INAR

The extratropical transition of Hurricane Ophelia (2017) as diagnosed with omega equation and vorticity equation

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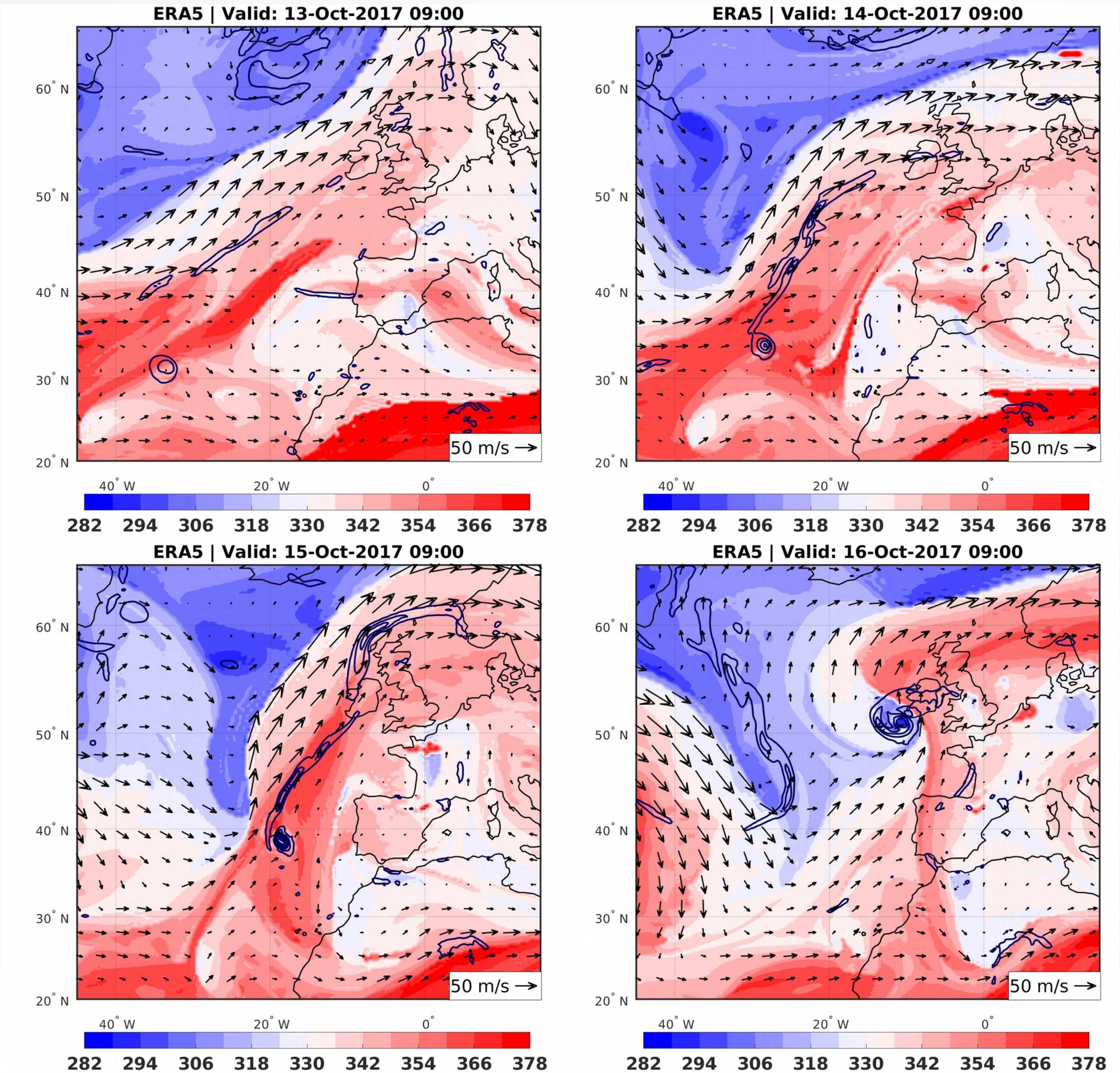
University of Reading, UK

Ophelia was the farthest-east major hurricane observed in the satellite era



- Formed in the central North Atlantic on 9 October 2017

- Developed to category 3 hurricane (959 hPa and 51 m/s)

- Transformed to a mid-latitude cyclone and hit Ireland on 16 October 2017

Potential temperature (colors) + wind at 2 PVU level and 950-850 hPa relative vorticity (contours)

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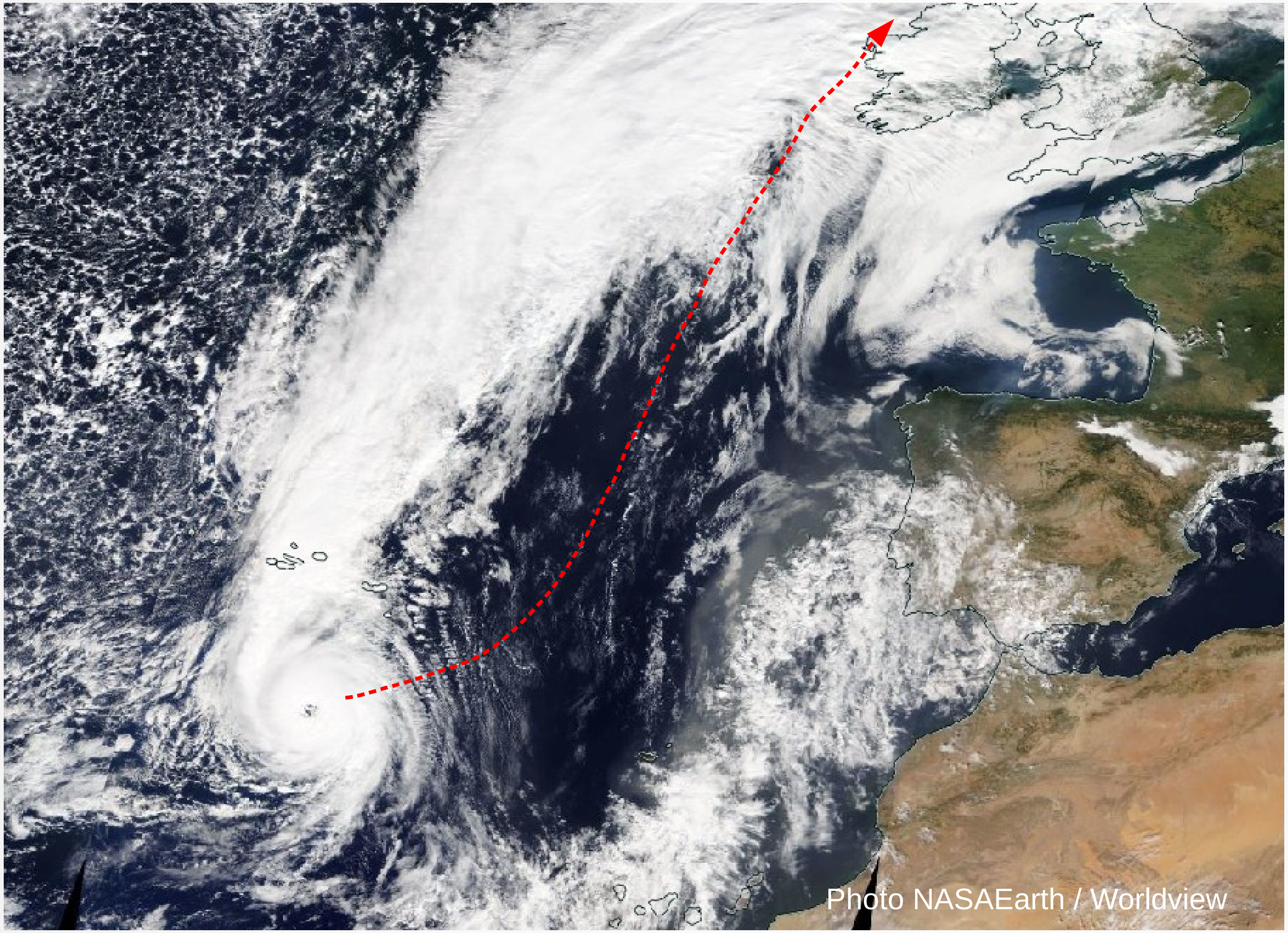
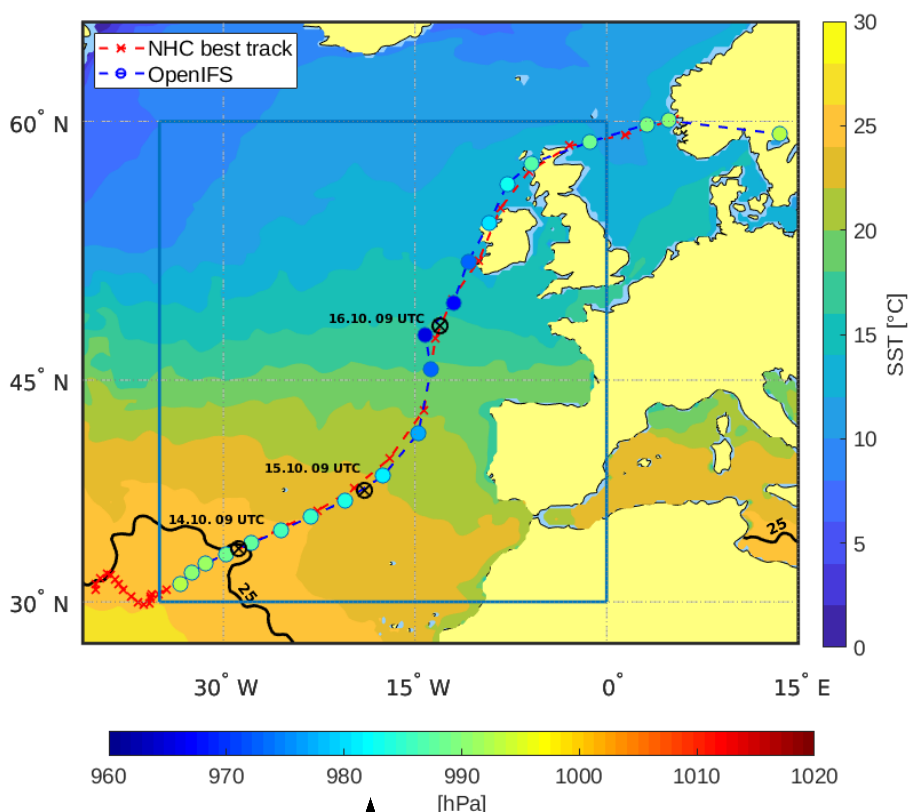


