INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS
INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION
WORLD METEOROLOGICAL ORGANIZATION

WORLD CLIMATE RESEARCH PROGRAMME

International Programme for Antarctic Buoys (IPAB)

Wind, temperature and ice motion statistics in the Weddell Sea

(A compilation based on data from drifting buoys, vessels, and operational weather analyses)

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January 1997
WMO/TD-No. 797
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Wind, temperature and ice motion statistics in the Weddell Sea

(A compilation based on data from drifting buoys, vessels, and operational weather analyses)

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Abstract

The data from sea ice buoys, which were deployed during the Winter Weddell Sea Project 1986, the Winter Weddell Gyre Studies 1989 and 1992, the Ice Station Weddell in 1992, the Antarctic Zone Flux Experiment in 1994, and several ship cruises in Austral summers, are uniformly reanalyzed by the same objective methods. The buoys were capable of monitoring atmospheric pressure, air and ice temperatures, as well as position. The buoys were frequently arranged within groups of three to seven to allow calculation of reliable estimates of geostrophic winds and ice motion and under favorable conditions their spatial derivatives. Geostrophic winds for buoys operational regions are derived after matching of the buoy pressure data with the surface pressure fields of the European Centre for Medium Range Weather Forecasts. Historical data from drifting ships are included into the temperature, air pressure and ice drift analyses.

This report documents the mean structure as well as the variability of ice motion and spatial derivatives of ice motion, the statistics of surface pressure, geostrophic winds and air temperatures in the sea ice covered part of the Weddell Sea. To reflect the characteristics of ice dynamics on the basin-scale, all ice drift data are related to the geostrophic winds based on a complex linear model for daily averaged data. The composite patterns of mean ice motion, geostrophic winds, and geostrophic surface currents document cyclonic basin-wide circulations. Geostrophic ocean currents are generally small in the Weddell Sea. Significant features are the coastal current near the southeastern coasts and the bands of larger velocities following the northward and eastward orientation of the continental shelf breaks in the western and northwestern Weddell Sea. In the southwestern Weddell Sea the mean ice drift speed is reduced to less than 0.5 % of the geostrophic wind speed and increases rather continuously to 1.5 % in the northern, central, and eastern Weddell Sea. The linear model accounts for less than 50 % of the total variance of drift speeds in the southwestern Weddell Sea and up to 80 % in the northern and eastern Weddell Sea.

The transmission of in-situ data from buoys to the Global Telecommunication System improves the quality of atmospheric analyses of the Numerical Meteorological Centers (NMC) significantly. This report presents atmospheric analyses of the European Centre for Medium Range Weather Forecasts for the periods with the largest number of buoys operational in the Weddell Sea. The analyses are used to obtain mean spatial distributions of 2-m temperatures and 10-m winds for different seasons. The variances of temperatures and winds with 6-hourly resolution are given for comparison with the variances derived from the buoy-measurements. ECMWF 2-m temperatures reflect only a very small fraction of the true variance until 1991. After a change in the ECMWF analysis scheme in 1992, the variance of the 2-m temperatures is only about 20 % smaller than the variance documented by the buoy measurements. The variance of ECMWF-10-winds is about 80 % of the variance of geostrophic wind fluctuations derived from the buoy data.

1 Objective of the report

The role of sea ice within the polar climate system is determined by its motion in response to winds and ocean currents and by its thermodynamically induced formation and melting. The presence of sea ice significantly affects the energy and momentum exchanges between
the atmosphere and ocean. The dynamics and thermodynamics of sea ice are closely coupled by various processes. Among the quantities describing the development of the oceanic ice cover, the vector of sea ice motion is of special importance. The dominant time scale of ice motion variability is determined by the wind forcing, and thus reflects the close link in sea ice/atmosphere interaction. Spatial differences of sea ice motion are responsible for the opening and closing of leads between ice floes. These areas of open water contribute remarkably to the large scale heat flux from the ocean to the atmosphere particularly in wintertime. Sea ice motion and the salt rejection during ice formation generate turbulence in the oceanic mixed layer which may cause entrainment of warm intermediate water across its lower boundary. On a larger scale, the mean ice motion both contributes to the seasonal cycle of ice extent and transports fresh water from the regions of freezing to the regions of melting.

The coupling of processes on different scales must be adequately represented in numerical models of the atmosphere, the sea ice and the ocean in order to obtain realistic results. For this purpose several parameters have to be determined from observations. Measurements are also needed to force numerical models and to test their quality. Automatic buoys on drifting sea ice provide an important and rather efficient means for a reasonable surface data acquisition. These systems are capable of measuring atmospheric pressure, air and ice temperatures to be communicated by satellites which also track the positions of the buoys. Systematic observations of this kind were started in 1986 and last up to the present time. Consequently large regions of the Antarctic sea ice belt were covered. The buoys were frequently arranged within groups of three to seven to allow calculation of reliable estimates of geostrophic winds and ice motion and, under favourable conditions, their spatial derivatives. Descriptions of the individual programs and related process studies have been published [Ackley and Holt, 1981, Allison, 1989, Crane and Bull, 1990, Hoebler, 1991, Kottmeier and Hartig, 1990, Ackley, 1981, Vihma and Launiainen, 1993, Wadhams et al., 1989, Kottmeier and Sellmann, 1996, Martinson and Wamser, 1990, Limbert et al., 1989].

The buoy data obtained can be also used as surface verification data for the satellite remote sensing of ice motion [Viehoff and Li, 1994, Drinkwater and Kottmeier, 1994].

On the basis of the above mentioned data of the Weddell Sea we will subsequently

- describe the mean structure and the variability of sea ice motion and of spatial derivatives of ice motion,
- provide statistics of the surface pressure, the geostrophic wind and the air temperature for the sea ice region,
- demonstrate the relationship between the ice motion, the surface wind field and ocean currents,
- indicate improvements of the surface analyses of the European Centre for Medium Range Weather Forecasts due to the surface buoy measurements which are fed in near real time into the WMO Global Telecommunication System (GTS).

Basically the report aims to characterize the full buoy data set from the Weddell Sea and to give an idea on the potential use for different research purposes. It is not the purpose of this report to present data records from certain regions or periods or to publish original
scientific results. The basic data from individual buoys as well as the gridded fields shown
in this report are available on request for scientific applications. We consider the data
presented in this report as especially relevant for the verification of sea ice models.

