JOINT WMO TECHNICAL PROGRESS REPORT ON THE GLOBAL DATA PROCESSING AND FORECASTING SYSTEM AND NUMERICAL WEATHER PREDICTION RESEARCH ACTIVITIES FOR 2015
Met Office, United Kingdom

1. Summary of highlights

The following upgrades were made to the major components of our Production NWP System during the accounting year April 2015-March 2016. The changes were introduced following 2 parallel suites each of 1 month duration to ensure robust changes at expected quality.

PS36 25 August 2015	Migration to new Cray XC40 High Performance Computer system
PS37 15 March 2016	

Table 1 - Global Model and Data Assimilation changes

PS36 25 August 2015	Migration to new Cray XC40 High Performance Computer system
PS37 15 March 2016	

Table 2- Regional Model and Data Assimilation changes

PS36 25 August 2015	Migration to new Cray XC40 High Performance Computer system
PS37 15 March 2016	

Table 3- Global model Data Assimilation changes

PS36 25 August 2015	Migration to new Cray XC40 High Performance Computer system
PS37 15 March 2016	MOGREPS-15 retired.

Table 4- Ensemble Modelling System changes

PS36 25 August 2015	Migration to new Cray XC40 High Performance Computer system
PS37 15 March 2016	Addition of surface current forcing, derived from NW European Shelf Seas model, to UK 4km wave model. 18km Persian Gulf wave model retired.

Table 5 - Ocean and Wave Modelling changes

PS36 25 August 2015	Migration to new Cray XC40 High Performance Computer system
PS37	

15 March 2016	

Table 6 – Sub-seasonal and Seasonal forecasting changes

PS36 **25 August 2015**	Migration to new Cray XC40 High Performance Computer system
PS37 **15 March 2016**	Adoption of new 'ENDGAME' dynamical core. Increase vertical resolution from L38 to L63.

Table 7- Regional air quality model changes

2. Equipment in use Stuart Bell

2.1 HPC Platform

The second phase of a three phase deployment of Cray XC40 systems was accepted in Feb 2016. The current deployment of 6212 nodes comprising a mix of Intel Haswell and Intel Broadwell processors delivers a total compute capacity is 6.8 PFlops (Linpack). A 12PByte Cray Sonexion provides the Lustre File System.

2.2 MASS storage system

New hardware (MASS4G) supplied by Oracle who delivered the tape libraries, tapes, tape drives and robotic; and SGI who delivered the disk storage caching and network elements has been installed and accepted. This will provide the storage capacity to meet the increased data delivered from the Cray HPC platforms. The front end "MOOSE" in-house software has been retained and upgraded. Capacity is expected to reach ~300PBytes by 2020 and current archive rates are approaching 100TB/day..

3. Data and Products from GTS in use Rick Rawlins, Roger Saunders

3.1 Observations

Non-real-time monitoring of the global observing system includes:-

- Automatic checking of missing and late bulletins.
- Annual monitoring checks of the transmission and reception of global data under WMO data-monitoring arrangements.
- Monitoring of the quality of marine surface data as lead centre designated by CBS. This includes the provision of monthly and near-real-time reports to national focal points, and 6-monthly reports to WMO (available on request from the Met Office, Exeter).
- Monthly monitoring of the quality of other data types and the provision of reports to other lead centres or national focal points. This monitoring feeds back into the data assimilation by way of revisions to reject list or bias correction.

Within the NWP system, monitoring of the global observing system includes:-

- An automated quality control system with 3 stages, an internal consistency check, a comparison against model first guess and a buddy check against neighbouring observations.
- A real-time monitoring capability that provides time series of observation counts, reject counts and mean/root-mean-square departures of observation from model background; departures from the norm are highlighted to trigger more detailed analysis and action as required;
- Monitoring of satellite observations includes time series of comparisons of observations versus model background for all data assimilated see http://www.nwpsaf.eu/monitoring.html

The global data assimilation system makes use of the following observation types. The counts are based on a snapshot taken on 12 July 2016.

Observation Code	Number available in 24 hour period	% usage by Data Assimilation
ATOVS Global	3612182	5.4%
ATOVS Local	1100596	
IASI Global	647875	17.2%
IASI Local	11670	
AIRS WF	322650	11.1%
AIRS Local	61020	
ATMS	350880	19.1%
CRIMSS	321360	14.1%
SSMIS	5308740	0.7%
SAPHIR	4800000	1.8%
AMSR-2	13997043	0.5%
MWS (FY-3C)	216360	22.2%
ASCAT	2671704	3.0%
WINDSAT	1252634	
RapidScat	1048255	
ESA HRVW	9017	3.3%
ESA HRWVW	98685	
ESA CSWVW	9591	
ESA CMW	38957	
GOES BUFR	2201058	
MSG WINDS	2691288	
JMA WINDS	1563644	
MSGCSR (SEVIRI Clear)	906144	4.2%
GOESCSR (GOES Clear)	642174	1.5%
ESACSR (MVIRI Clear)	369098	1.7%
GPSRO	3560	40.0%
GPSIWV (GroundGPS)	607540	0.2%
SATAOD	275225	0.1%
MSGAOD	2352311	
LNDSYN	85795	58.2%
SHPSYN	23565	

BUOY	**27950**	
TCBOGUS	**12**	
MOBSYN	**10702**	
METARS	**151429**	
AIREPS	**26492**	**18.1%**
AMDARS	**623946**	
TEMP	**1365**	**71.7%**
PILOT	**818**	
DROPSOND	**2**	
BUFR SONDE	**193**	
WINPRO	**20260**	**16.2%**

Table 8 Observations in Global Data Assimilation on 12 July 2016

3.2 Gridded products

Products from **WAFC** Washington are used as a backup in the event of a system failure. The WAFS Thinned GRIB products are received every 6 hours extending out to **T+36.**

Products from ECMWF are the used as primary guidance at 5 days and beyond and are blended with in-house model products within the site-specific post-processing system.

Models products from other NWP Centres are available to forecasters as additional guidance.

4. Forecasting system

The forecasting system consists of:-

Atmosphere Models David Walters, Mike Bush, Craig Maclachlan

- Global atmospheric forecast model at 17km L70 supported by 4D-Var 6 hour cycle hybrid data assimilation system
- European Mesoscale (4-km) atmospheric forecast model downscaler, reconfigured from the Global atmospheric forecast model.
- UK convection-permitting variable resolution (with inner domain at 1.5-km) atmospheric forecast model supported by 3D-Var 3 hour cycle data assimilation system
- Global atmospheric ensemble forecast model (12 members, 33km L70) with ETKF initial perturbations and Stochastic physics model perturbations running on a 6 hour cycle with products making use of 24 members by multiple cycles via lagging.
- UK convection-permitting variable resolution (with inner domain at 2.2-km) atmospheric downscaler ensemble forecast model (12 members, 2.2km, L70) driven by the Global EPS running on a 6 hour cycle
- Ensemble Sub-seasonal to Seasonal Forecasting System using coupled atmosphere/land/ocean/sea-ice (0.833 × 0.556 degree L85 atmosphere resolution and 0.25 degree ocean resolution), with Stochastic Physics model perturbations. Ensemble members are combined in a lagged ensemble.
- *North Atlantic and Europe regional atmospheric forecast model at 12km L70 supported by 4D-Var 6 hour cycle data assimilation system –**retired**.*

“Wet” Models John Siddorn, Andy Saulter

- Global wave hindcast and forecast (35km) system using WAVEWATCH III®
- European wave hindcast and forecast system using WAVEWATCH III® at 8km resolution
- UK wave hindcast and forecast system using WAVEWATCH III® at 4km resolution
- Atlantic ensemble on SMC grid using WAVEWATCH III® using variable resolution (25:12:6 km)
- Global deep ocean model (NEMO) at 0.25degree
- Regional deep ocean models (NEMO) at 1/12 degree: North Atlantic, Mediterranean, Indian Ocean
- Tidal Shelf-seas models (NEMO): NW European shelf (7 km), Persian Gulf (4 km)
- Tide-surge models for UK Continental Shelf (12km, deterministic and ensemble), Bristol Channel (4 km) and Severn Estuary (1.3 km).

Other Bruce Wright, Simon Jackson

- Post-processing system mapping surface variables on to fixed 2 or 5km grids with topographic adjustment and encompassing an ensemble Nowcasting system
- Site-specific post-processing system including Kalman Filter statistical correction
- Transport and dispersion model
- Air Quality Model at 12km resolution over the UK using a configuration of the Unified Model with chemistry and aerosols.
- Additional regional Model configurations away from the UK to meet particular customer requirements. This includes a 4km resolution model over Lake Victoria region in support of WMO activities and which was extended to cover much of East Africa early in 2014.