Aims of the study:

1. To determine the contributions of different **atmospheric forcing terms** for the evolution of Ophelia

2. To identify which of them led to the **strengthening** of the storm as post-tropical

OpenIFS (v40r1) simulation

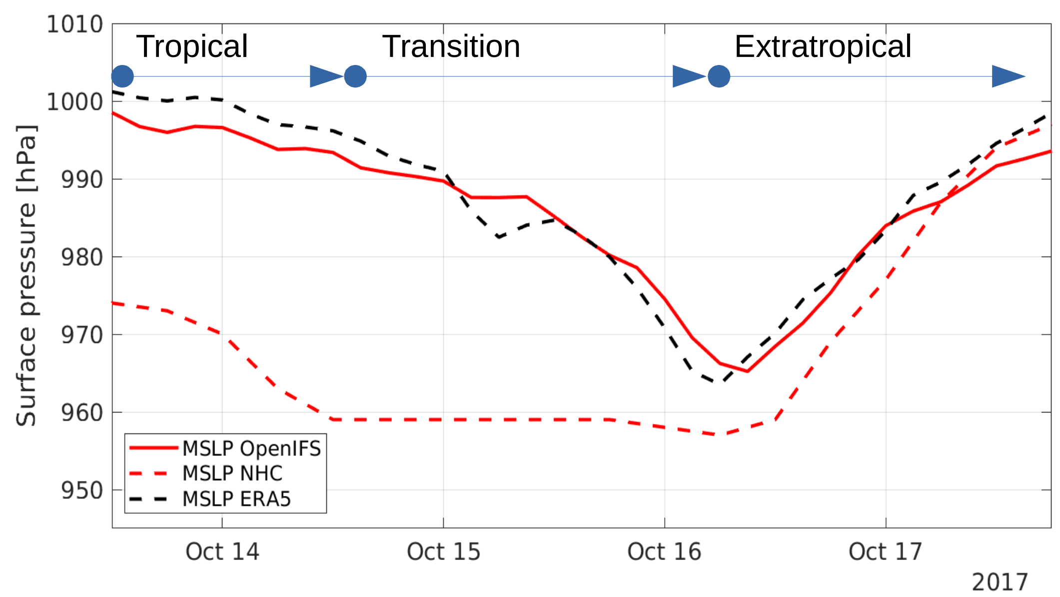


- Initial conditions from ECMWF operational analyses, at 12 UTC 13 October 2017

- Resolution T639 L137 (31 km grid spacing)

- NHC and OpenIFS tracks aligned well

- Intensity was underestimated by both OpenIFS & ERA5



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OZO diagnostic software

1.

OpenIFS: hourly output of
T, $\overline{\boldsymbol{V}}$, ζ, p_s, Q and $\overline{\boldsymbol{F}}$ fields

2.

OZO: solving of generalized omega equation & vorticity equation

3.

ω_{total} →

ω_V = Vertical motion caused by vorticity advection

ω_T = … by temperature advection

ω_Q = … by diabatic heating

ω_F = … by friction

ω_A = … by imbalance term

Indirect effect of vertical motion

4.

$$\frac{\partial \zeta}{\partial t} = \left(\frac{\partial \zeta}{\partial t}\right)_V + \left(\frac{\partial \zeta}{\partial t}\right)_T + \left(\frac{\partial \zeta}{\partial t}\right)_F + \left(\frac{\partial \zeta}{\partial t}\right)_Q + \left(\frac{\partial \zeta}{\partial t}\right)_A$$

1st version of the software published in GMD:

OZO v.1.0: software for solving a generalised omega equation and the Zwack–Okossi height tendency equation using WRF model output

Geoscientific Model Development
Open Access
EGU

Adiabatic & diabatic terms

ω_V	= Vertical motion caused by vorticity advection	Adiabatic terms
ω_T	= … by temperature advection	
ω_Q	= … by diabatic heating	Diabatic term
ω_F	= … by friction	
ω_A	= … by imbalance term	

ω_{total} → ω_V, ω_T, ω_Q, ω_F, ω_A

$$\frac{\partial \zeta}{\partial t} = \left(\frac{\partial \zeta}{\partial t}\right)_V + \left(\frac{\partial \zeta}{\partial t}\right)_T + \left(\frac{\partial \zeta}{\partial t}\right)_F + \left(\frac{\partial \zeta}{\partial t}\right)_Q + \left(\frac{\partial \zeta}{\partial t}\right)_A$$

Example: vorticity tendency by vorticity advection

$$\left(\frac{\partial \zeta}{\partial t}\right)_V = -\boldsymbol{V} \cdot \boldsymbol{\nabla}(\zeta + f) - \omega_V \frac{\partial \zeta}{\partial p} + (\zeta + f)\frac{\partial \omega_V}{\partial p} + \boldsymbol{k} \cdot \left(\frac{\partial \boldsymbol{V}}{\partial p} \times \boldsymbol{\nabla}\omega_V\right)$$

