A REVIEW OF U. S. NAVY ATMOSPHERIC MODEL PRODUCTS IN THE ARABIAN GULF – An Examination of NORAPS and COAMPS

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ABSTRACT

Recent U.S. Navy operational atmospheric products, the Navy Operational Regional Atmospheric Prediction System (NORAPS) and the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS), are reviewed relative to the Arabian Gulf waters. Only the most recent complete calendar years of each product is considered. The structure and description of five products (air temperature, heat flux, surface pressure, wind speed, and wind stress) relevant to the Naval Research Laboratory's coastal modeling efforts for the Arabian Gulf are explained. A detailed discussion of the dynamics and variability observed in the annual and seasonal mean fields are presented. Within this context, the NORAPS and COAMPS products are contrasted. Observations for each of the five atmospheric quantities have been identified in the literature. RMS errors and correlations are computed from comparisons between the Navy atmospheric basin-wide mean products and the observed data. These comparisons provide an avenue to assess the quality of the atmospheric data products with respect to the observed environment. Good agreement between the atmospheric data products and the open literature is found for scalar quantities such as air temperature and surface pressure. Wind speeds and wind stresses tend to be under-predicted with respect to the Winter Shamal though no definitive conclusions can be reached about overall quality due to the high degree of variability in the observed wind sources. On the contrary, heat flux products are determined to be quite poor, at least over Arabian Gulf waters when compared to available observations. Lastly, the preprocessing of the atmospheric products prior to implementation in an oceanic modeling context is included as an appendix.

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1. INTRODUCTION

The surface forcing applied to any coastal circulation model should be of high resolution and quality. Predictions on the order of weeks to days to hour time scales additionally require frequent and reliable data sources. The U.S. Navy has made available atmospheric model products derived in an operational setting. These products contribute exclusively to the surface forcing for coastal, finite element circulation models in the Arabian Gulf.

At the Naval Research Laboratory located at Stennis Space Center, Mississippi (NRL-Stennis), these finite element circulation models include the Advanced Circulation Model for Shelves, Coasts, and Estuaries (ADCIRC) described by Luettich et al. (1992) and the Dartmouth College Model (QUODDY) detailed by Lynch et al. (1996). These models are used as research tools for the study of coastal circulation dynamics and for the development of coastal forecast systems. To date, the atmospheric model products primary used in conjunction with modeling efforts in the Arabian Gulf are wind speed and heat flux.

This report presents a review of recent Navy atmospheric model products obtained for the Arabian Gulf. For our purposes, the products of interest are limited to air temperature, heat flux, pressure, wind speed, and wind stress. (Note: The atmospheric model products are often referenced as “data” throughout the remainder of this report.) Contained within this report are general descriptions of available atmospheric products, processing details for derived products, dynamical interpretation of product fields, and comparisons of atmospheric products to observations published in the literature.

2. ATMOSPHERIC PRODUCT DESCRIPTION

The Navy Operational Regional Atmospheric Prediction System (NORAPS) and the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) atmospheric models have been researched and developed at the Naval Research Laboratory, Monterey, California. The operational execution of the NORAPS and COAMPS models in selected regions occurs at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) in Monterey, California. The daily atmospheric data products are distributed to U.S. Navy Operational Centers such as the Naval Oceanographic Office (NAVOCEANO) at Stennis Space Center, Mississippi. NRL-Stennis personnel locally access these operational products through the mass storage facility associated with the NAVOCEANO MSRC (Major Shared Resource Center), a part of the High Performance Computing program of the U.S. Department of Defense.

The COAMPS and NORAPS models are designed to provide higher resolution in regional areas than the uniform 1.0 degree Navy Operational Global Atmospheric Prediction System (NOGAPS), the standard atmospheric product (Hogan and Rosmond 1991; Hogan et al. 1991). The NORAPS data for the Arabian Gulf is extracted from the

Indian Ocean (ind2) geometry shown in Fig. 1. The NORAPS daily products discussed have a resolution of 0.5 degrees (149 × 81 grid points). Data for the Arabian Gulf are more recently extracted from the COAMPS Southwest Asia Nest 2 operational area depicted in Fig. 2. COAMPS daily products in this operational area have a resolution of 0.2 degrees or approximately 27 km (151 × 127 grid points). The more recent COAMPS replaces the NORAPS regional system and is considered the standard U.S. Navy product for meteorological forcing over coastal waters (Hodur 1993).

All daily atmospheric model products contain one analysis field at the beginning of each forecast file. Calculation of the NORAPS analysis fields begins with boundary conditions from either the NOGAPS analysis or forecasts (Hodur 1982.) Analysis fields are produced at 00Z and 12Z; forecast fields are produced in between analysis fields at a frequency of 6 hours up to 36 hours. COAMPS model products consist of one analysis record at 00Z and 12Z and forecasts every 6 hours through a 60 hour time period. Table 1 lists the temporal breakdown of the file structures.

Table 1 - Description of Atmospheric Model Product File Structures

Data Source	**Analysis Hours (Z)**	**Forecast Hours (Z)**
NORAPS	00	06,12,18,24
NORAPS	12	18,24,30,36
COAMPS	00	06,12,18,24,30,36,42,48
COAMPS	12	18,24,30,36,42,48,54,60

Daily extractions of atmospheric model-computed air temperature, heat flux, pressure, wind speed, and wind stresses have been obtained for the Arabian Gulf region since October 1996. NORAPS was the source of these atmospheric products during the period October 1996 to July 1998 and COAMPS has replaced NORAPS starting in July 1998 to the present. The five atmospheric products relevant to the Arabian Gulf marked for daily extraction and processing consist of two vector quantities and three scalar quantities. The vector quantities are wind speed (m/s) at 10 m height above surface and wind stress (New/m^2). Scalar quantities include air temperature at 2 m height above the surface (°K), total heat flux (Watts/m^2), and mean sea level pressure (millibars for NORAPS and Pascals for COAMPS). The total heat flux is defined as the sum of sensible and latent heat fluxes. More discussion of the heat flux definition follows. For uniformity, relevant figures contained in this report illustrate air temperatures in degrees Celsius (°C) and pressures in millibars (mbars).

The total heat flux is an important indicator of ocean and atmospheric interaction (Rao 1977) but often is represented in a variety of forms. The total heat flux relative to the COAMPS and NORAPS data products is cast as a heat gain (relative to the atmosphere) and is thus positive upward from the ocean surface. These heat flux values act as a heat loss for the ocean and thus are marked by a negative sign with respect to the ocean. Throughout this report, the sign of the COAMPS/NORAPS heat fluxes is expressed in terms of its atmospheric orientation (positive into the atmosphere or a net heat loss from the ocean).

3. METHODS OF DATA PROCESSING

3.1 Movies

Initial processing of the atmospheric model products consists of reading all available data records and converting to an x-y-z columnar format required by the Xvision software (Baird and Associates 1998). Within Xvision, movie loops of each atmospheric product are generated. Separate movies depicting time series of individual analysis fields 0Z and 12Z, as well as the entire time series of analysis and forecast products are created. These movies depict the atmospheric products on their native, uniformly spaced grid and are particularly useful in examining data trends and diagnosing irregularities.

3.2 Data Gaps

Even with the most reliable data sources, there will be days when the product is unavailable or data fields become corrupt. For example, during 1997, 67 days of downloaded NORAPS fields contained some type of missing data. There were 38 days in the 1999 COAMPS in which some variable of interest was missing. Because the computer models of interest require uniform temporal forcing data that span the entire simulation period, such data gaps must be addressed. Missing data are reintroduced using a linear interpolation between the last complete record and the next suitable record as described below. Obviously in an operational setting, forecast or analysis fields at a future time may not be available.

The reliability of the forecast fields (distinct from analysis fields) (Hodur 1982; Hodur 1997) gives a degree of confidence in using forecast fields out to 24 or 48 hours to fill a large gap in the data. Thus, a data gap is filled by interpolation between the last forecast record and the first analysis field available in the next complete data file (see Table 1 for file structure). The six-hour temporal spacing of the data is preserved. Because of the overlapping of forecast hours between operational product files, the last file containing a forecast hour identical to the first missing files' starting hour can simply replace that first hour's missing value with the forecast value. For example, if the last available forecast field is at 18Z, and a file that would normally begin at 12Z is missing, the first two records of the missing file are filled in with forecast fields at 12Z and at 18Z. Any records that remain missing are filled in using linear interpolation.

The time series of atmospheric products that result when applying this approach to remove data gaps appear consistent as demonstrated in Fig. 3, which shows the results of this replacement and interpolation approach applied to fill in two missing files from January 1997. Figure 3 only shows the first records (usually an analysis record). January 6, 1997 at 00Z was the first record of the last file remaining before the data gap. A forecast replacement was used to fill in the missing records shown in Figs. 3(b) and 3(c).

Figure 3(d) shows the first record from the next available file that began on January 7, 1997 at 12Z.

3.3 Mean Quantities

Surface forcing for the ocean models can assume either the form of daily products or of computed means. Computed means of the atmospheric products at monthly, bi-monthly, seasonal, or annual time scales can be useful not only as forcing for a model but such fields are readily compared to observational data and other atmospheric products derived from observations.

Mean fields are computed by summing all records, analysis and forecast, over the period for which a mean is desired and dividing by the total number of records (see Table 2). Outliers in the NORAPS and COAMPS wind stress fields are removed from the mean computation. Most of the outliers are at least two orders of magnitude above most of the wind stress values. Therefore, the outliers are defined as those locations whose stress values are greater than 10 N/m^2.

All atmospheric data products are interpolated to the nodes of a finite element grid using bilinear interpolation and are written in the format and units required by the ADCIRC model. These same files are converted as necessary for implementation by the QUODDY model. A detailed description of software components comprising the COAMPS and NORAPS processing system can be found in the Appendices. Apendix A provides flowcharts of the atmospheric data processing. Definitions of the programs identified in Appendix A are given in Appendix B.

Table 2: Time Domain Definitions for Mean Computations

Data Source	Mean Descriptor	Months	Days	Hours
NORAPS	Annual	1 - 12	1-28/30/31	00,06,12,18,24, 12,18,24,30,36
NORAPS	Seasonal	12-3,4-5, 6-9,10-11	1-28/30/31	00,06,12,18,24, 12,18,24,30,36
NORAPS	Bimonthly	1,3,5,7,9,11	15 (previous month) -15 (following month)	00,06,12,18,24, 12,18,24,30,36
NORAPS	Monthly	1,2,3,4,5,6,7,8, 9,10,11,12	1-28/30/31	00,06,12,18,24, 12,18,24,30,36
COAMPS	Annual	1 - 12	1-28/30/31	00,06,12,18,24, 30,36,42,48, 12,18,24,30,36, 42, 48,54,60
COAMPS	Seasonal	12-3,4-5, 6-9,10-11	1-28/30/31	00,06,12,18,24, 30,36,42,48, 12,18,24,30,36, 42,48,54,60
COAMPS	Bimonthly	1,3,5,7,9,11	15 (previous month) -15 (following month)	00,06,12,18,24, 30,36,42,48, 12,18,24,30,36, 42,48,54,60
COAMPS	Monthly	1,2,3,4,5,6,7,8, 9,10,11,12	1-28/30/31	00,06,12,18,24, 30,36,42,48, 12,18,24,30,36, 42,48,54,60

4. DYNAMICAL DESCRIPTION OF DATA

A dynamical description of the five fields of interest (to the coastal circulation modeling efforts) is now presented using the specific years of 1997 and 1999. The year 1997 is selected as the last full year for which NORAPS data was extracted at NRL-Stennis. The transition from NORAPS to COAMPS data was made in July 1998, making 1999 the first full year for COAMPS products at NRL-Stennis.

