GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 3667–3671, doi:10.1002/grl.50705, 2013

Observations of the ocean response to cold air outbreaks and polar lows over the Nordic Seas

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Received 16 May 2013; revised 28 June 2013; accepted 28 June 2013; published 30 July 2013.

[1] The impact of intense atmospheric mesocyclones—polar lows—on the ocean circulation at high latitudes, as well as the role of ocean feedbacks on the evolution of these atmospheric systems themselves, is under debate. Here, the upper ocean response to atmospheric forcing before, during, and after polar lows events over the Nordic Seas is studied. A set of 96 unique polar low tracks from 2002 to 2010 are collocated with satellite-based sea surface temperature and altimeter observations, and with surface drifter observations. The satellite data show systematic temperature and sea level drops and enhanced geostrophic kinetic energies over the days leading up to polar low events. These data however reveal little information about the ocean response to the polar lows themselves. The drifter observations largely agree with the satellite data on the response to synoptic conditions, but they also give indication of enhanced upper-ocean kinetic energies immediately following the passage of polar lows. **Citation:** Isachsen, P. E., M. Drivdal, S. Eastwood, Y. Gusdal, G. Noer, and Ø. Saetra (2013), Observations of the ocean response to cold air outbreaks and polar lows over the Nordic Seas, *Geophys. Res. Lett.*, *40*, 3667–3671, doi:10.1002/grl.50705.

1. Introduction

[2] High-intensity weather systems, even if rare, are key ingredients of the Earth's climate system. At low latitudes, tropical cyclones—enormous heat engines driven by the temperature contrast between the warm tropical oceans and the cold upper layers of the atmosphere—create the world's strongest winds. These winds also cause intense and deep-reaching vertical mixing in the ocean and upwelling of cold waters that have originally been formed at high latitudes. Being particularly effective at bringing such waters up to the surface, to then be warmed up again in the tropics, hurricanes and typhoons may thus contribute significantly to the oceanic meridional heat transport [*Emanuel*, 2001].

[3] High latitudes have their own high-intensity weather systems that have, however, been much less studied. Polar lows (PL) are strong mesocyclones that typically form on baroclinically unstable synoptic fronts generated where cold and dry polar air spills out over warm and moist air from lower latitudes [*Rasmussen and Turner*, 2003]. The synoptic *cold air outbreaks* are large scale, typically last for more than a week and are thus usually well predicted by models. In contrast, the mesocyclones are small ($L < 500$ km), short-lived ($T \sim 1$ day), and notoriously difficult to forecast. Fully developed polar lows that have wind speeds over 20 m/s are relatively rare, but they do hit e.g., the Norwegian coast and the British isles a few times every winter with severe consequences for mariners.

[4] There exist important unanswered questions about the interaction between atmosphere and ocean during polar low events. As for tropical cyclones, PLs can gain some of their energy from the warm ocean below. So, from a weather forecasting perspective, one wonders, for example, whether the evolution of these atmospheric systems can be impacted by sea surface temperature (SST) changes driven by the wind-induced vertical mixing. Most of the upper ocean is temperature-stratified, so vertical mixing should lead to lowered SSTs that help stabilize any diabatically-driven atmospheric system. But *Saetra et al.* [2008] have also suggested that polar lows that happen to pass over salt-stratified regions at high latitudes may instead bring warmer waters up to the sea surface that help intensify the systems. Accounting for such feedbacks via SSTs, negative or positive, may potentially have a considerable impact on the skill of weather prediction in these regions.

[5] A second interest in polar lows stems from modeling studies by *Condron et al.* [2008] and *Condron and Renfrew* [2013] on the impact of polar mesocyclones on the ocean heat budget at high latitudes. The high wind speeds associated with such mesoscale systems necessarily cause strong air-sea fluxes, and the studies in question focused on the bias inherent in coarse-grained climate simulations that do not resolve them. By boosting the winds speeds of mesocyclones over the northern North Atlantic and Nordic Seas in coarse-resolution atmospheric reanalyses (based on a Rankine vortex model tuned with an empirical relationship between vortex size and strength), these authors found that net air-sea heat fluxes increased by a few percent. They also found a corresponding impact on regional mixed-layer depths and on the poleward heat transport farther south in the North Atlantic Ocean.

[6] The potentially important impact of polar lows on both the weather and climate prediction problems warrants detailed investigations of the ocean response to such systems. But the few studies that exist have been rather limited in scope. The numerical study of *Saetra et al.* [2008] was highly idealized and focused exclusively on the initial mixing response. And *Condron et al.* [2008] and *Condron and Renfrew* [2013] used relatively coarse-grained ocean models to study integrated effects rather than the details of the dynamical response.

