Air-Sea fluxes in SURFEX (ECUME)

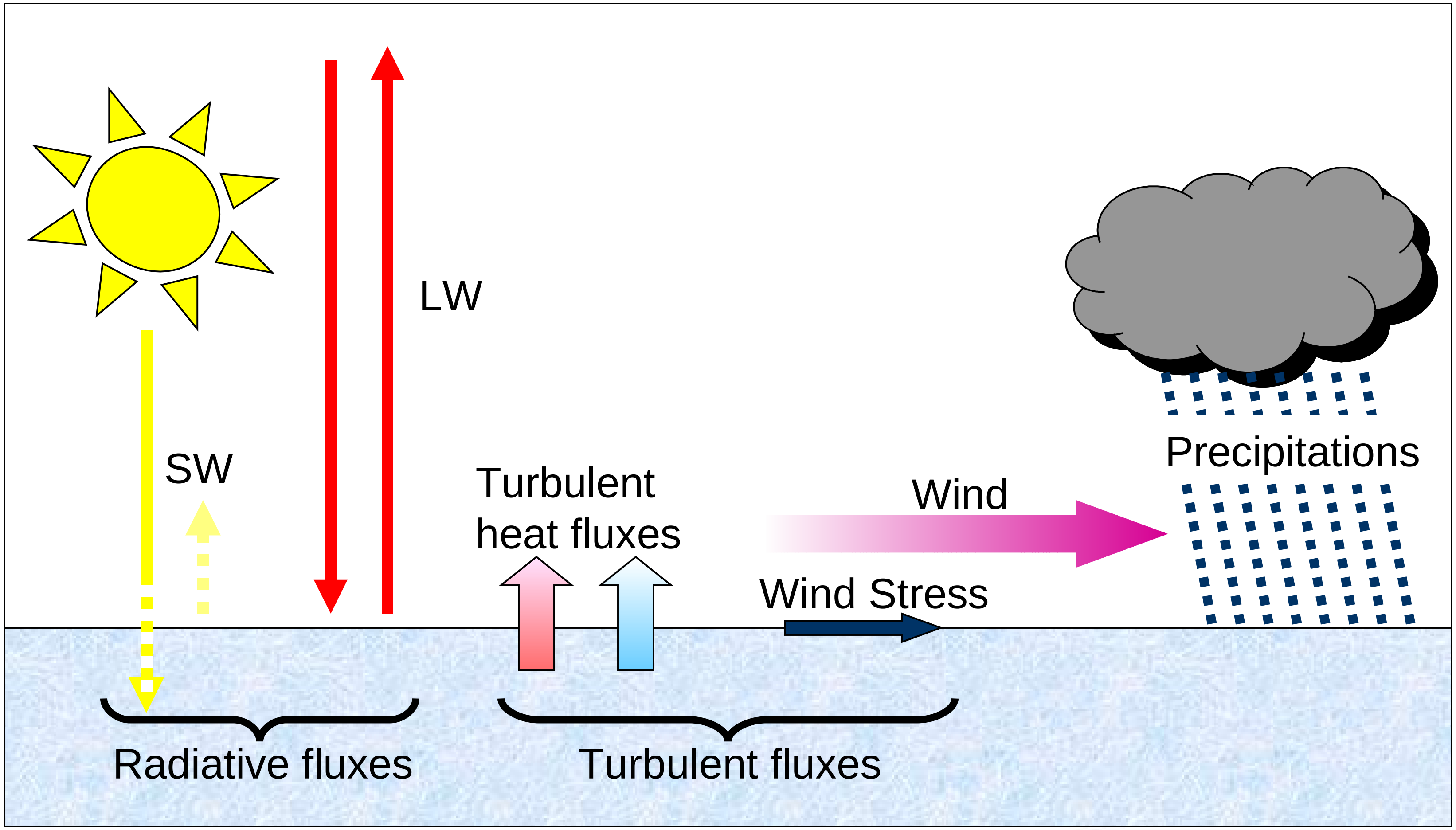
Coupling Atmosphere and 1D-Ocean with SURFEX

S. Belamari

(CNRM/GMGEC/MEMO)

METEO FRANCE
Toujours un temps d'avance

Air-Sea exchanges



Radiative fluxes

Turbulent fluxes

Air-Sea fluxes

- Over the ocean, one needs to take into account :
  - The net radiative fluxes
    - Shortwave heat flux (Solar component, SW)
    - Longwave heat flux (Infra-Red heat flux, LW)
  - The turbulent fluxes
    - Wind stress (*exchange of momentum*)
    - Sensible heat flux (*exchange of temperature*)
    - Latent heat flux (*exchange of humidity*)
  - The water flux = precipitation - evaporation

Air-Sea *Turbulent* Fluxes

- Air-sea turbulent fluxes can be written as :

$$
\begin{aligned}
\tau &= \rho_a \left(\overline{w'u'}.i + \overline{w'v'}.j \right) \\
Q_{sen} &= \rho_a . c_{p_a} . \overline{w'\theta'} \\
Q_{lat} &= \rho_a . L_v . \overline{w'q'}
\end{aligned}
$$

with :

  - (u,v) = horizontal components of the wind
  - θ = air potential temperature
  - q = air specific humidity
  - C_p = specific heat
  - L_e = vaporisation heat

- They can be estimated through 3 methods :
  - The Eddy Correlation Method (ECM)
  - The Inertio-Dissipative Method (IDM)
  - The bulk method

The Eddy-Correlation Method (ECM)

- Principle :
  - Direct measurement of the variances $(\overline{x'^2})$ and co-variances $(\overline{x'y'})$ describing the atmospheric turbulence
  - Requires the use of rapid sensors (from 22 min to 1 Hz)
    - Sonic anemometer (→u', v', w', θ')
    - Licor (→q')
    - Refractometer (→θ', q')
    - …

- Drawbacks :
  - Wind speed fluctuations measurements are affected by errors due to the platform motions (pitching, roll, rotation, translation, …)
  - Need to be corrected from the airflow distorsion due to the platform

The Inertio Dissipative Method (IDM)

- Principle :
  - Relies on the use of the equations of variances for the momentum, temperature and humidity
  - Turbulent fluxes are derived from the rate of dissipation of the turbulent kinetic energy, temperature and humidity in the inertial zone of the spectrum (1-20 Hz)

- Advantages :
  - The inertial zone is above the fequency of the ship motion $\Rightarrow$ No wind correction needed for the ship motions
  - Less sensible to the airflow distorsion

The bulk method (1/2)

- Principle :
  - Air-sea turbulent fluxes are linked to mean meteorological and oceanic parameters (either measured or issued from numerical models) through exchange coefficients (C_D, C_H, C_E) :

$$
\begin{aligned}
|\tau| &= \rho_a.\overline{w'u'} &&= -\rho_a.u_*^{\,2} &&= -\rho_a.C_D.\ \Delta U^2 \\
Q_{sen} &= \rho_a.c_{p_a}.\overline{w'\theta'} &&= -\rho_a.c_{p_a}.u_*\theta_* &&= -\rho_a.c_{p_a}.C_H.\Delta U.\Delta\theta \\
Q_{lat} &= \rho_a.L_v.\overline{w'q'} &&= -\rho_a.L_v.u_*q_* &&= -\rho_a.L_v.C_E.\Delta U.\Delta q
\end{aligned}
$$

where :

- u_*, θ_*, q_* are scale parameters (Monin-Obukhov theory)
- ∀ ΔU, $\Delta\theta$, Δq are the vertical gradients of the mean atmospheric parameters between z level and sea surface

$$
C_D = \left(\frac{u_*}{\Delta U}\right)^2 \qquad C_H = \frac{u_*.\theta_*}{\Delta U.\Delta\theta} \qquad C_E = \frac{u_*.q_*}{\Delta U.\Delta q}
$$

METEO FRANCE
Toujours un temps d’avance

The bulk method (2/2)

- The exchange coefficients C_D, C_H, C_E
    - Depend on the atmospheric stratification (stable < unstable)

- The way C_D, C_H, C_E are computed is specific to each bulk parametrisation
    - ***Direct parametrisations (e.g. Louis, 1979)***

$$C_D = C_{D10n} \times F_D^{2}(Ri, z, z_0) \qquad C_H = \sqrt{C_{D١٠n}}.\sqrt{C_{H١٠n}} \times F_{H'}^{۲}(Ri, z, z_٠, z_{٠H}) = C_E$$

where $z_٠ = \dfrac{\alpha . u_*^{۲}}{g} + \dfrac{\beta . \nu}{u_*}$ is the roughness length[1] (Smith [1988])

- ☐ ***Iterative parametrisations (e.g. COARE3.0, ECUME)***
    - Relies on the iterative computation (Liu et al [1979]) of the scale parameters in order to get the exchange coefficients using the previous equations :

$$C_D = \left(\frac{u_*}{\Delta U}\right)^2 \qquad C_H = \frac{u_* . \theta_*}{\Delta U . \Delta \theta} \qquad C_E = \frac{u_* . q_*}{\Delta U . \Delta q}$$

---

[1]: α is the Charnock's constant, β is a numerical constant, and ν denotes the dynamical viscosity.