4.1 System run schedule and forecast ranges Dave Robinson

RunID	Model Description	Data Time	Start Time	Forecast Period
QU18	Global Update	18Z	0:15	T+9
EK03	UK Ensemble	21Z	0:30	T+36
QN18	Ocean wave updates	18Z	1:50	T+6
Q400	UK 4km	00Z	2:00	T+3
QV00	UK 1.5km	00Z	2:00	T+3
QD00	UK ocean wave	00Z	2:30	T+60
QG00	Global	00Z	2:40	T+144
EG00	Global Ensembles	00Z	3:30	T+72
QW00	Global & NAEX ocean wave s	00Z	4:15	T+144
Q403	UK 4km	03Z	4:20	T+36
QV03	UK 1.5km	03Z	4:25	T+36
Q500	Extended UK 4km	00Z	4:45	T+120
EN00	Global FOAM NEMO	00Z	5:00	T+144
Q600	OSTIA SST	00Z	5:50	
ES00	Shelf Seas	00Z	6:15	T+144
QU00	Global Update	00Z	6:15	T+9
EK03	UK Ensemble	03Z	6:30	T+36
QN00	Ocean wave updates	00Z	7:50	T+6
QV06	UK 1.5km	06Z	7:50	T+3
Q406	UK 4km	06Z	8:30	T+3
QD06	UK ocean wave	06Z	8:30	T+60
QG06	Global	06Z	8:30	T+48
EG06	Global Ensembles	06Z	9:30	T+72

EE06	Extended Surge Ensembles	06Z	9:55
Q409	UK 4km	09Z	9:55 T+36
Q506	Extended UK 4km	06Z	10:15 T+60
QV09	UK 1.5km	09Z	10:15 T+36
EO00	Glosea Seasonal		12:15
QU06	Global Update	06Z	12:15 T+9
EK03	UK Ensemble	09Z	12:30 T+36
QN06	Ocean wave updates	06Z	13:50 T+6
Q412	UK 4km	12Z	14:00 T+3
QV12	UK 1.5km	12Z	14:00 T+3
QD12	UK ocean wave	12Z	14:30 T+60
QG12	Global	12Z	14:40 T+144
EG12	Global Ensembles	12Z	15:30 T+72
QW12	Global, NAEX ocean wave s	12Z	16:15 T+144
Q415	UK 4km	15Z	16:20 T+36
QV15	UK 1.5km	15Z	16:25 T+36
Q512	Extended UK 4km	12Z	17:00 T+120
QU12	Global Update	12Z	18:15 T+9
EK03	UK Ensemble	15Z	18:30 T+36
QN12	Ocean wave updates	12Z	19:50 T+6
QV18	UK 1.5km	18Z	20:00 T+3
QD18	UK ocean wave	18Z	20:30 T+60
QG18	Global	18Z	20:45 T+48
Q418	UK 4km	18Z	21:05 T+3
EG18	Global Ensembles	18Z	21:30 T+72
EM00	Glosea sub-seasonal		21:30
EE18	Extended Surge Ensembles	18Z	21:55
Q518	Extended UK 4km	18Z	22:15 T+60
Q421	UK 4km	21Z	22:20 T+36
QW18	Global & European ocean waves	06Z	22:20 T+60
QV21	UK 1.5km	21Z	22:20 T+36
QM18	Air Quality UM	18z	23:30

Table 9 – Production Schedule

4.2 Medium range forecasting system (4-10 days)

4.2.1 Data assimilation, objective analysis and initialization Rawlins

4.2.1.1 In operation

Analysed variables	Velocity potential, stream function, unbalanced pressure and transformed humidity control variable (Ingleby et al., 2012)
Analysis domain	Global
Horizontal grid	Same as model grid, but resolution is 0.376º latitude and 0.5625º longitude
Vertical grid	Same levels as forecast model
Assimilation method	En-4D-Var - a hybrid method using 4D variational analysis of increments (Rawlins et al.,2007) but with estimates of error statistics augmented by 'errors of the day' obtained from ensemble forecasts (Clayton et al.,

	2012). A Perturbation Forecast (PF) model and its adjoint represent model trajectories during the data window. The PF model operates on the assimilation grid and is based on the full forecast model but simplified to provide fast linear calculations of small increments for fitting observations. In particular the PF model omits most physics schemes. Data is grouped into 6-hour time windows centred on analysis hour for quality control. A pre-conditioning step at lower resolution provides an approximate solution in order to allow timely convergence at full assimilation resolution. A separate Extended Kalman Filter land surface assimilation system supplies analyses of soil moisture derived from screen-level temperature and humidity increments together with ASCAT soil wetness data (Dharssi *et al*., 2011)
Covariance statistics	A hybrid combination of climatological statistics and updated error modes. The latter are obtained using differences between short range Unified Model forecasts from the operational global model ensemble prediction system (MOGREPS-G), valid at the start of the data window. Climatological model error statistics are based on a single, static between an ensemble of short range Unified Model forecasts at resolution (0.562º latitude, 0.376º longitude), processed by a covariance model applying balance and other constraints. Each member is generated using an initial increment taken from an ensemble of perturbed analyses.
Assimilation cycle	6-hourly
Initialisation	Increments are not initialised explicitly, but gravity-wave noise is reduced by use of a weak constraint penalising filtered increments of a pressure based energy norm, similar to the method of Gauthier and Thepaut (2001). The initialised increments are inserted directly at T–3.

4.2.1.2 Research performed in this field: See section 6.

4.2.2 Model Walters

4.2.2.1 In operation

Basic equations	Non-hydrostatic finite difference model with height as the vertical co-ordinate Full equations used with (virtually) no approximations; suitable for running at very high resolution
Independent variables	Latitude, longitude, eta (η), time
Primary variables	Horizontal and vertical wind components, dry virtual potential temperature, pressure, dry density, water vapour mixing raio, cloud water mixing ratios (liquid and frozen), prognostic cloud fractions (liquid, frozen and mixed-phase), prognostic rain mixing ratio, dust aerosol mixing ratio (2 size bins)
Integration domain	Global
Horizontal grid	Spherical latitude-longitude with poles at 90º N and 90º S. Resolution: 0.234º latitude and 0.352º longitude. Arakawa 'C'-grid staggering of variables.
Vertical grid	70 levels Charney-Philips grid staggering of variables The normalised vertical co-ordinate η is hybrid in height, varying from $\eta = 0$ at the surface to the top level at $\eta = 1$, where zero vertical velocity w is applied. The lowest level is purely terrain following and there is a smooth (quadratic) transition to

	a specified number of 'flat' upper levels where the height of each point at a level is constant. Model top is 80km
Integration scheme	Two time-level iterative semi-Lagrangian advection with a pressure correction semi-implicit time stepping method using a Helmoltz solver to include non-hydrostatic terms (Wood et al., 2014). Model time step = 450 s.
Filtering	No explicit filtering is applied.
Horizontal diffusion	None.
Vertical diffusion	None.
Orography	GLOBE 1km orography dataset The model mean orography is calculated using the 1km dataset and then filtered to remove grid-scale and near-grid-scale structure using a sixth-order low-pass implicit tangent filter which is constrained so that the filtering is isotropic in real space. The sub-grid orography fields used by the flow-blocking and gravity wave drag scheme characterise the orography on scales between the model grid-scale and about 6km, which is typically the shortest scale that forces gravity waves. The 1km dataset is therefore filtered to remove the scales less than 6km before the sub-grid fields are derived. The sub-grid orography fields used by the orographic roughness scheme (which represents the effects of scales less than 6km) are calculated from 100m resolution data for the UK and most of Europe. These fields are derived globally by using the GLOBE dataset standard deviation field which has been scaled by a least squares fit between this dataset over Europe and the fields derived from the 100m dataset.
Surface classification	Sea: global sea-surface temperature (SST) analysis performed daily; Sea ice: analysis using EUMETSAT OSI_SAF sea ice.

Physics parameterisations:

The science configuration of the model used for deterministic global and short/medium-range global ensemble forecasting is Global Atmosphere 6.1 (GA6.1). This configuration is described in Walters *et al.* (2016). The highlights of this configuration are as follows:

a) Surface and soil

- Joint UK Land Environment Simulator (JULES: Best *et al.* 2011 and Clark *et al.* 2011).
- Uses a single aggregate tile for surface energy balance.
- 4 layer soil model using van Genuchten (1980) soil hydrology.

b) Boundary layer

- First order turbulence closure
- Unstable boundary layers use a K-profile scheme with non-local fluxes of potential temperature and momentum and a subgrid inversion diagnosis to parametrize entrainment fluxes at the boundary layer top
- Stable boundary layers use a local stability dependent formulation
- Existence and depth of unstable layers are diagnosed initially by moist adiabatic parcels and then adjusted to limit the buoyancy consumption of turbulence kinetic energy

- The resulting diffusion equation is solved using a monotonically-damping second-order-accurate unconditionally-stable numerical scheme
- The kinetic energy dissipated through the turbulent shear stresses is returned to the atmosphere as a local heating term.

c) Cloud

- Prognostic cloud fraction and prognostic condensate cloud scheme (PC2, Wilson *et al.* 2008).
- The prognostic variables are liquid water content, ice water content, liquid cloud fraction, ice cloud fraction and mixed-phase cloud fraction.
- Calculate the impact of each of the physical processes in the model on the cloud fields and then advect the updated cloud fields using the model winds.

d) Precipitation

- Wilson and Ballard (1999) microphysics scheme, coupled with the PC2 cloud scheme.
- Prognostic rain, with one iteration for every two minutes of timestep.
- Abel and Shipway (2007) rain fall speeds.

e) Radiation

- Edwards and Slingo (1996) radiation scheme with a configuration based on Cusack (1999) with a number of significant updates.
- The correlated-k method is used for gaseous absorption with 6 bands and a total of 21 k-terms in the SW, and 9 bands and 33 k-terms in the LW.
- Full radiation calculations made every hours with corrections applied for changing solar zenith angle during intermediate timesteps.
- Sub-grid cloud structure represented using the Monte Carlo Independent Column Approximation with a configuration described in Hill (2011).
- Direct and indirect effects ares included for climatologies of the following aerosols: ammonium sulphate, mineral dust, seasalt, biomass-burning, fossil-fuel black carbon, fossil-fuel organic carbon, and secondary organic (biogenic) aerosols.

f) Convection

- Mass flux scheme based on Gregory and Rowntree (1990) including updraughts and downdraughts, and including momentum transport.
- Different entrainment/detrainment rates and closures for shallow and deep convection.

g) Gravity-wave drag

- Orographic scheme representing sub-grid orography and flow blocking.
- Non-orographic scheme representing the effects of gravity waves in the stratosphere and mesosphere.

