P&P Dynamics and predictability of midlatitude weather systems and their higher and lower latitude interactions.

Short descriptive sentence (not more than 40 words).

This article summarizes the substantial progress during the THORPEX decade and pressing research challenges in the analysis and physical understanding of the dynamics and predictability of midlatitude weather systems and their interaction with the tropical and polar regions.

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ABSTRACT

- An abstract with no more than 150 words.

This theme addresses all aspects of the dynamics and predictability of midlatitude weather systems including Rossby wave trains, high-pressure systems and blocking, extratropical cyclones and fronts, and also embedded mesoscale phenomena. A particular focus is on studies investigating interactions of these midlatitude systems with the (sub)tropics and polar regions, and on high-impact weather events. Also included are novel results from recent field experiments, theoretical and idealised studies, numerical modelling case studies, and ensemble and long-term evaluations of the forecasting performance for specific midlatitude weather systems. The article provides a selective overview on key research accomplishments during the last decade and highlights important open science question for the coming years – some of them requiring continued international collaboration and increased cooperation between operational weather centres and academic research institutions.

INTRODUCTION

- An introduction with no more than 300 words.

Research on the dynamics and predictability of midlatitude weather systems has been a central element of the 10-year WMO/WWRP research programme THORPEX – The Observing System Research and Predictability Experiment – from 2004 to 2014. Improved numerical models, the availability of global and high-resolution limited-area ensemble prediction system and high-quality multi-decadal reanalysis datasets, increased computational possibilities – in combination with in an increased cooperation of and knowledge transfer between operational centres and academia – led to substantial progress in the analysis, understanding, and prediction of the different categories of midlatitude weather systems and in particular high-impact events. This article summarizes some of the key achievements in this vibrant research area during the last decade and suggests a selection of unresolved research questions to be addressed by the global research community, supported by WWRP, in the near future. The article is structured into seven sub-themes, which however overlap substantially; emphasizing the challenging interactions associated with midlatitude weather systems in terms of regions (e.g., interactions with polar and tropical weather systems), scales (e.g., upscale error growth and spawning of mesoscale subsystems), and processes (e.g., interactions between dry dynamics and cloud processes). This research summary and outlook will elucidate the following aspects of this research field as particularly novel, fruitful and important:

- the potential vorticity framework as a particularly insightful theoretical backbone for the analysis of synoptic weather systems (cyclones and anticyclones) and large-scale Rossby waves and waveguides,
- the quantification of the role of diabatic processes (e.g., latent and radiative heating and cooling associated with stratiform and convective clouds), and their model representation, for the evolution and prediction of midlatitude weather systems as an outstanding challenge,
- the advent of convection-permitting numerical weather prediction models (both deterministic and ensemble systems) as a potential quantum-jump for investigating mesoscale details in weather systems and improving their prediction,
- and the combination of novel diagnostics, high-resolution modelling, and modern observational techniques, in particular during field experiment, as a promising strategy for further enhancing our understanding and predictive capability of potentially high-impact midlatitude weather systems.

SUB-THEMES

- The number of sub-themes is left to the discretion of the conveners (2 to 6 at most), but each should be not more than 1500 words.
- The proposed sub-theme structure is such that many co-authors can contribute in an efficient manner and ease the work of the conveners.

1 Tropical interactions

The movement of tropical cyclones from the tropics into the midlatitude and their development into extratropical cyclones is generally referred to as extratropical transition (ET). The state of knowledge and future challenges in this field were reviewed by Jones et al. (2003); substantial research and advancement of understanding in this area has occurred since this review. The ET process often has a negative impact on the atmospheric predictability, both of the transitioning tropical cyclone and downstream through its influence on the Rossby waveguide (Anwender et al. 2008). Case studies have been performed using potential vorticity techniques to characterize the transition and its interaction with the midlatitudes (e.g., Robcke et al., 2004; Agusti-Panareda et al., 2004; Agusti-Panareda et al., 2005; Pantillon et al., 2013a). Idealised modelling studies have been also performed (Riemer et al., 2008; Riemer and Jones 2010). The aim of these studies has typically been to characterize scenarios leading to the different outcomes of ET, i.e., strong or weak reintensification of the transitioning cyclone as an extratropical cyclone or decay of the transitioning tropical cyclone.