Direct effect + indirect effects

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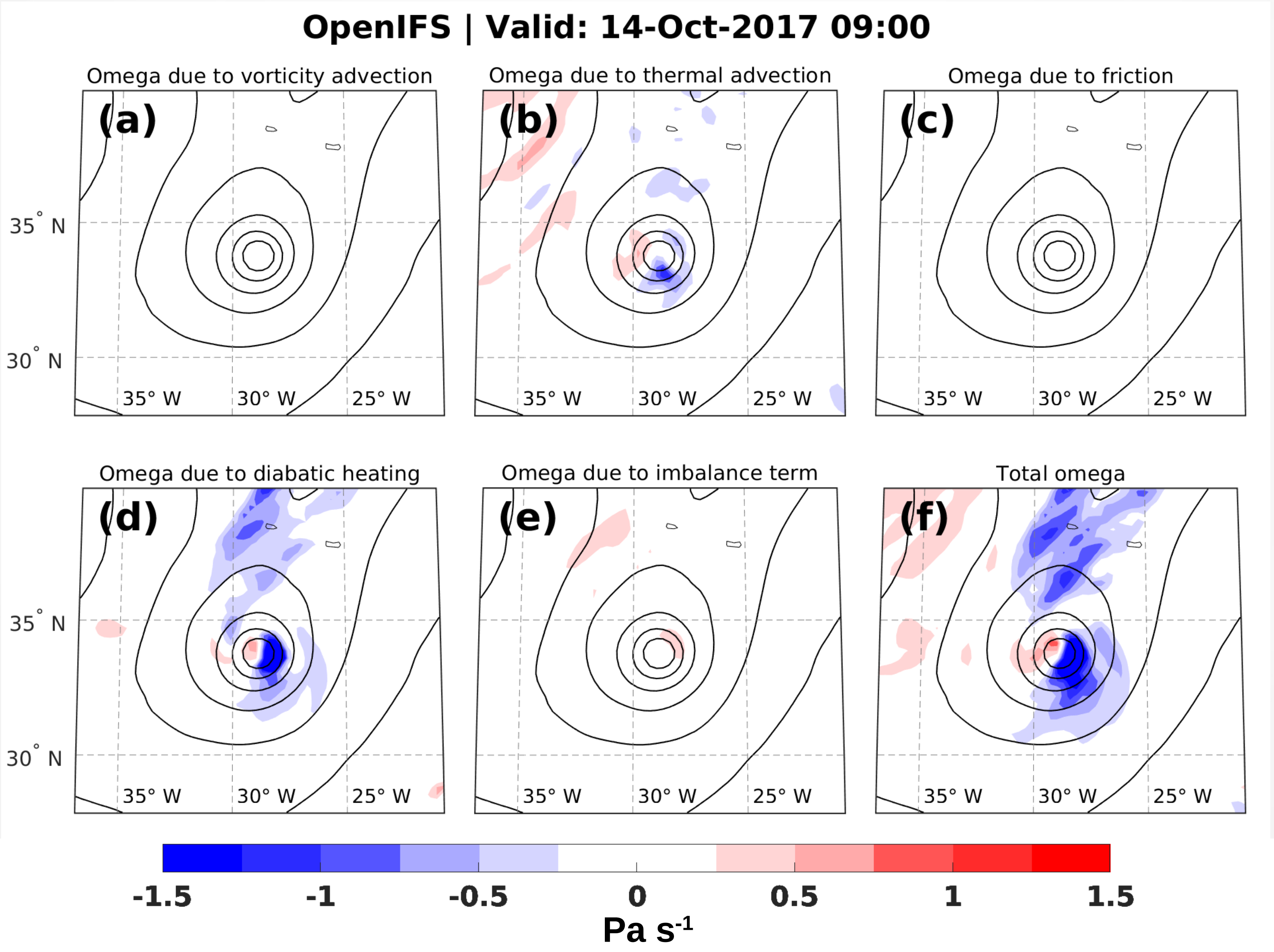
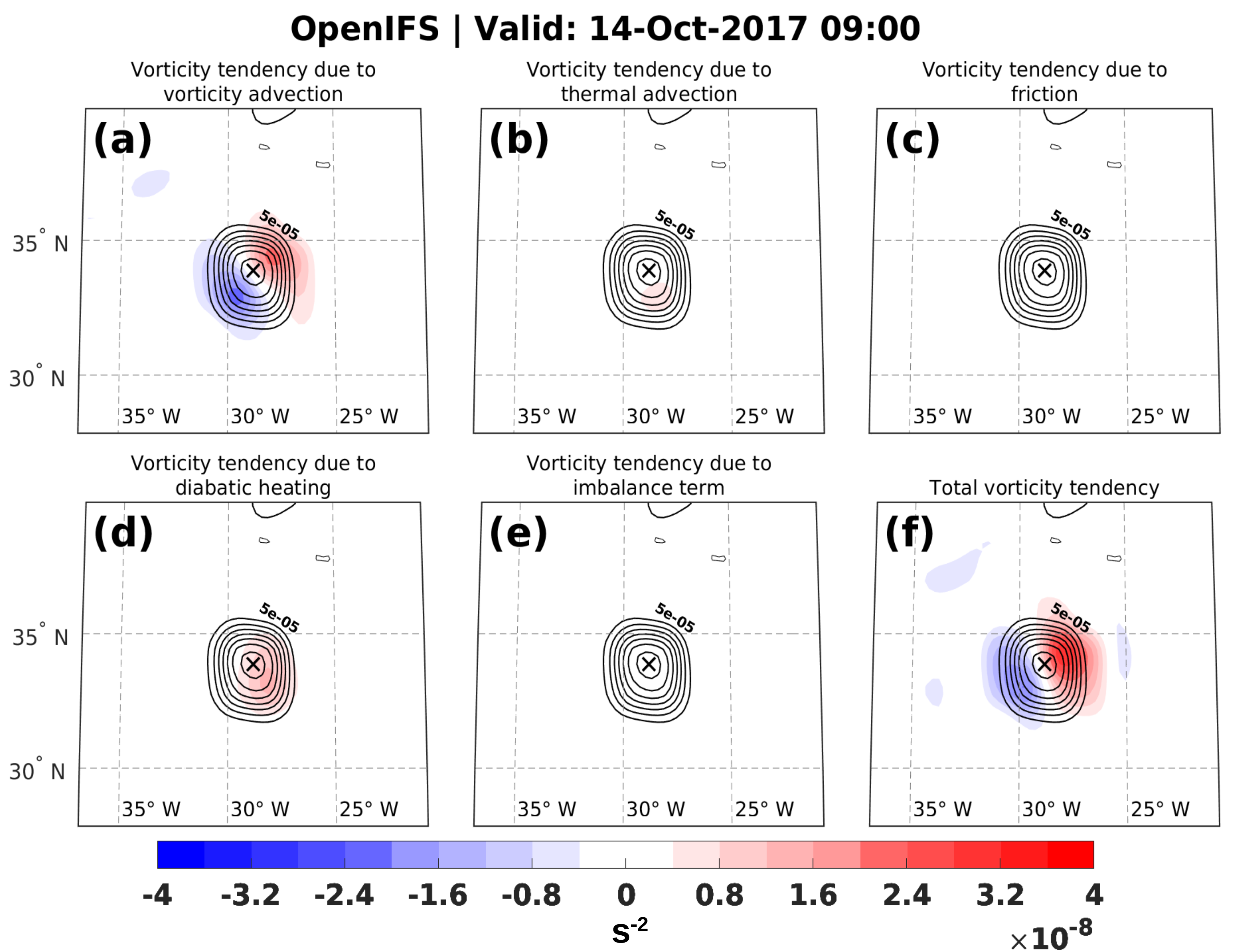
Vertical motion at 700 hPa induced by the forcing terms in the tropical phase of Ophelia



Contours = MSLP

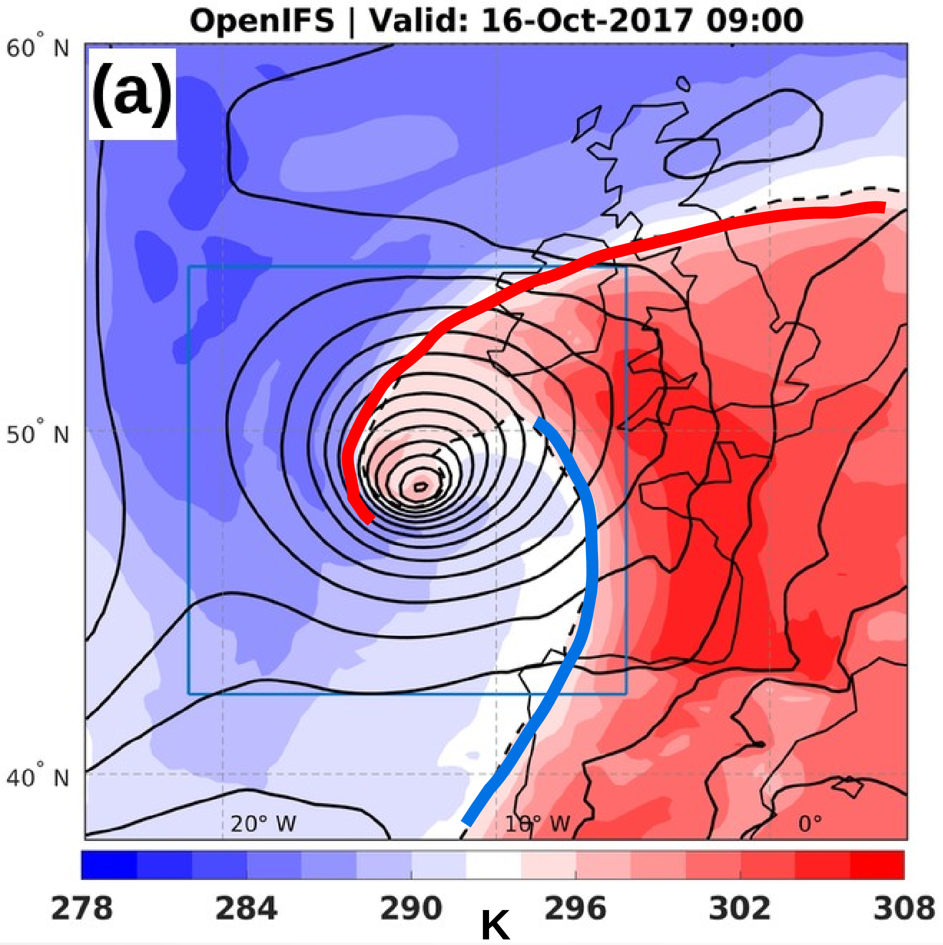
Low-level vorticity tendency induced by the forcing terms in the tropical phase of Ophelia



