ERA report series

1 The ERA-Interim archive

Version 2.0

Paul Berrisford, Dick Dee, Paul Poli, Roger Brugge, Keith Fielding,
Manuel Fuentes, Per Kållberg, Shinya Kobayashi,
Sakari Uppala and Adrian Simmons

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Version information

Date	Version	Comments
August 2009	1.0	Original version
October 2011	2.0	• Addition of vertical integrals • Enhanced web-based data services • Extension of ERA-Interim to 1979 • Various updates and minor corrections

European Centre for Medium Range Weather Forecasts
Shinfield Park, Reading, Berkshire RG2 9AX, United Kingdom

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1. Introduction

This document describes the ERA-Interim Archive at ECMWF. ERA-Interim is a reanalysis of the global atmosphere covering the data-rich period since 1979 (originally, ERA-Interim ran from 1989, but the 10 year extension for 1979-1988 was produced in 2011), and continuing in real time. As ERA-Interim continues forward in time, updates of the Archive will take place on a monthly basis.

The ERA-Interim project was initiated in 2006 to provide a bridge between ECMWF's previous reanalysis, ERA-40 (1957-2002), and the next-generation extended reanalysis envisaged at ECMWF. The main objectives of the project were to improve on certain key aspects of ERA-40, such as the representation of the hydrological cycle, the quality of the stratospheric circulation, and the handling of biases and changes in the observing system. These objectives have been largely achieved as a result of a combination of factors, including many model improvements, the use of 4-dimensional variational analysis, a revised humidity analysis, the use of variational bias correction for satellite data, and other improvements in data handling.

The ERA-Interim atmospheric model and reanalysis system uses cycle 31r2 of ECMWF's Integrated Forecast System (IFS), which was introduced operationally in September 2006, configured for the following spatial resolution:

- 60 levels in the vertical, with the top level at 0.1 hPa;
- T255 spherical-harmonic representation for the basic dynamical fields;
- a reduced Gaussian grid with approximately uniform 79 km spacing for surface and other grid-point fields.

The atmospheric model is coupled to an ocean-wave model resolving 30 wave frequencies and 24 wave directions at the nodes of its reduced $1.0^{o}\mathrm{x}1.0^{o}$ latitude/longitude grid. Documentation of the IFS is published on the ECMWF website at http://www.ecmwf.int/research.

A comprehensive documentation of the ERA-Interim reanalysis system has been published as an open-access article in the Quarterly Journal of the Royal Meteorological Society, and can be downloaded from http://onlinelibrary.wiley.com/doi/10.1002/qj.828/abstract. See Section 4 in this document for ERA-Interim product access information via the ECMWF Data Server at http://data.ecmwf.int/data. Additional information e.g. on current data availability is available on the ECMWF website at http://www.ecmwf.int/research/era.

Archived ERA-Interim products described in this document comprise:

- analysis and forecast fields from the assimilating atmospheric model at full resolution[1];
- analysis and forecast fields from the atmospheric model evaluated on standard pressure levels;
- analysis fields from the atmospheric model evaluated on isentropic and PV = ± 2 PVU surfaces;
- analysis and forecast fields from the coupled ocean-wave model at full resolution;
- vertical integrations of analysed model level fields;
- various monthly means for these fields.

Details of the way basic fields are post-processed to produce the archived fields are given in the IFS documentation. Reference should be made in particular to Appendix D: FULL-POS user guide, of Part VI: *Technical and computational procedures*.

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[1] These data are model level and surface and single level fields

2. Analysis and forecast fields

2.1. Product generation

The ERA-Interim data assimilation and forecast suite produces:

- four analyses per day, at 00, 06, 12 and 18 UTC;
- two 10-day forecasts per day, initialized from analyses at 00 and 12 UTC.

The analysis produced at 00 UTC on a given day involves observations taken between 15 UTC on the previous day and 03 UTC on the present day; the analysis at 12 UTC involves observations between 03 UTC and 15 UTC.

Unless specified otherwise, forecast data on pressure levels (levtype=pl in MARS) and for the surface and single level parameters (levtype=sfc) are archived at the 28 ranges, or steps, of 3-, 6-, 9-, 12-, 15-, 18-, 21-, 24-, 30-, 36-, 42-, 48-, 60-, 72-, 84-, 96-, 108-, 120-, 132-, 144-, 156-, 168-, 180-, 192-, 204-, 216-, 228-, and 240-hours from the twice daily forecasts at 00 and 12 UTC. Forecast model level data (levtype=ml) are archived at 3-, 6-, 9-, and 12-hour ranges from 00 and 12 UTC. Forecast data are not available for fields on isentropic (levtype=pt) and PV = ±2 PVU (levtype=pv) levels. On the ECMWF Data Server forecasts are only available for surface and single level fields and only up to a range of 12-hours.

Fields from the atmospheric model are archived either at the full T255 spectral resolution or on the corresponding N128 reduced Gaussian grid, depending on their basic representation in the model. Fields from the coupled ocean-wave model are saved on its reduced 1.0°x1.0° latitude/longitude grid.

The N128 reduced Gaussian grid is symmetric about the equator, with a north-south separation which is close to uniform in latitude, with a spacing of about 0.703125°. There are 128 points aligned along the Greenwich Meridian from equator to pole. The number of points in the east-west varies with latitude, with uniform grid spacing along a particular line of latitude. This spacing is 0.703125° in most of the tropics. The grid is specified (for the Northern Hemisphere) in Table 1, which gives the latitude values (accurate to two decimal places) and the corresponding number of points in the east-west direction. Similar information, for several reduced Gaussian grids commonly used at the ECMWF, is available at http://www.ecmwf.int/publications/manuals/libraries/interpolation/gaussianGridsFIS.html.

The WMO format FM92 GRIB is used to represent all analysis and forecast fields. In general, ERA GRIB data are coded using ECMWF's local versions of GRIB code table 2 (version number 128 for atmospheric products, 140 for wave products), which gives parameter names and units. An additional local version, 162, is used for atmospheric parameters that are not included in the standard table version 128. These include the "Additional vertical integrals for energy, mass, water and ozone budgets" in Section 2.5 and the "Additional fields accumulated from the physical parametrizations" in Section 2.7. All local ECMWF versions of GRIB code table 2 are tabulated in http://www.ecmwf.int/services/archive.