2 Data used for the analysis

2.1 Data buoy measurements

The first observations of about one year's period from the Weddell Sea in Austral winter
were gathered during the involuntary drifts of the vessels *Deutschland* in 1911 and *En-
durance* in 1915/1916, which got stuck in the pack ice [Meinardus, 1938]. During the First
Global Experiment of the Global Atmospheric Research Program (GARP) in 1979, me-
teorological buoys were deployed by parachute drop into the western Weddell Sea for the
first time, providing meteorological data about every 1 or 2 days [Ackley and Holt, 1981].
Buoys were used more frequently in the years after 1986. During several wintertime ship
operations such as the Winter Weddell Sea Project 1986 (WWSP86), the Winter Wed-
dell Gyre Studies 1989 and 1992 (WWGS89, WWGS92), the Ice Station Weddell in 1992
(ISW), and the ANZFLUX study in 1994 buoys were launched, most of which survived
Finnish meteorological buoys were deployed under FINNARP-expeditions in 1990 and

The total number of drifting buoys and vessels in the Weddell Sea which provided a record
length of at least one month, amounts to 80. Among these, 54 have been deployed in arrays
of three to seven instruments. Data from summer ship operations are not included in this
study.

The buoys were produced by several manufacturers, who used quite different mechanical
and electronic designs. The sensor equipment of the buoys also varied considerably. Most
of the floatable buoys had an ice-strengthened nonmagnetic alloy or plastic hull. Air
temperatures usually were measured by a thermistor within a radiation-shielded and self-
aspirated housing about 1m above the ice surface. The hull temperature was frequently
measured by a sensor in thermal contact to the hull and the snow. These temperatures
have been shown to differ considerably from the air temperature in summer and are not
used here. Atmospheric pressure was measured by almost all buoys and, with only a few
exceptions, by the very accurate and stable Paroscientific Digiquartz sensor (longterm
accuracy of ~0.15 hPa). Various additional sensors were run successfully with drifting
buoys but are not used in this analysis. These comprise wind, humidity, and snow fall
sensors, thermistor profilers of about 2m length through the sea ice, thermistor chains of
250m length through the mixed layer and the pycnocline, and ocean currents meters and
CTDs at certain depths.

Data logging systems within the buoys collect and average the sensor data (usually over
10 minutes) and transmit them to two polar-orbiting satellites every 60 or 90 seconds.
The buoy locations are determined from the Doppler shifts of the transmitter signals
observed at different satellite positions. The accuracy of the buoy positions depends on
the oscillator stability of the buoy transmitter, on the geometry of the satellite pass, on the movement of the buoy, and on the inaccuracies in the satellite orbit ephemeris. The data transmission and localisation are done under the responsibility of the Argos Collect Localisation Satellites Company. In general the accuracy of the Argos positioning is estimated to be $\approx 350\,m$. Location accuracies of 150m now can be achieved by improved methods of Argos CLS but were not available for the full data set on a regular basis. The location accuracy is confirmed by the Argos positioning of an automatic weather station on the Filchner-Ronne Ice Shelf, which moves with a constant speed of 1000m per year. During the last years (starting in 1994) several buoys have been equipped with GPS receivers (Global Positioning System), which provide an improved location accuracy. Using the GPS transmission of the Standard Positioning Service (SPS) and averaging times of 10 minutes, position accuracies of better than 50m are obtained.

The basic processing of raw data transmitted via the Argos system is carried out under responsibility of each program's Principal Investigator, but the methods applied have been described in a number of reports (Crane and Bull, 1990, Hoeber, 1991, Wadhams et al., 1989, Vihma and Launiainen, 1993) and are rather similar. The data of the buoys run by the University of Hannover and the AWI, as an example, have been processed as follows:

First, the data from all buoys contained in the monthly record of all platforms within a program are stored separately. Only the data set with the largest number of identical transmissions within a satellite pass is saved. Typically about 25 independent data transmissions are available for each platform per day. The transmissions are separated by about 20 minutes to 4 hours. The data are transmitted in binary or hexadecimal format; they are finally converted to physical units based on the specifications of the sensors, partly also on additional calibrations and buoy comparisons. All data are checked with respect to the permitted sensor ranges, and a replacement value is assigned to erroneous data. Then the data are rearranged in chronological order. Outliers are found by both objective methods and by viewing the data with a graphical editor. The components of ice drift velocity are derived from the changes of positions. Using a smoothing cubic spline interpolation, regularly spaced time series are generated, which have a time resolution of 3 hours. Long gaps are filled by linear interpolation.

2.2 Surface data set of the European Centre for Medium Range Weather Forecasts (ECMWF)

The Surface And Diagnostic Fields Data Set from the ECMWF/WCRP Level III-A Global Atmospheric Data Archive were obtained from the ECMWF for the period from April 1985 to June 1995. The data comprise among others: 10-m winds, 2-m temperatures, and mean sea level pressure. The ECMWF analyses take into account the data from buoys and other stations by the data assimilation procedure [ECMWF, 1992]. We have used data with a spatial resolution of 1.125 degrees both for the latitude and the longitude and with a temporal resolution of 6 hours.

2.3 Sources of auxiliary data used for the analyses

Ice concentrations for the buoy locations have been derived from Special Sensor Microwave
Imager data (SSM/I) using the NASA-Team algorithm. SSM/I-data have been provided by the National Snow and Ice Data Center, University of Colorado, Boulder, Colorado.

Bathymetric information and coastlines have been extracted from the "The GEBCO Digital Atlas" of the British Oceanographic Data Centre.

2.4 Derived quantities

Geostrophic winds are derived by combining ECMWF and buoy pressure data for all periods when at least three buoys were operating in reasonable configuration (see Fig. 1). The horizontal pressure gradients reflected by the ECMWF grid point data generally smooth the actual pressure gradients. A second order polynomial is fitted to a combination of buoy and ECMWF pressure data and takes the form

\[ p(x, y) = a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 y^2 + a_5 x y. \]  

The geostrophic wind vector results as

\[ \mathbf{V}_g = (v_x, v_y) = \frac{1}{\rho f} \left( \frac{\partial p}{\partial y}, -\frac{\partial p}{\partial x} \right) \]

\[ = \frac{1}{\rho f} \left( -2a_5 y - a_4 x - a_2, 2a_5 x + a_4 y + a_3 \right). \]

For the least squares fit of the function in Eq. (1), a higher weight is applied to the buoy data than to the ECMWF grid values (20 instead of 1), giving them a much stronger impact on the fitting curve than the ECMWF data. The ECMWF data, however, suppress unrealistically large pressure gradients near the margins of the buoy field, which would result from fitting polynomials to the buoy data alone. The spacing of about 100 km between the buoys adequately resolves the true pressure gradients, since spatial correlation lengths of air pressure have been derived to range from 500 and 1000 km in the Weddell Sea from WWSP86 data [Kottmeier et al., 1992]. Comparable length scales were found for the central and western Weddell Sea [Vihma et al., 1996].

