

Using Moored Buoy Observations to Assess and Improve a Circulation Model In Near-Real-Time

Frank L Bub, Charles W. Horton, Melody A. Clifford, Dennis Krynen, Richard Myrick

Naval Oceanographic Office
1002 Balch Blvd.
Stennis Space Center, MS 39522, USA
BubF@NAVO.NAVY.MIL

Abstract—The Naval Oceanographic Office (NAVOCEANO) deployed a Texas Automated Buoy System (TABS) during January 2003 to collect data expressly for the assessment and improvement of our operational Shallow-Water Analysis and Forecast System (SWAFS) model. TABS observed ocean temperatures, salinity, depth, and currents, along with air temperature, humidity, pressure and winds. These data were stored and relayed at half-hour intervals via Iridium, processed, archived, and made available to NAVOCEANO modelers in near-real-time. Using time series and inferred Lagrangian drifts, comparisons are made between these observations and ocean properties predicted daily by 48-hour SWAFS forecasts. The information is used to make model adjustments leading to improvements in forecast current speed, direction, and phase. The decay of model skill over the forecast period is examined, and we discuss how these comparisons can be used to provide users of SWAFS (and similar ocean models) with guidance on model uncertainties, strengths, and weaknesses.

I. INTRODUCTION

The Naval Oceanographic Office (NAVOCEANO) deployed a Texas Automated Buoy System (TABS) in the Northern Arabian Gulf on 19 January 2003 to collect ocean and atmospheric data. The main objective was the assessment and improvement of the Northern Arabian Sea (NAS) nest of NAVOCEANO's operational Shallow-Water Forecast and Analysis System (SWAFS). This model provides daily 48-hour forecasts of ocean current, temperature, and salinity information to Navy assets in the area.

The TABS observations are being used to assess SWAFS by considering the following:

- Whether the model depicts oceanographic reality.
- How to quantify our confidence in model products by placing bounds on forecast information and making error estimates.
- The effects when model changes are made.
- Relationships between forcing and ocean processes.

The purpose of the NAVOCEANO ocean modeling effort is to provide Navy users with information that enhances and improves their operational capabilities. Thus, we are required to provide real-time forecasts that are useful tools for exercise planning and execution. These products must be updated daily in a timely manner. Part of the delivery should include a sense of accuracy and applicability in a given situation. Thus, model assessments are an important part of any product suite.

This paper begins with a summary of the data collected. After briefly describing the SWAFS model, we discuss the approach used to make our assessments. Our comparison will be used to answer the questions listed above and our findings are summarized in the conclusions.

II. THE DATA

The observational data were collected by a TABS (Fig.1) at a depth of 24 m in the Northern Arabian Gulf. The buoy ended reliable transmission on 15 March 2003 after 54 days of operation.

The following meteorological and oceanographic measurements were collected:

- At 3.0 m elevation—wind direction and speed, air temperature and humidity, and atmospheric pressure.
- At 2.1 m depth—temperature and salinity using a Seabird SBE-37 Microcat.
- At 2.5 m depth—horizontal currents (u and v) and temperature using an Aanderaa DCS 3900R current meter.
- Between approximately 8 and 24 m—horizontal velocity profiles in 2-m bins using a RDI 300 kHz Workhorse Acoustic Doppler Current Profiler (ADCP).
- The ADCP also measured temperature at 2.1 m and varying water depth as a measure of distance between instrument face and the bottom.

TABS data were logged every 30 minutes and transmitted hourly via Iridium. At NAVOCEANO, the data were automatically collected, checked, collated, plotted,

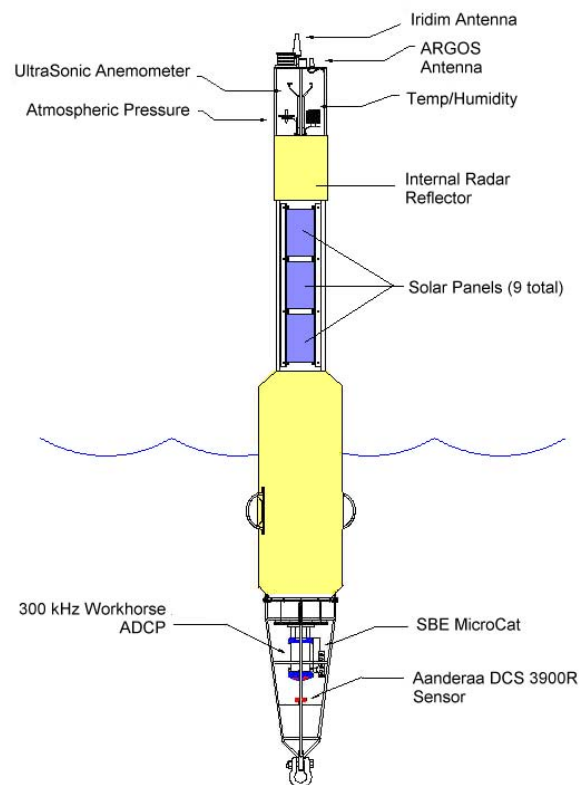


Fig. 1. TABS schematic.

