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CONVEX AIR-SEA HEAT FLUX CALCULATIONS

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I. INTRODUCTION.

According to Pickard and Emery (1982), air-sea heat flux is given by:

$$Q_n = Q_i + Q_b + Q_s + Q_e \tag{1}$$

where Q_n is the net vertical heat flux (Wm^{-2}), Q_i is the incident short-wave radiational heat flux, Q_b is the long-wave radiational heat flux, Q_s is the conductive (sensible) heat flux, and Q_e is the evaporative heat flux. Each of these terms is in turn a complex function. Positive values indicate heat flux into the ocean.

After a comprehensive review of the literature, Miller (1999) assembled and used the bulk formulae presented in Section II to estimate the relevant winter 1997-98 CONVEX heat and associated mass fluxes from available measurements. Mupparapu and Brown (1999) used an alternate set of bulk formulae (see Appendix) to estimate the heat and mass fluxes for the winter 1986-87 scenario they considered. In both cases, some measurements necessary to compute the heat fluxes from the respective set of bulk formulae at the Wilkinson Basin 1998 buoy site were not available. Therefore Miller (1999) devised a procedure to estimate wind, dew point temperature (*i.e.* related to relative humidity) and air temperature at the Wilkinson Basin 1998 buoy site using National Weather Service (NWS) and National Data Buoy Center (NDBC) measurements surrounding Wilkinson Basin. That procedure and the results are presented in Section III. The approach used by Mupparapu and Brown (1999) is discussed in the Appendix.

II. BULK FORMULAE.

The incident *short-wave radiational heat flux* is given by:

$$Q_i = (1 - Ab)\, I_{sw} \tag{2}$$

where Ab is the sea-surface albedo, and I_{sw} is the incident short-wave radiation (Wm^{-2}) (Beardsley, *et al.*, 1998).

Albedo is a function of atmospheric transmittance and solar elevation angle, quantified in tabular form by Payne (1972). Atmospheric transmittance is a dimensionless number between 0 and 1, and is given by:

$$Tr = \frac{I_{sw}\, \gamma^2}{S \sin|\varphi|} \tag{3}$$

where gamma is the multiple of the mean Earth-Sun distance (a number approximately equal to one), S is the solar "constant" (1353 Wm^{-2}), and phi is terrestrial latitude (degrees) (Payne, 1972). The Earth-Sun distance multiple (gamma) is calculated according to:

$$\gamma = 1.00011 + 0.034221 \cos(\alpha) + 0.00128 \sin(\alpha) + 0.000719 \cos(2\alpha) + 0.000077 \sin(2\alpha) \tag{4}$$

where alpha is the day angle, which is in turn calculated by:

$$\alpha = 2\pi(N-1.0)/365.0 \tag{5a}$$

$$\alpha = 2\pi(N-1.0)/366.0 \tag{5b}$$

where N is the day of the year. (5b) is used for leap years, and (5a) for ordinary years (Iqbal, 1983).

The solar elevation angle (theta) (degrees) is calculated by:

$$\theta = 90 - \mathrm{acos}(\cos Z) \tag{6}$$

where cosZ (the cosine of the zenith angle) is calculated by:

$$\cos Z = \sin(\phi)\ \sin(\sigma) + \cos(\phi)\ \cos(\sigma)\ \cos(H) \tag{7}$$

where phi is the terrestrial latitude (degrees), sigma is a function of the day angle, and H is the hour angle (degrees). Sigma and H are calculated by:

$$\begin{aligned}\sigma = {} & 0.006918 - 0.399912\cos(\alpha) + 0.070257\sin(\alpha) - \\ & 0.006758\cos(2\alpha) + 0.000907\sin(2\alpha) - \\ & 0.002697\cos(3\alpha) + 0.00148\sin(3\alpha)\end{aligned} \tag{8a}$$

$$H = 15.0\ (12.0 - \mathrm{Hour}) \tag{8b}$$

where Hour is the decimal hour (local standard time), and alpha is the day angle (Iqbal, 1983).

The *long-wave radiational heat flux* is given by:

$$Q_b = \varepsilon\ ((I_{lw} - 0.036 I_{sw}) - \sigma T_s^4) \tag{9}$$

where epsilon is the emissivity of the sea-surface (0.985), I_{lw} is the incident long-wave radiation (Wm^{-2}), I_{sw} is the incident short-wave radiation (Wm^{-2}), sigma is the Stefan-Boltzmann constant (5.673 x 10^{-8} $Wm^{-2}K^{-4}$), and T_s is the sea-surface temperature (Kelvins) (Beardsley, *et al.*, 1998).

The constant 0.036 applied to I_{sw} is a sensor correction, and the value of emissivity (epsilon) for both Atlantic and Pacific seawater at 300 Kelvins is taken as 0.985 +/- .010 (Dickey, et al., 1994).

The *sensible heat flux* through the sea surface is given by:

$$Q_S = -\rho_a \, c_p \, C_S \, (T_S - T_a) \, W \qquad (10)$$

where roe$_a$ is the density of the moist air at ten meters (kg m^{-3}), c_p is the specific heat coefficient of moist air at constant pressure (J kg^{-1} K^{-1}), C_s is the sensible heat transfer coefficient (Stanton number), T_s and T_a are the temperatures of the sea-surface and the air at ten meters above the sea-surface (Celsius), and W is wind speed (ms^{-1}) (Gill, 1982). The density of the moist airmass is calculated by means of the ideal gas law:

$$\rho_a = p/(R_d \, T_v) \qquad (11)$$

where p is the atmospheric pressure (pascals), R_d is the specific heat constant of dry air (287 J kg^{-1} K^{-1}), and T_v is the virtual temperature (Kelvins) (Hess, 1959). Virtual temperature (in Kelvins) is in turn calculated by:

$$T_v = T\left(\frac{1 + \frac{w}{\varepsilon}}{1 + w}\right) \qquad (12)$$

where epsilon is the ratio of the mean molecular weight of water to the mean molecular weight of dry air (0.62197), w is the mixing ratio of water vapor to dry air, and T is the dry air temperature (Kelvins) (Hess, 1959). The mixing ratio (w) is calculated by:

$$w = \frac{\varepsilon e}{p - e} \qquad (13)$$

where e is the vapor pressure. (Any units of e and p are allowable, provided they are the same units.) (Hess, 1959.) The vapor pressure is calculated by means of the Classius-Clapeyron equation:

$$e = e_0 \exp\left[\left(\frac{L_v}{R_v}\right)\left(\frac{1}{T_0} - \frac{1}{T_d}\right)\right] \qquad (14)$$

where e_0 is the reference pressure (611.12 pascals), L_v is the latent heat of vaporization (J kg^{-1}), R_v is the specific gas constant of water vapor (461 J kg^{-1} K^{-1}), T_0 is the reference temperature for e_0 (273.16 Kelvins), and T_d is the dew point (Kelvins) (Hess, 1959). The latent heat of vaporization is calculated by:

$$L_v = L_{v0} - 2369T \tag{15}$$

where L_{v0} is the value of L_v at 0 degrees C, taken as 2500297.8 Jkg^{-1}, and T is the temperature in Celsius (Hess, 1959). The specific heat coefficient of moist air is calculated by:

$$c_p = c_{p0} \left[\frac{1 + w \left[\frac{c_{pv}}{c_{p0}}\right]}{1 + w} \right] \tag{16}$$

where c_{p0} is the value of cp at zero relative humidity (1004.6 J kg^{-1} K^{-1}), w is the water vapor mixing ratio, and c_{pv} is the specific heat constant of water vapor (1870 J kg^{-1} K^{-1}) (Rogers and Yau, 1989). C_s is the sensible heat transfer coefficient (Stanton number), and is calculated by:

$$C_s = \begin{cases} W < 8\ ms^{-1}: & (0.720+[0.0175\ W\ (T_s-T_a)])\times 10^{-3} \\ W \geq 8\ ms^{-1}: & (1.000+[0.0015\ W\ (T_s-T_a)])\times 10^{-3} \end{cases} \tag{17}$$

where W is the wind speed (ms^{-1}), and T_s and T_a are the sea-surface and airmass temperatures, respectively (degrees C) (Wu, 1992).

The *latent (or evaporative) heat flux* is given by:

$$Q_e = -\rho_a\, L_v\, C_e\, (q_s - q_a)\, W \tag{18}$$

where roe_a is the density of the moist air at 10 meters (kgm^{-3}), L_v is the latent heat of vaporization (J kg^{-1}), C_e is the evaporative heat transfer coefficient (Dalton number), q_s and q_a are the specific humidities at the sea-surface and the air at ten meters above the sea-surface, and W is wind speed (m s^{-1}) (Gill, 1982). The airmass density and the latent heat of vaporization are as described above. The transfer coefficient (Dalton number) is taken as a constant equal to 1.5 x 10-3. Specific humidities are calculated by:

$$q = \frac{\varepsilon e}{p - (1 - \varepsilon) e} \tag{19}$$

where p is the atmospheric pressure, e is the vapor pressure, and epsilon is the ratio of the mean molecular weight of water to the mean molecular weight of dry air (0.62197). (Any units for p and e are permissible, provided they are the same units.) (Rogers and Yau, 1989.)

III. SYNTHESIS OF METEOROLOGICAL VARIABLES FOR THE WILKINSON BASIN SITE.

Many of the CONVEX Wilkinson Basin (WB) mooring's meteorological sensors failed shortly after deployment. Of the full meteorological instrument package deployed, only the air temperature sensor survived for the full duration of the period covered by this study: 10 January 1998 2130 through 06 February 1998 0830 Greenwich Meridian Time (GMT). The remainder of the data needed -- *relative* humidity, sea-level (atmospheric) pressure, and wind velocity components -- were estimated from the measurements at twelve NOAA operational observing locations in and around the Gulf of Maine in a procedure outlined here. Table 1 lists the NOAA sites utilized, and Figure 1 shows the locations of these sites.

Table 1: Meteorological Data Recording Locations.

Sources: National Data Buoy Center, National Climatic Data Center, U.S. Government Airport/Facility Directory, National Weather Service. For NDBC sites and the Provincetown Lighthouse, elevation refers to the height of the barometer. For NOAA and DOD airfields, elevation indicates altitude of runway centerline.

Ident	Full Name	Lat [dN]	Lon [dW]	Elevation [m]	Type
MDRM1	Mt. Desert Rock	43.97	68.13	16.5	C-MAN Station (NDBC)
MISM1	Matinicus Rock	43.78	68.86	26.5	C-MAN Station (NDBC)
KNHZ	Brunswick NAS, Maine	43.88	69.93	23.1	Airfield (U.S. Navy)
KPWM	Portland Jetport, Maine	43.65	70.32	13.2	Airport (NOAA)
44007	Portland, Maine	43.53	70.14	2	Moored Buoy (NDBC)
KPSM	Pease ANGB, New Hampshire	43.08	70.82	31.1	Airfield (USAF)
IOSN3	Isle of Shoals, New Hampshire	42.97	70.62	18.9	C-MAN Station (NDBC)
44013	Boston, Massachusetts	42.35	70.69	2	Moored Buoy (NDBC)
KBOS	Logan IAP, Boston, Massachusetts	42.37	71.03	4.6	Airport (NOAA)
KPVC	Provincetown Light, Massachusetts	42.07	70.22	2.0	Automated Observing Site (NOAA)
KCQX	Chattam Airport, Massachusetts	41.68	69.98	20.9	Airport (NOAA)
44011	Georges Bank	41.08	66.58	2	Moored Buoy (NDBC)