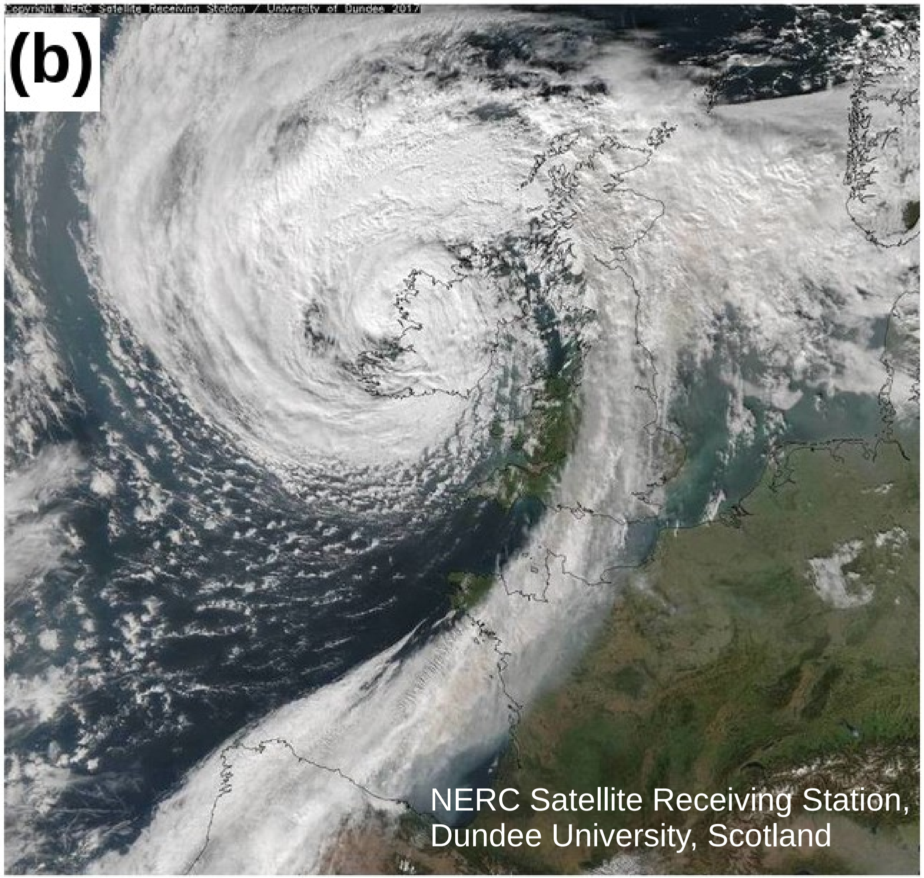
Contours = 900-800 hPa relative vorticity