Table 1: The N128 Gaussian grid

Row no.	Lat.	Points	Row no.	Lat.	Points	Row no.	Lat.	Points	Row no.	Lat.	Points
1	89.46	18	2	88.77	25	3	88.07	36	4	87.37	40
5	86.66	45	6	85.96	50	7	85.26	60	8	84.56	64
9	83.86	72	10	83.16	72	11	82.46	80	12	81.75	90
13	81.05	90	14	80.35	100	15	79.65	108	16	78.95	120
17	78.25	120	18	77.54	125	19	76.84	128	20	76.14	144
21	75.44	144	22	74.74	150	23	74.03	160	24	73.33	160
25	72.63	180	26	71.93	180	27	71.23	180	28	70.53	192
29	69.82	192	30	69.12	200	31	68.42	216	32	67.72	216
33	67.02	216	34	66.32	225	35	65.61	240	36	64.91	240
37	64.21	240	38	63.51	250	39	62.81	250	40	62.11	256
41	61.40	270	42	60.70	270	43	60.00	288	44	59.30	288
45	58.60	288	46	57.89	300	47	57.19	300	48	56.49	320
49	55.79	320	50	55.09	320	51	54.39	320	52	53.68	324
53	52.98	360	54	52.28	360	55	51.58	360	56	50.88	360
57	50.18	360	58	49.47	360	59	48.77	360	60	48.07	375
61	47.37	375	62	46.67	375	63	45.96	375	64	45.26	384
65	44.56	384	66	43.86	400	67	43.16	400	68	42.46	400
69	41.75	400	70	41.05	405	71	40.35	432	72	39.65	432
73	38.95	432	74	38.25	432	75	37.54	432	76	36.84	432
77	36.14	432	78	35.44	450	79	34.74	450	80	34.04	450
81	33.33	450	82	32.63	450	83	31.93	480	84	31.23	480
85	30.53	480	86	29.82	480	87	29.12	480	88	28.42	480
89	27.72	480	90	27.02	480	91	26.32	480	92	25.61	480
93	24.91	486	94	24.21	486	95	23.51	486	96	22.81	500
97	22.11	500	98	21.40	500	99	20.70	500	100	20.00	500
101	19.23	500	102	18.60	500	103	17.89	512	104	17.19	512
105	16.49	512	106	15.79	512	107	15.09	512	108	14.39	512
109	13.68	512	110	12.98	512	111	12.28	512	112	11.58	512
113	10.88	512	114	10.18	512	115	9.47	512	116	8.77	512
117	8.07	512	118	7.37	512	119	6.67	512	120	5.96	512
121	5.26	512	122	4.56	512	123	3.86	512	124	3.16	512
125	2.46	512	126	1.75	512	127	1.05	512	128	0.35	512

2.2. Upper air parameters on model and pressure levels

Upper air data are saved on each of the 60 “full” model levels and on 37 pressure levels, except where stated otherwise. Model “half-level” pressures, $p_{k-1/2}$, are defined by

$$p_{k-1/2} = A_{k-1/2} + B_{k-1/2} p_s$$

where p_s is surface pressure and k =1,2,3,…61. The pressures of the “full” model levels, p_k,, are defined by

$$p_k = \frac{1}{2}\left(p_{k-1/2} + p_{k+1/2}\right)$$

Precise values for $A_{k-1/2}$ and $B_{k-1/2}$ should be read from Section 2, the Grid Description Section, of a GRIB file for model-level data. Values accurate to up to five significant figures are given in Table 2, together with half and full level pressures assuming a surface pressure of 1013.25 hPa. The corresponding heights, z_k, of the full levels are also shown, using a uniform scale height of 7 km for pressure. For this scale height the model level spacing is precisely 1.5 km in the middle stratosphere. The 37 pressure levels to which the model-level fields are interpolated are also indicated in Table 2.

Table 2: Model and pressure levels

Model levels						**Pressure levels (hPa)**
k	$A_{k-1/2}$ **(hP)**	$B_{k-1/2}$	$p_{k-1/2}$ **(hPa)**	p_k **(hPa)**	z_k **(km)**	
1	0.00	0.00000	0.00	0.10	64.56	
2	0.20	0.00000	0.20	0.29	57.06	
3	0.38	0.00000	0.38	0.51	53.16	
4	0.64	0.00000	0.64	0.80	50.04	
5	0.96	0.00000	0.96	1.15	47.46	1
6	1.34	0.00000	1.34	1.58	45.27	
7	1.81	0.00000	1.81	2.08	43.33	2
8	2.35	0.00000	2.35	2.67	41.58	3
9	2.98	0.00000	2.98	3.36	39.96	
10	3.74	0.00000	3.74	4.19	38.41	
11	4.65	0.00000	4.65	5.20	36.90	5
12	5.76	0.00000	5.76	6.44	35.40	7
13	7.13	0.00000	7.13	7.98	33.90	
14	8.84	0.00000	8.84	9.89	32.40	10
15	10.95	0.00000	10.95	12.26	30.90	
16	13.56	0.00000	13.56	15.19	29.40	
17	16.81	0.00000	16.81	18.81	27.90	20
18	20.82	0.00000	20.82	23.31	26.40	
19	25.80	0.00000	25.80	28.88	24.90	30
20	31.96	0.00000	31.96	35.78	23.40	
21	39.60	0.00000	39.60	44.33	21.90	
22	49.07	0.00000	49.07	54.62	20.44	50
23	60.18	0.00000	60.18	66.62	19.05	70
24	73.07	0.00000	73.07	80.40	17.74	
25	87.65	0.00008	87.73	95.98	16.50	100

Model levels						Pressure levels (hPa)
k	$A_{k-1/2}$ (hP)	$B_{k-1/2}$	$p_{k-1/2}$ (hPa)	p_k (hPa)	z_k (km)	
26	103.76	0.00046	104.23	113.42	15.33	125
27	120.77	0.00182	122.61	132.76	14.23	
28	137.75	0.00508	142.90	154.00	13.19	150
29	153.80	0.01114	165.09	177.12	12.21	175
30	168.19	0.02068	189.15	202.09	11.29	200
31	180.45	0.03412	215.03	228.84	10.42	225
32	190.28	0.05169	242.65	257.36	9.59	250
33	197.55	0.07353	272.06	287.64	8.81	300
34	202.22	0.09967	303.22	319.63	8.08	
35	204.30	0.13002	336.04	353.23	7.38	350
36	203.84	0.16438	370.41	388.27	6.71	400
37	200.97	0.20248	406.13	424.57	6.09	
38	195.84	0.24393	443.01	461.90	5.50	450
39	188.65	0.28832	480.79	500.00	4.94	500
40	179.61	0.33515	519.21	538.591	4.42	550
41	168.99	0.38389	557.97	577.38	3.94	
42	157.06	0.43396	596.78	616.04	3.48	600
43	144.11	0.48477	635.31	654.27	3.06	650
44	130.43	0.53571	673.24	691.75	2.67	700
45	116.33	0.58617	710.26	728.16	2.31	750
46	102.10	0.63555	746.06	763.20	1.98	775
47	88.02	0.68327	780.35	796.59	1.68	800
48	74.38	0.72879	812.83	828.05	1.41	825
49	61.44	0.77160	843.26	857.34	1.17	850
50	49.42	0.81125	871.42	884.27	0.95	875
51	38.51	0.84737	897.11	908.65	0.76	900
52	28.88	0.87966	920.19	930.37	0.60	925
53	20.64	0.90788	940.55	949.35	0.46	950
54	13.86	0.93194	958.15	965.57	0.34	
55	8.55	0.95182	972.99	979.06	0.24	975
56	4.67	0.96765	985.14	989.95	0.16	
57	2.10	0.97966	994.75	998.39	0.10	1000
58	0.66	0.98827	1002.02	1004.64	0.06	
59	0.07	0.99402	1007.26	1009.06	0.03	
60	0.00	0.99763	1010.85	1012.05	0.01	
61	0.00	1.00000	1013.25			

Table 3 gives details of the "upper air" parameters on model and pressure levels. These include surface geopotential and the logarithm of surface pressure. Although not strictly upper air parameters, these are produced in spherical-harmonic form along with the model level data. Surface pressure is needed to compute the distribution of pressure on the model surfaces as indicated above. The table indicates which parameters are stored on model levels and which are stored on pressure levels. The two horizontal representations are indicated by **sh** (spherical harmonics) and **gg** (Gaussian grid). Parameters are available both from analyses and forecasts. Except where indicated forecasts are available at the 28 steps to 10 days (see Section 2.1) on pressure levels and 4 steps to 12 hours on model levels. **Code** refers to the parameter reference number in GRIB code table 2, ECMWF local version 128. Note that the horizontal wind- components (**code**s 131/132) are evaluated from the archived vorticity and divergence by the MARS software when requested.