Recognition of the reduction in forecast skill often associated with ETs of tropical cyclones led to a component of The THORPEX Pacific Asian Regional Campaign (T-PARC) being focused on identifying important physical characteristics associated with these ETs. During T-PARC an international field program was conducted in 2008 to investigate the development, intensification, and extratropical transition of tropical cyclones in the western North Pacific Ocean (Elsberry and Harr, 2008). The predictability of the downstream impacts of ETs have been assessed in a number of studies using ensemble forecasts (Anwender et al., 2008; Harr et al., 2008; Torn and Hakim, 2009; Torn, 2010; Pantillon et al., 2013b)

The use of trajectories and moisture tagging to identify the sources of moisture for heavy precipitation events has led to the terminology “atmospheric rivers” (ARs) and “tropical moisture exports” (TMEs) entering or being more widely used in the dynamical meteorology literature. ARs are typically identified as long narrow plumes of high integrated water vapour (e.g. Special Sensor Microwave Imager (SSM/I) integrated water vapor (IWV) values of at least 2 cm that are at least 2000 km long and not more than 1000 km wide); this terminology originated the work of Newell in the 1990s (e.g., Newell et al. 1992; Zhu and Newell 1998) but there has been an increasing number of recent papers using it. The related TMEs are strong water vapour fluxes from the subtropics into the extratropics as defined by Knippertz et al. (2013). ARs are not necessarily but typically of tropical origin (and so TMEs).

Open questions:

- **What factors control the reduction of predictability associated with the extratropical transition of tropical cyclones and how can they be minimised?**
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2 Heavy precipitation events

Heavy precipitation events can have devastating impacts due to the associated flash flooding. These events have been the subject of national and international projects, recognizing the need to coordinate the work of meteorologists, hydrologists and emergency responders in this field. Of particular note within Europe are the HyMEX (Mediterranean) and MAP (Alps) projects:

HyMeX (HYdrological cycle in the Mediterranean EXperiment) aims at a better understanding and quantification of the hydrological cycle and related processes in the Mediterranean, with emphasis on high-impact weather events, inter-annual to decadal variability of the Mediterranean coupled system, and associated trends in the context of global change. This project initially began as a French initiative in 2007 but has now extended to the international community.

The Mesoscale Alpine Programme (MAP) was a major international research initiative in the Alpine region. It aimed towards better understanding and improved numerical prediction of atmospheric flow, precipitation, and hydrological processes in the Alpine region. Particular consideration was given to natural hazards such as heavy precipitation, flash flooding and wind storm events. The project culminated in a large international field campaign in the Alpine region in 1999 and a demonstration period of hydrological forecasting in 2007 (MAP D-PHASE).

The reduction of risk associated with heavy precipitation events is a multifaceted problem. Focusing on the dynamics and predictability component of the associated weather systems research has (i) examined the moisture sources of the weather systems through the development of new techniques such as ‘water-tagging’ using water vapour tracers (e.g., Sodeman et al., 2009; Winschall et al., 2012), (ii) characterized the importance of the forcing from upper-level stratospheric streamers or intrusions with high values of potential vorticity (e.g., Martius et al., 2006; Vich et al., 2012; Martius et al., 2013), (iii) explored the role of orographic forcing and enhancement (e.g., Chiao et al., 2004; Trapero et al., 2013) and (iv) more generally explored the environmental and mesoscale ‘ingredients’ necessary for heavy precipitation (e.g., Kunz and Kottmeier, 2006; Ducrocq et al., 2008). Predictability studies using ensemble forecasts are still in their infancy with Nuissier (2012) (on Mediterranean heavy prediction events) and Barrett et al. (2014) (on mesoscale precipitation bands) being notable exceptions.