Fields smoothed to T127 resolution

Ophelia developed to warm seclusion extratropical cyclone

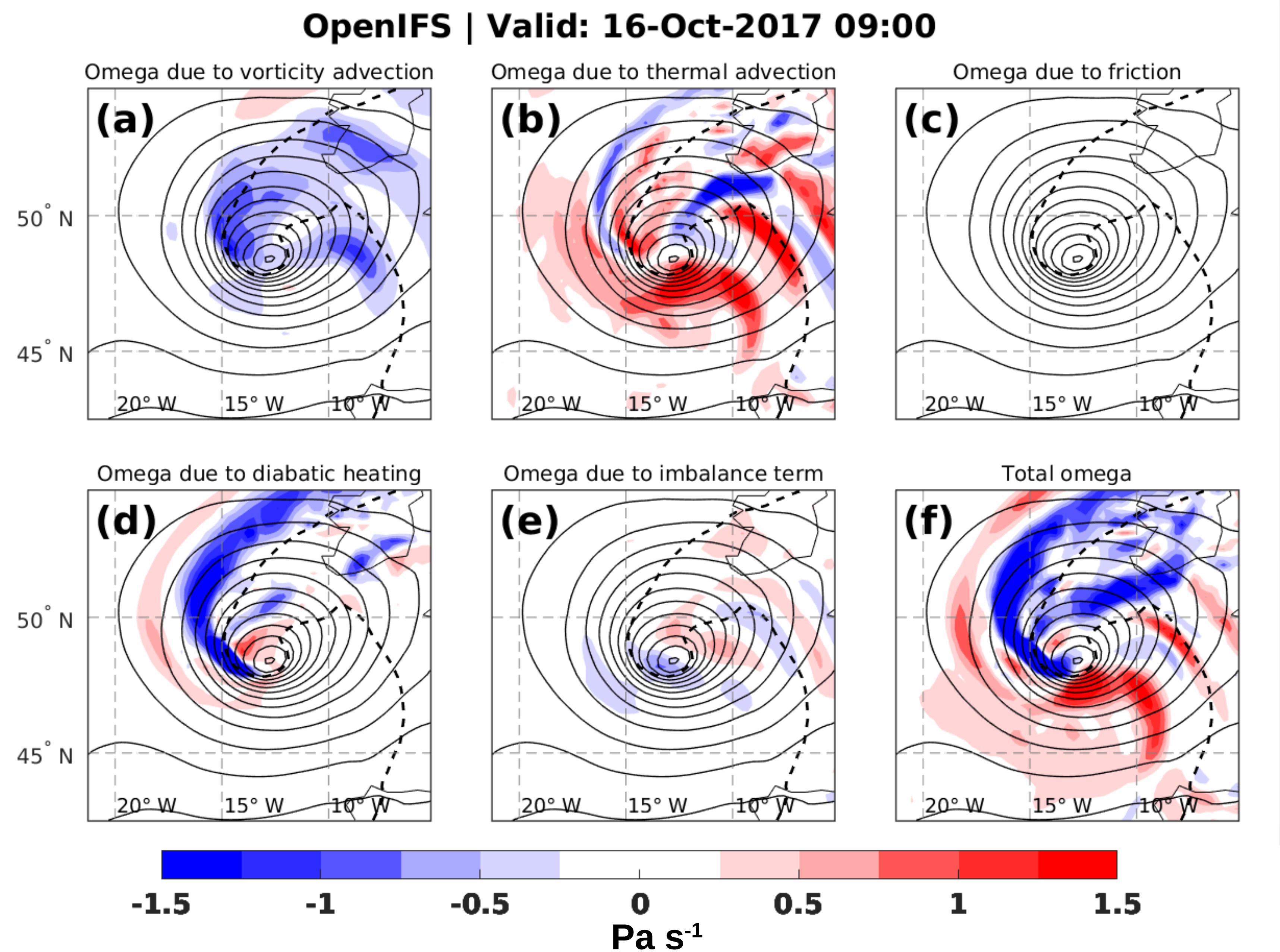


Potential temperature at 850 hPa + MSLP with 4 hPa intervals



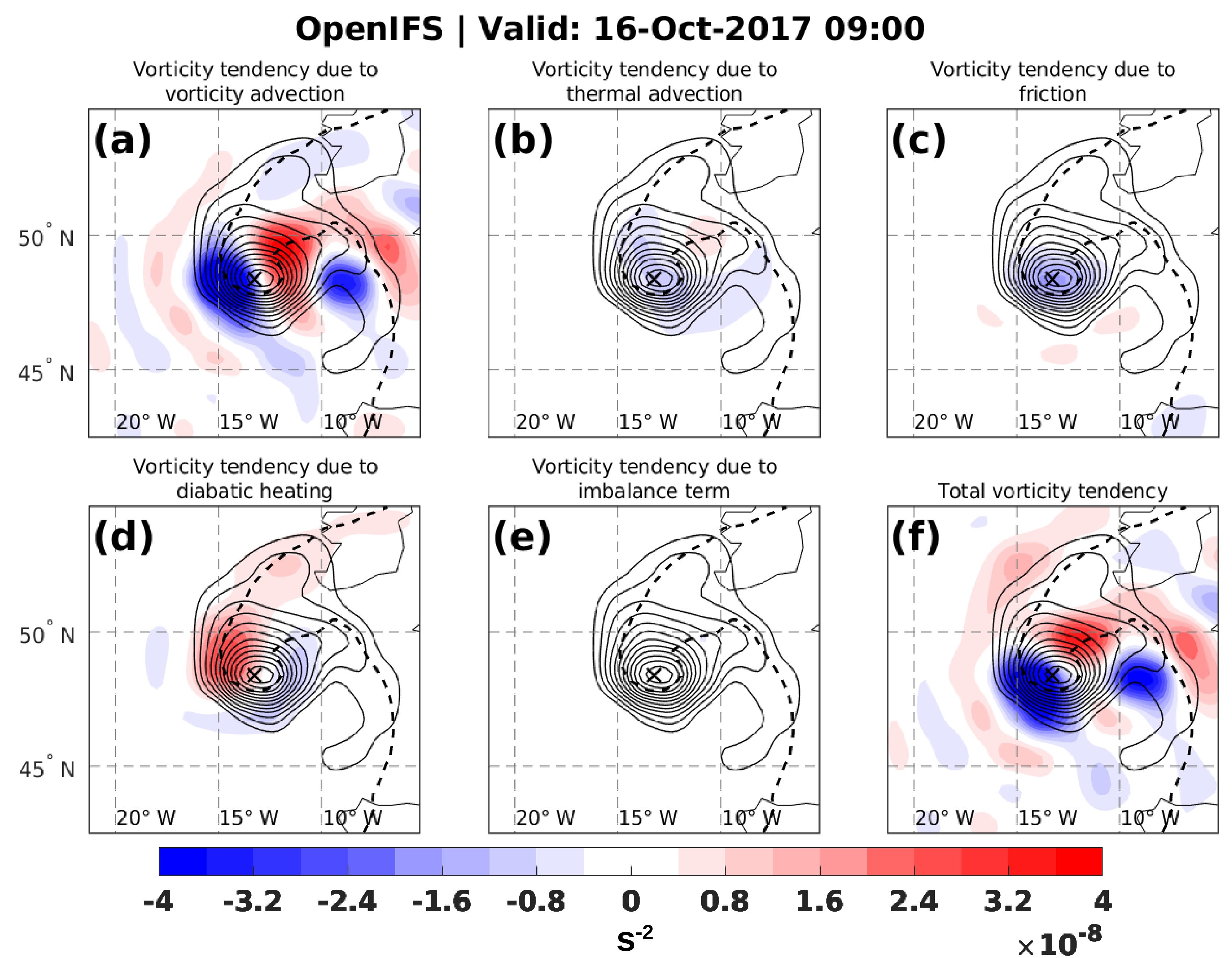
Visible satellite image at 12.43 UTC 16 October 2017

Vertical motion at 700 hPa induced by the forcing terms in the extratropical phase of Ophelia



Contours = MSLP

Low-level vorticity tendency induced by the forcing terms in the extratropical phase of Ophelia

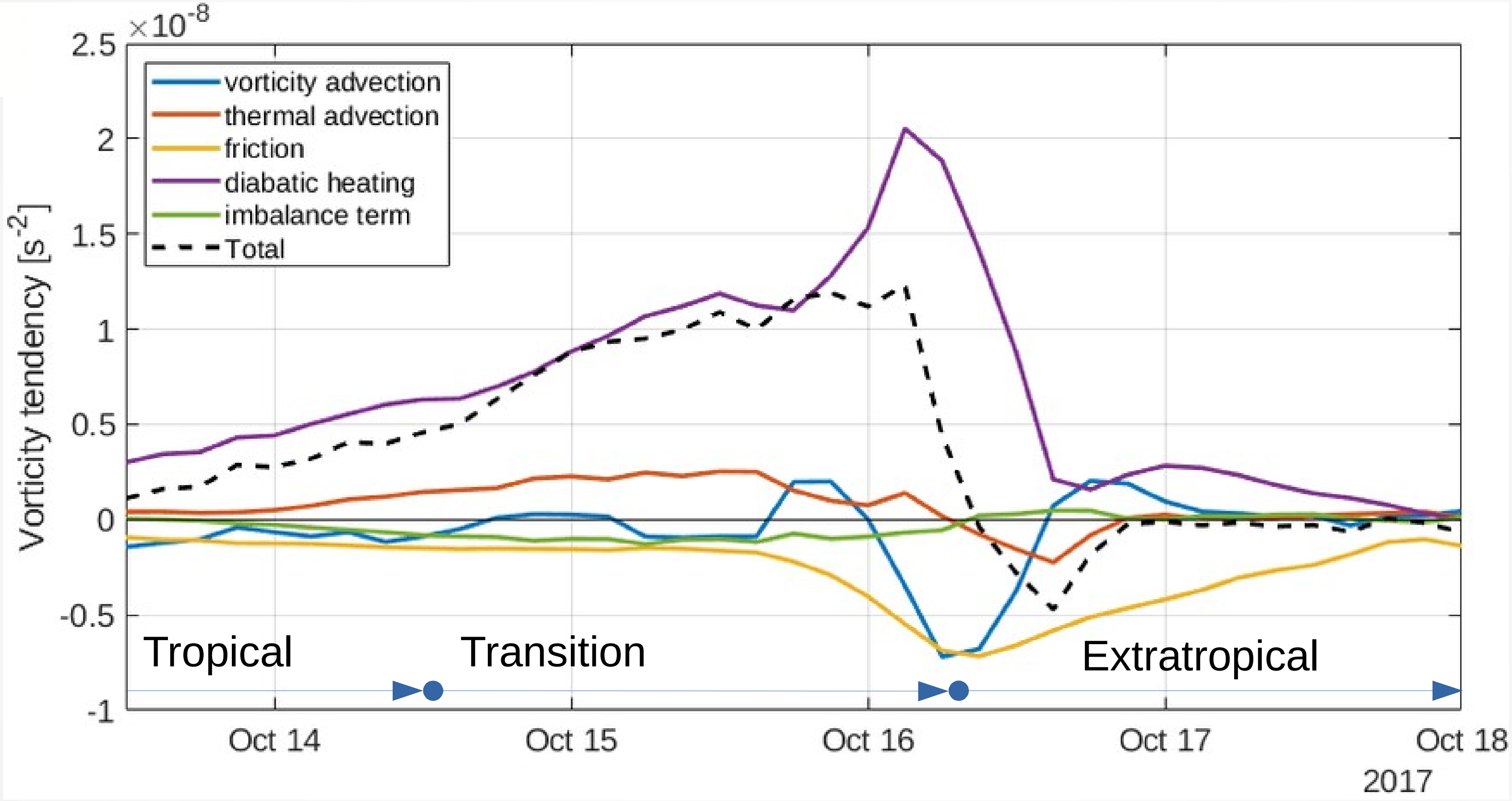


Contours = low-level relative vorticity

Low-level = 900-800 hPa

Fields smoothed to T127 resolution

Time series of vorticity tendencies at the cyclone centre



Positive: the forcing is intensifying the storm

Negative: the forcing is weakening the storm

- Diabatic processes (purple) were dominating

- Net effect of vorticity advection (blue) negative due to divergent circulation: divergent vorticity advection transports air with lower cyclonic vorticity to the area of high cyclonic vorticity

