# Response to referees – "Front-orography interactions during landfall of the New Year's Day Storm 1992"

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We thank both referees for their constructive and detailed criticism. We agree with most of the comments and adapted the manuscript to mitigate concerns and correct errors. Specific replies to the issues raised are below. Our replies are marked blue.

# Referee 1

**General criticism** My general criticism of the paper is that the concluding section does not link back to the introduction, and to the existing literature on the effect of orography on fronts. As a result it is impossible to see what is new in this paper and what corroborates (or contradicts) previous results (other than the null effect on the CCB wind maximum). The summary and conclusions need re-writing to place the current results in context, and should concentrate on verifiable results rather than speculation (e.g. 1.319-20, 328-32). This is a well-established area of research in meteorology. Only if the authors can show a genuine novel result should this paper be published.

We revised the introduction and conclusions to better link these sections and make the novel aspects of our study more visible. To this end, we make reference in the concluding section to three specific research questions posed in the revised introduction:

- 1. Did the landfall of the storm affect the formation of its poisonous tail?
- 2. Did the landfall affect the track of the New Year's Day Storm?
- 3. How did the landfall affect the warm and cold fronts of the New Year's Day Storm?

These questions reflect the discussions in sections 4.1-4.3 and are taken up again in the summary-andconclusions section.

Further, the present case study adds to the existing literature in two ways:

- 1. Our results indicate that the cyclone core and its warm sector might evolve into dynamically independent entities with the onset of the occlusion process. This presents in our view a genuinely novel result, as most of the literature we are aware of discuss and thus implicit consider occluded cyclones as one system.
- 2. Our results suggest that IGW activity might have played a role in eroding the fronts and communicating the orographic impact to the middle and higher troposphere. In our view that is an interesting novel perspective, as the role of IGWs in front-orography interactions has so far not been systematically assessed.

Section 3 The figures that accompany this section show fields from both NORA and WRF, but the text does not make it clear which model field is being discussed. I would have thought that the reanalysis would be closer to reality than a free-running model so the synoptic discussion should be confined to NORA, making it a little easier to follow. I'm not sure why you need all the WRF graphs as their only purpose as far as I can tell is to satisfy the reader that the WRF simulation looks sufficiently similar to the reanalysis. Section 3.4 is far too superficial to require 13 figure panels (figs 2, 3, 4).

The NORA10 data set is a set of short hindcasts without data assimilation. Technically, NORA10 is closer related to our WRF simulation than it is to a reanalysis product. More specifically, NORA10 is a blend of members within a sequence of short (<9h lead time) mesoscale model integrations initialised

and forced by ERA-40. Based on the available data and observations, it is difficult to identify which one of the two data sets is closer to reality, as both have strengths and weaknesses. We therefore prefer to keep both datasets for the discussion of the vertical wind field (Fig. 2 and Fig. 4). But, as is suggested by the reviewer, we confine the discussion Figs. 3 and 6 to NORA10 data.

Line 256-260/Unwarranted speculation The authors propose that IGWs are responsible for the effect of orography on mass transport at 500 mb. This need not be so: the mountains change the thermodynamic fields at the lower levels and therefore the height field at 500 mb. Mountain waves can only impart momentum to the flow if they break, and as they are fixed relative to the topography their effect would be to slow the winds at 500 mb. That would disturb the geostrophic balance, suggesting a flow towards low pressure, which is the opposite of that shown in fig 9b. In the absence of any evidence this paragraph is pure speculation, quite probably wrong, and should be removed.

The same unwarranted speculation continues in the first paragraph of the next section, which should either be removed or solid evidence be presented for this conjecture.

We thank the reviewer for sharing these concerns. According to the literature, IGWs can impart momentum to the flow also when they non-linearly interact with each other or the "background state" on which they propagate (e.g. Einaudi et al., 1978; Plougonven and Zhang, 2014; Fritts et al., 2016). We further agree with the physical reasoning of the reviewer that the waves would slow down the flow at 500 hPa, and thus induce flow towards the cyclone center. That is also exactly what we see along the Norwegian west coast in Fig 9b, positive values indicate flow towards lower geopotential (cf. caption of Fig. 8).

Finally, it is true that the changing thermal structure will change the geopotential structure aloft. The winds will thereafter however only change through geostrophic adjustment, which is a comparatively slow process (e.g. Blumen, 1972) and inconsistent in direction with the observed anomalous mass flux.

In response to the concerns raised by both reviewers, we revised these paragraphs into a separate subsection to accomodate the additional arguments outlined above, and in response to referee 2 (sec. 4.4, L299-327). We toned down the wording and highlight that we present a hypothesis. We removed speculations from the abstract and concluding section.

#### Typos

Thanks for pointing these out, we corrected them.

# Referee 2

**General comments** The interactions of the fronts of the famous New year's day storm from 1992 with the Norwegian orography is investigated in this paper through analysis of the NORA10 reanalysis data and three simulations with the WRF model (a control and two simulations with modified orography). The study is presented well with detailed analysis and should be of interest to readers of this journal. It would be strengthened by the results being placed more firmly in the context of those from other studies. I recommend that the authors consider my, mainly minor, comments below.

**Summary and conclusions** This section is rather brief and just summarises the results from the paper rather than placing these results in the context of other studies. Please link the results to those from the other studies discussed in the introduction.

We agree with both referees in that the introduction, results and conclusions sections need to be better linked. We revised these sections and introduce specific research questions in the introduction to which we explicitly refer in the discussion of the results and the concluding section.

We further link our findings better to the results of earlier studies, for example:

- Braun et al. (1997), Kljun et al. (2001), and Neiman et al. (2004) as contrasting case studies for cold front-orography interactions.
- Doyle and Bond (2001) as a contrasting case study of warm front-orography interactions.
- Davies (1984), Blumen and Gross (1987), and Egger (1992) as conceptual context for front-orography interactions in general.
- Einaudi et al. (1978), Plougonven and Zhang (2014), and Fritts et al. (2016) as context for the potential role of IGWs in our case study.

Most of these citations are put into context in the revised introduction, thus providing further links between the introduction, discussion and conclusion sections.

Section 2 You say how many vertical model levels there are in the NORA10 hindcast and WRF simulations but please add information about the model top and the mid-tropospheric vertical model level spacing (i.e. before interpolating to pressure levels).

Both models have the hybrid model levels with the top model level at 10 hPa, and about 35-40 hPa resolution in the middle troposphere (at a surface pressure of about 1000 hPa). We added this information to the descriptions of the model setup.

L69 I got confused by these two timescales. Initially I thought that  $UTC_{Sat}$  was the actual time whereas  $UTC_{No}$  was an adjusted time to take account of the 1.5 hr time displacement in the hindcast such that e.g. 0000  $UTC_{No}$ No would actually be 0130 UTC in the run. From the caption of Fig. 5 I worked out that both times are the actual times, but that  $UTC_{No}$  indicates the time in the lagging hindcast run. It might be easier to remove this notation but instead just note the times corresponding to the same stage of the evolution in the hindcast run where required. Relating to this point, how does the timing of the evolution in the WRF control simulation match to the satellite inferred development, is it better than that in the NORA10 hindcast? If so, do you have any idea why? The warm air seclusion is not as warm in the WRF control run as in the NORA10 hindcast, is this important?

We agree with the referee that the two different time axes can be confusing. With this comment in mind, we have come to the conclusion that it will be clearest for the reader if we only mention the differences in timing when assessing the WRF simulation.