Open questions:

- **What can we learn from predictability studies of heavy precipitation events given the complexity of processes causing them?**
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3 Mesoscale (sub)structures (sting jets, convective systems)

The last 10 years has seen a series of papers on a phenomenon called a ‘sting jet’ – a jet that descends from the tip of the hooked cloud head in rapidly intensifying extratropical cyclones. This jet reaches the top of the boundary layer in the dry slot of the cyclone and has been associated with strong or intensified surface winds and wind gusts in European windstorms. The terminology ‘sting jet’ came from a reanalysis of the Great October storm of 1987 by Browning (1994) in which he identified the feature from observations and called it ‘the sting at the end of the tail’, terminology similar to that used by Grønås (1995). Modelling studies of this and other cases followed (e.g., Clark et al., 2005; Parton et al., 2009; Martínez-Alvarado et al., 2010; Smart and Browning, 2014). Studies have also associated cloud banding observed in satellite imagery with sting jets (Browning 2004; Browning and Field 2004). Proposed mechanisms are the release of conditional symmetric instability and evaporative cooling (see previous papers and Gray et al. 2011) and frontolysis (Schultz and Sienkiewicz, 2013). To date identified cases in the published literature have only originated in the North Atlantic – a climatology of cases in this region has been published in Martínez-Alvarado et al. (2012). Sting jets have also been simulated in idealized baroclinic lifecycle simulations of extratropical cyclones (Baker et al., 2014).

The UK DIAMET (DIAbatic influence on Mesoscale structures in ExTratropical storms) project (2010-2015) provided some unique airbourne (with the UK BAe 146 aircraft) and ground-based observations of mesoscale structures in extratropical storms affecting the UK. Mesoscale structures observed include a sting jet (Martínez-Alvarado et al. 2014; Baker et al. 2013) and a prefrontal gravity wave (Knippertz et al. 2010); an overview of the DIAMET cases is presented in Vaughan et al. (2014).

The US BAMEX (Bow Echoes and Mesoscale Convective Vortices (MCVs) Experiment (field campaign in 2003) has provided insights into rotationally-dominated mesoscale convective systems (e.g., Smith et al., 2009).

Recent research into mesoscale convective systems (and associated vorticies and tornadic systems) in the midlatitudes has considered case studies (e.g., Browning et al., 2010; Smart et al. 2012; Clark, 2012), regional environmental climatologies (e.g., UK – Lewis and Gray, 2010 and Clark 2013; Iberia and Balearic Islands – Garcia-Herrera et al., 2005; US – Schumacher and Johnson, 2005; Finland – Punkka and Bister, 2005) and predictability (Wandishin et al., 2010; Jirak and Cotton, 2007).

- Gravity waves

Open questions:

- **Do sting jet cyclones only occur in the North Atlantic (and if so why?)**
- **What is the upscale influence (i.e. effect on synoptic-scale predictability) of midlatitude mesoscale convective systems and how does this upscale influence occur?**
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Baker, L. H. et al., 2014. Idealised simulations of sting-jet cyclones, Q. J. R. Meteorol. Soc., 140, 96-110, doi: 10.1002/qj.2131

Baker, L. H. et al., 2013. Flying through extratropical cyclone Friedhelm. Weather, 68, 9-13, doi: 10.1002/wea.2047

Browning K. A. and Field, M. 2004. Evidence from Meteosat imagery of the interaction of sting jets with the boundary layer. Met. Apps., 11, 277-289, doi: 10.1017/S1350482704001379

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Martínez-Alvarado, O. et al., 2012. Sting jets in intense winter North-Atlantic windstorms, Env. Res. Letts., 7, 024014, doi: 10.1088/1748-9326/7/2/024014
Martínez-Alvarado, O. et al., 2014. Distinguishing the cold conveyor belt and sting jet air streams in an intense extratropical cyclone, Mon. Wea. Rev., early view, doi: 10.1175/MWR-D-13-00348.1.
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4 Polar interactions

Midlatitude weather systems can potentially be influenced by the polar latitudes through disturbances to the Rossby waveguide from tropopause polar voticies or from polar mesocyclones or polar lows. Tropopause polar voticies are coherent radiatively-maintained cyclonic circulation features over the Arctic with lifetimes up to months and radii up to 800 km (Cavallo and Hakim, 2013). Polar mesocyclones are small but intense cyclones typically forming in cold air outbreaks via mixed baroclinic and convective processes, with polar lows being a more intense subset of these (Bracegirdle and Gray, 2009).

