JAVIER AMEZCUA - *University of Reading, UK*

Properties of ensemble smoothers in the linear-Gaussian case under different types of model error

J. Amezcua and P.J. Van Leeuwen

We determine the statistical properties of families of weak-constraint 4DVar's and 4DVarBen's (using sample background covariances). In the linear case, we distinguish the contributions from sampling error, linear in-breeding and nonlinear in-breeding error. The non-linear case is more complicated.

ALI AYDOGDU - *NERSC, Norway*

Observing system simulation experiments in the Marmara See

A high resolution ocean circulation model and an ensemble data assimilation tool are coupled in the Turkish Straits System. The OSSE methodology is used to assess the possible impact of a ferrybox network in the eastern Marmara Sea. A reference experiment without assimilation is performed. Then, synthetic temperature and salinity observations are assimilated along the track of the ferries in the second experiment. The results suggest that a ferrybox network in the Marmara Sea may improve the analysis significantly. The salinity and temperature errors get smaller in the upper layer of the water column.

The impact of the assimilation is negligible in the lower layer due to the strong stratification. The circulation in the Marmara Sea, particularly the Bosphorus outflow, helps to propagate the error reduction towards the western basin where no assimilation is performed. Overall, the proposed ferrybox network can be a good start to design an optimal sustained marine observing network in the Marmara Sea for assimilation purposes.

DEEP SANKAR BANERJEE - *ESSO-Indian National Centre for Ocean Information Services (INCOIS), India*

Observational error plays an important role in data assimilation as it directly influences the innovation term and thereafter the analysis. It consists of two elements (1) instrument error, and (2) Representation error. Usually the mean and variability of observational error is determined largely by representation error especially when assimilating in-situ temperature and salinity observations in ocean data assimilation systems. Representation error is linked closely to spatial (horizontal and vertical) resolution of the model. The main significance of this quantity lies in the fact that it is generated due to the variability of the observed field at scales smaller than those resolved by the assimilating dynamical model. In practice, observational errors are indirectly estimated from vertical gradients in the observed in-situ temperature and salinity profiles. Clearly, such methods suffer from the sparseness of observations in regions with significant horizontal variability. In the present work we estimated observational errors in the Indian Ocean domain directly from high resolution model simulations on a coarser grid.

These model based estimates of observation errors are validated against observation based estimates. We find that observational errors display significant spatial and temporal variability. Incorporation of these model based estimates of observational errors in a regional ocean data assimilation system, LETKF-ROMS, improves ocean analysis considerably.

NIKOLAY BARANOV – *Dorodnicyn Computing Centre, Federal Research Centre "Computer Science and Control" of Russian Academy of Science, Russia*

Space-temporal blending estrapolation of remote sensing temperature data for nowcasting

N.A. Baranov[1]

[1] *Dorodnicyn Computing Centre, Federal Research Centre "Computer Science and Control" of Russian Academy of Science*

Nowcasting of hazardous weather phenomena has a significant impact on the safety and cost-effectiveness of air transport. In turn, the formation of weather phenomena is determined in large part by the dynamics of the atmosphere surface layer temperature. However, the information provided by numerical models is not always sufficient because of their low resolution in the surface layer.

At present, the instruments for remote measurement of the temperature profile up to heights of 1-2 km, using the technology of microwave sounding, are effectively developing. Existing technologies provide a high-frequency flow of temperature profile data with high spatial resolution.

However, the nowcasting requires, on the one hand, the temporal extrapolation of the observational data for a period up to 4-6 hours, and on the other hand, an extension of the altitude range.

In the presented report, an approach to spatial-temporal extrapolation of observational data based on blending technology with numerical modeling results is described. Blending is applied to estimates of the space-time gradients of the measured temperature profile and their calculated predicted values. After this the current measured temperature profile is extrapolated in "height-time" coordinates.

The weight coefficients of blending are corrected by minimizing the extrapolation errors of the temperature profile in the nodes of the altitude mesh for a certain time interval in comparison to the observations data.

The described approach was being used in the processing of observational data using the temperature profiler MTP-5, performed in collaboration with IANS and ATTEX. Data of aerological sounding and aircraft measurements were used to estimate the quality of extrapolation from height.

The described technology can be effectively used to forecasting of fogs, icing, the types of precipitation, in particular, freezing rains, identification of weather phenomena in radar.

The work was partially supported by the Russian Foundation for Basic Research (project No. 16-07-01072).

ROBERTO BENZI - *Dip Physics Univ. Roma "Tor Vergata", Italy*

From Navier-Stokes equation to earthquakes

Many materials around us respond elastically to small applied stresses, but flow once a threshold stress (the yield stress) is exceeded. This is the case for food products, powders, cosmetics, foams, etc… It turns out that understanding the yield stress transition in these materials, often called soft glasses, is a challenging question. Similar to structural glasses, soft glasses exhibit aging and complex dynamics. Also, the size of the elementary building block of a soft glass is usually ranging from 1 micron to 1mm, ruling out the possibility to investigate the problem by molecular dynamics.

Recently, a new approach has been proposed: using a mesoscopic formulation of the system, the dynamics of relative simple soft glasses, like foams or micro emulsions, has been investigated. Numerical simulations allow the computation of several important properties of the systems, such as the yield stress transition. In this talk, I will review the new approach and explain how the complexity of soft glass dynamics may be disentangled in a systematic way.

Last but not least, I will show that if the material is slimulated below yield stress, plastic events occur, which have strong similarities to seismic events. Based on a suitable definition of displacement in the continuum, I show that the plastic events obey a Gutenberg-Richter law with exponents similar to those for real earthquakes.

MARC BOCQUET - *École des Ponts ParisTech, France*

On the convergence of (ensemble) Kalman filters and smoothers onto the unstable subspace

M. Bocquet[1], A. Carrassi[2], K. S. Gurumoorthy[3], A. Apte[3], C. Grudzien[2], and C. K. R. T. Jones[4]

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The characteristics of the model dynamics are critical in the performance of (ensemble) Kalman filters. In particular, as emphasized in the seminal work of Anna Trevisan and co-authors, the error covariance matrix is asymptotically supported by the unstable and neutral subspace only, i.e., it is spanned by the backward Lyapunov vectors with non-negative exponents. This behavior is at the heart of algorithms known as Assimilation in the Unstable Subspace (AUS), although its formal proof was still missing. This convergence property, its analytic proof, meaning and implications for the design of efficient reduced-order data assimilation algorithms are the topics of this talk.

Firstly, we provide the analytic proof of the convergence on the unstable and neutral subspace in the linear dynamics and linear observation operator case, along with rigorous results giving the rate of such convergence. Numerical results are also shown to illustrate and support the mathematical claims.

Secondly, we discuss how this neat picture is modified when the dynamics become nonlinear and chaotic and when it is not possible to derive analytic formulas. An ensemble Kalman filter (EnKF) is used in this case. We also explain why, in the perfect model setting, the iterative ensemble Kalman smoother (IEnKS), as an efficient filtering and smoothing technique, has an error covariance matrix whose projection is more focused on the unstable-neutral subspace than that of the EnKF. We conclude that the (deterministic) EnKF and IEnKS are, in practice and in the regime where they successfully track the truth, natural implementations of the AUS paradigm.

References:

M. Bocquet, K. S. Gurumoorthy, A. Apte, A. Carrassi, C. Grudzien, and C. K. R. T. Jones. Degenerate Kalman filter error covariances and their convergence onto the unstable subspace. SIAM/ASA J. Uncertainty Quantification, 5:304-333, 2017.

M. Bocquet and A. Carrassi. Four-dimensional ensemble variational data assimilation and the unstable subspace, Tellus A, 69:1304504, 2017.

MARC BOCQUET - *École des Ponts ParisTech, France*

Four-dimensional ensemble variational data assimilation and the unstable subspace

M. Bocquet[1] **and A. Carrassi**[2]

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The performance of (ensemble) Kalman filters used for data assimilation in the geosciences critically depends on the dynamical properties of the evolution model. A key aspect is that the error covariance matrix is asymptotically supported by the unstable–neutral subspace only, i.e. it is spanned by the backward Lyapunov vectors with non-negative exponents. The analytic proof of such a property for the Kalman filter error covariance has been recently given, and in particular that of its confinement to the unstable–neutral subspace. In this paper, we first generalize those results to the case of the Kalman smoother in a linear, Gaussian and perfect model scenario. We also provide square-root formulae for the filter and smoother that make the connection with ensemble formulations of the Kalman filter and smoother, where the span of the error covariance is described in terms of the ensemble deviations from the mean. We then discuss how this neat picture is modified when the dynamics are nonlinear and chaotic, and for which analytic results are precluded or difficult to obtain. A numerical investigation is carried out to study the approximate confinement of the anomalies for both a deterministic ensemble Kalman filter (EnKF) and a four-dimensional ensemble variational method, the iterative ensemble Kalman smoother (IEnKS), in a perfect model scenario. The confinement is characterized using geometrical angles that determine the relative position of the anomalies with respect to the unstable–neutral subspace. The alignment of the anomalies and of the unstable–neutral subspace is more pronounced when observation precision or frequency, as well as the data assimilation window length for the IEnKS, are increased. These results also suggest that the IEnKS and the deterministic EnKF realize in practice (albeit implicitly) the paradigm behind the approach of Anna Trevisan and co-authors known as the assimilation in the unstable subspace.

References:

M. Bocquet, K. S. Gurumoorthy, A. Apte, A. Carrassi, C. Grudzien, and C. K. R. T. Jones. Degenerate Kalman filter error covariances and their convergence onto the unstable subspace. SIAM/ASA J. Uncertainty Quantification, 5:304-333, 2017.

M. Bocquet and A. Carrassi. Four-dimensional ensemble variational data assimilation and the unstable subspace, Tellus A, 69:1304504, 2017.

MASSIMO BONAVITA – *ECMWF, UK*

Advancing Data Assimilation in Global NWP: the ECMWF Perspective

The recent evolution of data assimilation systems in global NWP has been characterised by the increasing convergence and combination of Variational and Ensemble DA methods. This trend has been spurred by the desire to overcome their respective limitations; by current and foreseeable developments in supercomputer architectures; and by a broader appreciation of the fundamentally probabilistic nature of the estimation and forecasting problem. In this talk we describe the ECMWF experience in combining the two approaches and we discuss some of the DA challenges ahead in light of the ambitious goals set in the ECMWF 2016-2025 Strategy.

ROBERTO BUIZZA – *ECMWF, UK*

How far ahead can we provide skillful forecast?

How far ahead can we provide skilful forecasts? More precisely, if we consider phenomena with increasingly coarser scales (both spatially and temporally), how far ahead can we predict them? These questions are addressed by looking at the forecast skill horizon of ensemble-based, probabilistic forecasts. Results based on one year of forecasts indicate that the forecast skill horizon for instantaneous, grid-point fields is between 16–23 days, while it is considerably longer for time- and spatial-average fields. Forecast skill horizons longer than the two weeks thought to be possible up to twenty years ago, are now achievable thanks to major advances in numerical weather prediction. Skill extension beyond two weeks has been achieved by contrasting error propagation from the smaller to the larger scales, with the propagation of predictable signals from the larger to the smaller scales. In other words, the butterfly effect has been tamed!

These aspects of predictability, and how ECMWF plans to further exploit them in the future to further extend the forecast skill horizon, will be discussed in this talk.

ANDREA BUZZI - *Istituto di Scienze dell'Atmosfera e del Clima, CNR-ISAC, Bologna, Italy*

Dynamics of upper-level atmospheric frontogenesis: a brief review

Frontogenesis and frontal dynamics is a classical problem investigated in Meteorology, since the Norwegian School basic contributions in the early XX century. Upper level frontogenesis, that is frontogenesis in the middle and upper troposphere, became an important subject mainly in the second half of the century. This happened after observations from radiosondes, instrumented aircraft and, later, satellites indicated strict connections between upper-level fronts and other atmospheric phenomena as jet streaks, clear air turbulence, descent of stratospheric air into the troposphere (associated with the formation of positive anomalies of potential vorticity and ozone), and cyclogenesis.

Since the early studies, it became clear that the dynamical mechanisms of upper-level frontogenesis were different from those associated with frontogenesis near the surface. In particular, evidence of fundamental differences in the Sawyer-Eliassen cross-frontal circulation associated with frontogenesis in the upper and lower troposphere posed interesting and long-lasting interpretation problems.

Anna Trevisan gave very important contributions to our understanding of the above problem in the late 70s, early 80s, working in Bologna and at NCAR (with Chester Newton). I shall try to outline Anna's and her collaborators' findings, in the context of research on the upper frontogenesis topic, particularly for what concerns the definition and application of the so-called "frontogenetical function".

Although it is my impression that a full understanding of complexities of upper-level frontogenesis has not been gained yet, a few contributions on this subject appeared in the literature in the last twenty years. However, one of these (1), that I considered misleading (for the reasons I'll try to explain), prompted me to write a comment (2), in which I indicate that Anna Trevisan and Chester Newton, already in the early 80s, had clearly stated the distinction and meaning of the 2-D and 3-D frontogenetical function.