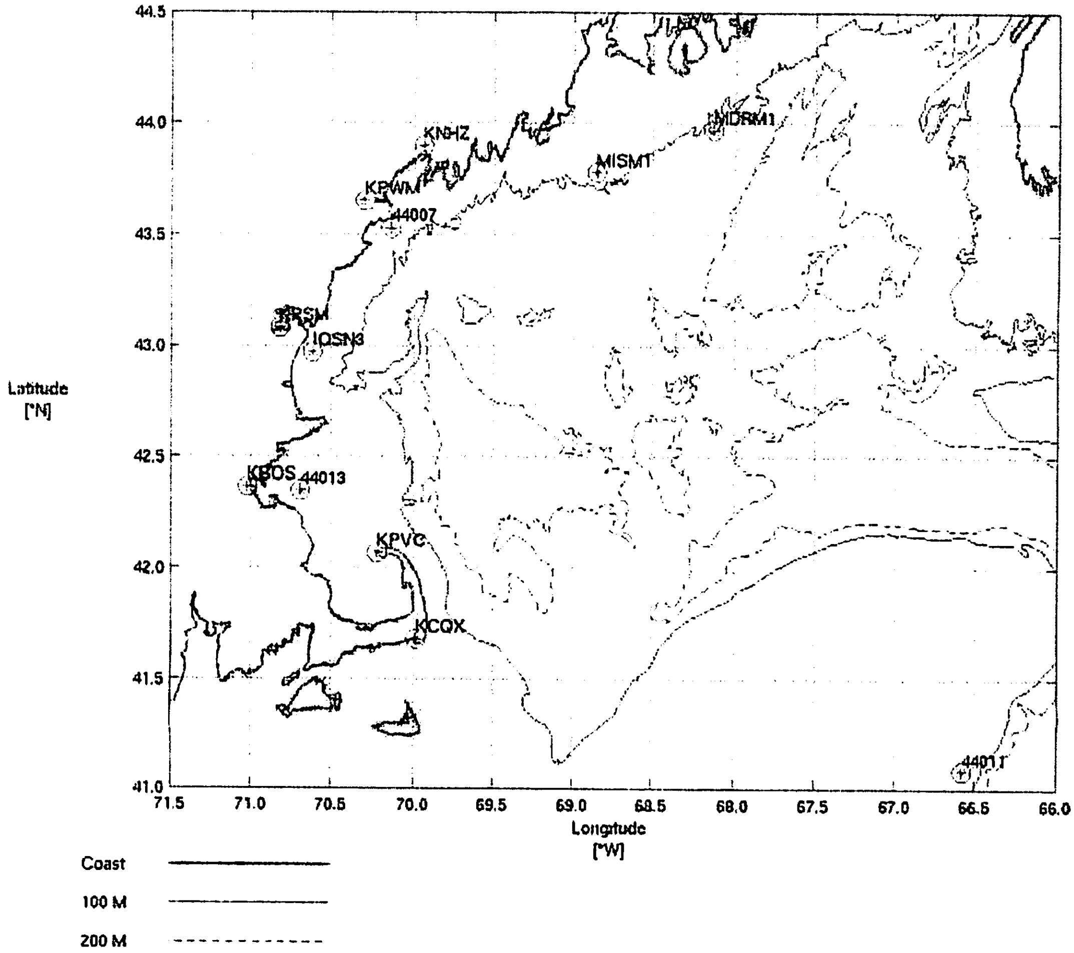

Fig 1: Meteorological Data Recording Locations.
Also see Table 1.

Hardcopies of the Brunswick NAS (KNHZ), Pease ANGB (KPSM), and Provincetown Lighthouse (KPVC) meteorological records for January and February, 1998 were obtained from one local weather station (KPSM) and the National Climatic Data Center (KNHZ and KPVC). A single digital file was created for each station (hereafter referred to as an "archive"), containing temperature, dew point, pressure, wind direction, and wind speed over the two-month period.

Logan IAP (KBOS), Chattam Airport (KCQX), and Portland Jetport (KPWM) meteorological records for January through May, 1998 were downloaded from the National Climatic Data Center website (http://www.ncdc.noaa.gov/). Software was developed that read each month-long file as a string, picked out the same key data elements noted above, and created an archive spanning the whole five-month period.

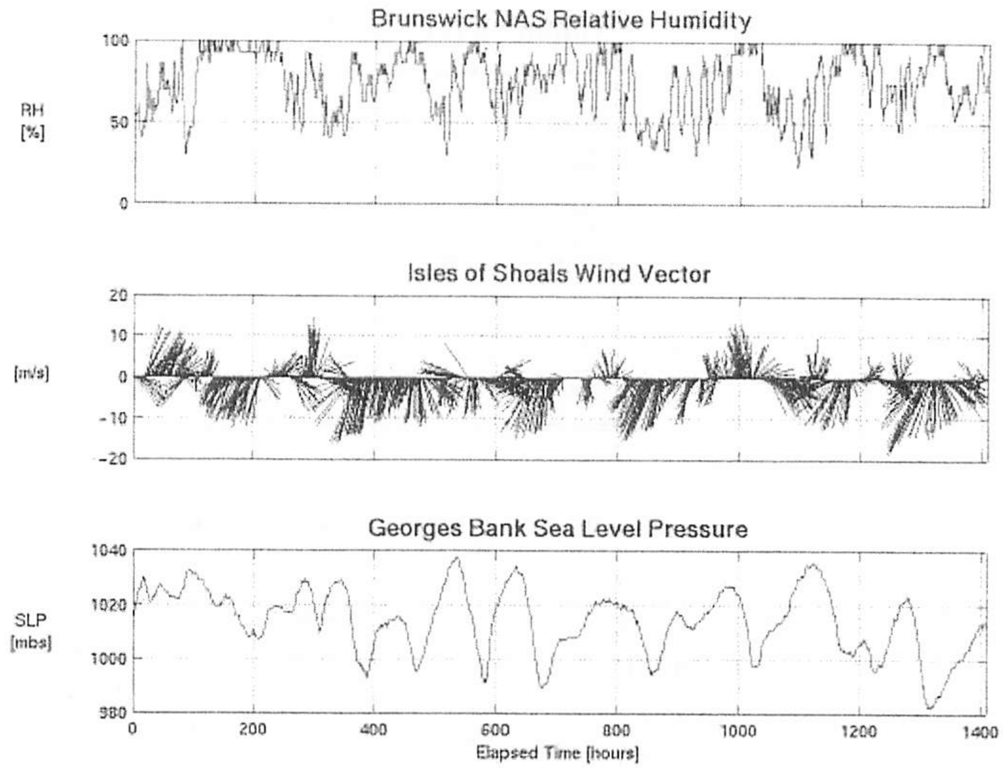

Fig 2: Representative Time Series.
Each series begins on 01 January 98 0600 GMT and ends on 01 March 1998 0500 GMT. For the Isles of Shoals wind vector, "up" is northward. Also see Tables 2, 3a, 3b, and 4.