[7] So much remains to be understood. But if such systems bear any resemblance to ordinary synoptic storms or hurricanes, we can, in addition to the initial mixing response,

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0094-8276/13/10.1002/grl.50705

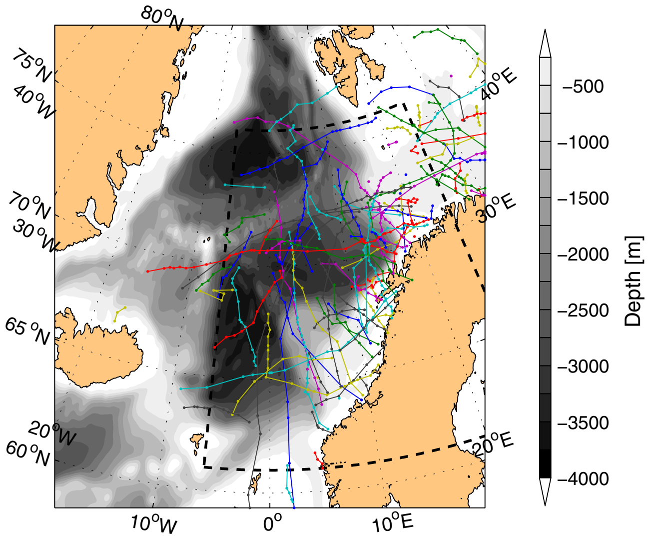

Figure 1. Polar low tracks in the Nordic Seas from 2002 to 2010. Black dashed lines show the region over which the SST, sea level anomalies (SLA), and surface kinetic energy response were studied. The ocean depth is indicated by gray shading.

expect the excitation of near-inertial oscillations and also a range of instability mechanisms that lead to gradual restratification of the mixed layer. The ocean should, in other words, respond with both enhanced turbulent and eddy kinetic energy levels. The net air-sea fluxes will thus be influenced both by small-scale vertical mixing and the advective restratification processes.

[8] *Haine et al.* [2009] have presented some high-resolution primitive equation simulations of the ocean response to high-intensity weather over the Denmark Strait. And one of the specific cases studied did involved a polar low outbreak on 25 February 2008. Interestingly, the authors found that the modeled ocean circulation was *weaker* during this polar low outbreak than in the rest of their simulation, a result seemingly in contradiction with the expected dynamical response. The authors, however, attributed part of the weak response to limitations in experimental setup (the polar low passed near the boundary buffer zone of the model). Their findings should thus be considered inconclusive.

[9] Any model study, like the ones mentioned above, will of course be sensitive to parametrization choices for vertical mixing and also, to some extent, to parametrization choices for the restratification processes (e.g., submesoscale mixed-layer instabilities). Observations from the real oceans are therefore vital. But, to our knowledge, a systematic analysis of existing data has yet to be made. In anticipation of future numerical and theoretical studies, this letter therefore presents a set of observational estimates of the typical upper ocean response to atmospheric conditions before, during, and after polar low events.

2. Data and Methods

[10] A new catalog of polar low events over the Nordic Seas and northern North Atlantic has been compiled at the Norwegian Meteorological Institute as part of the Sea Surface Temperature and Altimetry Synergy project (STARS; http://polarlow.met.no/stars). The time, position, and approximate size of 138 unique polar lows from 2002 to 2010 have been recorded based on remote sensing information and operational analyses [*Noer et al.*, 2011]. Each polar low was typically observed several times, giving a total of 1095 polar low "sightings." For our study, a subset of this data, limited to the eastern Nordic Seas between 6°W–25°E and 61°N–76°N, was used (96 unique tracks with a total of 709 sightings). This is a region with a particularly high density of polar lows (Figure 1), and it also represents one primary oceanographic regime, namely surface waters dominated by warm and salty Atlantic Waters flowing northward along the Norwegian coast.

[11] To study the SST response to these polar lows, we used the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) [*Donlon et al.*, 2011], covering the period 2006–2010. The OSTIA data set contains some *in situ* observations but is still overwhelmingly dominated by data from spaceborne instruments (infrared and active microwave). The data set is distributed once a day on a $0.05° \times 0.05°$ geographic grid, but the effective resolution is somewhat coarser in both time and space.