References:

Mak, M., Y. Lu, and Y. Deng, 2016: Dynamics of upper-level frontogenesis in baroclinic waves. J. Atmos. Sci., 73, 2699–2714.

Buzzi, A, 2017: Comments on ‘‘Dynamics of Upper-Level Frontogenesis in Baroclinic Waves’’. J. Atmos. Sci., 74,309–312.

ALBERTO CARRASSI – *NERSC, Norway*

Probabilistic forecast using a Lagrangian sea-ice model: application for search and rescue operations

We will present a sensitivity analysis of a novel sea ice model. *neXtSIM* is a continuous Lagrangian numerical model that uses an elasto-brittle rheology to simulate the ice response to external forces. The response of the model is evaluated in terms of simulated ice drift distances from its initial position and from the mean position of the ensemble. The simulated ice drift is decomposed into advective and diffusive parts that are characterized separately both spatially and temporally and compared to what is obtained with a *free-drift* model, i.e. when the ice rheology does not play any role. Overall the large-scale response of *neXtSIM* is correlated to the ice thickness and the wind velocity fields while the *free-drift* model response is mostly correlated to the wind velocity pattern only. The seasonal variability of the model sensitivity shows the role of the ice compactness and rheology at both local and Arctic scales. Indeed, the ice drift simulated by *neXtSIM* in summer is close to the *free-drift* model, while the more compact and solid ice pack is showing a significantly different mechanical and drift behavior in winter. In contrast of the *free-drift* model, *neXtSIM* reproduces the sea ice Lagrangian diffusion regimes as found from observed trajectories. The forecast capability of *neXtSIM* is also evaluated using a large set of real buoy's trajectories. We found that *neXtSIM* performs better in simulating sea ice drift, both in terms of forecast error and as a tool to assist search-and-rescue operations.
Adaptive meshes, as the one used in *neXtSIM,* represents a challenge in developing compatible data assimilation schemes, as the dimension of the state space we wish to estimate can change over time when these remeshings occur. We highlight the challenges that such a modeling framework represents for data assimilation setup.

References:

M. Rabatel, P. Rampal, A. Carrassi, L. Bertino and C. K. R. T. Jones. Probabilist forecast using a Lagrangian sea-ice model: application for search and rescue operations. *The Cryosphere - Submitted*.

ALBERTO CARRASSI – *NERSC, Norway*

Estimating model evidence using data assimiation: the model selection and the attribution problem

In recent years, there has been a growing interest in applying data assimilation (DA) methods, originally designed for state estimation, to the model selection problem. Along these lines, Carrassi et al. (2017) introduced the contextual formulation of model evidence (CME) and showed that CME can be efficiently computed using a hierarchy of ensemble-based DA procedures. Although Carrassi et al. (2017) analyzed the DA methods most commonly used for operational atmospheric and oceanic prediction worldwide, they did not study these methods in conjunction with localization to a specific domain. Yet any application of ensemble DA methods to realistic geophysical models requires the study of such localization. The present study extends the theory for estimating CME to ensemble DA methods with domain localization. The domain- localized CME (DL-CME) developed herein is tested for model selection with two models: (i) the Lorenz 40-variable mid-latitude atmospheric dynamics model (L95); and (ii) the simplified global atmospheric SPEEDY model. The CME is compared to the root-mean-square-error (RMSE) as a metric for model selection. The experiments show that CME improves systematically over the RMSE, and that such an improved skill is further enhanced by applying localization in the estimate of the CME, using the DL-CME. The potential use and range of applications of the CME and DL-CME as a model selection metric are also discussed.

References:

Carrassi, A., M. Bocquet, A. Hannart and M. Ghil, 2017: Estimating model evidence uising data assimilation. *Q. J. R. Meteorol. Soc.,* 143, 866-880

Metref, S., A. Hannart, J. Ruiz, M. Bocquet, A. Carrassi, and M. Ghil, 2017: Estimating model evidence uising ensemble-based data assimilation with localisation – The model selection problem. *Q. J. R. Meteorol. Soc.*, Submitted

ALBERTO CARRASSI – *NERSC, Norway*

Data assimilation on non-conservative adaptive grids

Guider, C.[1], **A. Aydogdu, A. Carrassi and C.K.R.T. Jones**

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Adaptive mesh methods are used to model a wide variety of physical phenomena. Some of these models, in particular those of sea ice movement, are particularly interesting in that they use a remeshing process to remove and insert mesh points at various points in their evolution. This presents a challenge in developing compatible data assimilation schemes, as the dimension of the state space we wish to estimate can change over time when these remeshings occur. In this work, we first describe a remeshing scheme for an adaptive mesh in one dimension. We then develop advanced data assimilation methods that are appropriate for such a moving and remeshed grid. We hope to extend these techniques to two-dimensional models, like the Lagrangian sea ice model neXtSIM [Rabatel *et al.*, 2017].

References:

Rabatel, M., P. Rampal, A. Carrassi, L. Bertino and C.K.R.T. Jones, 2017. Probablisitc forecast using a Lagrangian sea ice model: application for search and rescue operations. The Cryosphere Discuss, https://doi.org/10.5194/tc-2017-200, in review, 2017.

DIEGO SAÚL CARRIÓ CARRIÓ - *Universitiy of Balearic Islands, Spain*

Storm-scale data assimilation using enkf: impact of conventional and radar data on the prediction of heavy precipitations during hymex iop13.

The Special Observation Period 1 (SOP1) was a great milestone reached by the HyMeX scientific community. Observations sampling on 20 cases of severe weather were taken under an unprecedented international collaboration. The underlying objective of this campaign was to improve the knowledge of the mechanisms leading to heavy precipitation and flash flooding in the Mediterranean.

IOP 13 occurred between 15-16 October 2012 and was characterized by heavy precipitation over northern and central Italy. Storms formed over the French coastlands and over the sea, progressing eastwards across the Gulf of Genoa. The most affected areas were north-eastern Italy (160mm/24h), Liguria- Tuscany (120mm/24h) and central Italy (600mm/24h). The prediction of these maritime convection driven cases is highly demanding for both operational offices and high resolution numerical models. Ensemble data assimilation methods provide the tools to combine observational and modeling information to formalize the problem of optimal use and transference of information in the initialization and integration of a forecasting system.

We assess the benefits offered by a high-resolution (2.5 km) Ensemble Kalman Filter (EnKF) system for the prediction of the IOP13 event. We evaluate the impact of various in-situ observations such as buoys, aircrafts, metar or rawins, together with the inclusion of reflectivity data from Doppler radars. We discuss the performance of the EnKF system producing new analyses through statistical scores (RMSI, spread, BIAS sawtooth plots and consistency ratio plots). Then, we quantitatively verify the quality of the short-range forecast using statistical verification methods, such as ROC curves (or AUC; area under ROC curves) or Brier Skill scores. We discuss not only on the forecasts products but also in terms of the relevant physical mechanisms involved in this event.

PAOLA CESSI - *Scripps Institution of Oceanography – UCSD, USA*

Topographic Enhancement of Eddy Efficiency in Baroclinic Equilibration

The processes that determine the depth of the Southern Ocean thermocline are considered. In existing conceptual frameworks the thermocline depth is determined by a competition between mean and eddy heat transport, with a contribution from the interaction with the stratification in the enclosed portion of the ocean. Using numerical simulations, we examine the equilibration of an idealized circumpolar current with and without topography. We find that eddies are much more efficient when topography is present, leading to a shallower thermocline than in the flat case. A simple quasigeostrophic analytical model shows that the topographically induced standing wave increases the effective eddy diffusivity by increasing the local buoyancy gradients and lengthening the buoyancy contours across which the eddies transport heat.

In addition to this local heat flux intensification, transient eddy heat fluxes are suppressed away from the topography, especially upstream, indicating that localized topography leads to local (absolute) baroclinic instability, and its subsequent finite amplitude equilibration, which extracts available potential energy very efficiently from the time mean flow.

TSE – CHUNG CHEN - *University of Maryland, USA*

A proactive QG to improve the quality of analyses and forecasts: impact of Anna's insight

Massive amounts of observations are being assimilated every day into modern Numerical Weather Prediction (NWP) systems. This makes difficult to estimate the impact of a new observing system with Observing System Experiments (OSEs) because there is already so much information provided by existing observations. In addition, the large volume of data also prevents monitoring the impact of each assimilated observation with OSEs.

We demonstrate in this study how effectively the use of Ensemble Forecast Sensitivity to Observations (EFSO) can help to monitor and improve the impact of observations on the analyses and forecasts in Hybrid GSI/LETKF system. In addition, we show how EFSO can identify flow dependent detrimental observations from overall beneficial observing systems. Especially in MODIS polar winds, a flow dependent detrimental condition is discovered using EFSO. Furthermore, we show how to identify and reject these detrimental observations within each observing system using EFSO, which has been termed as Proactive Quality Control (PQC). The withdrawal of these detrimental observations leads to improved analyses and subsequent 5-day forecasts, which also serves as a verification of EFSO.

Finally, we display the feasibility of PQC towards operational implementation and provide a theoretical justification of the PQC and its connection to dynamical instability characteristics with a simple Lorenz 96 model. The potential of using EFSO and PQC to efficiently improve both observations and analyses is clearly shown in this study.

ANNALISA CHERCHI - *CMCC/INGV, Italy*

The South Asian monsoon and the Mediterranean summer: Extreme years and onset

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The Mediterranean sector is characterized by dry summers with descending motion, typical northerly winds at the surface and mostly westerlies in the mid-troposphere. In the summer the subsidence over the Mediterranean has been related to the tropical monsoon southeastward (i.e. the South Asian) through the monsoon-desert mechanism by linear models theory and then verified both in atmospheric re-analyses and in CMIP5 historical simulations.

Following from this it is expected that year-to-year variations in monsoon intensity (i.e. severe strong or weak monsoon years exceeding 15% of summer mean climatology) may affect abnormal summer seasonal climate variations over the Euro-Mediterranean region. Compositing rainfall and SST for unusual wet summers over the Mediterranean region provide indication of weaker than normal precipitation over the South Asian monsoon region but also of an equatorial Pacific Ocean wetter and colder than normal. In 2014 Italy and the surrounding Mediterranean countries experienced an unusual wet summer: analysis of data and available coupled model experiments suggested that the anomalously high precipitation was associated with positive sea surface temperature and convective anomalies in the tropical Pacific through atmospheric teleconnection. An anomalous cyclonic circulation occurred in Southern Europe weakening the seasonal high and causing heavy precipitation.

In the monsoon-desert mechanism the starting forcing from the monsoon precipitation is largely modulated by the monsoon onset that could be dynamically related with the beginning of the summer season over the Euro-Mediterranean region. A preliminary identification of the beginning of the summer season in the Euro-Mediterranean sector by means of the seasonal transition of the vertical velocity at 500 hPa reveals that it follows the onset of the summer monsoon over India by 10-15 days. This is in agreement with the dynamics and propagation of the Rossby waves. A detailed investigation of these dynamical aspects in the 20th century climate combining observations/re-analyses and general circulation models could reveal interesting and useful signatures for the predictability of the summer in the Mediterranean and Europe.

ALESSANDRO COMUNIAN – *University of Milan, Italy*

Improving estimates of evaporation with the "Bowen ratio" method

Alessandro COMUNIAN[a], Mauro GIUDICI[a,b], Luca LANDONI[c], Sergio PUGNAGHI[d]

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The application of the Bowen ratio method to estimate evaporation is heavily affected by uncertainties on the measured quantities. Standard techniques of error propagation can be used to reject, from a time series of hydro-meteorological variables, the measurements collected at time steps for which a reliable estimate of evaporation cannot be computed. However, simply discarding some values might introduce a bias in the cumulative evaporation for long time intervals, also depending on the threshold of acceptance. One solution is to use a direct sampling technique, based on multiple-point statistics simulation, to integrate the time series of reliable evaporation estimates. In this work we test the application of this technique on a two-years-long time series of data collected with a hydro-meteorological station located in the Po plain (Italy). In particular, we explore the impact that a different threshold of acceptance has on the final estimates of evapotranspiration. The results obtained up to date allow to evaluate the impact that a reject-only strategy has on the estimates of evaporation, and provide guidelines for the selection of reliable threshold of acceptance.

GIOVANNI CONTI - *Hamburg University, Germany*

Hyperbolic Covariant Coherent Structures in two dimensional flows

A new method to describe hyperbolic patterns in two dimensional flows is proposed. The method is based on the Covariant Lyapunov Vectors (CLVs), which have the properties to be covariant with the dynamics, and thus being mapped by the tan- gent linear operator into another CLVs basis, they are norm independent, invariant under time reversal and can be not orthonormal. CLVs can thus give a more de- tailed information on the expansion and contraction directions of the flow than the Lyapunov Vector bases, that are instead always orthogonal. We suggest a definition of Hyperbolic Covariant Coherent Structures (HCCSs), that can be defined on the scalar field representing the angle between the CLVs. HCCSs can be defined for every time instant and could be useful to understand the long term behaviour of particle tracers.

