Polar low interaction with the ocean

Torsten Linders

Institutt for geofag, Universitetet i Oslo

Series of dissertations submitted to the
Faculty of Mathematics and Natural Sciences, University of Oslo
Nr. 856

ISSN 1501-7710

Cover: Inger Sandved Anfinsen.
Printed in Norway: AiT e-dit AS, Oslo, 2009.

Produced in co-operation with Unipub AS.
The thesis is produced by Unipub AS merely in connection with the
thesis defence. Kindly direct all inquiries regarding the thesis to the copyright
holder or the unit which grants the doctorate.

Unipub AS is owned by
The University Foundation for Student Life (SiO)

Polar low interaction with the ocean

Torsten Linders

1 Introduction

Polar lows are important for society because of the sometimes extreme and potentially destructive weather that accompanies them. They appear most frequently at high latitudes on the northern hemisphere, especially over the Nordic Seas but also over the North Western Atlantic and the Northern Pacific. Therefore it is not surprising that researchers in Scandinavia and Great Britain but also in North America and Japan have given special attention to polar lows. The journal *Tellus*, published on behalf of the International Meteorological Institute in Stockholm, has devoted several special issues to investigations of polar lows. In Norway there have been conferences and workshops on polar lows and the Norwegian Meteorological Institute has a special group monitoring and tracking polar lows over the Nordic Seas. The present standard literature on the subject is *Polar Lows*, published in 2003 and edited by Erik Rasmussen of the University of Copenhagen and John Turner of the British Antarctic Survey.

Polar lows are an intriguing and challenging phenomenon to study. Their small size and the sparse observational network in the region where they occur make them difficult both to observe and forecast. The introduction of satellite observations has revealed a great deal about their frequency, appearance and characteristics. There are however still very fundamental questions unanswered or poorly understood. This is reflected by the lack of a generally accepted definition of what a polar low is. Rasmussen and Turner (2003) uses the following definition:

> *A polar low is a small, but fairly intense maritime cyclone that forms poleward of the main baroclinic zone (the polar front or other major baroclinic zone). The horizontal scale of the polar low is approximately between 200 and 1000 kilometres and surface winds near or above gale force.*

Perhaps the most central and still unanswered question is which mechanism is forcing polar lows. As can be seen this issue is left out of the definition above. The two main candidates are baroclinic instability and latent heat release in deep convection. If the forcing process is baroclinic instability it would mean that polar lows are similar to ordinary synoptic scale low pressure systems. If the forcing process is latent heat release in deep convection it would mean that polar lows are similar to tropical cyclones. It is often assumed that the systems identified as polar lows fall within a spectrum which includes both these processes (Rasmussen and Turner, 2003).

Polar lows typically share many apparent characteristics with tropical cyclones. One of the most basic is that they are both exclusively marine phenomena. It is today well established that tropical cyclones are forced by self-induced heat fluxes (predominantly latent) from the ocean. The interaction between the ocean and tropical cyclones has been the topic of many investigations. Some of these have focused on how oceanic conditions may favour or restrain the development of tropical cyclones (e.g. Shay *et al.*, 2000; Emanuel *et al.*, 2004; Kafatos *et al.*, 2006). Some investigations have focused on the short term response by the ocean and how this response may feed back on the atmosphere and work as a controlling mechanism for the intensity of tropical cyclones (e.g. Shade and Emanuel, 1999; Hong *et al.*, 2000; Zedler *et al.*, 2002). Some investigations have focused on the effects on the ocean on longer time scales and how this may affect climate (e.g. Emanuel, 2001; Sriver and Huber, 2007; Korty *et al.*, 2007).

The interaction between the ocean and polar lows is much less investigated. Perhaps this can be attributed to the fact that few oceanographers have taken an interest in polar lows. Perhaps it is also a consequence of the above mentioned difficulties in establishing definitively whether the ocean actually contributes to their forcing. Tropical cyclones are of course even more intense than polar lows and globally a more frequent phenomenon with more easily imagined effects on climate. However, from a global climate perspective it should be remembered that polar lows are frequent over the Nordic Seas, which is the main entrance to the Arctic Ocean. The heat fluxes from the Nordic Seas are possibly of immense importance for deep water formation in the northern hemisphere, with global effects on ocean circulation and climate (Aagaard and Carmac, 1994; Rudels *et al.*, 1994; Pfirman *et al.*, 1994).

