Intrinsic dynamics and long-term evolution of a convectively generated oceanic vortex in the Greenland Sea

Angelo Rubino,¹ Alexey Androssov,² and Sergey Dotsenko³

Received 9 May 2007; revised 3 July 2007; accepted 31 July 2007; published 28 August 2007.

1 Nonstationary dynamics, realistic long-term evolution, and influence on local convection characterizing an oceanic vortex similar to those observed in the central Greenland Sea were investigated using in situ data, a hierarchy of numerical models, and an analytical theory. A nonhydrostatic model for the simulation of convective plumes was nested into a regional ocean-ice model forced and initialized by a global, atmosphere/ocean/ice model. In the central Greenland Sea, water masses similar to those observed in a convectively-generated vortex and a corresponding numerically reconstructed 3D velocity were imposed in the non-hydrostatic model. Under atmospheric/oceanic realistic conditions and forcing, the simulated vortex evolved as an almost circular, nonstationary, long-lived, predominantly anticyclonically rotating feature. As time elapsed, it detached from the sea surface and became an intermediate vortex, which influenced the local convective preconditioning. Its inertial pulsations, shape, and velocity structure closely resemble corresponding characteristics of recently discovered theoretic nonstationary anticyclones.


1. Introduction

[2] Mesoscale as well as submesoscale vortices are abundant in the World Ocean [see, e.g., McWilliams, 1985; Olson, 1991]. In accordance to this relevancy, the study of origin, development, and decay of mesoscale as well as submesoscale oceanic surface and intermediate vortices has been the object of numerous theoretical, observational, and experimental investigations [see, e.g., Csanady, 1979; Gill, 1981; Nof, 1983; McWilliams, 1985, 1988; Hedstrom and Armi, 1988].

[3] During the last years a renewed attention has been devoted to the study of mesoscale as well as submesoscale oceanic surface and intermediate vortices [see, e.g., Lee and Niller, 1998; Rubino et al., 1998, 2002; Wadhams et al., 2002; Gascard et al., 2002; Rubino and Brandt, 2003; Wadhams et al., 2004; Budéus et al., 2004; Dotsenko and Rubino, 2006; Zhai et al., 2007]. In fact, recent investigations have demonstrated the important role they exert in the formation and transformation of water masses [see, e.g., Gascard et al., 2002; Wadhams et al., 2002; Budéus et al., 2004; Ronski and Budéus, 2005]. Moreover, they are able to profoundly influence the downward propagation of wind-generated near-inertial waves [Lee and Niller, 1998; Zhai et al., 2007].

[4] In particular, convectively generated, long-lived coherent vortices have been frequently observed in the central part of the Greenland Sea, where they seem to constitute “hot spots” for intermediate and deep water formation [Gascard et al., 2002; Wadhams et al., 2002; Budéus et al., 2004]. Their life span is supposed to be large, mostly as a result of the capacity demonstrated by eddies located in regions prone to open-ocean convection to “be recharged” by surface interactions [Budéus et al., 2004]. Using the available in situ data, their evolution in the Greenland Sea has been tentatively schematized as follows: Open ocean convective activity is considered to be responsible for their formation, preferentially in the central part of the Greenland gyre, where winter doming is strongest. As time elapses, they tend to evolve into intermediate rotating vortices, whose position and characteristics may be, at least partly, preserved. These peculiarities render thus the local recharge and hence the occurrence of similar features during the next winter season not improbable [Wadhams et al., 2004]. Their observed intrinsic dynamics seem to be characterized by several major characteristics: they rotate mostly anticyclonically and show a core area characterized by high negative vorticity, with swirl velocities linearly increasing with their radius [Budéus et al., 2004].

[5] In this paper the nonstationary structure, the intrinsic dynamics, as well as the long-term evolution of a convectively generated vortex observed in the Greenland Sea are explored, under realistic conditions, using in situ data, a hierarchy of nested numerical models and a recently developed analytical theory. As a result, we recognize the simulated features to belong to intermediate, stratified, nonstationary pulsion-like vortices of high order [see Rubino et al., 1998; Dotsenko and Rubino, 2006]. By comparing the simulated water mass squared Brunt-Väisälä frequency in the central Greenland Sea with and without assuming the presence of a convectively generated vortex in the area, the influence exerted by such rotating features on the convective activity in the central Greenland Sea is discussed.