We consider three examples: a simple autonomous Hamiltonian system, as well as the non-autonomous "double gyre" and Bickley jet, to see how well the angle is able to describe particular patterns and barriers. We compare the results from the HCCSs with other coherent patterns defined on finite time by the Finite Time Lyapunov Exponents (FTLEs), to see how the behaviour of these structures change asymptotically.

SUSANNA CORTI – *CNR ISAC, Italy*

From Medium to (quite) Extended range Predictions over the Northern Extratropics: some notes.

Here some recent results are presented on the prediction skill of weather and climate forecasts over the Northern Extratropics. In particular I will show i) flow dependent verification of the ECMWF medium range ensemble over the Euro-Atlantic region, ii) sensitivity of seasonal and multi-year predictions to model resolution, and iii) impact of initialisation versus external forcing in decadal predictions.

SILVIO DAVOLIO - *CNR ISAC, Italy*

High-resolution modeling studies of heavy precipitation events

ISAC numerical modeling chain, based on BOLAM and MOLOCH mesoscale models, is applied to study heavy precipitation events over Liguria region. In particular, the convection-permitting model MOLOCH is applied at different spatial resolutions in order to investigate the main dynamical processes responsible for the onset, lifecycle, intensity and localisation/propagation of the mesoscale convective systems and to assess the ability of the model in quantitative precipitation forecasting (QPF) with respect to initial conditions and model horizontal resolution. Moreover, a procedure for assimilating radar rainfall estimate in MOLOCH, based on nudging, is implemented and evaluated over a relevant number of severe weather episodes.

PAOLA DE RUGGIERO - *Dipartimento di Scienze e Tecnologie, Università di Napoli Parthenope, Italy*

Modeling the intrinsic variability of the Antarctic Circumpolar Current

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A modelling study of the intrinsic variability of the Antarctic Circumpolar Current in a wide sector of the Southern Ocean (SO) in summer conditions is presented. A sigma-coordinate ocean general circulation model with a spatial resolution of 0.18° and 12 vertical sigma levels is implemented in a domain extending from 30°S to 80°S and from 90°E to 110°W (thus including the SO sector south of Australia and New Zealand as well as the Ross Sea). Periodic conditions are imposed along the two meridional lateral boundaries. Realistic bathymetry and coastlines and relatively idealized latitude-dependent stratification and surface momentum and heat fluxes are used. The Southern Ocean Database (SODB) for the initialization and the ERA-Interim ECMWF modelling data for the atmospheric forcing are used. Steady climatological surface fluxes are imposed to identify intrinsic low- and high-frequency fluctuations, whose analysis suggests possible mechanisms of mutual interactions (we acknowledge support from the ACCUA and MOMA projects of the Italian Programma Nazionale di Ricerche in Antartide - PNRA).

CECILE DEFFORGE – *CEREA, France*

Improving local scale atmospheric simulation using data assimilation

Cécile L. Defforge*[1], Bertrand Carissimo[1], Raphaël Bresson[1], Marc Bocquet[1]

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Local scale atmospheric simulations are necessary to address various issues related to micrometeorology such as dispersion of pollutants or wind potential estimate. However, local wind fields in wind farms, around industrial sites, and in urban neighbourhoods have very complex structures. These complex wind field structures, which are sensitive to geometrical features such as topography and building set up, are difficult to simulate with CFD models.

To perform small scale simulations, CFD models – for instance the atmospheric version of Code_Saturne (Archambeau, 2004) – generally use as inputs meteorological data obtained from measurements or larger-scale model outputs (used as initial and boundary conditions). These data often lack precision, may not contain all necessary information, and are not appropriate for the detailed features of local scale, especially the topography and the presence of buildings.

A few measurements, although very local, have the potential to greatly enhance the precision of the simulations using data assimilation.

Data assimilation techniques developed so far in meteorology (Kalnay, 2003; Asch et al., 2016) are generally applied to larger scale simulations that are mainly driven by initial conditions and deal with simple geometries (no obstacle). The present work aims at developing local-scale data assimilation techniques that focus on boundary conditions rather than initial conditions and may deal with very complex geometries.

Two relatively new data assimilation techniques are studied here: the back and forth nudging (BFN, Auroux and Blum, 2005) and the iterative ensemble Kalman smoother (IEnKS, Bocquet and Sakov, 2014).

The BFN is an iterative algorithm of direct and backward integrations with nudging terms and the IEnKS is an ensemble variational method. Both techniques have the advantage to avoid using the tangent linear and the adjoint of the observation operator and evolution model. The BFN and the IEnKS have been adapted to include boundary conditions within control variables. Their performances are first evaluated using a shallow water model and will then be analysed on the CFD code. Twin experiments are performed for simple cases with 1D or 2D idealised topography (flat bottom, smooth bump) and for one case with real topographic profile. The present work assesses the ability of BFN and IEnKS to reduce the error on boundary conditions and thus on the wind simulations.

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LAURENT DESCAMPS - *Météo-France, France*

Representing model uncertainties in the Météo-France global ensemble prediction system

Ensemble prediction aims at quantifying forecast uncertainties in operational numerical weather prediction. Building an ensemble forecast system (EFS) requires the representation of the two main sources of uncertainties: initial state uncertainties and model uncertainties.

At the moment, the latter are represented in operational EFS using various techniques such as the multi-model approach, the multi-parametrisation approach, the stochastically perturbed parametrisation tendency scheme or the stochastic energy backscatter scheme.

At Météo-France, research in underway to evaluate pragmatic approaches combining perturbed parameters and stochastic techniques. Here, first results will be presented including sensitivity studies to select the parameters which mostly impact the forecast value and probabilistic evaluations of introducing local stochastic perturbations to the selected set of parameters.

TANMAY DHAR - *Uttarakhand State Disaster Management Authority, India*

A comprehensive study on dynamic modeling of cloudburst in Garwal and Kumaon Himalayas

Cloud bursts are devastating weather phenomena representing highly concentrated rainfall over a small area lasting for a short time. They lead to flash floods, landslides and human casualties on large scale. Though the exact mechanism of these systems is not yet perfectly understood, research bibliography suggests that they are manifestations of intense vortices on small scale. These vortices generate strong convective currents which lift the moisture laden air with sufficient rapidity to form cumulonimbus clouds which shed their water load with great strength and ferocity. Orographic configuration and glacial lakes of central Himalayas add to the vertical lifting necessarily complex for the formation of cumulonimbus clouds. This paper aims on challenges of predictability of cloudburst in the central Himalayas through holistic approach.

GREGORY DUANE - *University of Bergen, Norway*

Data Assimilation as Synchronization of Truth and Model, and Inter-model Data Assimilation as ``Supermodeling"

A perfect model synchronizes with a real system perfectly; an imperfect model does so imperfectly, thus providing perhaps the ultimate application of the synchronized chaos paradigm that has been extensively investigated in nonlinear dynamics. Further, it has been shown that Kalman filtering, and the various extensions and implementations thereof, define the optimal way to reduce synchronization error in the general case.

If we let alternative models of the same objective process assimilate data from one another in run time, we have a "supermodel" that can potentially resolve differences among IPCC-class climate models and achieve consensus. While supermodeling offers improved numerical weather prediction, the application to climate projection has attracted more interest, but requires attractor matching rather than strict synchronization.

Here we explore a hypothesis that such attractor matching can be usefully conceived as learned criticality (a variant of "self-organized criticality"), achievable through extensions of traditional synchronization/data assimilation methods.

GEIR EVENSEN – *IRIS, Norway*

Solving inverse problems by using iterative ensemble smoothers

New iterative ensemble smoothers provides a mean for solving nonlinear inverse problem of high dimension and are used in among others oil-reservoir model conditioning on nonlinear measurements. The inverse problem and the use of iterative smoothers will be presented and illustrated with simple examples.

ALBAN FARCHI – *CEREA, France*

Challenges in localising particle filters

A. Farchi and M. Bocquet

Particle filtering (PF) is a generic weighted ensemble data assimilation (DA) method based on sequential importance sampling, suited for non-linear and non-Gaussian filtering problems. However, PF practitioners often experience weight degeneracy leading to poor estimates of the model state. In fact, the number of ensemble members required for a successful application typically scales exponentially with the problem size. This phenomenon is known as the curse of dimensionality and prevents one to use PF methods for high-dimensional DA.

The use of local analyses to counteract the curse of dimensionality was suggested early on. Indeed, localisation is the main idea that makes the EnKF efficient in high-dimensional systems - which explains the popularity of this DA method. On the other hand, implementations of localisation in the PF is a challenge because there is no trivial way of gluing local updated particles together across domains.

In this presentation we review recent implementations of the local PF in geoscience. We suggest practical solutions to the difficulties of local particle filtering, that lead to improvements in the design of local PF algorithms. The performance of our algorithms is then illustrated using twin experiments with low-order models.

MARIA FATTORINI - *CNR Ibimet – LaMMA, Italy*

Application of Singular Values Decomposition and correlation analysis to the design of ocean observation networks

A methodology for identifying operational criteria to design marine observation networks at regional scale is proposed. Ocean forecasting systems require data to keep model forecast error acceptable and to reduce the natural divergence of numerical solutions from reality. The application of this concept poses many problems especially in oceanography, because of the difficulties that have ocean models in reaching an acceptable state of equilibrium, of the high measurement costs and of difficulties in realizing them. The aim of the proposed methodology is to optimize the available resources by positioning the instruments so that Data Assimilation is able to minimize the related forecast error. A suitable approach can be based on Singular Vectors Decomposition of the tangent linear model and can give strong local indication on the error dynamics. In addition, for the purpose of avoiding redundancy of information in the data, a minimal distance among data positions has been set on the base of a spatial correlation analysis of the hydrodynamic fields taken into consideration.

In this study we will present some results concerning the significant impact of the dataset configuration, and in particular of data positioning, on the evaluation of the overall forecasting reliability of an ocean model.

The proposed methodology has been evaluated through twin experiments by implementing the available ROMS routines in a simplified ideal double-gyre model: a variational assimilation algorithm (4D-var) was used to find an optimal configuration of a sensor network and the results were compared to the assimilation of random observations.

THOMAS GASTALDO - *University of Bologna and Arpae Servizio Meteo-Idro-Clima, Italy*

Studying the imbalances of analysis fields in a LETKF scheme

Thomas Gastaldo, Virginia Poli, Chiara Marsigli, Tiziana Paccagnella and Pier Paolo Alberoni

The length of assimilation window is currently one of the main scientific issues in data assimilation. Dealing with EnKF systems for high resolution NWP models, in which small scale features need to be assimilated, this problem become even more relevant. On the one hand, short length assimilation windows would be desirable in order to avoid that dynamical features leave the area where localized increments are significant. On the other hand, a too short window would lead to imbalances in the analysis, since the model has no the time to filter them out.

At Arpae a study is on-going on the assimilation of radar reflectivity observations with an ensemble data assimilation system at the convection permitting scale (KENDA) based on the LETKF scheme, developed for the Consortium for Small scale Modeling (COSMO) model. The impact of the length of the assimilation window on the balance in analyses and on the quality of the forecasts have been investigated. Tests on both vertical and horizontal localization, which is thought to be the main responsible of imbalances, have been performed. Furthermore, in order to use only the most recent information to determine the state of the atmosphere, only the observations closer to analysis time have been assimilated. The amount of imbalances is evaluated in terms of surface pressure tendencies and the quality of analyses and forecasts is verified using statistical methods.

MICHAEL GHIL - *Ecole Normale Supérieure, Paris, and University of California, Los Angeles, France and USA*

Predictability of the Atmosphere, Ocean and Climate: Anna Trevisan's Contributions and her Legacy

This talk is based on the published record of Anna's work, as well as on what knowledge I have of her ongoing legacy, through students, friends and other collaborators. Her work has addressed and made an impact on overlapping areas of the atmospheric sciences and dynamical systems theory. It is in this overlap that our tastes and affinities converged, although this convergence was much more in the highly rarefied space of intellectual endeavor than in physical space and time.

I will try to give an overview of several subfields of this overlap, as time permits, and conclude with novel developments in the application of nonautonomous and random dynamical systems to the understanding of anthropogenic effects on climate and on possible changes in its predictability.

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PAOLO GHINASSI - *Johannes Gutenberg University Mainz, Germany*

Identification of Rossby Wave packets using Local Finite Amplitude Wave Activity

Paolo Ghinassi[1] , Volkmar Wirth[1],Tobias Selz[2], George Craig[2]

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Upper tropospheric Rossby wave packets (RWPs) are often associated with weather systems and can thus have a strong influence on surface weather. They sometimes act as pre-cursors to blocking or intense extratropical cyclones and are, in this sense, connected with severe weather episodes. Therefore, understanding the dynamics of RWPs is of fundamental importance in the context of predictability. This contribution presents local finite amplitude wave activity (LWA) as a novel diagnostic for RWPs. LWA, which is an extension of the finite amplitude wave activity of Nakamura and Solomon, is proportional to the local meridional displacement of contours of potential vorticity (PV) from zonal symmetry. The advantage of using LWA consists in the fact that its formulation does not make any small amplitude assumption; it is able to faithfully identify nonlinear phenomena such as Rossby wave breaking, blocking, PV streamers, or cutoffs. Furthermore, LWA has an exact conservation relation which allows one to formulate a budget equation for its evolution and to quantify the impact of non-conservative processes as a residuum from the LWA budget. Following the main idea of upscale error propagation, this diagnostic is applied to data from the global forecast model ICON to quantify the error growth at the planetary scale. At the same time, the LWA budget equation is used to estimate the magnitude of the nonconservative term. A challenge in this context is the cascade of enstrophy to smaller scales, which results in an unavoidable sink term in the LWA budget. The results show that nonconservative processes play a non-negligible role in the propagation of RWPs, suggesting that their misrepresentation in the models can lead to poor forecasts.