Table 2: Basic Statistics for Relative Humidity Series.

Station	Maximum [%]	Minimum [%]	Mean [%]	Standard Deviation [%]
Brunswick NAS	100.00	23.30	74.95	18.61
Portland	100.00	24.20	73.82	18.34
Pease ANGB	100.00	20.50	73.16	18.77
Logan IAP	100.00	22.00	78.01	19.36
Chattam	100.00	30.90	77.08	15.83
Provincetown	100.00	33.83	71.41	14.19

Table 3a: Basic Statistics for U Wind Component Series.

Station	Maximum $[ms^{-1}]$	Minimum $[ms^{-1}]$	Mean $[ms^{-1}]$	Standard Deviation $[ms^{-1}]$
Mt. Desert Rock	19.00	-19.90	-0.82	7.21
Matinicus Rock	23.30	-21.50	-0.22	7.61
Portland Buoy	13.80	-16.00	0.49	4.42
Isles of Shoals	16.70	-14.90	0.21	6.01
Boston Harbor Buoy	14.70	-15.30	0.57	5.20
Georges Bank Buoy	16.10	-18.70	0.02	6.60

Table 3b: Basic Statistics for V Wind Component Series.

Station	Maximum $[ms^{-1}]$	Minimum $[ms^{-1}]$	Mean $[ms^{-1}]$	Standard Deviation $[ms^{-1}]$
Mt. Desert Rock	17.20	-17.60	-3.51	6.27
Matinicus Rock	17.70	-18.30	-3.72	6.68
Portland Buoy	13.10	-14.60	-3.19	5.64
Isles of Shoals	14.90	-18.80	-3.08	6.04
Boston Harbor Buoy	10.30	-16.10	-2.91	5.47
Georges Bank Buoy	14.20	-16.50	-2.77	5.81

Table 4: Basic Statistics for Sea-Level Atmospheric Pressure Series.

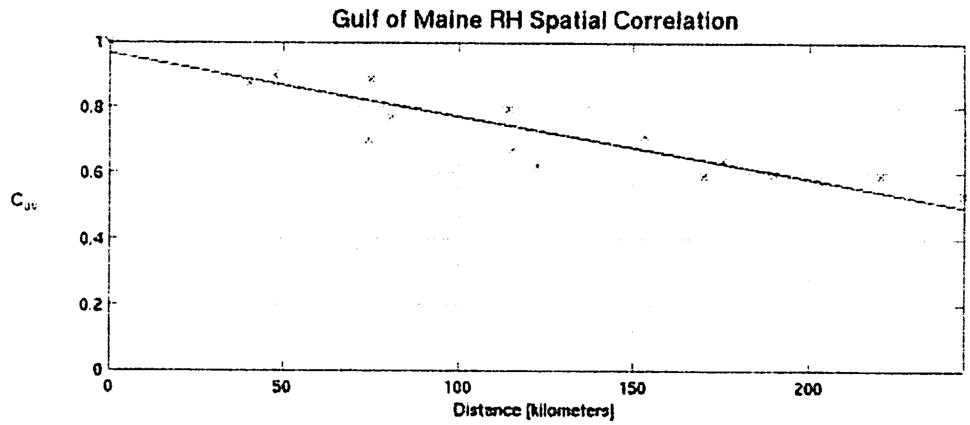

Fig. 3: Relative Humidity Cross-Correlation as a Function of Distance in the Gulf of Maine.

Table 6: Slopes, Intercepts, and Standard Deviations (sigma) Associated with Linear Spatial Correlation Functions.

Variable	**Slope [km^{-1}]**	**Intercept [unitless]**	**Sigma [unitless]**
Relative humidity	-0.00192	0.96517	0.05522
U component	-0.00058	0.95261	0.05044
V component	-0.00144	1.02314	0.04299
Atmospheric Pressure	-0.00025	1.01196	0.00973

Synthesized Series.

Given these spatial correlation functions and the repaired series discussed above, time series of relative humidity, the U and V components of wind, and atmospheric pressure were synthesized for the WB mooring location. The hourly data series were then linearly interpolated to 30-minutes, and truncated to begin on 10 January 1998 2130 GMT and end on 06 February 1998 0830 GMT. (See Figure 4.)