4.2.2.2 Research performed in this field See section 6
Developied and tested a series of physics changes to be included in the Global Atmosphere 7.0 (GA7.0) science configuration, which includes a new multilayer snow scheme, improved numerics

in the convection scheme, a number of cloud/radiation developments and a unified stochastic physics package to be applied in all global ensemble and climate modelling systems.

4.2.3 Operationally available Numerical Weather Prediction Products

Global GRIB products routinely available on 2.5degree grid as follows

Heights, temperatures, wind components on standard levels 1000hPa to 30hPa
Relative Humidity on standard levels 1000hPa to 500hPa
Surface temperatures, relative humidity and wind components
Maximum wind components and pressure of max wind
Total accumulated precipitation
Mean sea level pressure
Tropopause temperature and pressure.

For the following forecast times T+96,108,120 and 144. See section 4.3.3 for reference to earlier forecast times.

4.2.4 Operational techniques for application of NWP products

4.2.4.1 In operation

Site-specific deterministic forecasts are stored in our site-specific database for 10000 sites world-wide. A Kalman filter is employed, where synoptic observations of winds and temperatures are available, to correct for local biases. Where observations are not available, physically-based corrections are applied to correct for height differences between the model grid and the sites' height. Forecasts are time-lagged to improve run-to-run consistency, and a fuzzy logic scheme is used to diagnose the weather type.

4.2.4.2 Research performed in this field: See section 6

4.2.5 Ensemble Prediction System (EPS) Tennant

4.2.5.1 In operation

The ECMWF Ensemble Prediction System (ENS) is utilised for medium-range forecasting, mainly during week two of the forecast..

A 12-member global ensemble, MOGREPS-G, is run 4 times per day using a model with a nominal grid length of 33 km. Initial condition perturbations are provided using an ETKF (Ensemble Transform Kalman Filter) method. The model also includes stochastic physics schemes, viz. SKEB, perturbed parameters, and initial perturbations to SST, soil-moisture and deep-soil temperature (Tennant and Beare, 2014) to account for the effect of model errors on forecast uncertainty. Output from MOGREPS–G is post-processed to provide forecasters and customers with numerous chart displays including spaghetti diagrams, ensemble means, individual ensemble members and tracks of tropical and extra-tropical cyclones. Charts are generated showing grid-point probabilities of a wide range of variables including wind-speed, precipitation accumulations and temperature anomalies. In most cases, global ensemble products are based on a lagged pair of MOGREPS-G runs, which allow products to be based on 24 members with a forecast range of 168 hours (7 days). A smaller range of products is also generated from ECMWF ENS data, and some experimental multi-model ensemble products are produced.

In addition Site-specific ensemble forecasts of temperature, wind speed, precipitation cloud cover and sunshine are stored in our site-specific database for 10000 sites worldwide. A Kalman Filter MOS (Model Output Statistics system) is employed to correct for local biases, and derive maximum and minimum temperatures, for over 300 sites world-wide. Ensemble probabilities are calibrated to optimise performance using Rank Histogram verification (Hamill and Colucci 1997). Operational verification shows that the Kalman Filter MOS leads to significant improvements in probabilities compared to direct ensemble output; the calibration adds a small further improvement for certain products. Site-specific ensemble data are also stored from the ECMWF ENS and also include significant wave heights for ocean points.

MOGREPS-G is also used to drive a storm surge model for waters around the British Isles, to provide probabilistic forecasts of coastal storm surges out to 7 days ahead.

The ECMWF ENS is scanned daily for probabilities of severe weather (severe gales, heavy rain or snow) and provides first-guess risk-based warnings to forecasters when defined probability thresholds are exceeded. Verification shows that 3- to 4-day forecasts of severe weather have useful probabilistic skill.

Output from MOGREPS-G is also being written to the TIGGE (The International Grand Global Ensemble) database. The TIGGE database includes a standard set of ensemble forecast outputs from several operational numerical weather prediction centres, and provides an invaluable resource for research into ensemble prediction, especially the benefits of using multi-model ensemble techniques.

4.2.5.2 Research performed in this field: See section 6

4.2.5.3 Operationally available EPS Products

EPS products from ECMWF ENS and the MOGREPS-15 ensemble are operationally supported. Key products from each system include:

ECMWF ENS:

- Ensemble mean of PMSL, 500hPa Geopotential height, 1000-500hPa thickness and 850hPa wet-bulb potential temperature.
- Spaghetti charts of 500hPa height
- Surface weather probabilities for selected surface weather variables over the UK
- First-guess warnings of severe weather over the UK.
- Site-specific meteograms including ocean points for wind and wave height.
- Clustering by regime type.

MOGREPS-G:

- Mean and spread for PMSL, 500hPa Geopotential height, 1000-500hPa thickness and 850hPa wet-bulb potential temperature
- Probabilities of multiple thresholds of surface weather variables including min/max temperatures, windspeed and gusts, precipitation accumulations, snowfall accumulations, low cloud and visibility.
- Site-specific products for 10000 sites worldwide (5000 in UK)
- Tropical and extra-tropical cyclone tracking
- Clustering by regime type.
- Storm surge ensemble forecasts for UK coastlines.

4.3 Short-range forecasting system (0-72 hrs) Bush

Our global modelling system does of course contribute to the short range forecasting for aviation and for other customer requirements away from the UK. Additionally we run limited area modelling systems at higher resolution (4km Europe and 1.5km UK) which are described in this section. We also run short-range ensemble systems, in particular a variable resolution 2.2km UK ensemble, also described.

4.3.1 Data assimilation, objective analysis and initialization

4.3.1.1 In operation

Local Data assimilation (for both 4km and variable resolution 1.5km models)

Analysis variables	as in the global model, but includes aerosol content
Analysis domain	as model integration domain
Horizontal grid	model resolution (3km fixed resolution analysis grid is used for the variable resolution model)
Vertical grid	as model levels
Assimilation method	3DVAR with adaptive vertical grid (Piccolo and Cullen, 2011, 2012); plus latent heat nudging scheme for radar precipitation data

Assimilation cycle	Analysis increments are introduced gradually into the model using an Incremental Analysis Update (Bloom *et al.,* 1996) over a 2-hour period (T−1 to T+1), while increments from rainfall data are added by nudging.
Data	In addition to the data referenced in Table 8 which might be applicable to a regional domain, we also use - Surface visibility observations (Clark *et al*. 2008) - a cloud top pressure and amount derived from SEVIRI is assimilated (Renshaw and Francis, 2011). - 12.5km coastal winds from ASCAT on Metop-A/B - An hourly precipitation rate analysis, derived from radar, is assimilated by latent-heat nudging (Jones and Macpherson, 1997, Macpherson, 2001). - A reconfigured global soil-moisture analysis (based on screen nudging) and ASCAT soil wetness. - temperature and relative humidity from roadside sensors, - high-resolution Atmospheric Motion Vectors, - SEVIRI Channel 5 radiances over low cloud, - Doppler radial winds from UK weather radars.

4.3.1.2 Research performed in this field – see section 6

4.3.2 Model

4.3.2.1 In operation

The 2 regional /local model configurations share many model components with global (see section 4.2.2.1) and with each other. Significant differences are as follows

UKV differences from Global

Integration domain	The British Isles and all surrounding sea areas, near-continental Europe (approximately 60º N to 48º N, 11º W to 3º E in the inner area, 62º N to 46º N, 13º W to 5º E in the full domain)
Horizontal grid	Spherical rotated latitude-longitude with pole at 37.5º N, 177.5º E. Resolution: Variable; 0.0135º in the area of interest stretching to 0.036 º in the borders.
Vertical grid	70 levels and 40-km top
Time step	50s
Horizontal diffusion	None, instead a Smagorinsky Subgrid Turbulence scheme is used.
Vertical diffusion	None, however a local Richardson Number based boundary layer parameterisation extends from the top of the non-local Boundary Layer to the top of the model to allow mixing.
Orography	No subgrid orographic scheme is used.
Boundary values	Specified from Global forecast model with the previous data time (T−3, i.e. forecasts from 0000, 0600, 1200 and 1800 UTC).

Physics parametrizations:-

a) Convection	Convection is explicitly resolved.
b) Gravity wave Drag	Gravity wave drag is explicitly resolved

c) Cloud	Uses diagnostic scheme (Smith, 1990) instead of prognostic (PC2)
d) Boundary layer	Contribution to mixing from Boundary Layer and Subgrid Turbulence schemes blended to provide a smooth transition in turbulence the grey zone. Stochastic perturbations of theta in the bottom level to improve initiation of convection.