Because these products are of interest to a coastal ocean circulation modeling effort, the discussion will be limited to the products located over water, i.e., products over land are not considered. The study area includes the Arabian Gulf waters and adjacent water bodies such as the northern Gulf of Oman. Figure 4 places these waters in a geographical/political context that is useful in the discussion that follows. Color scales for the plots are chosen to be the same for both COAMPS and NORAPS to facilitate comparison of these products. Presented below are comparisons of the NORAPS and

COAMPS computed means on the annual, seasonal and monthly time scales. Bimonthly means, while computed, are not discussed in detail in this report.

4.1 Annual Means

An initial understanding of the regional meteorology over the Arabian Gulf can be obtained first by examining annual means of the atmospheric products, e.g., wind speed, wind stress, mean sea level pressure, air temperature, and total heat flux. The annual means clearly indicate the degree of spatial inhomogeneity present in a particular field over the Arabian Gulf basin. This may provide an early indication as to the relative importance of this field in the circulation dynamics of the region. Comparisons of the NORAPS 1997 and COAMPS 1999 annual means illustrate spatial differences between the magnitudes of these various atmospheric products over the Arabian Gulf. The disparate resolution between the NORAPS and COAMPS fields is apparent in the mean computation, i.e., more detail is recognizable in the higher resolution COAMPS fields.

Figure 5(a) shows the annual mean air temperature computed from NORAPS. The 1997 air temperature mean has its lowest values between 15 °C and 19 °C at the far northwestern Gulf and along the Iranian coast. The air temperatures over water increase gradually toward the southeast. The highest values, having a maximum of approximately 22 °C, are located in the central Arabian Gulf. The COAMPS annual mean air temperatures (Fig. 5(b)) are warmer than those of NORAPS and range from 24 – 28 °C over Arabian Gulf waters. There is a discernible change in the central Arabian Gulf where the temperatures to the southeast are higher by a couple of degrees. As for the NORAPS air temperatures, the lowest temperature values in the COAMPS field hug the Iranian coast. The COAMPS annual mean temperatures are considerably warmer (more than 5 °C) than those produced by NORAPS. The NORAPS products show extremely low values over water, whereas COAMPS has such low temperatures confined to the mountainous land regions north of the Gulf over Iran.

The annual mean for NORAPS total heat fluxes in 1997 (Fig. 6(a)) contains some extremely high values in the central Arabian Gulf. Recall that these total heat fluxes are the sum of sensible and latent heat fluxes. The positive values in these graphics indicated heat loss from the ocean surface. The range of this data is quite substantial from 167 W/m^2 along the far northern boundary near Kuwait to 570 W/m^2 in the central Arabian Gulf. Midrange values of the heat flux follow both the Iranian and Saudi Arabian coasts. A uniform increase in heat flux is found to progress from coastal areas to the central Gulf waters. The annual mean for COAMPS heat fluxes in 1999 (Figure 6(b)) shows a markedly different spatial structure, one that is less varied and has a smaller range in magnitude, i.e., 97 to 278 W/m^2 over Arabian Gulf waters. As with the COAMPS annual mean temperatures, there is a clear shift in the central Gulf from lower heat flux values in the north and along the southern and western coasts to higher values in the central and southern Gulf. Unlike the NORAPS heat flux, the COAMPS heat fluxes are highest long the Iranian coast and continue through the Strait of Hormuz into the northern coast of the Gulf of Oman.

The 1997 NORAPS annual mean sea level pressure data, shown in Fig. 7(a), has rather high values ranging from 1018 to 1021 mbars. The pressure decreases from the northernmost reaches of the Gulf to the Strait of Hormuz. The COAMPS annual mean sea level pressure for 1999 is completely uniform over the Arabian Gulf waters, maintaining a value of 1011 mbars (Fig. 7(b)). Additionally, very little variation of pressure can be found over the surrounding land mass, i.e., pressure ranges from 1007 to 1013 mbars.

The 1997 annual mean for NORAPS wind vectors shown in Fig. 8(a) depicts a northwest–to-southeast flow over the Arabian Gulf waters. Magnitudes range from 1 to 2.7 m/s with smaller values positioned toward the Gulf exit along the northern Iranian coast and the Strait of Hormuz. The 1999 annual mean for the COAMPS wind vectors seen in Fig. 8(b) shows the same general flow from the northwest to the southeast. However, the higher resolution COAMPS fields depict more detailed features such as northerly winds blowing southward over water from the Iranian coast. Once over water, however, these winds shift dramatically toward the east. Winds over the southeast Gulf are diminished and circulate as a cyclonic gyre centered over the southern Strait of Hormuz. Magnitudes of the COAMPS annual mean winds have a similar range as the NORAPS fields, 1.2 to 2.4 m/s over water.

The 1997 NORAPS annual mean wind stresses in Fig. 9(a) have values ranging from 0.006 to 0.066 N/m^2 over the Arabian Gulf waters. The stress direction is generally northwest to southeast following the direction of wind vectors previously discussed. The stresses are notably smaller in the northwestern and southeastern Gulf. The largest values over water occur in the central Gulf. Note the largest 1997 annual mean stresses shown in Fig. 9(a) are located in the mountainous area over Iran, northeast of the Arabian Gulf. The 1999 COAMPS annual mean wind stress in Fig. 9(b) again shows a northwest-to-southeast flow with similar magnitudes ranging from 0.008 to 0.06 N/m^2 over water. The northwest wind stress at the head of the Gulf splits to the south after a short distance to follow a direction along the coastline. Otherwise, wind stress direction mirrors the COAMPS wind vectors. The exception is in the Strait of Hormuz, where the cyclonic gyre in wind stress is shifted to the east, creating a very different circulation pattern than seen in the wind vectors (Fig. 8(b)). Both the COAMPS and NORAPS annual mean wind stresses show good agreement outside of the eastern Gulf and Strait of Hormuz. They both increase in land regions over the mountain range to the north, though COAMPS values show a marked decrease over water as compared to land.

4.2 Seasonal Means

Strong seasonal variability over the Arabian Gulf has been observed and noted in the literature, e.g., Hunter 1982; Walters and Sjoberg 1988; and Sultan and Ahmad 1993. Table 3 defines the seasonal means presented here. The parenthetical climatological regimes are identical to the definitions of Walters and Sjoberg (1988) based upon the classification of this area as a monsoon climate.

Table 3: Seasonal Definitions

Season (Climatological Regimes)	Months
Winter (Northeast Monsoon)	December January February March
Spring (Spring Transition)	April May
Summer (Southwest Monsoon)	June July August September
Fall (Fall Transition)	October November

Quantities that depict an obvious seasonality are air temperature and mean sea level pressure. Seasonal differences in air temperature naturally derive from the solar cycle and come as no surprise. The seasonal differences in pressure stem in part from the effects of the winter (Shamal winds) and summer monsoons (Walters and Sjoberg 1988).

Figure 10 shows the NORAPS seasonal means for air temperature. For the winter mean, temperatures range from 9 to 15 °C. In spring, the air temperature warms to between 26 and 29 °C with the warmest temperatures situated over northern, near-coastal waters and along the shallow southwestern coast of the Gulf. A gradient in the mean air temperature, one that decreases along the axis of the Gulf, is evident in the summer mean. As with spring, warmer temperatures persist over Arabian and U.A.E. coastal waters in summer. The maximum summer mean air temperature is 35 °C located just north of the Shatt-al-Arab river inflow (near the Iran-Iraq border). Moving to fall, cooling of the mean air temperature is evident starting at the head of the Gulf and extending along the northern Iranian coast and through the Strait of Hormuz. Mean air temperatures over much of the Gulf in fall remain warmer than those computed for the spring period. Fall and spring mean air temperatures retain a traditional role as transitional periods (Walters and Sjoberg 1988) between winter and summer.

Figure 11 shows the 1999 COAMPS seasonal means for air temperature. Similar trends across the seasons are evident, but magnitudes vary considerably in comparing the COAMPS and NORAPS products. For example, COAMPS mean air temperatures in summer have a similarly placed gradient in the north but the values are consistently several degrees warmer than the NORAPS field. The summer air temperatures in the central Gulf are on the order of a couple of degrees warmer. The COAMPS mean air temperatures in spring and fall again have a structure similar to that of the NORAPS products but magnitudes of the air temperature are different. Far more detail is gained by the higher resolution COAMPS data. For example, the winter mean air temperature contains a broadly increasing gradient in air temperature from the Shatt-al-Arab to the east-central portion of the Gulf with a range from near 16 °C to approximately 22 °C. Also seen in the COAMPS field in spring is a low of 23 °C centered in the open water of the northern Gulf and a local maximum of 26 °C off the Iranian coast. In the fall, higher air temperatures off the Iranian coast are evident. Generally, fall air temperatures show the beginnings of a cooling period and development of a winterlike structure.

Figure 12 shows the 1997 NORAPS seasonal means for total heat flux. Of note are the extremely high values of total heat flux that persist through all seasons and the fact that the mean heat flux throughout the year always results in net heat loss for the ocean. The winter mean contains the lowest value of the year (221 W/m^2) and a maximum value near 458 W/m^2 along the axis of the central Gulf. Along the Iranian and Arabian coasts are the intermediate values ranging from 222 to 333 W/m^2. The spring mean has values that are noticeably greater and vary from 427 to 504 W/m^2. The greatest magnitudes are located in the south-central Gulf and in particular off the Iranian coast. As summer arrives, the heat flux values continue to increase with 1997 summer mean values essentially uniform having a narrow range between 529 and 594 W/m^2. The fall total heat flux means are generally greater in magnitude and more structured than the spring scenario. Clearly fall values are a transition to the mean winter heat flux configuration. Maximum values remain in the central Gulf, with a decreasing gradient toward coastal waters with the most dramatic reduction seen in the far northern Gulf.

The COAMPS total heat flux seasonal means from 1999 (Fig. 13) are dramatically reduced in magnitude over the NORAPS mean fields. The range of the COAMPS mean heat flux over all seasons is compressed relative to NORAPS with a maximum value close to 301 W/m^2 and a minimum in the vicinity of 48 W/m^2. Despite these differences, the winter means exhibit an increasing gradient in heat flux moving from the northern head of the Gulf to the largest values of 278 W/m^2 in the central Gulf and in coastal regions off Iran. Southern coastal areas retain generally lower heat flux values in winter, on the order of 111 to 167 W/m^2. The spring mean heat flux values are quite different from those associated with the NORAPS model. COAMPS values drop as the low heat fluxes form a tongue that moves southward covering the entire northern Gulf and down into the area surrounding Qatar. This drop in the heat flux indicates a trend towards the addition of heat to the ocean surface as opposed to a loss, though the positive sign indicates that heat loss is still taking place. The largest spring mean values are decreased over the winter magnitudes and persist along the Iranian coast. In summer, the total mean heat flux increases back to between approximately 111 and 167 W/m^2 across much of the Arabian Gulf. The exception again is a maximum of 208 W/m^2 in the north central coastal waters. The fall COAMPS heat flux means show sharply decreasing gradients in the mean heat flux moving from the central Gulf to the coastline. The values in fall show the most significant variability of the year ranging from 48 to 301 W/m^2. The open waters in the central Arabian Gulf have a heat flux range of 222 to 278 W/m^2. While the magnitudes between COAMPS and NORAPS seasonal heat flux means are radically different, it can be argued that the trend of the total heat flux mean remains rather consistent across the seasons.