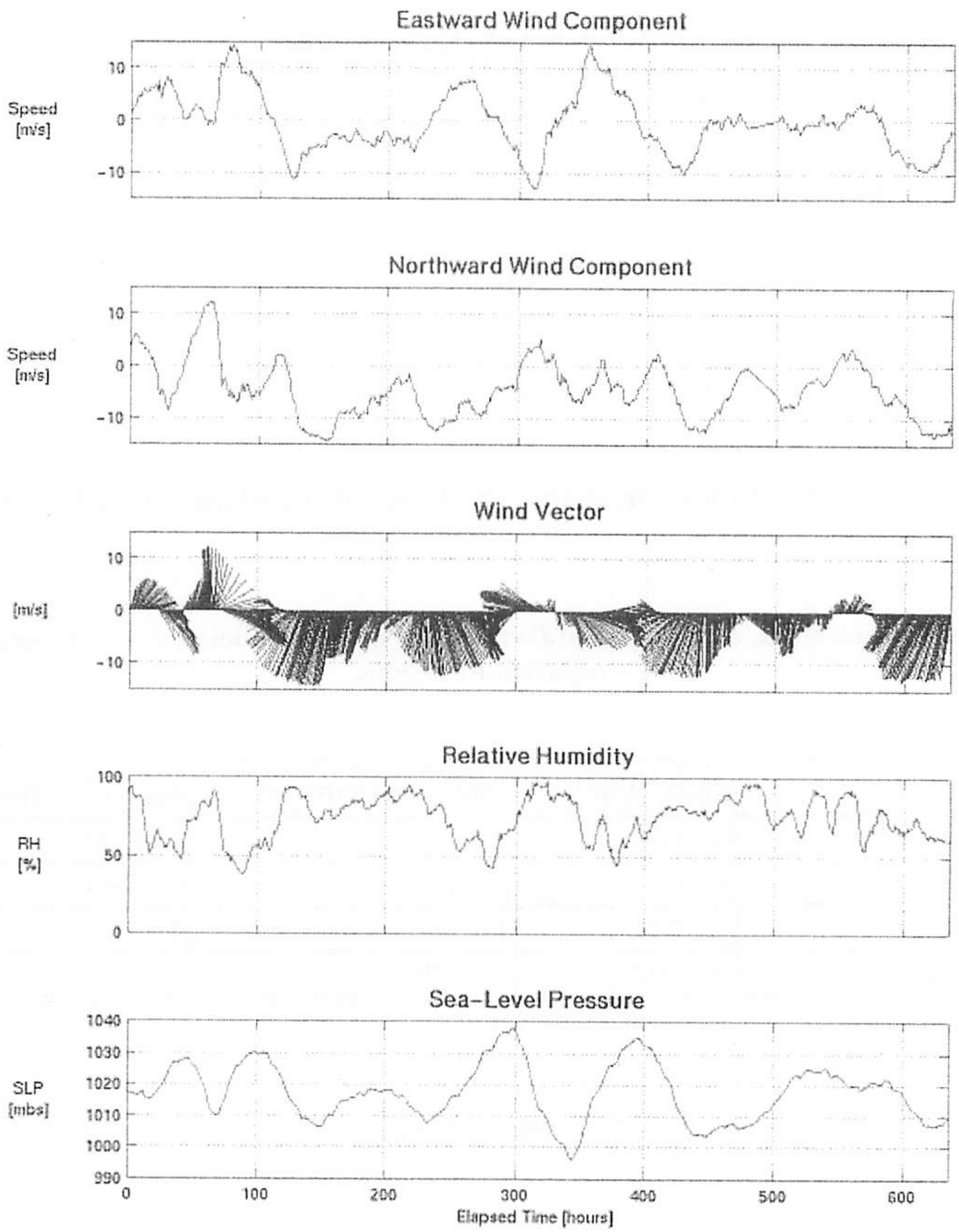

Fig 4: Synthesized Meteorological Series for Wilkinson Basin.

These series were synthesized from the repaired series discussed in the text, spatial correlation functions determined for each variable, and a table of distances between the twelve original reporting locations. Each series begins on 10 January 1998 2130 GMT, and ends on 06 February 1998 0830 GMT. Time interval between series elements is 30 minutes. See Table 6 for uncertainties. Northward is "up" in the wind vector plot.

Wind Stress Vector Calculations.

The wind stress time-series was computed from the synthesized Wilkinson Basin U and V wind-component series. The wind stress vector time-series was rotated in 10-degree increments through the compass circle to obtain wind stress component time-series in each of 36 directions. The uncertainty in the wind stress series is assumed to be a maximum of thirty percent, based on arguments presented above. Figure 5 is a vector plot generated from the due eastward and due northward wind stress series. For the details of this calculation, see Irish and Brown (1986).

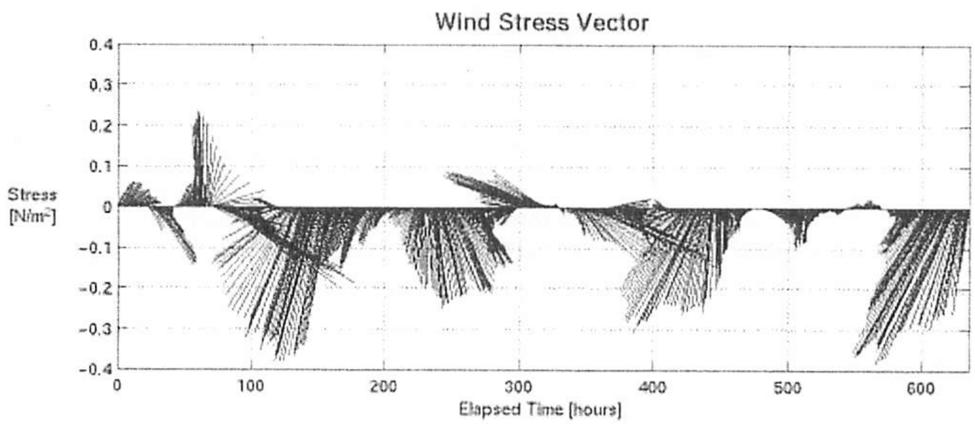

Fig 5: Wind Stress Vector Plot for the Wilkinson Basin Mooring Location.

In-Situ Air Temperature Measurements and Processing.