Euro4 differences from global:-

Integration domain	From the NW Atlantic including Iceland to the Black Sea and northern Africa (approximately 70º N to 30º N, 20º W to 50º E, but distorted due to rotated grid).
Horizontal grid	Spherical rotated latitude-longitude with pole at 41º N, 193º E. Resolution: 0.04º.
Vertical grid	70 levels and 40-km top
Time step	100s
Horizontal diffusion	2D Smagorinsky subgrid turbulence scheme
Vertical diffusion	None
Orography	A simpler and more robust sub-gridscale orography scheme; Orographic roughness parameters derived from 1-km (based on 100-m) data.
Boundary values	Specified from global forecast model with the previous data time (T–6, i.e. forecasts from 1800, 0000, 0600 and 1200 UTC).

Physics parameterisations: mostly same as global model. The main exception is the continued use of the diagnostic (Smith, 1990) scheme instead of PC2 (prognostic).

4.3.2.2 Research performed in this field : see section 6

4.3.3 Operationally available NWP products

Global GRIB products routinely available on 2.5degree grid as follows
- Heights, temperatures, wind components on standard levels 1000hPa to 30hPa
- Relative Humidity on standard levels 1000hPa to 500hPa
- Surface temperatures, relative humidity and wind components
- Maximum wind components and pressure of max wind
- Total accumulated precipitation
- Mean sea level pressure
- Tropopause temperature and pressure.

For the following forecast times T+0 to T+48 in 6 hour steps, T+48 to T+96 in 12 hour steps

Regional Model GRIB products (from the Euro4 model) are available on a 1.25 degree grid. As follows
- Heights, temperatures, wind components on standard levels 1000hPa to 100hPa
- Relative Humidity on standard levels 1000hPa to 500hPa
- Surface temperatures, relative humidity and wind components
- Total accumulated precipitation
- Mean sea level pressure
- Fog Fraction, Wind Mixing, Sensible and Latent Heat Flux, Net Solar radiation and Net IR Radiation (*)

For the following times T+0 to T+36 in 3 hour steps except for the (*) items which are available to T+24

Additionally global cut-outs covering Africa are available at 0.36 degree resolution for the following fields

Accumulated dynamic and convective precipitation
500hPa height
Outgoing longwave radiation
Mean sea level pressure
850 hPa Wet bulb potential temperature
700hPa, 850hPa and 925hPa Relative Humidity and Temperature
200hPa, 700hPa and 850hPa wind components
Surface temperatures and wind components

For the following times T+0 to T+60 in 6 hour steps

4.3.4 Operational techniques for application of NWP products Jackson

4.3.4.1 In operation

Shorter-range site-specific forecasts are treated as described in section 4.2.4, including Kalman Filtering and time-lagging. Hourly gridded nowcasts over the UK area are generated on a 2km grid (UK National Grid projection) using the UKPP system to provide short-range guidance on rainfall, visibility, clouds etc. Site-specific forecasts from these nowcasts are included in the in the data feed to the site-specific database to ensure that short-range forecasts are kept up to date.

4.3.4.2 Research performed in this field – see section 6

4.3.5 Ensemble Prediction System Hagelin

4.3.5.1 In operation

MOGREPS (Met Office Global and Regional Ensemble Prediction System) provides a 12-member UK ensemble at 2.2km resolution running 4 times daily to 36h ahead, MOGREPS-UK. The global ensemble, MOGREPS-G (see section 4.2.5), provides the lateral boundary conditions for the regional ensemble. Initial condition perturbations are provided through the ETKF (Ensemble Transform Kalman Filter) method calculated using the global ensemble. The initial conditions for MOGREPS-UK are obtained by blending the perturbations from MOGREPS-G with the UK determenistic analysis using the Incremental Analysis Update. Chart-based products include probabilities for a wide variety thresholds for surface parameters relevant to the short-range forecast, plus also postage stamp charts.

4.3.5.2 Research performed in this field – see section 6

4.3.5.3 Operationally available EPS Products

EPS products from global ensemble MOGREPS-G are operationally supported. Key products include:

- Mean and spread for PMSL, 500hPa Geopotential height, 1000-500hPa thickness and 850hPa wet-bulb potential temperature
- Probabilities of multiple thresholds of surface weather variables including min/max temperatures, windspeed and gusts, precipitation accumulations, snowfall accumulations, low cloud and visibility.
- Site-specific products for around 15000 sites worldwide (over 5000 in UK)
- Storm surge ensemble forecasts for UK coastlines.

4.4 Nowcasting and Very Short-range Forecasting Systems (0-6 hrs) Wright

4.4.1 Nowcasting system

4.4.1.1 In operation

UKPP - UK Post Processing System for Nowcasting and Product generation

The UKPP post-processing system produces analyses and nowcasts of precipitation and other surface weather parameters. These include a set of soil moisture products, precipitation type, visibility, cloud amount, cloud base and cloud top height, wind speed and direction, temperature, gust intensity, towering convection and probabilities of snow, lightning and fog for the period T+0 to T+6 hours. Products are refreshed on a sub-hourly orhourly cycle. Nowcasts are produced by blending current observations with forecasts from the most recent run of a convection permitting configuration of the Unified Model (currently, the 1.5 km grid length UKV). The UKV forecasts are re-projected and interpolated on to a 2km grid. In the case of precipitation and cloud variables, observations are advected using motion fields diagnosed from a time series of recent, radar and satellite-based analyses of surface precipitation rate. For precipitation, the blending of the extrapolation nowcast with a UKV forecast is performed using a scale decomposition technique. This recognises the markedly non-linear relationship between predictability and spatial scale (dynamic scaling), and allows the contribution made by the extrapolation nowcast and UKV forecast to vary with averaging scale and lead time.

In most cases, the nowcasts generated within UKPP are deterministic solutions, although for some variables (precipitation, lightning and fog) neighbourhood sampling and other post-processing techniques are applied to account for nowcast uncertainties and provide probabilistic guidance. For precipitation, an ensemble of 24 members is generated on a 15 minute cycle using scale decomposition and noise generation techniques integrated within the Short-Term Ensemble Prediction System. These ensembles are employed by the FFC for operational, fluvial and pluvial flood prediction using a distributed hydrological model.

Beyond T+6 hr, UKPP provides 2km post-processed NWP forecast products in a consistent format to the Nowcast products. These are updated in line with forecast model product delivery: 3 hourly from the UKV 1.5km model out to T+36 and 6 hourly from the Euro4 4.4km model out to 60 hours or 5 days. A seamless product out to 5 days is also available, which combined the nowcast and post-processed forecasts from the models.

Ensemble products are also being generated from the MOGREPS-UK 2.2km convection-permitting ensemble every 6 hours out to T+36. STEPS is used to generate MOGREPS-UK-based blended, ensemble nowcasts (every 15 minutes to T+7 hours) and forecasts (every 6 hours out 32 hours) of precipitation. Noise generation techniques are employed to increased the ensemble size from 12 members to 24 members with a view to better characterising the convective scale forecast uncertainties for flood forecasting applications. An extended, 2km precipitation forecast out to 6.5 days using STEPS to statistically downscale MOGREPS-G global ensemble precipitation forecasts was introduced operationally this year. These ensemble precipitation predictions are used to drive a 1km hydrological model, Grid-to-Grid (G2G), which provides predictions of river flows and surface run-off.

Euro4 model data are also post-processed onto a 5km grid covering most of Europe and a nowcast for this area is also run every hour. Global model data are also post-processed (downscaled) onto two grids covering the earth, at 15km and 25km resolution at the pole, although this will be rationalised to a single grid in future. The aim is to provide a one-stop shop for a consistent set of post-processed model fields and nowcasts.

Grids	There are several configurations, one covering the UK, one covering the European area and a further one covering the globe. The UK grid is set up on Transverse Mercator projection (UK National Grid), with the domain covering a domain approximately 48^{o} N to 60^{o} N, 13^{o} W to 6^{o} E.,The European grid currently uses a different Transverse Mercator projection (UTM32), although this is likely to change in the future, with a domain extending from 30^{o} W to 43^{o} E at 60^{o} N and from 10^{o} W to 25^{o} E at 35^{o} N. The Global area uses latitude-longitude grid, with grid-spacing s of 0.1351 deg and 0.2252 ded.,

Data Inputs	Imagery from the UK and European radar, Meteosat and MSG visible and infrared imagery, NWP model fields (UKV, Euro4, Global, MOGREPS-UK and Global models) and surface weather reports
Forecast time step	5 minutes for precipitation forecasts to T+1 and 15 minute to T+6, but 60 minutes for other fields.

4.4.1.2 Research performed in this field – see section 6

4.5 Specialized numerical predictions

4.5.1 Assimilation of specific data, analysis and initialization (where applicable)

4.5.1.1 In operation

Global ocean model – FOAM (Forecasting Ocean Assimilation Model) Deep ocean Siddorn

Data assimilation	Uses NEMOVAR (Mogensen et al., 2009); a 3D variational data assimilation system developed for use in the NEMO ocean model. Temperature and salinity profile data, sea-surface temperature data (in-situ and satellite), altimetric sea-surface height data and sea-ice concentration data are assimilated. Analysis steps are performed once per day over a 2 day analysis period, with a first-guess-at-appropriate time scheme used to calculate the model equivalents of the observations, and the Incremental Analysis Updates scheme of Bloom et al. (1996) used to add in the increments. The scheme includes multivariate balance relationships (Weaver et al., 2005) and uses a diffusion operator to efficiently model univariate correlations (Mirouze and Weaver, 2010). A pressure correction technique (Bell et al. 2004) is employed to improve the dynamical balance near the equator, large-scale biases in satellite SST data are corrected using the scheme described in Storkey et al. (2010), and errors in the mean dynamic topography are corrected using the scheme of Lea et al. (2008).