Polar lows in the North Atlantic have been found to occur preferentially in specific wintertime weather regimes (Claud et al., 2007; Mallet et al., 2013). Several studies have explored the climatology and environmental conditions favorable for polar low development (most recently Kolstad, 2011 and Noer et al., 2011). There are commonalities with extratropical cyclones in the methods used to analyse these polar weather features, in particular the use of potential vorticity diagnostics including potential vorticity inversion and surgery techniques (e.g.,Bracegirdle and Gray, 2009; Cavallo and Hakim, 2009; Nordeng and Rosting, 2011).

Recent field campaigns focusing on the influence of the polar regions on weather include the Greenland Flow Distortion experiment (GFDex) (see overview paper by Renfrew et al., 2008). GFDex was an international fieldwork and modelling-based project to investigate the role that Greenland plays in distorting atmospheric flow over and around it and its affect on local and remote weather systems and, via air-sea interaction processes, the coupled climate system.

In recognition of importance of the polar regions for weather and climate prediction, the World Weather Research Programme (WWRP) of WMO have established the Polar Prediction Project (PPP), whose mission is to “Promote cooperative international research enabling development of improved weather and environmental prediction services for the polar regions, on time scales from hours to seasonal.”

Open questions:

- **Given the relatively small size of tropopause polar vorticies and polar mesocyclones, can they perturb the Rossby wave guide enough to have an important effect on downstream predictability?**
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Bracegirdle, T. J. and S. L. Gray, 2009. The dynamics of a polar low assessed using potential vorticity inversion, Q. J. R. Meteorol. Soc., 135, 880-893, doi: 10.1002/qj.411
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5 Diabatic processes in extratropical cyclones

Diabatic processes in extratropical cyclones can modify the structure and amplitude of tropopause-level ridges and troughs. Errors in the representation of diabatic processes in extratropical cyclones, perhaps resulting from the necessity to parameterize convection and other diabatic processes in global (and most regional) weather forecast models, could thus lead to errors in forecasts. Brennan et al. (2008) advocated a PV-based interpretation in operational forecasting to identify diabatically-driven parts of the model solutions that might thus be associated with increased uncertainty. A failure to forecast Rossby wave breaking can result in so called `forecast busts'. For example, Rodwell et al. (2013) hypothesized that mis-representation of diabatic processes within mesoscale convective systems across North America leads to the most extreme forecast busts over Europe. Gray et al. (2014) diagnosed systematic error in Rossby-wave structure (ridges develop insufficient amplitude with too weak isentropic potential vorticity gradient) in medium-range model forecasts from the Met Office, ECMWF and NCEP.

One focus of research during the past 10 years has been in the use of piecewise PV inversion to attribute the development of weather systems to different potential vorticity anomalies (upper-level PV anomalies, surface potential temperature anomaly and diabatically generated PV anomalies in the lower-mid troposphere (around 700 hPa)). This technique has been applied, for example, to extratropical cyclones (Ahmadi-Givi et al., 2004), Mediterranean cyclones (Romero, 2008), tropopause polar cyclones (Cavallo and

Hakim, 2009), mesoscale snowbands (Novak et al., 2009), and the downstream effects of precipitation near surface warm fronts (Baxter et al., 2011). An alternative approach to attributing the diabatic contribution to the development of extratropical cyclones is through the use of the pressure tendency equation (Fink et al., 2012). A more recent strand of work has developed diagnostics to attribute the role of individual diabatic processes (e.g., different cloud microphysical processes and radiation) leading to the modification of potential vorticity (Joos and Wernli, 2012; Chagnon et al., 2013).

