climatological values. The 1.5° east-west resolution of the NMC hindcast was slightly greater than the 1° longitudinal spacing of the Philander/GFDL OGCM; the 1/3° north–south resolution between 10°S and 10°N remained unchanged. Weekly averaged hindcasts were stored on a 1°-latitude and 1.5°-longitude grid. The vertical resolution and the 1-h time step of the NMC hindcast were the same as the Philander/GFDL OGCM. There were 10 equal layers above 100 m, and we used the uppermost 19 levels, which occurred above 423 m. The NMC hindcast methodology did not alter the Richardson Number dependent vertical-mixing parameterization used in the Philander/GFDL OGCM. Also, the horizontal eddy-exchange coefficients (1 x 10^3 m^2 s^-1) were the same. The net air–sea heat flux was set to zero because SST was continuously assimilated.

A continuous data-assimilation scheme, which was implemented at NMC in 1989 (Ji and Leetmaa 1991), uses variational optimal interpolation (Derber and Rosati 1989) to combine surface and subsurface temperature measurements with the modeled temperatures. The SST data were obtained from a variety of instrument platforms: day and night multichannel SST retrievals from NOAA polar-orbiting satellites; ships; satellite-tracked drifting buoys. Subsurface temperature measurements were recorded from moored buoys and from XBTs launched from the ship-of-opportunity network (Fig. 1). The depths of all XBT temperatures were increased by 5% (Hanawa and Yoritaka 1987).

Extensive quality control eliminated spurious subsurface temperature measurements. Each subsurface temperature profile was compared with the profile computed from the hindcast from the previous week and/or a climatological-mean profile at the same site where data considered incorrect can be discarded. Approximately 2%–5% of the weekly XBT dataset were discarded. Comparison of a ship’s track, determined from the locations affixed to XBT data and the ship’s weather reports, revealed location errors.

Data assimilation was done continuously during model integration. At an assimilation time step, all subsurface temperature observations recorded two weeks before and two weeks after this time, and all SST data recorded 1 week before and 1 week after this time, were assimilated. The hindcast temperature at the time step immediately prior to the assimilation time serves as the first-guess estimate. For each grid point, error covariances and temperature differences were computed between the first-guess temperature field and all data occurring within a 4° domain of influence. The error covariances were weighted with a Gaussian function to account for the distances between data values. An objectively analyzed temperature correction, which was computed with the error covariances and temperature differences (Lorenc 1986), and which was weighted by the two-week or four-week data window (Derber and Rosati 1989), was added to the first-guess temperature to create the optimal interpolated temperature for the next integration time step. The assimilation was made for three consecutive 1-h time steps every 12 h of integration time. The small modification made to the hindcast on all of the 1-h integration time steps allows the circulation to adjust to the thermal field almost instantaneously.

A 12–18 January weekly averaged surface wind-stress distribution, which was centered at 1200 UTC on 15 January, was computed from the six-hourly NMC global atmospheric forecast-analysis system. The weekly averaged wind stress was linearly interpolated at 1-h intervals to match the hindcast integration time step.

3. Results

The XBT surface temperatures at 110°, 124°, 139°, and 140°W on 28 December and 10, 13, and 19 January, respectively, were virtually identical to 1-m depth daily averaged measurements recorded at moored buoys at 110°, 125°, and 140°W (Freitag and McPhaden 1992; Hayes 1992).

The observed XBT temperature section (Fig. 2a) was gridded to conform to the depths and longitudes of the NMC hindcast. A 1-m averaged XBT temperature centered at the middle depth of each OGCM layer was computed. We intentionally did not compute the average XBT temperatures within the depth intervals corresponding to the hindcast layers because the ob-
Fig. 1. Locations of temperature profiles used in the preparation of the 12–18 January 1992 hindcast. A total of 2321 temperature profiles (983 from XBTs and 1338 from moored buoys) were assimilated in January 1992 to produce the weekly averaged hindcast centered on 15 January. Small dots represent XBT observations from the ship-of-opportunity network. Triangles represent moored-buoy sites, which are described by Hayes et al. (1991).

jective is to determine the hindcast representativeness of the natural state. Temperature at the hindcast 1.5°-longitudinal interval was linearly interpolated from the XBT data adjacent to the hindcast longitudes. A less intense vertical gradient of temperature occurs in the thermocline of the gridded XBT data (Fig. 2b). The 100-m thick near-surface mixed layer and the 100-m thick 13°C thermocline (defined as the 12°–14°C depth interval) were independent of the depth-longitude grid resolution.