For each analysis the observed pressure differences between all pairs of buoys have been compared with the pressure differences of the polynomials at the buoy locations. The mean difference, normalized to a distance of 100 km, has been used as a quality indicator for the model fit to the data. The quality indicator has been stored for each data set and used to flag inconsistent geostrophic wind data for subsequent analyses. It has been aimed to keep the uncertainty below 0.2 hPa per 100 km, corresponding to 1.5 m/s possible error of the geostrophic wind for correct pressure data. The errors grow, when the buoy array becomes closely one-dimensional. With an error estimate of 2 m/s for each component, we obtain the error values of Table 1. Geostrophic wind errors decrease with the number of independent observations, i.e., with the length of the averaging period. Geostrophic wind components are accurate to ±1 m/s for averaging periods beyond one day due to
the adequately spaced buoy stations. When the above method is applied to the ECMWF
data without the local buoy pressure data, the errors of geostrophic wind components are
of the order of 3 m/s. When the GTS-transmission of buoy data is interrupted, rms-errors
of geostrophic wind components based on ECMWF analyses increase up even to 7 m/s.
Whenever the ECMWF data are incorrect, geostrophic winds are calculated from linear
functions fitted to the buoy pressure observations. Eq.(1) as a steady function fulfils the
condition of non-divergence of the geostrophic wind, since \( \frac{\partial}{\partial y} \frac{\partial F}{\partial x} = \frac{\partial}{\partial x} \frac{\partial F}{\partial y} = a_4 \).

Linear functions are fitted to the drift components \( D = (d_x, d_y) \) of each buoy array
according to

\[
d_x = b_1 x + b_2 y + b_3 \tag{3}
\]

\[
d_y = c_1 x + c_2 y + c_3. \tag{4}
\]

Due to their smoothing effect on measurement errors for a small number of measure-
ments, first-order polynomials are found more suitable to fit ice drift components than
second-order polynomials. First-order polynomials adequately resolve the spatial gra-
dients of ice drift, since spatial correlation lengths of ice drift are between 360km and
540km for WWSP86 data [Kottmeier et al., 1992]. All spatial derivatives of ice drift and
of geostrophic wind components are thus known from the coefficients and allow us to
calculate the differential kinematic parameters, i.e. the drift vorticity

\[
curl_x(D) = \frac{\partial d_y}{\partial x} - \frac{\partial d_x}{\partial y},
\]

the geostrophic wind vorticity

\[
curl_x(V_g) = \frac{\partial v_{gy}}{\partial x} - \frac{\partial v_{gx}}{\partial y},
\]

the drift divergence

\[
div(D) = \frac{\partial d_x}{\partial x} + \frac{\partial d_y}{\partial y},
\]

and the shearing rate of ice drift

\[
shear(D) = \sqrt{\left(\frac{\partial d_x}{\partial x} - \frac{\partial d_y}{\partial y}\right)^2 + \left(\frac{\partial d_x}{\partial y} + \frac{\partial d_y}{\partial x}\right)^2}.
\]

The accuracy of the ice drift and its derivatives is estimated from the rms-error of Ar-
gos positioning at \( \approx 350 \text{ m} \). The errors of the ice drift components also decrease with
increasing averaging periods.
Table 1: Estimates of the errors and signal-to-error-ratios for typical signal magnitudes for daily averaged quantities used to study ice dynamics.

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<th>typical signal magnitude</th>
<th>error estimate</th>
<th>signal-to-error-ratio</th>
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<tr>
<td>drift vector components</td>
<td>0.2 m/s</td>
<td>0.005 m/s</td>
<td>40</td>
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<tr>
<td>geostrophic wind components</td>
<td>10 m/s</td>
<td>1.5 m/s</td>
<td>7</td>
</tr>
<tr>
<td>ice drift divergence</td>
<td>0.3 x 10^{-6} s^{-1}</td>
<td>0.1 x 10^{-6} s^{-1}</td>
<td>3</td>
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<tr>
<td>ice drift vorticity</td>
<td>0.6 x 10^{-6} s^{-1}</td>
<td>0.1 x 10^{-6} s^{-1}</td>
<td>6</td>
</tr>
<tr>
<td>drift/wind speed ratio (10 m/s)</td>
<td>0.016</td>
<td>0.004</td>
<td>4</td>
</tr>
</tbody>
</table>

The accuracy of the ratio of ice drift and geostrophic wind components depend their magnitude, since their relative errors add up to the total relative error. The drift and geostrophic wind errors mainly cause noise in the observed quantities but little systematic bias. The calculation method for geostrophic winds used here depends much more on the buoy pressure data than on the ECMWF analyses [ECMWF, 1992] due to the large weights of measured data used in deriving a fitted pressure field. Signal-to-error ratios for the quantities used to study ice dynamics on the basis of data averaged over 24 hours are shown in Table 1. Although a rather high basic data accuracy is achieved by the methods used in this study, the errors have a considerable effect on the study of ice dynamics and tend to reduce the level of correlation between quantities.

The data processing leads to clean data and to certain derived quantities with a temporal resolution of 3 hours (buoy based data) and 6 hours (buoy data matched with ECMWF data).

3 Gridded composite fields

The measurements are from different years, seasons, and regions and thus generally form a inhomogeneous data set. A composite method is applied to display the basic information which the data set contains. Each buoy record is divided into segments of 30 days. Means and variances are calculated for all quantities based on the resolution of 3 or 6 hours and the record length. During all seasons, and in all regions of the Weddell Gyre, ice drift and geostrophic wind spectra have maxima at periods between 1 and 7 days associated with atmospheric disturbances. To obtain the band-pass-filtered variance for the period range from 1.5 to 10 days, the time series are spectrally filtered. This band covers the periods of synoptic-scale vortices in the atmosphere but excludes seasonal fluctuations, diurnal cycles and inertial motion as well as tidal effects which in shallow water regions may cause significant additional peaks.

The means, the variances, and 1.5-10 day bandpass-filtered variances of all quantities are assigned to the mean positions and the mean observational times of each record. The mean ice motion during the 30-day intervals is typically about 200 km and thus causes a certain spatial averaging. The seasonal and spatial coverage of this kind of monthly data is shown in Fig. 1. On the basis of ice concentration data derived from SSM/I satellite radiometry, we decided whether a buoy was in open water or on sea ice. Records from ice-free regions have been excluded. It is obvious that almost all parts of the Weddell Sea have been sites of buoy measurements on sea ice.
The seasonal data coverage varies considerably. The ice motion away from the coast causes the southern Weddell Sea to be uncovered by instruments during winter. Buoy deployments in early winter in the northern Weddell Sea were mostly unsuccessful due to instrumental failures in the period of rapid refreezing and frequent events of strong ice pressure. The large seasonal amplitude of ice extent generally prevents a homogeneous data coverage of the Weddell Sea, independent of the number of buoys involved. When the region north of 75°S is divided into segments of 5° longitude and 2.5° length, at least one month of buoy measurements is available for each segment.