[12] OSTIA SSTs were bilinearly interpolated onto each polar low position as recorded in the STARS data set. Such interpolation was repeated every day from –32 days to +32 days relative to the time of the PL observation. The typical (sample mean) SST response could thus be plotted as a function of time relative to the event itself. To filter out the persistent seasonal cooling from these estimates, an average seasonal SST cycle was also calculated and subtracted (see below). Finally, the sample standard error was used as our uncertainty estimate.

[13] The sea level and geostrophic velocity response was studied using along-track data from the Envisat altimeter instrument. The monomission data set provided by AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data; http://www.aviso.oceanobs.com) was used here; it provides sea level anomalies (SLA) observations at an along-track resolution of approximately 6.7 km and a repeat cycle of about 35 days.

[14] Because of the much lower data coverage of the along-track altimeter data, the sea level response was estimated not by interpolation but by averaging over SLA observations within a 200 km radius of each polar low position. Again, the calculation was done every day from –32 to +32 days relative to the events. This accounting was made for SLA itself and also for the geostrophic kinetic energy anomaly,

$$KE'_g = \left(\frac{g}{f}\frac{\partial \eta'}{\partial x}\right)^2,$$

where η' is SLA, x is the along-track distance, and g and f are the gravitational acceleration and the Coriolis parameter, respectively. Although some polar low sightings were not in close enough proximity to available along-track data, the high number of total sightings allowed for sample mean and standard error estimates to be made, as for SSTs.

[15] Finally, surface drifter data from the Nordic Seas was gathered from the Global Drifter Program (http://www.aoml.noaa.gov/phod/dac). Temperature measurements are collected 30 cm under the sea surface with an accuracy of 0.1°C. The drifter positions are tracked by the Argos (http://www.argos-system.org) satellite system, yielding positions with 150–1000 m accuracy up to 50 times a day. The data

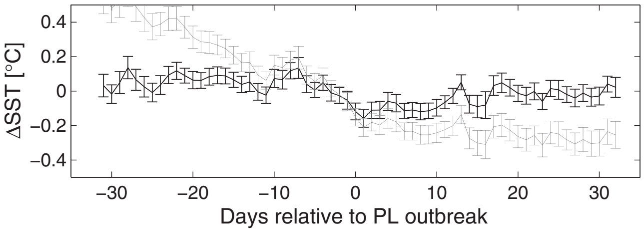

Figure 2. OSTIA sea surface temperatures interpolated to polar low positions, from 32 days before events to 32 days after: (gray line) before and (black line) after the mean seasonal cycle has been removed.

set used here has been quality controlled and interpolated via a kriging method to yield time series with 6 h resolution [*Lumpkin and Pazos*, 2007].

[16] Drifter SSTs and kinetic energies (estimated from the displacements) were made from all drifters that passed within 75 km from any polar low sighting, from 7 days before to 7 days after the sighting. With such stringent sampling criteria, many polar low sightings were out of reach for the drifter data set. The resulting data set is thus rather sparse ($N \sim 100$), so to reduce bias from outliers, the statistics calculated were the sample median and median absolute deviations.

3. Results

[17] The statistics of the OSTIA-based SST anomalies from 32 days before PL events to 32 days after the events are shown in Figure 2. Clearly seen is a persistent cooling taking place over the winter season. But after an estimate of the seasonal cycle has been subtracted, the data show an unmistakable SST drop during the week leading up to a polar low. This systematic drop likely reflects the integrated effect of cooling by the synoptic-scale cold air outbreaks that typically precede the mesoscale systems.

[18] The plot suggests that the lowest SSTs are typically reached a day after polar low events, but this detail likely falls within the noise level of the calculation. The data then show a recovery of SSTs. This rise, lasting 1 to 2 weeks, presumably indicates advective recovery back to conditions found prior to the cold air outbreaks.

[19] The SLA and geostrophic kinetic energy responses are shown in Figure 3. The uncertainties of these calculations are larger because of lower data coverage. But, as with SSTs, we see a clear seasonal-scale lowering of the sea level, likely reflecting the contraction of the water column from the seasonal cooling. In contrast, the geostrophic kinetic energies do not show this seasonal trend. This is not entirely unexpected since geostrophic velocities rely on sea surface slope and thus on smaller spatial scales (the seasonal signal is large scale).

[20] With the seasonal signal removed, the SLA response near polar low events stands out more clearly. SLAs begin to drop some days before a polar low, just like SSTs do. But, unlike SSTs, the sea surface height continues to drop for about a week afterward. This somewhat unexpected result presumably suggests that the SLA drop is due to both dynamic and thermodynamic effects. One possible dynamic response is the spinning up and spinning down of large-scale gyres [*Isachsen et al.*, 2003] in response to the anomalous wind stresses associated with cold air outbreaks and polar lows.