2. Numerical Experiments and Analytical Modeling

[6] The configuration of the numerical models used in the present investigation is schematized in Figure 1: The nonhydrostatic and the regional hydrostatic model are similar to those used in previous studies [see, e.g., Romeiser et al.,
to which the reader is referred for further details about the employed numerical techniques. These models are coupled to an ice model similar to that of Hibler [1979]. The regional model, which describes the hydrodynamics of an oceanic area encompassing the Greenland Sea (see Figure 1) was initialized and forced using the results of larger scale simulations performed with the REMO/MPI-OM coupled model [Maier-Reimer, 1996], which is an atmospheric/oceanic/ice model. In particular, wind forcing consists of six-hourly data simulated by the REMO model (its horizontal resolution is 1°) adequately temporally and spatially interpolated to match the requirements of the higher resolution regional model. In the central part of the model domain, which corresponds to a mean position of the centre of the cyclonic gyre of the Greenland Sea (supposed here to be located near 75° N 0° E/W, where a model focus was implemented), a very high resolution, fully non-hydrostatic model (minimum horizontal grid step = 125 m) was nested to the regional model. The selected initial fields of the REMO/MPI-OM model were chosen to represent, realistically, a winter (January) scenario in the central Greenland Sea. In the core-area of that region (centred at 75° N 0° E/W), in correspondence with the centre of the simulated Greenland Sea cyclonic gyre, temperature and salinity values similar to those observed locally in a convectively generated vortex during April 2001 [Wadhams et al., 2002] and a corresponding simulated 3D velocity field were imposed as a part of the model solution after three months simulation time. Note that the vortex observed by Wadhams et al. [2002] and, consequently, the vortex we imposed in the central part of our model, are almost vertically homogenous in salinity. Given the imposed vortex structure, a diagnostic model run was thus used to simulate a 3D associated velocity structure. As a result, an anticyclone emerged, characterized by a high negative vorticity core, in accordance with different theories and experiments describing mesoscale and submesoscale coherent features [see, e.g., Csanady, 1979; Gill, 1981; McWilliams, 1988; Hedstrom and Armi, 1988; Rubino and Brandt, 2003; Dotsenko and Rubino, 2006]. On such a basis, the numerical model was then allowed to further evolve, under atmospheric and lateral forcing from the REMO/MPI-OM coupled model, as long as 36 months. In Figure 2 zonal vertical sections across the vortex centre depicting the distribution of potential temperature one week (Figure 2a), one month (Figure 2b), two months (Figure 2c), and three months (Figure 2d) after the insertion of the vortex in the model central area are delineated. Initially, the coldest vortex isotherm largely outcrops (Figures 2a and 2b). This stage of the vortex evolution corresponds to a possible stage of its “recharge” by surface cooling. As time elapses, the exposure of the vortex core to the atmosphere is substantially eroded (Figure 2c); but, rather than loosing its coherence, it tends to transform into a noticeably stable, intermediate vortex (Figure 2d). The results of our numerical simulations indicate that, in this stage of the vortex life, its shape does not deviate substantially from circular symmetry. Note that, in a central region within the vortex body, the shape of the isopycnals seems to be parabolic, whilst it largely deviates from parabolicity at the vortex periphery. The temporal evolution of the simulated vortex tangential velocity, normalized by a mean vortex velocity, about 20 km from the vortex centre is depicted in Figure 3a. Indepen-

Figure 1. Configuration of the numerical models used in the present investigation: (a) REMO/MPI-OM coupled model; (b) regional hydrostatic and local nonhydrostatic model.
dently on depths, the vortex is characterized by exact inertial pulsations which are in phase throughout its body. Note, however, that the amplitude of the pulsations largely varies with depth. During most of the inertial period, the vortex rotates anticyclonically at all depths, its average magnitude being largest around 1600 m depth and decreasing toward the bottom and toward the surface. Very noticeably, there are time intervals within the inertial period during which the circulation of part of the vortex periphery is reversed, as the rotation is cyclonic there (Figure 3a).

In Figure 3b, the simulated vortex tangential velocity, normalized by a mean vortex velocity, is depicted, as a function of the vortex radius, for a selected time of the inertial period, at three different depths. Independently on depth, in a central region, extending about 12 km from the vortex centre, the vortex tangential velocity can be accurately described as a linear function of the radial coordinate. Outside the core, the tangential velocity substantially deviates from linearity: It decreases toward the periphery and tends to connect to the ambient velocity field. These characteristics of the simulated vortex, which are consistent with observations [see, e.g., Budéus et al., 2004] resemble characteristics of recently discovered theoretical oceanic nonstationary, stable pulsating vortices, which

Figure 2. Zonal vertical sections across the vortex centre depicting the distribution of potential temperature (a) one week, (b) one month, (c) two months, and (d) three months after the insertion of the vortex in the model central area.