ANDREY GRITSUN - *Institute of Numerical Mathematics, Moscow, Russia*

Instability characteristics of blocking regimes in a simple quasi-geostrophic atmospheric model

In this talk we study statistics and instability characteristics of blocking events in the three layer quasi-geostrophic model of atmosphere by Marshall and Molteni. It is shown that the model is able to produce reasonable longitudinal distribution of blocking events as well as simulate blocking events with lifetime of up to 40 days. Using covariant Lyapunov exponents we analyze predictability of onset, duration and decay of blockings. It is shown that on the average blockings are less predictable than the system trajectory with the blocking onset and decay being the most unstable. We verify our findings by looking at unstable periodic orbits (UPOs) of the system representing blocking and nonblocking events. It was found that blocking UPOs have 20% more positive (unstable) Lyapunov exponents than the system trajectory with the leading exponent being 50% larger in the case of blockings.

COLIN GRUDZIEN - *Nansen Environmental and Remote Sensing Center, Norway*

Extending Assimilation in the Unstable Subspace to the presence of additive model error

C. Grudzien[2], A. Carrassi[2] and M. Bocquet[1]

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It is well understood that dynamic instability is among the primary drivers of forecast uncertainty in chaotic, physical systems and a variety of data assimilation techniques are designed specifically to exploit this phenomena.

Recent mathematical work provides formal proofs of the central hypothesis of the Assimilation in the Unstable Subspace methodology of Anna Trevisan and her collaborators: for filters and smoothers in perfect, linear models, the distribution of forecast errors asymptotically conforms to the unstable-neutral subspace, i.e., the column span of the error covariance aligns with the span of backward Lyapunov vectors with non-negative exponents.

While earlier mathematical studies have focused on perfect models, this current work now formally explores the relationship between dynamical instability, the precision of observations and the evolution of forecast error in linear, time-varying models with additive modeling error. We prove upper and lower bounds for the asymptotic uncertainty in terms of observational accuracy and the rate of dynamical expansion. As corollaries we provide novel criteria, one necessary and one sufficient, for the boundedness of forecast errors. While forecast error in the stable subspace may not generically vanish, we show that even without observations, uncertainty remains uniformly bounded due its dynamical dissipation. However, the continuous re-injection of uncertainty from modeling errors may be excited by transient instabilities in the weakly stable modes of high variability, rendering forecast uncertainty impractically large.

Expanding on earlier studies, we expose the fundamental, first order effect of transient instability in weakly stable modes on the growth of forecast uncertainty for reduced rank, sub-optimal filters: to maintain forecast error comparable with a full rank filter in the presence of model error, it is necessary to control the growth of uncertainty in modes outside of the unstable subspace, increasing the filter dimension, or ensemble size, to account for the unstable, neutral and stable modes with frequent occurrences of positive local Lyapunov exponents.

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VICTOR HOMAR SANTANER - *Universitat de les Illes Balears, Spain*

High-resolution EnKF for a medicane event: predictability challenges

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A small quasi-tropical cyclone of small dimensions formed in central Mediterranean on 7th November 2014, affecting the islands of Pantelleria, Lampedusa, Malta and Sicily, reaching hurricane wind speeds. The physical analysis of this so-called Medicane clearly shows the tropical transition of the initial baroclinic development into a pure warm-core axisymmetric system. Medicanes have got the attention of the community in the recent years and there is still open debate regarding their definition, genesis mechanisms, discriminant parameters for their formation and the requirements to predict them.

We investigate the physical processes of the development and the predictability properties of the 7 November 2014 event by means of an ensemble data assimilation system based on Kalman filtering (EnKF). The predictability of these systems is typically very limited owing to the highly diabatic (nonlinear) physical processes involved and their maritime (highly unobserved) origin. Consequently, we generate the ensemble assimilation and forecasting system sampling the uncertainty space of initial conditions and physical processes. Initial conditions sampling is adopted from the ECMWF ENS global forecasts. Additionally, multiple PBL, Microphysics and radiative parameterized schemes are used to account for physical processes uncertainties.

The experimental high resolution ensemble allows one to produce probabilistic forecasts of specific aspects of the genesis and evolution of the event. Besides providing a probability of occurrence of the event with lead times up to 24-36h, forecasts provide valuable information about the intensity the wind and pressure fields. The trajectory forecast is a key aspect for accurate civil protection actions. The experimental system produces a fairly uncertain and inaccurate trajectory, which largely depends on small scale features of the environment.

Additionally, we investigate the covariances that can be derived from the ensemble in order to shed some light on the discriminant aspects between medicane formation and non formation scenarios. Although constrained by linear assumptions, results show the connections of the central pressure and wind fields of the medicane with preceding fields. Although based on a single case study, results are encouraging regarding the predictability of the formation, trajectory and intensity of medicanes based on ensemble data assimilation techniques. Additionally, covariance fields provide a valuable tool for physical processes diagnosis even in these highly nonlinear evolutions.

MARC HONNORAT – *EXWEXs, France*

Data assimilation systems for routine weather forecasts currently use a lot of satellite data

Geostationary satellites are thus widely used in assimilation methods. If the cloud cover is one of the data provided by this kind of satellite, the clear sky radiance is the major product assimilated by the weather forecast systems. However, in tropical regions for instance, the information regarding cloud types and their vertical extension is really valuable to initiate an accurate forecast of convection.

This work deals with an original approach for introducing cloud effects in an assimilation system for a mesoscale tropical weather forecast of the convection.

SERGIY IVANOV - *Odessa State Environmental University, Ukraine*

The impact of radar data pre-processing on precipitation simulations in the Harmonie model

Serguei Ivanov, Silas Michaelides, Julia Palamarchuk, Igor Ruban

The data assimilation system in the HARMONIE numerical weather prediction model has been further developed by involving radar reflectivity measurements. The focus was on optimizing pre-processing procedures. The thinning and superobbing approaches with different internal parameters were explored at the pre-processing step. Results have shown that radar data allow for a better simulation of precipitation due to the correction of water content in the low troposphere and as a result increasing the rain rate at the surface. Assimilating radar reflectivity influences the model output only over the radar location area. However, the impact is sensitive to the choice of a pre-processing approach and its internal parameters. The difference between the control and radar assimilation runs shows heterogeneous intermittent form with the opposite signs, although the rain rate has increased up to 10 mm/12 hours in total over the selected part. The vertical distribution of precipitable water in the atmosphere has also been increased. The main changes have occurred within the layer between 850 and 600 hPa and achieved values up to 5-7 mm/hour.

The series of numerical experiments with various thinning and superobbing parameters have shown similar impacts in general mapping, however, there were visible differences in the fine-scale cells. Their sizes, configuration and signs were dependent on the thinning values and superobbing meshes. Thus, in pursuing the compatibility between the model resolution, radar observation density and dominating precipitation patterns, further tuning of optimal parameters for a superobbing mesh size will be performed for particular regions and atmospheric flow regimes.

EUGENIA KALNAY - *University of Maryland, USA*

Anna Trevisan: How she influenced me through modeling, predictability and data assimilation

I met Anna around 1974, when she visited Jule Charney (Arnt Eliassen was also visiting him, see cover photo). We became like sisters, enjoying and learning from each other. I started my career as a modeler (my 4th order global model at NASA was efficient and accurate, and was used for data assimilation and climate simulations for two decades). But my interaction with Anna pushed me towards predictability, where she pioneered the idea of Analysis in the Unstable Space (AUS) by doing data assimilation in a subspace of growing Bred Vectors. Her visionary work in this area culminated in her magnificent 2010 paper with D'Isidoro and Talagrand. This paper inspired a student of mine (Tse-Chun Chen) to do Proactive Quality Control by accepting only the observations that are beneficial for the 6hr analysis, and even more beneficial for the 24hr analysis.

This "Beneficial Growing Modes" method, inspired by AUS, rejects a huge number of observations, but as predicted by Anna, it results in a remarkable improvement of the forecasts.

FRANK KWASNIOK - *University of Exeter, UK*

The structure of predictability in an intermediate-complexity atmospheric model

The predictability of large-scale atmospheric flow is characterised by finite-time Lyapunov exponents and Lyapunov vectors. The fluctuations of the Lyapunov exponents and the Kolmogorov-Sinai entropy as a function of prediction time are discussed. Extreme value theory is used to study the tail behaviour of the distributions. Then predictability is investigated conditional on large-scale weather regimes. A cluster algorithm is used to identify flow patterns associated with low and high predictability. The study is performed in a three-level quasigeostrophic atmospheric model with realistic mean state and variability.

FRANK KWASNIOK - *University of Exeter, UK*

Reduced dimension and increased regime predictability in an atmospheric model due to stochastic forcing

The low-frequency variability in an intermediate-complexity atmospheric model is investigated under stochastic forcing in terms of the number of degrees of freedom and the regime behaviour as extracted by a hidden Markov model analysis. A resonance-like effect is observed: The dimension decreases and the regime predictability increases with increasing noise level up to an optimal value.

PATRICK LALOYAUX – *ECMWF, UK*

The ECMWF weak constraint 4D - Var formulation

Patrick Laloyaux, Jacky Goddard, Martin Leutbecher, Simon Lang, Sarah-Jane Lock, Yannick Tremolet, Mike Fisher

In most operational implementations of four-dimensional variational data assimilation, it is assumed that the model used in the data assimilation process is perfect or, at least, that errors in the model can be neglected when compared to other errors in the system. ECMWF has been developing a weak-constraint 4D-Var formulation where a model-error forcing term is explicitly estimated to take into account model imperfections. This problem is very similar in nature to strong constraint 4D-Var as it is essentially an initial-condition problem with parameter estimation where the additional parameters represent model error.

ECMWF has implemented a new version of its forecasting system in November 2016 where the weak constraint option of 4D-Var has been reactivated using a model error forcing term active in the stratosphere above 40 hPa. The model error covariance matrix is based on statistics generated by special runs of the ensemble predication system with identical initial conditions but with different realisations of model error from the SPPT and SKEB stochastic physics schemes. Future work will aim to improve the specification of the model error covariance matrix and the interaction with the variational bias correction.

DAMIAN LIU - *LTO, South China Sea Institute of Oceanology, Chinese Academic of Science, Guangzhou, China*

Model-based assessment of mesoscale monitoring capability for a Northwestern Tropical Pacific moored array

Liu danian, Shu yeqiang

The Northwestern Tropical Pacific Ocean (NWTPO) moorings observing system, including 15 moorings, was established in 2013 to provide velocity profile data. Observing system simulation experiments (OSSEs) were carried out to assess the mesoscale monitoring capacity of the observation system as a pilot study, where ideal "moored velocity" was assimilated using Ensemble Optimal Interpolation (EnOI) based on the Regional Oceanic Modeling System (ROMS). Because the initial field errors have obviously mesoscale structure, a random ensemble derived from 20–90-day bandpass-filtered eight-year model outputs is proved to be more appropriate for NWTPO mooring array assimilation than a random ensemble derived from a 30-day running mean. Different temporal-spatial signals are presented by these two ensemble schemes. The former presents a mesoscale signal with intraseasonal timescale variability, and the latter mainly shows a flow-dependent signal with a lower-frequency timescale variability. Results of OSSEs assimilating velocity profiles with an intraseasonal bandpass-filtered ensemble show that NWTPO moorings observing system has a good mesoscale monitoring capacity in the North Equatorial Current (NEC) area, North Equatorial Countercurrent (NECC) area, and South Equatorial current (SEC) area, where the RMSEs of the velocities reduced more than 10% relative to the control run.

The improvements of the velocity simulation in the downstream area are larger than that in the upstream area. However, the mesoscale monitoring capability of NWTPO moorings observing system has mainly represented a local-scale feature. The observation system has limited roles to monitor the mesoscale ocean state outside of the area 0°–18°N, 120°E–150°E. OSSEs with objective ensemble-based method are also used to compare with the DA experiments. The results show the locations of NWTPO moorings observing system compare well to the objectively model-derived arrays. Similar with DA results, it's also hard to monitor the mesoscale ocean state in area north of 18°N only by NWTPO moorings observing system.