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and appended to a set of Web-served files. We have collected and compared data covering 52 full sets of 48-hour SWAFS forecast periods between 20 January and 13 March 2003 (SWAFS did not run on 2 February).

III. THE MODEL

SWAFS is described in detail by [1] and [2]. It is a primitive equation, three-dimensional circulation model referred to as the Princeton Ocean Model (POM) [3]. SWAFS uses a 2.5-layer surface turbulence closure model according to [4].

The NAS SWAFS nest was initiated in October 2002 on a nominal 2-km grid north of 19.2N including the Gulf of Oman and the Arabian (Persian) Gulf. There are 47 sigma layers in the vertical bounded by isopycnal interfaces. The model provides a 48-hour forecast daily after a warm start with 24-hour hindcast (which is considered an analysis). Vertical oceanic boundary conditions from a larger Northern Indian Ocean SWAFS domain are applied along the southern boundary. The model is forced at the surface using wind stress and heat fluxes derived from a blend of Fleet Numerical Meteorological and Oceanographic Center (FLENUMMETOCCEN) Monterey Navy Operational Global Atmospheric Prediction System (NOGAPS) and Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) winds and air temperatures at 6-hour time steps through 48 hours. Fresh water inputs from historical river runoffs are used when available.

There is a near-real-time assimilation of Conductivity, Temperature, and Depth (CTD) profiles, Expendable Bathythermograph (XBT) data, and PALACE float observations using optimal interpolation (OI) techniques. Sea surface temperatures come from NAVOCEANO Multi-Channel Sea Surface Temperature (MCSST) derived from Advanced Very High Resolution Radiometer (AVHRR) satellite data. Also assimilated are sea surface elevations from daily NAVOCEANO analyses of collected satellite altimetry. These data are blended with subsurface temperature and salinity structure from a daily update of the NAVOCEANO Modular Ocean Data Analysis System (MODAS) in water deeper than 600 m. For this study, daily model derived profiles at the TABS site were saved at 1-hour time steps.

The bottom bathymetry used for the NAS SWAFS was found to be inaccurate and the possible source of large forecast errors. For example, model depth at this site was 20 m while the TABS measured a mean of approximately 24 m.

Prior to the deployment of the TABS, a number of steps was taken to improve SWAFS forecasts. These steps were mainly adjustments to model parameters to better replicate phase and amplitude derived from historical tidal constituents at a series of coastal tidal stations. Until the TABS data were available, these tidal comparisons were the primary method of model assessment.

Changes after the October 2002 installation of the NAS 2-km SWAFS included adjustments to the minimum height used for nudging the tidal database and the addition of constituent data for a total of 31 Arabian Gulf stations. Variable time offsets for each tidal station were applied to improve the results. Heat flux code was modified to put a cap in the air-sea differences. MCSST decay distances were adjusted, and in December 2002

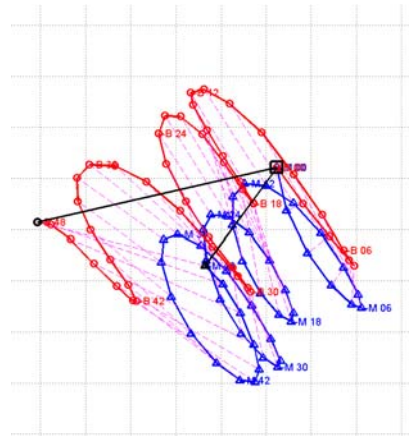


Fig. 2. A 48-hour Lagrangian track of a water particle at 2-m depth originating at the TABS buoy (black square) at 00Z on 20 February 2003. Grids at 1-minute. Red path derived from TABS current observations and blue path from SWAFS forecast. Dots at hourly time steps. Black vectors show net motion. Here forecast vector is 4.4 km toward 216 while actual vector is 8.8 km toward 257.

we began using the high resolution Local Area Coverage (LAC) MCSST. By late January 2003, river flows had been increased to 100 percent. In January 2003, FLENUMMETOCCEN began supplying 18-km resolution COAMPS wind fields to force the NAS.

