CONTINUOUS OBSERVATIONS FROM THE WEATHER SHIP *POLARFRONT* AT STATION M

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1. ABSTRACT

This paper will describe the climate-related *in-situ* measurements made from the world's last weather ship "*Polarfront*" which operates year-round at Station M (66 N, 2 E). Station M has been occupied by a weather ship continually for 60 years. The *Polarfront* is owned and operated by Misje Rederi AS under contract to the Norwegian Meterological Institute, DNMI.

In early 2009, DNMI announced that funding for the ship was being withdrawn: the ship is due to cease operations at the end of 2009.

In addition to the meteorological measurements made for DNMI, there are also a number of important long-term climate programs which are based on board *Polarfront*. These include a 60 year hydrographic program and two 30 year programs of atmospheric gas sampling and surface wave measurements. These climate programs are described in detail below. More recent measurement programs are also briefly described.

2. LONG TERM CLIMATE RECORDS

2.1 60-year hydrographic record

In addition to the DNMI operations, the ship's crew also carry out measurements as part of a hydrographic program for the Geophysical Institute and Bjerknes Centre for Climate Research (GFI and BCCR) at the University of Bergen. The hydrographic program has been continuous since 1948. It comprises a daily CTD to a depth of 1000m and a weekly full-depth (2200m) CTD, with bottle samples taken at various depths. This is one of the longest hydrographic time series, and has the highest temporal resolution, making this climate record unique. The station monitors the Atlantic Water flowing northwards towards the Arctic Ocean, as well as the deep Norwegian Sea [1]. The station is near to the Polar Front so the observations are also used to study Arctic Waters changes and spreading [2]. The longevity and homogeneity of the data record has led to it being a key resource in understanding large-scale and local patterns of variability and their causes. Some research highlights include:

- Since the mid-1990s unusually high salinity, warm waters from the subpolar gyre have been observed in the Norwegian Sea, en route to the Arctic Ocean where they have a profound effect on the upper ocean processes [3,4]. See Fig. 1.
- The recognition of basin-scale fluctuations in upper ocean salinity that propagate from the high latitude Nordic Sea, into the sub-polar gyre, and return to the Arctic via the Norwegian Sea: the Great Salinity Anomaly of the 1970s [5]. Subsequently similar low salinity events were identified in the 1980s and 1990s [6,7].
- More recently the relationship between the western and eastern northern north Atlantic has been further explored and the mechanism found to be more complex than simple propagation of anomalies [8].
- Combining the Station M data with results from across the Nordic Seas has shown that the local upper ocean variability is strongly controlled by exchange with atmosphere [9], but also with the inflow of Arctic surface waters [10].
- Profound and unexpected changes observed in the deepest layer have indicated that the deep Norwegian Sea has been warming since 1990. The causes are complex, related both to the absence of deep convection in the Greenland Sea and the increased exchange of warm surface waters with the Arctic Ocean, as well as reversal of deep currents [11].
- The high resolution time series provides an important ground-truth resource to evaluate satellite and VOS-derived products which are often used to represent climate variability. Reference [12] showed that commonly used sea surface temperature products have reduced skill in this region, showing erroneous variability on timescales of 3 years or less.
- Other result are discussed in the OceanObs additional contribution "Station M in the Norwegian Sea" by Østerhus et al., in session 02A.

2.2 30-year greenhouse gas record

An atmospheric gas sampling program has been carried out at Station M since 1981. Air samples are collected by the crew twice per week in glass flasks and sent to NOAA's Earth System Research Laboratory for analysis of many climate-related gases including CO_2 (since 1981), CH_4 (1983), CO and H_2 (1990), N_2O and SF_6 (1997) and $^{13}C/^{12}C$ and $^{18}O/^{16}O$ of CO_2 (1994). These irreplaceable measurements provide valuable information on the temporal distributions of long-lived greenhouse