JUAN M. LÓPEZ - *Instituto de Física de Cantabria, Spain*

Initial perturbations for ensemble prediction systems: the good, the bad and the ugly

Making predictions in systems with spatio-temporal chaos involves not only an analysis of error amplifications, coming from model uncertainties and assimilation defects, but also a study of the spatial propagation of perturbations. Suited perturbations are daily used in weather forecasting in the generation of initial ensembles. The so-called Ensemble Prediction System (EPS), which is the main operative tool used in today's forecasting, estimates the error evolution by means of deterministic forecast integration given by an atmospheric/ocean model. The choice of a proper initial ensemble is crucial for the final result and some kind of control— in order to obtain a determined statistics or spread on the initial ensemble evolution— is necessary. Most of the existing studies limit their analysis to the behaviour of the perturbation amplitude (the norm), paying very little or no attention to the spatial correlation.

Here we present a diagnosis tool to differentiate the good from the bad perturbations to initialize an ensemble forecasting system. We study the evolution of finite perturbations in the Lorenz '96 model, a meteorological toy model of the atmosphere. The initial perturbations are chosen to be aligned along different dynamic vectors: bred, singular, and characteristic Lyapunov vectors. We discuss the corresponding advantages of using those different vectors for preparing initial perturbations to be used in ensemble prediction systems, focusing on key properties: dynamic adaptation to the flow, robustness, equivalence between members of the ensemble, etc. Among all the vectors considered here, the so-called characteristic Lyapunov vectors are possibly optimal, in the sense that they are both perfectly adapted to the flow and extremely robust.

VALERIO LUCARINI - *University of Reading, UK*

Covariant Lyapunov Vectors and Lyapunov Exponents for Atmospheric and Oceanic Flows

One of the most relevant weather regimes in the mid-latitudes atmosphere is the persistent deviation from the approximately zonally symmetric jet to the emergence of blocking patterns. Such configurations are usually connected to exceptional local stability properties of the flow which come along with an improved local forecast skills during the phenomenon. It is instead extremely hard to predict onset and decay of blockings. Covariant Lyapunov Vectors (CLVs) offer a suitable characterization of the linear stability of a chaotic flow, since they represent the full tangent linear dynamics by a covariant basis which explores linear perturbations at all time scales. Therefore, we assess whether CLVs feature a signature of the blockings. As a first step, we examine the CLVs for a quasi-geostrophic beta-plane 2-layer model in a periodic channel baroclinically driven by a meridional temperature gradient Delta T. An orographic forcing enhances the emergence of localized blocked regimes.

We detect the blocking events with a Tibaldi-Molteni scheme adapted to the periodic channel. When blocking occurs, the global growth rates of the fastest growing CLVs are significantly higher. Hence, against intuition, the circulation is globally more unstable in blocked phases. Such an increase in the finite time Lyapunov exponents with respect to the long term average is attributed to stronger barotropic and baroclinic conversion in the case of high temperature gradients, while for low values of Delta T, the effect is only due to stronger barotropic instability. In order to determine the localization of the CLVs we compare the meridionally averaged variance of the CLVs during blocked and unblocked phases. We find that on average the variance of the CLVs is clustered around the center of blocking. These results show that the blocked flow affects all time scales and processes described by the CLVs.

Additionally, we show the potential of using the formalism of CLVs to understand the multiscale dynamics of a severely simplified coupled atmosphere-ocean model. The presence of many near-zero LEs results from the vast time-scale separation between the characteristic time scales of the two fluids, and leads to nontrivial error growth properties in the tangent space spanned by the corresponding CLVs, which are geometrically very degenerate. Such CLVs correspond to two different classes of ocean/atmosphere coupled modes. The tangent space spanned by the CLVs corresponding to the positive and negative LEs has, instead, a non-pathological behaviour, and one can construct robust large deviations laws for the finite time LEs, thus providing a universal model for assessing predictability on long to ultra-long scales along such directions. Our results suggest the need for accurate analysis of error dynamics on different time scales and domains and for a careful set-up of assimilation schemes when looking at coupled atmosphere-ocean models.

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CHIARA MARSIGLI - *Arpae SIMC, Italy*

Predictability of severe weather phenomena with a convection-permitting ensemble

The COSMO-IT-EPS convection-permitting ensemble is based on the COSMO model run at a resolution of 2.2 km, aiming at providing probabilistic information in the context of operational forecast of mescoscale phenomena and severe weather over Italy.

The strategy adopted in the ensemble construction includes the representation of different uncertainty sources: Initial Condition perturbation from a LETKF-based data assimilation, Boundary Condition perturbation from a coarser-resolution ensemble and perturbation of the COSMO model by combining the perturbation of a set of parameters of the physics schemes and the perturbation of the physics tendencies.

The predictability of severe weather phenomena (with focus on thunderstorms) over Italy is here studied, focussing on the effect of the selected perturbation strategy. In particular, it is shown and discussed the role of the Initial Condition perturbations for high resolution precipitation forecast at the very short range, and the role of physics perturbation in determining the onset and evolution of the precipitation systems.

The spread/skill relation of the ensemble is also presented, by using a novel approach to assess how the different perturbations affect the precipitation foreacast, focussing on the physics perturbations. The method permits to distinguish the impact of these perturbations on the uncertainty in the timing, in the amounts, in the structure and in the localization of the phenomena.

VINCENZO MAZZARELLA - *University of Naples "Parthenope", Italy*

Short-term quantitative precipitation forecasts for a flash flood event in central Italy: a comparison between 3DVAR and 4DVAR assimilation methods

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Nowadays, the use of numerical weather prediction (NWP) models, with high horizontal and vertical resolution, requires very accurate initial conditions because the smaller scale processes have still errors because of the difficulty in correctly forecasting the timing and the exact location of precipitating cells. In this respect, the assimilation of a dense network of conventional observations and of local measurements with a high spatial and temporal resolution such as radar data, may produce an improvement of initial conditions and consequently of the estimated rainfall.

The goal of this study is to provide a preliminary comparison between three dimensional and four dimensional variational data assimilation systems (3DVAR and 4DVAR) of the Weather Research and Forecasting (WRF) model to forecast heavy precipitation in a complex orography region.

Radial velocity (RVE) and reflectivity (RRF), acquired by Mt. Midia C-band radar and conventional observations, provided by the Global Telecommunication System (GTS), have been assimilated into the WRF model to simulate a damaging flash flood event in central Italy.

The case study occurred during the intensive observation period IOP4 (14 September 2012) as part of the HYdrological cycle in the Mediterranean EXperiment (HyMeX); it was characterized by a cut-off low pressure system, over the Tyrrhenian Sea. The interaction between cool Bora and warm, moist Sirocco winds, triggered convective activity along the eastern coast of central Italy, with heavy and persistent rain exceeding 150 mm in 24h.

In order to evaluate the impact of 3DVAR and 4DVAR assimilation systems for the estimation of short-term quantitative precipitation forecasts (SQPF), several experiments are carried out using conventional observations with and without radar data, also ingesting RVE and RRF alternatively. Rainfall evaluation/assessment has been performed matching the predicted and observed fields through a neighborhood approach. In this respect, three statistical indicators false alarm rate, (FAR) critical success index (CSI) and fractions skill score (FSS) have been evaluated. Finally, a spatial verification method, i.e. Method for Object-Based Diagnostic Evaluation (MODE), has been used to assess the

ability of assimilation techniques to reproduce the convective structures. The method identifies the objects, namely precipitation patterns, in the forecast and observed fields and compares them through a fuzzy logic approach. The results show the positive impact of data assimilation in the first hours of simulations. Moreover, the use of radar data led to an improvement of the SQPF skills over the study area.

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MARIO MARCELLO MIGLIETTA - *ISAC-CNR, Italy*

Numerical simulations of a tornadic supercell in the Mediterranean

Mario Marcello Miglietta (ISAC-CNR), Jordi Mazon (University of Barcelona), and Richard Rotunno (NCAR)

An EF3 tornado occurred in southeastern Italy causing one casualty and estimated damage of 60 M€ on 28 November 2012. At approximately 1050 Local Time, this tornado, which initially formed as a waterspout, moved inland. The environment where the tornadic supercell developed was characterized by large vertical wind shear in the lowest 1 km of the atmosphere and moderate conditional instability.

The WRF-model numerical simulations show that it is possible to produce the track, change in intensity, and evolution of a simulated supercell thunderstorm similar to the actual one that spawned the tornado in Taranto, southern Italy. The genesis of the simulated supercell is due to a combination of mesoscale-meteorological features: warm low-level air advected toward the Ionian Sea, combined with a mid-level cooling due to an approaching trough, increased the potential instability; the intense vertical shear favored the possibility of supercell development. An unusual feature of the present case of tornadogenesis is the central role of the orography, which was verified in a sensitivity experiment where the orography of Calabria was reduced by 80%.

DANIELE MINGANTI – *BIRA-IASB, Belgium*

Stratospheric circulation investigated in the WACCM chemistry climate model comparing mean age of air with observations and chemistry transport models driven by reanalyses

The mean age of air is a classical diagnostic of the transit time from the troposphere to the various regions of the stratosphere, providing insights on the strength and structure of the Brewer-Dobson circulation (BDC), the polar vortex, and irreversible mixing in the mid-latitudes. We apply this diagnostic to the chemistry-climate model WACCM for the 1985-2014 period. A comparison is presented between unconstrained simulations, simulations nudged to the MERRA-2 reanalysis (SD- WACCM), in-situ measurements and other chemistry-transport models driven by modern reanalyses. The results compare well with the observations, with mean age of air values at 20 km height reaching 1 year at the equator, and 4.5-5 years at the Poles. WACCM provides more realistic age of air in the Tropics than the CTMs, probably due to its better representation of tropical deep convection.
Despite the good representation of the mean age of air, further studies have to be carried out investigating the multi-decadal trends of mean age of air and involving actual tracers.

This study is part of the ACCROSS project, in collaboration with the University of Liège.

ISABELLE MIROUZE - *CMCC foundation, Italy*

Handling boundaries with the recursive filter

Isabelle Mirouze[1] and Andrea Storto[1]

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Ocean reanalyses and forecast systems generally use models at high resolution. The associated data assimilation scheme is often configured to use the same resolution. For example, at the CMCC (Centro Euro Mediterraneo sui Cambiamenti Climatici) foundation, we developped a 1/16 degree system that uses OceanVar, a 3D-VAR FGAT (First Guess at Appropriate time) scheme. High resolution systems are challenging however, since they require an important computation time and a substancial amount of memory.

Implementing an efficient, affordable and scalable correlation operator for modelling the background error covariance is part of the challenge. OceanVar associates an EOF (Empirical Orthogonal Functions) decomposition for the vertical covariances to a recursive filter for the horizontal correlations. To handle the boundaries defined by coastlines and domain borders, we use a grid extension strategy that consists to adding fictitious ocean grid points near the boundaries in order to absorb their effect on the correlation function. Although accurate, this strategy leads to non negligible costs due to the extra grid points to process.

In this presentation, we show that the classical definition of the recursive filter can be slightly modified to account for Neumann, Dirichlet or periodic boundary conditions, in order to handle the boundaries without the need of any grid extension. To do so, extra coefficients are calculated through simple recursive formulae depending on the required boundary condition. In a global ¼ degree configuration, this new formulation of the recursive filter proves to be less expensive in terms of CPU time and memory consumption than using a grid extension. Experiments are currently being performed at the 1/16 degree resolution.

GIULIO MONTE - *Università di Bologna - DIFA, Arpae-SIMC, Italy*

Visibility field forecasting using COSMO Model in the Po Valley

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The forecast of visibility is a complicated task, due not only to the different methods implemented in NWP models but also to the lack of data that makes very difficult an objective comparison between forecast and observations. In the framework of SRNWP-EPS II Programme, three new implementation methods, namely Boudala method, Zhou method and liquid water content (LWC) method, are used with COSMO model to assess the visibility field in the Po Valley region for a number of cases corresponding to different meteorological situations that led to the formation of either radiation or advection fog.

The results obtained for this geographic area are quite different, depending on the method used for the calculation of visibility field. In particular, a qualitative comparison of the forecasts with some observation data deduced by Metar reports and satellite imagery shows that Boudala method (and, to a less extent, LWC method) seems to provide more realistic fields for the different case studies. On the other hand, the Zhou method tends to produce only some small but very foggy areas, with visibility values below 50 meters, which are not observed. Some tuning of this latter method is also tested to improve the forecast skill.

Ensemble applications at different horizontal resolutions are also presented to investigate the possibility to generate probabilistic forecast of visibility on a quasi-operational basis with COSMO-based ensemble systems.

LUIGI PALATELLA - *Liceo Scientifico "C. De Giorgi" – Lecce, Italy*

Assimilation in the unstable subspace and the extended Kalman filter

In this talk we describe the application of the Assimilation in the Unstable Space (AUS) for the Extended Kalman Filter (EKF). We present the standard application that reproduces the algorithm of the EKF, then we show a proposal for taking into account the nonlinear interaction between the most unstable Lyapunov vectors. This nonlinear generalization is applied to the Lorenz96 model showing an abrupt decrease in the probability of filter divergence. After that we show how it is possible to implement these algorithms when the Jacobian cannot be defined/calculated. We also propose a simple approach to handle the presence of the model error in the framework of the EKF-AUS algorithm.

The last case is illustrated with a Simultaneous Localization and Map Model (SLAM).