After TABS was deployed on 19 January 2003, adjustments were made to bring the forecast in compliance with the buoy observations. Each step represented a time boundary for the "weekly" assessments presented later. On 24 January, the MCSST assimilation scheme was revised so data were held for a shorter period of time, and the MCSST nudging parameter was lowered to make the model more responsive to sea surface temperature changes. On 28 January, near-bottom speeds were increased by lowering the bottom friction layer roughness parameters. On 04 February, we switched from the 18-km to higher resolution 6-km COAMPS wind forcing. On 12 February, the surface layer turbulence exchange was revised to increase downward mixing processes in shallow water. This was done to "spread" excessive surface current speeds deeper into the mixed layer. Consistent differences between TABS and COAMPS air temperatures led us to discover that the new 6-km COAMPS fields had been accidentally displaced geographically. FLENUMMETOCCEN corrected this problem in early March.

IV. THE MODEL ASSESSMENT METHODS

After the data are linearly interpolated to hourly intervals, they are then presented as a Lagrangian display of object drift over the forecast period (Fig. 2). The observed (red) and forecast (blue) pathlines or tracks begin at the TABS at time zero and propagate according to hourly velocities. This approach assumes that TABS lies in a spatially uniform field of flow—reasonable as the path excursions are generally less than 5 km or two gridpoints. At the end of the forecast period, vector speeds and directions are indicated by the black lines. Vector speeds, vector directions, and instantaneous speeds are then compared for each forecast period.

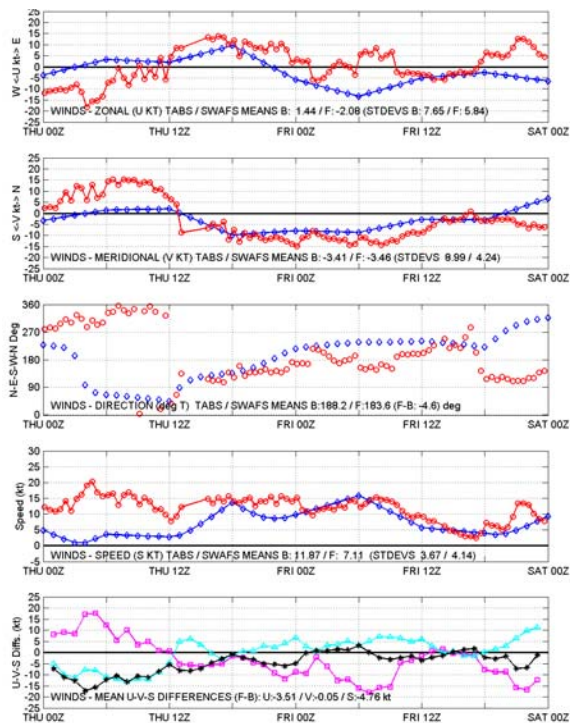


Fig. 3. A 48-hour time series of TABS (red) and FLENUMMETOCEN COAMPS (blue) winds for the 20 February 2003 forecast period. From top to bottom: zonal wind speed (u, +eastward, kt), meridional wind speed (v, +northward, kt), wind direction (000 northward), wind speed (kt), forecast minus observed differences (u-magenta, v-cyan, speed-black).

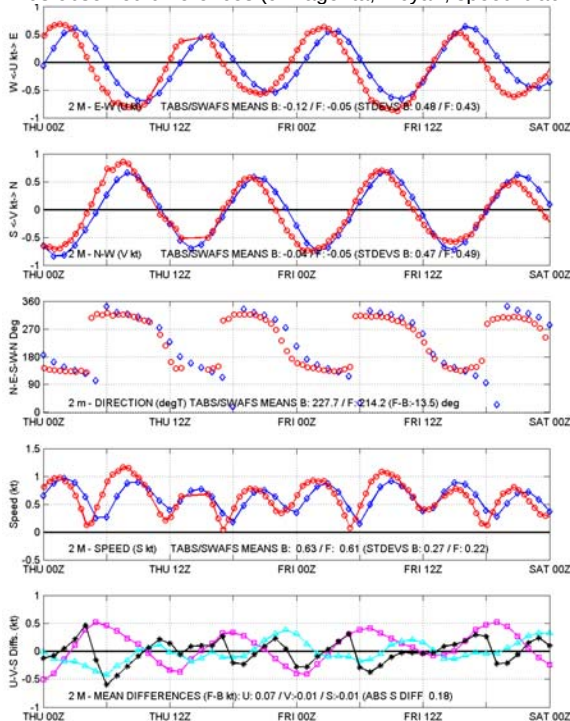


Fig. 4. A 48-hour time series of TABS (red) and SWAFS (blue) 2-m depth currents for the 20 February 2003 forecast period. From top to bottom: zonal current speed (u, +eastward, kt), meridional current speed (v, +northward, kt), current direction (000 northward), current speed (kt), forecast minus observed differences (u-magenta, v-cyan, speed-black).