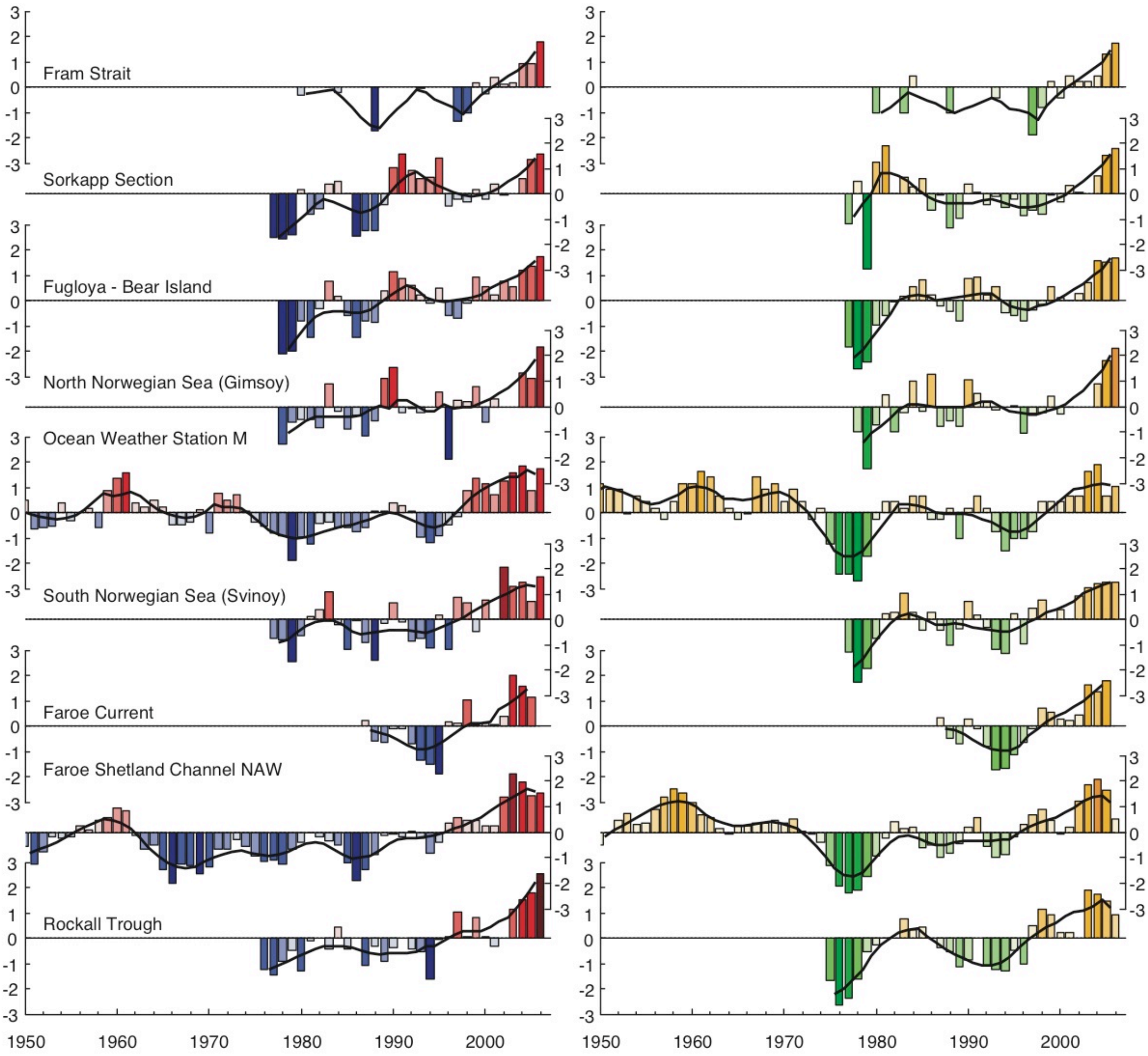

Figure 1. Normalised annual average upper layer anomalies from the longest time series of in-situ hydrographic data: temperature (left) and salinity (right). Note the unusually long record at Station M.

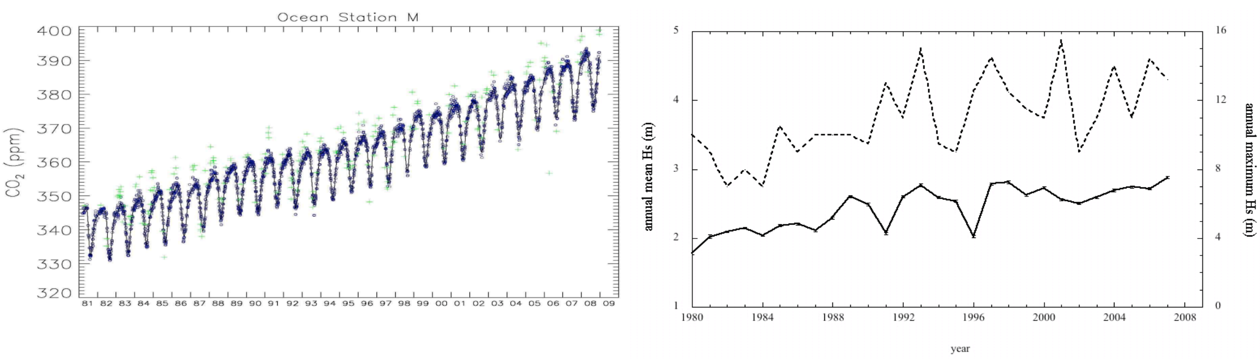

Figure 2. Two 30 year time series at Station M. a) Left panel shows twice-weekly atmospheric CO_2 measurements. The blue circles indicate samples representative of relatively unpolluted marine air and the green crosses indicate statistical outliers (>3σ from the fitted curve) that may be due to pollution sources (winter) or biospheric uptake (summer) in Europe. b) Right panel shows wave heights: solid black line is the annual average of significant wave height, Hs (m), with errors bars showing the standard error of the mean. Dotted line is the maximum values of Hs each year. Note separate y axes.