Regional ocean models – FOAM (Forecasting Ocean Assimilation Model) Deep ocean

Data assimilation	Uses NEMOVAR (Mogensen et al., 2009); a 3D variational data assimilation system developed for use in the NEMO ocean model. Temperature and salinity profile data, sea-surface temperature data (in-situ and satellite), altimetric sea-surface height data and sea-ice concentration data are assimilated. Analysis steps are performed once per day over a 2 day analysis period, with a first-guess-at-appropriate time scheme used to calculate the model equivalents of the observations, and the Incremental Analysis Updates scheme of Bloom et al. (1996) used to add in the increments. The scheme includes multivariate balance relationships (Weaver et al., 2005) and uses a diffusion operator to efficiently model univariate correlations (Mirouze and Weaver, 2010). A pressure correction technique (Bell et al. 2004) is employed to improve the dynamical balance near the equator, large-scale biases in satellite SST data are corrected using the scheme described in Storkey et al. (2010), and errors in the mean dynamic topography are corrected using the scheme of Lea et al. (2008).

Shelf-seas forecast model – FOAM (Forecasting Ocean Assimilation Model) Shelf seas

Data assimilation	Uses NEMOVAR (Mogensen et al., 2009); a 3D variational data assimilation system developed for use in the NEMO ocean model. Sea-surface temperature data (in-situ and satellite) are assimilated. Analysis steps are performed once per day over a single day's analysis period, with a first-guess-at-appropriate time scheme used to calculate the model equivalents of the observations, and the Incremental Analysis Updates scheme of Bloom et al. (1996) used to add in the increments. Large-scale biases in satellite SST data are corrected using the scheme described in Storkey et al. (2010).

4.5.1.2 Research performed in this field – see section 6

4.5.2 Specific Models (as appropriate related to 4.5)

4.5.2.1 In operation

Global ocean model – FOAM (Forecasting Ocean Assimilation Model) Deep ocean Siddorn

Model type	The FOAM system (Storkey *et al* 2010) uses the Global Ocean 5.0 (GO5.0) configuration (Megann *et al* 2014) of the NEMO ocean community code (Madec 2008). It uses a linear free-surface and an energy- and enstrophy-conserving form of the momentum advection. The lateral boundary condition on the momentum equations is free slip. The horizontal momentum diffusion uses a combination of bilaplacian operators. The tracer equations use a TVD advection scheme and the tracer diffusion operator is laplacian and along-isopycnal. The vertical mixing uses a single-equation TKE scheme with an algebraic expression for the mixing length based on the local density. Sea ice is simulated using the CICE sea ice model (Hunke and Lipscomb, 2010).
Integration domain	Global
Horizontal grid	A tripolar curvilinear Arakawa-C grid giving 0.25º x 0.25º resolution at the equator and increasing resolution towards the poles
Vertical grid	75 geopotential (z) levels with partial cells at the seabed and high resolution near the surface, including a 1m surface cell.
Surface fluxes	Bulk formulae using fields from the global NWP model, 3-hourly with 1-hourly winds

Wave hindcast and forecasting system: global wave model Saulter

Model type	3rd generation spectral phase averaged WAVEWATCH III® (Tolman, 2009)
Integration domain	Global
Grid	Spherical latitude-longitude from 80ºN to 79ºS Resolution: 1/3º latitude, 2/5º longitude
Frequency resolution	30 frequency components spaced logarithmically between 0.0412 Hz and 0.653 Hz
Direction resolution	24 equally spaced direction components
Integration scheme	Fractional time-stepping method Advection timestep is frequency dependent (max of 300s), intra spectral timestep = 1800s, source term integration timestep = 60s. Spatial advection scheme is the 2nd order scheme of Li (2008)
Boundary forcing	Winds at 10 m, updated hourly
Surface classification	Sea-ice analyses as in the global model
Physics parameterisations	Source terms (input and dissipation) of WAM Cycle 4, using modifications documented in Saulter (2015). Non-linear interactions calculated using discrete interaction approximation (DIA) (Hasselman et. al, 1985) Shallow-water terms are included (shoaling, bottom friction, refraction). Surf breaking term of Battjes & Janssen (1978).

Regional ocean models – FOAM (Forecasting Ocean Assimilation Model) Deep ocean Siddorn

Model type	The FOAM system is based on the NEMO ocean community code (Madec 2008). It uses a linear free-surface and an energy- and enstrophy-conserving form of the momentum advection. The lateral boundary condition on the momentum equations is partial slip. The horizontal momentum diffusion uses a combination of laplacian and bilaplacian operators. The tracer equations use a TVD advection scheme and the tracer diffusion operator is laplacian and along-isopycnal. The vertical mixing uses a single-equation TKE scheme with an algebraic expression for the mixing length based on the local density. Sea ice is simulated in the North Atlantic configuration using the CICE sea ice model.
Integration domain	(1) North Atlantic; (2) Mediterranean; (3) Indian Ocean
Horizontal grid	(1) North Atlantic $1/12^o$ x $1/12^o$ rotated grid, approx 20N - 80N, 90W - 20E (2) Mediterranean $1/12^o$ x $1/12^o$ regular lat-lon grid, 30N - 47.5N, 05.5W - 42E (3) Indian Ocean $1/12^o$ x $1/12^o$ regular lat-lon grid, 25S - 31N, 33E - 106E
Vertical grid	50 geopotential (z) levels with partial cells at the seabed and high resolution near the surface, including a 1m surface cell.
Surface fluxes	Bulk formulae using fields from the global NWP model, 3-hourly plus 1-hourly winds
Boundary data	From global FOAM

Wave hindcast and forecasting system: regional wave models Saulter

All models use a flavour of WAM Cycle 4 as the source term physics package based on modifications in Bidlot et al. (2012). All deterministic configurations are run 4 times daily to 66hrs and Global, European and Persian Gulf models are run or 144hrs twice daily. All model use 17km wind forcing from the global atmospheric model. The Atlantic ensemble runs 4 times daily to 168hrs forced by MOGREPS-G ensemble members.

Model type	3rd generation spectral phase averaged WAVEWATCH III® (Tolman, 2009)
Integration domain	North-West European continental shelf
Integration domain	Persian Gulf
Integration domain	European
Integration domain	Atlantic ensemble
Grid	European rotated spherical latitude-longitude from approx 32º N to 70º N and 20º W to 42º E. Resolution: 0.08º latitude, 0.08º longitude; UK rotated spherical latitude-longitude from approx 48º N to 61º N and 12º W to 5º E. Resolution: 0.04º latitude, 0.04º longitude; Persian Gulf 47.5-59.98 E, 22.5-30.5 N, 0.04^o x 0.04^o (approx 4km); Atlantic ensemble: variable resolution grid 6-12-25km. Longitudinal resolution doubles at higher latitudes (60N, 75.5N, 82.8N)
Boundary forcing	1) European, UK, PG: winds from the global NWP model for 66-hour forecast (4 times daily) with (Persian Gulf European) extension to 144hrs twice daily. The Atlantic ensemble is forced by MOGREPS-G ensemble members. 2) Spectral values at lateral boundaries from the global wave model, updated hourly

	3) UK model applies hourly surface current fields derived from the AMM7 Northwest European Shelf Seas model.
Surface classification	Sea ice as in global model.
Physics parameterisations	All models use source term physics from WAM Cycle 4 derivative based on Bidlot et al. (2012)

Shelf-seas forecast model – FOAM (Forecasting Ocean Assimilation Model) Shelf seas Siddorn

Model type	The FOAM system is based on the NEMO ocean community code (Madec 2008) which has been adapted for shelf seas. A configuration of this model is running for the NW European shelf area (O'Dea et al 2010). It uses the non-linear free surface option, with baroclinic total variation diminishing (TVD) advection scheme and k-epsilon turbulent mixing.
Integration domain	North-West European continental shelf
Horizontal Grid	Spherical latitude-longitude from 40º N to 65º N, and from 20º W to 13º E. Resolution 7km latitude, 7km longitude
Vertical Grid	51 levels, using a hybrid S/sigma/z vertical co-ordinate (Siddorn and Furner 2013)
Boundary forcing	1) Hourly winds and pressures, 3-hourly averaged fluxes from global NWP model; 2) Deep-ocean temperature and salinity, barotropic current and elevation from the Atlantic FOAM model; 3) River inflows – hydrological model inputs from SMHI's E-Hype; 4) Tidal elevations from 15 harmonic constituents.
Surface classification	No sea ice; no wetting or drying.
Ecosystem model	The physical model has been coupled with a generic ecosystem model, ERSEM-2004 (Blackford *et al*., 2004). The ERSEM code is driven by temperature, salinity and diffusivity from the physical model. ERSEM has 100 biological, pelagic and benthic state variables with multiple classes of phytoplankton and zooplankton. The model also considers bacteria, dissolved and particulate organic matter and nutrients.