This study focusses on the spatial and seasonal variability of the ice drift and the state of the lower atmosphere. There are no means to distinguish between spatial and seasonal changes in a perfect sense due to the generally northward displacement of the buoys to the north and northeast in the course of the year. To separate both influences approximately, (a) spatially smoothed and gridded distributions of all quantities are derived by an objective method, and (b) the deviations from the gridded field are plotted as a function of the day of year. The smoothed, gridded distributions are achieved by calculating the weighted means of all data points within an acceptance circle of \( \approx 300 \text{ km} \) around each grid point. The weight is inverse to the distance from the grid point, normalized with the radius of the acceptance circle, raised to the power of 1.5. If too few or no data points lie within the acceptance circle to make an estimate for the grid point value, the radius has been increased until a successful approximation can be made. The radius of the acceptance circle has been chosen to average as much as possible of the temporal variability, while large scale spatial signatures remain.
Data analysis

Figure 2: Monthly mean air temperatures in °C (numbers in the main part of the figure) and gridded field (contours). Upper left: deviations of the contoured field from mean temperatures (in °C) during the year. Numbers middle left: relative variance of the 30-day means explained by the gridded field (left), relative variance of the 30-day means additionally explained by the cosine function of the date (right).

The mean air temperature distribution from buoy data (Fig. 2) is used to test the scheme. The residuals from the smoothed spatial interpolation show a seasonal cycle with an amplitude of about 15 K, which is close to the 2m-temperature differences between the first and third quarters of the year as reflected by the ECMWF analyses (Fig. 47 and 49). Therefore major spatial and seasonal changes seem to be separated robustly by the scheme.

Although all quantities have been analysed by the same methods, all resulting composite maps need specific interpretation, which will be given below.

The grid point data from the ECMWF analyses have been interpolated on the grid of the buoy data without smoothing. A polar stereographic projection has been used for all maps.

4 Data analysis

The results of data analysis are presented in the following sections

- Ice motion statistics
- Wind statistics
- Air pressure and temperature statistics
Figure 3: 30-day mean ice drift vectors in the Weddell Sea from all buoy and vessel drift data (pale arrows) and a smoothed, gridded mean ice drift field (dark arrows). Upper left: deviations (modulus in m/s) of the gridded field from 30-day mean drift during the year. Numbers middle left: meaning as in Fig. 2.

- Ice drift and geostrophic wind relationships
- Seasonal and spatial variability from ECMWF analyses during periods of drifting buoy operations.

4.1 Ice motion statistics

The composite ice drift pattern constructed in this way from all buoys and vessel drifts is shown in Fig. 3. The pattern is that of a cyclonic basinwide circulation but without a southwards return limb at the eastern margin of the Gyre. We infer from the picture that the presence of sea ice in the Weddell Gyre, in general, does not exceed 2 years. The variability of the composite pattern is due to spatial, seasonal, and interannual changes. There is no significant seasonal variation (upper left of Fig. 3). In certain regions ice drift information is available for several years. In the western Weddell Sea the drift of buoys in 1979/80, 1992, and the ship drifts of the “Endurance” and “Deutschland” are rather similar. The same is observed in the northeastern Weddell Sea, where buoys operated in 1986, 1989 and 1992. In the central part of the regime, differences between years are significant. The 1991 data document that the mean motion stopped for a period of several months, while continuous motion was observed in 1992 in the same region.
The variance of ice drift (see Fig. 4), defined via the variance of ice drift components as $\sqrt{(a_\alpha^2) + (a_\beta^2)}$, generally ranges from $10 \cdot 10^{-3} \, m^2/s^2$ in the southwestern Weddell Sea to $50 \cdot 10^{-3} \, m^2/s^2$ in the northeastern Weddell. The variance of ice drift, when bandpass-filtered for the range periods between 1.5 and 10 days (Fig. 5), contributes about 60% to the total variance and has a similar spatial distribution. The smoothed spatial pattern explains 62% (unfiltered) or 60% (filtered) of the variance of the monthly means. No distinct seasonal dependence is found.
Figure 4: Variance of the ice drift velocity (in $10^{-3} \text{m}^2 \text{s}^{-2}$), calculated as $\sqrt{(\sigma_x^2)^2 + (\sigma_y^2)^2}$. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.

Figure 5: Variance of the ice drift velocity (in $10^{-3} \text{m}^2 \text{s}^{-2}$), calculated as $\sqrt{(\sigma_x^2)^2 + (\sigma_y^2)^2}$, after filtering with a 1.5 - 10 day bandpass. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.
Divergent ice motion within a field of ice floes causes the opening of leads and enhances the average oceanic heat loss to the atmosphere. With convergent ice motion the floe separation decreases and the number of floe contacts increases thereby significantly affecting internal ice stress. The monthly means of ice drift vorticity (Fig. 6) are mostly negative (cyclonic; clockwise), except in a region in the southwestern Weddell, where the ice thickness and ice movement resistance increases towards the Antarctic peninsula. Minimum values down to $-10^{-6}\, s^{-1}$ are found off the coast of Cape Norwegia and to the east of the Drake Passage. Monthly means of anticyclonic vorticity do not exceed $0.2 \cdot 10^{-6}\, s^{-1}$. The residuals (in same units) from the composite spatial pattern vary within $\pm0.3 \cdot 10^{-6}\, s^{-1}$ but show no seasonal trend.

The majority of monthly means of ice drift divergence (Fig. 7) are within $\pm0.1 \cdot 10^{-6}\, s^{-1}$. Significant mean convergence occurred in the region off the coast of Cape Norwegia, where also strong mean cyclonic vorticity is found (Fig. 6).

In contrast to the monthly means of ice drift vorticity and divergence, the standard deviations (variances) of these quantities are relatively large (Fig. 8 and Fig. 10). Standard deviations of ice drift divergence are typically about $0.3 \cdot 10^{-6}\, s^{-1}$ (variances of $10^{-13}\, s^{-2}$). The variance of ice drift vorticity in the period band from 1.5 to 10 days (Fig. 11) contributes 30 to 50% to the total variance. The drift divergence generally is of an oscillating character with little mean divergence. Leads in the pack ice tend to open and close with periods of a few days, and hence the variance of ice drift divergence in the period band from 1.5 to 10 days (Fig. 9) has the largest contribution to the total variances. There are good reasons to speculate that this implies an effective mechanism.

Figure 6: Mean ice drift vorticity (in $10^{-6}\, s^{-1}$) from all groups of buoys. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.
for intense ice production. The amount of thin sea ice formed in the leads, where the freezing rate is very large, is compressed during drift convergence. This dynamic mechanism causes artificially larger average freezing rates than homogeneous thermodynamic ice formation. Its effectiveness will increase with the amplitude and decrease with the period of divergence variations. The variance of ice drift vorticity in the period band from 1.5 to 10 days (Fig. 11) usually contributes 30 to 50% to the total variance.