TIM PALMER – *Oxford University, UK*

Nonlinear model error and the overspreading of seasonal forecast ensembles

In 2014 it was shown by Eade et al that the Met Office seasonal forecast ensemble means correlate better with observations in the North Atlantic region than with other ensemble members, suggesting the ensembles are somehow too noisy. At face value, the very last thing one might therefore want to do is add further stochastic noise to the model. And yet there is evidence from a variety of other timescales that stochastic parametrisations can improve model skill and reduce systematic bias compared with their deterministic counterparts. It is important, therefore, to try to understand this dilemma. Here the hypothesis is developed that the overspreading of seasonal forecasts is associated with the failure of relatively low-resolution deterministic models to adequately describe circulation regime characteristics in the North Atlantic region. I will show some recent results from both idealised model and comprehensive climate models which illustrate the counterintuitive nonlinear impact of stochastic parametrisation on seasonal ensemble spread over the North Atlantic region.

MARIA PARFENOVA - *Moscow Institute of Physics and Technology (State University), A.M. Obukhov Institute of Atmospheric Physics of Russian Academy of Sciences, Russia*

1-D nonhydrostatic model (NH3D) simulation of high latitude ABL structure above sea ice edge

The research is conducted in order to investigate the thermodynamic characteristics of the atmospheric boundary layer at high-latitudes depending on the surface type. The comparison of the observational data and the results of numerical simulations is made, using the 1-D version of a nonhydrostatic model (NH3D).

The observational data is obtained from the meteorological temperature profiler MTP5 during the expeditions NABOS -2013 and NABOS-2015 in the Eurasian and Makarov basins of the Arctic Ocean. The data includes temperature profiles and sea ice observations in the areas where five large ice floes of highly consolidated ice were crossed by the RV. As a result of the analysis of the data, the following conclusions are made:

- The underlying surface has a significant impact on the thermal structure of the ABL. In the areas of high ice concentrations, the cooling of the lower layers is observed as a result of the underlying surface influence.
- The air temperature drops by 4-5 °C when the direction of the ice edge crossing is from the open water towards the ice floe. The air temperature increase of 3-4 °C is observed when the ice edge is crossed from the open water to the ice floe.
- Changes in the temperature dynamics of the ABL are observed at all the measured heights during the surface type changing.

A nonhydrostatic model (NH3D) was used for idealized quasi 1-D simulations of ABL thermal structure. Previously, the NH3D model was successfully used to reproduce orographic gravity waves, but its one-dimensional version has never been used to simulate meteorological processes in the frontal boundary layer of the Arctic region. Despite the idealized setup, the model results agree well with the observational data that was obtained from the expeditions NABOS-2013 and NABOS-2015. According to the present simulations, the occurrence, strength, and the height of the inversions are well represented in the results of simulations.

SEON KI PARK - *Ewha Womans University, South Korea*

Ensemble Based Data Assimilation for Air Quality Prediction using Synthetic Radiance Observations from Future Geostationary Satellite

The Geostationary Environmental Monitoring Spectrometer (GEMS) which is a UV-visible scanning spectrometer is planned to be launched in 2019. The missions of GEMS are to monitor and provide information from air pollutions events such as emission with diurnal variability, wild fire, Asian dust storm, and etc. over Asia in daytime. This high spatiotemporal information is expected to improve an air quality prediction. Therefore, we assess potential impact of the GEMS observation on air quality prediction using ensemble based data assimilation method.

In this study, we assimilate synthetic radiance observations using ensemble based Maximum Likelihood Ensemble Filter (MLEF) with Weather Research and Forecasting model with chemistry (WRF-Chem). Based on some target air pollutants of the GEMS (e.g., O3 , NO2 , SO2 , HCHO, and aerosol), several wavelengths are chosen to simulate synthetic radiances. The results will be discussed about decrease of forecast uncertainty, analysis increment, and efficient assimilation time.

SEON KI PARK - *Ewha Womans University, South Korea*

An improved parameterization of assimilated carbon allocation to plant parts in vegetation dynamics for Noah-MP

In this study, we developed a parameterization scheme to characterize the allocation of assimilated carbon to plant parts, including leaves, woods, and fine roots, for land surface models. This scheme determines carbon allocation amount, considering the carbon masses of plant parts and long-term averaged annual net primary production. This scheme was implemented in Noah land surface model with multiple parameterization options (Noah-MP) and evaluated with tower measurements and satellite retrievals. The evaluation demonstrated that the new scheme improved the presentation of the seasonality of leaf area index (LAI), gross primary productivity (GPP), and ecosystem respiration (ER). In particular, significant improvements were found in simulating amplitudes and phase shift timings in the LAI seasonal cycle, and the amount of GPP and ER in the growing season.

STEPHEN PENNY - *UMD / NCEP, USA*

Hybrid-grain data assimilation and the synchronization of chaotic systems

A form of hybrid data assimilation (DA) in which the Kalman gain matrix is formed directly from a combination of gain matrices derived from both dynamic (ensemble-based) and static (climatological) error covariance estimates (called Hybrid-Gain DA) will be described in the context of the synchronization of one-way coupled chaotic dynamical systems. Implications for simple models and large scale ocean and atmospheric general circulation models will be discussed.

The development of this work has been influenced by the research of Anna Trevisan and her colleagues, in general the perspective of following the insights gained from dynamical systems theory, and in particular the ideas of assimilation in the unstable subspace.

STEFANO PIERINI - *Dipartimento di Scienze e Tecnologie, Università di Napoli Parthenope, Italy*

Intrinsic aspects of the Kuroshio Extension low-frequency variability revealed by the combined use of numerical modeling and altimeter data

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Several numerical model studies (e.g., [1-3]) have suggested the possibility that the Kuroshio Extension low-frequency variability, as observed through altimeter data [4], may be partly controlled by an intrinsic oceanic mode of variability. Here we provide further evidence that this may be the case (in particular during the period 1998-2006) by making combined use of numerical simulations performed with model [1] and of altimeter data analyzed through the dynamical index proposed in [5] for this specific phenomenon.

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STEFANO PIERINI - *Dipartimento di Scienze e Tecnologie, Università di Napoli Parthenope, Italy*

Exploring the pullback attractors of a low-order quasigeostrophic model subject to periodic and aperiodic forcing

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A low-order quasigeostrophic model [1] captures several key features of intrinsic low-frequency variability of the oceans' wind-driven circulation. This double-gyre model is used here as a prototype of an unstable and nonlinear dynamical system with time-dependent forcing to explore basic features of climate change in the presence of natural variability. The studies rely on the theoretical framework of nonautonomous dynamical systems and of their pullback attractors (PBAs), namely the time-dependent invariant sets that attract all trajectories initialized in the remote past [2,3]. Ensemble simulations help us explore these PBAs.

The chaotic PBAs of the periodically forced model [4] are found to be cyclo-stationary and cyclo-ergodic. Two parameters are then introduced to analyze the topological structure of the PBAs as a function of the forcing period; their joint use allows one to identify four distinct forms of sensitivity to initial state that correspond to distinct system behaviors. The model's response to periodic forcing turns out to be, in most cases, very sensitive to the initial state. The system is then forced by a synthetic aperiodic forcing [5]. The existence of a global PBA is rigorously demonstrated. We then assess the convergence of trajectories to this PBA by computing the probability density function (PDF) of trajectory localization in the model's phase space. A sensitivity analysis with respect to forcing amplitude shows that the global PBA experiences large modifications if the underlying autonomous system is dominated by small-amplitude limit cycles, while the changes are less dramatic in a regime characterized by large-amplitude relaxation oscillations. The dependence of the attracting sets on the choice of the ensemble of initial states is analyzed in detail. The extension to random dynamical systems is finally outlined.

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NADIA PINARDI - *University of Bologna, Italy*

The large scale steady state and low frequency variability of the Mediterranean Sea circulation

After 30 years of continuous development in modeling, analyses and forecast of the Mediterranean Sea a new view of the general circulation is emerging where the seasonal cycle and multi-decadal changes are found to compose the main variability of the large scale flow field. The variability is atmospherically driven and modulated by the Gibraltar Strait inflow/outflow system.

Anna Trevisan's contribution to the large scale Mediterranean Sea modeling (Pinardi, Speranza and Trevisan, 1985) was instrumental to start the dynamical understanding of the energy and vorticity dynamics of the basin scale flow field, an attempt that is still novel and remarkable in its simplicity but relevance. This past work will be overviewed and reproduced with today's numerical techniques and for the overall Mediterranean Sea. The steady state currents emerging from the Fofonoff nonlinear potential vorticity conservation model will be compared to the climatological currents emerging from a 60 years recently developed reanalysis (1955-2014).

IGNACIO PISSO – *NILU, NOrway*

Urban greenhouse gas emission assessment through inverse modeling

Norway has set the target of cutting greenhouse gas (GHG) emissions by at least 40% compared to 1990 levels by 2030. This goal will require the implementation of policy measures aiming at strong reductions of GHGs emissions, especially in the urban environment. The implementation of urban policy measures is still a challenging task and it requires control and verification for success. The URGE project aims at assessing the emission flux of GHGs including comprehensive uncertainty estimates based on inverse transport modelling techniques and optimized use of measurements.

The final goal is to establish a coherent and consistent GHG urban emission inventory. This will be carried out in a case study in Oslo (Norway), where CO2 will be the priority compound. The overall outcome of the project will provide support in the development of strategies to effectively reduce GHG emissions in the urban environment. The overall goal will be reached through the following activities: establish the baseline urban CO2 emission inventory for Oslo (NILU-INBY); determine the optimal measurement locations based on transport modelling (flexpart-wrf); design and carry out a pilot measurement campaign of the CO2-rich air downwind of the city plume combining state-of-the-art instruments (Picarro) and small sensors; assess the feasibility of determining the background concentration surrounding the city with satellite measurements (OCO2); and provide optimised estimates of the emissions and their uncertainties via inverse modelling (source-receptor relationship).

We will present the overall project and the preliminary results of the network design.

VIRGINIA POLI - *Arpae-Servizio Idro- Meteo-Clima, Italy*

Data assimilation of radar reflectivity volumes in a LETKF scheme

Virginia Poli, Thomas Gastaldo, Chiara Marsigli, Tiziana Paccagnella and Pier Paolo Alberoni

To improve the reliability of high resolution forecasts the main issue is to produce an analysis that gives a precise description of the present state of the atmosphere. In particular, for very localized and rapidly evolving precipitating systems such as summer thunderstorms, the assimilation of very frequent and accurate observations becomes fundamental. In the COSMO Consortium (Consortium for Small-scale Modeling), the assimilation of radar data is now on-going into the Kilometer-scale ENsemble Data Assimilation (KENDA) LETKF system by means of the COSMO Radar Forward Operator (EMVORADO).

At Arpae-SIMC, the LETKF system has an operational set-up with the assimilation of only conventional observations. In the experimental set-up reflectivity radar volumes from the Italian radar network are used into assimilation cycles.

Results both in the assimilation and in the forecast cycles are dependent on the configuration used. Since a larger spread of the assimilation ensemble allows a more effective assimilation of observations, different techniques to increase the spread are evaluated. The impact of assimilating various subsets of the radar reflectivity volumes is also investigated, as well as the horizontal and vertical localization of the data. Finally, the length of the assimilation window is taken into account for field balancing reasons.

The performances of the different configurations used are diagnosed by means of a statistical analysis and the verification of forecasted fields.

FRANCO PRODI - *ISAC CNR, Italy*

Deep Convection and other precipitating systems in Salento with the Torchiarolo Radar of RIVONA Project

F. Prodi, G. Trivellone, F. Congedo, V. Pupillo and F. Pasqualucci

The Project/Network of Laboratories RIVONA (RIschi per il VOlo e Nowcasting Aeroportuale/ Meteorological Risks to aviation and Aeroport Nowcasting) aims at reduction of meteorological risks for flight in the airport area. Two meteorological radars of advanced characteristics (Doppler, double polarization, multiparametric) have been installed at optimal locations for observation of the Aeroporto del Salento (Brindisi), at two directions at 90°. Selected locations are Torchiarolo and Mesagne. In addition a mobile Ka band radar, three MW disdrometers and 6 microbarometers, at proper distances to detect gravity waves originated by storms will be deployed. Torchiarolo radar has been operating since 2013. The outline of the project will be presented first, then squall line events during 2015 will be shown, characteristic MCS with cells along a line. These systems are formed by convergence along the line of a cold front. The radar images of the different parameters are commented and features like bounded week echo region (BWER) and cyclonic meso-vortices associated are shown.

Other precipitating systems as ASES (Adriatic Sea Effect Snow clouds), a case of snowfall with graupels, an hailstorm and stratiform rain by baroclinic instability will be presented. Hydrometeor identification is performed by combining multiparametric images.