The WRF simulation seems to lag a bit less behind the satellite imagery than the NORA10 data. Testing different initialisation times for the WRF simulation, we noted that the simulated intensity of the storm is quite sensitive to the initialisation time. It seems plausible that the sensitivity in intensity goes hand in hand with a sensitivity in timing. Further, the WRF version we used for our simulations is considerably newer than the version of HIRLAM used to create the NORA10 hindcasts. Amongst other parameterisation, in particular different representations of moist diabatic processes could lead to a more-or-less explosive development of the storm and thus timing differences.

We think the slightly warmer warm seclusion in NORA10 has no substantial influence on the frontorography interactions around the storm's warm sector, because the simulations compare well for other parts of the storm. The simulated wind speeds along the coast are in reasonable agreement with observations for both simulations. They both have their strength and weaknesses and it is thus important to have them both in one manuscript.

L127 Presumably the main reason that the absolute wind is weaker along the developing bent-back front than along the cold front is because it is in the opposite direction to the motion of the cyclone i.e. although the earth-relative winds are weak, the cyclone-relative winds would be stronger.

We agree with the argument and added it to the discussion in the manuscript.

Fig 5 What is the meaning of the blue spots in panels (a) and (c)?

Thanks for pointing those out. Those were the locations of synthetic soundings we included in an earlier revision of the manuscript. We removed them.

L187 Do you mean to refer to Fig. e,f rather than d,e? The low-level jet associated with the bent-back front is a long way from the coast in panel d.

Thanks for pointing out this odd reference. It is actually supposed to refer to Fig. 3g,h.

**L196** It would be helpful to mark the regions of descent (Fig 4f) and patchy up and down drafts (fig 4e) in the corresponding figs. Note that difference in the vertical motion dynamics referred to in the text is only really clear in panels e,f and not also at the later time shown in panels g,h.

We agree with the referee. We marked the regions with a circle, and limit our reference to Fig. 4e,f.

**L207** Move shorthand terminology for the runs to section 2.1 as the terminology is first used there (L89: "in the Ocean simulation").

Thanks for pointing this out, we adapted accordingly.

**L211** Which bit of the warm sector are you referring to when you mention the "ongoing occlusion process"? Is it the weak filament of warm air over Scandinavia in Fig 7a which isn't there in Fig 2h, so indicating a slower occlusion process in the Ocean simulation?

We refer to the rather long and thin warm sector between about 60°N and the Norwegian coast line near the warm seclusion, which seems to be exactly the feature the reviewer refers to. We added a letter mark to the map to be able to point directly to the specific location we have in mind.

L215 You say that the detected bent-back front extends further around the warm air seclusion in the Ocean simulation. Which run are you comparing with here though, the control run or that with Double orography? The extent of the bent-back front on the northern side of the seclusion is greatest in the control run (Fig 2h).

Thanks for pointing out this inconsistency! We added the comparison to the control simulation to the sentence. It now reads: "In the Double simulation, the detected bent-back front extends less far around the warm-air seclusion than in the Ocean and Control simulations, indicating a less locally confined  $\theta_e$  gradient on the northern side of the seclusion without orographic influence (Figs. 2h; 7)."

**Fig 7 caption** I think you mean "Fig 2h" as both panels show results from the WRF runs (whereas Fig 2g is for the NORA10 hindcast).

We agree and have corrected.

L244 Can you provide some extra information to help me locate where you mean by "the cold sector"?

We refer to narrow north-south oriented feature just south of the cyclone core in Figs 8a-d. We added letter marks on the map to be able to directly point to the features we have in mind.

L258 Given that air is pretty much incompressible is it really surprising that the ascent and mass transport that occurs as the flow impinges on the orography is pretty much instantaneously seen at all levels (including the weak ascent at 500 hPa)?

It seems very plausible that the forced ascent in the lowest troposphere is at least in part the dynamical origin of the signal we observe at the 500 hPa-level. However, our trajectory analysis suggest that the first parcels of near-surface air are only reaching the 500 hPa level after 9-12 hours of ascent, such that vertical mass transport is too slow to account for the vertical communication of the anomaly signal. The dipole in the mass flux appears nearly instantaneously, and extends throughout most of the troposphere. In the light of the strong wave signal seen in the vertical velocity field, it seems plausible to us that IGWs played a role in propagating the signal upwards from the lowest troposphere.

We revised this section into a separate subsection and included the arguments offered here and in response to referee 1 (sec. 4.4, L299-327). We clearly mark our interpretation as a hypothesis and reduced its prominence in the abstract and conclusions.

Fig 11 Please clarify in the text whether the maps in the right hand column are  $\theta_e$  differences (as they appear to be from comparison with the left hand column plots) or wind speed (as in Fig 10 which Fig 11 is supposed to mirror in structure).

These are  $\theta_e$  differences. We clarified the caption, stating explicitly that  $\theta_e$  differences are shown in both the section and the map.

L291 Please add some detail about how the trajectories were calculated. From Fig. 12d I think the trajectories all run to 18 UTC and are started at 0, 3 and 6 UTC. But each panel seems to have 4 sets of circle markings along the trajectories—what times are these at? The caption refers to 3 hour trajectory segments so does e.g., Fig. 12a just show the trajectories from 0 to 9 UTC? "The caption states that the trajectories are coloured by the pressure of the preceding timestep" does this mean that the colour of the first segment of the trajectories in panel a relates to the pressure of these trajectories at 0 UTC? Why are the pressures then all negative in the colour bar under panel c? Finally, why are the last set of circle markers along the trajectories red whereas the other ones seem to match the colour of the trajectory segments?

Thanks for pointing out this inconsistency between the trajectory map and height plot. The circles mark the trajectory locations at 3-hourly intervals. So you have been interpreting the Figure correctly, for panel (a) the circles mark the locations at 00, 03, 06 and 09 UTC.

You're interpreting the color of the trajectory segments correctly. The negative pressures are a typo, resulting from a struggle with the plotting library. The absolute numbers give pressure in hPa. Thanks for pointing this out!

The final circles are red rather than black just for visual distinction from the previous time step. Some trajectories (for example those close to the cyclone core) do not move much in the last of the 3-hour intervals, such that the circles would become ambiguous were they black, too. We added small circles to the trajectory height plot to make that correspondence between the panels more intuitive, and clarified the Figure caption.

### **Technical errors**

Thanks for pointing these out, we corrected them.

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# Front-orography interactions during landfall of the New Year's Day Storm 1992

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**Abstract.** Although following a common synoptic evolution for this region, the New Year's Day Storm 1992 was associated with some of the strongest winds observed along the Norwegian West Cost. The narrow wind band along its bent-back front became famous as the "poisonous tail", and paved the way towards today's sting jet terminology. This article re-examines the storm's landfall with a particular focus on the interaction with the orography.

- 5 Sensitivity analyses based on WRF simulations demonstrate that the formation and the evolution of the warm-air seclusion and its "poisonous tail" are largely independent from orography. In contrast, the warm sector of the storm is undergoing considerable orographically induced modifications. Both-While moving over the orography, both warm and cold fronts are eroded rapidly, and the. This development fits neither the cold-air-damming nor the passive-advection paradigms describing front-orography interactions. The warm sector is lifted over the orography, thereby accelerating the occlusion process. The
- 10 insensitivity of the warm-air seclusion to the orographic modifications of the warm sector raises the question to which extent these entities are still interacting after the onset of the occlusion process.