The spatial inhomogeneity of tidal and inertial motion over the continental shelves effectively controls the variability of divergence. Over the continental shelves and slope regions the standard deviation of drift divergence is more than one order of magnitude larger than over the deep ocean. The variance of drift divergence is maximum in the southern Weddell Sea near the Filchner-Ronne Ice Shelf. For sea ice modelling, it is recommended superimposing the mean divergence derived from drift solutions at the grid points together with statistical noise for the specific geographical region, i.e. a standard deviation of 0.3 \( \times 10^{-6} \text{s}^{-1} \) in the central and northern parts of the Weddell Sea and 2 \( \times 10^{-6} \text{s}^{-1} \) in the shelf regions. Assuming harmonic variations of the ice drift divergence with a period of one day, the corresponding maximum rate of ice concentration changes is 0.17/\text{day} (2 \( \times 10^{-6} \text{s}^{-1} \)) over the shelves. During the half cycle of opening, the effect accounts for a maximum percentage of open water of 0.17/\text{day} \cdot 0.5 \text{days} \cdot 2/\pi = 5.4 \%.

The corresponding maximum rate of ice concentration changes over the deep ocean is 0.026\%/\text{day} (0.3 \( \times 10^{-6} \text{s}^{-1} \)) and assuming a 5-day period, the maximum amount of open water is 4 \%.

**Figure 7: Mean ice drift divergence (in \( 10^{-6} \text{s}^{-1} \)) from all groups of buoys. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.**
Figure 8: Variance of ice drift divergence (in $10^{-12} \text{s}^{-2}$) from all groups of buoys. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.

Figure 9: Variance of ice drift divergence (in $10^{-12} \text{s}^{-2}$) after filtering with a 1.5 - 10 day bandpass from all groups of buoys. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.
Figure 10: Variance of ice drift vorticity (in $10^{-12} s^{-2}$) from all groups of buoys. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.

Figure 11: Variance of ice drift vorticity (in $10^{-12} s^{-2}$) after filtering with a 1.5 - 10 day bandpass from all groups of buoys. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.
4.2 Wind statistics

The composite geostrophic wind distribution (Fig. 12) is constructed from the monthly mean geostrophic wind vectors, based on pressure data of buoys arranged in groups of three to seven. The pattern reflects a basin-wide cyclonic circulation of geostrophic winds over the Weddell Sea. Coastal easterlies are obvious in the eastern Weddell Sea, whereas a mean northward flow along the Antarctic peninsula represents the barrier winds in that region. The wind pattern is similar to that of mean ice motion (Fig. 3). North of 65°S, the mean geostrophic flow is strictly eastward.

The mean distribution of the ECMWF winds at a level of 10 m (Fig. 13) is shown for comparison. It is based on 3 years of ECMWF analyses, covering the period from July 1986 to June 1987 and the years 1989 and 1992. The 4380 individual analyses originate from periods when the largest number of GTS-transmitting buoys was active in the region. We expect that the buoy data have favourably supported the quality of the ECMWF-analyses. The 10-m winds have been generated from the pressure analyses at the lowest model level, which is ≈ 5 hPa (30 m) above the Earth's surface. The boundary layer scheme to calculate 10-m winds involves the surface roughness length (specified as 1 mm for sea ice), lower atmospheric stability, and geostrophic winds. We compared ECMWF winds with geostrophic winds derived from the ECMWF pressure data at the surrounding grid points. It is found that the boundary layer scheme, on average, causes the 10-m wind speed to be 60% of the geostrophic wind speed and the 10-m wind direction to be deflected by 12° to the right of the geostrophic wind direction.

Obviously the resulting mean ECMWF wind field (Fig. 13) seems to provide an appropriate standard climatological wind forcing, since it is based

- on results from an operational atmospheric analysis model (ECMWF) with advanced model physics and assimilation schemes for surface, upper-air and satellite remote sensing data,
- on 36 months of analysis data covering periods when the largest number of GTS-transmitting buoys was present in the Weddell Sea,
- on a detailed spatial and temporal resolution, i.e., four analyses per day and 1.125° latitude and longitude.

The spatial distributions of Fig. 12 and Fig. 13 resemble each other, with a stronger northward wind in the western Weddell Sea in Fig. 13, however. The ECMWF 10-m winds are generally weaker than the buoy-based geostrophic winds, which is consistent with boundary effects. We conclude that the full assembly of buoy data used in this study does not reflect generally abnormal wind forcing conditions.

From a comparison of Figures 12 and 13 we conclude that both wind patterns reflect a large scale cyclonic circulation over the Weddell Sea. The zone of winds from the south in the southwestern Weddell Sea extends to more than 500km offshore in the buoy composite image and is narrower in the ECMWF analyses. The westerlies in the zone between 60°S and 65°S are less intense in the ECMWF analyses. It has been shown [Karoly and Oort, 1987], that atmospheric circulation statistics in the Antarctic from different operational analysis systems as well from rawinsonde data sets differ considerably.
Figure 12: Mean geostrophic winds in the Weddell Sea, based on buoy pressure data and ECMWF analyses (pale arrows) and a smoothed gridded geostrophic wind field (dark arrows). Upper left: deviations (modulus in m/s) of the gridded field from 30-day mean winds during the year. Numbers middle left: meaning as in Fig. 2.

Figure 13: Mean distribution of 10-m winds in the Weddell Sea based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).
This is due to the sparse observational network and to deficiencies in the analysis methods. Having in mind such possible shortcomings of the ECMWF analyses, we consider the composite geostrophic wind pattern in Fig. 12 as rather representative for the mean wind forcing conditions.

It is noteworthy, that the scalar mean wind speeds (Fig. 15 and Fig. 14) in the Weddell Sea are significantly higher than reflected by the mean vectors displayed in Figures 12 and 13. Scalar wind speeds are important for applications like the calculation of the turbulent heat transfer between the sea and the atmosphere. Caused by the smoothing of wind fields and by the reduction of speeds in the atmospheric boundary layer, mean 10-m wind speeds are smaller in the ECMWF analysis than mean geostrophic wind speeds from buoy data.

The geostrophic wind variance, calculated as $\sqrt{(\sigma_u^2)^2 + (\sigma_v^2)^2}$ (Fig. 16), is of the order of 40 $m/s^2$. There are no pronounced spatial gradients, and the smoothing contour surface does not explain more than 37% of the variance of monthly mean values. The variability of geostrophic winds is quite large in all regions and periods. The variance of geostrophic winds in the period band from 1.5 to 10 days, i.e., at periods of cyclonic vortices (Fig. 18), contributes about 90% to the total variance of the 6-hourly data.