In the papers included in this thesis my coauthors and I investigate the interaction between polar lows and the ocean. The focus is on the Nordic Seas. We assume that the ocean is a possible contributor to the forcing of polar lows. Paper I deals with how polar lows may affect the upper ocean. It starts with a look at the rather special vertical temperature profiles that occur in the Nordic Seas and continue with investigating how the strong winds associated with a polar low can change these profiles. Paper II deals with the effect of changes in the sea surface temperature (SST) on the intensity of a polar low. Ensembles of numerical simulations are compared with the results from an analytical model. Paper III deals with a unique data set of resent observations of polar lows. Two different theories for polar lows, both assuming forcing by latent heat release in deep convection, are compared with the data set. The papers are summarised in sections 2–4, respectively. In section 5 I give some concluding remarks and speculate on how the results in this thesis can be interpreted.

2 Summary of Paper I

In this paper we start from the observation that the hydrology of the Nordic Seas sometimes display what we call a temperature inversion in the upper 100 metres, meaning that the temperature increases with depth from the mixed surface layer and downwards. This is contrary to the case in the low latitude oceans, where the mixed layer invariably is warmer than the water beneath it. The deepening of the mixed layer induced by tropical cyclones leads to a cooling of the ocean surface and acts as a controlling factor for the cyclone intensity. In the Nordic Seas, in case of a temperature inversion, the effect could be the opposite, with a warming of the ocean surface.

Using an large data base of observations in the Nordic Seas we investigate the frequency of temperature inversion during the winter months November to April. If the threshold for temperature inversion is defined as the occurrence in the upper 100 metres of a temperature more than 1 °C warmer than the SST, then the total frequency is 17 %. There are large variations depending on the month, location and threshold values.

Two observed temperature profiles with strong temperature inversion are used to initialise a numerical model simulating the effect of a polar low on the upper ocean. The one-dimensional model uses a turbulence closure based on one equation for the turbulent kinetic energy and one algebraic expression for the mixing length. The model is validated against a laboratory experiment and against the observed and simulated response of the ocean to the forcing of a tropical cyclone.

The simulations indicate that in case of strong temperature inversion a surface warming of more than 1 °C may take place within a few hours. Evidence from cloud penetrating microwave satellite observations supports this finding. In one illustrative event a polar low passed over an area where the warm and highly saline water of the North Atlantic Current is likely to sub-duct fresher and colder water masses, creating a temperature inversion. The passage coincided with a rapid increase in the SST, with up to 2 °C. A pool of warm surface water remained in the area during several days.

3 Summary of paper II

This paper is partly motivated by the finding of Paper I, that a polar low can it self induce a warming of the ocean surface with around 1 °C and thereby increasing the heat fluxes from the ocean. Such an effect would enhance the forcing mechanism of Wind-Induced Surface Heat Exchange (WISHE), which is the state of the art theory for tropical cyclones. One central idea of WISHE is that "the intensification and maintenance of tropical cyclones depend *exclusively* on self-induced heat transfer from the ocean" (Emanuel, 1986a). WISHE has from its conception been used also to explain polar lows (Emanuel, 1986b). As a polar low moves over the ocean surface it is likely to experience a changing SST. The change will most of the time not be self-induced but caused by preexisting horizontal variations, which are typical for the Nordic Seas.

We simulate polar lows in an axis-symmetric non-hydrostatic numerical model with explicit representation of convection. The model was originally developed to simulate tropical cyclones (Rotunno and Emanuel, 1987) but has also been used to simulate polar lows (e.g. Emanuel and Rotunno, 1989). We run 5 control simulations with different SSTs. Then we run a total of 100 simulations where we perturb the SST. The sensitivity is defined as the difference between the perturbed simulations and the control runs, scaled with the SST perturbation.

The sensitivity of the simulated polar lows is found to be independent of the magnitude of the SST perturbation, i.e. the effect is proportional to the SST change. This is true both for the deepening of the depression and the increase of the maximum azimuthal wind. The effect also appears to be independent of when the SST is perturbed. The mean sensitivity of the depression is -0.6 hPa $°C^{-1}$ and the mean sensitivity of the maximum azimuthal wind is $+0.6$ m s^{-1} $°C^{-1}$. It takes the model around 15 hours to respond to the perturbations.