Evidence of the importance of diabatic Rossby waves as a low-level cyclonic precursor to rapid deepening extratropical cyclones has grown from idealised modelling experiments (Moore and Montgomery, 2004) through case study analysis (Moore et al., 2008; Boettcher and Wernli, 2011) to climatological analysis (Boettcher and Wernli, 2013).

Analysis of the structure of diabatically produced potential vorticity anomalies in convection-permitting simulations has demonstrated the existence of horizontally-oriented dipoles, in agreement with theory and contrary to the vertically-oriented dipoles found in coarser-resolution simulations (Chagnon and Gray, 2009).

Climatological analysis of the PV structure in extratropical cyclones has revealed regional variations in the contribution of the lower-tropospheric diabatically produced anomalies (Campa and Wernli, 2012) with stronger values in western parts of the ocean basins and in the more intense cyclones. Climatologically, the mean PV evolution in ascending warm conveyor belts has been shown to increase to almost 1 PVU at 700 hPa and then decrease to less than 0.5 PVU at 300 hPa, a significant negative PV anomaly that can influence downstream flow (Madonna et al., 2014).

Open questions:

- **What are the systematic effects of diabatic processes on the development of extratropical cyclones and downstream evolution?**
- **Are limitations in our ability to represent diabatic processes in weather and climate forecast models (given they are typically parameterized) limiting our forecasting abilities?**
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6 Rossby wave triggering, amplification, breaking and blocking

During the past 10 years much research effort has focused on the categorisation and generation of climatologies of Rossby-wave breaking and the link between Rossby-wave breaking, blocking and teleconnection patterns such as the North Atlantic Oscillation (Berrisford et al. 2007; Woollings et al. 2008; Strong and Magnusdottir 2008; Altenhoff et al. 2008; Gabriel and Peters 2008; Song et al. 2011; Ndarana and Waugh 2011)

More recent work has examined the link between Rossby waves and Rossby-wave breaking and high impact weather events. Associations have been found between long-lived Rossby wave trains and/or Rossby-wave breaking and intense European cyclones (Wirth and Eichhorn, 2014; Gomara et al., 2014), torrential rainfall and heatwaves in Japan (Enomoto et al., 2009), Southern Hemisphere cut-off lows (Ndarana and Waugh, 2010), high-impact weather in the Mediterranean and subtropical Africa (Lambert and Cammas, 2010), heavy precipitation events on the Alpine south side (Martius et al., 2008), and the extratropical transition of tropical cyclones (Pantillon et al, 2013).

Other recent work has examined the predictability of Rossby-wave breaking using ensemble forecasts and found systematic errors and underdispersive behaviour in the subtropics during PV streamer events (Wiegand and Knippertz, 2014) implying forecast busts could result in the forecasts of heavy precipitation events in the Mediterranean region and Saharan dust outbreaks.

Novel diagnostics are being developed for the identification and categorization of Rossby wave trains (Glatt and Wirth, 2014; Glatt et al. 2011).

Medium-range ensemble forecasts (from the TIGGE archive) have been shown to be capable of predicting blocking (Matsueda, 2009) and several papers have explored the ingredients required for successful numerical modelling of long-lived blocking. High resolution (Matsueda et al., 2009; Scaife et al., 2011), correct simulation of upstream troughs (Matsueda, 2011) and correct simulation of the mean state, in particular sea surface temperatures (Scaife et al., 2011), have all been shown to be important under certain conditions and in certain models. Croci-Maspoli et al. (2009) explicitly suggested that the correct representation of diabatic features might play a crucial role in the forecast of blocking. This is consistent with the association found between improved blocking frequencies in the ECMWF model over the North Pacific and Euro-Atlantic region and the introduction of a new convection scheme (Jung et al., 2010). Zappa et al. (2014) found some evidence that CMIP5 models with stronger cyclones upstream tend to have higher European blocking frequencies, again consistent with a role for diabatic processes since stronger cyclones tend to have stronger warm conveyor belts.