The variances of 10-m winds from ECMWF data (Fig. 17), based on three years of ECMWF analyses, amount to about 80% of the buoy-based geostrophic wind variances. The differences reflect considerable smoothing of the pressure fields by the ECMWF model, which is a result of the poor data coverage of the region. The variance of 10-m winds is smallest over the Antarctic continent, increases sharply in the coastal regions, and obtains maximum values north of 65°S.
Figure 14: Mean geostrophic wind speeds in m/s (numbers in the main part of the figure) and gridded field (contours), based on buoy data matched with ECMWF analyses. Upper left: deviations of the contoured field from 30-day mean wind speeds in m/s during the year. Numbers middle left: meaning as in Fig. 2.

Figure 15: Mean distribution of 10-m wind speeds in m/s in the Weddell Sea based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).
Figure 16: Variance of the geostrophic wind velocity in $m^2s^{-2}$, calculated as $\sqrt{(\sigma_u^2)^2 + (\sigma_v^2)^2}$. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.

Figure 17: Variance of the ECMWF 10-m wind in $m^2s^{-2}$, calculated as $\sqrt{(\sigma_u^2)^2 + (\sigma_v^2)^2}$.
Figure 18: Variance of the geostrophic wind velocity in m$^2$s$^{-2}$, filtered with a 1.5 - 10 day bandpass, calculated as $\sqrt{(\sigma_n^2 + \sigma_\sigma^2)}$; Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.

Figure 19: Mean geostrophic wind vorticity (in $10^{-6}\text{s}^{-1}$), based on the spatial derivatives of geostrophic winds from all groups of buoys; Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.
Figure 20: Variance of geostrophic wind vorticity (in $10^{-8}\text{s}^{-2}$), based on the spatial derivatives of geostrophic winds from all groups of buoys; Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.

Figure 21: Variance of geostrophic wind vorticity (in $10^{-8}\text{s}^{-2}$), filtered with a 1.5 - 10 day bandpass, based on the spatial derivatives of geostrophic winds from all groups of buoys; Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.
The geostrophic wind vorticity (on the basis of monthly means), derived from the buoy arrays (Fig. 19), is predominantly cyclonic in the northern and eastern Weddell Sea and anticyclonic in the southwestern Weddell Sea. The range of magnitude of mean geostrophic wind vorticity is $20 \times 10^{-6} \text{s}^{-1}$, corresponding to mean shear of the geostrophic wind components of only $\frac{1 \text{m/s}}{100 \text{km}}$. The variances of geostrophic wind vorticity are comparatively large (Fig. 20). The variances of about $10^{-8} \text{s}^{-2}$ correspond to standard deviations of the geostrophic wind shear of $\frac{10 \text{m/s}}{100 \text{km}}$, with values increasing from southern to the northern Weddell Sea. The variance of the geostrophic wind vorticity in the west near the Antarctic peninsula is distinctly lone. It is shown by bandpass filtering the full-resolution geostrophic vorticity data (Fig. 20) that about 50% of the variance is associated with atmospheric variability in the period range from 1.5 to 10 days (Fig. 21).
4.3 Air pressure and temperature statistics

The smoothed mean surface pressure distribution based on all buoy data (Fig. 22) shows generally small gradients. The mean pressure decreases from 1000 hPa in the southwest, close the Antarctic peninsula, to 980 hPa in the northwestern Weddell Sea. Individual monthly pressure data deviate considerably from the smoothed composite distributions, reflecting the large variability of air pressure, even for long time scales. The pressure distribution, averaged over three years of ECMWF analyses, shows even weaker gradients (Fig. 23), in particular in the east-west direction. We may conclude that the buoy measurements reflect rather representative atmospheric pressure conditions.

The variance of air pressure (Fig. 24) increases continuously from small values of about 60 hPa$^2$ near the coast to 100 - 180 hPa$^2$ north of 65°S. Maximum variance is found in the northwestern Weddell west of 30°W. Month-to-month variability is superimposed on the smoothed spatial distribution. The 1.5 - 10 day band-pass filtered variance of air pressure amounts to about 60% of the total variance (Fig. 26). The MSL air pressure variance from 3 years of ECMWF analyses (Fig. 25) is rather consistent with the findings from the buoy data, both with respect to the magnitude and the spatial variability.
**Figure 22:** Surface air pressure (in hPa), based on all buoy data. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.

**Figure 23:** Mean distribution of MSL air pressure (in hPa) in the Weddell Sea, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).
Figure 24: Variance of air pressure in hPa², based on the data from drifting buoys. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.

Figure 25: Mean distribution of MSL air pressure variances (in hPa²) in the Weddell Sea, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).
Figure 26: Variance of air pressure in hPa^2; filtered with a 1.5 - 10 day bandpass filter. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.
The mean 2-m air temperatures from 3 years of ECMWF analyses (Fig. 27) are very close to the climatological (mean monthly) surface temperatures, prescribed in the ECMWF analysis scheme. The sharp decrease of 2-m ECMWF temperatures over Antarctica results from the terrain slope. The coverage of the Weddell Sea by buoys, however, is not sufficient to obtain a better climatology. The mean air temperatures from the buoys (Fig. 2) are slightly below the ECMWF results, since the buoy data are restricted to the periods with sea ice present. Matching the historical climatology with the buoy data would be important to obtain better estimates.

The variances of air temperature from buoy data (Fig. 29) of about 20 $K^2$ contrast significantly to the variances of 2-m temperature from ECMWF analyses (Fig. 30) of less than 4 $K^2$. The variance in the period band from 1.5 to 10 days (Fig. 28) accounts for about 50% of the total variance. The ECMWF analysis scheme rejects air temperature from buoys and calculates 2m temperatures by interpolating temperatures at the lowest model level with the surface temperature. Up to 1991 mean monthly climatological surfaces temperature used in the procedure. In 1992 the analysis scheme for surface air temperatures above the polar oceans has been modified by the ECMWF (Viterbo, personal communication, 1996). In the sea ice region, a simplified surface energy balance equation is solved to obtain surface air temperature, instead of the fixed monthly mean air temperature.

The buoy measurements reflect the rapid adjustments of air temperature at the surface to changes in wind speeds, cloudiness and radiation fluxes. Presumably some of the variance

![3_years_ECMWF_2m-temperature](image)

**Figure 27:** Mean distribution of 2-m air temperatures (in °C) in the Weddell Sea, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).
in the buoy temperatures also arises because of opening and closing of leads, which is a sub-grid scale process for the ECMWF analysis. The change in the analysis scheme caused the variance of 2-m temperatures to increase to $\approx 5-10 \, K^2$ in wintertime. The effects of the change are reflected by Figures 31 and 32. Few buoy data were available in the years 1991 and 1993. The differences thus are mainly caused by the modified ECMWF analysis scheme. Variances after the change are of the same order of magnitude as variances estimated from the buoy data in other years.