The 12–18 January weekly NMC hindcast of the upper-ocean temperature distribution (Fig. 2c), which was computed with assimilation of the 12–13 January Vickers XBT data from 130°–139°W, resembled the gridded XBT observations (Fig. 2b). The hindcast (Fig. 2c) was very similar to the corresponding hindcast (not shown) computed without assimilating any Vickers XBT data: all grid-point differences were smaller than 0.5°C, except between 25 and 75 m from 133° to 138°W where the differences were less than 1.0°C. Assimilation of 139°–130°W Vickers XBT data had almost no effect upon the NMC hindcast thermocline.

Throughout the 139°–103°W interval, the XBT and hindcast temperatures (Figs. 2b,c) within the uppermost 100 m and from 200–363 m were especially similar (Fig. 2d). Larger differences occurred within the thermocline at depths between 100 and 200 m (Fig. 2d). The gridpoint maximum absolute value temperature difference was 6.3°C at 136 m at 114°W, where the depth-averaged 100–150-m hindcast temperature was 5°C less than that observed (Fig. 2e).

Between 139° and 120°W, the hindcast produced higher temperatures in the thermocline (Fig. 2d). This phenomenon may be explained by an upwelling transient event that was not resolved by the hindcast-analysis system. An upwelling event was recorded at the moored buoys at 2°S and 2°N along 140°W on about 10 January.

Between 120° and 110°W the hindcast temperatures in the upper portion of the thermocline were substantially lower (Fig. 2d). At 114°W the observed 150-m depth of the 20°C isotherm, which occurs in the middle of the equatorial thermocline (Colin et al. 1971; Halpern 1987), and which is considered representative of the depth of the thermocline, was 35 m deeper than in the hindcast (Fig. 2f).

A possible cause of the 120°–110°W downward displacement of the measured thermocline is eastward propagation of a downwelling Kelvin wave. Evidence was found in the 0°, 155°W and 0°, 125°W moored-buoy measurements of the depth of the 20°C isotherm (Hayes 1992) that from 2 to 17 December a 25-m
Fig. 2. Upper-ocean temperature distribution (°C; contour interval is 1°C) along the equator: (a) XBT measurements recorded from the R/V Vickers during 27 December 1991–13 January 1992; (b) XBT measurements to conform with the hindcast grid; (c) 12–18 January NMC weekly averaged hindcast with assimilation of R/V Vickers XBT data recorded from 139°E to 130°W; (d) gridpoint temperature differences (in degrees celsius; contour interval is 0.5°C) between gridded XBT data, (b), and NMC hindcast, (c); (e) Longitudinal distributions of depth-average temperature over a variety of depth intervals, which were computed from the gridded XBT measurements, (b) and the NMC hindcast, (c). The dashed line represents gridded XBT data; the solid line represents the NMC hindcast; (f) Longitudinal distributions of the depths of the 20°C isotherm. Dashed line represents gridded XBT data, (b); solid line represents NMC hindcast, (c).
downwelling disturbance in the thermocline moved
eastward from 155° to 125°W at about 2.5 m s⁻¹ (i.e.,
about 2° longitude per day), which corresponded to
the propagation speed of a first-mode baroclinic Kelvin
wave (Knox and Halpern 1982). Inspection of Mc-
Phaden’s (personal communication, 1992) daily-av-
ergaged equatorial undercurrent (EUC) transports per
unit latitudinal width at 0°, 140°W and 0°, 110°W
revealed that the maximum EUC transport during 10
November to 20 January occurred at 140°W on 4 De-

cember and at 110°W on 21 December; thus, the east-
ward speed of the maximum EUC transport was 2.2
m s⁻¹. The thermocline depression was also observed
on 22 November at 0°, 170°W (Hayes 1992) and trav-
elled to 0°, 155°W at 2.0 m s⁻¹. Had the thermocline
depression at 125°W continued eastward at 2.5 m s⁻¹,
then the maximum depth of the feature would have
passed 114°W on about 22 December, which was
nearly 12 days before the Vickers XBT measurement
was made at 114°W, and would have reached the Ga-
lápagos Archipelago on 3 January. Examination of Wy-
rfki’s (personal communication, 1992) sea level
measurements at Baltra (0°, 90°W) indicated a nearly
monotonic 15-cm rise from 21 December to 1 January.
Baltra sea surface heights were nearly uniform from
3–8 January and then experienced a rapid 10-cm rise
reaching a maximum for the month on 13 January,
which was 10 days after the maximum depression
passed 114°W. The time interval for a Kelvin wave
pulse moving at 2.5 m s⁻¹ to travel from 114°W to
Baltra would be about 12 days, which was nearly the
same as the 10-day observed time separation. A sea
level variation similar to the one at Baltra was subse-
quently observed along the coast of Peru (Enfield
1992). An increase in sea surface height corresponds
to a thermocline depression because the increased
quantity of heat stored above the thermocline produces
higher sea surface height. The Vickers data combined
with the Hayes (1992) and Wyrtki (personal com-

munication, 1992) measurements suggest the occur-
rence of a Kelvin wave pulse from 170° to 155°W,
155° to 125°W, and 114° to 90°W. That the travel
time between 125° and 114°W was not consistent with
the Kelvin wave evidence is an enigma. Did the Kelvin
wave speed decrease in the eastern Pacific, such as ob-
served by Halpern and Zlotnicki (1992) during the
1987 El Niño, or was there more than one Kelvin wave
pulse are questions beyond the scope of this report.