The contributions from different model parametrizations to diabatic heating

In OpenIFS, the total diabatic heating rate consists of five parts:

$$Q = Q_r + Q_v + Q_g + Q_c + Q_{mp}$$

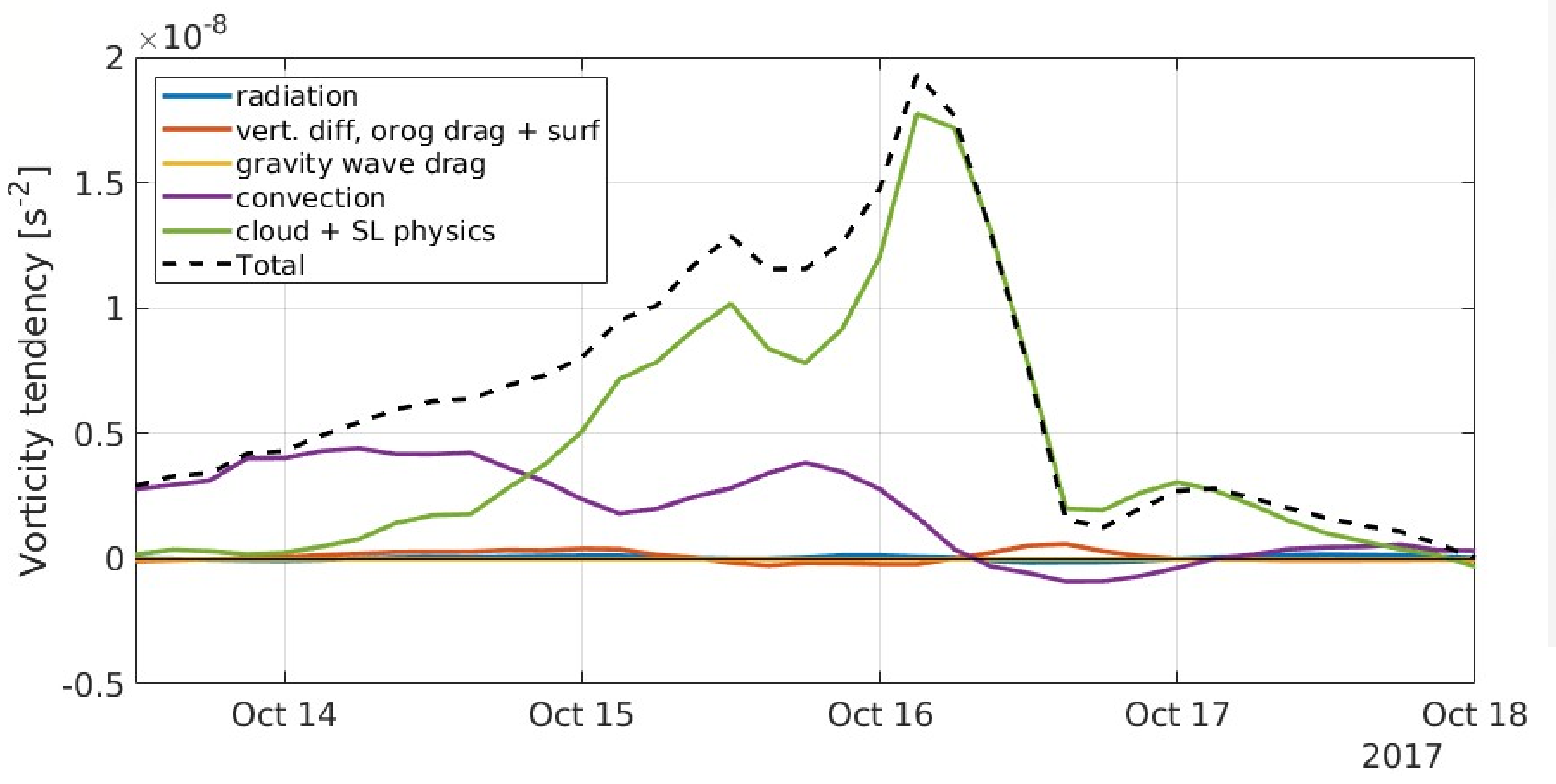
Negligible vorticity tendency for Ophelia ($Q_r + Q_v + Q_g$)

Dominating parts ($Q_c + Q_{mp}$)

Temperature tendency caused by

- radiation (Q_r),
- surface processes (Q_v),
- gravity wave drag (Q_g),

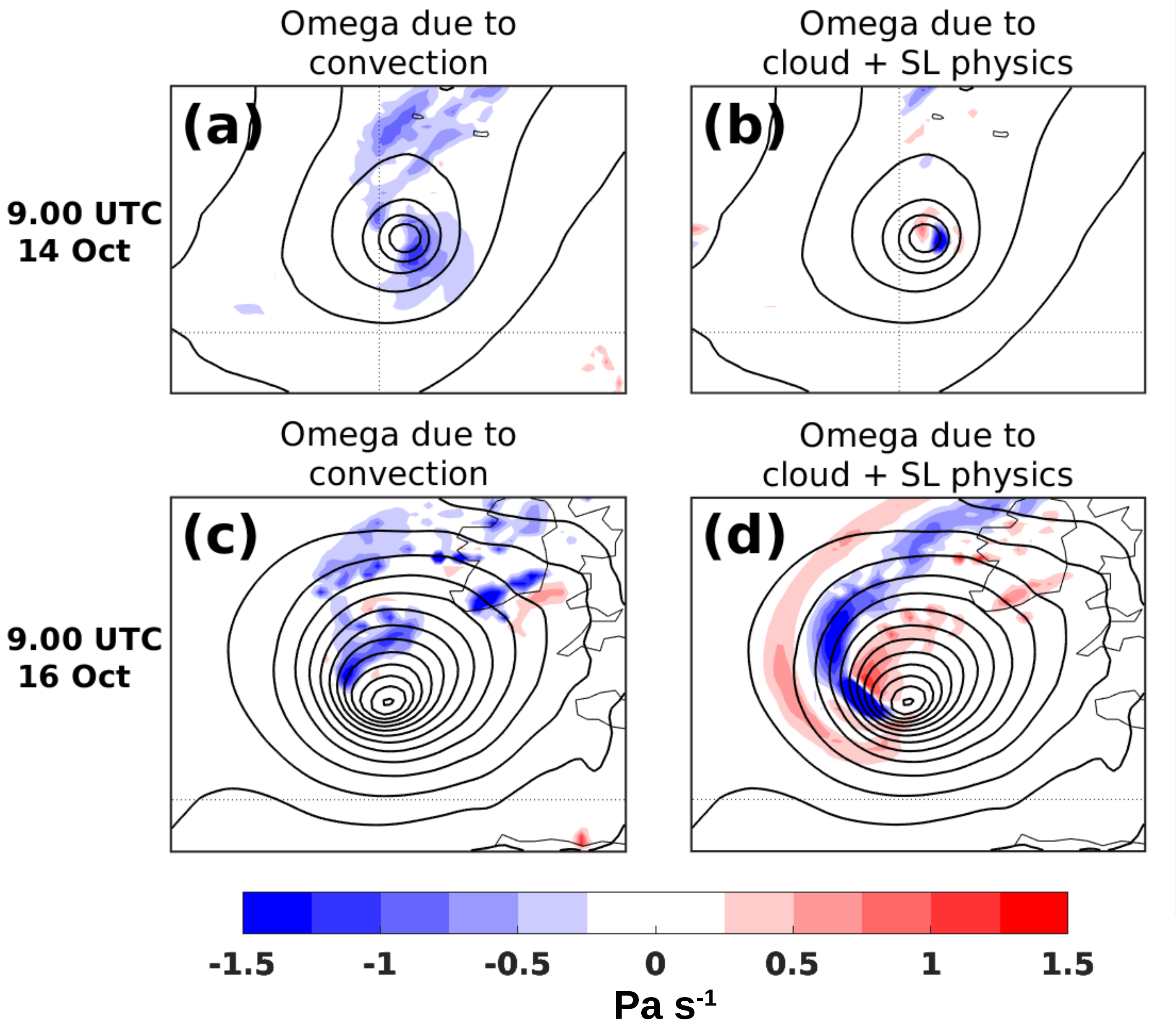
- convection (Q_c) and
- cloud microphysics (Q_{mp})