Storm-surge model Saulter

A depth-averaged storm-surge model, developed by the Proudman Oceanographic Laboratory, is run operationally on behalf of DEFRA (the Department of the Environment, Food and Rural Affairs) for the Storm-Tide Forecasting Service. The model is implemented on a grid at 1/9º by 1/6º resolution covering 48º N to 63º N, 12º W to 13º E and is forced at the deep-ocean boundaries by 15 tidal harmonic constituents. The model is run 4 times daily, using hourly values of surface pressure and 10-m winds from the NWP model to provide a 36-hour forecast. 7-days ahead ensemble storm-surge forecasts are also provided using wind and pressure forcing from the MOGREPS-G ensemble (see 4.2.5.1, 4.2.5.3, 4.3.5.3, 4.5.5.1).

Transport and dispersion model Hort

A model for short- to long-range transport and dispersion (NAME – Numerical Atmospheric-dispersion Modelling Environment) is available to be run in the event of a atmospheric release of hazardous pollutants. Applications include nuclear emergencies, volcanic eruptions, chemical releases or fires, biological species e.g. the foot and mouth virus and plant spores, and certain disease vectors e.g. the Bluetonge vector. With a comprehensive chemistry scheme it is also used for understanding air quality, for episode studies and volcanic gases. The model provides forecasts of concentrations at any altitude as well as wet and dry deposition to the surface. It uses analysis and forecast fields from global and high resolution limited area NWP models maintained in on-line archives. The NAME model may be run at any time in hindcast or forecast mode. The model can also be used to compute three-dimensional trajectories.

Model type	Three-dimensional Lagrangian particle Monte Carlo model simulating the short- or long-range transport, dispersion and deposition of airborne pollutants
Domain	Arbitrary from global to local nested as required.
Model grid	Lagrangian model so no actual model grid. However can be considered to have a resolved resolution identical to the driving NWP be that global, or limited area high resolution models (e.g. 1.5 km over UK as of April 2013). The transport model can access fields from multiple input NWP models simultaneously with an option to use the best resolution available at every particle position. The output grids are user defined and of any resolution.
Meteorological input	Meteorological fields from the driving NWP model (Global and Limited Area); single site observations (for local dispersion); and high-resolution rainfall rates derived from radar.
Integration scheme	A forward Euler-Maruyama method is used to solve the stochastic differential equations governing the particle positions. Two different schemes are available. For the diffusive long range scheme the time step is specified by the user. For the near-source scheme with velocity memory, the time step has an upper limit determined by the user but the time step is refined as necessary to resolve the changes in particle velocity.
Parameterisations	Range of random walk schemes used to represent mixing due to turbulence, utilising profiles of velocity variances and time scales. Parameterisations include: low-frequency wind meandering, plume rise, gravitational settling, the venting of pollutants from the boundary layer by strong convection, and small-scale entrainment at the boundary-layer top. Loss processes include: wet and dry deposition, biological species loss due to environmental conditions e.g., high temperature and low humidity. Radiological processes consisting of half-life decay, decay chains and cloud gamma radiation shine. A detailed chemistry scheme (37 species) includes both dry and aqueous phase reactions.
Special features	Utilises high-resolution rainfall rates derived from radar products for detailed wet deposition over north-west Europe. Source attribution scheme for identifying the origin of material at a given receptor; Can handle multiple and complex sources.

Air Quality Forecast Model Agnew

AQUM (Air Quality in the Unified Model) is a limited area application using the Global Atmosphere configuration of the UM (Walters et al., 2016), which is almost identical to that used for global NWP.. The UKCA sub-model for gas phase chemistry is used, together with the CLASSIC aerosol scheme.

Model type	Three-dimensional Eulerian with on-line chemistry and aerosol coupling.
Domain	Limited area covering UK, Ireland and the near continent
Model grid	A 12 km horizontal grid with 63 non-uniform levels in the vertical, extending to approximately 39km.
Meteorological input	Meteorological initial and lateral boundary conditions from the Met Office Global Model.
Integration scheme	Iterative semi-implicit, semi-Lagrangian (Wood et al., 2014)
Parameterisations	Boundary layer mixing is parameterised with a non-local, first-order closure, multi regime scheme (Lock et. al. 2000). Convection is

	represented with a mass flux scheme with downdraughts, momemtum transport and CAPE closure (Gregory and Rowntree, 1990). Gas phase chemistry uses the 'Regional Air Quality' scheme which includes 40 transported and 18 non-transported species, on-line photolysis and removal by wet and dry deposition. More details are available in Savage et al., 2013).
Special features	Chemical lateral boundary fluxes are taken from the ECMWF C-IFS model. Pollutant emissions are derived from the UK National Atmospheric Emission Inventory (for the UK) and MACC (rest of Europe). A high resolution shipping dataset is used for UK waters, North Atlantic and North Sea.

4.5.2.2 Research performed in this field – see section 6

4.5.3 Specific products operationally available Saulter

Global Wave Model GRIB products routinely available on 2.5degree grid as follows

- Swell Direction, Height and Period.

For the following forecast times T+0 to T+48 in 6 hour steps, T+48-120 in 12 hour steps

4.5.4 Operational techniques for application of specialized numerical prediction products *(MOS, PPM, KF, Expert Systems, etc..)* (as appropriate related to 4.5)

4.5.4.1 In operation

none

4.5.4.2 Research performed in this field – see section 6

4.5.5 Probabilistic predictions (where applicable)

4.5.5.1 In operation

Storm-surge model Saulter

The Storm Surge Model (described at 4.5.2.1) is also run twice daily in a 24-member ensemble driven from NWP EPS Systems MOGREPS-G to T+168.

4.5.5.2 Research performed in this field – see section 6

4.5.5.3 Operationally available probabilistic prediction products

Not freely available. Surge ensemble Products for the UK are delivered to the Environment Agency under contract.

4.6 Extended range forecasts (ERF) *(10 days to 30 days)* Maclachlan

and

4.7 Long range forecasts (LRF) *(30 days up to two years)*

4.7.1 In operation

The ECMWF Ensemble Prediction System (ENS) is utilised for days 10-15 (see section 4.2.5).. Beyond that the monthly and seasonal forecasting system (GloSea5) supports this requirement.

GloSea5, features a high horizontal resolution. The atmosphere and land surface resolution have a resolution of 0.833 × 0.556 degrees .The grid spacing in the ocean and sea-ice models is 1/4 degree.The ocean and sea-ice in the model are initialised using the NEMO 3-dimensional variational ocean data assimilation based on the multi-institution NEMOVAR project. This data assimilation system uses the same resolution and physical parameterisations as the ocean model in GloSea5 and includes sea-ice assimilation.

A full description of GloSea5 can be found in MacLachlan et al., 2014.

Initialisation

Daily forecast initialisation

GloSea5 forecasts are initialised daily (using the 00Z analysis) with two ensemble members run to 64 days ahead and two ensemble members run to 216 days ahead. A stochastic physics scheme, SKEB2 (Bowler et al. 2009), is used to give spread between members initialised from the same analysis.

Seasonal forecasts are updated weekly using a lagged approach combining all forecast members available from the last three weeks to generate a 42-member ensemble for the next 6 months.

Monthly forecasts are updated daily using a lagged approach combining all forecast members available from the last 7 days to generate a 28-member ensemble for the next 45 days.

A companion hindcast set with 12 ensemble members is generated in real time covering the 1993-2015 period.

The initial atmospheric conditions for the forecast members are generated from the Met Office operational Numerical Weather Prediction analysis. The ocean and sea-ice initial conditions are taken from the integrated Met Office ocean data assimilation system (FOAM).

Re-analyses from the European Centre for Medium-Range Weather Forecasts' (ECMWF) ERA-Interim project are used to initialise the atmosphere and land surface in the hindcast members. Soil moisture is initialised in the forecast and hindcast from a climatology. The same system used for the initialisation of the ocean and sea-ice has been run with historical forcing to produce a re-analysis. This is used to initialise the ocean and sea-ice components in the hindcast. This is discussed in the next section.

Ocean and sea-ice initialisation

GloSea5 uses the Forecast Ocean Assimilation Model (FOAM) Ocean Analysis (Blockley 2013) to initialise the ocean and ice components of the coupled forecast. An identical product, the GloSea5 Ocean and Sea Ice Analysis, a 26 year (1990- 2015) re-analysis, supplies initial conditions for the hindcasts. Both ocean analyses use the new NEMOVAR (Waters2013; Mogensen et al. 2012) assimilation system developed jointly by the UK Met Office, CERFACS, INRIA/LJK, andECMWF. For the historical GloSea5 Ocean and Sea Ice Analysis the observations system and surface boundary forcing had to be changed, except for this the analyses are completely identical.

The NEMOVAR system, used to create the forecast and hindcast analyses, uses the same ocean and sea-ice model (NEMO/CICE ORCA 0.25 L75) as the coupled model used in GloSea5. In the ocean–sea-ice data assimilation system the surface boundary forcing is calculated using the CORE bulk formula formulation of Large and Yeager (2009). The Met Office NWP atmospheric analysis is used to force the forecast ocean analysis (FOAM) and ERA-I atmospheric analysis (Dee et al. 2009) is used for the hindcast ocean re-analysis (GloSea5 Ocean and Sea Ice Analysis).