Louis (1979) parametrisation (1/1)

- **Neutral coefficients** C_{D10n} and C_{H10n} ($C_{E10n}=C_{H10n}$) are computed as :

$$\sqrt{C_{D10n}} = \frac{\kappa}{\ln\left(1+z/z_0\right)} \qquad \sqrt{C_{H10n}} = \frac{\kappa}{\ln\left(1+z/z_{0_H}\right)}$$

with $z_0 = \dfrac{0.015.u_*^2}{g}$ (Charnock [1955]'s relationship)

- **Louis's functions** F_D and $F_{H'}$ (depending on the stability through *Ri*) are given by :

$$F_{\dots}\left(Ri, z, z_0, z_{0_H}\right) = \begin{cases} \left(A - \dfrac{b.Ri}{1+c\sqrt{-Ri}}\right)^{\frac{1}{2}} & for \quad Ri \le 0 \\ \left(\dfrac{A}{1+b'\dfrac{Ri}{\sqrt{1+c'Ri}}}\right)^{\frac{1}{2}} & for \quad Ri \ge 0 \end{cases}$$

  - Note that numerical values of *A, b, b', c, c'* (Mascart et al [1995], Giordani et al [1996] are distinct for F_D and $F_{H'}$

METEO FRANCE
Toujours un temps d'avance

COARE parametrisation (1/2)

- Developed during the TOGA (Tropical Atmosphere and Global Ocean) experiment
  - Several versions : COARE2.5b (Fairall et al [1996]), COARE3.0 (Fairall et al [2003])
  - Base of the Mondon and Redelsperger [1998] parametrisation
- Main features of the **COARE3.0 algorithm**

Scale parameters (first guess or issued from previous iteration) $u_*^{\,p},\quad \theta_*^{\,p},\quad q_*^{\,p}$	
$z_0 = \frac{\alpha . u_*^{\,2}}{g} + \frac{\beta . \nu}{u_*}$ $z_{0H} = MIN\left(1.15\ 10^{-4}, 5.5\ 10^{-5} \times \left(\frac{\nu}{z_0 . u_*}\right)^{0.6}\right)$	Dynamical (z_0) and thermal (z_{0H}) roughness lengths ↳ Smith [1988]'s relation in which β=0.11 and Charnock's parameter α is a wind dependent parameter (Hare et al [1999])
$\varsigma^{p+1} = \frac{z}{L^{p+1}}$ with $L^{p+1} = L^{p+1}\left(u_*^{\,p}, \theta_*^{\,p}, q_*^{\,p}\right)$	Monin-Obukhov parameter
$\psi_m\left(\zeta^{p+1}\right),\quad \psi_h\left(\zeta^{p+1}\right)$ 2 formulations whether stable (ζ ≥ 0) or unstable (ζ <0) atm. If ***unstable***, $\psi_{...} = (1-f).\psi_{...K} + f.\psi_{...C}$ with $f = \zeta^{٢} / \left(١ + \zeta^{٢}\right)$	Modified Businger's stability functions ψ_m and ψ_h Depend on the stability of the atmosphere
Scale parameters u_*, θ_*, q_* $u_*^{\,p+1} = \frac{\kappa . \Delta U}{\ln\left(z/z_0\right) - \psi_m\left(\zeta^{p+1}\right)}$ $\theta_*^{\,p+1} = \frac{\kappa . \Delta \theta}{\ln\left(z/z_{0_H}\right) - \psi_h\left(\zeta^{p+1}\right)}$ $q_*^{\,p+1} = \frac{\kappa . \Delta q}{\ln\left(z/z_{0_H}\right) - \psi_h\left(\zeta^{p+1}\right)}$	

C_D, C_H, C_E

COARE parametrisation (2/2)

- **Remark**
  - A reduction of 2% of the specific humidity at saturation is applied (Kraus [1972]), in order to take into account the reduction of saturated vapor pressure due to the seawater salinity

- **Corrections that can be applied in the COARE3.0 algorithm**
  - **Gustiness** correction on the wind speed (Deardorff [1976])
    - ☹ uses for the atmospheric boundary layer height a constant value (600m)
  - **Rainfall** correction on both the wind stress and the sensible heat flux :

$$\tau_{precip} = \frac{R.\Delta U}{3600}$$

Fairall et al [1996]

$$Q_{lat(precip)} = -R'.c_{p_r}.\varepsilon.\Delta T\left(1+\frac{1}{B}\right)$$

Gosnell et al [1995]

R and *R'* denote the precipitation rate in mm.h^{-1} and kg.s^{-1}, respectively

C_{pr} is the water specific heat

B is the Bowen's ratio

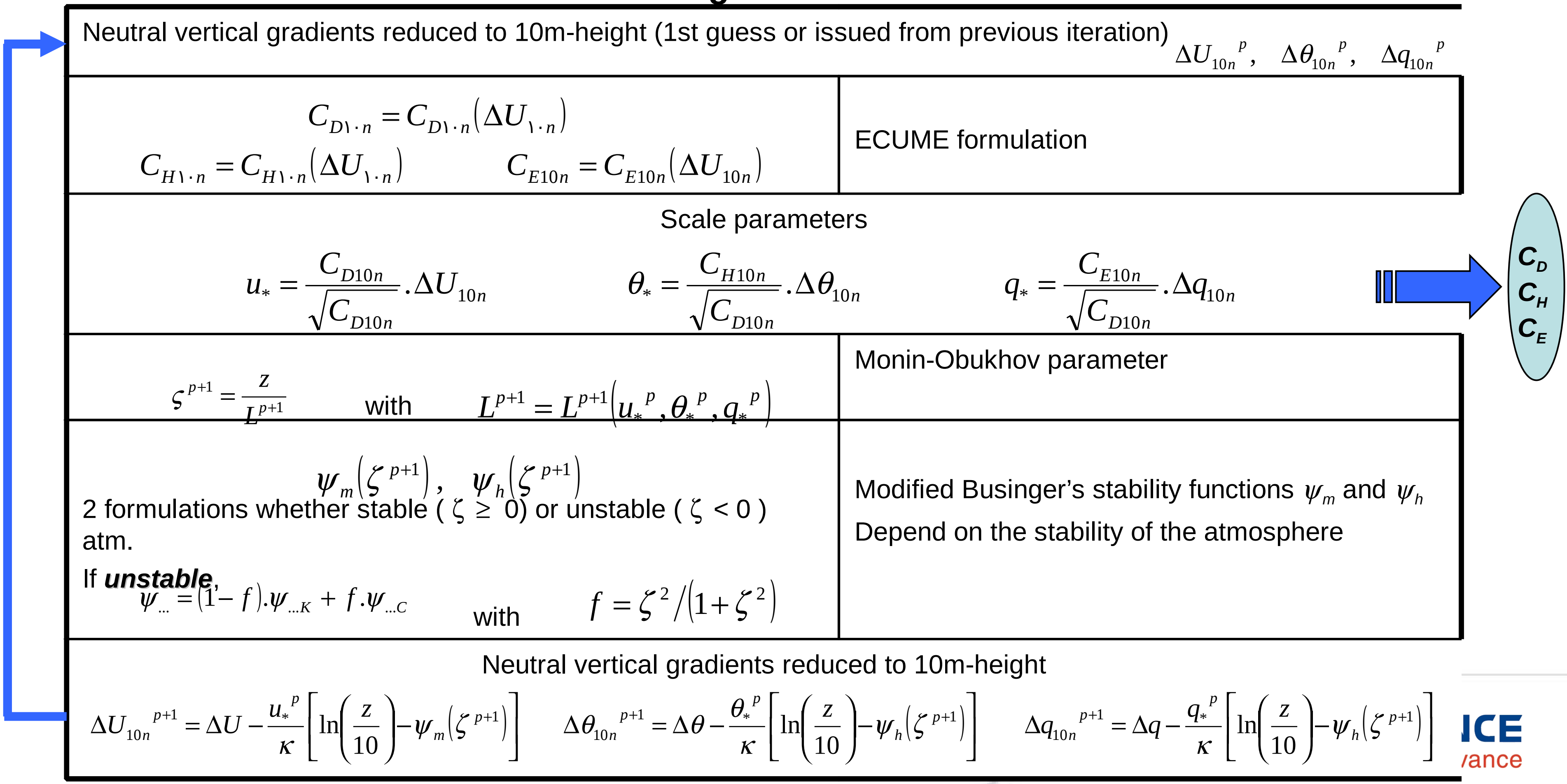
ε *is* the dew point factor

  - **Waves effect** on roughness length (Taylor and Yelland [2001], Oost et al [2002])

ECUME* parametrisation (1/8)

***E**xchange **C**oefficients from **U**nified **M**ulti-campaign **E**stimates

- Relies on the analytical formulation of the neutral coefficients C_{D10n}, C_{H10n}, C_{E10n} deduced from the multi-campaign (Weill et al, 2003) ALBATROS database (http://dataserv.cetp.ipsl.fr/FLUX/)
- Main features of the **ECUME algorithm**



Neutral vertical gradients reduced to 10m-height (1st guess or issued from previous iteration) $\Delta U_{10n}{}^{p},\quad \Delta\theta_{10n}{}^{p},\quad \Delta q_{10n}{}^{p}$

$$C_{D10n} = C_{D10n}(\Delta U_{10n})$$

$$C_{H10n} = C_{H10n}(\Delta U_{10n}) \qquad C_{E10n} = C_{E10n}(\Delta U_{10n})$$

ECUME formulation

Scale parameters

$$u_* = \frac{C_{D10n}}{\sqrt{C_{D10n}}}.\Delta U_{10n} \qquad \theta_* = \frac{C_{H10n}}{\sqrt{C_{D10n}}}.\Delta\theta_{10n} \qquad q_* = \frac{C_{E10n}}{\sqrt{C_{D10n}}}.\Delta q_{10n}$$

C_D

C_H

C_E

$\varsigma^{p+1} = \frac{z}{L^{p+1}}$ with $L^{p+1} = L^{p+1}(u_*{}^{p}, \theta_*{}^{p}, q_*{}^{p})$

Monin-Obukhov parameter

$$\psi_m(\varsigma^{p+1}),\quad \psi_h(\varsigma^{p+1})$$

2 formulations whether stable ($\zeta \geq 0$) or unstable ($\zeta < 0$) atm.