Open questions:

- **How does model error affect the amplification and propagation of Rossby wave trains?**
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7 Synoptic climatologies

The availability of several novel and temporally extended reanalysis data sets (e.g., ERA-Interim (Dee et al. 2009), MERRA (Rienecker et al. 2011), 20CR reanalyis (Compo et al. 2011)) has been very useful for compiling a large number of synoptic climatologies for a diversity of atmospheric flow features on the global and regional scale. Classical approaches (e.g., composites) and new technical approaches have been developed and applied. Only a few of them are mentioned here as important examples.

Several global climatologies of extratropical cyclones were produced during the last decade (e.g., Hoskins and Hodges 2002; Jung et al. 2006; Trigo 2006; Wernli and Schwierz 2006; Inatsu 2009; Hewson and Titley 2010; Hodges et al. 2011), using different cyclone identification and tracking algorithms. Raible et al. (2008) compared three of these techniques and found that for trend analyses, results are sensitive to both the choice of the detection and tracking scheme and the reanalysis dataset. This was an important motivation for starting a major cyclone tracking intercomparison project, which identified the robust and more sensitive aspects of cyclone climatologies produced with different algorithms (Neu et al. 2012). Some of these techniques have also been applied to investigate the occurrence of cyclones in simulations of the present and future climate (e.g., Lionello et al. 2002; Löptien et al. 2008; Bengtsson et al. 2009; Raible et al. 2010; Ulbrich et al. 2012).

Other climatological cyclone studies looked in more detail at specific characteristics or categories of extratropical cylcones, e.g., dynamical forcing mechanisms (Gray and Dacre 2006), extreme North Atlantic cyclones (Pinto et al. 2009), explosive cyclones (Allen et al. 2010), the vertical PV structure of cyclones (Campa and Wernli 2012), and the specific category of diabatic Rossby waves (Boettcher and Wernli 2013).

Other novel synoptic climatologies focused on surface fronts (Berry et al. 2011; Simmonds et al. 2012), atmospheric blockings (Pelly and Hoskins 2003; Croci-Maspoli et al. 2007), jet streams (Koch et al. 2006; Schiemann et al. 2009; Limbach et al. 2012; Manney et al. 2014), Rossby wave breakings (Peters and Waugh 2003; Waugh and Funatsu 2003; Wernli and Sprenger 2007; Martius et al. 2007), and in processes leading to heavy precipitation events (e.g., Reale and Lionello 2013; Lavers and Villarini 2013; Viale and Garreaud 2014; Collins et al. 2014; Winschall et al. 2014). It is important to note that a broad range of methodological concepts have been used in these studies, including the shape of contours, potential vorticity anomalies, and region growing algorithms for 4-dimensional feature detection – illustrating that progress in this area is also related to methodological innovation.

Open questions:

- **How skilful is the representation of extreme events by reanalysis datasets?**
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CONCLUSION

- A conclusion with no more than 300 words.

Emphasize

- progress in understanding and level of detail of investigation
- new possibilities due to high-quality reanalysis datasets, high-resolution models, ensemble systems (TIGGE, …)
- fruitful synergies between different research themes (give examples)
- increasing consideration of interactions between dynamics and physics, but for understanding of weather systems and improved prediction
- more emphasis on feature-based / dynamically motivated analysis of weather systems and model errors
- need for field experiments
- interactions between the historically separate fields of ‘weather’ and ‘climate’ due to the common use of reanalysis datasets, the capability to run climate integrations at weather forecast resolutions (grid lengths ~10 km) and the focus on the diagnosis of model error (particularly in seamless model prediction systems such as the Met Office Unified Model).
- interactions across space and time scales (e.g. upscale influence of deep convection on synoptic-scale predictability and downscale control of synoptic-scale on convection) facilitated by the capability to run synoptic-scale convection-permitting model simulations.
- key open questions in this research field
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Acknowledgements

References

Tables and Figures