Further, we observe ubiquitous and large-amplitude internal gravity waves (IGWs) during the landfall of the warm and cold fronts, exceeding in amplitude the cross-frontal circulation. As the spatial scales of the IGW pattern and of the fronts are comparable, we speculate that wave-front interactions are plausible and might have contributed to the rapid erosion of the

15 cross-frontal temperature gradient over the orography. Further, IGWs might also provide a plausible cause for we hypothesize that IGWs contribute to the observed near-instantaneous flow deflection around the orography at 500hPa, which is well above crest height.

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#### 1 Introduction

20 The New Year's Day Storm 1992 (norw.: *Nyttårsorkanen*) was one of the most vigorous winter storms in the history of recorded storms over Norway. Its wind gusts exceeded the upper limits of measurement stations along the Norwegian West Coast. Through extrapolation, the Norwegian national weather service (MET Norway) estimated wind gusts exceeding 60 m s<sup>-1</sup> and

10-min mean wind speeds exceeding 45 m s<sup>-1</sup> at Svinøy lighthouse during the landfall (locations and orography shown in Fig.

1; Aune and Harstveit, 1992). Along the coastline from the Svinøy Lighthouse to the vicinity of Trondheim, the wind speeds are estimated to have had return periods of more than 200 years (Aune and Harstveit, 1992).

Consequently, the storm attracted the attention of the scientific community. In particular the formation of the extreme wind speeds along the bent-back front and the formation of a warm-air seclusion received attention (Grønås, 1995; Browning, 2004; Clark et al., 2005). With his study, Grønås (1995) introduced the "poisonous tail" as a widely-used metaphor to the scientific literature. The term "poisonous tail" was already used by to the Norwegian forecasting community before the work

- of Grønås (1995), who learned about it while working as a forecaster at MET Norway in the 1960s. Later, Browning (2004) and Clark et al. (2005) turned the "poisonous tail" into the "sting at the end of the tail", which has become a term popular even in the media (Schultz and Browning, 2017). In his analysis of the New Year's Day Storm, Grønås (1995) found that moist diabatic processes played a crucial role in the formation and evolution of the warm-air seclusion. We complement his analysis, investigating the role of front-orography interactions in the evolution of the storm. Specifically, we investigate the role of the
- 35 landfall on the Scandinavian coastal range (Scandes) in the formation and evolution of the warm-air seclusion, addressing the following questions:
  - 1. Did the landfall of the storm affect the formation of its poisonous tail?
  - 2. Did the landfall affect the track of the New Year's Day Storm?
  - 3. How did the landfall affect the warm and cold fronts of the New Year's Day Storm?
- 40 To shed light on these questions, we contrast WRF simulations with double the Scandinavian orography and with no Scandinavian orography.

Previous case studies on front-orography interactions often focus only on cold fronts (e.g. Braun et al., 1997; Kljun et al., 2001; Neiman et al., 2004), although a limited number also consider bent-back fronts (e.g. Steenburgh and Mass, 1996) or warm fronts (e.g. Doyle and Bond, 2001). Together, these case studies document numerous processes that can be at play

45 during front-orography interactions, for example front dissipation due to orographic flow deformation (Braun et al., 1997), the formation of barrier jets (Braun et al., 1999; Yang et al., 2017), front retardation due to blocking (Doyle and Bond, 2001; Neiman et al., 2004), as well as foehn and cyclogenesis in the lee (Kljun et al., 2001).

Due to the complexity of the front-orography interplay, only a limited number of conceptual models exist. One of the earliest efforts is presented by Bjerknes and Solberg (1921), who summarised rain observations over Scandinavia in a conceptual model

- 50 of a warm front moving over a ridge. Their conceptual model includes a pocket of trapped cold air upstream of the ridge and a warm front modified by the vertical motion up- and downstream of the ridge. Davies (1984) and Egger (1992) apply the idea of orographically blocked flow to a non-linear analytical model of cold fronts approaching a triangular ridge. In their model, the approaching cold front is entirely blocked in a certain parameter regime, for example for strong stratification. In contrast, if the flow is less stratified, the approaching front might be linearly advected by flow over the ridge (Blumen and Gross, 1987;
- 55 Blumen, 1992). Here the flow over the ridge causes a weakening of the front upstream, and a strengthening downstream. The

antipodal conceptual models of Davies (1984) and Blumen and Gross (1987) provide the framework within which we will interpret our results.

As is shown in this study, the synoptic evolution of the New Year's Day Storm during landfall, including the formation of the warm-air seclusion, closely followsthe conceptual model in Fig. 7 of Bjerknes and Solberg (1922). Two aspects make

- 60 this similarity noteworthy. First, it indicates that the storm followed a common synoptic evolution for this region. This seems surprising for such an extreme event. If the evolution followed a common pattern, why did this particular storm produce low-level winds with return periods of 200 years or more? While we do not claim to provide the ultimate answer, our analyses allow an hypothesis on what separates the New Year Day's Storm from more average intense winter storms in the region. Second, the conceptual model in Fig. 7 of Bjerknes and Solberg (1922) is only a special case of their conceptual model of
- 65 secondary cyclogenesis at the occlusion point (their Fig. 6). Hence, as Bjerknes and Solberg (1922) were well aware, the formation of a warm-air seclusion can occur also without any orographic influence. This raises the question to which extent the warm-air seclusion of the New Year's Day Storm formed due to the Scandes. Here, a sensitivity analysis allows us to draw a definitive conclusion. This study is organised as follows. A description of the underlying data sets, model simulations and analysis methods (sec. 2) is followed by a detailed synoptic discussion of the event (sec. 3). In section 4 we investigate the
- <sup>70</sup> impact of the Scandes on the storm and address the questions we raised. We close with our summary and conclusions (sec. 5).

#### 2 Data and methods

We base our analysis on 3-hourly data from the Norwegian Reanalysis Archive (NORA10; Reistad et al., 2011) as well as on sensitivity experiments using the Weather Research and Forecasting model (WRF; Skamarock et al., 2008). The horizontal resolution of the NORA10 data set varies between 10 and 11 km, with the NORA10 orography and domain boundaries indi-

75 cated in Fig. 1. In the vertical, the data is interpolated from 40 hybrid model levels to 25 pressure levels, covering the lower troposphere (1000–700hPa) with a uniform resolution of 25 hPa, and a resolution of 50 hPa above. In the course of our analyses we noted that for this explosively developing case and the time period we consider in this study, the NORA10 hindcast appears to lag behind the actual development as seen on satellite imagery by about 1-1.5 hours. We therefore refer to the respective time scales as UTC<sub>N0</sub> for the hindcast and UTC<sub>Sat</sub> for the satellite imagery where ambiguous.

#### 80 2.1 WRF control and sensitivity simulations

The WRF model setup parallels that of the NORA10 hindcasts. We use a constant horizontal resolution of 10km, but the WRF standard configuration with 60 hybrid model levels in the vertical. The In both models the uppermost grid point is at 10hPa, and the vertical resolution in the middle troposphere is about 35-40hPa. The WRF output is interpolated to the same 25 pressure levels as the NORA10 data. The domain horizontally covers an area of  $6000 \times 4000$  km, including most of the North Atlantic

and of Scandinavia. The domain fully covers the region shown in Fig. 1. The Norwegian West Coast is located centrally in the eastern half of the model domain to minimise the impact of the model boundaries.