Table 3: Upper air parameters on model and pressure levels

Parameter	**Model levels**		**Pressure levels**		**Code**	**Units**
	gg	**sh**	**gg**	**sh**		
potential vorticity[1]			X		60	$m^{2} s^{-1} K kg^{-1}$
surface geopotential		X			129	$m^{2} s^{-2}$
geopotential				X	129	$m^{2} s^{-2}$
temperature		X		X	130	K
eastward wind component					131	$m s^{-1}$
northward wind component					132	$m s^{-1}$
specific humidity	X		X		133	kg/kg
vertical velocity		X		X	135	$Pa s^{-1}$
vorticity		X		X	138	s^{-1}
log surface pressure (Pa)		X			152	
divergence		X		X	155	s^{-1}
relative humidity				X	157	%
ozone mass mixing ratio	X		X		203	kg/kg
cloud liquid water content	X		X		246	kg/kg
cloud ice water content	X		X		247	kg/kg
cloud cover	X		X		248	(0-1)

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[1] Forecasts are only available up to a range of 12-hours

2.3. Upper air parameters on isentropic and PV = ±2 PVU surfaces

Analysed fields only are interpolated to sixteen isentropic surfaces. The potential temperatures defining these surfaces are specified in Table 4, which also shows corresponding pressures and heights for a hypothetical 250 K dry isothermal atmosphere.

Table 4: Isentropic levels and corresponding pressures and heights

Θ(K)	***P(hPa)***	***Z*(km)**
265	815	1.5
275	716	2.4
285	632	3.4
300	528	4.7
315	445	5.9
320 [1]	427	6.2
330	378	7.1
350	308	8.6
370	254	10.0
395	202	11.7
430	150	13.9
475	106	16.4
530	72	19.2
600	47	22.4
700	27	26.4
850	14	31.3

[1] Only PV is archived at 320 K

Table 5 shows the parameters and horizontal representations of the fields archived on the isentropic surfaces.

Table 5: Parameters on isentropic surfaces

Parameter	**gg**	**sh**	**Code**	**Units**
Montgomery potential		X	53	$m^2 s^{-2}$
pressure		X	54	Pa
potential vorticity [1]	X		60	$m^2 s^{-1} K kg^{-1}$
eastward wind component			131	$m s^{-1}$
northward wind component			132	$m s^{-1}$
specific humidity	X		133	kg/kg
vorticity		X	138	s^{-1}
divergence		X	155	s^{-1}
ozone mass mixing ratio	X		203	kg/kg

[1] Only PV is archived at 320 K

Montgomery potential is defined as $\phi + c_{pd}\theta(p/p_0)^{\kappa_d}$, where ϕ and p are respectively the geopotential and the pressure of the constant-θ surface, c_{pd} is the specific heat of dry air at constant pressure and $\kappa_d = R_d / c_{pd}$, where R_d is the gas constant of dry air. Note, however, that θ is defined by $\theta = T(p/p_0)^{-\kappa}$ with κ defined for a moist atmosphere: $\kappa = R/c_p$, where $R = R_d(1+(R_v/R_d-1)q)$ and $c_p = c_{pd}(1+(c_{pv}/c_{pd}-1)q)$, with q the specific humidity, and R_v and c_{pv} respectively the gas constant and specific heat at constant pressure of water vapour. The effect of moisture is also included in the calculation of ϕ, as described in the documentation of the model.

Analysed fields only are also produced on the "PV= ±2 PVU" surface on which the potential vorticity takes the value +2 PVU (1 PVU=10^{-6} $m^2s^{-1}Kkg^{-1}$) in the Northern Hemisphere and -2 PVU in the Southern Hemisphere, provided such a surface can be found searching downwards from the model level close to 96 hPa. Values at this model level are used where the search is unsuccessful.

Table 6 shows the parameters archived on the PV = ±2 PVU surface. All fields are saved on the model's Gaussian grid.

Table 6: Parameters on the PV = ±2 PVU surface

Parameter	Code	Units
potential temperature	3	K
pressure	54	Pa
geopotential	129	$m^2\ s^{-2}$
eastward wind component	131	$m\ s^{-1}$
northward wind component	132	$m\ s^{-1}$
specific humidity	133	kg/kg
ozone mass mixing ratio	203	kg/kg

2.4. Surface and single level parameters

A variety of instantaneous, surface and single level parameters are saved on the model's Gaussian grid. The list of these differs according to whether they are produced by the analysis (**An**), or the forecast (**Fc**), and are given in Table 7 (for temporally invariant parameters) and Table 8 (for temporally varying parameters) below. Except where indicated forecasts are available at the 28 steps to 10 days (see Section 2.1).

Table 7:Instantaneous, invariant, surface and single level parameters

Parameter	An	Fc	Code	Units
low vegetation cover	X		27	(0-1)
high vegetation cover	X		28	(0-1)
low vegetation type (table index)	X		29	index
high vegetation type (table index)	X		30	index
standard deviation of filtered subgrid orography	X		74	m
surface geopotential	X	X	129	$m^2 s^{-2}$
standard deviation of orography	X		160	m
anisotropy of orography	X		161	
angle of sub-grid scale orography	X		162	
slope of sub-grid scale orography	X		163	
land/sea mask	X	X	172	(0,1)

Table 8: Instantaneous, varying, surface and single level parameters

Parameter	An	Fc	Code	Units
sea ice fraction	X	X	31	(0-1)
snow albedo	X	X	32	(0-1)
snow density	X	X	33	$kg m^{-3}$
sea surface temperature	X	X	34	K
sea ice temperature layer 1	X	X	35	K
sea ice temperature layer 2	X	X	36	K
sea ice temperature layer 3	X	X	37	K
sea ice temperature layer 4	X	X	38	K
soil moisture level 1 (volumetric)	X	X	39	$m^3 m^{-3}$
soil moisture level 2 (volumetric)	X	X	40	$m^3 m^{-3}$
soil moisture level 3 (volumetric)	X	X	41	$m^3 m^{-3}$
soil moisture level 4 (volumetric)	X	X	42	$m^3 m^{-3}$
convective available potential energy		X	59	$J kg^{-1}$
total column liquid water		X	78	$kg m^{-2}$
total column ice water		X	79	$kg m^{-2}$
surface pressure [1]	X	X	134	Pa
total column water	X	X	136	$kg m^{-2}$
total column water vapour	X	X	137	$kg m^{-2}$
soil temperature level 1	X	X	139	K