Figure 14 shows the NORAPS seasonal mean pressures computed for 1997. High pressures in winter (on the order of 1016 mbars) extend basin-wide with slightly higher pressures (1019 mbars) from the central Gulf to the northernmost coastline. An essentially uniform and lower pressure near 1009 mbars results in spring. Summer values are also fairly uniform with values ranging between 1001 and 1002 mbars throughout the basin. The fall mean pressure shows a significant increase and is constant throughout the basin (values are approximately 1014 to 1015 mbars). The COAMPS seasonal mean surface pressures (Fig. 15) are in general somewhat lower though essentially comparable to values given by the NORAPS product. For the COAMPS pressure field, winter values have the largest magnitude from 1015 to 1016 mbars. The pattern of the winter pressures mirrors that of the NORAPS fields, i.e., maximum values are present in the northern Gulf with a gradient across the north-central Gulf delineating lower values of 1015 mbars to the south. The spring mean pressures are less than NORAPS with magnitudes of 1009 mbars over most of the basin, decreasing to 1007 mbars in the eastern part of the Gulf. The summer values are the lowest and fairly homogeneous, ranging between 999 and 1000 mbars. In the fall, COAMPS mean pressures are uniform and range between 1012 and 1014 mbars.

The seasonal mean wind speeds associated with the 1977 NORAPS model (Fig. 16) display a generally northwest to southeast flow during all four seasons. The winter mean has the highest values of 1 to 3.8 m/s and a strongly uniform flow field over the entire Arabian Gulf. The spring and fall wind means have values ranging from 0.1 to 2.5 m/s and both show substantially decreased magnitudes in the northern Arabian Gulf. The lower magnitude winds (0.1 to 2 m/s) follow along the northeast Arabian coast during fall. The summer mean winds, by contrast, contain the highest magnitudes of the year in the northern Gulf (a maximum of 3.2 m/s). The lowest wind speeds during summer (0.4 to 2 m/s) are located in the southeast portion of the Gulf, with the direction of the wind vectors turning northward across the Strait of Hormuz.

The COAMPS seasonal mean winds (Fig. 17), in contrast to the NORAPS mean winds, have their maximum values in the central Arabian Gulf during the fall and spring seasons (values approach 4 m/s). The winter COAMPS mean wind has magnitudes ranging from 0.6 to 3 m/s. The direction of the winds is generally northwest to southeast, though winds in the northeast are flowing into the Gulf in a direction normal to the coastal boundary. The spring COAMPS mean wind magnitudes span from 1.3 to 4.3 m/s. Spring winds in the northeast corner of the Gulf veer to the east and then flow along the coast. In addition, winds now coming off the Iranian coast over the length of the Arabian Gulf and increase in magnitude over winter values. A strong line of winds results offshore from Iran in the zone of convergence between winds moving southeast down the basin and those coming off the northern coast and veering southeast. The summer mean wind deviates from the largely northwest to southeast flow seen throughout the rest of the year. A complex pattern develops with divergence of the wind vectors in the southern Gulf from the center of the basin toward the coasts. The northern Gulf wind circulation is dominated by a cyclonic gyre. Overall, the mean wind magnitudes are the lowest during summer, with a range of 0.1 to 1.8 m/s, as compared to values computed for the other three seasons. As with the NORAPS winds, there is a counterclockwise circulation in the southeastern corner of the Gulf that orients the winds in a direction perpendicular to the northern coast. The fall seasonal mean wind speeds have a magnitude range of 0.7 to 3.8 m/s and a consistent northwest-to-southeast flow over most of the Gulf. As with the spring wind vectors, a zone of convergence off the Iranian coast is present, although it is not as strong as in spring. Lastly, the counterclockwise gyre in the southeast Gulf in summer has shifted to a clockwise direction in fall.

Figure 18 shows the seasonal mean wind stresses from the 1997 NORAPS data. The NORAPS winter mean wind stress shows a consistent directional pattern from northwest to southeast with magnitudes ranging from a very small 0.0079 N/m^2 to 0.09 N/m^2. The spring and fall wind stress means both have ranges that are barely discernible. The spring maximum is 0.05 N/m^2 off the Iranian coast and the smallest values are seen in the northern Gulf. The summer means range from 0.003 to 0.14 N/m^2 with a clockwise circulation in the northern Gulf and southward stress vectors in the southeastern Gulf. During fall, the wind stress mean has a more westward component in the southeast Gulf than has been seen during other seasons of the year.

The COAMPS seasonal mean wind stresses computed for 1999 (Fig. 19) have very small magnitudes that are quite similar to those seen for NORAPS. The COAMPS winter seasonal mean wind stress vectors display a flow pattern similar to that of the wind velocities seen in Fig. 17. Magnitudes are fairly uniform with ranges of 0.006 to 0.07 N/m^2. The smallest mean wind stress vectors are found in spring and summer with a range from 0.002 to 0.05 N/m^2. Stronger stresses in spring are found off the Iranian coast in the central Gulf, while during summer the larger stress values are located off the U.A.E. coastal waters. In fall, COAMPS mean wind stresses range in magnitude from 0.016 to 0.07 N/m^2, similar to that of the winter stresses. The directions also are quite similar to the winter pattern and clearly represent a transition from summer to winter.

4.3 Monthly Means

Figures 20 through 29 present the computed monthly mean fields for the five atmospheric products being considered (air temperature, total heat flux, surface pressure, wind velocity, and wind stress) for each of the models, NORAPS and COAMPS. These figures are included for completeness and for reference in the subsequent comparison of the NORAPS and COAMPS products to monthly mean values published in the literature. A detailed discussion of each monthly mean field is not included as it likely does not add significantly to the body of knowledge already presented relative to the computed seasonal means. The basic trends reported between the NORAPS and COAMPS model products are upheld in the monthly mean fields included here.

5. EVALUATION OF PRODUCT QUALITY

One method of evaluating the validity of the NORAPS and COAMPS atmospheric operational products is to compare their values to other data products and against values published in the literature, including refereed journals and climatological atlases. Some quality checks of the COAMPS operational product have been made according to Hodur (1997); the COAMPS fields were used in limited real-time experiments associated with the America's Cup races in 1995 and in 1991 in hindcasts of the 1989 tropical cyclone, Hurricane Gilbert, in the Gulf of Mexico. In Schwingshakl (1997), COAMPS fields were compared with meteorological observations during strong wind events and mountain waves occurring in central California. The following section evaluates NORAPS and COAMPS data products only over Arabian Gulf waters.

Published values for the five quantities considered in the Arabian Gulf (air temperature, total heat flux, mean sea level pressure, wind speed, and wind stress) have been identified such that a fairly complete evaluation is rendered. Naturally, only like quantities (i.e., total heat flux) in compatible units are inter-compared. Computed means for the COAMPS and NORAPS data products are presented as minimum and maximum values over Arabian Gulf waters. The root mean square (RMS) error and the correlation between each operational product and the available data sources are calculated using a midpoint between the maximum and minimum values. They offer a way to quantitatively evaluate the NORAPS and COAMPS data products. It should be noted, however, that several of the *in situ* data comparisons use data collected in different years than those of the COAMPS and NORAPS data. Still such comparisons can provide insight into the quality of the atmospheric products.

5.1 Air Temperature

Seven sources (e.g., 1980 Climatic Study of the Persian Gulf and Gulf of Oman; Walters and Sjoberg 1988; Ahmad and Sultan 1991; Brower et al. 1992; Reynolds 1993; Sultan and Ahmad 1993; El-Gindy 1994)) discuss monthly, seasonal, and/or annual mean air temperatures over the Arabian Gulf. Note that the mean air temperature values contained in Ahmad and Sultan (1991) are found by averaging the meteorological data at Dhahran (26.3°N, 50.2°E). Likewise, mean monthly values for Sultan and Ahmad (1993) are obtained from a single station in the Strait of Hormuz. In Table 4 these sources are labeled as 1980, 1988, 1991, 1992, 1993a, 1993b, and 1994, respectively. The observations presented are used to evaluate the mean air temperatures computed from NORAPS and COAMPS data. Table 4 also presents the minimum and maximum mean air temperatures for NORAPS and COAMPS data. RMS errors and correlations for the NORAPS and COAMPS mean data with respect to the literature sources are displayed as curves in Figs. 30 (NORAPS) and 31 (COAMPS).

Four sources (1980, 1991, 1992, and 1993b) contain monthly mean values available for comparison. In general, NORAPS mean air temperatures post higher RMS errors than the COAMPS data when compared to the four sources for monthly mean observations. The highest RMS errors with respect to the NORAPS monthly mean air temperatures are obtained with respect to the U.S. Navy Climatic Study of 1980 (4.61 °C) and the Sultan and Ahmad (1993) observations (5.24 °C). The largest RMS error for COAMPS (3.21 °C) occurs for the same data source, the Sultan and Ahmad (1993) data. Discrepancies with this source (1993b) are not surprising since this source consists of values confined to the Strait of Hormuz. The NORAPS RMS error for the 1991 (3.45 °C) and 1992 (3.84 °C) sources are similar and reduced over the RMS error computed for 1980 data. The COAMPS monthly mean air temperature values compare more favorably with RMS errors of 2.14 °C, 1.45 °C and 1.19 °C for the 1980, 1991, and 1992 sources, respectively.

Seasonal mean air temperature comparisons are possible using the climatological study from Walters and Sjoberg (1988), data from the Mt. Mitchell cruise (Reynolds 1993), and data obtained at the Doha Airport station (25.27 °N, 51.55 °E) in Qatar (El-Gindy 1994). Note that the Mt. Mitchell cruise data and data from the Doha Airport station do not represent all four seasons. Mt. Mitchell data were measured during winter and the Doha Airport station provides values for both winter and summer seasons.

The seasonal mean NORAPS RMS errors are similar in magnitude to those computed for the monthly time scales. The NORAPS data have an RMS error of 3.12 °C when compared with the Walters and Sjoberg (1988) climatological study. An even larger RMS error of 4.95 °C for the seasonal mean air temperature is found with respect to the Mt. Mitchell measurements (Reynolds 1993). When compared to the same source, the COAMPS data have an RMS error that is reduced by more than half, 2.12 °C. In comparison to the 1988 climatology, the COAMPS seasonal air temperatures have a slightly larger RMS error of 2.29 °C, a value still reduced over the NORAPS computed RMS error. Both atmospheric model products fared slightly better when compared with the Doha Airport station. The NORAPS seasonal mean air temperatures had an RMS value of 3.81 °C while the COAMPS data posted an RMS error of 1.58 °C. Extremely low values of the NORAPS winter mean air temperature are the main cause for high RMS errors in these comparisons. In general, the RMS errors associated with the COAMPS mean air temperatures are maintained at a consistent level regardless of the source for comparison with the exception of the Mt. Mitchell data.

Both the NORAPS and COAMPS data are highly correlated with mean observed air temperatures. The lowest correlation coefficients for both NORAPS and COAMPS are associated with the U.S. Navy Climatic Study of 1980 (0.84 for NORAPS, and 0.96 for COAMPS) and with the Sultan and Ahmad obsevations in 1993 (0.86 for NORAPS, and 0.95 for COAMPS). The latter observations are derived from a single point so any discrepancy is not unexpected. For NORAPS, very good correlations are computed for the Walters and Sjoberg (1988) seasonal values (0.93) and with the 1991 (0.90) and 1992 (0.89) monthly values. COAMPS products have even greater correlations with the Walters and Sjoberg (1988) seasonal values (0.98) and the 1991 and 1992 monthly values (0.99 for both). Correlation coefficients are not calculated for the two seasonal data sets that are incomplete, the Mt. Mitchell cruise and the Doha Airport station.