The initial state and boundary conditions are derived from 6-hourly ECMWF operational analyses. As the operational analyses for the study period do not include sea-surface temperature, we supplement with those from ERA-Interim (Dee et al., 2011). We initialise the model on 31 December 1991 06 UTC, roughly 21, 24, and 27 hours before the landfall of the warm,

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cold, and bent-back fronts, respectively. We chose this initialisation time as a trade off between having sufficient model spin-up time and the accuracy of the simulation. We tested initialisation dates between 30 December 1991 12 UTC and 31 December 1991 UTC and find that the earlier the initialisation date, the weaker becomes the simulated New Year's Day Storm.

We use WRF version 3.8.1 in a configuration with YSU boundary layer physics, the revised MM5 scheme (based on a Monin Obukhov surface layer with Carlson-Boland viscous sublayer), and the WRF three-class single moment cloud microphysics scheme. The parameterisation of cumulus convection is enabled, using the Kain Eritsch scheme updated every 5 minutes

95 scheme. The parameterisation of cumulus convection is enabled, using the Kain-Fritsch scheme updated every 5 minutes. Radiation is calculated using the RRTM for long wave lengths, and the Dudhia scheme for short wave lengths, both updated every 10 minutes. The land surface is parameterised using a thermal diffusion model with five layers.

To test the sensitivity of the evolution of the New Year's Day Storm to the Scandinavian orography, we compare the control a simulation with full orography ("Control") to (a) a simulation in which the orography is removed and the land surface replaced

100 by ocean (<u>"Ocean</u>"), and (b) a simulation in which we double the height of the Scandes (<u>"Double</u>"). In the Ocean simulation, sea-surface temperatures over the Scandinavian peninsula are defined by iteratively minimising the local Laplacian given the observed surface temperatures in the surrounding seas (277-280K in the Atlantic and North Sea ; 275-278K in the Baltic; 273-275K in the White Sea).

#### 2.2 Front detection

- 105 For our analysis of the landfall, we require a front detection scheme to track and visualise the evolution of the fronts close to orography in the comparatively high-resolution NORA10 hindcasts and WRF simulations. There are different approaches for the automated detection of fronts, but all of them struggle to detect fronts in the vicinity of orography. Many of the difficulties arise from the need of higher derivatives to pinpoint the exact location of a front line (e.g. in Hewson, 1998; Jenkner et al., 2010; Berry et al., 2011). We therefore follow the approach of Spensberger and Sprenger (2018) and detect frontal volumes
- 110 instead of front lines. Frontal volumes are defined as coherent volumes where the local thermodynamic gradient exceeds a given threshold

$$|\nabla \tau| > K,\tag{1}$$

and that exceed a given minimum volume. With this approach, we require only a first derivative of a thermodynamic field.

Spensberger and Sprenger (2018) developed this approach to detect fronts in the ERA-Interim data set. In our comparatively high-resolution data sets, mesoscale processes can lead to locally strong thermodynamic gradients independent from a synopticscale frontal system. We are however only interested in local thermodynamic gradients associated with a synoptic-scale front, and therefore require a minimum thermodynamic gradient both at the native resolution of the input data and in a smoothed version of the thermodynamic field. With this extension, we are able to identify only those mesoscale gradients that belong to a synoptic scale system, and define only those as fronts.

- For the thermodynamic field  $\tau$ , we use equivalent potential temperature  $\theta_e$  to include both temperature and moisture gradients in the front definition [see Schemm et al. (2017) and Thomas and Schultz (2019) for a comprehensive discussion on the merits and drawbacks of  $\theta_e$  for objective front detection]. We detect frontal volumes between 700 and 950 hPa with a minimum volume of 7500km<sup>2</sup>·250hPa. Furthermore, we use a local  $|\nabla \theta_e|$ -threshold of 6.0K (100km)<sup>-1</sup> and a threshold for the smoothed field of 4.5K (100km)<sup>-1</sup>. The conclusions of this study are independent from the exact values used for these thresholds.
- To arrive at the lower-resolution data set, we smooth the  $\theta_e$  field by 30 passes of a three-point filter  $\tau_i^* = \tau_i + (\frac{1}{4}\tau_{i-1} \frac{1}{2}\tau_i + \frac{1}{4}\tau_{i+1})$  in both horizontal dimensions. Here, *i* is the grid point index and \* denotes the new value after one pass of the filter. With 30 passes, this filter largely suppresses waves shorter than 10 grid points (approx. 110 km), while waves longer than approximately 20 grid points retain more than 50% of their amplitude.

#### 3 Synoptic evolution during landfall

#### 130 3.1 Explosive deepening over the central North Atlantic

We start following the synoptic evolution at 00 UTC <sub>No</sub> on 1 January 1992, corresponding to 18 hours lead time of the WRF simulations (Fig. 2). At this point in time, the cyclone underwent an explosive deepening of approximately 40hPa during the preceding 24 hours (Grønås, 1995). Its structure is that of a mature cyclone following the Shapiro and Keyser (1990) conceptual model (Fig. 2a, b). The warm sector is bounded on the northern side by a well-developed bent-back front, and to the west by several cold front segments. On the warm front side, however, the  $\theta_e$  gradient is below the detection threshold.

At this point in time, the strongest winds occur along the cold front (Fig. 3a,b), in agreement with, for example, the lowlevel jet described in Lackmann (2002). This low-level jet ahead of the cold front transports warm moist air towards the cyclone core, providing the inflow to a warm conveyor belt, as indicated by the broad area of stratiform ascent along the bent-back and warm fronts (vertical wind in Fig. 4a,b; cloud observations in Fig. 5). Although the absolute wind speed is smaller along the developing bent-back front than along the cold front jet, stronger ageostrophic winds indicate considerable flow imbalances along the developing bent-back front (exceeding 20 m s<sup>-1</sup> in the NORA10 hindcasts<del>and 25 m s<sup>-1</sup> in the WRF control simulation;</del> Fig. 3a,b). Parts of the wind speed difference between the bent-back and cold front might be due to the cyclone's direction of propagation: the winds along the cold front are largely parallel to this direction, whereas the flow along the bent-back front is largely opposing this direction.

#### 145 3.2 Landfall of the warm sector

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At 03 UTC on 1 January 1992, the leading edge of the warm sector arrives at the Scandes (Fig. 2c, d). At 850 hPa, the warm front does not fulfil our detection criteria except for a small region close to Svinøy on the northwestern cape of the West Coast, but at 925 hPa the temperature gradient exceeds the detection threshold in a line connecting Bergen with the cyclone's bent back front (not shown). The temperature gradient tightens as the front approaches the coast line, consistent with increased  $\theta_e$ 

150 frontogenesis at 850hPa driven by flow deformation (not shown). This flow deformation is consistent with an increase in ascent long along the warm front as it approaches the Scandes (Fig. 4c, d).

The intensification of the fronts approaching the Scandes indicates some orographic blocking of the warm air mass that acts frontogenetically. The orographic flow distortion is associated with increasing ageostrophic wind components where the Scandes intersect with the 850hPa surface (Fig. 3e, db). In contrast, at 700hPa, parts of the warm sector already moved over

155 the Scandes (not shown), which reach up to a crest height of about 850-800 hPa. Both the 700 hPa  $\theta_e$  distribution and the corresponding cloud cover on the Meteosat 4 satellite imagery show hardly any orographic distortion (Fig. 5a), confirming that only levels below 850 hPa are affected by some degree of orographic blocking.