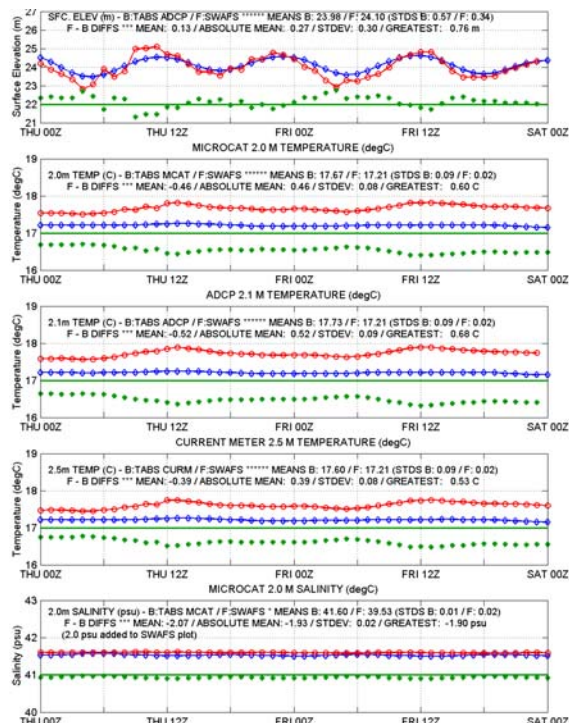


Fig. 5. A 48-hour time series of TABS (red) and SWAFS (blue) comparisons for 20 February 2003. From top to bottom: surface elevation (m), temperatures at 2.0, 2.1, and 2.5 m (deg C) and salinity at 2.1 m (psu). Note that 2.0 psu is added to SWAFS salinity for this comparison. Green dots indicate SWAFS-TABS differences plotted at same scales relative to the green lines.

TABS wind, current, surface elevation, temperature, and salinity data are plotted in 24- and 48-hour time series with the corresponding FLENUMMETOCEN wind (Fig. 3) and SWAFS forecasts (Figs. 4 and 5). Means and standard deviations of the data sets for the forecast period and their hour-to-hour differences are used to assess the SWAFS forecast skills. Here, the "difference" between forecast and observed values is the metric to represent "simple model error." These results are tabulated for daily 24-hour forecast periods at 2-m and 20-m depths and the 48-hour forecast period at 20 m. Because most Navy applications require speeds in knots, we have used these non-cgi units.

Note that calculating mean speed and direction from both the time series (Fig. 3) and the vector plots (Fig. 2) will yield exactly the same results.

V. RESULTS

We initially look at the plots to determine whether the model is reproducing the observed physical processes. For example, in Fig. 4 the forecast velocity amplitudes and periods follow the observations very well. The direction panel suggests the observed currents swing back and forth rather than rotating through 360 degrees (there are no red dots in the northeastward quadrant). The speed panel indicates a lag of approximately one hour at slack tide. The elevation panel (Fig. 5) shows that the model is reproducing the rise and fall of the tides extremely well. In this example, temperatures are under-forecast by approximately 0.5°C, and the model does not appear to reproduce the small daily increases seen around 1200Z. The model consistently under-forecast the

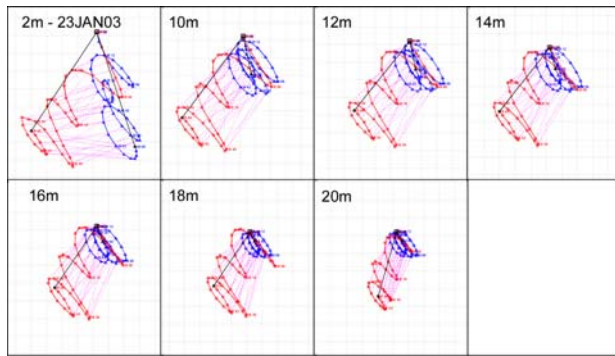


Fig. 6.a. Same information as Fig. 5 at the indicated depths for 23 January 2003.