The air temperature series utilized for the WB mooring location was measured on a surface buoy in Wilkinson Basin (Miller *et al.*, 1999). The raw series recorded by the CONVEX sensor is shown in Figure 6. The "spikiness" of the series was corrected by passing it through a smoothing filter that flagged temperature differences greater than +/- 0.1 degrees C in two minutes, and replaced the offending datapoint with a linearly-interpolated value based on neighboring good values. Then, the series was processed through a low-pass cosine filter that reduced the temporal resolution from two to 30 minutes. Finally, the series was truncated so that it begins on 10 January 1998 2130 and ends on 06

Station	Maximum [mbs]	Minimum [mbs]	Mean [mbs]	Standard Deviation [mbs]
Mt. Desert Rock	1039.7	986.0	1015.8	10.6
Matinicus Rock	1039.4	986.2	1015.7	10.5
Brunswick NAS	1039.6	989.2	1016.7	10.0
Portland	1039.8	989.4	1017.4	10.0
Portland Buoy	1038.7	988.0	1016.7	10.2
Pease ANGB	1037.9	988.8	1016.8	9.8
Isles of Shoals	1037.1	987.3	1016.1	10.0
Logan IAP	1036.7	987.8	1016.7	9.9
Boston Harbor Buoy	1035.2	984.6	1015.4	10.2
Provincetown	1037.9	985.4	1017.2	10.3
Chattam	1036.4	983.0	1016.1	10.6
Georges Bank Buoy	1038.0	982.2	1014.5	11.8

Different sets of locations were utilized for estimating different variables (see Table 5). Because no dew point data were available from NDBC sites, the relative humidity time-series was synthesized from air temperatures and dew points recorded at the six land-bound sites on the periphery of the Gulf. Wind component series were synthesized from the six NDBC buoy and C-MAN locations only, because the winds recorded at the oceanic locations are more representative of the surface wind over the ocean surface than are the winds recorded at the land-bound sites. The atmospheric pressure series was synthesized from all twelve locations.

Table 5: Meteorological Data Recording Locations Used for Synthesizing Specific Meteorological Variables.

Variable	Sites Utilized
Relative humidity	KNHZ, KPWM, KPSM, KBOS, KCQX, KPVC
U component of wind velocity	MDRM1, MISM1, 44007, IOSN3, 44013, 44011
V component of wind velocity	MDRM1, MISM1, 44007, IOSN3, 44013, 44011
Sea-level (atmospheric) pressure	MDRM1, MISM1, KNHZ, KPWM, 44007, KPSM, IOSN3, KBOS, 44013, KCQX, KPVC, 44011

Spatial Correlation Functions.

Mt. Desert Rock (MDRM1), Matinicus Rock (MISM1), Portland Buoy (44007), Isle of Shoals (IOSN3), Boston Buoy (44013), and Georges Bank Buoy (44011) meteorological records for January and February, 1998 were downloaded from the National Data Buoy Center website (http://seaboard.ndbc.noaa.gov/). Software was developed that read each month-long file, picked out the key data elements, and created an archive spanning the two-month period.

Temperature, dew point, and atmospheric pressure data from each of the six land station archives were combined to create relative humidity series spanning the January-February period. The relative humidity (RH) is calculated according to:

$$RH\ [\%] = \frac{e}{e_s} \times 100\% \qquad (20)$$

The vapor pressure (e) and saturation vapor pressure (e_s) were calculated from dew point and temperature according to equation 14 (above). Small gaps (one or two hours) in the relative humidity series were patched via linear interpolation. Three large gaps in the Provincetown humidity series (as long as 220 hours) were patched by linearly regressing the overlapping Provincetown RH data against the Chattam RH series for the same period. A similar procedure was used to create and repair two-month records of barometric pressure for the same six land stations.

January-February series of the U (eastward) and V (northward) components of wind, along with atmospheric pressure, were created for the six ocean stations from their respective archives. As with the RH series, gaps of an hour or two were bridged via linear interpolation. A gap of nearly 600 hours in the Mt. Desert Rock wind records, spanning the majority of February, was repaired by linearly regressing the overlapping Mt. Desert Rock wind-component series against similar series for Matinicus Rock.

Figure 2 shows a representative time series of each of the estimated variables. Table 2 lists the basic statistics for all of the relative humidity series, Tables 3a and 3b show the statistics for the wind component series, and Table 4 shows the statistics for the sea-level atmospheric pressure series.

Gulf of Maine isotropic spatial correlation functions were calculated for relative humidity, U and V wind components, and atmospheric pressure using the repaired series listed in Table 5 and a table of distances between reporting stations. The method used was adapted from that discussed in Feng (1996) and Mooers et al. (1976).

A full set of zero time-lag cross-correlations were computed between pairs of time-series specified for each of the four meteorological variables. Figure 3 shows the relative humidity correlation as a function of distance in the Gulf. The cross-correlations were carried out utilizing the Ocean Analysis Software Package (OASP) described in Irish and Brown (1986). We computed linear fits to the estimates of zero-lag correlation versus distance R according to

$$C_{uv} = a + bR \tag{21}$$

where C_{uv} is the correlation value, a is the intercept, b is the slope (km^{-1}), and R is the distance (km). Specific uncertainties (standard deviations) associated with the linear curve fits are summarized in Table 6.

One may use C_{uv} as a weighting factor (W_{ij}) for the value of a variable recorded at the ith observing location. The value of W_{ij} is a function of the distance (R_{ij}) between location i and any point j as assigned by equation 21. The variable in question can then be estimated for the jth location according to:

$$Y_j = \frac{\sum_{i}^{N} W_{ij} X_i}{\sum_{i}^{N} W_{ij}} \tag{22}$$

where Y_j is the value of the meteorological variable for point j, X_i is the value for the meteorological variable at observing location i, and W_{ij} is the weight assigned to the value of the variable recorded at observing location i.

February 1998 0830 GMT. The refined series is shown in Figure 7. Uncertainties associated with the temperature series are instrument-based only, and in the range of +/- 0.35 degrees C.

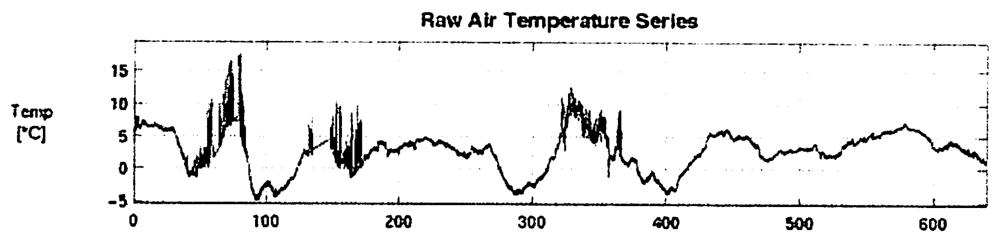

Fig 6. Raw Air Temperature Series Recorded by Buoy A Met Sensor.