Between 03 and 06 UTC, the cold front crosses the North Sea and is at 06 UTC about to make landfall on the Norwegian West Coast (Fig. 2e, f). With the approaching cold front, the warm sector narrows to a thin filament along the coast line north of Bergen. To the south of Bergen, the Scandes are lower and the warm sector continues to propagate eastward relatively unaffected by the orography. This north-south difference in propagation speed further indicates that the warm front is partly blocked to the north of Bergen. At 850hPa and below, the core of the cyclone is already largely cut off from the warm sector (Fig. 2e, f), while at 700hPa core and warm sector remain connected (not shown).

Along the coast line between Svinøy and Trondheim (Fig. 1), both the NORA10 hindcasts and the WRF control simulation
 exhibit an area of increased wind speeds (Fig. 3e, f). In WRF this area is a homogeneous tongue of high wind speeds associated with descent at 700 hPa (Fig. 4f). In contrast, the NORA10 hindcasts show pronounced small-scale variations in the horizontal wind speed collocated with varying up- and downdrafts (Figs. 3e, 4e).

During the landfall of the cold front, between 0430 UTC sat to and 0600 UTC sat, satellite imagery shows the development of a cloud-free area on the eastern side of the Scandes (Fig. 5d). This cloud-free area indicates descending air masses and cloud

170 evaporation. There is however some indication that this descent does not reach the lowest troposphere. First, the southwesterlies in the warm sector at 850hPa are not evident in the wind field in the lee of the Scandes (Fig. 2e, f). Second, the 850hPa temperature in this region remains unchanged between 03 UTC and 06 UTC  $_{No}$  (Fig. 2c-f), suggesting that the lowest levels in the lee of the Scandes are at 06 UTC still covered by the incipient cold air mass.

Although some of the cold air moved over the Scandes after 09 UTC (Fig. 2g-j), the temperature gradient in the lee has 175 become too diffuse to qualify as a cold front following our definition. Further, the previously clear signal in the vertical wind associated with the warm front (Figs. 4c,d) disappears over the Scandes. Over and in the lee of the Scandes, the vertical wind pattern is now dominated by wave structures indicating considerable activity of orographically triggered gravity waves (IGWs; Figs. 4c-h). These waves dominate over the organised vertical wind structure associated with the frontal circulation over the Atlantic and North Sea. The larger scale structure of the horizontal wind in the warm sector is re-emerging in the lee

180 of the Scandes (compare Figs. 3<del>c,d and 3g,hb and 3d</del>), although the peak wind speed is considerably reduced and features a superposed a wavy pattern consistent with IGWs. In contrast, over southern Sweden and Denmark, the cold front could propagate eastward without encountering any orography, leaving the wind structure largely intact (Figs. 3<del>g,hd</del>).

#### 3.3 Evolution of the warm-air seclusion

So far we focused the synoptic discussion on the landfall of the cold and warm front fronts, and orographic impacts on the warm

185 sector. In the following, we shift focus towards the remaining front structure, the bent-back front, and its evolution in tandem with the warm-air seclusion.

At 09 UTC<sub>No</sub>, the warm-air seclusion is fully cut off from the warm sector at 850 hPa (Fig. 2g,h). The warm sector is located entirely on the eastern side of the Scandes, and covers the southern part of Scandinavia (Fig 2g,h). At 700 hPa, however, the warm-air seclusion is still largely connected with the warm sector, although the warm-air seclusion is now associated with a

190 separate  $\theta_e$  maximum close to the bent-back front (Fig. 6a<sub>5</sub>). At 925 hPa, the Scandes separate the warm sector to the south from the warm-seclusion to the north (Fig. 6b).

With the formation of the warm-air seclusion, the cloud cover in the cyclone core starts to change. At 0300  $\text{UTC}_{\text{Sat}}$ , the cyclone core is covered by low-level clouds, and partly even cloud-free. From 0430 UTC <sub>Sat</sub>-onward, the cyclone core is increasingly covered by spots of high-top convective clouds (Fig. 5c-e). The temporal correlation with the formation of the

195 warm-air seclusion indicates suggests that the onset of the convective activity in the cyclone core is dynamically linked with the cut-off of the seclusion from its warm sector. At 0730 UTC <sub>Sat</sub>-most of the warm-air seclusion is covered by patchy high clouds (Fig. 5e).

From 00 UTC to 09 UTC, the bent-back front continuously changes orientation. At 00 UTC the tip of the bent-back front points to the southwest, at 06 UTC to the south, and at 09 UTC to the southeast. The change of orientation is particularly pronounced between 06 UTC and 09 UTC, while the tip of the bent-back front is rapidly approaching the coast line. Between

09 UTC and 12 UTC, the bent-back front makes landfall and its orientation stops changing. Thus, the low-level jet associated with the bent-back front impinges on the coast line almost perpendicularly (Fig. 2d, e3d).

The following hours are characterised by a rapid decay of the warm-core seclusion (not shown). The weakening cyclone core crosses the Scandes between 15 and 18 UTC at around 65°N, where the Scandes are lower than further south. Together

205 with the cyclone core, parts of the warm-air seclusion cross the Scandes, but in this process the temperature gradient along the bent-back front weakens, and no longer qualifies as a front following our definition.

#### 3.4 Assessing the WRF control Control simulation

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Overall, WRF reproduces the synoptic evolution of the New Year's Day Storm well compared to the NORA10 reanalyses and the satellite imagery (Figs. 2-62, 4, 5). As indicated in the discussion of the synoptic evolution, there are however more or
less subtle differences between NORA10 and WRF. Conceptually, the most prominent difference concerns the dynamics of the flow in the lee of the Scandes, between Svinøy and Trondheim at 06 and 09 UTC (Figs. 3e-h; 4e-hblue circles in Fig. 4e,f). Here, WRF simulates a coherent region of descent which might be indicative of a foehn event, while the NORA10 hindcasts exhibit patchy up- and downdrafts indicative of convective activity. This and-

In addition, the NORA10 hindcasts seem to lag behind both the satellite imagery and the WRF simulations. For example, the landfall of the cold front makes landfall on the Norwegian west coast around 06 UTC in NORA10 (Fig. 2e), compared to

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around 0430 UTC in the satellite imagery (Fig. 5c) and around 05 UTC in the WRF simulation (not shown). These and other differences between NORA10 and WRF are however inconsequential for the following discussion of orographic effects.

#### 4 Orographic impacts

#### 4.1 Little impact on the formation of the warm-air seclusion and its poisonous tail

- In the synoptic evolution of the New Year's Day Storm in NORA10 and WRF, we observe <u>a</u> clear orographic influence on the storm. In particular, we found a separation of the cyclone core from its warm sector below 850hPa, a synoptic evolution similar to the one described in Bjerknes and Solberg (1922). However, the extent to which the formation of the warm-air seclusion was forced or accelerated by the orography remains unclear. Levels above 850hPa did not experience an orographically forced cut-off of a pocket of warm air from the warm sector but still see a warm-air seclusion. To assess the impact of orography on the storm, we performed sensitivity analyses in in the following compare simulations in which we either replaced the Scandinavian
- peninsula by ocean<del>("Ocean" simulation)</del>, or doubled the height of the Scandes<del>("Double" simulation)</del>.