[21] Geostrophic kinetic energies also reveal a dynamic response to the synoptic forcing leading up to the polar low outbreaks. Kinetic energies (KEs) peak around or just before the outbreak of the mesoscale events then drop to background levels a few days afterward. Interestingly, there is no obvious one-to-one agreement between geostrophic KE and the SLA signal itself. Again, this can be understood, in part, from the fact that kinetic energies are dominated by smaller spatial scales than the SLA signal (in the Fourier domain, KEs are weighted by the square of the wave number relative to SLAs). So the integrated SLA response likely reflects predominately basin-scale dynamics while kinetic energies reflect more of mesoscale dynamics.

[22] Finally, statistics from the drifter data set is presented in Figure 4. Because of the relatively low number of drifters, an estimate of the seasonal cycle could not be made and subtracted here. The drifter SST response should thus be compared to the corresponding *uncorrected* estimate from OSTIA (Figure 2, gray line). As it turns out, the drifter observations largely agree with the OSTIA product in showing an SST drop over the week leading up to the polar low itself and then a flattening out or, taking the seasonal cooling into account, possibly a gradual recovery after that.

[23] Surface kinetic energies, estimated from drifter displacements, are also shown. They also largely agree with the satellite observations in indicating that KE levels rise some days before the polar low outbreaks. But the *in situ* data also suggest that the elevated levels last a few days past these events, a signal less pronounced in the altimeter data. In particular, there is a KE peak 1 to 2 days after polar low outbreaks, a possible first indication of a direct dynamic ocean response to the mesoscale systems themselves.

[24] There are, however, also peaks of comparable amplitude about 3 days before and 3 days after the outbreak, so the statistical robustness is again in question. To check this, the variance of the drifter positions was also plotted. This field integrates up errors in the Argos positioning technology

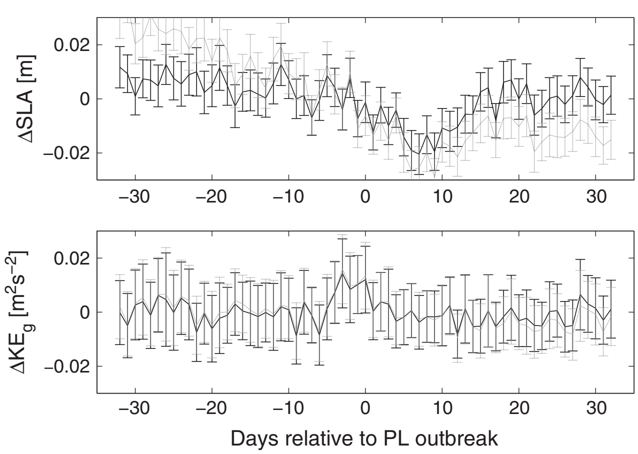

Figure 3. Altimeter observations averaged around polar low events: (top) sea level anomalies and (bottom) geostrophic kinetic energy anomalies. Gray and black lines show data before and after an estimate of the seasonal cycle has been subtracted.

but should also capture some real variability at time scales shorter than those represented by the 6-hourly mean fields. As it turns out, the data also indicate enhanced variability in the day or so following polar low events, while correspondence with the other two peaks is less pronounced. So, although the signal-to-noise level here is still clearly a concern, we take this as an indication of a possible direct dynamic response of the ocean to the passage of polar lows.

4. Summary and Discussion

[25] All data sets studied here suggest a systematic ocean response to atmospheric conditions found around the time of polar low events over the Nordic Seas. But the strongest signals by far are those tied to the synoptic weather systems, typically cold air outbreaks, that precede polar lows. The observations show a persistent SST drop in the days leading up to PL events, consistent with the notion that the region is then typically exposed to exceptionally cold and dry Arctic air masses. We also observe lowered sea level anomalies and enhanced geostrophic kinetic energies associated with the synoptic background flow.

[26] Signs of a direct ocean response to the polar lows themselves were harder to find. Can this be explained by the small scale and short life of these mesoscale systems? The STARS data set contains information about PL translation speeds v_{pl} and PL radii R_{pl}, and from these we can make estimates of an effective forcing period, $T_f = R_{\mathrm{pl}}/v_{\mathrm{pl}}$. A cumulative histogram of this (not shown) suggests that more than 50% of polar lows force any one patch of the ocean for less than 6 h, and 90% force any one location for less than 12 h. So polar lows force the ocean for very brief periods of time compared to the larger-scale and longer-lived synoptic weather systems. And, as suggested by the observations studied here, their net impact on ocean hydrography and circulation is therefore likely quite small.