[1] Forecasts are only available up to a range of 12-hours

Parameter	An	Fc	Code	Units
snow depth	X	X	141	m of water equivalent
Charnock parameter	X	X	148	
mean sea level pressure	X	X	151	Pa
boundary layer height		X	159	m
total cloud cover	X	X	164	(0-1)
10 metre eastward wind component	X	X	165	m s^{-1}
10 metre northward wind component	X	X	166	m s^{-1}
2 metre temperature	X	X	167	K
2 metre dewpoint	X	X	168	K
soil temperature level 2	X	X	170	K
surface roughness	X		173	m
albedo (climate)	X		174	
soil temperature level 3	X	X	183	K
low cloud cover	X	X	186	(0-1)
medium cloud cover	X	X	187	(0-1)
high cloud cover	X	X	188	(0-1)
skin reservoir content	X	X	198	m of water
total column ozone	X	X	206	kg m^{-2}
instantaneous eastward component of turbulent stress		X	229	N m^{-2}
instantaneous northward component of turbulent stress		X	230	N m^{-2}
instantaneous surface heat flux		X	231	W m^{-2}
instantaneous moisture flux (evaporation)		X	232	kg m^{-2} s
log. surface roughness length (m) for heat	X		234	
skin temperature	X	X	235	K
soil temperature level 4	X	X	236	K
snow temperature	X	X	238	K
forecast albedo		X	243	
forecast surface roughness		X	244	m
forecast log. surface roughness length (m) for heat		X	245	

Table 9 lists the accumulated (from the beginning of the) forecast, surface and single level parameters, which are also saved on the model's Gaussian grid. These forecasts are available at the 28 steps to 10 days (see Section 2.1).

Table 9: Forecast accumulated surface and single level parameters

Parameter	Code	Units
clear sky surface photosynthetically active radiation	20	W m^{-2} s
snow evaporation	44	m
snow melt	45	m
large-scale precipitation fraction	50	s
downward UV radiation at the surface	57	W m^{-2} s
surface photosynthetically active radiation	58	W m^{-2} s
large-scale precipitation	142	m of water

Parameter	Code	Units
convective precipitation	143	m of water
snowfall	144	m of water equivalent
boundary layer dissipation	145	W m^{-2} s
surface sensible heat flux	146	W m^{-2} s
surface latent heat flux	147	W m^{-2} s
downward surface solar radiation	169	W m^{-2} s
downward surface thermal radiation	175	W m^{-2} s
surface solar radiation	176	W m^{-2} s
surface thermal radiation	177	W m^{-2} s
top solar radiation	178	W m^{-2} s
top thermal radiation	179	W m^{-2} s
East-West component of turbulent stress	180	N m^{-2} s
North-South component of turbulent stress	181	N m^{-2} s
evaporation	182	m of water
sunshine duration	189	s
East-West component of gravity wave stress	195	N m^{-2} s
North-South component of gravity wave stress	196	N m^{-2} s
gravity wave dissipation	197	W m^{-2} s
runoff	205	m of water
top solar radiation clear sky	208	W m^{-2} s
top thermal radiation clear sky	209	W m^{-2} s
surface solar radiation clear sky	210	W m^{-2} s
surface thermal radiation clear sky	211	W m^{-2} s
top incident solar radiation	212	W m^{-2} s
total precipitation	228	m of water
convective snowfall	239	m of water equivalent
large-scale snowfall	240	m of water equivalent

Table 10 lists the forecast minimum/maximum, surface and single level parameters, which are also saved on the model's Gaussian grid. These fields contain the minimum or maximum values of the parameter since the previous post-processing and are available at the 28 steps to 10 days (see Section 2.1).

Table 10: Forecast minimum/maximum surface and single level parameters

Parameter	Code	Units
wind gusts at 10 m	49	m s^{-1}
maximum 2m temperature since last post-processing step	201	K
minimum 2m temperature since last post-processing step	202	K

2.5. Additional vertical integrals for energy, mass, water and ozone budgets

The standard model post-processing produced the surface and single-level fields given in Tables 7-10. A number of additional “single-level” fields of vertical integrals relating to the budgets of mass, water, ozone and energy have been derived from the instantaneous analysed model-level data. They are listed in Table 11. Further details are given in Annex I. **Code** refers to the parameter reference number in GRIB code table 2, ECMWF local version 162.

Table 11: Vertical integrals for budgets

Parameter	**Definition**	**Code**	**Units**
mass of atmosphere	$\frac{1}{g}\int_0^1 \frac{\partial p}{\partial \eta} d\eta$	53	kg m^{-2}
temperature	$\frac{1}{g}\int_0^1 T\frac{\partial p}{\partial \eta} d\eta$	54	K kg m^{-2}
water vapour	$\frac{1}{g}\int_0^1 q\frac{\partial p}{\partial \eta} d\eta$	55	kg m^{-2}
cloud liquid water	$\frac{1}{g}\int_0^1 (CLW)\frac{\partial p}{\partial \eta} d\eta$	56	kg m^{-2}
cloud frozen water	$\frac{1}{g}\int_0^1 (CIW)\frac{\partial p}{\partial \eta} d\eta$	57	kg m^{-2}
ozone	$\frac{1}{g}\int_0^1 O_3\frac{\partial p}{\partial \eta} d\eta$	58	kg m^{-2}
kinetic energy, *KE*	$\frac{1}{g}\int_0^1 \frac{1}{2}(\underset{\sim}{v}\cdot\underset{\sim}{v})\frac{\partial p}{\partial \eta} d\eta$	59	J m^{-2}
thermal energy	$\frac{1}{g}\int_0^1 c_pT\frac{\partial p}{\partial \eta} d\eta$	60	J m^{-2}
potential+internal energy	$\frac{1}{g}\int_0^1 (c_pT+\phi s)\frac{\partial p}{\partial \eta} d\eta$	61	J m^{-2}
potential+internal+latent energy	$\frac{1}{g}\int_0^1 (Lq+c_pT+\phi s)\frac{\partial p}{\partial \eta} d\eta$	62	J m^{-2}
total energy, *TE*	$\frac{1}{g}\int_0^1\left(\frac{1}{2}(\underset{\sim}{v}\cdot\underset{\sim}{v})+Lq+c_pT+\phi_s\right)\frac{\partial p}{\partial \eta} d\eta$	63	J m^{-2}
energy conversion	$\frac{1}{g}\int_0^1 \frac{RT\omega\partial p}{p\;\partial \eta} d\eta$	64	W m^{-2}
eastward mass flux	$\frac{1}{g}\int_0^1 u\frac{\partial p}{\partial \eta} d\eta$	65	kg m^{-1} s^{-1}
northward mass flux	$\frac{1}{g}\int_0^1 v\frac{\partial p}{\partial \eta} d\eta$	66	kg m^{-1} s^{-1}
eastward kinetic energy flux	$\frac{1}{g}\int_0^1 u\frac{1}{2}(\underset{\sim}{v}\cdot\underset{\sim}{v})\frac{\partial p}{\partial \eta} d\eta$	67	W m^{-1}
northward kinetic energy flux	$\frac{1}{g}\int_0^1 v\frac{1}{2}(\underset{\sim}{v}\cdot\underset{\sim}{v})\frac{\partial p}{\partial \eta} d\eta$	68	W m^{-1}
eastward heat flux	$\frac{1}{g}\int_0^1 uc_pT\frac{\partial p}{\partial \eta} d\eta$	69	W m^{-1}