It is interesting to note in looking at Figs. 30 and 31 that the correlation coefficients for both NORAPS and COAMPS are highest during months that have the lowest RMS errors. For NORAPS this occurs in comparing seasonal means to those of Walters and Sjoberg (1988) and monthly means to Ahmad and Sultan (1991). For COAMPS, the comparisons to the monthly means of Ahmad and Sultan (1991) and Brower et al. (1992) have the highest correlation and the smallest RMS errors. Lastly, note that the COAMPS computed annual mean (RMS error of 1 °C) compared quite well with the annual mean of 26 °C provided at the Doha Airport (El-Gindy, 1994). The same did not hold true for the NORAPS annual mean with an RMS error of 7 °C.

Table 4 - Mean Air Temperature in °C

Month	**NORAPS**	**COAMPS**	**1980**	**1988**	**1991**	**1992**	**1993a**	**1993b**	**1994**
January	16-22	15-21	19-21		15	15-22		22	
February	13-20	16-22	19-21		16.5	16.21		21.7	
March	18-23	18-22	20-23		20.1	19-23		24.6	
April	23-27	23-27	23-26		25	23-36		27.5	
May	29-32	27-33	28-29		30.7	28-29		31.1	
June	32-38	30-37	29-31		33.9	31-33		31.8	
July	33-39	31-37	32-33		35	32-34		30.9	
August	33-39	32-36	33-34		33.9	33-34		29.4	
September	22-25	30-34	32-33		31.4	32		30.3	
October	30-31	27-28	30-31		27.1	28-31		29.2	
November	23-28	19-27	25-27		21.8	23-27		26.4	
December	8-14	15-23	21-23		16.6	17-23		23.5	
Season									
Winter	9-15	16-22		7-23			14-23		16-18
Spring	26-29	23-26		16-36			22-34		
Summer	30-35	31-37		23-44					34-35
Autumn	27-30	23-28		13-35					
Annual	15-22	24-28							26

1980 – Climatic Study – Naval Oceanography Detachment, Asheville, NC
1988 – Walters and Sjoberg
1991 – Ahmad and Sultan
1992 – Brower et al.
1993a – Reynolds
1993b – Sultan and Ahmad
1994 – El-Gindy

5.2 Total Heat Flux

Recall from Sections 2 and 4 that the total heat flux product from both NORAPS and COAMPS is the sum of the sensible and the latent heat fluxes. Table 5 compares mean values of the total monthly, seasonal, and annual heat fluxes from the NORAPS and COAMPS data products with the sum of sensible and latent heat flux values presented in three literature sources. Positive values here indicate heat loss from the ocean surface.

Table 5 - Mean Total Heat Flux in W/m^2

Month	**NORAPS**	**COAMPS**	**1991**	**1992**	**1993**
January	221 - 570	40 - 343	140	90	145
February	318 - 507	70 – 143	102	110	127
March	322 - 416	65 - 212	87	40	81
April	372 - 470	53 - 176	124	20	97
May	453 - 520	69 - 191	146	40	104
June	542 - 578	88 - 197	245	50	101
July	543 - 653	90 - 175	273	45	76
August	535 - 608	91 - 287	279	80	52
September	427 - 601	134 - 351	180	95	79
October	350 - 605	86 - 369	174	40	120
November	273 - 523	27 - 359	129	150	104
December	214 - 450	51 - 293	124	150	121
Season					
Winter	221 - 458	66-246			
Spring	427 - 504	104-208			
Summer	529 - 594	65-278			
Autumn	276 - 551	48-301			
Annual	167 - 570	97 - 278	167	76	99
1991 - Ahmad and Sultan					
1992 – Chao et al. (from Hastenrath and Lamb 1979b)					
1993 - Sultan and Ahmad					

Net heat flux, as generally defined for oceanographic applications, is computed as the sum of the solar radiation absorbed by the ocean surface (positive in a downward direction), sensible, latent, and infrared (IR) heat fluxes (all negative, directed upward, away from the ocean surface). The sign convention generally accepted is that heat loss from the ocean is negative. The total heat flux quantities identified in the literature follow this definition and are presented in Table 6 for completeness.

Ahmad and Sultan (1991) compute heat fluxes from the meteorological and oceanographic data collected at Dhahran. Values listed in Chao et al. (1992) are taken from the atlas of Hastenrath and Lamb (1979b). The sensible and latent heat flux quantities are not specified in Chao et al. (1992) but are calculated by subtracting the radiative heat flux components from the net heat flux component. Total heat fluxes presented by Sultan and Ahmad (1993) are from measurements taken at a station outside of the Arabian Gulf in the Gulf of Oman.

Table 6 - Net Mean Heat Flux in W/m^2

Month	**1991**	**1992**	**1993**
January	-83	-40	-64
February	-8	-40	-14
March	62	60	68
April	41	120	90
May	66	160	113
June	-15	160	111
July	-53	160	125
August	-70	120	142
September	-16	80	104
October	-48	10	24
November	-56	-50	1
December	-72	-120	-46
Annual	-21		55
1991 - Ahmad and Sultan			
1992 – Chao et al. (from Hastenrath and Lamb 1979b)			
1993 - Sultan and Ahmad			

The RMS errors computed for the COAMPS monthly heat fluxes are far less than those found relative to the NORAPS product. However, both products post large errors in comparison to the observed values. Specifically, in comparison to Ahmad and Sultan (1991), COAMPS monthly mean heat flux has its lowest RMS error of 69.02 W/m^2 while the NORAPS RMS error value is 296.73 W/m^2, likewise its lowest value. The RMS errors for monthly mean heat flux peak when compared to the atlas values cited in Chao, et al. (1992), 102.14 W/m^2 for the COAMPS data and 400.45 W/m^2 for NORAPS. Magnitudes of the RMS errors computed with respect to the observations of Sultan and Ahmad (1993) for both NORAPS (374.31 W/m^2) and COAMPS (81.57 W/m^2) fall between the 1991 and 1992 comparisons.

Figures 32 (NORAPS) and 33 (COAMPS) present both the RMS error and correlation curves that result when each product is compared with the monthly data sources. With only three observational data sources, there is no discernible trend in the RMS errors or the correlations. Surprisingly, though, it is the NORAPS products that are better correlated across the months than the COAMPS data. For example, when compared with the Ahmad and Sultan (1991) data, NORAPS has a correlation coefficient of 0.92, which is very good. In contrast, the COAMPS mean heat fluxes compared to the identical source posted a correlation coefficient that is quite small, 0.18. The heat fluxes cited in Chao et al. (1992) are negatively correlated (i.e., they have a coefficient of –0.43) with the NORAPS values; COAMPS in this case is positively correlated with the observations, though not strongly. Lastly the correlation coefficients computed for both NORAPS and COAMPS are negative when compared with the heat flux data from Sultan and Ahmad (1993), -0.59 and –0.03, respectively.

In considering the seasonal mean heat fluxes computed for NORAPS and COAMPS heat flux fields, a far greater range in the spring and summer seasons is seen in the COAMPS values than in NORAPS. The range of the values in the fall and winter is comparable between the two atmospheric products. Generally, the NORAPS heat fluxes are several hundred W/m^2 greater than COAMPS values. Across the seasons, though, the trends in heat flux data products appear consistent with what is known about the atmospheric environment over the Arabian Gulf. Heat flux in the summer months decreases in response to the increase in outgoing shortwave radiation. This increase is demonstrated by Hastenrath and Lamb (1979b), who show the highest net short-wave radiation during the months of May through September. Since radiative components are not present in the COAMPS and NORAPS heat quantities, it is difficult to draw definitive conclusions regarding the validity of the data for application in coastal ocean models.

For the annual mean, the minimum heat fluxes computed for the NORAPS and COAMPS data products are of a similar order of magnitude as the observational source annual means. If one considers the midrange annual mean values for NORAPS and COAMPS, the differences computed between the midrange and the published annual means for 1991, 1992, and 1993 sources, respectively, are 229 W/m^2, 320 W/m^2, and 297 W/m^2 for NORAPS and 11 W/m^2, 102 W/m^2, and 79 W/m^2 for COAMPS. From this analysis, COAMPS annual mean values appear to be much closer to the measured annual mean heat flux. However, the magnitudes of these differences are still quite large.

5.2 Pressure

Mean values for the surface pressure in mbars from the two sets of atmospheric products (NORAPS and COAMPS) are compared to mean monthly values from the *Climatic Atlas* of Hastenrath and Lamb (1979a) in Table 7. No other sources for pressure were located in the literature. Again, a reminder that the midpoint of the maximum and minimum NORAPS and COAMPS mean pressures presented is the value used for statistical and error calculations.

Table 7 - Mean Sea Level Pressure in mbars

Month	NORAPS	COAMPS	1979a
January	1017 – 1020	1016 - 1017	1017 - 1018
February	1013 – 1016	1015 - 1016	1015 - 1017
March	1013 – 1014	1011 - 1012	1013 - 1014
April	1011	1008 - 1010	1010
May	1007 – 1008	1002 - 1005	1006 - 1007
June	1002	999 - 1000	1000
July	997	996 - 997	1003
August	1000 – 1001	998 - 999	999
September	1006 – 1007	1003 - 1004	1005
October	1012 – 1013	1010 - 1011	1011 - 1012
November	1016 – 1017	1015 - 1017	1016
December	1017 –1019	1018 - 1020	1017 - 1019
Season			
Winter	1017 – 1019	1015 - 1016	
Spring	1009	1007 - 1009	
Summer	1001 – 1002	999 - 1000	
Autumn	1014 – 1015	1012 - 1014	
Annual	1018 – 1021	1011	
1979a – Hastenrath and Lamb			

As is consistent with the analyses previously presented, NORAPS products show considerable deviation from the published literature. The RMS error for the monthly mean pressure from NORAPS data as compared to the Hastenrath and Lamb (1979a) monthly pressure data is 2.17 mbars. Similarly, the monthly mean pressure from COAMPS has an RMS error of only 2.12 mbars. The COAMPS and NORAPS pressures have an extremely high correlation coefficient of 0.97 and 0.95, respectively. It is important not to draw too many conclusions since only one source of data is available for comparison.

The seasonal and annual mean pressure values computed for NORAPS and COAMPS fields are presented for completeness though their validity cannot be addressed. The trend of lower pressures during the summer months is seen for both NORAPS and COAMPS. This corresponds to the presence of a low pressure trough in the summer season (Walters and Sjoberg 1988). The NORAPS and COAMPS data show considerable agreement across all seasons. The annual means remain widely disparate between the two sources of atmospheric products as seen in Table 7.

5.4 Wind Speed

Wind speed is a fundamental component of atmospheric circulation and, thus, is a quantity that is more often measured and studied. Table 8 contains wind speeds reported by 11 sources located in the literature. Each source is identified at the bottom of Table 8. All winds are converted from their native units to m/s for comparison. Note that COAMPS and NORAPS wind speeds are calculated at 10 m above the water surface.

Some observations of the wind speed are measured at single meteorological stations off the Saudi Arabian coast, i.e., Ahmad and Sultan (1991) and Meshal and Hassan (1986). Ahmad and Sultan (1991) report from Dhahran (26.3 °N, 50.2 °E) and Meshal and Hassan (1986) collected monthly wind data from 1975 to1981 at Doha, Qatar (25.27 °N, 51.55°E), and from 1982 to1984 at Manama, Bahrain (26.27 °N, 50.62 °E). The wind speed data from Sultan and Ahmad (1993) is taken from a station located in the Strait of Hormuz. Lastly, wind speeds published by Al-Rabeh et al. (1993) were derived from drifting buoys placed in the northeast and central Gulf during the Mt. Mitchell expedition of March to April, 1992.