These changes to the orography have surprisingly little impact on the evolution of the storm (Fig. 7). In particular, these simulations demonstrate that the warm-air seclusion would have formed even in the absence of orography (Fig. 7a). Without orography, the warm sector would have deformed to a long arched filament on 850hPa (mark A in Fig. 7a), indicating an ongoing occlusion process independent from orography. The Scandes however accelerated this deforming and separation in an

230 ongoing occlusion process independent from orography. The Scandes orographic occlusion process.

In tandem with the largely unaffected warm-air seclusion, the bent-back front shows hardly any orographic impact prior to its own landfall around 09 UTC (Fig. 7). In the Ocean Double simulation, the detected bent-back front extends further less far around the warm-air seclusion than in the Ocean and Control simulations, indicating a more less locally confined  $\theta_e$  gradient

on the northern side of the seclusion without orographic influence - (Figs. 2h; 7). The structure of the wind field around the poisonous tail however are largely unaffected by the orography (not shown), and in particular unaffected by the landfall and decay of the storm's warm sector.

This insensitivity of the wind field might indicate that the extreme winds in the storm's poisonous tail are part of a sting jet, dynamically arising from downward transport of momentum (Schultz and Browning, 2017; Clark and Gray, 2018). However,

240 in neither the NORA10 hindcasts nor our WRF simulations, there is a region of coherent descent that would indicate a sting jet (Fig. 4c-h). We therefore interpret the poisonous tail as predominantly a cold conveyor belt jet (Clark and Gray, 2018). In synthesis with the results of Grønås (1995), we suggest that the dynamics of the poisonous tail are more determined by local moist diabatic effects than the somewhat more remote orographic flow distortions.

In summary, the warm-air seclusion and its poisonous tail exhibit only weak sensitivity to the partial cut-off and rapid decay of the warm sector. This weak sensitivity suggests that the cyclone core and its warm sector hardly interact at this stage in the development. The fronts fronts framing the warm sector decay quickly when moving over the Scandes and the warm conveyor belt inflow is at least partially interrupted. Yet, the warm-air seclusion evolves largely unaffected. Consequently, it might be most appropriate to regard the seclusion and the warm sector as two dynamically independent entities as soon as the occlusion process started. The evolution of these entities would then be in sync primarily because of a joint history rather than because

250 of a persistent dynamical linkage.

> The observation of Bjerknes and Solberg (1922) that secondary cyclogenesis frequently occurs at the occlusion point corroborates our interpretation. Cyclogenetic processes in the warm section sector frequently lead to the formation of a secondary core rather than intensifying the incipient cyclone. Secondary cyclogenesis thus provides further indication that the dynamical ties between the warm sector and the incipient cyclone core tend to weaken considerably with the onset of the occlusion process.

#### 4.2 Northward displacement of the warm-air seclusion

The main impact of the Scandes on the warm-air seclusion is a slight displacement to the north in the presence of orography that goes along with higher pressure on the upstream side of the Scandes. These orographically induced differences in the pressure (and hence mass) distribution are consistent with the orographically impacted mass transports in Figure 8. Figure 8 shows the mass transport  $\sigma$  at 850 hPa perpendicular to the geopotential isolines at this level. Here,

$$\sigma = -\rho \boldsymbol{v} \cdot \frac{\nabla \phi}{|\nabla \phi|} \quad , \tag{2}$$

where  $\rho$  is density, v the horizontal wind vector and  $\phi$  geopotential.

Before landfall, mass transport towards the lower geopotential occurs primarily along the cold front (mark A) as well as a convergence line in the cold sector (mark B; Fig. 8a, b). Further, the mass transport exhibits a pronounced dipole structure around the cyclone core, which we expect mainly reflects the movement of the low pressure centre. 265

Even before the landfall of the fronts, the Scandes induce some mass transport towards lower pressure along the Norwegian west coast, peaking close to Svinøy (Fig. 8b). The mass transport peaks around 03 UTC (Fig. 8d), the time of the landfall of the warm front and the associated start of the orographic occlusion process. It is still a prominent feature of the mass transport around 06 UTC (Fig. 8f), when the orographic occlusion process completed the separation of the cyclone core from its warm sector. It is plausible that this orographically induced mass transport caused both the displacement of the cyclone core to the

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north, as well as the higher pressures along the Norwegian west coast. Interestingly, this orographic mass transport is not restricted to the height of the orography. Although it is most pronounced

below crest level, it remains visible throughout the troposphere, as for example at 500 hPa, shown in Figure 9. At this level, the orographic impact is evident in a dipole pattern centred over the Scandes in southern Norway that is consistent with a ridge evolving over the orography.

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While the appearance of this orographically induced mass transport in the middle troposphere is hardly surprising, it might be instructive to ask what process causes its appearance. The 500 hPa mass transport evolves in tandem with the one at 850 hPa without discernible delay (shown for 03 UTC, compare Figs. 8d, 9b). Whatever does communicate the orographic impact to 500 hPa must hence do so rapidly. In the light of the ubiquitous and high-amplitude IGW signatures in the vertical wind over and in the lee of the Scandes (Fig. 4), it seems plausible that IGWs are responsible for the changing mid-tropospheric flow

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pattern.

#### 4.3 Considerable impact on the warm and cold fronts

IGWs might also have impacted the evolution of the warm sector, and in particular the cold front. The cross-front temperature contrast is considerably smoother in the lee of the Scandes (Fig. 2), suggesting that the cold front largely decayed while passing

- 285 over the Scandes. Further, over and in the lee of the mountains the vertical wind does no longer show any signs of the frontal circulation (Fig. 4e-h). As the wave length of the IGWs over the Scandes is comparable to the cross-frontal length scale of the approaching cold front, interactions between the frontal circulation and IGWs seem likely. This interaction would need to be non-linear in order for IGWs to be able to alter the background state on which they propagate (e.g., review on the sources and effects of IGW
- 290 In order to investigate further, we follow the evolution of the warm and cold fronts in cross sections through the warm sector in the Ocean and Double simulations (Figs. 10, 11). Without orography, the cold sector catches up with the warm sector around 05 UTC, and an occlusion process begins (Fig. 10b). In this simulation ageostrophic winds exceeding  $15 \,\mathrm{m\,s^{-1}}$  occur solely in the boundary layer and along the eastward end of a wind maximum in the upper troposphere, around 400 km along the section in Fig. 10b.
- 295 In the Double simulation, the equivalent potential temperature and wind structure differs considerably from that in the Ocean simulation (Fig. 11). Most prominently, upstream of the Scandes a cold anomaly exceeding 8K is evident both at 03 and 05 UTC. This cold anomaly indicates the orographically retarded propagation of the warm front at 03 UTC and a leftover pocket of incipient cold air trapped below 900 hPa at 05 UTC (Fig. 11a, b), similar to the one included the conceptual model of Bjerknes and Solberg (1921). Both at 03 UTC and at 05 UTC, low-level ageostrophic winds upstream of the Scandes exceed  $35 \text{ m s}^{-1}$ .
- Throughout the shown evolution, wavy patterns in the ageostrophic wind component indicate IGW activity over the leeward 300 slopes of the Scandes (Fig. 11). Consistent with our interpretationas IGWsthis interpretation, these wavy patterns are even more pronounced in the stratosphere and there exceed amplitudes of 20K in  $\theta_e$ .