Parameter	Definition	Code	Units
northward heat flux	$\frac{1}{g}\int_0^1 vc_pT\frac{\partial p}{\partial \eta}d\eta$	70	W m^{-1}
eastward water-vapour flux	$\frac{1}{g}\int_0^1 uq\frac{\partial p}{\partial \eta}d\eta$	71	kg m^{-1} s^{-1}
northward water-vapour flux	$\frac{1}{g}\int_0^1 vq\frac{\partial p}{\partial \eta}d\eta$	72	kg m^{-1} s^{-1}
eastward geopotential flux	$\frac{1}{g}\int_0^1 u\phi\frac{\partial p}{\partial \eta}d\eta$	73	W m^{-1}
northward geopotential flux	$\frac{1}{g}\int_0^1 v\phi\frac{\partial p}{\partial \eta}d\eta$	74	W m^{-1}
eastward total energy flux	$\frac{1}{g}\int_0^1 u\left(\frac{1}{2}(\underset{\sim}{v}\cdot\underset{\sim}{v})+Lq+c_pT+\phi\right)\frac{\partial p}{\partial \eta}d\eta$	75	W m^{-1}
northward total energy flux	$\frac{1}{g}\int_0^1 v\left(\frac{1}{2}(\underset{\sim}{v}\cdot\underset{\sim}{v})+Lq+c_pT+\phi\right)\frac{\partial p}{\partial \eta}d\eta$	76	W m^{-1}
eastward ozone flux	$\frac{1}{g}\int_0^1 uO_3\frac{\partial p}{\partial \eta}d\eta$	77	kg m^{-1} s^{-1}
northward ozone flux	$\frac{1}{g}\int_0^1 vO_3\frac{\partial p}{\partial \eta}d\eta$	78	kg m^{-1} s^{-1}
divergence of cloud liquid water flux	$\nabla\frac{1}{g}\int_0^1 \underset{\sim}{v}CLW\frac{\partial p}{\partial \eta}d\eta$	79	kg m^{-2} s^{-1}
divergence of cloud frozen water flux	$\nabla\frac{1}{g}\int_0^1 \underset{\sim}{v}CIW\frac{\partial p}{\partial \eta}d\eta$	80	kg m^{-2} s^{-1}
divergence of mass flux	$\nabla\frac{1}{g}\int_0^1 \underset{\sim}{v}\frac{\partial p}{\partial \eta}d\eta$	81	kg m^{-2} s^{-1}
divergence of kinetic energy flux	$\nabla\frac{1}{g}\int_0^1 \underset{\sim}{v}\frac{1}{2}(\underset{\sim}{v}\cdot\underset{\sim}{v})\frac{\partial p}{\partial \eta}d\eta$	82	W m^{-2}
divergence of thermal energy flux	$\nabla\frac{1}{g}\int_0^1 \underset{\sim}{v}c_pT\frac{\partial p}{\partial \eta}d\eta$	83	W m^{-2}
divergence of moisture flux	$\nabla\frac{1}{g}\int_0^1 \underset{\sim}{v}q\frac{\partial p}{\partial \eta}d\eta$	84	kg m^{-2} s^{-1}
divergence of geopotential flux	$\nabla\frac{1}{g}\int_0^1 \underset{\sim}{v}\phi\frac{\partial p}{\partial \eta}d\eta$	85	W m^{-2}
divergence of total energy flux	$\nabla\frac{1}{g}\int_0^1 \underset{\sim}{v}\left(\frac{1}{2}(\underset{\sim}{v}\cdot\underset{\sim}{v})+Lq+c_pT+\phi\right)\frac{\partial p}{\partial \eta}d\eta$	86	W m^{-2}
divergence of ozone flux	$\nabla\frac{1}{g}\int_0^1 \underset{\sim}{v}O_3\frac{\partial p}{\partial \eta}d\eta$	87	kg m^{-2} s^{-1}
eastward cloud liquid water flux	$\frac{1}{g}\int_0^1 uCLW\frac{\partial p}{\partial \eta}d\eta$	88	kg m^{-1} s^{-1}
northward cloud liquid water flux	$\frac{1}{g}\int_0^1 vCLW\frac{\partial p}{\partial \eta}d\eta$	89	kg m^{-1} s^{-1}

Parameter	Definition	Code	Units
eastward cloud frozen water flux	$\frac{1}{g}\int_0^1 uCIW \frac{\partial p}{\partial \eta} d\eta$	90	kg m^{-1} s^{-1}
northward cloud frozen water flux	$\frac{1}{g}\int_0^1 vCIW \frac{\partial p}{\partial \eta} d\eta$	91	kg m^{-1} s^{-1}
mass tendency	$\frac{1}{g}\frac{\partial p_s}{\partial t}$	92	kg m^{-2} s^{-1}

2.6. Ocean-wave data

A set of ocean-wave products are generated by the wave analysis, at 00, 06, 12 and 18 UTC, and the coupled wave-model forecasts. Unless indicated otherwise, the latter are available at 21 regularly spaced forecast steps from zero up to 10 days, from forecasts initiated twice daily at 00 and 12 UTC. They are archived together with parameters of gridded data from the altimeters on the ERS-1 and ERS-2 satellites. The archived fields are identified in MARS by **stream=wave** and are listed in Table 12. **Code** refers to the parameter reference number in GRIB code table 2, ECMWF local version 140. Data are stored on the wave model's reduced 1.0°x1.0° latitude/longitude grid.

Table 12: Wave and gridded ERS altimeter parameters

Parameter	An	Fc	Code	Units
model bathymetry	X		219	m
mean wave period from 1st moment	X	X	220	s
mean wave period from 2nd moment	X	X	221	s
wave spectral directional width	X	X	222	
mean wave period from 1st moment of wind waves	X	X	223	s
mean wave period from 2nd moment of wind waves	X	X	224	s
wave spectral directional width of wind waves	X	X	225	
mean wave period from 1st moment of swell	X	X	226	s
mean wave period from 2nd moment of swell	X	X	227	s
wave spectral directional width of swell	X	X	228	
significant wave height	X	X	229	m
mean wave direction	X	X	230	degrees
peak period of 1d spectra	X	X	231	s
mean wave period	X	X	232	s
coefficient of drag with waves [1]	X	X	233	
significant height of wind waves	X	X	234	m
mean direction of wind waves	X	X	235	degrees
mean period of wind waves	X	X	236	s
significant height of total swell	X	X	237	m
mean direction of total swell	X	X	238	degrees
mean period of total swell	X	X	239	s
mean square slope of waves	X	X	244	

---

[1] Forecasts are also available at a range of 3-hours

Parameter	An	Fc	Code	Units
10m wind speed modified by wave model[1]	X	X	245	m s^{-1}
gridded ERS altimeter wave height[2]	X		246	m
gridded corrected ERS altimeter wave height[2]	X		247	m
gridded ERS altimeter range relative correction[2]	X		248	
2D wave spectra (single)[3]	X	X	251	m^2 s $radians^{-1}$
wave spectral kurtosis	X	X	252	
Benjamin-Feir index	X	X	253	
wave spectral peakedness	X	X	254	s^{-1}

[1] Forecasts are also available at a range of 3-hours
[2] Available from late 1991
[3] Available for 30 frequencies and 24 directions

2.7. Additional fields accumulated from the physical parametrizations

The data described in the following subsections are accumulated from the beginning of the forecasts, initialised at 00 and 12 UTC, over the ranges of 3-, 6-, 9- and 12-hours. **Code** refers to the parameter reference number in GRIB code table 2, ECMWF local version 162. These parameters are saved on the model's Gaussian grid.