At first glance, one notices that the minimum mean values presented for NORAPS 1997 data and the COAMPS 1999 data are far lower in magnitude than the values shown for all sources in Table 8. FNMOC states up front that the Shamal winds are underestimated in COAMPS Southwest Asia Nest 2 operational products (FNMOC internet address: http://www.fnmoc.navy.mil/PUBLIC/MODEL_REPORTS/MODEL_TENDENCY_REVIEW/tendencies.html#COAMPS). This statement is supported by poor agreement with observed wind speeds during the winter months. Some carry over is realized for the spring and summer months as well. This limitation in representing the Shamal does not, however, entirely explain the general bias towards low wind speeds throughout the year.

The seasonal and annual mean comparisons between NORAPS and COAMPS atmospheric data and observed values accentuate the degree of underprediction by the operational products. The oldest source for wind speed values (Hastenrath and Lamb 1979a) is the one that most closely resembles the wind speed magnitudes presented for NORAPS and COAMPS fields. The climatic study from 1980 and Brower et al. (1992) as well as Lardner et al. (1988) all contain higher values for the wind speed throughout the year than those associated with the operational products. In comparison to the annual mean published by Lardner et al. (1988), the NORAPS data has an annual mean error of 2.65 m/s while the annual mean error for COAMPS data is even larger at 3.2 m/s.

The RMS error computed for the NORAPS seasonal mean wind speed as compared to Walters and Sjoberg (1988) is 3.73 m/s, a value very similar to the COAMPS RMS error of 3.76 m/s for the same seasonal means. The RMS errors are slightly reduced when computed with respect to Al-Rabeh and Gunay (1992), who derive seasonal means from U.S. Navy meteorological data. For NORAPS the seasonal mean data has an RMS error of 2.77 m/s, whereas the COAMPS RMS error for the same seasonal mean is 2.54 m/s. In considering the recent field expeditions during spring and winter reported by Al-Rabeh et al. (1993), the NORAPS spring and winter mean wind speed RMS error is 1.1 m/s. Compared to the same observations, the COAMPS spring and winter mean wind speeds have an RMS error of 0.85 m/s. Generally the NORAPS and COAMPS seasonal means have analogous errors when compared to the available data sources.

With a couple of exceptions, RMS errors for the NORAPS wind speeds as compared to the observational sources in Fig. 34 hover in the 2.5 to 3.0 m/s range. Correlations against all observed data are generally quite low and rather variable across sources. No correlation coefficient is computed for Al-Rabeh et al. (1993) since all four seasons are not available. It is curious to note that the most highly correlated data source with the NORAPS fields also generates the larger RMS error (Walters and Sjoberg 1988).

Figure 35 presents the RMS errors and correlation coefficients for the COAMPS wind speeds compared with the seven data sources. The RMS error profile is quite similar to that seen in the case of the NORAPS data and magnitudes are similar, as previously mentioned. The COAMPS products are largely uncorrelated with the observations. In contrast to the NORAPS fields, the highest RMS error recorded (a comparison to Walters and Sjoberg (1988)) has a strong negative correlation coefficient of –0.87. The highest correlation coefficients have values of 0.3 and 0.26 and are calculated from comparisons between COAMPS wind speeds and the Ahmad and Sultan (1991) and Al-Rabeh and Gunay (1992) data, respectively. Both of these comparisons yield some of the lower RMS errors.

Table 8 - Mean Wind Speed in m/s

Month	**NORAPS**	**COAMPS**	**1979**	**1980**	**1986**	**1988a**	**1988b**	**1991**	**1992a**	**1992b**	**1992c**	**1993a**	**1993b**
January	0.7 – 4.0	0.6 – 3.4	1.0-3.0	4.1-6.1	5.2	5.3		4.1		5.1	4.1-6.1	4.5	
February	1.7 - 6.0	0.6 - 2.0	2.0-4.0	4.6-6.1	5.1	5.5		4.1		5.1	4.6-6.6	4.8	
March	0.1 - 2.4	0.2 – 2.4	2.0-3.0	5.1-6.1	5.2	5.0		4.6		5.6	4.6-6.1	4.1	2.4
April	0.1 – 1.8	1.3 – 3.8	2.0-3.0	4.6-5.6	4.8	4.5		4.6		4.6	4.1-5.6	3.8	2.1
May	0.2 - 2.7	1.4 - 4.8	2.0-3.0	4.1-4.6	4.9	4.7		5.1		3.6	3.6-5.6	3.4	
June	0.7 - 2.0	1.3 - 4.0	2.0-4.0	4.1-5.6	5.8	4.9		5.7		4.1	4.1-6.1	3.9	
July	0.4 - 5.6	0.1 - 4.5	1.0-4.0	3.6-4.1	4.8	3.9		5.1		3.1	3.1-4.1	4.4	
August	0.4 - 5.6	0.3 - 2.3	2.0	3.1-4.1	5.1	3.0		4.6		3.3	3.1-4.6	4.0	
September	0.8 - 3.2	0.9 – 2.5	1.0-2.0	3.1-4.1	3.9	3.5		3.6		3.3	3.1-4.1	3.8	
October	0.2 - 3.0	1.0 – 3.0	1.0-2.0	3.1-4.6	4.0	3.3		3.6		3.6	3.1-4.6	3.2	
November	0.2 - 1.6	1.5 - 4.5	1.0-3.0	3.6-5.6	4.5	4.7		3.6		4.1	3.6-5.6	3.2	
December	0.5 - 3.8	1.6 - 5.1	2.0-4.0	4.1-5.6	4.9	4.8		4.1		5.1	4.1-6.1	3.8	
Season													
Winter	1.0 – 3.8	0.6 - 3.0					5.1-7.7		5.2				2.0-4.7
Spring	0.1 - 2.2	1.3 - 4.3					2.6-6.1		4.7				1.8-2.2
Summer	0.4 - 3.2	0.1 - 1.8					5.1-7.7		3.9				
Autumn	0.1 - 2.5	0.7 - 3.8					2.6-7.7		3.8				
Annual	1.0 - 2.7	1.2 - 2.4				4.5							

1979 – Hastenrath and Lamb (1979a)	1980 – Climatic Study – Naval Oceanography Detachment, Asheville, NC
1986 – Meshal and Hassan	1992b – Chao et al. (1992)
1988a – Lardner et al. (1988)	1992c – Brower et al. (1992)
1988b – Walters and Sjoberg (1988)	1993a – Sultan and Ahmad (1993)
1991 – Ahmad and Sultan	1993b – Al-Rabeh et al. (1993)
1992a– Al-Rabeh and Gunay (1992)	

5.5 Wind Stress

As a derived quantity, one would expect wind stresses to compare in a way that is similar to that discussed for wind speeds. Table 9 presents the ranges of mean wind stress computed for the COAMPS and NORAPS operational products. The only observational data source found in the literature for mean wind stress is that of Chao et al. (1992) who present monthly wind stress data from the U.S. Hydrographic Office. Other sources for wind stress commonly available are the Hellerman-Rosenstein (H-R) monthly mean wind stresses (Hellerman and Rosenstein 1983) and the European Centre for Medium-Range Weather Forecasting (ECMWF) pseudo wind stresses (Gibson et al. 1997).

The RMS error for the monthly mean wind stress as compared with that from the U. S. Hydrographic Office is 0.04 N/m^2 for NORAPS and 0.03 N/m^2 for COAMPS. These errors are rather large considering that they are of a similar magnitude as the mean wind stress data itself. The RMS error computed between the NORAPS and ECMWF monthly mean wind stresses is 0.04 N/m^2; between COAMPS and ECMWF, the RMS error is 0.03 N/m^2. When compared to H-R monthly mean wind stresses, the COAMPS RMS error is nearly the same at 0.03 N/m^2, whereas for NORAPS, the RMS error is slightly larger, 0.06 N/m^2.

Figures 36 (NORAPS) and 37 (COAMPS) illustrate the RMS errors and the associated correlation coefficients as compared to each source of wind stress data. The NORAPS monthly mean wind stresses are negatively correlated with all of the data sources. The least negative correlation value (-0.14) is associated with the H-R dataset. The COAMPS monthly mean wind stress products exhibit a positive correlation to the H-R wind stresses though its magnitude is very small, 0.18.

No seasonal data are available for comparison, but in comparing the NORAPS and COAMPS seasonal mean wind stresses between themselves, considerable variability is evident by the wide range between the minimum and maximum values recorded in Table 9. The winter and autumn mean wind stresses have very different minima from one atmospheric product to the other. During spring and summer, it is the maxima that significantly differ. The annual mean wind stresses for COAMPS and NORAPS are quite similar.

Table 9 - Mean Wind Stress in N/m^2

Month	**NORAPS**	**COAMPS**	**1992**	**H-R**	**ECMWF**
January	0.007 – 0.6	0.0025 – 0.1	0.04	0.024 -0.033	0.01 - 0.04
February	0.05 – 0.12	0.0049 – 0.03	0.04	0.037 -0.047	0.02 -0.04
March	0.002 – 0.06	0.0012 – 0.04	0.048	0.035 -0.043	0.01 -0.04
April	0.004 – 0.09	0.005 – 0.14	0.04	0.017 -0.026	0.008 -0.03
May	0.002 – 0.08	0.003 – 0.07	0.032	0.030 -0.034	0.01 -0.04
June	0.0007 – 0.05	0.008 – 0.18	0.04	0.031 -0.041	0.02 -0.06
July	0.009 – 0.19	0.003 – 0.13	0.02	0.022 -0.027	0.02 -0.04
August	0.004 – 0.17	0.005 – 0.08	0.02	0.020 -0.022	0.01 -0.03
September	0.009 – 0.18	0.003 – 0.13	0.02	0.011 -0.028	0.01 -0.02
October	0.002 – 0.09	0.004 – 0.05	0.025	0.021 -0.025	0.009 -0.02
November	0.002 – 0.04	0.015 – 0.095	0.03	0.024 -0.034	0.01 -0.03
December	0.009 – 0.11	0.008 – 0.09	0.04	0.030 -0.040	0.01 -0.03
Season					
Winter	0.079 – 0.09	0.006 – 0.07			
Spring	0.002 – 0.09	0.002 – 0.05			
Summer	0.003 – 0.14	0.002 – 0.06			
Autumn	0.009 – 0.05	0.016 – 0.07			
Annual	0.006 – 0.066	0.008 – 0.06			
1992- Chao et al. (1992)					

The NORAPS and COAMPS monthly mean wind stresses shown in Figs. 38 and 39, respectively, can be compared visually against the H-R (Fig. 40) and ECMWF (Fig. 41) monthly mean wind stress fields. Note that the scale for the atmospheric product wind stresses is 10% larger than that used with the H-R and ECMWF wind stress fields. The H-R monthly mean wind stresses are averaged from 100 years of observational data and cast onto a grid of 2.0 degrees resolution. The original data were in units of dynes/cm^2 but converted here to units of N/m^2 for consistency with the COAMPS and NORAPS data products. Monthly mean wind stresses derived from the ECMWF 10 m winds are averaged for each month from 1979 to 1993. The resolution of the ECMWF wind stresses is even coarser, at 2.5 degrees. The ECMWF wind stresses shown in Fig. 41 are converted from the original pseudo-wind stress format in m^2/s^2 to N/m^2 through multiplication by a constant drag coefficient, 0.00155, and by the density of air, 1.2 kg/m^3.