In the same region, isentropes are pulled down to follow the orographic slope over varying fractions of the troposphere (Fig. 11a-d). These simulated downdrafts are consistent with the appearing cloud-free area observed in the satellite imagery after the 305 passing of the cold front (Fig. 5). Despite these downslope winds, neither the warm nor the cold sector affect the lowest level temperatures in the lee of the Scandes. This is particularly evident at 07 UTC, when the warm sector is located in the region between 800km and 1000km along the section in the Ocean simulation (Fig. 10c). In the same region, there is a pronounced cold anomaly below crest height in Figure 11c, showing that the orographically lifted warm sector hardly descends in the lee of the Scandes. This result confirms our previous interpretation of the orographic impact on the warm sector as an orographic occlusion.

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A trajectory analysis based on the NORA10 hindcasts provides further support. Air parcels released in the North Sea upstream of the Norwegian west coast at 925 hPa in (a) the incipient cold air mass, (b) the warm sector and (c) the cold sector all are first lifted above the Scandes and then either level off or continue their ascent. Only few trajectories released in the cold sector descend the lee slopes of the Scandes. The warm sector is thus lifted off the surface in the lee of the Scandes.

- 315 Based on the demonstrated orographic impact on the warm sector, we can finally form a hypothesis on why this particular storm was associated with extreme winds despite following a relatively typical pattern (Bjerknes and Solberg, 1922). Comparing our simulations, we note that the landfall of the warm sector in the Double and Control simulations coincides almost perfectly with the onset of With the flow moving predominantly over the Scandes, our case study differs considerably from previous case studies of cold and warm fronts impinging on the North American west coast (e.g. Braun et al., 1997; Doyle and Bond, 2001; Neiman et al.
- 320 of cold fronts impinging on the Alps (e.g. Kljun et al., 2001). All these case studies document larger degrees of orographic blocking and flow deviation around the orography. Consequently, the cold-air damming paradigm of Davies (1984) and idealised model of Egger and Hoinka (1992) provide little guidance to interpret our case study.

Although the flow is largely unblocked by the Scandes, the occlusion process in the Ocean simulation. As the occlusion process is only somewhat accelerated in the Double and Control simulations, the forming warm-core seclusion could evolve

- 325 largely unaffected by orography. Further, the landfall of forced ascent over the orography interrupts the lowest part of the warm conveyor belt inflow towards the cyclone core. By cutting this link between the cyclone core (here, the bent-back front a few hours after the begin of the orographic occlusion coincides very well with the most intense stage of the cyclone, which also for the New Year's Day Storm is observed slightly after the begin of the occlusion process (more generally documented in Schultz and Vaughar From these findings, we hypothesise that it was mainly the timing of the landfall within the life cycle of the New Year's Day
- 330 Storm that made this case such an extreme event.

In summary, we followed the synoptic evolution of the New Year's Day Storm from its mature stage and through the landfall of, in sequence, the warm, cold and bent-back front. Perhaps surprisingly, we find that the formation and evolution of the warm-air seclusion, the feature that Grønås (1995) made responsible for the storms devastating effects, is largely independent from the Scandinavian coastal range (Scandes). This insensitivity is largely due to the cyclone 's inherent occlusion process.

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The Scandes did hence not induce, but only accelerate the occlusion process without considerably affecting the formation and evolution of the warm-air seclusion. Further, we find that the extreme wind speeds along the bent-back front of the storm, the poisonous tail, form as a cold conveyor belt jet and occur irrespective of orography.

With that finding, the ) and its warm sector, the orographic impact on the New Year's Day Storm becomes an ideal natural experiment to clarify the dynamical relation between the cyclone core (here, the warm-air seclusion) and its warm sector

- 340 once the occlusion process has started. While the Scandes clearly affect the warm sector by retarding and eroding the fronts that move over the orography, the evolution of the warm-air seclusion is only slightly displaced to the north, but otherwise unaffected. This insensitivity of the core to the evolution of the warm sector suggests that the cyclone core at this stage of the life cycle has become a largely independent dynamical entity, that only co-evolves rather than interacts, with its warm sector. The observed tendency for secondary cyclogenesis at the occlusion point indicates that this finding for the New Year's Day
- 345 Storm might apply more generally.

Based on these findings, we speculate that the timing of the landfall within the life cycle of the

#### 4.4 Potential role of IGWs

Finally, we can based on the presented evidence discuss potential dynamical mechanisms linking the Scandes with the induced a mass transport in the middle troposphere (Fig. 9). A most straightforward explanation would be that this signal arises through

- 350 advection with the forced ascent on the upwind side of the Scandes. However, our trajectory analysis demonstrates that none of the parcels released at 03 UTC in the warm sector or at 06 UTC in the cold sector reach 500hPa (Fig. 12d). Some parcels in the warm sector admittedly ascend to nearly 500hPa, but their ascent to 550-600hPa takes between 9 and 15 hours (Fig. 12d). This advective time scale is by far too long to explain the observed near-instantaneous adaptation of the 500hPa flow, such that vertical ascent seems an implausible explanation.
- A combination of hydrostatic and geostrophic adjustment might constitute a second potential causal chain linking the Scandes and the mid- and upper tropospheric flow. At the time of the anomalous mass flux in Figure 9, we observe a pronounced cold anomaly in the Double simulation compared to the Ocean simulation (Fig. 11a). Hydrostatic adjustment will rapidly communicate that signal upwards, lowering the geopotential in the column above. The following geostrophic adjustment is however inconsistent with the observed anomalous mass flux. First, the initial adjustment would constitute an acceleration
- 360 towards the lowered geopotential, i.e. towards the Scandes, while the anomalous mass flux is directed along the coast line. Second, the geostrophically adjusted state would constitute an anomalous cyclonic circulation around the lowered geopotential. Along the coast line, this would imply a southward mass transport, which is the opposite of what we observe in Figure 9.

This leads us to hypothesize that the IGWs might have played a role in communicating the orographic flow distortion to the upper troposphere. We observed ubiquitous and high-amplitude IGW signatures in the vertical wind over and in the lee of the

365 Scandes (Fig. 4). Through non-linear interactions, both between different waves and between a wave and the background state, IGWs can impart momentum on the background state (e.g. Einaudi et al., 1978; Plougonven and Zhang, 2014; Fritts et al., 2016), plausibly leading to a deceleration in this case of orographically induced IGWs. In our case, the cross-frontal length scale of the approaching cold front is comparable to the wave length of the IGWs over the Scandes, such that wave-background state interactions seem plausible. A IGW-induced deceleration would in turn give rise to a geostrophic adjustment process with an

370 initial acceleration towards the cyclone core, consistent with Figure 9.

Consistent with this hypothesis, IGWs might explain the rapid decay of in particular the cold front over the Scandes. The cross-front temperature contrast is considerably smoother in the lee of the Scandes (Fig. 2), and the vertical wind no longer shows any signs of the frontal circulation (Fig. 4e-h). This decay of the fronts is inconsistent with the conceptual model of Blumen and Gross (1987), in which the fronts are passively advected over an orographic obstacle to re-emerge with equal intensity in the lee.

#### 5 Summary and conclusions

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In summary, we followed the synoptic evolution of the New Year's Day Storm was crucial to make it an extreme event. The from its mature stage and through the landfall of, in sequence, the warm, cold and bent-back front. Based on our results and discussion, we now return to the questions we posed in the introduction.