gases in the North Atlantic. They provide observational constraints for these gases in global budget studies, and are used by US, Norwegian, and other international research groups. The nearly 30 year continuous CO_2 record at Station M is among the longest in the NOAA Cooperative Global Air Sampling Network. Fig. 2a shows the classic CO_2 time series from Station M, illustrating the increasing trend of CO_2 and its seasonal cycle, and the interannual variability of both. These data, together with data from the entire global network, are used to calculate estimates of CO_2 sources and sinks on global, hemispheric, and regional scales. Recent studies have provided improved estimates of the marine and terrestrial carbon sinks, e.g. [13], and shown that the fraction of total CO_2 emissions taken up by the oceans may be decreasing [14]. The data from Station M are unique in that it usually samples clean air from the North Atlantic but during the winter we typically see episodic transport of polluted air from Europe. The data through 2008 are available from the ESRL website: ftp://ftp.cmdl.noaa.gov/ccg/

2.3 30-year wave height record

The 30 year time series of wave heights at Station M is shown in Fig. 2b. This shows that the annual mean significant wave height (Hs) has increased steadily from 2 m in 1980 to nearly 3 m today [15,16]. In contrast, the mean annual wind speed shows no increase over the same period. The annual maximum value of Hs shows a similar, if far more noisy trend. The large maximum Hs values of around 15 m may be due to strong Westerly winds persisting for days at a time, allowing the waves to develop over an unusually long fetch and duration [17]. In the absence of an increase in mean wind speeds, it is thought that an increase in the frequency of such weather systems is also responsible for the increase in mean wave heights.

Collection of the raw surface elevation data allows the peak-to-trough heights of individual waves to be measured. In the case of a storm on the 11th November 2001, the SBWR data from *Polarfront* recorded a 15.5 m maximum Hs value, accompanied by a peak-to-trough wave height of 27 m. These conditions were similar to those encountered by the *RRS Discovery* in the Rockall Trough region in February 2000: in this a case maximum Hs value of 18.5 m was accompanied by a peak-to-trough wave height of 29 m [17]. Such extreme waves are likely to occur more often if weather systems with persistent strong winds from a long-fetch direction occur more frequently.

3. OTHER IN-SITU MEASUREMENTS AT STATION M

3.1 The inorganic carbonate system

Since 2001 monthly water samples covering the full depth have been collected by the *Polarfront's* crew and shipped to Bergen, where analysis of inorganic carbon and alkalinity have been performed, see Figure 4. Over the years an increasing carbon content has been detected in the whole water column [18], which, for the surface water is connected to the increasing atmospheric CO_2 content, and for the deep water is partly due to the increased input of old Arctic water and partly due to input of water with an anthropogenic signal from Greenland and Iceland Sea surface water.

These carbon measurements give important information about the whole carbonate system, including the carbonate saturation, and are of vital importance for ocean acidification studies. A decrease in surface ocean pH of 0.03 units over 6 years has been calculated based on station M data.

Since 2005, *Polarfront* has continuously measured underway pCO_2 [19], and this dataset is primarily used in the air-sea fluxes determination explained in the next paragraph.

3.2 Air-sea flux measurements

Since 2006, the *Polarfront* has been equipped with fast-response sensors to make direct measurements of the turbulent air-sea fluxes of CO_2, sensible and latent heat and momentum [20]. The flux measurements are made continuously, and will be used to produce improved bulk formulae for moment and heat, and an improved parameterisation of the gas transfer velocity [21]. Downwelling short- and long-wave radiation sensors were also installed. This flux program is funded under UK-SOLAS. Near-real time (1 day old) data can be seen on the project web site at http://www.noc.soton.ac.uk/ooc/CRUISES/HiWASE/OBS/data_intro.php .

3.3 Directional waves system and whitecap cameras

As part of the same UK-SOLAS program the *Polarfront* has also been equipped with a commercial directional wave radar WAVEX. This uses the signals from a dedicated marine x-band scanner to produce 2-D wave spectra, thus providing the directional information which is absent from the ship's exiting SBWR system. In contrast, the WAVEX system does not measure wave height directly. The data from WAVEX and the SBWR are being combined to provide a complete description of sea state [22]. Three digital cameras have also been installed on the ship. These take images of the sea surface every 5 minutes during daylight hours. The images are being analysed to provide estimates of the whitecap fraction.

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