If ***unstable***, $\psi_{\ldots} = (1-f).\psi_{\ldots K} + f.\psi_{\ldots C}$ with $f = \varsigma^2/(1+\varsigma^2)$

Modified Businger's stability functions ψ_m and ψ_h

Depend on the stability of the atmosphere

Neutral vertical gradients reduced to 10m-height

$$\Delta U_{10n}{}^{p+1} = \Delta U - \frac{u_*{}^{p}}{\kappa}\left[\ln\left(\frac{z}{10}\right) - \psi_m(\varsigma^{p+1})\right] \qquad \Delta\theta_{10n}{}^{p+1} = \Delta\theta - \frac{\theta_*{}^{p}}{\kappa}\left[\ln\left(\frac{z}{10}\right) - \psi_h(\varsigma^{p+1})\right] \qquad \Delta q_{10n}{}^{p+1} = \Delta q - \frac{q_*{}^{p}}{\kappa}\left[\ln\left(\frac{z}{10}\right) - \psi_h(\varsigma^{p+1})\right]$$

ECUME parametrisation (2/8)

- **Remark**
    - As for COARE3.0, a reduction of 2% of the specific humidity at saturation is applied (Kraus [1972]), in order to take into account the reduction of saturated vapor pressure due to the seawater salinity

- **Corrections that can be applied in the ECUME algorithm**
    - No gustiness correction on the wind speed (that of Mondon and Redelsperger [1998] should be included in the next months)
    - **Rainfall** correction on both the wind stress and the sensible heat flux (same as in COARE3.0)
    - **Webb [1980]'s effect** on the latent heat flux (due to air density variations)

$$Q_{lat(Webb)} = \rho_a . L_w . \overline{w} . q \qquad \overline{w} = 1.61\,\overline{w'q'} + (1 + 1.61\,q)\,\frac{\overline{w'T'}}{T}$$

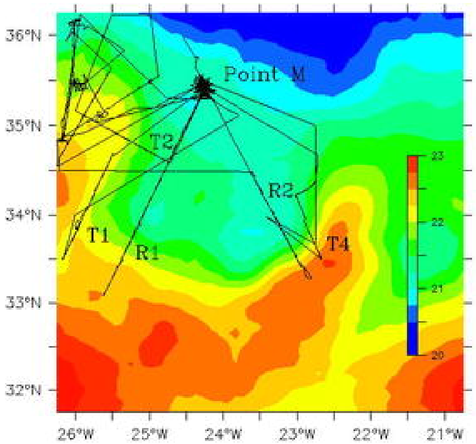
L_w is the latent heat of vaporisation for water

$\overline{w}$ denotes the mean vertical speed resulting from the turbulence

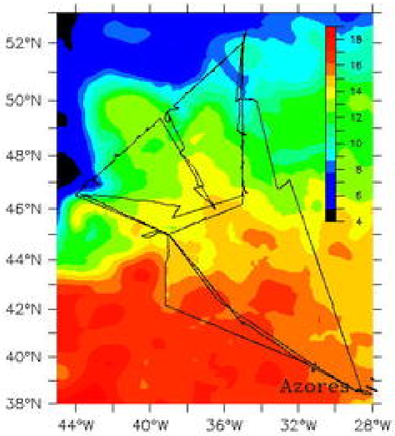
- No waves effect

ECUME parametrisation (3/8)

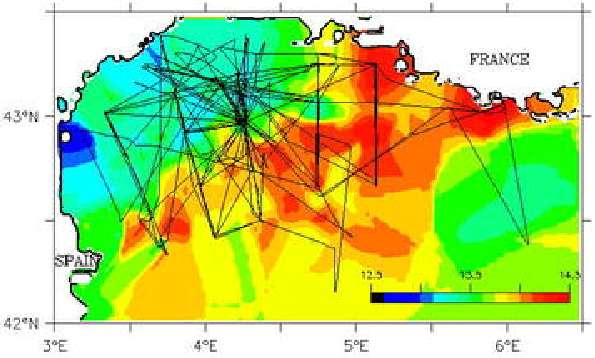
- An analytical formulation of the neutral coefficients (C_{D10n}, C_{H10n}, C_{E10n}) deduced from the multi-campaign ALBATROS dataset



SEMAPHORE
07/10/1993-15/11/1993

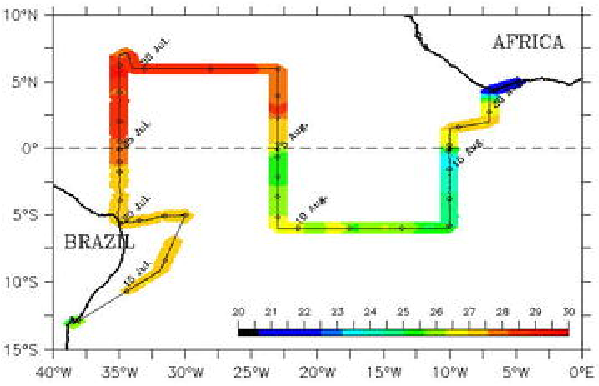


CATCH
08/01/1997-04/03/1997

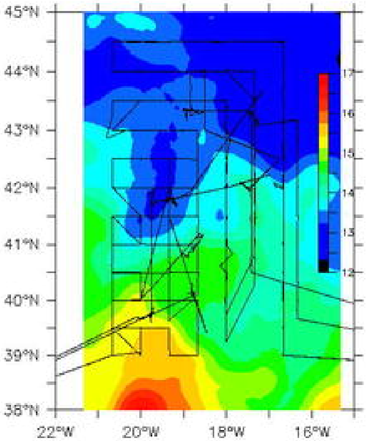


FETCH
13/03/1998-15/04/1998

In-situ measurements were performed in the :
- North Atlantic
- Equatorial Atlantic
- Mediterranean Sea



EQUALANT99 - 13/07/1999-21/08/1999



POMME
02/02/2001-04/04/2001

ECUME parametrisation (4/8)

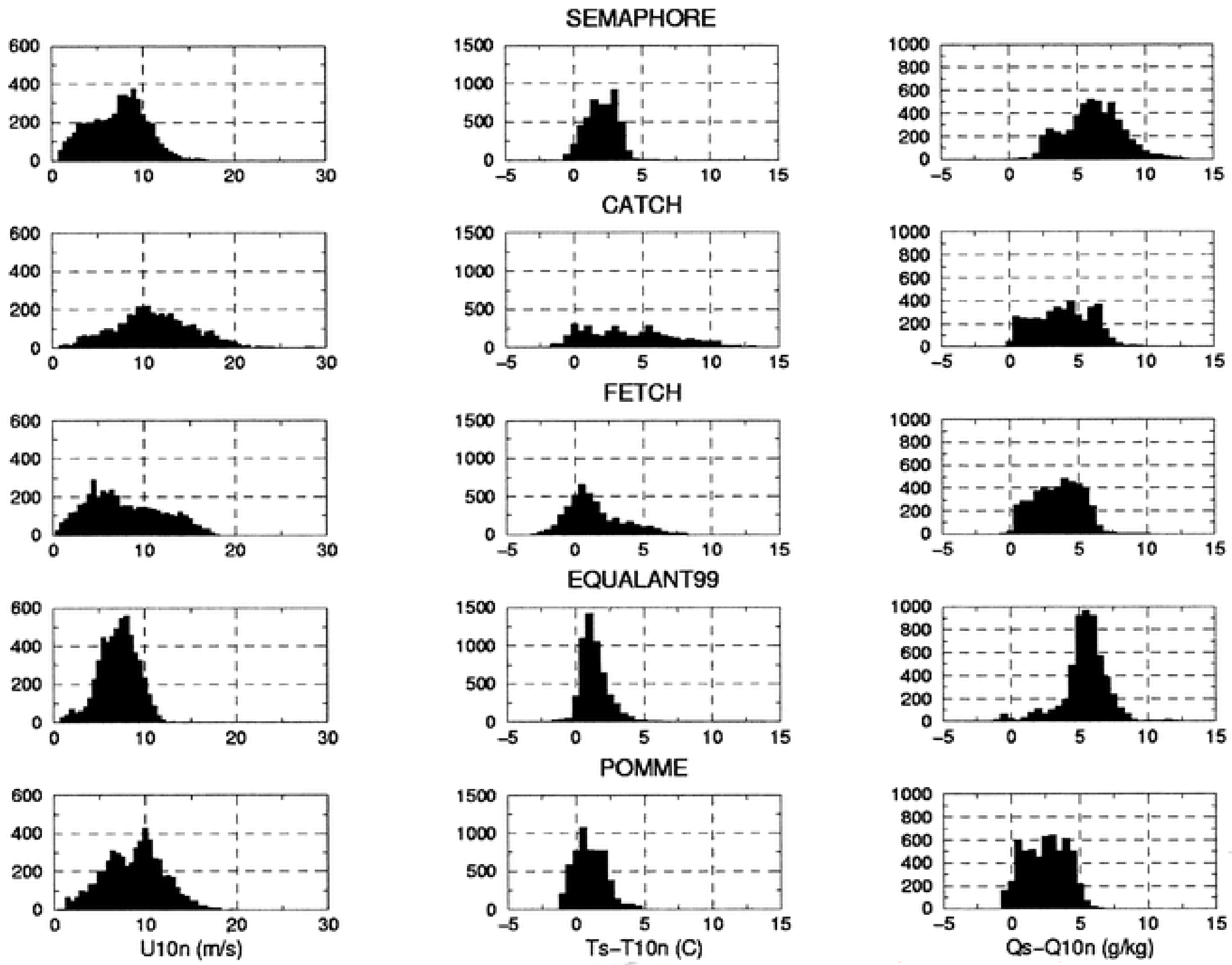
- A wide range of meteo-oceanic conditions