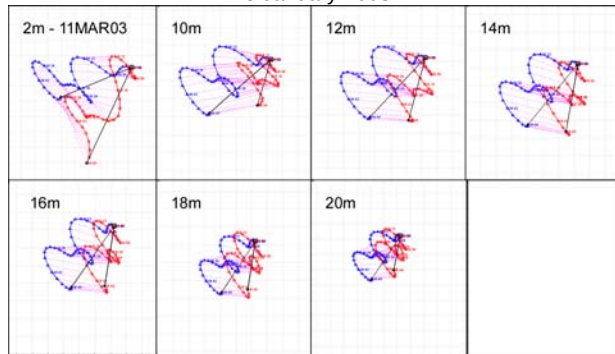


Fig. 6.b. Same as Fig. 6.a. for 11 March 2003.

salinities by about 2.0 psu. Fig. 2 indicates that the model reproduces a rotary tidal flow quite well. Note in this example that small directional errors are compounded over the 48-hour period, so the net forecast vector speed is half the observed value and the forecast direction is 41 degrees to the left of the actual direction.

Fig. 6.a illustrates vertical changes in the current structure as one proceeds downward in the water column. We note that while the red observed vector length decreases gradually with depth, the blue forecast vector length drops off quickly between the surface and 10 m. We used this information to adjust model parameters by reducing bottom friction and revising the surface layer energy transfer processes, with Fig 6.b an example of a successful result.

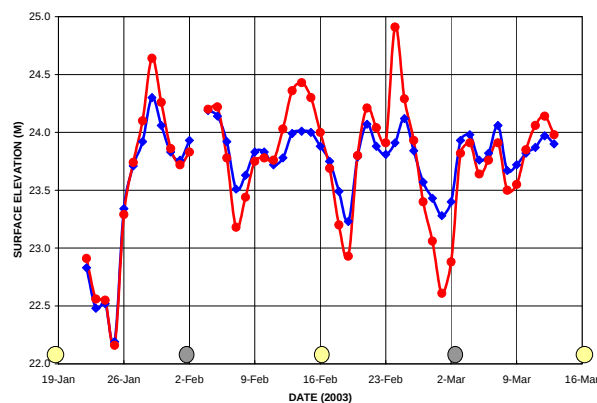


Fig. 7. Daily 24-hour mean surface elevations as measured by TABS (red) and forecast by SWAFS (blue). Yellow and grey dots show times of full and new moons, respectively. On 26 January 2003, the buoy was apparently moved to deeper water.

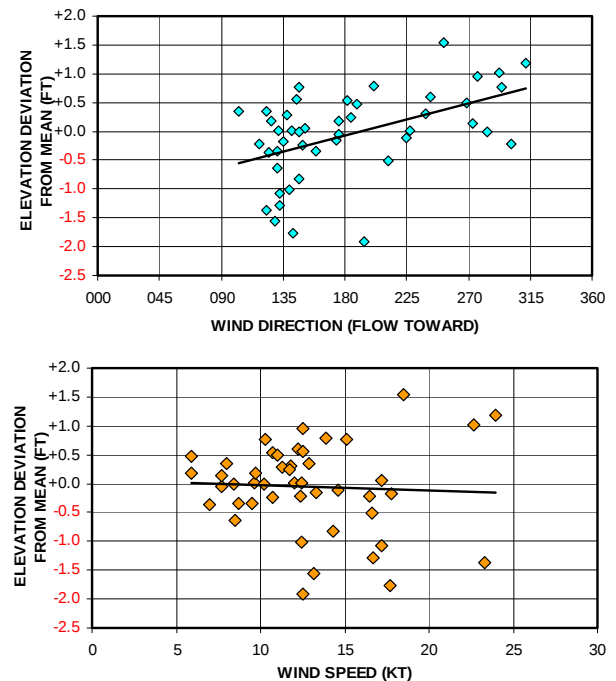


Fig. 8. Plots of 24-hour mean TABS observed surface elevation deviation from mean (ft) versus (a) wind speed and (b) wind directions (toward).

Mean daily surface elevations (Fig. 5) represent sub-tidal processes, biased slightly by the difference between solar and tidal periods. Fig 7 shows that SWAFS forecasts the phases and small-amplitude sub-tidal events well, but under-forecasts large amplitude variability by approximately 0.5 m. Fig. 8 indicates no apparent relationship between variations in surface elevation and local wind speed or direction. We note no wind toward the northeast quadrant during this seven-week period.

Week-to-week means of vector speed (Fig. 9), vector direction (Fig. 10), and instantaneous speed (Figs. 11 and 12) shown as forecast minus observed differences (or simple errors) provide insight into changes in model performance as revisions are made.