[27] And yet, the surface drifter observations did give some indication of a direct response, reflected in elevated kinetic energies and position variance fields a day or two following PL events. Independent indication that there is indeed an ocean response to PLs, and that this response is likely quite complex, is given in Figure 5. Shown is the difference in SST between 1 day before and 1 day after the passage of a polar low off the Norwegian coast on 3–4 March 2008. The observations, collected by active microwave instrument that can measure through clouds, suggest a larger-scale SST drop over the region of around 1°C, but also show regions of no change in temperature and, more interestingly, also a patch where SSTs have risen. The patch of increased SSTs may partially reflect contamination of the microwave data by high wind speeds (C. Donlon, personal communication, 2011). But it is located along the frontal zone between the temperature-stratified Norwegian Atlantic Current and the salt-stratified Norwegian Coastal Current, and may therefore also give evidence for actual upward mixing of saltier and warmer Atlantic Water (as investigated by *Saetra et al.* [2008]).

[28] Clearly the data sets studied here are either too smooth or too sparse to properly capture the kind of complex dynamic response suggested by Figure 5. In fact, given the small scales and intermittent nature of such events, it seems doubtful that any realistic observational campaign can be designed for this purpose. Making further progress will likely have to rely on a combination of both idealized and realistic high-resolution numerical experiments. The fidelity of such models, however, should be tested against the kinds of signals revealed by the present data sets.

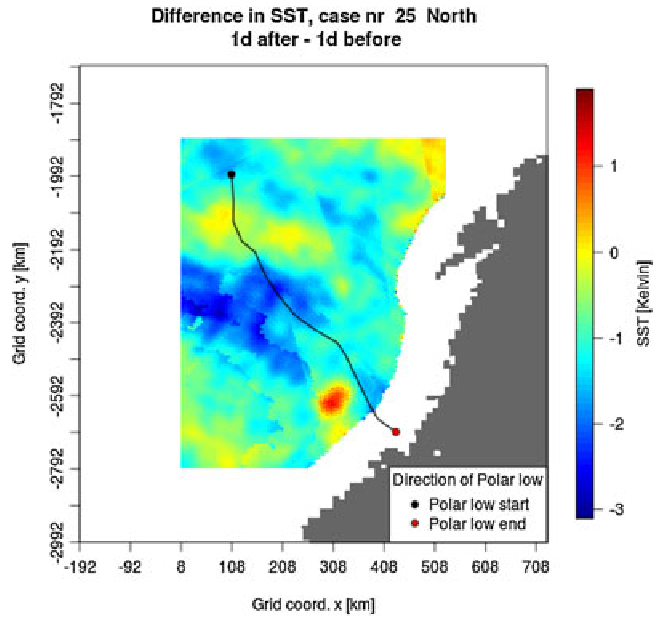

Figure 5. SST changes (from AMSR-E microwave observations) from 1 day before to 1 day after a PL event on 4–5 March 2008. The AMSR-E data have been produced and distributed by Remote Sensing Systems (http://www.remss.com).

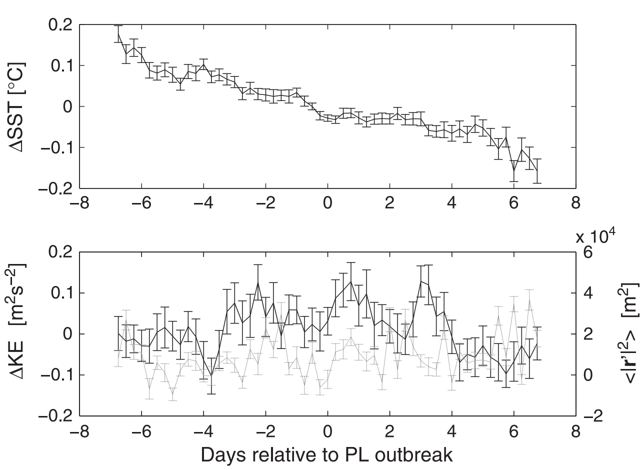

Figure 4. Surface drifter observations of (top) SST anomalies and (bottom) KE anomalies around polar low events. The bottom panel also shows anomalies in the variance of drifter positions (gray lines).

[29] **Acknowledgments.** This work was conducted under the STARS project (Sea Surface Temperature and Altimeter Synergy for Improved Forecasting of Polar Lows) funded by the European Space Agency. We wish to thank two anonymous reviewers for their reading and commenting on the manuscript.

[30] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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