The available data cover the widest range of atmospheric and oceanic conditions :

- from very light (0.3 ms^{-1}) to very strong (up to 29 ms^{-1}) wind speeds,

- from unstable to extremely stable atmospheric boundary layer stratification.

ΔU_{10n} $-\Delta T_{10n}$ $-\Delta q_{10n}$



ECUME parametrisation (5/8)

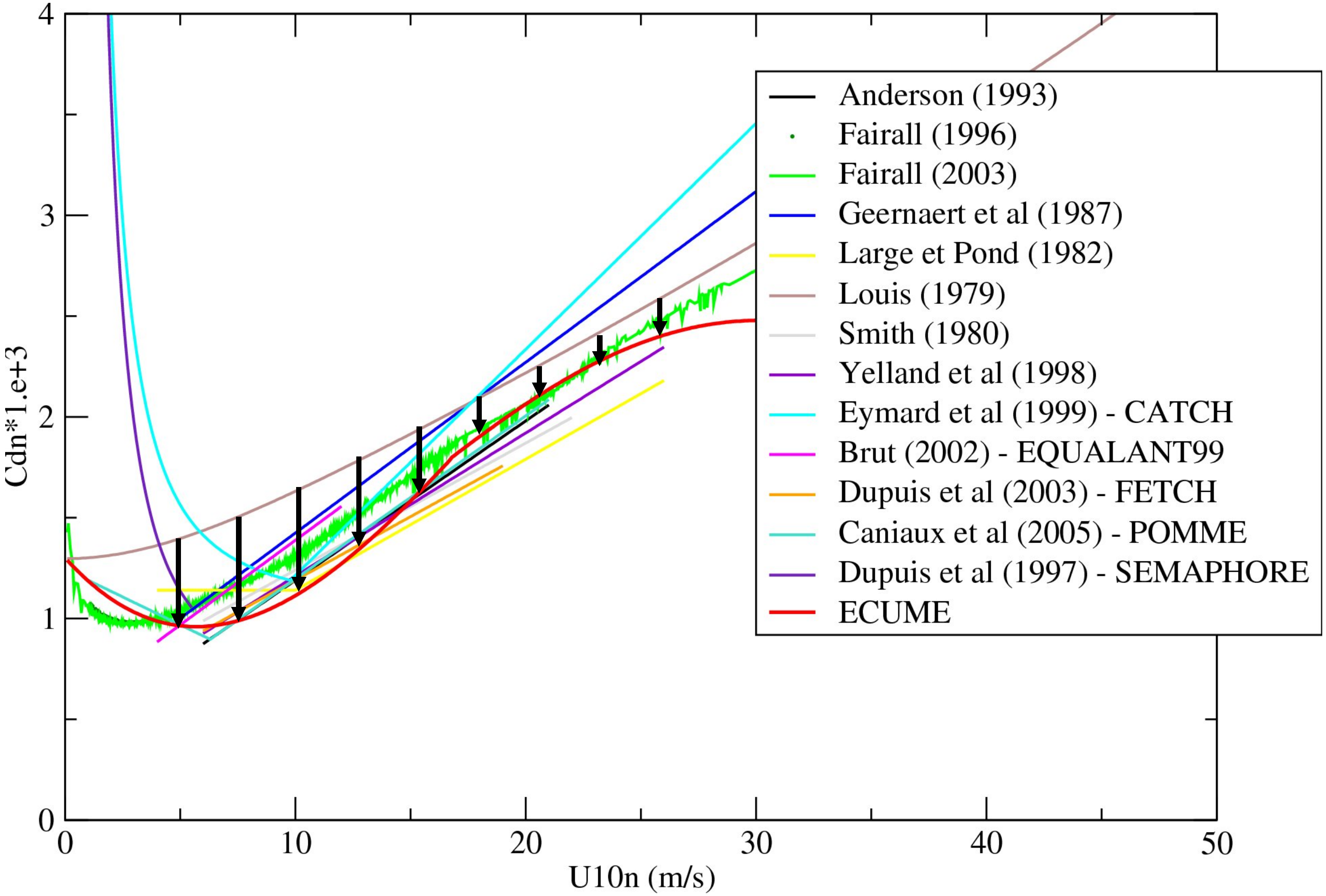
- More than 260 days of turbulence measurements (nearly 5700 hours)
  - More than 6000, 4600 and 2100 consistent values for the momentum (C_{d10n}), heat (C_{h10n}), and moisture (C_{e10n}) neutral exchange coefficients, respectively

- Particularly reliable as :
  - *Homogeneous* methods were used to get *concurrently measurements* for all the turbulent fluxes (wind stress, sensible and latent heat)
  - The available data cover the widest range of atmospheric and oceanic conditions, from very light (0.3 ms^{-1}) to very strong (up to 29 ms^{-1}) wind speeds, and from unstable to extremely stable atmospheric boundary layer stratification
  - A *similar treatment* (using both the ID and EC methods together with numerical and physical simulations to get airflow distorsion corrections) was used for all the experiments to derive consistent (« unified ») exchange coefficient values

- For wind speeds higher than 30ms^{-1}, the formulation is extrapolated using results from studies focusing on turbulent fluxes under cyclonic conditions (e.g. Donelan et al., 2004 ; Moon et al., 2004).

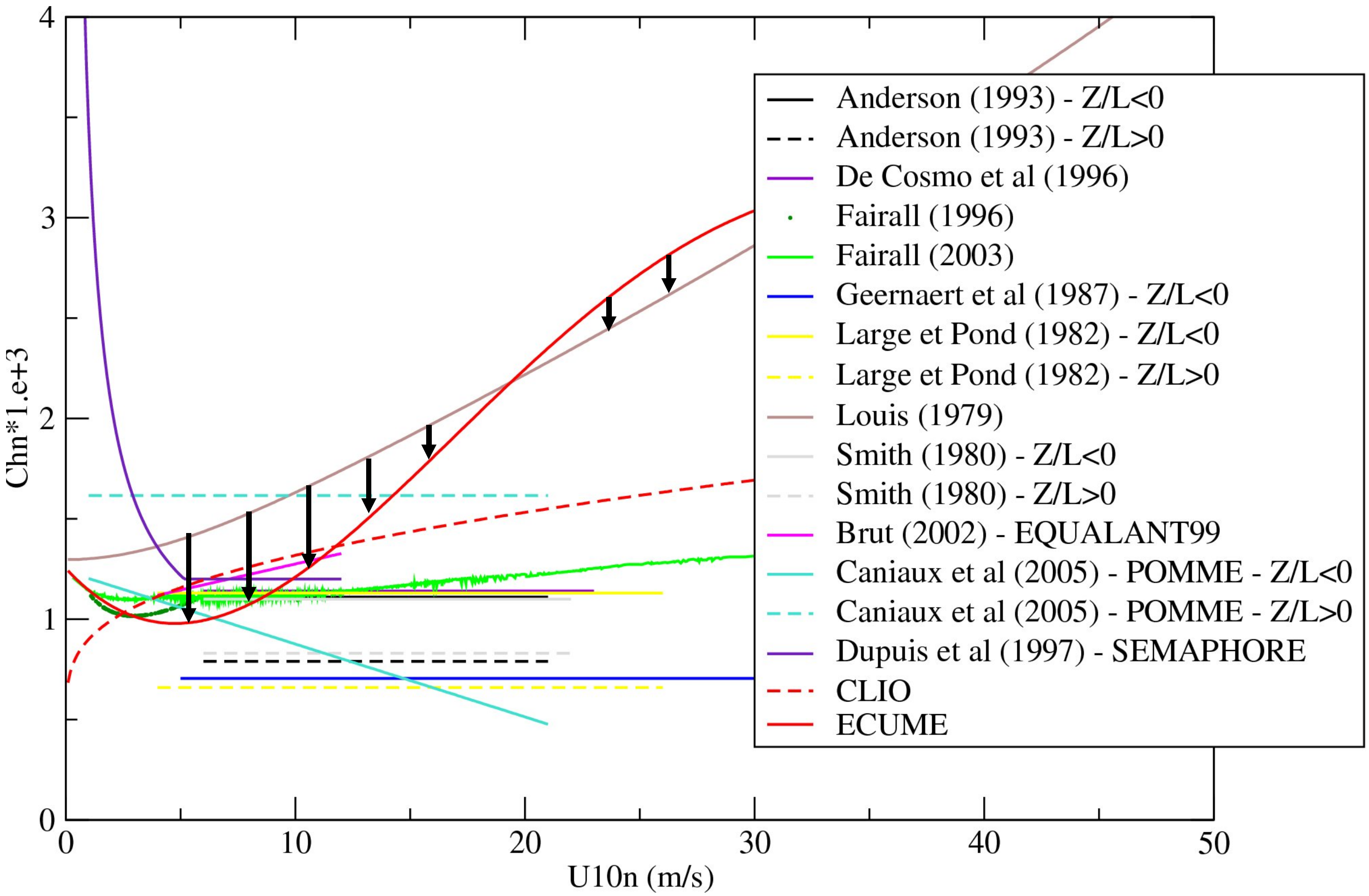
ECUME parametrisation (6/8)