Sea ice models have been shown to be rather sensitive to the prescribed air temperature [Fischer and Lemke, 1994]. Before 1992 results from model runs with daily atmospheric forcing from ECMWF data presumably become biased by such smoothed temperature data. A better choice would be to use the ECMWF temperature data at the lowest model level and an adequate boundary layer scheme to derive 2-m temperatures. The new scheme is also applied within the ECMWF reanalysis project, which consequently will provide better forcing data for sea ice modelling.

Figure 28: Variance of air temperatures in $K^2$, based on buoy data; filtered with a 1.5 - 10 day bandpass. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.
Figure 29: Variance of air temperatures (in K$^2$), based on buoy data. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.

Figure 30: Variances of 2-m air temperatures (in K$^2$) in the Weddell Sea, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).
Figure 31: Variances of 2-m air temperatures (in K^2) in the Weddell Sea, based on ECMWF analyses from May to October 1991, before a change in the ECMWF analysis scheme.

Figure 32: Variances of 2-m air temperatures (in K^2) in the Weddell Sea, based on ECMWF analyses from May to October 1993, after a change in the ECMWF analysis scheme.
4.4 Ice drift and geostrophic wind relationships

The response of the ice motion to the wind involves a considerable number of parameters whose relative importance varies regionally and seasonally with the states of the atmosphere, the ocean, and the sea ice. In the following we address the question, how general characteristics of the sea ice motion can be explained by a relatively simple linear ice drift model as described for Arctic ice motion [Thorndike and Colony, 1982].

The complex linear model of ice drift is applied to study the forcing of Weddell Sea ice motion. The relationship reads

\[ D = \overline{C_g} + \overline{A} V_g + \epsilon, \]  

(5)

where the constant parameter \( \overline{C_g} \) represents the part of the ice motion which is not wind-correlated, the parameter \( \overline{A} \) is a complex multiplier linearly relating ice drift fluctuations to geostrophic wind variations, and \( \epsilon \) is the complex residual covering drift fluctuations which are neither constant nor linearly related to winds. The parameter \( \overline{C_g} \) sums all effects which remain when the geostrophic wind - and, thus, the surface wind - is zero, i.e. the mean effects of internal stress and ocean surface tilt, the latter being proportional to the geostrophic ocean current. Below we shall endeavour to separate both forces which is possible due to the fluctuating nature of internal stress and steady nature of the geostrophic current. Eq. 5 is used as a regression equation to calculate the optimum parameters \( \overline{A} \) and \( \overline{C_g} \) for 30-day periods (120 pairs of \( D \) and \( V_g \)). Drift data are lowpass filtered with a threshold period of 24 hours to eliminate the semidiurnal maxima of tidal and inertial motion, which are not linearly related to winds. The regression is calculated for all buoys being part of arrays permitting geostrophic wind calculations. The composite geostrophic wind pattern for this data subset is shown in Fig. 12 and the composite ice drift in Fig. 3. The resulting \( \overline{A} \) and \( \overline{C_g} \) are assigned to the mean buoy position of the 30-day period. We obtain \( \overline{A} \) from a linear regression applied to

\[ D - D = \overline{A} (V_g - V_g) \]

and \( \overline{C_g} \) from \( \overline{C_g} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} V_g dt \), where \( r_1 \) and \( r_2 \) are the locations of the buoy at the beginning \( t_1 \) and at the end \( t_2 \) of the 30-day period.

The basic pattern of ice drift data used in this way (Fig. 33) is very similar to that in Fig. 3. Composites of \( \overline{A} \) and \( \overline{C_g} \) as well as relative explained variances of the relative drift speed \( |D - \overline{C_g}| \) are calculated for 30-day periods and displayed in Fig. 34 (modulus \( |\overline{A}| \) of \( \overline{A} \)), Fig. 35 (phase of \( \overline{A} \)), Fig. 36 (\( \overline{C_g} \)), and Fig. 37 (relative explained variance).

The drift velocity pattern is qualitatively similar to the mean geostrophic velocity. The multiplier \( \overline{A} \), however, varies regionally. In the southwestern Weddell Sea it is reduced to less than 0.5% and it increases rather continuously to 1.5% in the northern, central and eastern Weddell Sea. The average angle between the geostrophic wind and the ice motion varies between ±15°. Ice motion is generally almost parallel to the geostrophic wind and thus responds to the wind changes associated with the passage of cyclones. Relative explained variances correspond to squared correlation coefficients multiplied by 100. The distribution of relative explained variances documents that the linear model accounts for less than 50% in the southwestern Weddell Sea, but up to 75% of the total variance in the northern and eastern Weddell Sea. The linear model thus is a reasonable estimator of ice motion in large parts of the basin.
Figure 33: 30-day mean ice drift in the Weddell Sea from the buoys, whose arrangement provided estimates of geostrophic winds and ice deformation (pale arrows) and a smoothed gridded mean ice drift field (dark arrows). Upper left: deviations (modulus in m/s) of the gridded field from 30-day mean ice drift during the year. Numbers middle left: meaning as in Fig. 2.

Figure 34: Composite spatial distribution of the modulus of the complex multiplier $\bar{A}$ (in %), which relates the ice drift speed to the geostrophic wind speed. Upper left: deviations of the contoured field from 30-day means (in same units) during the year. Numbers middle left: meaning as in Fig. 2.
Figure 35: Composite spatial distribution of the phase of the complex multiplier $\hat{A}$ in degrees, i.e. the angle between ice motion and the geostrophic wind. The printed data represent the regression for 30-day-periods, the contours give the interpolated distribution. Upper left: deviations of the contour field from 30-day means (in degrees) during the year. Numbers middle left: meaning as in Fig. 2.

Figure 36: Smoothed distribution of 30-day mean oceanic surface currents $\overline{C_R}$ (in m/s) in the Weddell Sea from buoy data, based on the linear drift model of Thorndike and Colony (1981). Upper left: deviations (modulus in m/s) of the gridded field from 30-day mean currents during the year. Numbers middle left: meaning as in Fig. 2.
Geostrophic ocean currents derived by this method are generally small in the Weddell Sea. Significant features are the coastal current near the southeastern coasts and the bands of larger velocities of \( \approx 5 \text{cm/s} \) following the northward and eastward orientation of the continental shelf breaks in the western and northwestern Weddell Sea. The
ocean current along the Weddell Sea coast between 10°W and 30°W has been shown to comprise a significant wind-driven component due to Ekman transport towards the coast [Kottmeier and Engelbart, 1992]. In the formulation of Eq. (5), wind-driven currents should affect the multiplier $\mathbf{A}$ but not $\mathbf{C_g}$. These wind-related currents add to the mean current shown in Fig. 36 and presumably help to balance the inflow near the eastern coasts with an outflow in the western Weddell Sea. Recent oceanographic observations of the Weddell Gyre [Fahrbach et al., 1994] show roughly corresponding results for the transect from Cape Norvegia to the tip of the Antarctic Peninsula. Their one-year-averaged surface currents are slightly stronger in the coastal current near the eastern margin and slightly weaker in the west. Our estimates are within the fluctuations of mean monthly currents they obtained.