We formulate a simple analytical model for predicting the effect of an SST change, based on the WISHE theory. WISHE assumes that the polar low works like a Carnot engine. Energy comes from the (sensible and latent) heating of the air entering the surface boundary layer. The air convects out of the boundary layer and its original enthalpy is restored when the added heat is lost through radiative cooling at high altitude. The energy input of this cycle depends both on the heating in the boundary layer and on the difference between the temperature during the heating and the temperature during the high altitude cooling.

Our contribution consists of two parts. First, the cooling temperature is estimated by balancing the known state of the other relevant parameters, which all can be found in the boundary layer. Second, we introduce a non-dimensional number, Λ, to measure the influence of the SST on the air in the boundary layer. Λ takes values between 0 and 1, where 0 indicates that the air is not influenced by the SST and 1 indicates that the influence is at it theoretical maximum. Under additional assumptions this latter case means that the air is heated to the SST and becomes saturated. Λ is found by balancing the state of the boundary layer with bulk formula for the sea surface heat fluxes.

The analytical model is applied to the state of the control runs of the numerical model. The predicted effect agrees closely with the perturbed simulations. The effect is proportional to the SST change and the magnitude is approximately equal to how the numerical model respond.

The analytical model can be used as a prognostic tool but it requires a relatively detailed knowledge of the surface boundary layer. Sufficiently detailed observations of real polar lows are practically non-existent. To test the skill of the model would further require an observed time series. However, the analytical model can also be used for a process oriented analysis of polar lows. As it is rather general and builds upon a theory for tropical cyclones it should also be applicable to tropical cyclones.

4 Summary of paper III

The starting point for this paper is the arrival of the data set from the IPY-THORPEX flight campaign conducted over the Nordic Seas in February and March 2008. The observations during this campaign are unique in several respects. The data set includes a multitude of observations of atmospheric conditions over the Nordic Seas during the high season for polar lows. Of greatest value is the observations of one polar low development, which is covered by three flight missions during two days. The drop-soundings and the LIDAR (LIght Detection And Ranging) observations of humidity and wind give a three-dimensional picture of a polar low during several stages, and of a level of detail never achieved before.

I calculate the Convective Available Potential Energy (CAPE) for all of the soundings from the IPY-THORPEX campaign. Two striking results emerge. First, the vast majority of the soundings has very little CAPE and the soundings that have most CAPE are found inside the mature polar lows. Second, the higher CAPE values are associated with unconditional and not conditional instability. I.e. no additional mechanical energy is needed to lift the air to its Level of Free Convection in order to release the CAPE. The existing CAPE must thus be regarded as energy already in the process of being released and not as an reservoir of energy, which could be released at a later stage. Put slightly different, CAPE is a temporary stage in a flux of energy from the ocean to the upper atmosphere. It is entirely consistent with the fact that CAPE is found not in the ambient atmosphere but inside the polar lows, where both the energy transfer from the ocean and the atmospheric convection are strong.

The results contradict in a rather fundamental way what is stated by Rasmussen and Turner (2003). They maintain that the release of CAPE in a Conditional Instability of a Second Kind (CISK) is a possible explanation for polar lows. Specifically they state that "CAPE is *not* consumed as quickly as it is produced by large-scale processes". The CISK theory was originally developed for tropical cyclones (Charney and Eliassen, 1964) and was introduced as mechanism for polar lows by Rasmussen (1979). After the introduction of WISHE has CISK fallen into disrepute in the studies of tropical cyclones. I hope that the results presented here will put it to rest also in the field of polar lows.

I suggest a method for assessing the significance of a CAPE value. The method relates the CAPE to the heat fluxes from the ocean by calculating a timescale, t_{CAPE}, indicating how long it takes these fluxes to transfer an amount of energy corresponding to a given CAPE value. Calculations of t_{CAPE} for the highest CAPE values give a timescale of a few minutes. This limited timescale is once again consistent with CAPE as the expression of a flux rather than a reservoir.

I further calculate the stratification in terms of Convective INhibition (CIN) for all of the soundings. The stratification varies from from strongly stable to neutral and in the polar lows is even slightly unstable stratification found. This is qualitative agreement with the WISHE theory. A limited case study of the most intense polar low observed during the campaign also supports that WISHE is a possible mechanism for polar low maintenance. Here I utilise some parts of the analytical model presented in Paper II. The positive result for WISHE is probably less robust than the negative result for CISK.