In comparing the NORAPS monthly mean wind stresses (Fig. 38) with the H-R monthly mean wind stresses (Fig. 40) there is general agreement from January through June that winds are from the northwest. However, in summer and fall, the NORAPS and H-R wind stresses diverge. The H-R wind stress fields have a strong westerly component in the southern Gulf from July to September, while the NORAPS wind stresses retain the northwest flow with more spatial variability, particularly in September. A westward component in the south becomes evident in the NORAPS wind stresses of October to December. COAMPS wind stress fields (Fig. 39) behave similarly to the H-R data from November to June, with the exception of February when winds diminish dramatically in the southern Gulf. During the months of July to September, COAMPS wind stresses shift to a southeasterly direction, are quiet during August, and then transition to a northwesterly flow in September. The resolution of the ECMWF wind stresses (Fig. 41) is too coarse for meaningful comparisons with either NORAPS or COAMPS wind stress data. From these comparisons, one cannot conclude that either NORAPS or COAMPS monthly mean wind stresses are best. Clearly, though, there are differences with the coarser established data source of H-R. Further comparisons to spatially distributed observations are needed to fully assess the COAMPS and NORAPS wind stress data products.

In the process of working with daily COAMPS wind stress products, large differences in magnitude and direction between the 00Z and 12Z analysis fields have been noticed in some months. While these differences may be attributed to the expected diurnal wind cycle, the degree to which the wind field changes in a 12-hour period appears overly dramatic as shown in Fig. 42, for example. Another potential source of error causing this marked shift in the wind stresses may be the contamination of sea values with land values. Heating over land produces large wind stresses that would not be expected over water unless land values were “bleeding” onto sea points following interpolation. Such contamination could occur in processing the COAMPS model results for dissemination as an operational product. Note, furthermore, that 00Z corresponds to 0330 local time in the Arabian Gulf and likewise 12Z is 1530 local time. Consequently, land/ sea differences and 00Z/12Z differences may be interrelated.

Figure 43 presents the transitions from 00Z to 12Z for the ECMWF wind stress product for the same period in July 1999 as were shown in Fig. 42 for the COAMPS wind stress. No dramatic changes in the wind stress fields from 00Z to 12Z are evident in the ECMWF product. Lastly, Fig. 44 shows the 00Z and 12Z COAMPS wind stress analyses for two dates in December 1999. The extreme changes in wind stress are no longer seen giving support to the idea that land values are contaminating sea point values. This effect is particularly problematic during the summer months. Any further investigation of these issues is beyond the scope of this report.

6. SUMMARY

This examination of the operational atmospheric products generated by the NORAPS and COAMPS models is both necessary and beneficial. First, since these products serve as the external forcing for coastal circulation models, an understanding of how well these products capture the observed environment is very important, especially when it comes to evaluating the performance of the coastal circulation models. Good models can give poor results if forced by nonphysical or nonrepresentative values of surface wind stress or heat flux. Secondly, detailing the atmospheric products dynamically in time whether as annual, seasonal, or monthly means provides insight into the regional dynamics and helps one to form expectations in terms of oceanic circulation and the dominant forcing mechanisms before ever applying an ocean modeling system.

In evaluating the atmospheric products, it is important to independently examine raw products such as air temperature, wind speed, and pressure as well as derived products such as wind stress and heat flux. As we have seen, the quality of a derived product does not necessarily follow that of the raw product. From a coastal modeling perspective, decisions must be made whether to use derived products from the atmospheric model or raw quantities that are then fed into user-defined parameterizations to generate appropriate forcing fields. From the ocean modeling perspective, comparisons of simulations using wind stress atmospheric model products vs wind stresses computed by the user from atmospheric model product wind speeds is ongoing. Note also that heat flux can alternatively be calculated from wind speeds and air temperatures using the bulk aerodynamic equations (e.g., Hastenrath and Lamb 1979b). A similar comparison between coastal model forecasts using the atmospheric model heat flux or a derived heat flux should be undertaken as well.

In the evaluation presented here comparing NORAPS and COAMPS products to themselves, the higher resolution (27 km) of the COAMPS data clearly provides far more detail in the surface products, winds in particular. This detail in the wind field is likely to impact the computed oceanic circulation a great deal. It is important to recognize that the ocean models have resolution far greater than 27 km over coastal waters and so an atmospheric model product whose resolution closely approaches that of the circulation model will likely produce more accurate results based on the forcing alone.

The comparisons of the NORAPS and COAMPS computed mean values to observations recorded in the open literature demonstrate that the NORAPS and COAMPS products are generally acceptable, even if some of the stronger seasonal features, such as the Shamal winds, are underestimated. The NORAPS and COAMPS air temperatures and surface pressures have excellent correlation with the literature sources. RMS errors for COAMPS mean air temperature fields are on the order of only 2 degrees. The seasonal and monthly mean trends of the observed data for air temperature and sea surface pressure are clearly captured in the operational atmospheric products.

In contrast, the NORAPS and COAMPS heat fluxes have very large RMS errors and are essentially uncorrelated in comparison to recorded values. COAMPS heat flux products while showing marked improvement over NORAPS data, still remain unacceptable from the perspective of forcing for a coastal circulation model. Furthermore, atmospheric model heat fluxes composed only of sensible and latent components are of limited use in oceanographic modeling where it is the total heat flux (solar, latent, sensible, and infrared) that is needed.

The NORAPS and COAMPS wind speed and wind stress fields are comparable to one another in terms of the product source and with respect to physical (speed) vs derived (stress) quantities. However, the dramatic gradient in the wind stress across the land-sea interface tends to mask features of the wind stress over water. RMS errors for wind speed and stress associated with each atmospheric data product are essentially uniform with respect to the wide variety of observed sources identified. No clear conclusions can be drawn in correlating the atmospheric products to measured data across seasons or months due to the high degree of variability present in the measured data itself. With respect to the COAMPS wind products, further investigation is necessary to a) determine how realistic the observed diurnal cycling in the COAMPS wind stress products is for the Arabian Gulf region and b) assess the possible source of the land-sea differentials in wind stress and determine the extent to which land values interfere with over-water quantities.

As an aside, this effort has highlighted the importance of visualization of the atmospheric data products prior to implementation as forcing for coastal models. Several of the erroneous trends in the data fields would not have been easily found without the capability of observing the data in a visual context.

7. ACKNOWLEDGMENTS

The authors wish to thank the following individuals for their contributions: Ms. Pamela Posey of NRL-Stennis and Mr. James Dykes of the Naval Oceanographic Office who obtain the operational atmospheric products on a daily basis; Dr. Richard Hodur of NRL-Monterey for discussions of the COAMPS wind stress fields; Dr. Randal Pauley of FNMOC and Dr. Teddy Holt of NRL-Monterey for information on total heat flux calculations; Dr. Ruth Preller, Mr. Paul Martin, and Dr. John Kindle of NRL-Stennis and Ms. Melody Clifford of NAVO for useful discussions regarding their experiences using the same operational atmospheric model products; Mr. E. Joseph Metzger of NRL-Stennis for providing the ECMWF pseudo-wind stresses; Mr. Peter Flynn of Neptune Sciences, Inc. for his expertise in using the Xvision software; Ms. Catherine Edwards of NRL-Stennis for help with Matlab plotting routines; and Ms. Ashley McManus for the original design of the NORAPS data visualization. The High Performance Computing Program of the U.S. Department of Defense provided archival storage space and networking for data transfer. This work is funded through the Office of Naval Research NOMP program, program element 602435N, Shallow Water Dynamics of the Arabian Gulf.

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Appendix A
Atmospheric Data Processing

Figure A1 summarizes two possible pathways for the formatting of atmospheric model product data. The NORAPS and COAMPS data undergo several formatting changes prior to their use for either visualization or model input. The data originate at FNMOC as a binary pseudo-GRiB (GRid in Binary) format. This is a binary file with an accompanying table of attributes. GRiB is an accepted standard from the World Meteorological Organization (WMO) (http://dao.gsfc.nasa.gov/data_stuff/formatPages/GRIB.html). Pseudo-GriB is the FNMOC variation of GriB (James Dykes personal communication). The resulting files are commonly referred to as "Flat Files" because they are two-dimensional horizontal slices at a specified vertical reference. At NAVOCEANO, data are converted daily to network Common Data Form (netCDF) (Unidata Program Center in Boulder, Colorado, http://www.unidata.ucar.edu/packages/netcdf). NRL then converts the netCDF formatted data to a binary format for easy manipulation and smaller file sizes.

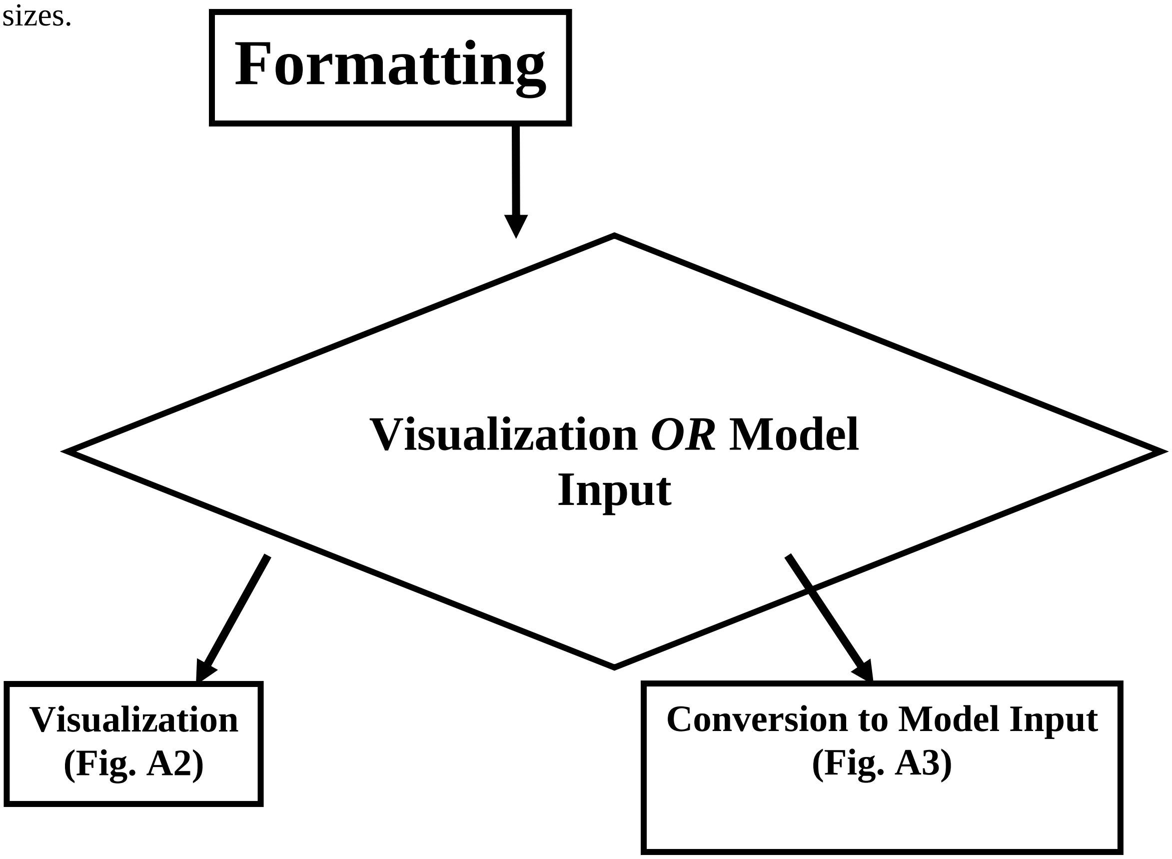

Fig. A1 – Different processing routines are used depending on whether the data will go into a visualization package or into a model.