NEMOVAR is a multivariate, incremental 3D-VAR first guess at appropriate time (FGAT) system. The system implemented at the Met Office operates on a daily cycle with a 1-day time window and uses an incremental analysis step. It assimilates both satellite and in-situ observations of Sea Surface Temperature (SST), sea level anomaly satellite data, sub-surface temperature and salinity profiles, and satellite observations of sea ice concentration. The temperature, salinity and sea level observations are assimilated in a multi-variate fashion using balance relationships between the variables (hydrostatic and geostrophic balance, plus preservation of the T-S relationship in density), while the sea ice concentration is assimilated as a univariate field. Furthermore, bias correction schemes are implemented to reduce the bias inherent in satellite measurements of SST (Donlon et al. 2012; Martin et al. 2007) and to reduce the bias in the (supplied) mean dynamic topography correction required to convert measurements of sea level anomaly into sea surface height (Lea et al. 2008).

Model configuration

The Global Coupled 2.0 (GC2.0) science configuration (Williams et al., 2015) used in the seasonal forecast system is comprised of the following components:

• Atmosphere: Met Office Unified Model (UM; Brown et al. (2012)), Global Atmosphere 6.0 (Walters et al., 2016)

• Land surface: Joint UK Land Environment Simulator (JULES; Blyth et al. (2006)), Global Land 6.0 (Walters et al., 2016)

• Ocean: Nucleus for European Modelling of the Ocean (NEMO; Madec (2008)), Global Ocean 5.0 (Megann et al., 2014)

• Sea-ice: The Los Alamos Sea Ice Model (CICE, Hunke and Lipscomb (2010)), Global Sea-Ice 6.0 (Rae et al., 2015)

The stochastic physics scheme SKEB2 (Bowler et al. 2009) is included to provide small grid-level perturbations during the model integration

4.7.2 Research performed in this field – see section 6

4.7.2 Operationally available EPS LRF products

For the UK, products are interpreted by forecasters and provided to the public as text forecasts. Otherwise forecasts are tailored for particular customers to meet agreed requirements. Global forecasts are included in the WMO Long-Range Forecast Multi-Model Ensemble (https://www.wmolc.org). A standard package of monthly means is available to other National Met Services. This data is updated each month. The following variables are available on a 1x1 degree grid: near surface temperature, MSLP, precipitation, surface temperature, geopotential height (500hPa), temperature (850hPa).k A subset of GloSea5 output will be made freely available through the Copernicus Climate Change Service – Seasonal Forecasts project.

5. Verification of prognostic products

5.1

Statistic	Parameter	Area	Verified against	T+24	T+72	T+120
RMS error(m)	Z 500	N.Hem	Analyses	6.39	19.71	40.64
RMS error(m)	Z 500	S.Hem	Analyses	7.98	25.00	50.79
RMS error(m)	Z 500	N.America	Observations	9.05	20.04	38.68
RMS error(m)	Z 500	Europe	Observations	11.16	21.75	42.39
RMS error(m)	Z 500	Asia	Observations	12.69	21.10	36.96
RMS error(m)	Z 500	Aus/NZ	Observations	11.52	18.82	33.37
RMSVW error (m/s)	W 250	N.Hem	Analyses	3.30	7.37	12.26
RMSVW error (m/s)	W 250	S.Hem	Analyses	3.51	8.01	13.48
RMSVW error (m/s)	W 250	N.America	Observations	5.57	9.51	14.49
RMSVW error (m/s)	W 250	Europe	Observations	5.00	8.99	14.75
RMSVW error (m/s)	W 250	Asia	Observations	5.21	8.45	12.28
RMSVW error (m/s)	W 250	Aus/NZ	Observations	5.05	8.06	11.85
RMSVW error (m/s)	W 850	Tropics	Analyses	1.73	2.74	3.44
RMSVW error (m/s)	W 250	Tropics	Analyses	3.22	5.66	7.37
RMSVW error (m/s)	W 850	Tropics	Observations	3.51	4.16	4.73
RMSVW error (m/s)	W 250	Tropics	Observations	5.00	6.77	8.17

Table 10: Standard WMO Verification for calendar year 2014

5.2 Research performed in this field – see section 6

6. Plans for the future *(next 4 years)*

6.1 Development of the GDPFS

6.1.1. Hourly cycling UK NWP nowcast system with hourly cycling 4D-Var data assimilation will be introduced. Enhanced resolution Global and MOGREPS-UK systems will also be introduced.

6.2 Planned research Activities in NWP, Nowcasting, Long-range Forecasting and Specialized Numerical Predictions

6.2.1 Planned Research Activities in NWP

Global Model Evaluation and Development – some of these activities equally applicable to Long-Range forecasting timescales **Walters**

Deliver a new global model formulation including (i) GA7.2 and/or (ii) N1024/N1280 horizontal resolution increase ready for inclusion in parallel suite 39.
Report providing assessment of the Global Coupled 4 configuration (and components), prioritisation of GC problems and review work of Process Evaluation Groups.
Report on the development, tuning and scientific impact of a prognostic diurnal skin SST scheme in the UM.
Report on benefits of increasing vertical resolution for global NWP (including DA/SA integration) & climate timescales
Global model resolution increase to N1280 (10km) and Global ensemble to N640 (20km)
Report on coupled versus uncoupled NWP performance in representative trials using high resolution N1024 or N1260 atmosphere/land coupled to ORCA025 (and possibly ORCA12) ocean/sea ice components.

Regional and Local Model Evaluation and Development Bush

Paper submitted on HiRA applied to MOGREPS-UK and UKV
Development of joint science plan with UM partners for convective scale modelling
Extended UK domain for UKV and MOGREPS-UK implemented with extended run lengths to T+54h
Introduce hourly cycling 12h NWP-nowcasts
Report on the performance of the UM re-run of the MesoVICT core case with the nested suite
Evaluation of the benefits of enhanced horizontal resolution in UK models
Diagnostic and Verification toolbox basic functionality available
Report on benefits of potential vertical resolution increase in RA model with recommendation for implementation

Dynamical Methods Wood

Report on understanding conservation issues which contribute to extreme precipitation in convective scale UM configurations along with plans to develop algorithms to alleviate the problem
Complete initial implementation of physics coupling to GungHo dynamical core

Improved use of satellite data Saunders

Operational implementation of VarBC in regional model.
Assimilation of Himawari-8 and GOES-R radiances and AMVs when available.
Assimilation of cloud affected microwave data, using the new cloud incrementing operator in UKV model.
Release of new version of RTTOV Fast radiative transfer model for radiance assimilation.
Use of locally derived AMVs and other satellite data at higher temporal frequency in 4DVar over UK.
Assimilation of more microwave radiances (e.g. on GPM, FY3).

Data Assimilation & Ensemble Forecasting Rawlins

Implementation of weakly coupled data assimilation system, including an assessment of the impact on short-medium range forecast skill in ocean and atmosphere.
Implementation of an hourly 4DVAR UKV model suitable for nowcasting.
Implementation of one or more upgrades to the use of observations and/or changes to the operational UK 1.5km DA algorithm, with candidates including revised cloud top profiles, MODE-S data and aircraft RH.
Implementation of hourly-updating time-lagged UK ensemble system
Implementation of one or more upgrades to the use of observations and/or changes to the operational globa lDA algorithm, with candidates including improved use of ensemble in hybrid-data assimilation scheme and possible introduction of global MODE-S aircraft observations.
Report on updated use of radar reflectivity in convective scale data assimilation.
Report on trials of global 4DVAR with more frequent update cycling.
Replacing the ETKF ensemble initial perturbation scheme with Ensembles of 4D-Ensemble-Var.
Operational implementation of next-generation UK ensemble/variational data assimilation system.
Replacing the ETKF ensemble initial perturbation scheme with Ensembles of 4D-Ensemble-Var.
Creation of UERRA ensemble of 4DVARs for regional reanalysis.
Continued evaluation of stochastic physics suitable for implementation in the UK ensemble.
Research on future configurations of UK ensemble.
Evaluate performance of En-4DEnVar as an alternative to ETKF for global ensemble initialization

Model Parametrizations and Processes – some of these activities equally applicable to Long-Range forecasting timescales **Vosper**

Assessments of representation of visibility in high resolution models including preliminary comparisons with data obtained during the LANFEX experiment.
Report on understanding conservation issues which contribute to extreme precipitation in convective-scale UM configurations along with plans to develop algorithms to alleviate the problem
The outline proposal for a NERC large grant as preparation for the YOPP campaign.
Report on JULES and UM changes to improve the clear sky diurnal cycle of temperature and winds based on comparisons with Cardington observations
Report on the modelling of cold pools and preliminary testing of their impact within the convection scheme
Report on tests of global model sensitivity to orographic drag parameters