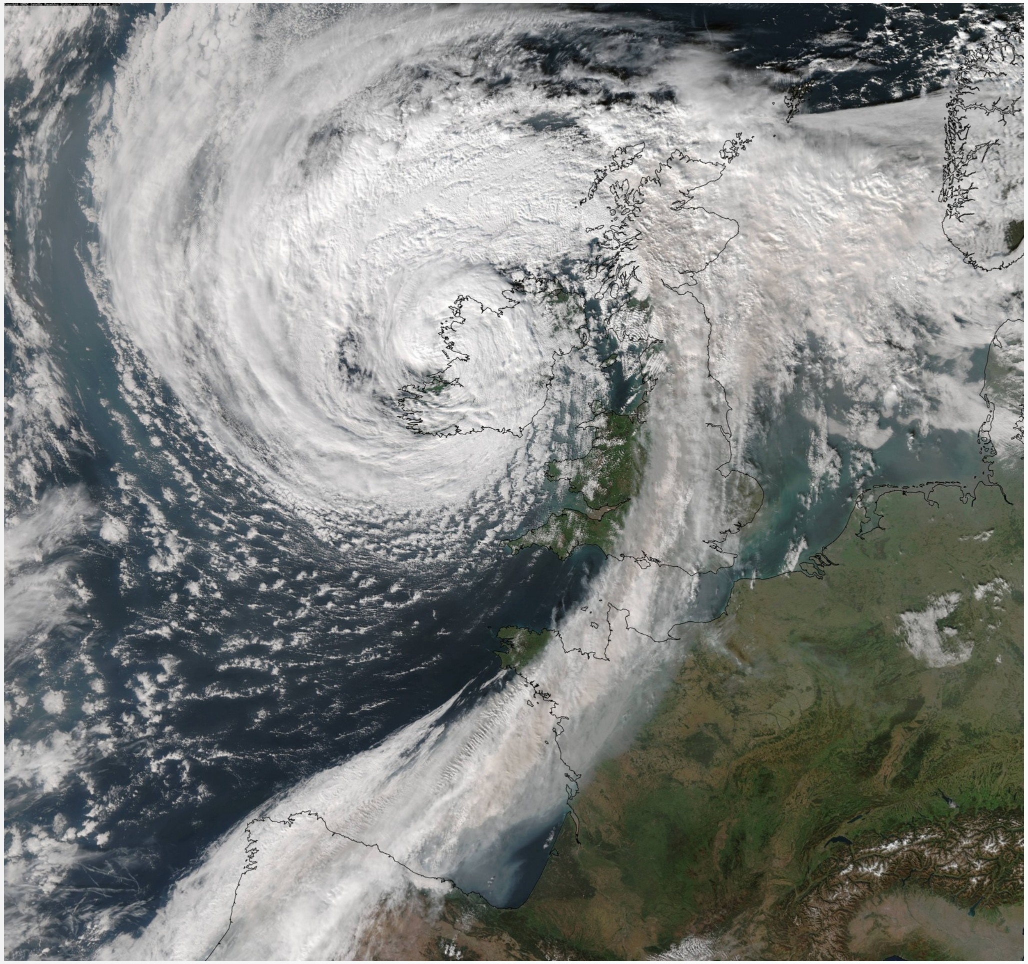
Vertical motion induced by the convection and microphysics schemes

Tropical phase

Extratropical phase



Main conclusions



- The post-ET intensification was mostly due to latent heat release in the warm front
→ generation of cyclonic vorticity

- Emphasizes the importance of resolving diabatic processes e.g. in climate models

- Baroclinic processes:
→ divergent VA was detrimental
→ WAA + in the tropical phase, but CAA – in the extratropical phase

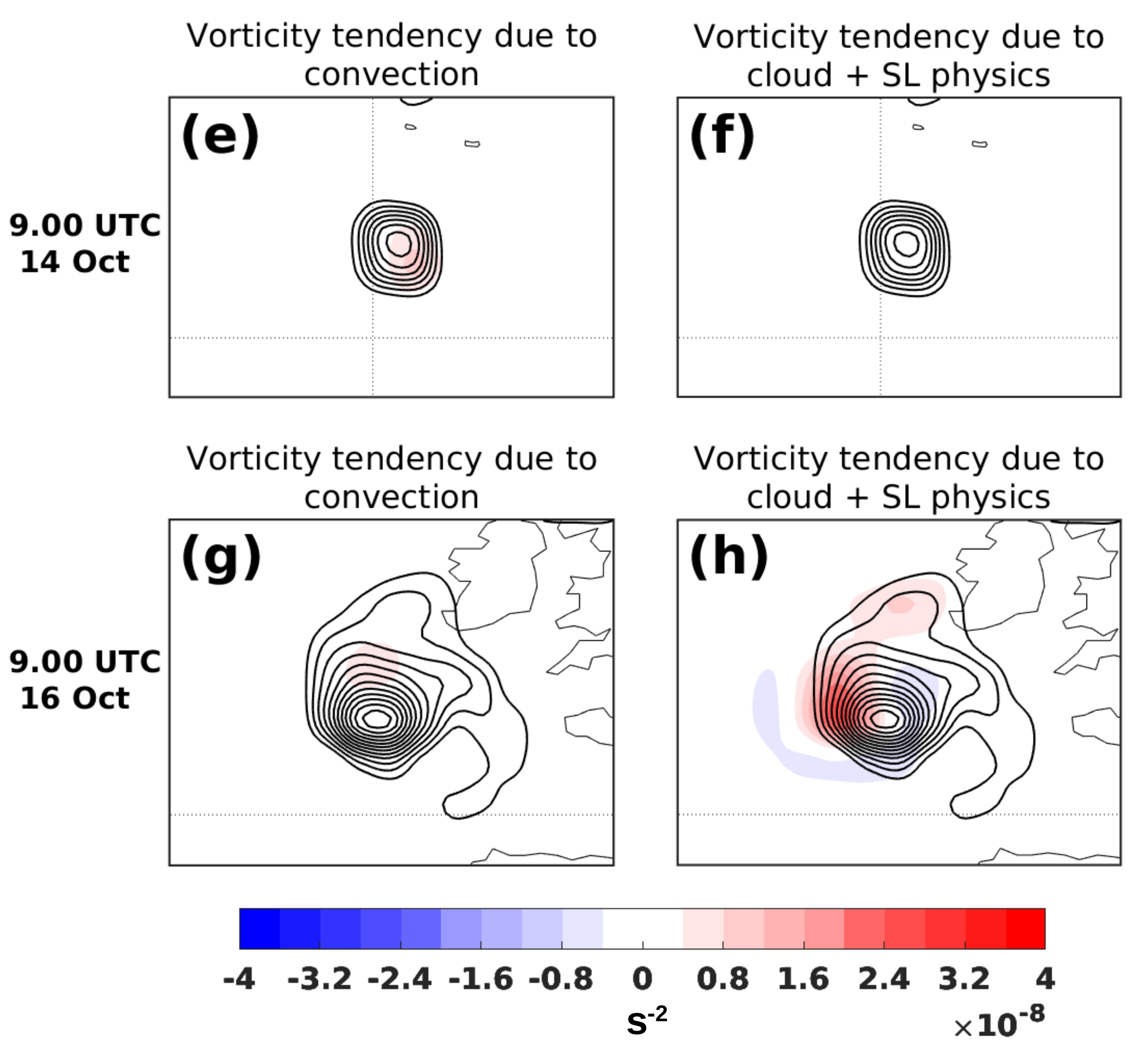
Rantanen et al: The extratropical transition of Hurricane Ophelia (2017) as diagnosed with a generalized omega equation and vorticity equation. *Submitted to Tellus A, 2019*

Thank you!