The visualization software, Xvision (Baird and Associates 1998), allows several input formats. The prototype format is a generic format that Baird and Associates (1998) found to be simplest for the regularly gridded NORAPS and COAMPS data sets of interest. The binary data are first converted (*read.f* and *read_wnd.f*) to ASCII files that contain the latitude and longitude values at the NORAPS and COAMPS grid points in addition to the data values. A C program (*to_proto.c* and *to_protoZero.c*) converts the ASCII file into the prototype format. A separate bathymetry file, taken from the DBDB-V database (NAVOCEANO 1998) is used to overlay the coastline of the Arabian Gulf onto plots and movies of the atmospheric model variables. Figure A2 summarizes the steps of data processing.

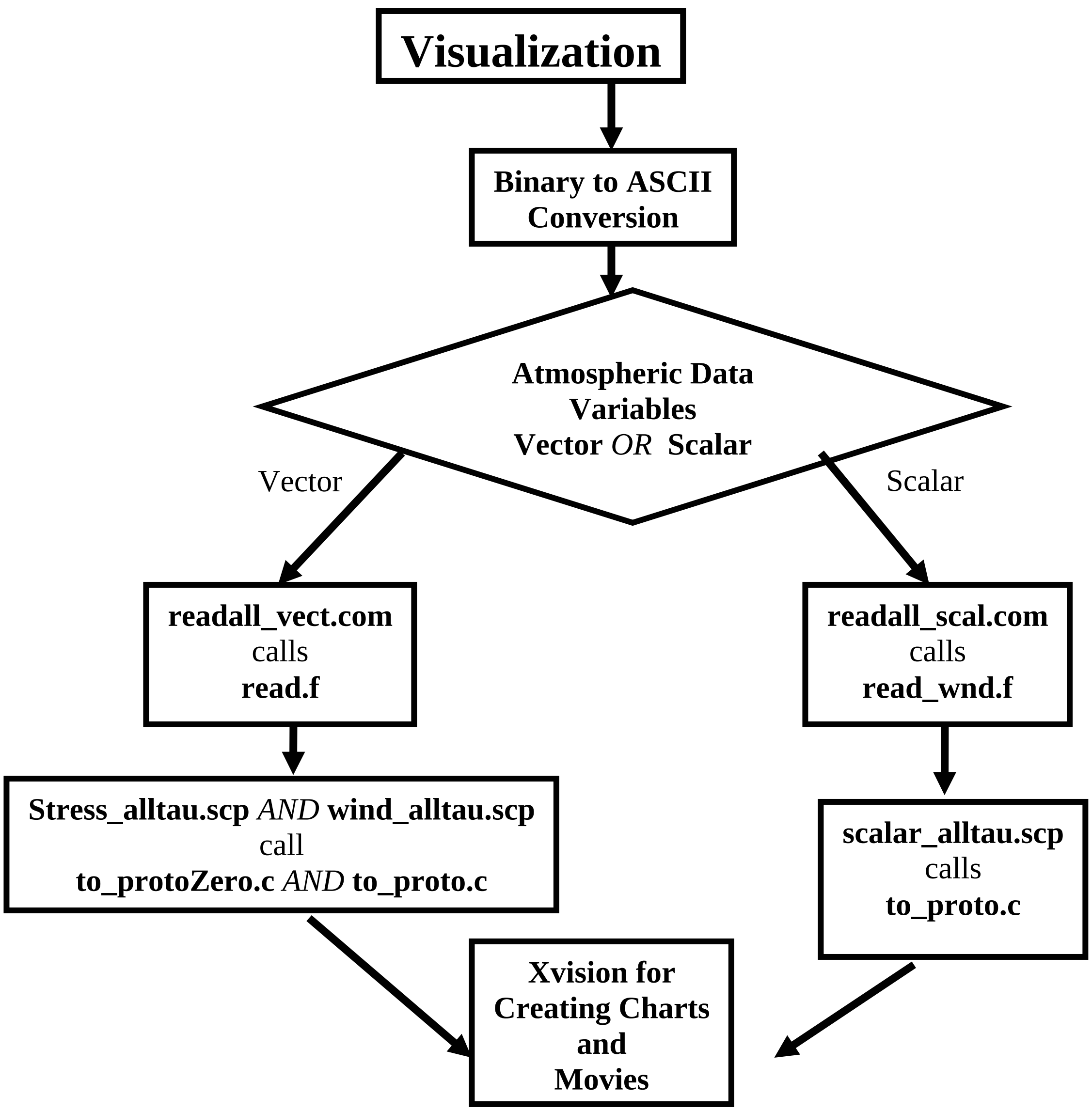

Fig. A2 – A schematic of the scalar and vector processing for the purposes of visualization.

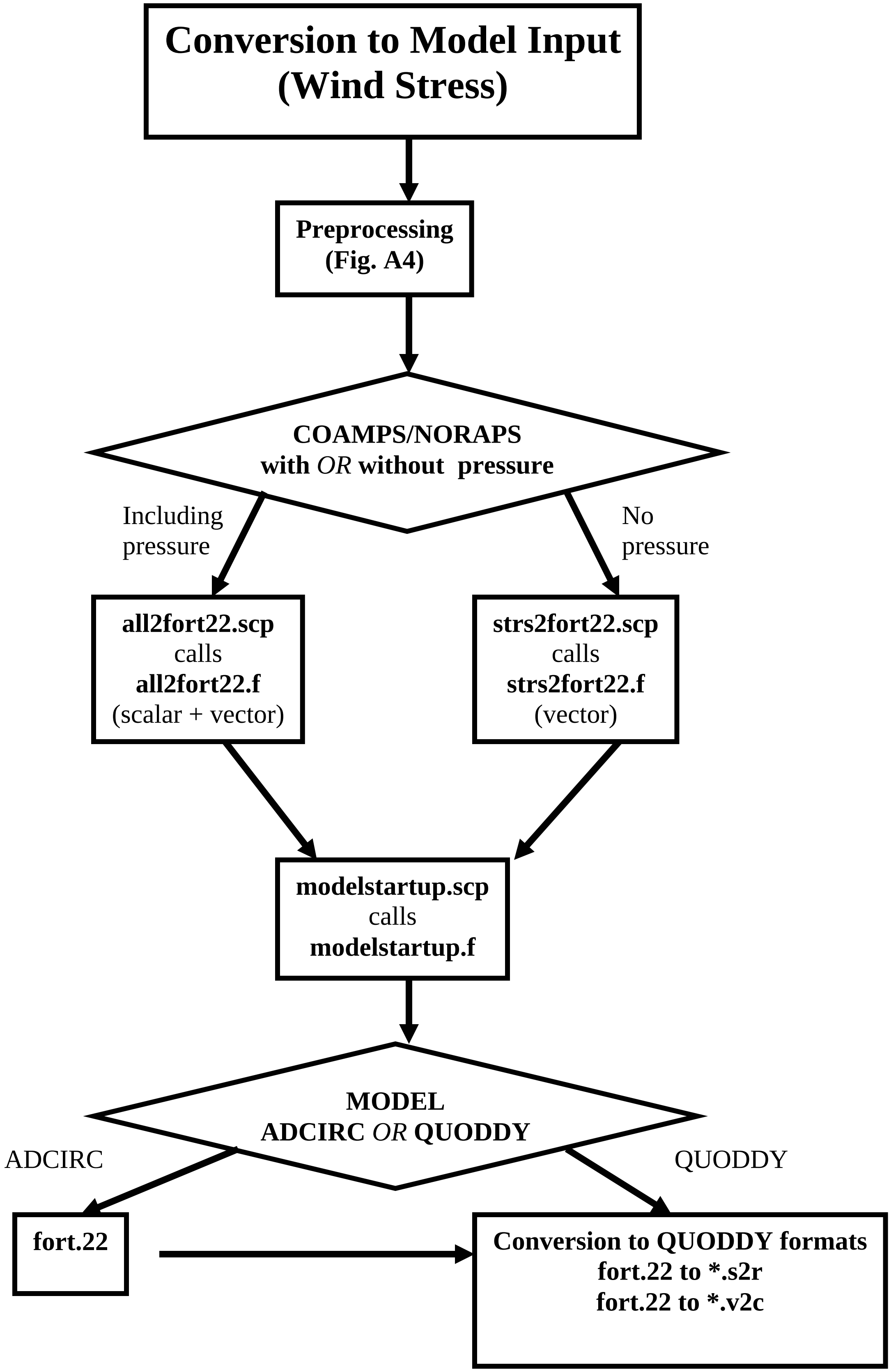

Fig. A3 – A schematic of the necessary steps to convert wind stresses into a suitable input file for the finite element circulation models ADCIRC and QUODDY.

Wind forcing (see Fig. A3) is introduced into the ADCIRC model in the form of a wind stress having units of m^2/s^2; mean sea level pressure forcing is expected in units of Pascals (NORAPS pressures are converted from mbars to Pascals). Atmospheric forcing for the ADCIRC model is specified in unit 22 (the fort.22 file). The *all2fort22.f* program is set up to read wind speeds and convert to wind stress (or use wind stress products directly, if available) and pressure data. The gridded wind and pressure data are then interpolated bilinearly to nodes in the finite element grid. Forcing for the QUODDY model requires only a format conversion from the fort.22 file standard to QUODDY file formats, *.s2r and *.v2r.

If pressure data are not required by the model, the program *strs2fort22.f* is used instead of the *all2fort22.f* program. For this case, the pressure array within the fort.22 file is uniformly set to zero.

The fort.22 file for the ADCIRC model must contain forcing values for the entire model simulation period. The program *modelstartup.f* is available as needed to add additional records at the head of the fort.22 file. This situation arises when the simulation period of the model is longer than the temporal range of an existing data file. Such is the case when a spin-up period is included at the beginning of a simulation. The added records are identical to the first record in the initial fort.22 file. The program *modelstartup.f* reads the existing fort.22 file and writes to a new fort.22 file the first record, repeated enough times to cover the length of the length of the spin-up period. Alternatively, the fort.22 file must contain at minimum two records, and so the *modelstartup.f* program can be used to create an appropriate fort.22 file in the case of constant wind stress forcing. This latter application is used to generate appropriate fort.22 input for mean wind stress forcing fields.

Forcing for coastal circulation models can assume a range of temporal scales including monthly, seasonal, annual, daily or hourly variability. For the case of annual, seasonal, or monthly forcing, a mean value is computed. For the case of daily or hourly forcing, temporal interpolation may be required to fill data gaps. Figure A4 shows the steps required to process the data depending on the temporal scale desired.

The ADCIRC and QUODDY models require atmospheric forcing data to retain a uniform temporal resolution. Thus, gaps in the atmospheric data product time series are handled by artificially reconstructing data at missing time periods. A simple linear temporal interpolation is the approach for filling such gaps (tempinterp.f). A user identifies the files containing missing data. Input to the tempinterp.f program includes names of available filenames that are chronologically closest to the missing data files.