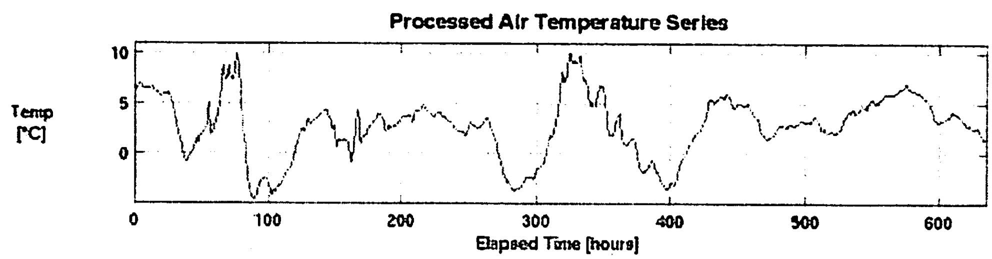

Fig 7. Air Temperature Series Refined from Raw Series Recorded by Buoy A Met Sensor. Series begins on 10 January 1998 2130 GMT and ends of 06 February 1998 0830 GMT. Delta-t is 30 minutes.

IV. UNCERTAINTY ESTIMATES.

The net uncertainty (imprecision) in a composite function (those consisting of more than one term, each with its own uncertainty) is estimated by:

$$\sigma_T = \sqrt{\sum_i^n \sigma_i^2} \qquad (23)$$

where $sigma_T$ is the total estimated uncertainty, $sigma_i$ is the uncertainty associated with an individual term, and n is the number of terms in the function.

Sources of Error in the Meteorological Time Series.

For the purposes of this study, it was assumed that the anemometers at all six wind reporting stations were at the same elevation: 10 meters above sea level. The actual anemometer heights ranged from 13 to 26 meters (see Table 1). The maximum (speed) error associated with this assumption is approximately 20 percent, which dominates the total uncertainty in reported winds. This estimate was made by assuming a neutral stability condition and extrapolating each wind series from its true anemometer height to ten meters, and subtracting the extrapolated series from the base series. Details of the neutral stability extrapolation to ten meters are detailed in Irish and Brown (1986).

The second major part of the wind component uncertainty comes from the use of the spatial correlation function. The software utilized to regress the observed wind components against linear spatial correlation functions of the U and V components of wind (see Irish and Brown, 1986) reported uncertainties (standard deviations) of 5.0 and 4.2 percent respectively. The third and least significant portion of the wind uncertainty is from the recording instruments, which is +/1 1.0 ms^{-1} and +/- 10 degrees (as reported by the NDBC website). In all, the wind velocity components are estimated to have a maximum combined uncertainty of 30 percent.

The uncertainty in the relative humidity series is equally split between instrument-related error and spatial correlation function-related error. The regression of observed humidities against a linear spatial correlation function yields uncertainties of 5.5 percent, and the instrument-based uncertainties for humidity (calculated from on-site temperature and dewpoint) are approximately 5 percent. The combined error is approximately 7.5 percent.

The uncertainty in the atmospheric (sea-level) pressure series is dominated by spatial correlation function-related error. The regression of observed pressures against a linear spatial correlation function yields an uncertainty of 1 percent, while the instrument-based uncertainties is +/- 1.0 millibars (approximately 0.1 percent). The combined error is approximately 1.0 percent.

Table 7: Summary of Maximum Estimated Uncertainties Associated with Meteorological Series Synthesized for WB Site.

Meteorological Observable	Estimated Maximum Uncertainty [%]
U-Component of Wind	30
V-Component of Wind	30
Relative Humidity	8
Sea-Level Pressure	1

Sources of Error in the Air-Sea Heat Flux Series.

Incident short-wave heat flux (Q_i) is a function of albedo (Ab) and the measured incident short-wave radiation field (I_{sw}). According to the method outlined in Payne (1972), Ab is primarily a function of atmospheric transmittance (Tr) and solar elevation angle (theta). For high Sun angles, Payne's method yields an Ab uncertainty of +/- 7 percent, and for low Sun angles, +/- 25 percent. Since the important contributions by Q_i occur at high Sun angles, this researcher uses the smaller uncertainty estimate. The uncertainty in I_{sw} is considerably smaller -- on the order of +/- 0.5 percent -- and is associated with the mooring instrumentation. Thus the combined maximum uncertainty for Q_i is conservatively estimated at ± 10 percent.

Long-wave (black-body) heat flux (Q_b) is a function of the measured incident short-wave radiation (I_{sw}) and long-wave radiation (I_{lw}) fields, the sea-surface temperature (T_s) raised to the fourth power, and the emissivity (epsilon) of the sea-surface. I_{sw} has an instrument-related uncertainty of ± 0.5 percent, and Ilw has an instrument-related uncertainty of +/- 1.0 percent. With an ocean temperature of approximately 1 degree Celsius, T_s has an uncertainty of approximately +/- 0.1 percent. According to Dickey *et al.*, 1994, the uncertainty associated with epsilon is on the order of +/- 1.0 percent (see above).

The value of I_{lw} is reduced by two orders of magnitude in the Q_b calculation, so its associated error is considered to be too small to be of concern. By raising T_s to the fourth power, its associated error increases by approximately an order of magnitude, to +/- 1.0 percent. Thus the combined maximum estimated uncertainty in the Q_b series is approximately +/- 1.5 percent.

Sensible heat flux (Q_s) is a function of the density of the air (roe_a), the specific heat coefficient of air at constant pressure (c_p), the transfer coefficient (C_s), the air and sea-surface temperatures (T_s and T_a), and the wind speed (W). The air and sea-surface temperatures were directly measured at the mooring location, and have associated uncertainties of +/- 0.35 and +/- 0.001 degrees Celsius, respectively.