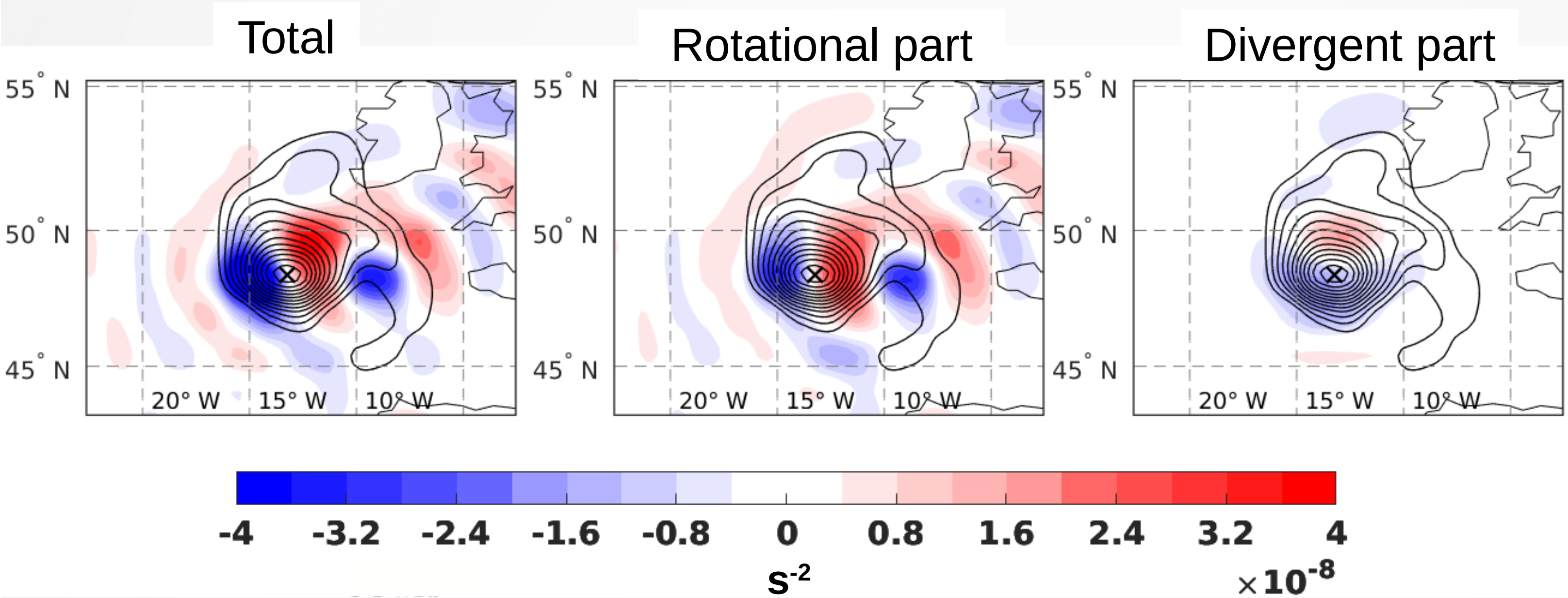
Vorticity tendency induced by the convection and microphysics schemes

Tropical phase

Extratropical phase



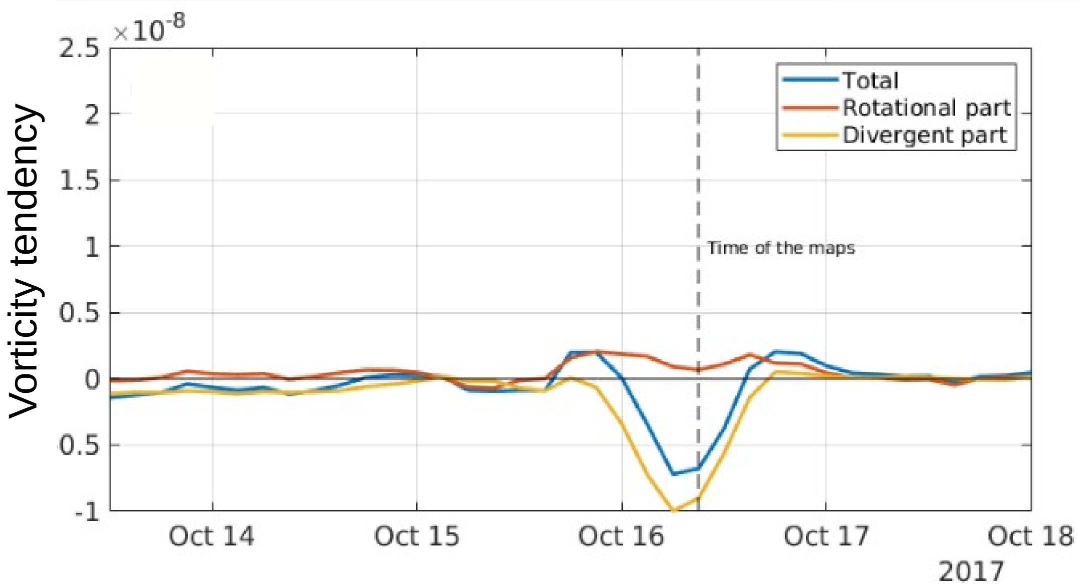
Vorticity tendency by rotational and divergent vorticity advection



Rotational = Non-divergent

- Rotational part close to zero in the cyclone centre

- Divergent part clearly negative



Divergent vorticity advection transports air with lower cyclonic vorticity to the area of high cyclonic vorticity

Cyclone phase space diagram of Ophelia

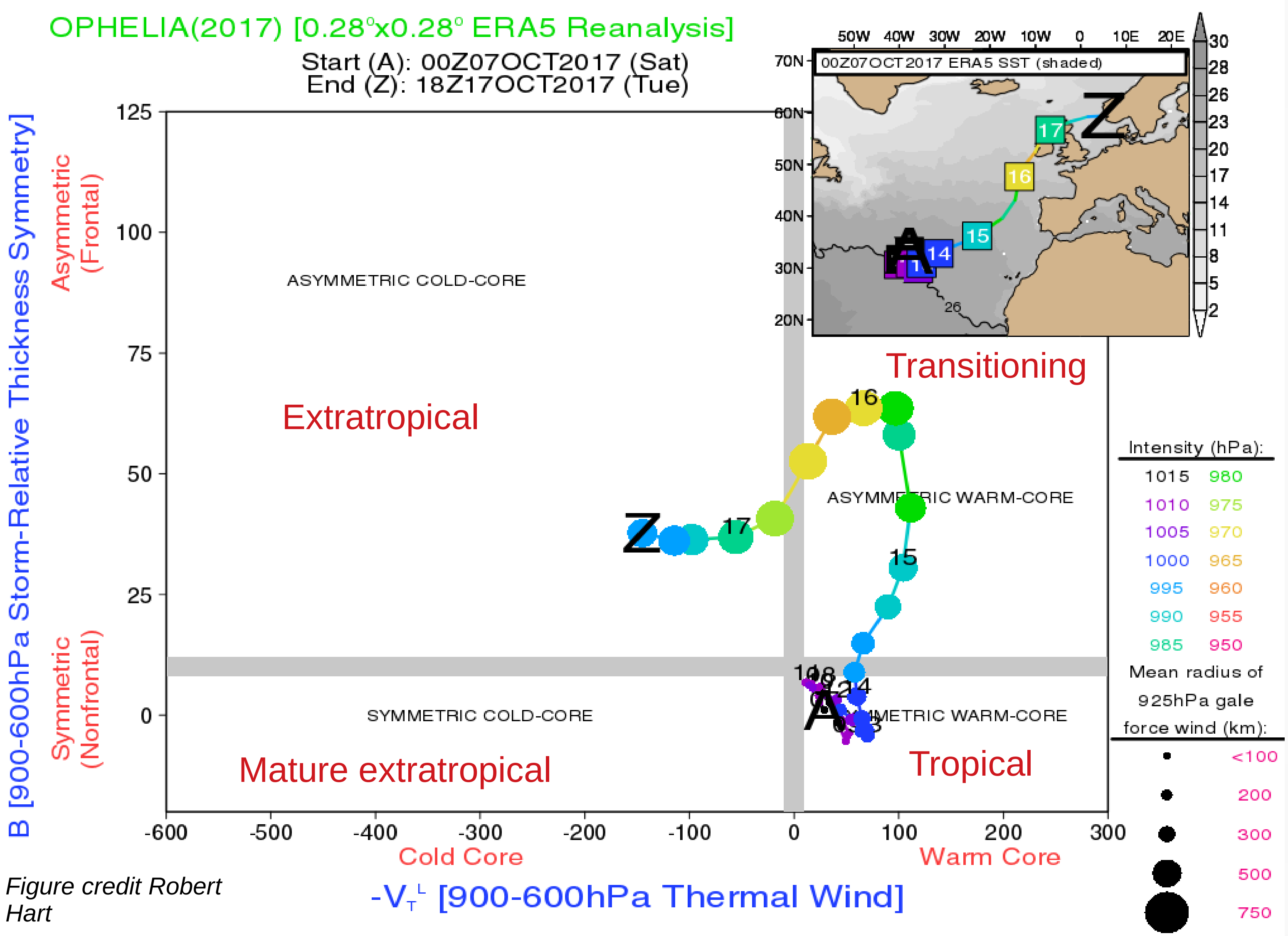


Figure credit Robert Hart

Based on Evans & Hart (2003),

1. The beginning of ET: B > 10

→ 14[th] Oct

2. The completion of ET: $-V_T^L < 0$

→ 16[th] Oct