- Exchange coefficient for momentum



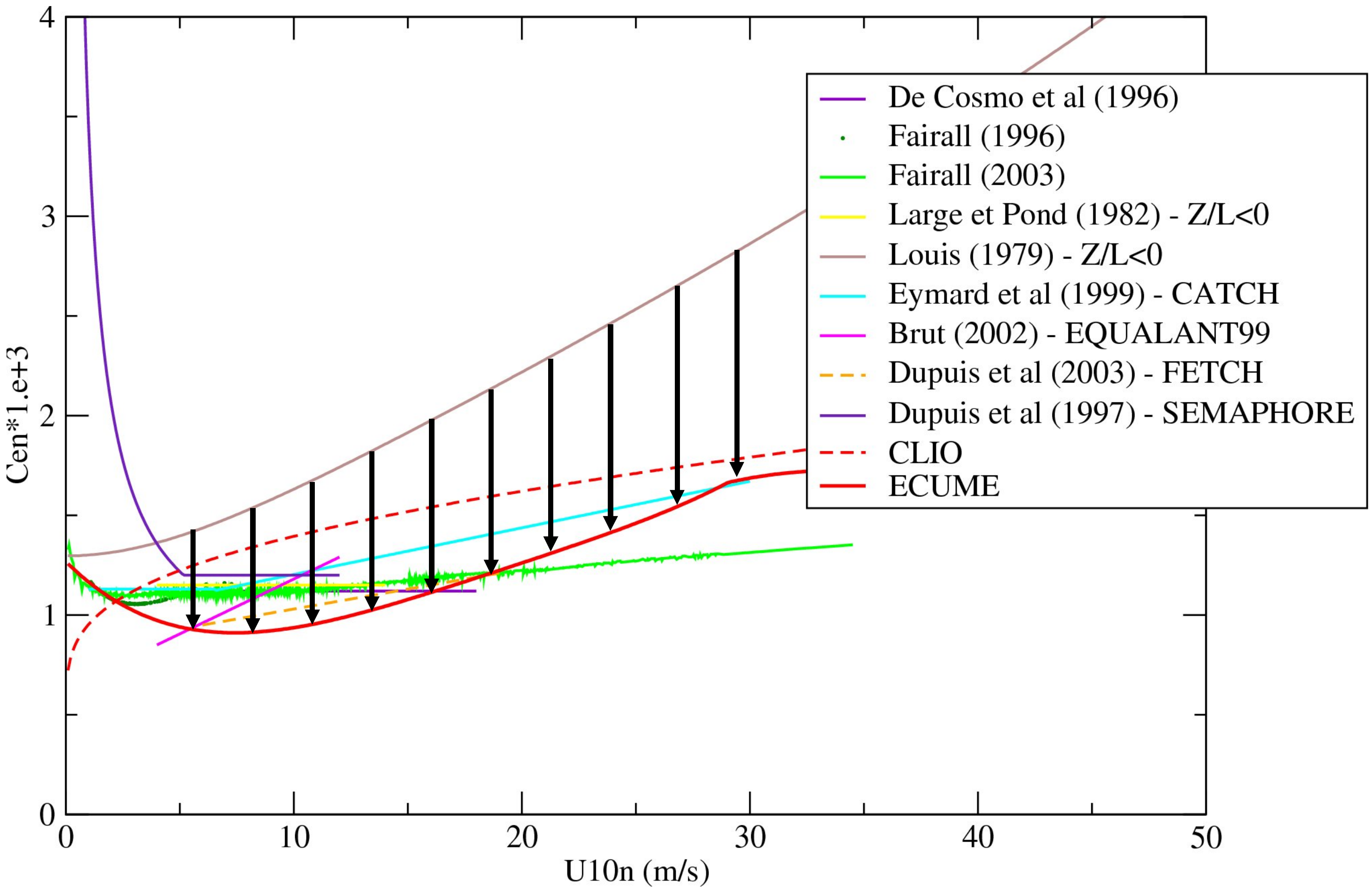
ECUME parametrisation (7/8)

- Exchange coefficient for temperature



ECUME parametrisation (8/8)

- Exchange coefficient for humidity



Summary

	LOUIS	COARE3.0	ECUME
Relies on	Charnock [1955]'s formulation of z_0	➢ Smith [1988]'s formulation of z_0 with α wind dependent (Hare et al [1999]) OR ➢ Taylor and Yelland [2001], Oost et al [2002]	$C_{D10n} = C_{D10n}(\Delta U_{10n})$ $C_{H10n} = C_{H10n}(\Delta U_{10n})$ $C_{E10n} = C_{E10n}(\Delta U_{10n})$
Stability functions	Louis [1979]	Businger et al [1971] modified	Businger et al [1971] modified
Salinity correction	No	**Yes**	**Yes**
Gustiness	No	**Yes**	*To be done*
Rainfall impact	No	**Yes**	**Yes**
Webb effect	No	No	**Yes**
Waves effect	No	**Yes**	No

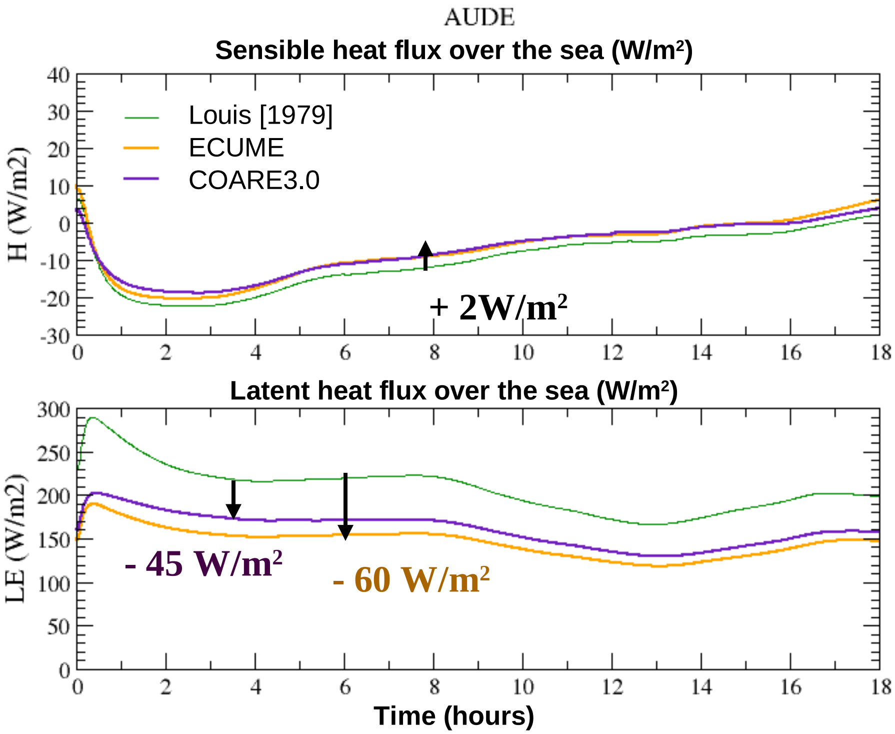
A
U
D
E

A first case study (1/2)