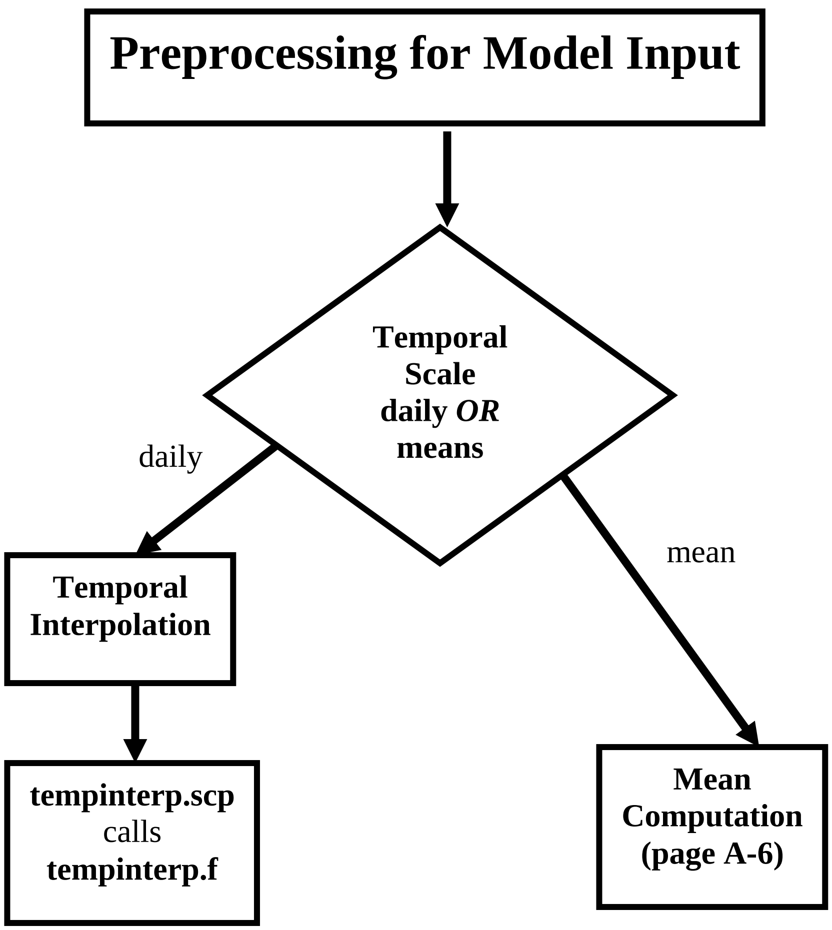

Fig. A4 – A schematic of the data preprocessing required for use as model input, based upon daily or mean forcing input.

Scalar and vector mean values are calculated separately (see Fig. A5) due to the dual file format of vector data (one file for each component). The *vect2monmean.f* and *scal2monmean.f* programs are simple arithmetic mean calculations and a Unix C shell script in each case concatenates selected files that are to be used in the computation of the mean field. A variety of Unix C-shell scripts calculate the various means that are then visualized by the user or used as forcing for the circulation models.

At present, *heat260daymean.f* has been used solely for calculating bimonthly means of heat flux values, but it can be adjusted for other scalar values. Heat flux data are presently used only by the QUODDY model. A special set of routines (including optimal interpolation) interpolates gridded mean data onto the finite element mesh.

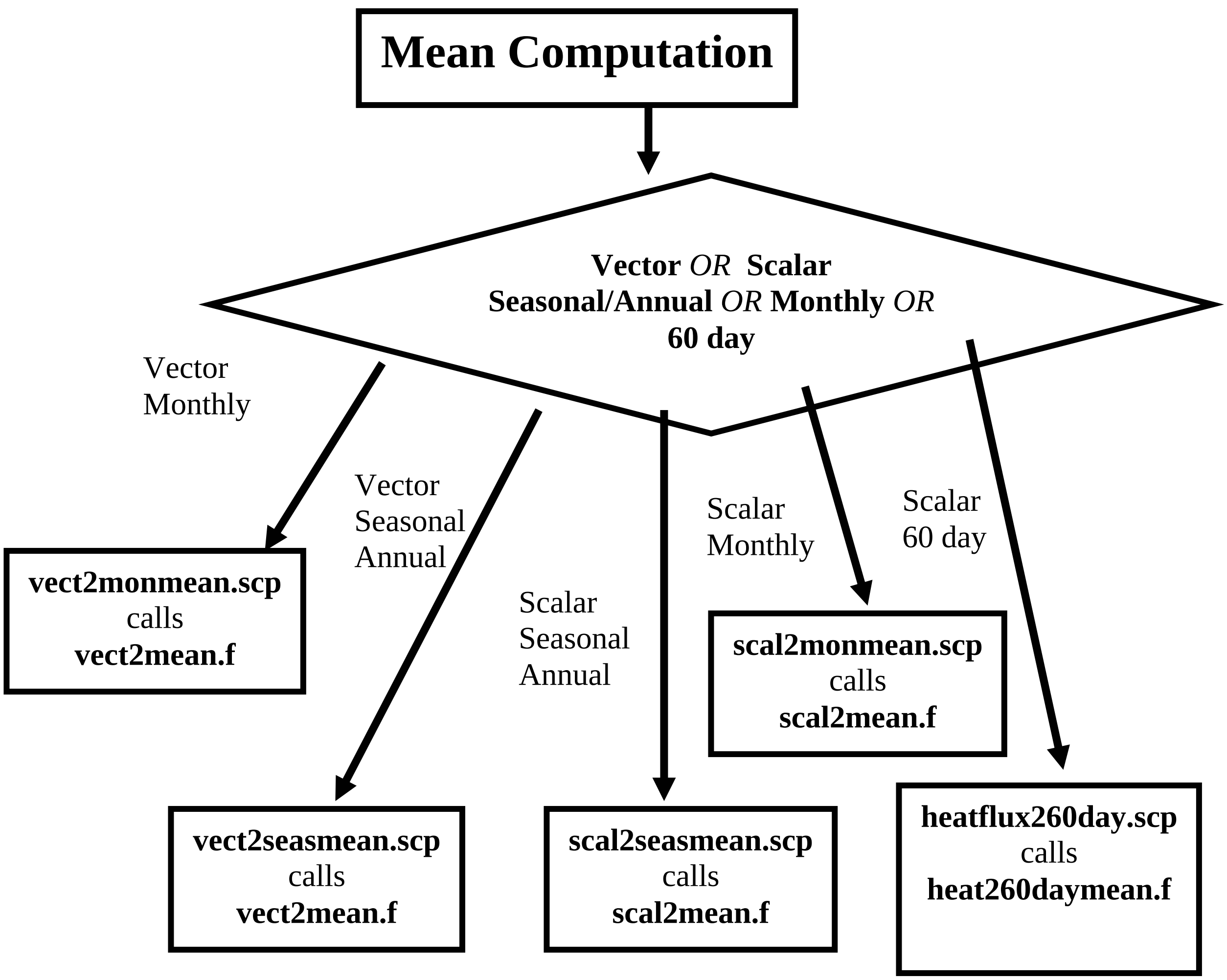

Fig. A5 – A schematic showing the range of possible mean computations.

Appendix B
Glossary of Programs

The series of programs used in the conversion of the U.S. Navy atmospheric to formats compatible with their use as model input or for visualization are defined.

all2fort22.f - reads in pressure files and either wind or wind stress files. Output is the fort.22 file. The fort.22 file is an ASCII file that is read directly by the ADCIRC model and various QUODDY model conversion programs. Wind speed values are converted to wind stress values using the Garratt formula (Garratt 1977). The pressure and wind stress values are interpolated onto a specified finite element grid that will be used by the ADCIRC or QUODDY models. A *.dim file contains parameter statements defining the array sizes. The program is called by the all2fort22.scp script.

heat260daymean.f - reads in user-specified starting and ending dates, reads in binary files containing scalar products, and outputs a binary file (unit 43) containing the bimonthly mean, and a file with a count of the sample size (unit 777). A *.dim file contains parameter statements defining the array sizes. Thus far, this program has been used solely for heat flux values, but it can be adjusted for other scalar values. The program is called by the heatflux260day.scp script.

modelstartup.f - reads in a fort.22 file and outputs a new fort.22 file containing additional initial records identical to the first record in the original fort.22 file. The user must input the number of extra records desired in the calling script (modelstartup.scp). A *.dim file contains parameter statements defining the array sizes.

read.f - reads a binary scalar file and outputs an ASCII file with columns of longitude, latitude, and the scalar value. Each file is input separately, but a calling script (readall_scal.com) handles a series of files (usually an entire month) at once. Separate versions of the script and program exist for COAMPS and NORAPS data. Array sizes are defined inside the program.

read_wnd.f - reads a binary vector file and outputs an ASCII file with columns of longitude, latitude, and the value of all vector components. Each file is input separately, but a calling script (readall_vect.com) handles a series of files (usually an entire month) at once. Separate versions of the script and program exist for COAMPS and NORAPS data. Array sizes are defined inside the program.

scal2mean.f - reads in user-specified starting and ending dates for the period of mean computation, reads in binary files containing scalar products, and outputs to units 51 through 53 a binary file containing the monthly, seasonal, or annual mean of each of the three scalar products. NORAPS mean sea level pressures are converted to Pascals for model input. COAMPS mean sea level pressures are converted to mbars if desired for visualization. Starting and ending dates must be input in the format specified by the calling script (vect2monmean.scp or vect2seasmean.scp), and the atmospheric data product to be used, NORAPS or COAMPS, must be specified. A *.dim file contains parameter statements defining the array sizes.

strs2fort22.f - reads in wind or wind stress files, and outputs a fort.22 file. The fort.22 file is an ASCII file that is read directly by the ADCIRC model and various QUODDY model conversion programs. Wind speed values are converted to wind stress values using the Garratt formula (Garratt 1977). The pressure and wind stress values are interpolated onto a specified finite element grid that will be used by the ADCIRC or QUODDY models. A *.dim file contains parameter statements defining the array sizes. The program is called by the strs2fort22.scp script.

tempinterp.f - reads last and next available binary files, interpolates to fill in missing records, and writes out binary files with the same temporal structure as the input files. The user inputs to the script (tempinterp.scp) the filenames of the last and next available binary files that bracket the missing data file; these are placed in Fortran input unit numbers, starting with 50 and ending with the sum of 50 plus the number of missing files. Output files are written to the Fortran unit numbers in between the input unit numbers. A *.dim file contains parameter statements defining the array sizes.

to_proto.c - reads ASCII files produced by **read.f** and **read_wnd.f** and outputs a prototype file of surface data that can be read by Xvision (Baird and Associates 1998). The program reads one file at a time, but a calling script handles a series of files (usually an entire month) at once. Separate versions of the script and program exist for COAMPS and NORAPS data. Array sizes are specified in the call of the program (inside the script scalar_alltau.scp, wind_alltau.scp or stress_alltau.scp).

to_protoZero.c - reads ASCII files from **read.f** and **read_wnd.f** and outputs a prototype file of the component velocity data, u and v, that can be read by Xvision (Baird and Associates 1998). The program reads one file at a time, but a calling script handles a series of files (usually an entire month) at once. Separate versions of the script and program exist for COAMPS and NORAPS data. Array sizes are specified in the call of the program (inside the scripts wind_alltau.scp and stress_alltau.scp).

vect2mean.f - reads in user-specified starting and ending dates for the period of mean computation, reads in binary files containing vector products, and outputs to units 54 through 57 a binary file containing the monthly, seasonal, or annual mean of each component for each vector product. Starting and ending dates must be input in the format specified by the calling script (vect2monmean.scp or vect2seasmean.scp), and the atmospheric data product to be used, NORAPS or COAMPS, must be specified. A *.dim file contains parameter statements defining the array sizes.

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