- First, we find that the landfall of the warm sector coincided well with the natural onset of the storm hardly affected the formation of the warm-air seclusion and the storm's occlusion process, thereby limiting the effect of the landfall on the poisonous tail. This insensitivity is largely due to the cyclone's inherent occlusion process. The Scandes hence did not induce, but accelerate the occlusion process without considerably affecting the formation and evolution of the warm-air seclusion. Further, we find that the extreme wind speeds along the landfall of the bent-back front coincided well with the peak intensity of the storm, a few hours after the beginning the poisonous tail, formed as a cold conveyor belt jet and would have occurred irrespective of orography. This insensitivity raises the question to which extent these the warm-core seclusion and the warm sector are still interacting after the onset of the occlusion process.
  - Second, the landfall affected the track of the warm-air seclusion. The Scandes induced an anomalous mass flux along the Norwegian west coast towards the cyclone core which is most pronounced in the lowest troposphere, but extends up to the tropopause. The anomalous mass flux is consistent with the more northerly track of the storm in the presence of the orography.

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- Third, the warm and cold fronts are strongly impacted by the landfall. While there is some indication of flow deviation around the orography and thus some degree of blocking, a trajectory analysis demonstrates that the flow was primarily moving over the Scandes. In this aspect, our case study deviates considerably from previous case studies in other regions which generally document a larger degree of blocking. For the same reason, the cold-air damming concept of Davies (1984) is not applicable to our case study. Neither, however, does our case study follow the Blumen and Gross (1987) paradign of passive advection over the orography, because both the warm and cold front decay rapidly while moving over the Scandes. The rapid decay suggests interactions between the fronts and the orographically distorted flow.
- In this study, we could not clarify why the evolution of the New Year's Day Storm constitutes a common pattern for the region. For this pattern to appear, storms which approach Norway would generally need to be at a similar stage of their life cycle. A climatological quantification of typical genesis regions for these storms could clarify this and put this case studyin a climatological context.

Finally, we highlighted Besides these questions, we describe two examples where internal gravity waves (IGWs) might have played a role in affected the synoptic evolution of the storm. First, they might be responsible for have contributed to the

- 405 orographically induced mass transport in the mid-troposphere that contributed to the northward displacement of the warm-air seclusion evolves in tandem with the low-level orographic flow distortion without discernible delay. Our trajectory shows that this mass transport emerges to rapidly to be explained by vertical advection. Further, the direction of the mass flux towards the cyclone core is consistent with a slow-down of the flow due to these orographic IGWs. Second, they IGWs might have contributed to the erosion of the cold front while it they passed over the Scandes. The cross-frontal length scale is comparable
- 410 to the wave length, such that interactions are plausible. To underpin these more tentative results, and generalise them beyond the case study presented here, we would require a more systematic assessment of the role of IGWs for front-orography interactions.

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**Figure 1.** Orographic height map [m] from the NORA10 data set. The white circles show the location of some major cities and the Svinøy Lighthouse mentioned in the text.



**Figure 2.** Frontal evolution for the New Year's Day Storm at 850hPa. Equivalent potential temperature shading [K] and geopotential height contours with an interval of 50m. Detected frontal zones are marked by dark shading. The panels show the development from (top row) 00 UTC through (bottom row) 12 UTC on 1 January 1992 in 3-hour intervals. The left column is based on the NORA10 hindcasts, the right on a WRF the Control simulation.



**Figure 3.** Full wind speed  $[m s^{-1}]$  at 850 hPa in the NORA10 hindcasts on (a,b) 00 UTC, (e,db) 03 UTC, (e,fc) 06 UTC and (g,hd) 09 UTC of 1 January 1992. Barbs and pale red contours show ageostrophic wind with contours at 15, 25, and  $35 m s^{-1}$ . Dark shared regions show location of front volumes at 850 hPa as in Fig. 2. The left column is based on the NORA10 hindcasts, the right on a WRF simulation.



**Figure 4.** Pressure vertical velocity  $[Pas^{-1}]$  at 700 hPa for (a,b) 00 UTC, (c,d) 03 UTC, (e,f) 06 UTC, and (g,h) 09 UTC. Dark grey contours show geopotential at 700 hPa, with a contour interval of 50 m, respectively. Blue shaded regions indicate the location of frontal zones at 850 hPa for both columns. The left column is based on the NORA10 hindcasts, the right on <u>a WRF the Control</u> simulation. For the blue circles in (e,f) refer to the main text.



**Figure 5.** Remapped infrared imagery (10.8µm wave length, in  $Wm^{-2}sr^{-1}$ ) from Meteosat 4 covering the landfall of the New Year's Day Storm from (a) 0130 UTC <sub>Sat</sub>-through (e) 0730 UTC <sub>Sat</sub>-on 1 January 1992 in 1.5-hour intervals. These times correspond approximately to the period 03 UTC<sub>No</sub>-09 UTC<sub>No</sub>. Imagery © EUMETSAT 2016.



**Figure 6.** As Fig. 2g, <u>h</u>, but for (a,b) 700hPa and (e,db) 925hPa.



Figure 7. As Fig. 2g,h, but for (a) the Ocean simulation, and (b) the Double simulation. For the mark A, refer to the main text.



**Figure 8.** Mass transport  $[kg s^{-1} m^{-2}]$  perpendicular to geopotential isolines at 850hPa, with positive values indicating transport towards lower geopotential. The rows show the time evolution for (a,b) 00 UTC, (c,d) 03 UTC and (e,f) 06 UTC. The left column is based on a WRF simulation in which the Scandinavian orography as been removed and converted to ocean, the right column on a WRF simulation in which the Scandinavian orography is twice its original height. For the marks A, B refer to the main text.



Figure 9. As Fig. 8c,d, but for mass transport at 500 hPa.



**Figure 10.** Cross section of wind speed (shading,  $m s^{-1}$ ), equivalent potential temperature (black contours with interval 5 K, 300,K and 350 K thickened) and ageostrophic horizontal wind with contours at 15, 25 and  $35 m s^{-1}$ . The blue and red lines mark subjectively analysed cold and warm fronts, respectively. The maps in the right column show wind speed at 850hPa as well as the location of the cross section with ticks every 200 km. The rows show (a) 03 UTC, (b) 05 UTC, (c) 07 UTC, and (d) 09 UTC on 1 January 1992 for the Ocean simulation.



**Figure 11.** As Fig. 10, but showing in shading the equivalent potential temperature difference in Kelvin between the Double and the Ocean simulation in both the section and the map. Contours show equivalent potential temperature and ageostrophic wind speed as in Fig. 10, but for the Double simulation.



Figure 12. Forward trajectories released from the box 58.0-62.0°N, 1.0-4.0°E at 925 hPa at (a) 00 UTC, (b) 03 UTC and (c) 06 UTC. The trajectory segments between the circles each cover 3 hours, and they are coloured by pressure [hPa] of the *preceding* time step. The position of the parcels 9 hours after the respective release are red. The grey shading and black contours shows show  $\theta_e$  and geopotential, respectively both at 925 hPa, at the release time of the trajectories with the same contour interval and limits as in Fig. 2. The bottom panel Panel (d) shows the median pressure evolution of the above parcels. Circles indicate time steps shown in the trajectory maps (a)-(c). The respective transparent shading indicates variability between the trajectories by the 15 and 85 percentiles.