CHENG QIAN - *Institute of Atmospheric Physics, Chinese Academy of Sciences, China*

Three approaches for statistical prediction of non-Gaussian climate extremes

Prediction of climate extremes is challenging, especially for non-Gaussian extremes, since the Gaussian assumption used in traditional linear regression is violated. Three approaches are introduced for statistical prediction of non-Gaussian climate extremes in this presentation. (1) The first one uses a multiple linear regression model after transforming the non-Gaussian predictant to a quasi-Gaussian variable when the predictant does not deviate from Gaussian distribution too much, and uses Pearson's correlation test to identify potential predictors (Qian et al. 2015, JC). (2) The second one uses a generalized linear model when the transformation is difficult and uses a nonparametric Spearman's correlation test to identify potential predictors (Qian et al. 2015). (3) With the help of the first-order difference (year-to-year increment), the difference series is more likely a Gaussian distribution than it was in the original series and is thus used as the predictant to find predictors and to construct a prediction model by using traditional linear regression. The difference is first predicted and is then added to the observed value of the target variable at the preceding time to obtain the final prediction result. This method can take the urbanization effect into account and is thus suggested for statistical prediction of climate extremes in urban areas (Qian et al. 2017). The non-Gaussian annual occurrence of hot days and hot nights at Macau and Hong Kong are used to illustrate the three approaches.

RICHARD ROTUNNO - *National Center Atmospheric Reseach, USA*

Anatomy of the Atmospheric Lee-Side Hydraulic Jump

Laboratory observations of the lee-side hydraulic jump indicate it consists of a statistically stationary turbulent motion in an overturning wave. From the point of view of the shallow-water equations (SWE), the hydraulic jump is a discontinuity in fluid-layer depth and velocity at which kinetic energy is dissipated. To provide an understanding of the origin and structure of the hydraulic jump, three-dimensional numerical solutions of the Navier-Stokes Equations (NSE) are carried out alongside SWE solutions for nearly identical physical initial-value problems.

Starting from a constant-height layer flowing over an obstacle at constant speed, it is demonstrated that the SWE solutions form a lee-side discontinuity owing to the collision of upstream-moving characteristics launched from the lee side of the obstacle. Consistent with the SWE solution, the NSE solution indicates the lee-side hydraulic jump begins as a steepening of the initially horizontal density interface. Subsequently, the NSE solution indicates overturning of the density interface and a transition to turbulence. Analysis of the initial-value problem in these solutions shows that the tendency to form either the lee-side height/velocity discontinuity in the SWE, or the overturning density interface in the exact NSE, is a feature of the inviscid, nonturbulent fluid dynamics. Dissipative turbulent processes associated with the lee-side hydraulic jump are a consequence of the inviscid fluid dynamics that initiate and maintain the locally unstable conditions.

PAOLO RUGGIERI - *Università degli studi dell'Aquila and CMCC, Italy*

Thermodynamic cycles in the stratosphere

Paolo Ruggieri[1], **Maarten H. P. Ambaum**[2]

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Mass transport in the stratosphere has been deduced decades ago from the observation of long-lived chemical species. A common and modern perspective is that potential vorticity (PV) can be used to diagnose the dynamical state of the system. Tropospheric, large scale waves mix PV and an overturning circulation arises to compensate the torque imposed by the breaking waves. In this view, heating is relaxational and the circulation is mechanically driven and thermodynamically indirect. Less attention has been devoted, in scientific literature, to the thermodynamical implications of a middle-atmosphere circulation driven primarily by differential heating, that can be significant in solstice seasons. This component of the circulation is deemed to be mechanically damped and thermodynamically direct. A thermodynamic analysis of these phenomena is presented. The analysis is based on data obtained from ERA-Interim and stream functions in a thermodynamic, log-pressure-temperature space are computed. Results suggest that the circulation in the lower stratosphere is substantially thermodynamically indirect. In the upper stratosphere an indirect circulation and a direct circulation coexist, a prominent semiannual cycle is detected.

Results also indicate that the basic (i.e. not perturbed by waves) overturning circulation in the stratosphere is largely thermodynamically direct and tropospheric waves induce the indirect component of the flow.

YEQIANG SHU - *LTO, South China Sea Institute of Oceanology, Chinese Academic of Science, Guangzhou, China*

Model-based assessment of mesoscale monitoring capability for a Northwestern Tropical Pacific moored array

Liu danian, Shu yeqiang

The Northwestern Tropical Pacific Ocean (NWTPO) moorings observing system, including 15 moorings, was established in 2013 to provide velocity profile data. Observing system simulation experiments (OSSEs) were carried out to assess the mesoscale monitoring capacity of the observation system as a pilot study, where ideal "moored velocity" was assimilated using Ensemble Optimal Interpolation (EnOI) based on the Regional Oceanic Modeling System (ROMS). Because the initial field errors have obviously mesoscale structure, a random ensemble derived from 20–90-day bandpass-filtered eight-year model outputs is proved to be more appropriate for NWTPO mooring array assimilation than a random ensemble derived from a 30-day running mean. Different temporal-spatial signals are presented by these two ensemble schemes. The former presents a mesoscale signal with intraseasonal timescale variability, and the latter mainly shows a flow-dependent signal with a lower-frequency timescale variability. Results of OSSEs assimilating velocity profiles with an intraseasonal bandpass-filtered ensemble show that NWTPO moorings observing system has a good mesoscale monitoring capacity in the North Equatorial Current (NEC) area, North Equatorial Countercurrent (NECC) area, and South Equatorial current (SEC) area, where the RMSEs of the velocities reduced more than 10% relative to the control run.

The improvements of the velocity simulation in the downstream area are larger than that in the upstream area. However, the mesoscale monitoring capability of NWTPO moorings observing system has mainly represented a local-scale feature. The observation system has limited roles to monitor the mesoscale ocean state outside of the area 0°–18°N, 120°E–150°E. OSSEs with objective ensemble-based method are also used to compare with the DA experiments. The results show the locations of NWTPO moorings observing system compare well to the objectively model-derived arrays. Similar with DA results, it's also hard to monitor the mesoscale ocean state in area north of 18°N only by NWTPO moorings observing system.

VICTOR SHUTYAEV - *Institute of Numerical Mathematics, Russian Academy of Sciences, Russia*

Sensitivity of the optimal solution of variational data assimilation problems

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The problem of variational data assimilation for a nonlinear evolution model is formulated as an optimal control problem to find the unknown parameters of the model. We study the problem of sensitivity of the optimal solution via variational data assimilation with respect to observation er-rors. On the basis of relations between the error of the optimal solution and the errors of observa-tional data through the Hessian of the cost functional, the algorithms are developed and justified for calculating the coefficients of sensitivity as the norms of the response operators occurring in the equations for errors. A numerical study of the sensitivity of the optimal solution on the exam-ple of the problem of variational data assimilation of sea surface temperature to restore the heat flows for the model of thermodynamics is presented. Numerical examples for data assimilation in the Baltic Sea dynamics model are given.

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LEONARD N. SMITH – *London School of Economy, UK*

Reconsidering the Aims of Weather Prediction, Again

Whoever first attempted to predict the weather no doubt tried to state (or control) what would happen in the future. By the time of Fitzroy, however, the realities of real-time weather forecasting had broadened those aims to "an idea of the weather thought probable," this in the face of attack both from the scientific establishment (the Royal Society) and from pre-existing economic competitors (almanac writers) . With the arrival of the electronic computer, von Neumann swung the pendulum back toward the goal of stating (or controlling) what would happen, even as Charney expressed reservations. The goal of stating the future was supplemented by Tennekes' "no forecast is complete without a forecast of the forecast skill" which in part led to Ensemble Forecasting Systems. Anna Trevisan's paper in the 90's appeared as Tennekes' call for expectation management morphed into a new aim: the provision of probability distributions. Today the field of battle has, to some extent, moved on from ensemble formation schemes to the development and evaluation of probability forecasts. Probability forecasts are, of course, also incomplete without a forecast of their relevance: the probability of a big surprise.

Today, might we reconsider whether or not we can achieve the aim of providing useful probabilities (probability which can be used as such) even in principle? Arguably, precise probabilities are not obtainable (due to model inadequacy) just as precise point forecasts were not obtainable (due to nonlinearity and chaos). I suggest we return to aims closer to those of Fitzroy: the early detection of significant events of interest to us. We can extend the application of modern data assimilation from assimilating an uncertain past to also assimilate uncertain information regarding the future; literally hunting for a glimpse of significant events in the extended range and then monitoring their plausibility as time passes. We will not know their probabilities, but then we do not have such things now! And we can see them coming much earlier if we aim for them.

FELIPE SOARES - *Prooceano Serviço Oceanografico e Ambiental LTDA, Brazil*

Projeto Azul: Advances in operational oceanography in the Santos Basin using variational data assimilation

Livia Sant'Angelo Mariano, Daiane Gracieli Faller, Gabriel Vieira de Carvalho, Mauricio da Rocha Fragoso, Felipe Lobo Mendes Soares, Luiz Paulo de Freitas Assad, Raquel Toste, Carina Stefoni Böck, Lívia Maria Barbosa Sancho, Bruna Reis, Luiz Landau

The Santos Basin Ocean Observing System (or Project Azul) was a pilot project designed to collect oceanographic data with enough time and spatial coverage to improve regional forecasts through data assimilation in the Santos Basin (Southeast Brazil) region. The Project was held between August, 2012 and August, 2015 and provided a significant set of in-situ data including TS profiles from gliders and profiling floats, and drifters trajectories (dos Santos et al. 2015). In situ TS profiles together with UK Met-Office EN3 project dataset (Surface and sub-surface hydrographic measurements of temperature and salinity) and remote data from POES AVHRR (1-day gridded, 0.1o resolution SST) and AVISO (1-day gridded, 0.3o composite of the MDT SSH) were used to feed the data assimilation process. The data assimilation was based in the Regional Ocean Modeling System (ROMS) 4D-variational (I4D-Var) data assimilation system (Moore et al, 2004).

The results from the assimilative model were compared with the non-assimilative model results as well as independent observations to determine the impact of the assimilation to improve the representation of the Santos Basin region dynamics. Indeed, the 4D-Var data assimilation system was successfully implemented, showing a great potential to improve the forecast skill of the local ocean dynamics (Fragoso, et al. 2016). Besides the significant insights gained from the project, new challenges were identified to obtain the best ocean estimate using the 4D-Var assimilative scheme. Highlights of the most recent developments in progress will be presented regarding several subjects such as the best assimilation window length, background error covariance matrix, best tuning of observation error, representation of shelf and coastal process in the assimilative results and system operationalization using cloud computing.

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ANTON SOKOLOV - *Laboratoire de PhysicoChimie de l'Atmosphère, Université du Littoral Cote d'Opale, France*

Analysis of wind profile variations in Mediterranean using RADAR and reanalysis data

Atmospheric measurements of a few meteorological RADARS were analysed together with first AROME-WMED reanalysis in the framework of HyMeX (HYdrological cycle in the Mediterranean EXperiment) project. Two-month dataset corresponding to a period of intensive observation in September – October 2012 was developed. We studied how the model reproduces local atmospheric statistical characteristics of wind profiles and estimated error covariance matrices.

Two characteristics were specifically considered for RADAR and AROME-WMED reanalysis data. Vertical mean squared variation shows the averaged discrepancy between wind speeds at different altitudes. Temporal mean squared variation of the wind speed indicates how the atmosphere "forgets" it initial state with time in a specific point in space.

It was shown that these wind variations are connected with periodical local phenomena such as sea/land/mountain breezes, and with atmospheric circulation at synoptic scale as Mistral, Tramontane and Westerly Mediterranean winds.

ANTONIO SPERANZA – *CINFAI, Italy*

The role of nonlinear self-interaction in the dynamics of planetary-scale atmospheric fluctuations.

A central role in the general circulation of the atmosphere is played by planetary scale inertial fluctuations with zonal wavenumber in the range k = 1–4. Geopotential variance in this range is markedly non-gaussian and a great fraction of it is non-propagating, in contrast with the normal distribution of amplitudes and the basically propagating character of fluctuations in the baroclinic range ($3 > k > 15$). While a wave dispersion relationship can be identified in the baroclinic range, no clear relationship between time and space scales emerges in the ultra-long regime ($k < 5$, period >10 days). The hypothesis that nonlinear self-interaction of planetary waves determines critical properties of the mobility (and, therefore, the dispersion) of ultra-long planetary fluctuations is investigated by means of a minimal analytic description of the impact of self-nonlinearityon mobility, showing that this is responsible for a correction term to phase speed, with the prevalent effect of slowing down the propagation of waves. The intensity of nonlinear self-interaction is shown to increase with the complexity of the flow, depending on both its zonal and meridional modulations. Reanalysis data of geopotential height and zonal wind are analysed in order to test the effect of self-nonlinearity on observed planetary flows.

ANDREA STORTO – *CMCC, Italy*

Comparing variational methods aware of model error evolution for long-term ocean applications with OceanVar

Traditional formulations of three-dimensional variational (3DVAR) data assimilation scheme for oceanographic applications neglect the temporal evolution of model errors within and across assimilation temporal windows. Such a simplification appears limiting for long-term applications (e.g. reanalyses), or low-resolution configurations with long assimilation time windows.

This work compares possible extensions of 3DVAR aiming at relaxing these assumptions. General formulations are proposed and implemented in order to extend the OceanVar data assimilation system into a simplified hybrid 4DVAR scheme. These two extensions (hybrid formulation of B and low-order 4DVAR) are compared to the standard 3DVAR scheme in terms of both accuracy gain and computational time increase, in order to draw sensible conclusions for practical applications.