Complete initial implementation of physics coupling to GungHo dynamical core
Suggest incremental modifications for a grey-zone convection parametrization for km scale models and report on an initial implementation
Evaluate downscaling algorithms in LANFEX.
Summary report of observations obtained during CLARIFY campaign and their future application to studies of biomass-burning aerosols and their impact on stratocumulus microphysical and optical properties.
Report on tests of Stochastic Convective Backscatter (SCB) in the MetUM
Progress report on sub-grid mixing scheme for use in sub-km UM configurations.
Report on km-scale model performance (e.g. UKV/MOGREPS-UK) from using either PC2 or Smith cloud schemes with alternative RHcrit, evaluated with a focus on summer-time convective situations, and looking at impact on the bias in surface short-wave radiation.
Interim report on progress of analysis of LANFEX observational data.
Assessment of potential approaches to include an urban canopy scheme in the UM
A report/paper on work diagnosing perturbations from resolved convection in a convection permitting regional model/ensemble and imposing them on the global ensemble to look at the influence on the larger scale flow.
Report on improvement to the representation of partially resolved turbulence, including input from the GREYBLS project.
Report on progress with the development of wave-atmosphere coupling for enhanced environmental prediction
Report on performance of UKV/MOG-UK from implementing parametrization changes aimed at reducing the surface short-wave bias.
Finalize physics code modifications required for Gung-Ho/LFRic version 0.1
Report on the comparison of coupled versus stand alone model evolution for JULES
Report on the climate change feedbacks from interactive methane emissions
Develop a new comprehensive benchmarking system for JULES through LVT
Develop a combined river routing / inundation scheme within JULES
Report on improvements to UM to reduce the summer-time warm continental bias (i.e. pull-through of CAUSES project results into GA configuration).
Assess options for including a representation of groundwater in JULES

Software Infrastructure for the NWP System Bell

Report on potential benefit of Knights Landing many-core processor to inform makeup of final phase of Cray XC40
Deliver UM10.5 including technical change to retire majority of common blocks from the UM.
Full LFRic developer environment completed and made available on external Science Repository Service and a collaborative HPC platform
Report on Scalability of global and regional UM configurations which are representative of 2020 operational model scenarios using the Cray XC40 phase 1b system
Deliver UM10.6 including technical changes to provide the UM FF unpacking code as a shared library for other uses without the need for a UM licence.
Implement Met office components of the archive synchronisation with BADC to support more efficient data transfer and management for public and controlled climate model datasets
Report on recent developments to Rose and Cylc to improve robustness and efficiency in anticipation of more complex suites
Implementation of Upgraded Data Assimilation Codes (OPS/VAR33)
Implementation of the first phase recommendations of the report on coupling

strategy
Deliver UM10.7 including technical changes to create a shared code library, with initial examples for use by other codes.
Global and Regional models using ancillaries built with the new ancillary system
Prototype implementation of Rose-based automated post-processing within climate suites for CSSP, or other CSSP-enabling software suites.

Observational Research Facilities Vosper

Complete documentation of HT-FRTC for dissemination in licensed versions.
Complete scheduled in-year flying programme.

NWP Post-Processing and Impacts Wright, Jackson

Real-time multi-model and individual ensemble tropical cyclone python products available with links to associated seasonal verification results
Upgrade Decider to display multi-model weather regime forecasts
Outline design proposal and implementation plan of how the verification and post-processing chain can be combined
Deliver a comprehensive set of data available to the Core Data Interface (HPC DSI Decoupler) from all the main atmospheric models (UKV, MOGREPS-UK, GM, MOGREPS-G, Euro4)
Post-processing systems ready to exploit hourly NWP nowcast runs
Deliver the BGD capability to support the Public Weather Media Service
Establishment a Defence BGD framework demonstrator running in real-time to drive one of more TDAs, including a process to allow Defence to rapidly deploy an new BGD grid anywhere in the world
Implement an improved wind downscaling with consistent corrections to 3d boundary layer winds.
Report on trial of ensemble spread calibration with recommendations for implementation
STEPS improved handling of precipitation blending and optical advection
Implement new convection nowcast capabilities
Plan for & implement the development of post-processing to effectively exploit the proposed hourly-cycling structure of the NWP System

Observations R&D Jones

Development ofnext generation AWS adopting ‘internet of things’ architecture.
Complete implementation of lidar network for volcanic ash monitoring
Continuation of dual-polarization upgrades to radars in the operational network
Introduce new radar quality control algorithms based upon dual-polarization parameters
Increased exploitation of amateur observer data in operations (including ingestion of crowd-sourced data from moving platforms, eg cars, into WoW)
Development of next generation ATD lightning detection system
Move towards operational MODE-S data availability and exploration of options for global access

Aviation Products Wells

Deliver combined clear air turbulence predictor based on EDR into operations for WAFC products
Implement comprehensive suite of WAFC forecast monitoring
Continue to enhance WAFC convection forecast verification with use of satellite data
Production of probabilistic WAFC hazard (turbulence, convection, icing) forecasts

based on multi-model ensemble, ready for operational implementation
Provide 3d radar information over the UK to forecasters
Assess the benefits of using very high resolution (333m) forecasts for low visibility forecasting at airports

6.2.2 Planned Research Activities in Nowcasting

Data Assimilation & Ensemble Forecasting Macpherson

Operational implementation of next-generation NWP-nowcasting system based on hourly 4DVAR assimilation in UK model.

6.2.3 Planned Research Activities in Long-range Forecasting Maclachlan

Global Model Evaluation and Development – some of these activities equally applicable to NWP timescales

HCCP & PWS -: Report providing assessment of the Global Coupled 4 configuration (and components), prioritisation of GC problems and review work of Process Evaluation Groups.
HCCP & PWS -: Report on the development, tuning and scientific impact of a prognostic diurnal skin SST scheme in the UM.
HCCP: Report/papers on implications of atmospheric vertical resolution for weather and climate prediction, and revised model development timelines

Model Parametrizations and Processes – some of these activities equally applicable to NWP timescales **Vosper**

Assessments of representation of visibility in high resolution models including preliminary comparisons with data obtained during the LANFEX experiment.
Report on understanding conservation issues which contribute to extreme precipitation in convective-scale UM configurations along with plans to develop algorithms to alleviate the problem
The outline proposal for a NERC large grant as preparation for the YOPP campaign.
Report on JULES and UM changes to improve the clear sky diurnal cycle of temperature and winds based on comparisons with Cardington observations
Report on the modelling of cold pools and preliminary testing of their impact within the convection scheme
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Evaluate downscaling algorithms in LANFEX.
Summary report of observations obtained during CLARIFY campaign and their future application to studies of biomass-burning aerosols and their impact on stratocumulus microphysical and optical properties.
Report on tests of Stochastic Convective Backscatter (SCB) in the MetUM
Progress report on sub-grid mixing scheme for use in sub-km UM configurations.
Report on km-scale model performance (e.g. UKV/MOGREPS-UK) from using either PC2 or Smith cloud schemes with alternative RHcrit, evaluated with a focus on summer-time convective situations, and looking at impact on the bias in surface short-wave radiation.

Interim report on progress of analysis of LANFEX observational data.
Assessment of potential approaches to include an urban canopy scheme in the UM
A report/paper on work diagnosing perturbations from resolved convection in a convection permitting regional model/ensemble and imposing them on the global ensemble to look at the influence on the larger scale flow.
Report on improvement to the representation of partially resolved turbulence, including input from the GREYBLS project.
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Report on the comparison of coupled versus stand alone model evolution for JULES
Report on the climate change feedbacks from interactive methane emissions
Develop a new comprehensive benchmarking system for JULES through LVT
Develop a combined river routing / inundation scheme within JULES
Report on improvements to UM to reduce the summer-time warm continental bias (i.e. pull-through of CAUSES project results into GA configuration).
Assess options for including a representation of groundwater in JULES

6.2.4 Planned Research Activities in Specialized Numerical Predictions

Atmospheric Dispersion & Composition Hort

Release NAME version with improved parametrizations wet deposition.
Further develop NAME version with flexibly combined Eulerian and Lagrangian sub-models.
Develop probabilistic dispersion forecasting capability.
Ongoing development of operational VAAC emergency response source term inversion scheme and extension to other emergency response applications.
Develop more advanced plume rise and umbrella cloud modelling capability in NAME for volcanic eruptions.
Validate NAME against CAPTEX, ANATEX and Joint Urban 2003 field campaign data
Development of a new framework for pollutant emissions in UKCA for AQUM.
Develop the capability for on-line calculation of biogenic ozone and aerosol precursor emissions in AQUM.
Develop a version of AQUM for the Copernicus Atmosphere Monitoring Service, Regional Air Quality Forecasting. To run over a wider European domain and include data assimilation of selected surface pollutants and birch pollen forecast.
Implement near-real-time biomass burning emissions in AQUM.
Development and implementation within AQUM of the GLOMAP-mode aerosol scheme.

Ocean Forecasting Research and Development Siddorn

Set up coupled N768/ORCA'12' Atmos-Land-Ice-Ocean model (without weakly coupled data assimilation)
Biogeochemistry data assimilation for operational forecasting
Investigate large-scale (EOF-based) error covariances for use in NEMOVAR
A NEMO version of the surge system developed and trialled against CS3X over a winter forecast trials period
Development of revised area UK coupled Ocean-Atmos system
Implementation of NEMOVAR in development version of global FOAM at ORCA12
Develop 4-2-1 km SMC UK wave model and post processing schemes
Develop and assess global coupled Atmos-Land-Ice-Wave-Ocean N768/ORCA'12' system with weakly coupled data assimilation
Test use of ensemble information in NEMOVAR
Test and review benefits of NEMOVAR wave data assimilation in regional/global wave forecast models

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