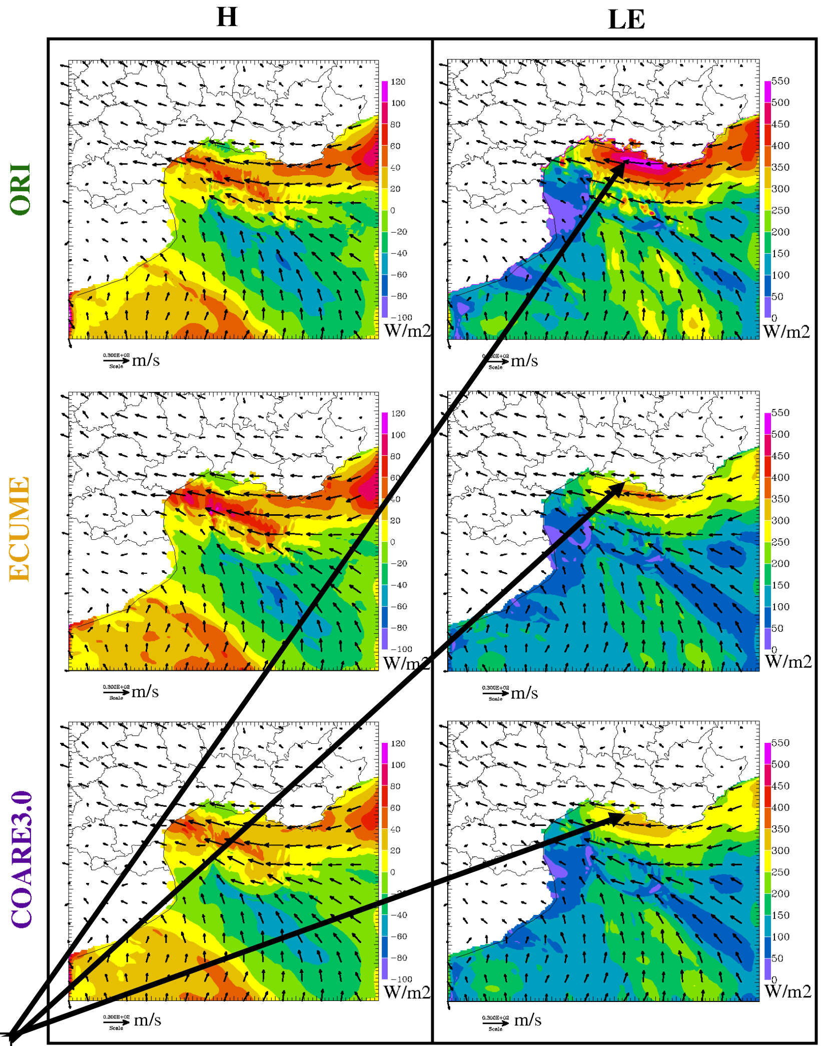
Extreme mediterranean rain event 12-13 nov. 1999

(from C. Lebeaupin-Brossier, 2007)

Quasi-stationnary meso-scale convective system : 551 mm in 24 hours
(Aullo et al., 2002 ;Ducrocq et al. 2003)



Mean turbulent heat fluxes** (W/m²) **over the sea



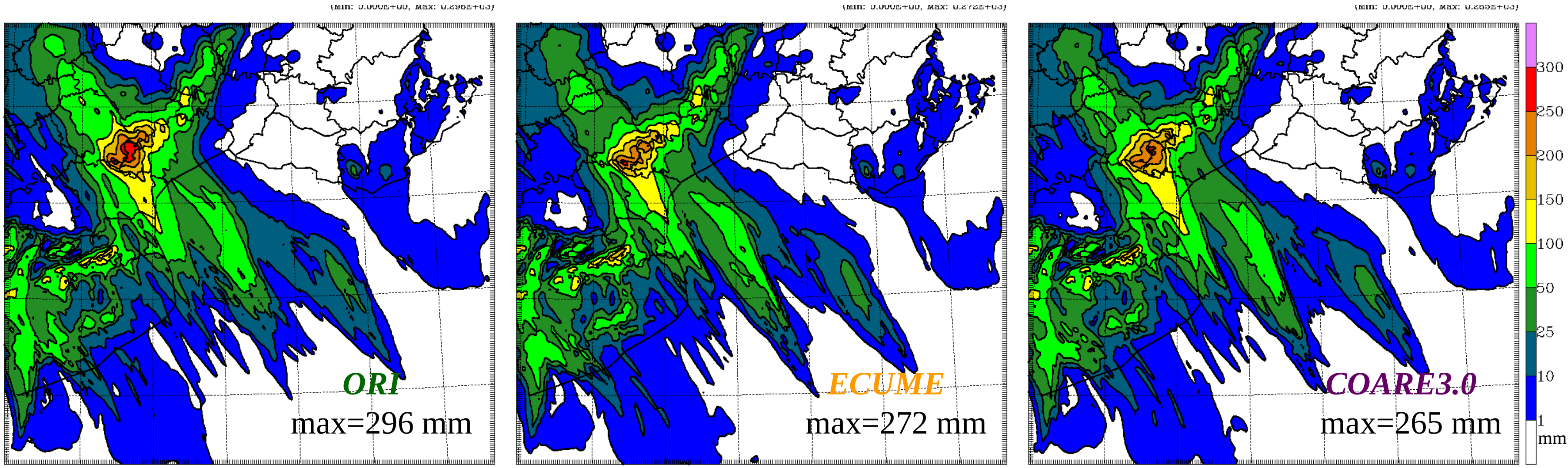
Latent heat flux LE is reduced of 150-200W/m² under the low level jet (≈ 30m/s)

Turbulent heat fluxes** (W/m²) **and low level wind** (36 m height , m/s) **13/11/1999 06 UTC

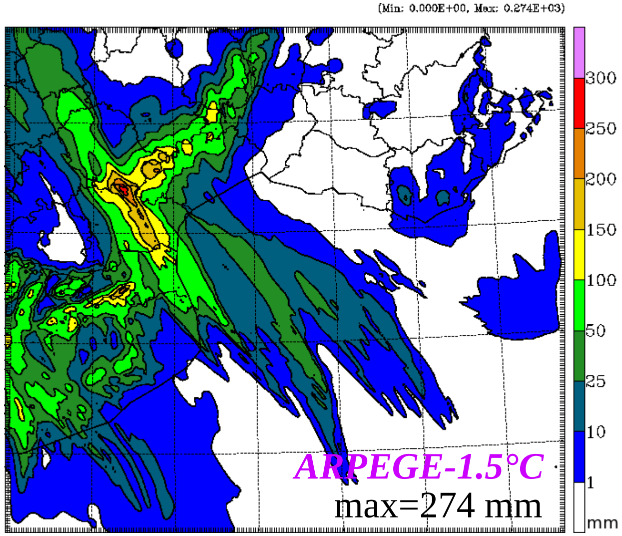
A first case study (2/2)

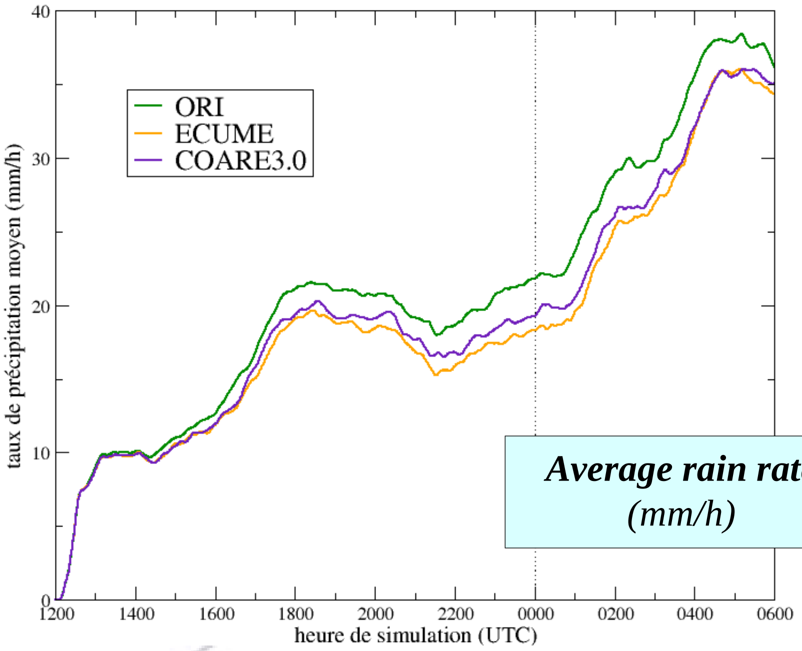
Extreme mediterranean rain event 12-13 nov. 1999

(from C. Lebeaupin-Brossier, 2007)