We conclude that the linear ice drift model [Thorndike and Colony, 1982] is a reasonable first guess of the mean ice drift and its synoptic scale fluctuations on time periods of one day and more. Its inverse application on the basis of high quality geostrophic winds provides a consistent distribution of geostrophic oceanic currents, which significantly force the sea ice motion on time scales of one month and beyond. This is also demonstrated by Fig. 38, which shows the observed and simulated drift trajectories from all programs with drifting buoy arrays in the Weddell Sea. The quantities essentially needed to force the linear model of ice motion in the Weddell Sea are actual geostrophic winds and the composite distributions of the complex $\mathbf{A}$ (Fig. 34 and Fig. 35) and of the mean geostrophic ocean current (Fig. 36).

The composite distributions of ice drift, geostrophic winds, the multiplier $\mathbf{A}$, and the geostrophic surface currents are obtained from data from different periods and therefore,

--- observed ice drift

--- simulated ice drift

Figure 38: Observed ice drift and simulated one-month trajectories based on the linear ice drift model of Thorndike and Colony (1981), taking the composite distributions of $\mathbf{A}$ (Figures 34 and 35) and of the geostrophic ocean current (Fig. 36) into account.
to a certain extent, are influenced by temporal variability. The present status of data availability does not provide deeper insight into seasonal variability, especially in the southwestern Weddell Sea. A distinct seasonal variability of the complex multiplier $\overline{A}$ is found for ice motion in the Central Arctic Ocean [Colony, 1994]. In the Weddell Sea almost no ice is present in the summer months and $\overline{A}$-estimates are confined to the other seasons.
4.5 Seasonal and spatial variability from ECMWF analyses during periods of drifting buoy operations.

The attached Figures 39 to 50 present the mean ECMWF analyses based on the periods when buoys were operated most actively in the Weddell Sea (1986/87, 1989, and 1992). The model output data are averaged over the quarters of the year.

With respect to mean winds and wind variances (Fig. 39 to 46), the results are considered as superior to older climatologies, since they are based

- on results from an operational atmospheric analysis model (ECMWF) with advanced model physics and assimilation schemes for surface, upper-air and satellite remote sensing data,
- on a detailed spatial and temporal resolution, i.e., four analyses per day and 1.125° latitude and longitude,
- on each 9 months of analysis data covering periods when the largest number of GTS-transmitting buoys was present in the Weddell Sea.

The temperatures (Fig. 47 to Fig. 50) mainly reflect the prescribed climatological data, which are used in the ECMWF schemes. Air temperature variances (see Fig. 30) are very small in the sea ice zone and not displayed. When there is no sea ice present at the ocean surface, the actual sea surface temperature (SST) is derived by means of an operational satellite SST analysis scheme.
Figure 39: Distribution of 10-m vectorial mean winds in the Weddell Sea from January to March, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).

Figure 40: Distribution of 10-m vectorial mean winds in the Weddell Sea from April to June, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).
Figure 41: Distribution of 10-m vectorial mean winds in the Weddell Sea from July to September, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).

Figure 42: Distribution of 10-m vectorial mean winds in the Weddell Sea from October to December, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).
Figure 43: Mean distribution of variances of 10-m winds (in m$^2$s$^{-2}$), calculated as $\sqrt{(\sigma_u^2)^2 + (\sigma_v^2)^2}$, in the Weddell Sea from January to March, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).

Figure 44: Mean distribution of variances of 10-m winds (in m$^2$s$^{-2}$), calculated as $\sqrt{(\sigma_u^2)^2 + (\sigma_v^2)^2}$, in the Weddell Sea from April to June, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).
Figure 45: Mean distribution of variances of 10-m winds (in m²s⁻²), calculated as $\sqrt{(\sigma_u^2 + \sigma_v^2)}$, in the Weddell Sea from July to September, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).

Figure 46: Mean distribution of variances of 10-m winds (in m²s⁻²), calculated as $\sqrt{(\sigma_u^2 + \sigma_v^2)}$, in the Weddell Sea from October to December, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).
Figure 47: Mean distribution of 2-m temperatures (in °C) in the Weddell Sea from January to March, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).

Figure 48: Mean distribution of 2-m temperatures (in °C) in the Weddell Sea from April to June, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).
Figure 49: Mean distribution of 2-m temperatures (in °C) in the Weddell Sea from July to September, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).

Figure 50: Mean distribution of 2-m temperatures (in °C) in the Weddell Sea from October to December, based on three years of four ECMWF analyses per day (July 1986 - June 1987, January to December 1989 and 1992).
5 Future perspectives

This study is mainly based on the measuring programs with drifting buoys in the Weddell Sea in the last decade. The WCRP International Programme for Antarctic Buoys (IPAB) was established in 1994 as a suitable basis for the maintainance of an internationally coordinated drifting buoy program in the Antarctic sea ice zone. Based on the IPAB-data, studies similar to this will be possible for other parts of the Antarctic sea ice zone.

Another perspective of future work will be the matching of in-situ data from drifting buoys with satellite remote sensing information, which has been successfully used to estimate the motion, extent, concentration, and types of sea ice.

6 Acknowledgements

The research was partly funded by the German Ministry of Research and Technology under grants 51 38391 KF 4 002 0 and 07KFT61 to the Universities of Bremen and Hannover.

Edgar Andreas acknowledges the U.S. National Science Foundation, which supported this work through grants OPP-90-24554 and OPP-93-12642.

Jouko Launiainen and Timo Vihma are grateful for funding of the field phases by the Finnish Antarctic Research Program. Juha Uotila is acknowledged for help in data processing.

Other national funding from Germany, U.S.A., United Kingdom, and Finland is gratefully acknowledged.

Specific thanks are due to Jörg Hartmann, who developed a data analysis and graphics package and gave advice to solve problems. Thomas Viehoff (i) helped to utilize the satellite data.

The ECMWF data have been received from the German Weather Service, Offenbach. Bathymetric information is from the “The GEBCO Digital Atlas” of the British Oceanographic Data Centre. SSM/I data were provided by the National Snow and Ice Data Center, University of Colorado, Boulder, Colorado.

Thanks are due Bruce Elder and Kerry Claffey, who helped calibrate the CRREL pressure sensors used on ICE Station Weddell.
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