In Fig. 9, we note that as model adjustments were made, both the 24- and 48-hour forecast trends in 2 m vector speed changed from a slight over-forecast to an under-forecast approaching -50 percent of the measured values. However, all weekly values lie within the one standard deviation range.

The -21 percent and -24 percent mean differences on Figs. 9.a. and 9.b. suggest a moderate degradation of forecast skill between 24- and 48-hours. On the other hand, the upward trend in Fig. 9.c. suggests revisions have slightly improved the near-bottom current forecasts, although they are still under-forecasting TABS data by -52 percent.

Fig. 10.a indicates that the SWAFS 24-hour 2-m vector forecasts average 19 degrees to the left of the observed directions, with large weekly variations. Over the study period, the 2-m 48-hour forecasts have been excellent for mean direction (02 degrees left with a 67 degree standard deviation) as the trend goes from about 45 degrees to the left to 45 degrees to the right of observations. At 20-m depth, the forecast averages 22 degrees left of the observations with an improving trend.

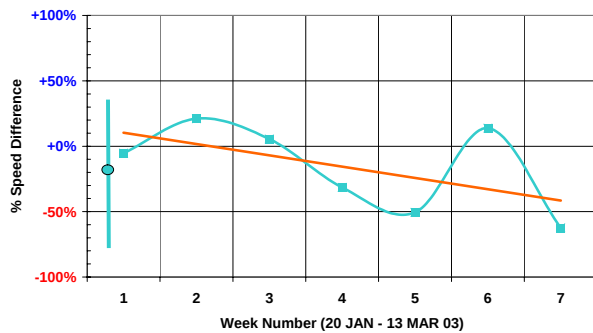


Fig 9.a. Mean weekly forecast minus observed difference in vector speeds at 2 m for 24-hour periods. Percentage is difference divided by observed speed. Overall mean and standard deviation shown at left (see Table 1).

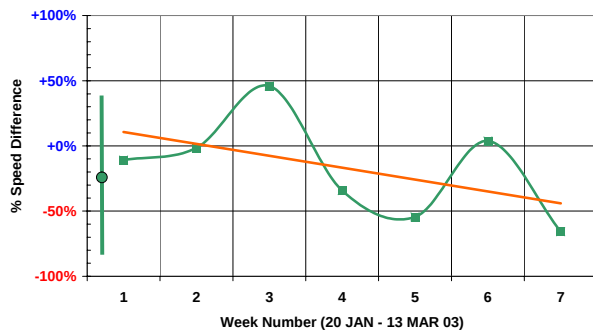


Fig. 9.b. Same as Fig. 9.a for 2-m depth and 48-hour periods.

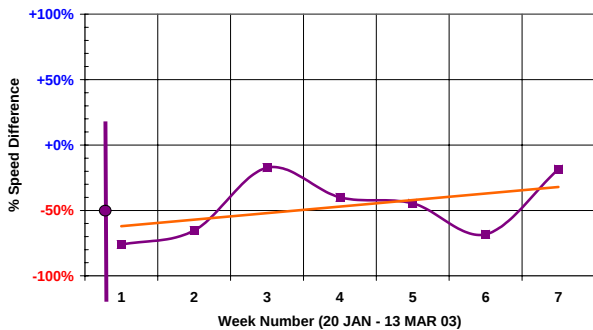


Fig. 9.c. Same as Fig. 9.a for 20-m depth and 48-hour periods.

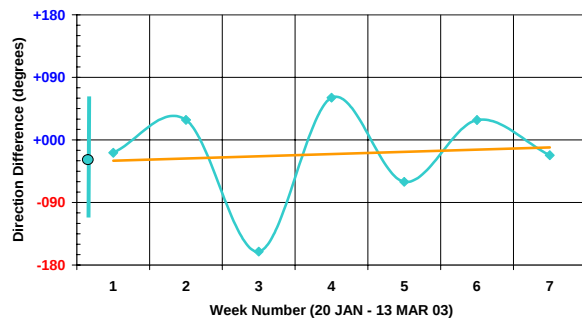


Fig. 10.a. Mean weekly forecast minus observed difference in vector directions at 2 m for 24-hours. Overall mean and standard deviation shown at left (see Table I).