***Accumulated precipitation over 18h** (mm)*





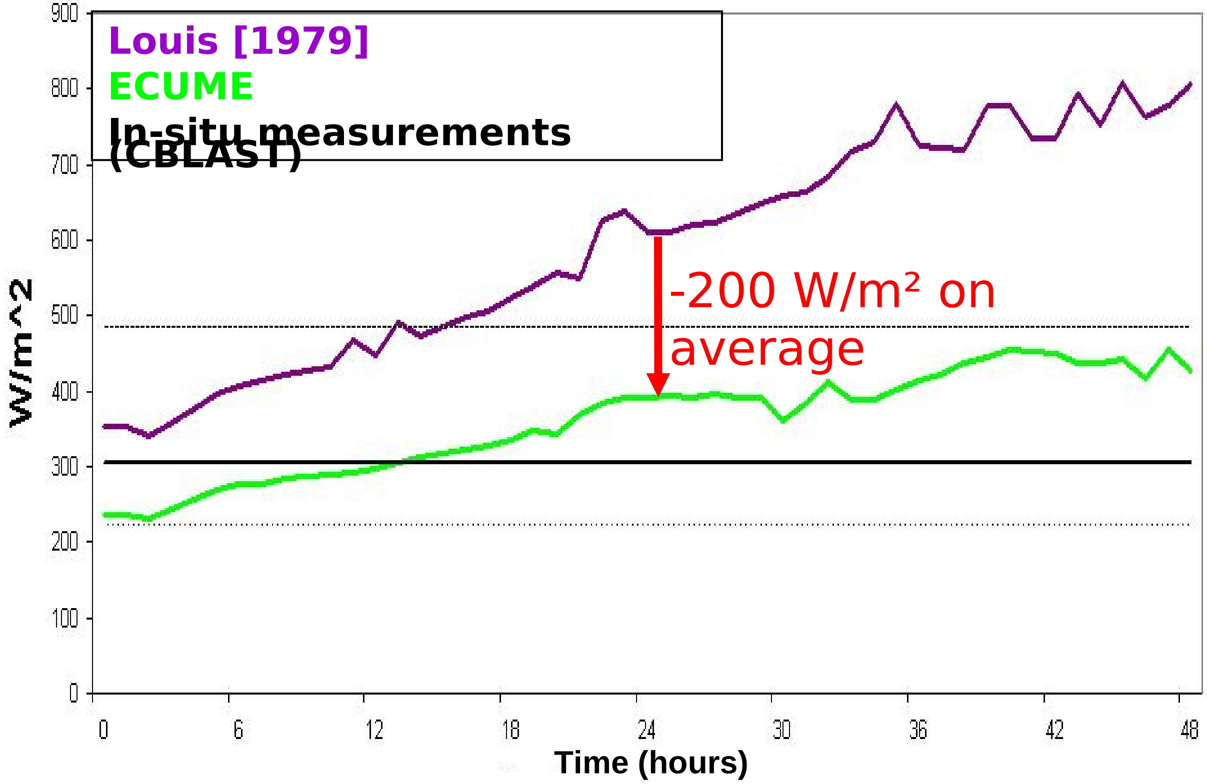
Average rain rate
(mm/h)

A second case study (1/1)

Cyclone ISABEL, september 2004 (Atlantic Ocean)

(from G. Samson, 2009)

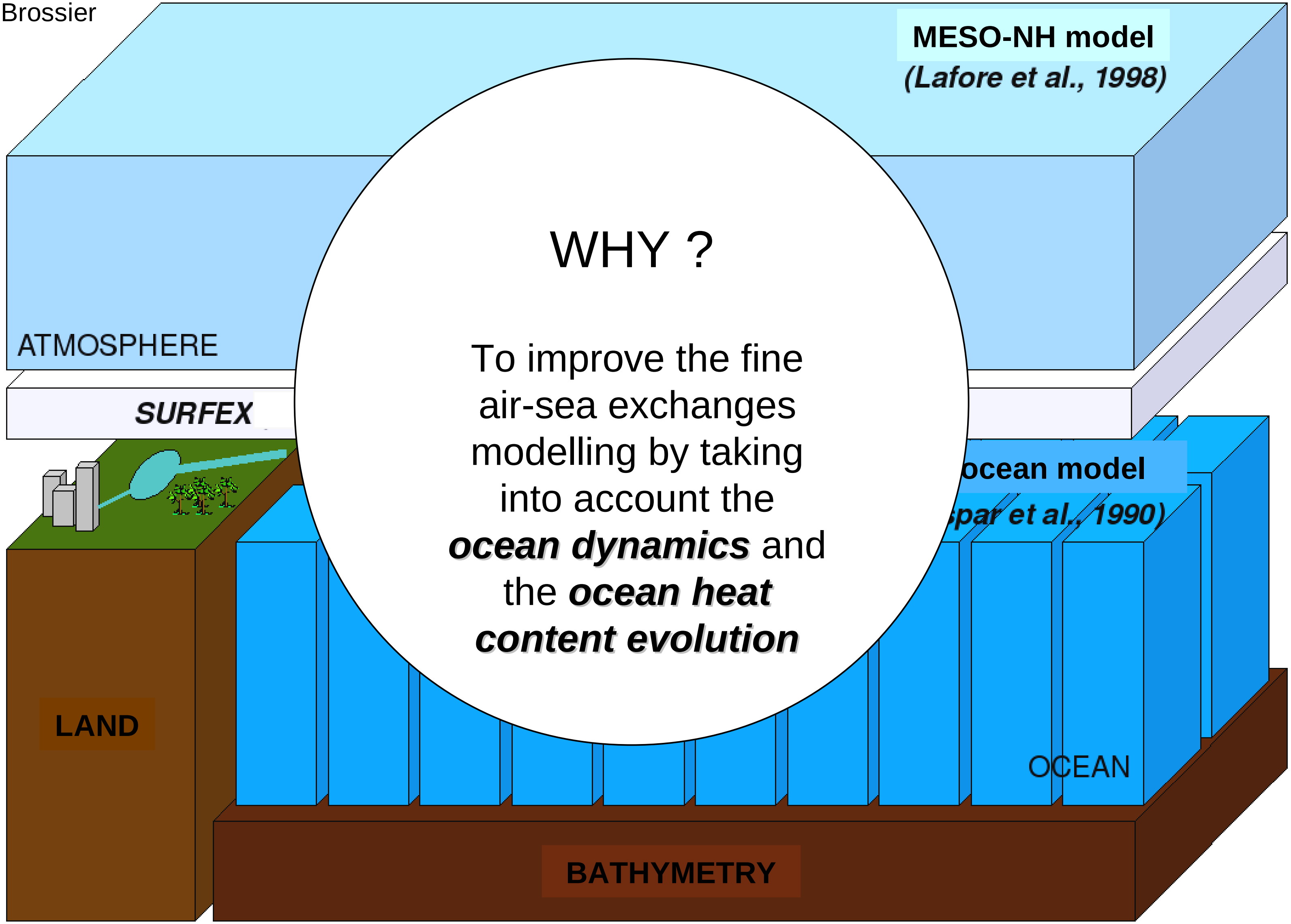
Measured and simulated latent heat flux



- Strong overestimation of the latent heat flux by the **Louis [1979]** formulation
- Saturation of the exchange coefficients for humidity at the end of the simulation when **ECUME** formulation is used
- Simulated latent heat flux with **ECUME** is in good agreement with in-situ measurements performed during CBLAST experiment

Coupling Atmosphere and 1D-Ocean with SURFEX

From C. Lebeaupin-Brossier (2007)