2.7.1. Parameters to support chemical-transport modelling

Table 13 lists the fields produced for use in chemical-transport modelling and other trajectory studies. These are archived on model half or model full levels, as indicated.

Table 13: Parameters to support chemical transport modelling

Parameter	Surfaces	Code	Units
updraught mass flux	half levels	104	kg m^{-2}
downdraught mass flux	half levels	105	kg m^{-2}
updraught detrainment rate	full levels	106	kg m^{-3}
downdraught detrainment rate	full levels	107	kg m^{-3}
total precipitation profile	half levels	108	kg m^{-2}
turbulent diffusion coefficient for heat	half levels	109	m^2

2.7.2. Radiative tendencies

The parameters indicated in Table 14 are tendencies from cloudy and clear-sky radiation, which are saved on full model levels.

Table 14: Parameters to validate clear sky radiation

Parameter	Code	Units
Short wave radiative tendency	100	K
Long wave radiative tendency	101	K
Clear sky short wave radiative tendency	102	K
Clear sky long wave radiative tendency	103	K

2.7.3. *Net tendencies from parametrized processes*

Net tendencies from parametrized processes are saved on full model levels and listed in Table 15.

Table 15: Net tendencies

Parameter	Code	Units
u tendency	112	m s^{-1}
v tendency	113	m s^{-1}
T tendency	110	K
q tendency	111	kg kg^{-1}

3. Monthly means

A variety of monthly means of many of the analysis and forecast fields described in Section 2 are computed and archived during the ERA-Interim production. Monthly means of the analysis fields are produced for surface and single level parameters and for parameters on model levels, pressure levels, the 15 isentropic levels excluding 320 K, and on the PV = ±2 PVU surface. Since forecast data are not available on isentropic levels or on the PV = ±2 PVU surface, monthly means of forecast fields are produced only for surface and single level parameters and for parameters on model and pressure levels.

The monthly mean parameters on model and pressure levels are the same as those listed in Table 3 while for the isentropic and PV = ±2 PVU surfaces they are listed in Tables 5 and 6. For the monthly averages of surface and single level parameters there are a few exceptions to the information given in Tables 7-10, as indicated in Table 16 (an "X" indicates the parameter is available). There are no averages of the "Ocean-wave data" described in Section 2.6 or of the "Additional fields accumulated from the physical parametrizations" in Section 2.7.

Table 16: Monthly mean surface and single level parameters: Exceptions from Tables 7-10

Parameter	An	Fc	Code	Units
magnitude of surface stress (*accumulated*)		X	048	N m^{-2} s
wind gusts at 10 m		no mean	049	
geopotential	X	no mean	129	m^2 s^{-2}
land/sea mask	X	no mean	172	(0,1)
max. temp. at 2 m since previous post-processing		no mean	201	
min. temp. at 2 m since previous post-processing		no mean	202	
10 metre wind speed	X	X	207	m s^{-1}

3.1. Synoptic monthly means

The monthly averages produced for each of the four main synoptic hours (00, 06, 12, and 18 UTC) are referred to as synoptic monthly means. These are identified in MARS by **stream=mnth**. The synoptic monthly means for analysed parameters are produced from the respective analyses at the appropriate synoptic hour for every day in the month.

The synoptic monthly means for instantaneous forecast parameters are produced from the set of appropriate 6- and 12-hour forecasts, initiated at either 00 or 12 UTC, that verify at a particular synoptic hour for every day within the month. (In addition, 3- and 9-hour forecasts are used to produce synoptic monthly means for surface and single level parameters.) The first member of this set is the 12-hour forecast initiated at 12 UTC on the last day of the previous month, while the last member is the 6-hour (or 9-hour for surface and single level parameters) forecast initiated at 12 UTC on the last day of the month. Similarly, the means for accumulated forecast surface and single level parameters involve all relevant forecasts that have an accumulation period contained within the month. The first member used is therefore the 3-hour forecast initiated at 00 UTC on the first day of the month, while the last member is the 12-hour forecast initiated at 12 UTC on the last day of the month.

3.2. Monthly means of daily means

Monthly means of daily means are produced for analyses (the average of the four main synoptic monthly means at 00, 06, 12, and 18 UTC) and instantaneous forecast data (the average of the four synoptic means at forecast steps of 6- and 12-hours from the forecasts initiated at 00 and 12 UTC). In MARS they are identified by **stream=moda**. These averages represent means for the entire month.

3.3. Monthly means of daily forecast accumulations

Monthly means of daily forecast accumulations are produced for the accumulated surface and single level fields (Tables 9 and 16) by averaging the twice daily forecasts (from 00 and 12 UTC) over the month, for the forecast ranges of 0-12 hours, 12-24 hours and 24-36 hours, and then scaling the results to have units “per day”. They are identified in MARS by **stream=mdfa**.

The monthly means of daily forecast accumulations include all relevant forecasts that have an accumulation period in the month and so represent accumulations for the entire month at the particular forecast range. Since the hydrological parameters are in units of “m of water per day”, they should be multiplied by 1000 to convert to $kgm^{-2}day^{-1}$ or to $mmday^{-1}$. Energy (turbulent and radiative) and momentum fluxes should be divided by 86400 seconds (24 hours) to convert to the commonly used units of Wm^{-2} and Nm^{-2}, respectively.

4. Product access

Most archived ERA-Interim data can be downloaded from the ECMWF Data Server at http://data.ecmwf.int/data, as described in Section 4.1 below. The data are available at full resolution with flexible options for regional selection and gridding. Please check http://www.ecmwf.int/research/era for updates on data availability and other pertinent information, and http://data.ecmwf.int/data for conditions on use .

The ERA-Interim Archive is part of ECMWF’s Meteorological Archive and Retrieval System (MARS), which is accessible to registered users in ECMWF Member States and Co-operating States. MARS supports the supply of ERA-Interim data on a range of grids; see http://www.ecmwf.int/services/archive for full details.

Arrangements exist at a national level within some Members States to supply data to users within that state who do not have direct access to MARS.

Based on an agreement with ECMWF, the National Center for Atmospheric Research (NCAR) maintains a copy of the complete contents of the ERA-Interim Archive to serve research and educational institutions in North America; see http://dss.ucar.edu/pub.

If needed, ERA-Interim products can be delivered on various media at handling charges by ECMWF Data Services via http://www.ecmwf.int/products/data.

4.1. ECMWF Data Server

ERA-Interim data in either GRIB or NetCDF format can be downloaded from the ECMWF Data Server. Global fields are available at full resolution, both vertically (on model levels) and horizontally. Data retrievals can be optionally restricted to a limited area and interpolated to a coarser grid. The data include:

- all 11 surface invariants, but at one analysis time only;
- all remaining analysed surface parameters, including vertical integrals (Section 2.5), at 0, 6, 12 and 18 UTC;
- 3 analysed wave parameters (significant wave height, mean wave direction and mean wave period) at 0, 6, 12 and 18 UTC;
- all forecast surface parameters (except the invariants) at steps of 3-, 6-, 9- and 12-hours from 00 and 12 UTC;
- all analysed upper-air parameters on 60 model levels at 00, 06, 12 and 18 UTC;
- all analysed upper-air parameters on 37 pressure levels at 00, 06, 12 and 18 UTC;
- all analysed parameters on 15 isentropic levels (not 320 K) at 00, 06, 12 and 18 UTC;
- all analysed parameters on PV = ±2 PVU at 00, 06, 12 and 18 UTC;
- all synoptic monthly means (except for the upper air forecast fields);
- all monthly means of daily means (except for the upper air forecast fields; if available, the analysed values at the surface are used instead of the forecast values);
- all monthly means of daily accumulations at step=0-12 only.