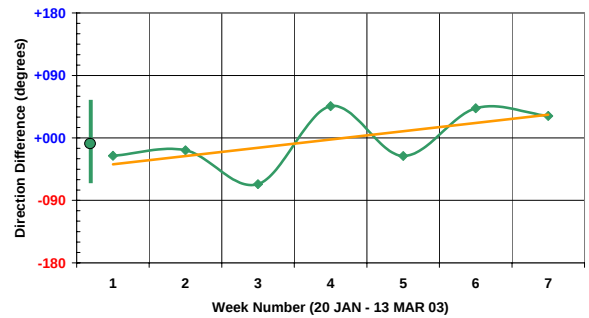


Fig. 10.b. Same as Fig. 10.a for 2-m depth and 48-hour periods.

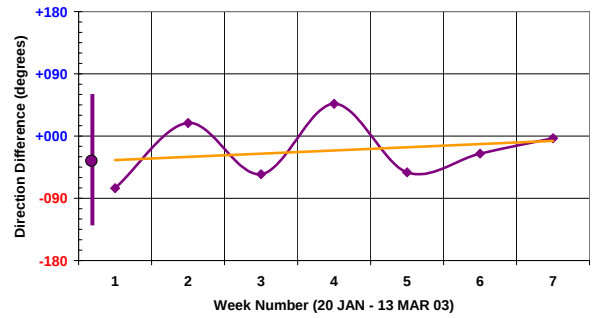


Fig 10.c. Same as Fig. 10.a for 20-m depth and 48-hour periods.

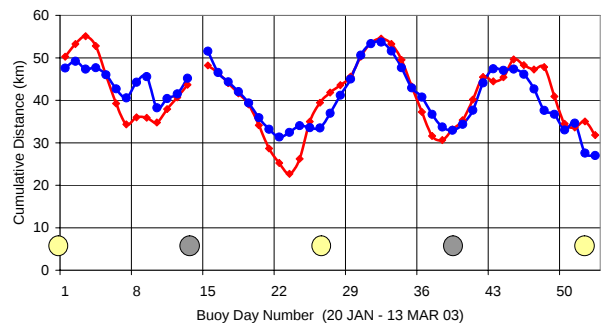


Fig. 11. Daily observed (red) and forecast (blue) distance traveled during a 48-hour period. Yellow and grey dots show times of spring tide during full and new moons, respectively.

In Fig. 11, we compare the 48-hour observed and forecast cumulative distances traveled by a water particle that originates at the buoy. We note that the rise and fall in these distances does not correspond with the phases of spring and neap tides. The mean instantaneous speed differences on Fig. 12 suggest that SWAFS forecasts the 2 m 24- and 48-hour instantaneous speeds very well, while the model under-forecasts the near-bottom speeds by -25 percent. Why SWAFS seems to forecast the instantaneous speeds (which are mostly tidal) well but underforecasts the sub-tidal velocities is a question that bears further study. Standard deviations of order 10 percent indicate little variance in the differences.

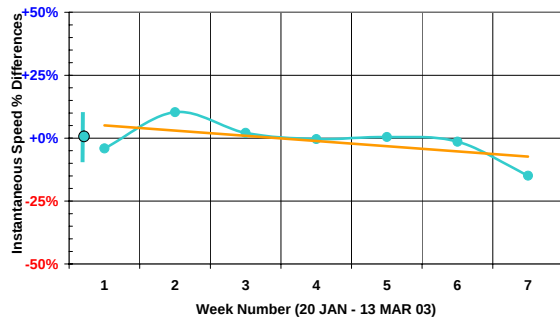


Fig. 12.a. Mean weekly forecast minus observed difference in instantaneous speed at 2 m for 24-hours. Percentage is difference divided by observed speed. Overall mean and standard deviation shown at left (see Table 1).

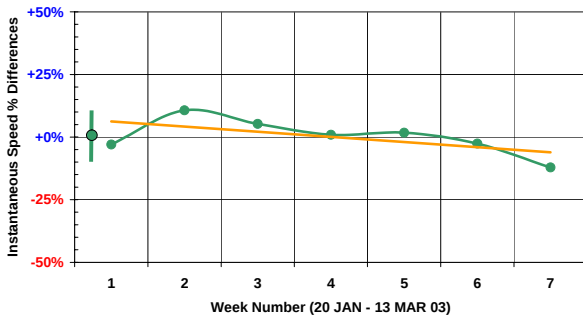


Fig 12.b. Same as Fig. 12.a for 2-m depth and 48-hour periods.

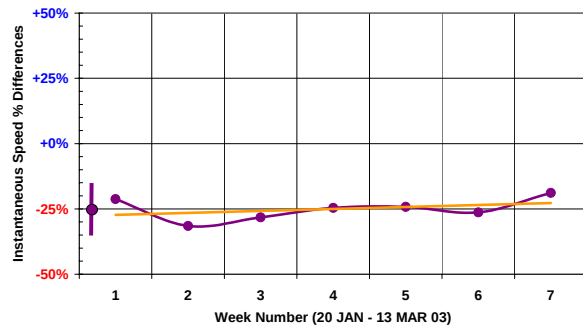


Fig 12.c. Same as Fig. 12.a for 20-m depth and 48-hour periods.