The 139°–103°W longitudinal-averaged hindcast
and observed depths of the 20°C isotherm were differ-
ent by 5 m. The two curves in Fig. 2f were not linearly
related because the correlation coefficient was less
than 0.1 and not statistically significant at the 95% level.
That the 17-m root-mean-square (rms) difference was
times larger than the mean difference means that
large differences occurred (Fig. 2f). The longitudinal-

averaged rms difference was similar to the 1985–1987
average rms difference at 140° and 110°W (Hayes et
al. 1989), which does not indicate a dramatic im-
provement in the hindcast depth of the center of the
thermocline.

Tidal internal gravity-wave motions produce vertical
displacements of the depth of the 20°C isotherm (and
all isotherms), which create an uncertainty in the in-
terpretation of XBT measurements. Two time series
of the depth of the 20°C isotherm were computed at 0°,
110°W, where conductivity–temperature–depth
(CTD) measurements were recorded at 2-h intervals
for 48 h on 9–11 February 1979 and at 1-h intervals
for 12 h on 4 May 1979 (Mangum et al. 1980). For
each time series the standard deviation of the vertical
displacements of the 20°C isotherm was 4 m. A similar
estimate of 20°C isotherm displacement was deter-
mined at 0°, 140°W from the Chereskin et al. (1986)
intensively sampled 12-day time series. If a normal dis-
tribution of isotherm depth fluctuations is assumed,
then twice the standard deviation represents the reli-
ability within 95% confidence limits of the depth of
the 20°C isotherm. Thus, the XBT and hindcast depths
of the 20°C isotherm (Fig. 2f) were statistically different
at the 95% confidence level throughout most of the
139°–103°W region.

4. Discussion

The 12–18 January 1992 NMC weekly averaged
hindcast of temperature along the equator in the eastern
Pacific was compared with XBT observations during
the anomalous ocean–atmosphere interactions asso-
ciated with the 1991/1992 El Niño. The XBT and
hindcast temperatures and depths of the mixed layer
were almost identical. Similarly, the 13°C thermosalt
was in excellent agreement.

The most substantial differences between the Vickers
data and the hindcast occurred within the thermocline.
Both the absence of the 9°-wide depression centered
near 115°W and the greater upward slope towards the
east from 139°–115°W in the hindcast may be caused
by a combination of inadequate surface wind and the
effects of the assimilation scheme, which are described
below. The influence of approximate 20-day period,
1000-km zonal wavelength current and temperature
oscillations (Halpern et al. 1988) is considered to be
negligible because the amplitude of the wave motion
is greatly reduced during an El Niño episode.

The surface wind field in the narrow equatorial wave
guide is very important to simulate thermal and flow
fields along the equator (McCreary 1976). For instance,
a 15% smaller westward wind stress leads to a deepening
of the hindcast thermocline, which increases from 5 m
at 140°W to 25 m at 105°W (Leetmaa and Ji 1989).
In March 1991, NMC introduced the T126 version of
the atmospheric general circulation model forecast-
analysis system. The new NMC-derived equatorial Pa-
cific surface wind field remains to be evaluated.

Another important factor contributing to the differ-
ences between the Vickers XBT and NMC hindcast
datasets is the data-assimilation technique. The 4° ra-
dians of influence and 4-week subsurface data window were designed to filter fluctuations with submonthly time scales. The moored-buoy measurements had a greater impact upon the hindcast in the narrow equatorial zone compared to XBT data because moored measurements were recorded continuously with time, unlike the sporadic XBT sampling. Inspection of Fig. 1 indicates that in the ±2°-latitudinal equatorial radius of deformation (Gill 1982) between 140°W and 103°W, the only subsurface temperature observations during January were the few XBTs from the *Vickers* and the continuous moored-buoy measurements at 140°, 125°, and 110°W. The time window for assimilation of moored-buoy data could be reduced for a weekly averaged hindcast, which would not diminish the quantity of data because the moored-buoy measurements are recorded continuously. The hindcast would then be expected to yield a more accurate representation of the transient thermocline depression. It remains to be tested whether the spatial-sampling resolution for oceanographic data assimilated into an OGCM need be as high as that described by the Nyquist Theorem.

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