5 Discussion

One of the more robust results in this thesis is that the SST can increase as an effect of the strong wind caused by polar lows. The wind supplies the necessary mechanical energy for deepening the mixed layer and in case of an upper ocean temperature inversion this leads to an increasing temperature in the mixed layer. A polar low can be especially effective in deepening the mixed layer. Its small size and fast translation speed mean that the wind vector will turn clockwise at a rate comparable to the inertial turning caused by the rotation of the earth (Göran Broström, personal communication). This is true on the right hand side of the polar low path, where the winds are stronger than on the left hand side. Winds caused by other weather systems, such as ordinary synoptic lows, can also cause an increasing SST by deepening of the mixed layer. Browsing through winter time weather charts covering the Nordic Seas it is quite common to see strong wind events coinciding with increasing SST.

It is possible to imagine at least three types of effects when the mixed layer deepens and its temperature increases. One is the immediate feed back on the atmosphere caused by the increased sea surface heat fluxes. This effect is investigated in Paper II. Another possible immediate effect is on ocean circulation caused by the horizontal density variations induced by the vertical mixing. A third possible effect is on the thermohaline circulation. Possibly there are effects on the global meridional overturning circulation (MOC). The polar lows would in that case contribute to lifting the warm Atlantic water to the surface where it is exposed to cooling from the atmosphere. At the other end of the MOC there exist a corresponding effect, with tropical cyclones lifting cold water to the surface in the low latitude oceans, where it is exposed to warming from the atmosphere (Emanuel, 2001; Sriver and Huber, 2007; Korty *et al*, 2007).

The feed back mechanism on a polar low from a rising SST is investigated in Paper II. It comes as a bit of a surprise to us that the intensity of our simulated polar lows shows so limited sensitivity to SST changes. The sensitivity in our simulations is an order of magnitude less than has been found for tropical cyclones (Shade and Emanuel, 1999) and for polar lows (Emanuel, 1986b). It should, though, be pointed out that Emanuel (1986b) studied the effect on the theoretical maximum intensity. The simple analytical model developed in Paper II gives an indication about why the actual sensitivity is much less than for the theoretical maximum. The limited sensitivity can in about equal parts be attributed to two reasons. First, the cooling temperature during the assumed Carnot cycle is a lot higher than the theoretical minimum at the tropopause. Probably this is at least partly because the mean convection simply does not reach that high. Second, during the time the air-parcels spend in the boundary layer their enthalpy is influenced by the heat fluxes from the ocean. This influence, which in Paper II is measured by the parameter Λ, is a lot less than the theoretical maximum influence, which would correspond to the air-parcels reaching saturation at SST. The effect of an SST change on the air-parcels' enthalpy is likewise not equal to the change of the theoretical maximum enthalpy, but is scaled by Λ.

During the investigations presented in Paper II there occurred an accidental result. Initially the control simulations were run with slightly different initial conditions. This was due to a misunderstanding of how the numerical model worked. The model domain is initially adjusted to the SST in order to achieve the 'warm, moist' profile of Emanuel and Rotunno (1989). The different initial conditions had a lot larger impact on the polar low intensity than the subsequent SST changes. This is especially interesting given that the numerical model being used was constructed to show that tropical cyclones and polar lows are forced by the heat fluxes from the ocean, and has indeed been used to that purpose (Rotunno and Emanuel, 1987; Emanuel and Rotunno, 1989).

This should be put in the context of Paper III. In this paper it is shown that it can be ruled out that polar lows are forced by preexisting CAPE. An atmospheric state with conditional instability, expressed as CAPE, is what forces polar lows according to the CISK theory, which hence must be discarded. In the same paper I find that it is at least possible that the forcing comes from the sea surface heat fluxes. The strongest evidence for the oceanic influence on polar lows remains the fact that they exist exclusively over the ocean. Their apparent similarities with tropical cyclones are a more circumstantial evidence. One tentative conclusion could be the following. The heat fluxes from the ocean, and possibly the lower surface friction compared to over land, are important or even necessary conditions for polar low developments. Of crucial importance for the intensity of polar lows is the state of the ambient atmosphere. The necessary atmospheric state only exists over the ocean. It is still tempting to look at the heat fluxes from the ocean as a reason for this, but apparently the explanation is not the buildup of CAPE. One possible explanation could be that during winter the heat fluxes from a warm ocean to a cold atmosphere leads to a lot of convection, which neutralises much of the stratification. When a more intense event occurs the weak stratification facilitates a deeper convection than would have been possible in more stratified atmosphere.