OLIVIER TALAGRAND - *Laboratoire de Météorologie Dynamique, École Normale Supérieure, Paris, France*

Data Assimilation

Data Assimilation, which originated from the need of defining initial conditions for Numerical Weather Forecasts, has gradually become over the years a major component of numerical modelling of the atmospheric and oceanic circulation.

Anna Trevisan's contribution to Data Assimilation bore largely on the close links it has with the predictability of the flow. Assimilation algorithms which are capable of carrying in time, not only an estimate of the state of the flow, but also an estimate of the associated uncertainty, lead to much better results (albeit of course at a significantly higher cost) than those which assume a 'static' uncertainty. The links between assimilation and the predictability, and state of (in)stability, of the flow will be discussed in detail. Stress will be put on the algorithms for Assimilation in the Unstable Subspace that have been developed by Anna and her collaborators. The close connection with various forms of ensemble assimilation will also be stressed.

Other questions which now arise in the context of assimilation will be discussed, such as observability (what can one obtain from what one observes?), and assimilation of images (coherent spatial structures).

NAZARIO TARTAGLIONE - *Uni Research Climate and Bjerknes Center for Climate Research, Bergen, Norway*

Stratospheric ozone distribution and its influence on the atmospheric circulation

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Stratospheric residual circulation, as defined by Transformed Eulerian Mean (TEM) framework, transports air from the tropical tropopause to extratropical latitudes. The bulk of this circulation is essentially driven by breaking extratropical planetary waves – sometimes referred to as the extra-tropical pump. In stratosphere the chemical transport circulation is referred to as Brewer-Dobson circulation that includes two-way mixing and mean mass transport that is related to the residual circulation. Although stratospheric residual circulation is essentially driven by synoptic and planetary waves, the presence of ozone represents a thermal source that can modify the stratospheric circulation.

We investigate how stratospheric ozone distribution can influence the stratospheric circulation and have an impact on the tropospheric circulation as well. We used the model WACCM, a high-top model of the atmosphere, to simulate two situations with different stratospheric ozone distributions. By changing geomagnetic indexes we can control the amount and the energy of the energetic electron precipitation (EEP) into the mesosphere. During the winter, a stronger geomagnetic activity drives more energetic electrons that produce more NOx and NOy in the mesosphere of polar regions, which descending in the upper stratosphere destroy ozone. With ozone missing at upper levels of the stratosphere, more ozone is created at lower levels due to the healing effect, in the sub-polar regions are reached by the solar light even during the winter. This leads to increase the temperature of lower stratosphere and a stronger residual circulation is observed, especially in the northern hemisphere. A significant increasing of the tropospheric zonal wind is observed in the sub-polar regions during the winter season.

STEFANO TIBALDI - *CMCC, Euro-Mediterranean Center on Climate Change, Italy*

Atmospheric blocking in observations and models

Stefano Tibaldi.[1] and Franco Molteni[2]

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Blocking is a typical feature of the atmospheric circulation of the mid-latitudes of both hemispheres. It occurs when the usual zonal flow is hindered by the establishment of a large amplitude, quasi-stationary, high-pressure meridional circulation structure which "blocks" the westerlies. The lifetime of such structures can vary from a few days to several weeks (in the most extreme cases) and their presence and persistence can strongly affect the propagation of synoptic systems and the weather of large portions of the midlatitudes leading to the establishment of anomalous precipitation episodes or persistent anticyclonic regimes, leading in turn to floods, extreme cold spells, heat waves, short-lived droughts or episodes of extremely poor air quality, e.g. high concentration of low-level ozone in summer and of particulate matter.
In winter, blocking tends to occur preferentially in certain longitudinal sectors. In the Northern Hemisphere such sectors are mainly the Euro-Atlantic sector and the Pacific sector. In the Southern Hemisphere, blocking frequencies are generally lower and the longitudinal localisation is less pronounced, but blocking in the New Zealand sector is noticeably more frequent.
Since the pioneering observational works of Berggren, Bolin, Rossby and Rex, between 1949 and 1950, atmospheric blocking has been the object of innumerable observational and theoretical studies which, first of all, tried to sharpen the picture of the synoptic phenomenon (starting from a commonly accepted structural definition), study its climatology in terms of the geographical distribution of its frequency of occurrence and the associated seasonal and inter-annual variability, and find a satisfactory theoretical model of its dynamical development that could account for its observational characteristics. Such theoretical studies focussed on a wide range of possible dynamical mechanisms, from large-amplitude planetary scale waves dynamics, multiple equilibria circulation regimes, large-scale anticylonic forcing by synoptic-scale eddies, finite-amplitude non-linear instability theory, influence of sea surface temperature anomalies and others.
Since the advent of widely available, numerically-produced, global medium-range weather predictions, with the establishment, in the late seventies, of the European Centre for Medium-Range Weather Forecasts, it became of relevance assessing the ability (or the lack of it) of models to forecast blocking with the correct space-time characteristics, e.g. location, time of onset, lifespan and decay. Early studies showed how models had substantial difficulties in correctly representing blocking, possibly in connection with their large systematic (mean circulation) errors.
Although such model errors have been progressively and continuously decreasing in the course of time, blocking still remains a challenge as an initial-value problem for global weather prediction models. The difficulties of correctly predicting blocking shown by weather forecasting models are partially reflected in the problems that Global Climate Models have in representing blocking climatology. Such problems have negative

consequences not only on the models' ability to represent the observed climate, but also on the possibility of producing high quality seasonal-to-decadal climate predictions, for which representing the correct space-time statistics of blocking occurrence is, especially for certain geographical areas, of paramount importance.

FRANCESCO UBOLDI - *ARIANET srl, Milan, Italy*

Multiple-scale error growth and data assimilation in convection-resolving models

During the linear regime phase, in dynamical systems such as the atmosphere, ocean and climate and their models, small perturbations grow along the unstable directions that characterize the local structure of the attractor, and multiple-scale, convection-resolving systems are no exception in this respect. As a consequence, an important component of the forecast error lies in the unstable subspace. This property is exploited to assimilate observations by the technique known as Assimilation in the Unstable Subspace (AUS).

In a multiple-scale systems, linear regime exponential growth and non-linear saturation of errors have different properties at different scales of motions. Linearly growing errors with different growth-rates and saturated errors of various magnitudes coexist in multiple-scale dynamical systems. Many independent instabilities with similar, competing growth rates are associated to small and fast convective scales, and trigger slower growth of less numerous instabilities associated to larger dynamic scales.

Moreover, non-growing error components may be present, especially in operational implementations, after being brought into the system by initial and boundary conditions from an external, larger-scale model.

The presentation will recall the principles of AUS and make use of that approach to discuss problems encountered when assimilating data in multiple-scale, convection-resolving systems in realistic simulations.

PETER JAN VAN LEEUWEN - *University of Reading and NCEO, UK*

On the (non-)degeneracy of particle filters

Particle filters for geoscience applications are maturing fast, driven by their applicability to highly nonlinear data-assimilation problems. However, when the number of observations is large the standard particle filters suffers from filter degeneracy. This means that one particle obtains weight one, while others have zero weight, leading to ensemble collapse.

Several solutions have been advocated to solve this problem, like localisation, optimal proposals and hybrids with 4DVar, equal-weight particle filters, and hybrids with ensemble Kalman Filters.

Driven by recent new insight in the behaviour of the weights I will present an overview of the accuracy and efficiency of these methods and show e.g. that localisation alone will not be enough, what the hybrids and equal-weight filters do, and potential future direction of research.

STEPHANE VANNITSEM - *Royal Meteorological Institute of Belgium*

Low-frequency variability and predictability of the ocean-atmosphere coupled system.

The low-frequency variability (LFV) of the atmosphere at mid-latitudes develops on a wide range of time scales. One particularly interesting indicator of this variability is the North Atlantic Oscillation index measuring the fluctuations of predominant weather patterns in the course of the years over the Atlantic and Western Europe. The source of variability is, however, controversial and several possibilities have been envisaged, including oceanic and coupled ocean-atmosphere variability and stratospheric warming, possibly related to ENSO in the tropical Pacific.
Recently we have demonstrated that genuinely coupled LFV can emerge in a very simple low-order, nonlinear, coupled ocean-atmosphere model. This LFV concentrates on and near a long-periodic, attracting orbit. This orbit combines atmospheric and oceanic modes, and it arises for large values of the meridional gradient of radiative input and of the frictional coupling. Chaotic behavior develops around this orbit as it loses its stability. The chaotic dynamics is still dominated by the LFV on decadal and multi-decadal time scales that is typical of oceanic processes. Furthermore, this natural coupled mode is still present as the number of variables is increased in the model.
The presence or not of the LFV has profound impact on the predictability of the system, in particular at long lead times. This aspect and the impact for real world applications will be discussed in some details.

GUOCAN WU - *Beijing Normal University, China*

A study on Soil moisture assimilation based on modified ensemble transform Kalman filter

Assimilating observations to a land surface model can further improve soil moisture estimation accuracy. However, assimilation results largely rely on forecast error and generally cannot maintain a water budget balance. In this study, shallow soil moisture observations are assimilated into Common Land Model (CoLM) to estimate the soil moisture in different layers. A proposed forecast error inflation and water balance constraint are adopted in the Ensemble Transform Kalman Filter to reduce the analysis error and water budget residuals. The assimilation results indicate that the analysis error is reduced and the water imbalance is mitigated with this approach.

WILLIAM YOUNG - *Scripps Institution of Oceanography, USA*

Beta-plane turbulence above topography: form stress and eddy saturation

Wind is an important driver of large-scale ocean currents, imparting momentum into the ocean at the sea surface. This force is almost entirely balanced by topographic form stress (that is the correlation of bottom pressure and topographic slope). The direct effect of bottom Ekman drag in turbulent boundary layers is almost negligible for the momentum balance.

Using a one-layer quasi-geostrophic model, we study the effect of random monoscale topography on forced beta-plane turbulence. The forcing is a uniform steady wind stress that produces both a uniform large-scale zonal flow U(t) and smaller-scale macroturbulence characterized by standing and transient eddies. The large-scale flow U is retarded by a combination of Ekman drag and the domain-averaged topographic form stress produced by the eddies. The topographic form stress typically balances most of the applied wind stress, while the Ekman drag provides all of the energy dissipation required to balance the wind work. A collection of statistically equilibrated numerical solutions delineates the main flow regimes and the dependence of the time-average of U on parameters such as the planetary vorticity gradient beta and the statistical properties of the topography. We obtain asymptotic scaling laws for the strength of the large-scale flow U in the limiting cases of weak and strong forcing.

If beta is significantly smaller than the topographic PV gradient then the flow consists of stagnant pools attached to pockets of closed geostrophic contours. The stagnant dead zones are bordered by jets and the flow through the domain is concentrated into a narrow channel of open geostrophic contours. In most of the domain the flow is weak and thus the large-scale flow U is an unoccupied mean.

If beta is comparable to, or larger than, the topographic PV gradient then all geostrophic contours are open and the flow is uniformly distributed throughout the domain. In this open-contour case there is an ``eddy saturation'' regime in which U is insensitive to large changes in the wind stress. We show that eddy saturation requires strong transient eddies that act effectively as PV diffusion. This PV diffusion does not alter the kinetic energy of the standing eddies, but it does increase the topographic form stress by enhancing the correlation between topographic slope and the standing-eddy pressure field. Using bounds based on the energy and enstrophy power integrals we show that as the strength of the wind stress increases the flow transitions from a regime in which the form stress balances most of the wind stress to a regime in which the form stress is very small and large transport ensues.

WEI ZHOU - *South China Sea Institute of Oceanology, China*

We applied an Ensemble Optimal Interpolation (EnOI) data assimilation method in the BCC_CSM1.1 to investigate the impact of ocean data assimilations on seasonal forecasts in an idealized twin-experiment framework. Pseudo-observations of sea surface temperature (SST), sea surface height (SSH), sea surface salinity (SSS), temperature and salinity (T/S) profiles were first generated in a free model run. Then, a series of sensitivity tests initialized with predefined bias were conducted for a one-year period; this involved a free run (CTR) and seven assimilation runs. These tests allowed us to check the analysis field accuracy against the "truth". As expected, data assimilation improved all investigated quantities; the joint assimilation of all variables gave more improved results than assimilating them separately.

One-year predictions initialized from the seven runs and CTR were then conducted and compared. The forecasts initialized from joint assimilation of surface data produced comparable SST root mean square errors to that from assimilation of T/S profiles, but the assimilation of T/S profiles is crucial to reduce subsurface deficiencies. The ocean surface currents in the tropics were better predicted when initial conditions produced by assimilating T/S profiles, while surface data assimilation became more important at higher latitudes, particularly near the western boundary currents. The predictions of ocean heat content and mixed layer depth are significantly improved initialized from the joint assimilation of all the variables. Finally, a central Pacific El Niño was well predicted from the joint assimilation of surface data, indicating the importance of joint assimilation of SST, SSH, and SSS for ENSO predictions.