4.2. MARS

Fields can be extracted from MARS in GRIB format, on the globe or in a limited area and at full or reduced resolution. Spectral fields can also be transformed to a grid. MARS users can either access the data from an ECMWF workstation or via the internet at http://www.ecmwf.int/services/archive, though the latter method does not have the full functionality of the former method. Full documentation for MARS can be found at http://www.ecmwf.int/publications/manuals/mars.

4.3. MARS retrieval examples

The following examples show how ERA-Interim data can be extracted from the MARS archive to an ECMWF workstation.

4.3.1. Example 1: instantaneous analysed surface pressure

```
Retrieve, Class=ei, Expver=1, Stream=oper, Type=an, Levtype=sfc, Param=sp,
Date=19890101, Time=00, Step=00, Target=myfile.grb
```

4.3.2. Example 2: synoptic monthly mean of analysed spectral geopotential at 500 hPa

```
Retrieve, Class=ei, Expver=1, Stream=mnth, Type=an, Levtype=pl, Level=500,
Param=z, Date=19890101, Time=06, Step=00, Target=myfile.grb
```

4.3.3. Example 3: monthly mean of daily mean of forecast 2m temperature

```
Retrieve, Class=ei, Expver=1, Stream=moda, Type=fc, Levtype=sfc, Param=2t,
Date=19890101, Time=00, Step=00, Target=myfile.grb
```

4.3.4. Example 4: monthly mean of daily forecast accumulation of total precipitation

```
Retrieve, Class=ei, Expver=1, Stream=mdfa, Type=fc, Levtype=sfc, Param=tp,
Date=19890101, Time=00, Step=12, Target=myfile.grb
```

4.3.5. Example 5: instantaneous analysed significant wave height

```
Retrieve, Class=ei, Expver=1, Stream=wave, Type=an, Levtype=sfc, Param=swh,
Date=19890101, Time=12, Step=00, Target=myfile.grb
```

Annex 1: Vertical integrals for energy, mass, water and ozone budgets

The continuous, adiabatic, frictionless form of the model's primitive equations may be manipulated to give the following equations, in standard notation:

Kinetic energy:

$$\frac{\partial}{\partial t}\left(E\frac{\partial p}{\partial \eta}\right)=-\nabla\cdot\left(\underset{\sim}{v}E\frac{\partial p}{\partial \eta}\right)-\nabla\cdot\left(\underset{\sim}{v}\phi-\phi\frac{\partial p}{\partial \eta}\right)-\frac{\partial}{\partial \eta}\left(\phi-\phi_s\int_0^{\eta}\nabla\cdot\underset{\sim}{v}\frac{\partial p}{\partial \eta}d\eta\right)$$
$$-\frac{RT\omega}{p}\frac{\partial p}{\partial \eta}-\underset{\sim}{v}\frac{\partial p}{\partial \eta}\cdot\nabla\phi_s \qquad \text{(A1.1)}$$

where

$$E=\frac{1}{2}\left(\underset{\sim}{v}\cdot\underset{\sim}{v}\right)$$

Potential+Internal energy:

$$\frac{\partial}{\partial t}\left(\left(c_pT+\phi_s\right)\frac{\partial p}{\partial \eta}\right)=-\nabla\cdot\left(\underset{\sim}{v}\left(c_pT+\phi_s\right)\frac{\partial p}{\partial \eta}\right)-\frac{\partial}{\partial \eta}\left(\dot{\eta}\left(c_pT+\phi_s\right)\frac{\partial p}{\partial \eta}\right)+\frac{RT\omega}{p}\frac{\partial p}{\partial \eta}+\underset{\sim}{v}\frac{\partial p}{\partial \eta}\cdot\nabla\phi_s \qquad \text{(A1.2)}$$

Mass:

$$\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial \eta}\right)=-\nabla\cdot\left(\underset{\sim}{v}\frac{\partial p}{\partial \eta}\right)-\frac{\partial}{\partial \eta}\left(\dot{\eta}q\frac{\partial p}{\partial \eta}\right) \qquad \text{(A1.3)}$$

Water vapour:

$$\frac{\partial}{\partial t}\left(q\frac{\partial p}{\partial \eta}\right)=-\nabla\cdot\left(\underset{\sim}{v}q\frac{\partial p}{\partial \eta}\right)-\frac{\partial}{\partial \eta}\left(\dot{\eta}q\frac{\partial p}{\partial \eta}\right) \qquad \text{(A1.4)}$$

Ozone:

$$\frac{\partial}{\partial t}\left(O_3\frac{\partial p}{\partial \eta}\right)=-\nabla\cdot\left(\underset{\sim}{v}O_3\frac{\partial p}{\partial \eta}\right)-\frac{\partial}{\partial \eta}\left(\dot{\eta}O_3\frac{\partial p}{\partial \eta}\right) \qquad \text{(A1.5)}$$

The notation is as in Simmons and Burridge(1981, *Mon. Wea. Rev*., **109**, 758-766). The gas constant, R, and specific heat at constant pressure, c_p, vary with specific humidity, q:

$$R=R_d\left(1+\left(\frac{R_v}{R_d}-1\right)q\right) \qquad \text{(A1.6)}$$

$$c_p=c_{pd}\left(1+\left(\frac{c_{pv}}{c_{pd}}-1\right)q\right) \qquad \text{(A1.7)}$$

where subscripts d and v denote values for dry air and water vapour respectively.

It should be noted that $\left(c_p T + \phi_s\right)\frac{\partial p}{\partial \eta}$ should strictly be interpreted in terms of potential+internal energy only when vertically integrated:

$$\int_0^1 \left(c_v T + \phi\right)\frac{\partial p}{\partial \eta} = \int_0^1 \left(c_p T + \phi - RT\right)\frac{\partial p}{\partial \eta} d\eta = \int_0^1 \left(c_p T \frac{\partial p}{\partial \eta} + \frac{\partial}{\partial \eta}\left(p\phi\right)\right) d\eta = \int_0^1 \left(c_p T + \phi_s\right)\frac{\partial p}{\partial \eta} d\eta \tag{A1.8}$$

Integrating the energy, mass, water vapour and ozone equations in the vertical, they may be written symbolically as:

$$\frac{\partial}{\partial t} KE = -\left(\nabla \cdot \underset{\sim}{F}_{KE}\right) - \left(\nabla \cdot \underset{\sim}{F}_{\phi - \phi_s}\right) + C_1 + C_2 \tag{A1.9}$$

$$\frac{\partial}{\partial t} PIE = -\left(\nabla \cdot \underset{\sim}{F}_{PIE}\right) - C_1 - C_2 \tag{A1.10}$$

$$\frac{\partial}{\partial t} Mass = -\left(\nabla \cdot \underset{\sim}{F}_{M}\right) \tag{A1.11}$$

$$\frac{\partial}{\partial t} TCWV = -\left(\nabla \cdot \underset{\sim}{F}_{q}\right) \tag{A1.12}$$

$$\frac{\partial}{\partial t} TCO = -\left(\nabla \cdot \underset{\sim}{F}_{O_3}\right) \tag{A1.13}$$