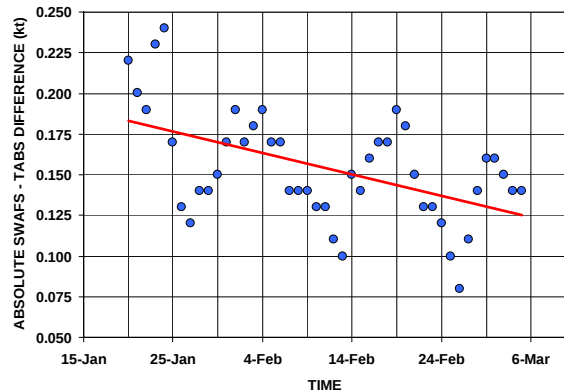


Fig. 13. Time series of absolute SWAFS minus TABS speed differences for 2 m, 48-hour forecast.

Fig. 13 illustrates a downward trend in the daily average of the absolute difference between forecast and observed speeds. This takes into account both amplitude

and phase changes and indicates that revisions to the NAS 2-km SWAFS model over the 7- week period resulted in positive improvements.

VI. SUMMARY AND CONCLUSIONS

For the 52 days that comparisons were made, there was only a slight drop in skill between the 24- and 48-hour forecasts (Table 1). At 48 hours, SWAFS under-forecasts the TABS mean vector speed by 24 percent near the surface and 52 percent near the bottom. The SWAFS vector forecast is only 2 degrees to the left of the mean observed direction at 2 m and 22 degrees left at 20 m. SWAFS forecasted the near-surface instantaneous speed measured by the buoy exactly but was 25 percent too slow near the bottom. Thus, while SWAFS forecasts the near-surface instantaneous speeds and vector directions quite well, it is still low on vector speed. Further adjustments are needed to increase SWAFS speeds near the bottom.

Over the seven-week period of this study, a number of adjustments were made to improve SWAFS current forecasts. As is often the case, changes to improve one parameter affects others.

TABLE I
COMPARISON STATISTICS FOR DEPTHS 2 AND 20 M AND
FORECAST PERIODS 24- AND 48-HOURS.

Depth & Forecast period	2m 24hr	2m 48hr	20m 48hr
TABS vector current speed (kt)	0.11	0.10	0.05
Standard deviation	0.06	0.05	0.03
Std dev as % of observed	56%	56%	60%
SWAFS current difference	-0.02	-0.02	-0.03
Difference as % of TABS	-21%	-24%	-52%
Difference std. dev.	65%	65%	63%
TABS vector direction (degrees)	238	244	224
Standard deviation	63	56	83
SWAFS direction diff.	-19	-02	-22
Left or right of TABS	Left	Left	Left
Difference Std. Dev.	94	67	98
TABS instantaneous current speed (kt)	0.45	0.46	0.38
Std dev as % of observed	0.09	0.07	0.07
SWAFS current difference	-0.00	0.00	-0.10
Percent of TABS	-1%	0%	-25%
Difference Std. Dev.	11%	10%	9%

For example, Fig. 9 shows that improvements in the bottom current vector forecasts are accompanied by changes from over- to under-forecasting at the surface (the net result was a small mean difference over the period). Changes to reduce bottom friction seem to have little effect on either the near-surface or near-bottom instantaneous currents (Fig. 12). In this tidally-dominated location, local wind forcing seemed to play a minor, or at least ill-defined, role in current processes (Fig. 8). We need to consider our Navy customers' requirements when assessing the causes and effects of our model changes.

In summary, the TABS observations were extremely useful to help evaluate SWAFS forecasts and to help us improve our understanding of the SWAFS forecasts in the Northern Arabian Gulf. The data showed that SWAFS forecasts the structure of the local currents well and that

forecast minus observed differences in our metrics of vector current speed, vector direction, and instantaneous speed were "reasonable." This work allowed us to estimate error and uncertainty to the SWAFS forecasts at the TABS site. We were also able to observe the results of revisions to the model, although most changes were very small. There were no strong indicators of relationships between local winds and surface currents during January to March 2003, and further work is needed.

The inclusion of names of any specific commercial or academic product, commodity, or service in this paper is for informational purposes only and does not imply endorsement by the Navy or NAVOCEANO.

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