The question of how polar lows are forced remains wide open.

6 Acknowledgements

My PhD studies were funded by the European Commission through a research fellowship under the ModObs project, contract MRTN-CT-2005-019369.

The Norwegian Meteorological Institute has been a great place to work at. Special thanks goes to all the wonderful people I have got to know at the Research Department and most of all in the Oceanography Section.

Dr Øyvind Saetra has been my supervisor and mentor. He is the prime reason way I have made progress and also have had much fun during my time in Oslo. Øyvind, you are my role model.

Göteborg   January 7, 2009

References

Aagaard K, Carmack EC. 1994. The Arctic Ocean and climate: a perspective. In *The polar oceans and their role in shaping the global environment*, ed. Johannessen OM, Muench RD, Overland JE. pp 5–20. American Geophysical Union, Washington DC

Charney JG, Eliassen A. 1964. On the growth of the hurricane depression. *J. Atmos. Sci.*, **21**, 68–75.

Emanuel KA. 1986a. An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance *J. Atmos. Sci.* **43**: 585–604.

Emanuel KA. 1986b. A two stage air-sea interaction theory for polar lows. *Proceedings of the international conference on polar lows, Oslo, Norway, 20 - 23 May 1986.* 187–200.

Emanuel KA. 2001. The contributions of tropical cyclones to the oceans' meridional heat transport. *J. Geophys. Res.* **106**: 1471–1482.

Emanuel KA, DesAutels C, Holloway C, Korty R. 2004. Environmental control of tropical cyclone intensity. *J. Atmos. Sci.* **63**: 843–851.

Emanuel KA, Rotunno R. 1989. Polar lows as arctic hurricanes. *Tellus.* **41A**: 1–17.

Hong X, Chanh SW, Raman S, Shay LK, Hodur R. 2000. The interaction between Hurricane Opal (1995) and a warm core ring in the Gulf of Mexico. *Mon. Wea. Rev.* **128**: 1347-1365.

Kafatos M, Donglian S, Gautam R ,Boybeyi Z, Yang R. 2006. Role of anomalous warm gulf waters in the intensification of Hurricane Katrina. *Geophys. Res. Let.* **33**: L17802.

Korty RL, Emanuel KA, Scott JR. 2008. Tropical cyclone induced upper-ocean mixing and climate: Application to equable climates. *J. Climate* **21**: 638–654.

Pfirman SL, Bauch D, Gammelsrød T. The Northern Barents Sea: water mass distribution and modification. In *The polar oceans and their role in shaping the global environment*, ed. Johannessen OM, Muench RD, Overland JE. pp 77–94. American Geophysical Union, Washington DC

Rasmussen EA. 1979. The polar low as an extratropical CISK disturbance. *Q. J. R. Meteorol. Soc.* **105**: 531–549.

Rasmussen EA, Turner, J, (eds). 2003. *Polar Lows*. Cambridge University Press, Cambridge. pp 612.

Rotunno R, Emanuel KA. 1987. An air-sea interaction theory for tropical cyclones. Part II: Evolutionary study using a nonhydrostatic axisymetric numerical model. *J. Atmos. Sci.* **44**: 542–561.

Rudels B, Jones EP, Andersson LG, Kattner G. 1994. On the intermediate depth waters of the Arctic Ocean. In *The polar oceans and their role in shaping the global environment*, ed. Johannessen OM, Muench RD, Overland JE. pp 33–46. American Geophysical Union, Washington DC

Shade LR, Emanuel KA. 1999. The ocean's effect of tropical cyclones: Results from a simple coupled atmosphere-ocean model. *J. Atmos Sci.* **56**: 642–651.

Shay LK, Goni GJ, Black PG. 2000. Effects of a warm oceanic feature on Hurricane Opal. *Mon. Wea. Rev.* **128**: 1366-1382.

Sriver RL, Huber M. 2007. Observational evidence for an ocean heat pump induced by tropical cyclones. *Nature* **447**: 577–580.

Zedler SE, Dickey TD, Doney SC, Price JF, Yu X, Mellor GL. 2002. Analyses and simulations of the upper ocean's response to Hurricane Felix at the Bermuda Testbed Mooring site: 13-23 August 1995. *J. Geophys. Res.* **107**: 1-29.

I

II

III