The vertically integrated variables are:

$$KE = \frac{1}{g}\int_0^1 \frac{1}{2}\left(\underset{\sim}{v} \cdot \underset{\sim}{v}\right)\frac{\partial p}{\partial \eta} d\eta \tag{A1.14}$$

$$PIE = \frac{1}{g}\int_0^1 \left(c_p T + \phi_s\right)\frac{\partial p}{\partial \eta} d\eta = CPT + \phi_s Mass \tag{A1.15}$$

$$CPT = \frac{1}{g}\int_0^1 c_p T \frac{\partial p}{\partial \eta} d\eta \tag{A1.16}$$

$$Mass = \frac{1}{g}\int_0^1 \frac{\partial p}{\partial \eta} d\eta = \frac{p_s}{g} \tag{A1.17}$$

$$TCWV = \frac{1}{g}\int_0^1 g \frac{\partial p}{\partial \eta} d\eta \tag{A1.18}$$

$$TCO = \frac{1}{g}\int_0^1 O_3 \frac{\partial p}{\partial \eta} d\eta \tag{A1.19}$$

The fluxes are:

$$\underset{\sim}{F}_{KE} = \frac{1}{g}\int_0^1 \underset{\sim}{v}\frac{1}{2}\left(\underset{\sim}{v}\cdot\underset{\sim}{v}\right)\frac{\partial p}{\partial \eta}d\eta \tag{A1.20}$$

$$\underset{\sim}{F}_{\phi-\phi_s} = \frac{1}{g}\int_0^1 \underset{\sim}{v}\left(\phi-\phi_s\right)\frac{\partial p}{\partial \eta}d\eta = \underset{\sim}{F}_{\phi} - \underset{\sim}{F}_{\phi_s} \tag{A1.21}$$

$$\underset{\sim}{F}_{\phi} = \frac{1}{g}\int_0^1 \underset{\sim}{v}\phi\frac{\partial p}{\partial \eta}d\eta \tag{A1.22}$$

$$\underset{\sim}{F}_{\phi_s} = \frac{1}{g}\int_0^1 \underset{\sim}{v}\phi_s\frac{\partial p}{\partial \eta}d\eta = \phi_s\underset{\sim}{F}_M \tag{A1.23}$$

$$F_{PIE} = \frac{1}{g}\int_0^1 \underset{\sim}{v}\left(c_pT+\phi_s\right)\frac{\partial p}{\partial \eta}d\eta = \underset{\sim}{F}_{CPT} + \phi_s\underset{\sim}{F}_M \tag{A1.24}$$

$$\underset{\sim}{F}_{CPT} = \frac{1}{g}\int_0^1 \underset{\sim}{v}c_pT\frac{\partial p}{\partial \eta}d\eta \tag{A1.25}$$

$$\underset{\sim}{F}_{M} = \frac{1}{g}\int_0^1 \underset{\sim}{v}\frac{\partial p}{\partial \eta}d\eta \tag{A1.26}$$

$$\underset{\sim}{F}_{q} = \frac{1}{g}\int_0^1 \underset{\sim}{v}q\frac{\partial p}{\partial \eta}d\eta \tag{A1.27}$$

$$\underset{\sim}{F}_{O_3} = \frac{1}{g}\int_0^1 \underset{\sim}{v}O_3\frac{\partial p}{\partial \eta}d\eta \tag{A1.28}$$

and the energy conversions are:

$$C_1 = -\frac{1}{g}\int_0^1 \frac{RT\omega}{p}\frac{\partial p}{\partial \eta}d\eta \tag{A1.29}$$

$$C2 = -\frac{1}{g}\int_0^1 \left(\underset{\sim}{v}\frac{\partial p}{\partial \eta}\cdot\nabla\phi_s\right)d\eta = -\underset{\sim}{F}_M\cdot\nabla\phi_s \tag{A1.30}$$

The conversion term C_2 is also given by:

$$C_2 = -\underset{\sim}{F}_M\cdot\nabla\phi_s = -\nabla\cdot\underset{\sim}{F}_{\phi_s} + \phi_s\nabla\cdot\underset{\sim}{F}_M = C_3 + \phi_s\nabla\cdot\underset{\sim}{F}_M \tag{A1.31}$$

where

$$C_3 = -\nabla\cdot\underset{\sim}{F}_{\phi s} \tag{A1.32}$$

The flux $\underset{\sim}{F}_{\phi s}$ can be simply calculated as $\phi_s\underset{\sim}{F}_M$ and the conversion term C_3 is given by the convergence of this flux.

The two energy equations can also be written:

$$\frac{\partial}{\partial t}KE = -\left(\nabla\cdot\underset{\sim}{F}_{KE}\right) - \left(\nabla\cdot\underset{\sim}{F}_{\phi}\right) + C_1 + C_3 \tag{A1.33}$$

$$\frac{\partial}{\partial t}PIE = -\left(\nabla\cdot\underset{\sim}{F}_{CPT}\right) - C_1 - C_3 \tag{A1.34}$$

Combining (A1.33), (A1.34) and L*(A1.12) gives the equation for total energy, *TE*, as

$$\frac{\partial}{\partial t}TE = -\nabla\cdot\underset{\sim}{F}_{TE} \tag{A1.35}$$

where

$$\begin{aligned} TE &= KE + L*TCWV + PIE \\ &= \frac{1}{g}\int_0^1\left(\frac{1}{2}\left(\underset{\sim}{v}\cdot\underset{\sim}{v}\right) + Lq + c_pT + \phi_s\right)\frac{\partial p}{\partial \eta}d\eta \end{aligned} \tag{A1.36}$$

and

$$\begin{aligned} F_{TE} &= \underset{\sim}{F}_{KE} + L\underset{\sim}{F}_{q} + \underset{\sim}{F}_{CPT} + \underset{\sim}{F}_{\phi} \\ &= \frac{1}{g}\int_0^1\underset{\sim}{v}\left(\frac{1}{2}\left(\underset{\sim}{v}\cdot\underset{\sim}{v}\right) + Lq + c_pT + \phi\right)\frac{\partial p}{\partial \eta}d\eta \end{aligned} \tag{A1.37}$$

Note that the surface geopotential, ϕ_s, is a fixed or invariant field, so that all RHS terms in the budget equations (A1.35) and (A1.9) to (A1.13) or (A1.33), (A1.34), (A1.11), (A1.12) and (A1.13) can thus be computed in terms of the supplied integrals, applying a divergence operator and simple multiplications where needed. These operations can be carried out either on the instantaneous values or on their monthly means.

A constant value, L=2.5008E+06 J kg^{-1} has been used for the latent heat coefficient in the energy integrals. In the enthalpy and energy integrals Cp = Cpd*(1.-q) + Cvd*q as defined in the IFS documentation. The vertical integral, $\frac{1}{g}\int_0^1 e\frac{\partial p}{\partial \eta}d\eta$, of a quantity *e* that is defined by its values e_k at the 60 full model levels is evaluated as $\frac{1}{g}\sum_{k=1}^{60} e_k\left(p_{k+\frac{1}{2}} - p_{k-\frac{1}{2}}\right)$