W was synthesized from data recorded at six distant sites and U- and V-component spatial correlation functions, and has a maximum uncertainty of approximately +/- 35 percent. roe_a is a function of T_a, relative humidity (RH), and atmospheric (sea-level) pressure (SLP), and has a combined estimated uncertainty of +/- 1 percent. c_p is, at base, a function of T_a and RH, and has an estimated maximum uncertainty of +/- 1 percent. C_s is a function of W, T_a and T_s, and also has a maximum combined uncertainty of +/- 1 percent. The uncertainties in roe_a, c_p, and C_s were based on experimentation with a range of typical values.

Thus, the uncertainty in the wind speed is believed to dominate the error in the Q_s series, which is estimated at +/- 35 percent.

Evaporative heat flux (Q_e) is a function of roe_a, the latent heat of vaporization (L_v), the transfer coefficient (C_e), specific humidities of the air at ten meters and near the sea-surface (q_a and q_s), and W. q_a and q_s are in turn functions of SLP, T, and RH, and (based on a range of experimental values) have a combined estimated maximum uncertainty of +/- 1 percent. roe_a has a similar uncertainty, based on arguments made above. The transfer coefficient (C_e) is a fixed constant and was assumed to have zero uncertainty. The function used for calculating L_v reproduces tabulated experimental values almost exactly when the temperature is near zero Celsius, thus, its error was conservatively estimated at +/- 1 percent.

Thus, the uncertainty in wind speed dominates the Q_e uncertainty, which is estimated at +/- 35 percent.

Uncertainties in the two summation series (Q_{emr}, which is the term-by-term sum of Q_i and Q_b, and Q_n, which is the sum of all four components) were estimated by taking the square root of the sum of the squares of the uncertainties of the component series.

Table 8 summarizes the uncertainties in the heat flux series.

Table 8: Summary of Air-Sea Heat Flux Uncertainties.

Heat Flux Series	Abbreviation	Estimated Maximum Uncertainty [%]
Long-Wave (Black-Body)	Q_b	+/- 1.5
Incident Short-Wave	Q_i	+/- 10
Total EMR (Qb + Qi)	Q_{emr}	+/- 10
Evaporative	Q_e	+/- 35
Sensible	Q_s	+/- 35
Sensible	Q_s	+/- 35
Total (net)	Q_n	+/- 50

APPENDIX. HEAT FLUX ESTIMATES: Winter 1986-87

For our Winter 1986-87 observations (Brown & Irish 1993) we did not have as full a suite of measurements to compute time series heat fluxes as for 1997-98. Thus we were forced to adopt the more approximate approach described next.

Considering the total air to ocean heat flux

$$Q_n = Q_I + Q_b + Q_s + Q_e \qquad \textbf{(1)}$$

where Q_n is the net air-sea heat flux (Wm^{-2}), Q_i is the incident short-wave radiational heat flux, Q_b is the long-wave radiational heat flux, Q_s is the conductive (sensible) heat flux, and Q_e is the evaporative heat flux.

The average solar insolation (AQI) for the 8-18 February (1987) was derived from the Hopkins and Garfield (1979) climatological monthly regression for February:

$$AQI\ (gm\text{-}cal/cm^2/s) = (1.73\ s + 90.08) / 3600 \qquad \textbf{(A1)}$$

where s is the percent of total possible hours of sunshine. The average of total number of hours of sunshine for Portland, Maine, 8-18 February 1987, is 10.2 hours according to the Astronomical Applications Department, U.S Naval Observatory. The diurnal variation of the solar insolation was simulated by a sinusoid with amplitude QI according to:

$$QI(t) = \frac{\pi QI}{2T_d} \times \sin\left|\pi\left[\frac{t - T_{sr}}{T_d}\right]\right| \qquad \textbf{(A2a)}$$

when $T_{sr} < t < (T_d + T_{sr})$, and when $T_{sr} > t > (T_d + T_{sr})$,

$$QI(t) = 0 \qquad \textbf{(A2b)}$$

where t is the time in hours since midnight of each day. T_d is the total number of hours of sunshine and T_{sr} is the time of sunrise for each day (from time of sunrise and sunset observations at Portland, Maine by the U.S Naval Observatory).

The long wave (IR) back radiation (Q_b, W m^{-2}) was computed according to the relation (Berliand and Berliand, 1952):

$$Q_b = 1.1365 \times 10^{-7} (t_w + 273.15)^4 (0.39 - 0.05e_a)(1 - 0.0068c^2) \times 0.484 \qquad \textbf{(A3)}$$

where, t_w is the sea surface temperature (degrees C) (by the UNH WB mooring surface at 1m), c is the percent cloud cover (assumed to be a constant 50 percent for the entire period), and e_a is the water vapor pressure (mb) of air at anemometer height (10m) (see below).

The latent heat flux was computed according to the relation (Brown and Beardsley, 1978),

$$Q_e = E\,L \qquad \textbf{(A4)}$$

where the coefficient of latent heat (L) is given by:

$$L\ (\text{cal/gm}) = 596 - 0.52\ t_w \qquad \textbf{(A5)}$$

The evaporative mass flux (E) is given by:

$$E\ (\text{gm/cm}^2\text{/day}) = 0.007\ (EW - e_a)\ W \qquad \textbf{(A6)}$$

where W is the wind speed (knots) and the water vapor pressures at the sea surface ew and at anemometer height ea are determined as follows.

The water vapor pressure at the sea surface temperature (e_w) is given by:

$$e_w\ (\text{mb}) = e_{sd}\ (1 - 5.37 \times 10^{-4}\ S) \qquad \textbf{(A7)}$$

where S is salinity (assumed to be 33 psu), and e_{sd} is the saturated water vapor pressure of distilled water at sea water temperature tw evaluated according to (Dutton, 1986):

$$e_{sd} = 6.11 \exp\left[\left(\frac{L}{0.1104}\right) \frac{t_a}{273.16\ (t_a + 273.16)}\right] \qquad \textbf{(A8)}$$

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