Figure 3. (a) Temporal evolution of the simulated vortex tangential velocity, normalized by a mean vortex velocity $v^* = 1.27$ cm/s, about 20 km from the vortex centre, at three different depths. (b) Simulated vortex tangential velocity, normalized by a mean vortex velocity $v^*$, as a function of the vortex radius, for a selected time of the inertial period, at three different depths. The time series ($T = 0$) begins circa 3 months after the insertion of the chimney in the central Greenland Sea.
are solutions of the nonlinear shallow water equations on an $f$-plane. Based on previous analytical theories [see, e.g., Gill, 1981; McWilliams, 1988; Rubino et al., 1998], Dotsenko and Rubino [2006] found analytical solutions describing nonstationary, nonlinear oceanic circular vortices. They are inertially pulsating, stable, circular features characterized by an arbitrary stable density distribution and by general shapes and structures of their tangential velocity. In their centre, the rotation is anticyclonic, but, at their periphery, cyclonic circulation is possible during part of an inertial cycle. In Figure 4 the shape of a stratified (seven layers) pulson of the 5th order and the structure of its tangential velocity (normalized by a mean vortex tangential velocity), obtained by considering typical stratification and density contrasts of the vortex simulated numerically, are depicted. A large similarity between analytical and numerical results can be evinced. In a central region within the vortex body, the shape of the isopycnals resembles a parabola, whilst it largely deviates from parabolicity at the vortex periphery. In such a central region the vortex tangential velocity can be accurately described as a linear function of the radial coordinate. Outside this region, however, the tangential velocity substantially deviates from linearity. Note that the similarity between numerical and analytical solutions encompasses different other properties, like, e.g., the presence of exact inertial pulsations, the vertical structure of the tangential velocity, and the coexistence of time intervals during which the vortices rotate cyclonically at its periphery. These similarities account for the robustness of pulson-like surface as well as intermediate vortices in the World Ocean [see Rubino and Brandt, 2003]. As indicated by different theoretical results [see, e.g., Lee and Niiler, 1998; Zhai et al., 2007], anticyclonic vortices are also able to induce downward near-inertial wave propagation, thus substantially contributing to drain wind-induced near-inertial energy toward the abyss. In order ascertain, at least partly, the origin of the simulated inertial oscillations and to test the capability of the simulated vortex to transport near-surface, near-inertial energy induced by the wind toward the abyss, we repeated our numerical simulations using a) a much weaker wind forcing and b) monthly averaged wind forcing. The results obtained in both simulations indicate that, indeed, a noticeably lower near-inertial energy is obtained within the vortex, when a lower wind activity is imposed and/or typical temporal scales of synoptic disturbances are neglected. This demonstrates the influence exerted by wind strength and synoptic variability in the near-inertial wave transmission to the vortex interior. Specifically, in our case, the vortex, initially located at the sea surface, tends to preserve a large part of its initial near-inertial energy while intruding at depth. In the layers located above its body, however, a complex, mostly cyclonic circulation is present, which renders the near-inertial downward wave transmission intricate.

It can be thus conjectured that characteristics of the simulated vortex, together with the specific features of the background circulation in the central Greenland Sea, be crucial for a comprehension of the longevity attributed to convectively generated vortices in the area. We performed, to this purpose, different numerical simulations characterized by the fact that the vortex was posed outside the centre of the Greenland Sea cyclonic gyre and we observed, in this case, a much faster dissipation of the vortex coherence.

In order to quantify the preconditioning exerted by the simulated vortex to open-ocean convective events, we repeated the numerical simulations described above without inserting, as a part of the oceanic stratification, the structure of the observed, convectively generated vortex in the central Greenland Sea. We analyzed the differences in the water mass squared Brunt-Väisälä frequency between the two experiments: they can be then used as a measure of the convective preconditioning induced by the simulated vortex. In particular, we compared the temporal evolution of the vertical distributions of the squared Brunt-Väisälä frequency at 75N 0E/W for the two experiments (see auxiliary material). During the first winter, the differences, which emerged, are obviously due to the insertion of the observed vortex, which represents a noticeable input of almost homogeneous water masses. Its presence, however, leaves a long-lived trace, as, almost throughout the water column, a smaller squared Brunt-Väisälä frequency was simulated in the experiment with the convective vortex during the successive winter. This trace decreased noticeably during the successive summer (which, from our model results, can be interpreted as the joint result of a shift in the position of the vortex core region and of a partial export of

---

the vortex water), but it was still evident during the successive winter and, indeed, continued throughout the whole simulation period (3 years).

3. Conclusions

A hierarchy of nested numerical models was implemented in the Greenland Sea and surroundings aimed at describing the nonstationary, convectively generated dynamics in the central Greenland Sea and the processes related to its small-scale and mesoscale manifestations by retaining a large part of the complexity inherent in the larger scale, oceanic and atmospheric variability in the area. As a result, we were able to describe, under realistic atmospheric and oceanic forcing, the intrinsic, nonstationary dynamics of a convectively generated vortex: it is demonstrated that the vortex can be accurately approximated by an intermediate pulson of high order [Dotsenko and Rubino, 2006]. This findings account for the robustness of pulson-like surface as well as intermediate vortices in the World Ocean. Such a characteristic, together with the specific features of the background circulation in the central Greenland Sea, seem to be crucial to the comprehension of the longevity attributed to convectively generated vortices in the area: A comparison between two long-term numerical experiments carried out with and without inserting the convectively generated vortex as a part of the stratification in the central Greenland Sea reveals that such vortices can contribute indeed to the destabilization of the water column, their presence being noticeable even several years after their insertion in the area. They seem moreover to contribute, even when located in the interior ocean, to drain wind-induced near-inertial energy toward the abyss.

References

Androssov, A., A. Rubino, R. Romeiser, and D. V. Sein (2005), Preconditioning to open-ocean convection in the Greenland Sea through a mesoscale chimney: simulations with a hierarchy of nested numerical models, Meteorol. Z., 14, 693–702.