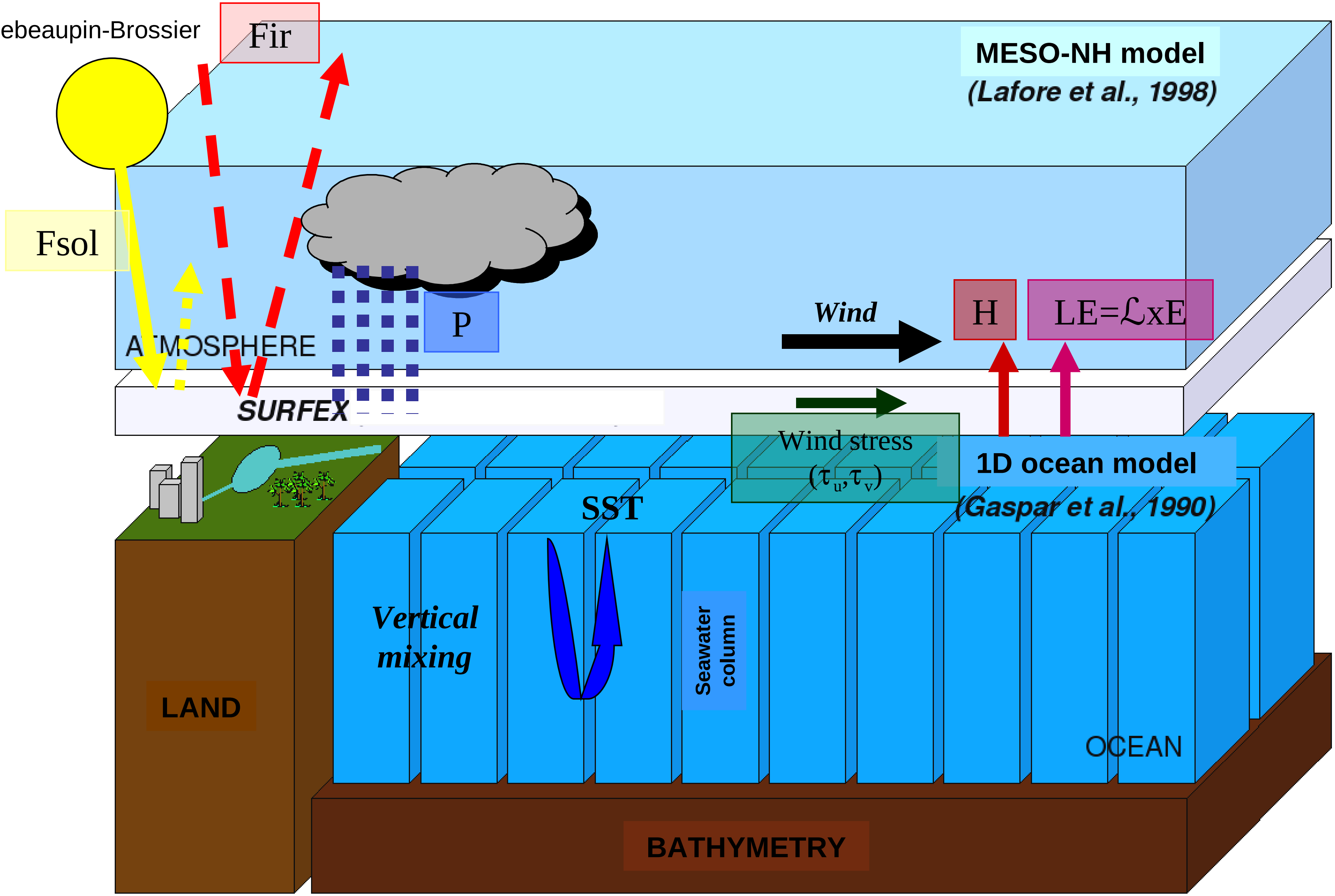


WHY ?

To improve the fine air-sea exchanges modelling by taking into account the ***ocean dynamics*** and the ***ocean heat content evolution***

Coupling Atmosphere and 1D-Ocean with SURFEX

From C. Lebeaupin-Brossier (2007)



The 1D-Ocean Model from Gaspar et al [1990] (1/2)

- Principle
  - The oceanic vertical mixing is represented according to the parametrisation of turbulence from Bougeault et Lacarrère [1989] adapted to the ocean

- Prognostic equations for :
  - ☐ Temperature (T) u
  - ☐ Salinity (S)
  - ☐ Current ( )
  - ☐ Turbulent Kinetic Energy (e) – 1.5 closure scheme

$$\begin{cases} \dfrac{\partial T}{\partial t} = \dfrac{F_{sol}}{\rho_0 c_p}\dfrac{\partial I(z)}{\partial z} - \dfrac{\partial \overline{T'w'}}{\partial z} \\[2em] \dfrac{\partial S}{\partial t} = -\dfrac{\partial \overline{S'w'}}{\partial z} \\[2em] \dfrac{\partial \vec{u}}{\partial t} = -f\vec{k} \times \vec{u} - \dfrac{\partial \overline{\vec{u}'w'}}{\partial z} \\ \dfrac{\partial \bar{e}}{\partial t} = -\dfrac{\partial}{\partial z}\left(\overline{e'w'} + \dfrac{\overline{p'w'}}{\rho_0}\right) - \overline{\vec{u}'w'} \times \dfrac{\partial \bar{\vec{u}}}{\partial z} + \overline{b'w'} - \varepsilon \end{cases}$$

METEO FRANCE
Toujours un temps d’avance

The 1D-Ocean Model from Gaspar et al [1990] (2/2)

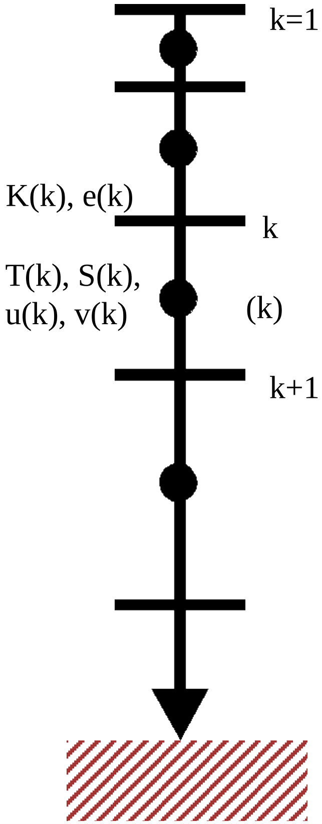
- Closure relationships

$$\begin{cases} -\overline{T'w'} = K_h \frac{\partial \bar{T}}{\partial z} \\ -\overline{S'w'} = K_s \frac{\partial \bar{S}}{\partial z} \\ -\overline{\vec{u}'w'} = K_m \frac{\partial \bar{\vec{u}}}{\partial z} \\ -\left(\overline{e'w'} + \frac{\overline{p'w'}}{\rho_0}\right) = K_e \frac{\partial \bar{e}}{\partial z} \end{cases}$$

with

$$K = c_k l_k \bar{e}^{\frac{1}{2}} = K_h = K_s = \frac{K_m}{Prt} \simeq K_m$$

$$K_e = c_\varepsilon l_\varepsilon \bar{e}^{\frac{1}{2}}$$



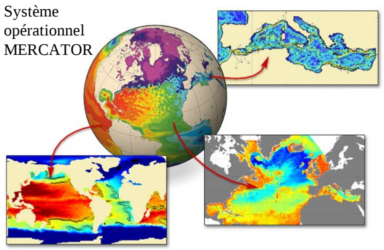
- Vertical discretisation on a z-coordinate grid

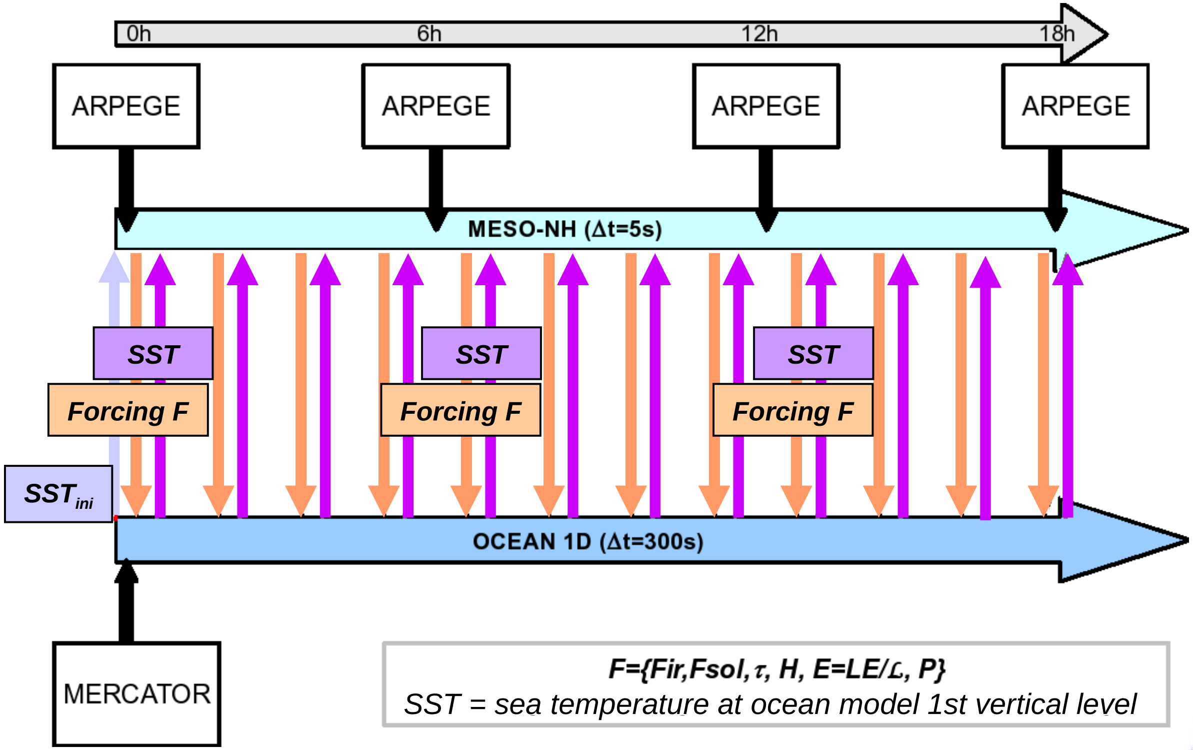
- Sea surface boundary conditions

$$\begin{cases} -\overline{T'w'}(0) = \frac{F_{nsol}}{\rho_0 . c_p} = \frac{H + LE + F_{IR}}{\rho_0 . c_p} \\ -\overline{S'w'}(0) = \frac{E - P}{\rho_0 . c_p} \\ -\overline{\vec{u}'w'}(0) = \frac{\vec{\tau}}{\rho_0 . c_p} \end{cases}$$

Coupling Atmosphere and 1D-Ocean with SURFEX

Initialisation of the 1D model with oceanic analyses issued from climatologies or from the MERCATOR operational model (Bahurel et al. [2004])




0h
6h
12h
18h

ARPEGE
ARPEGE
ARPEGE
ARPEGE

MESO-NH ($\Delta t=5s$)

SST
Forcing F
SST
Forcing F
SST
Forcing F
SST_{ini}

OCEAN 1D ($\Delta t=300s$)

MERCATOR

F={Fir,Fsol,τ, H, E=LE/£, P}
SST = sea temperature at ocean model 1st vertical level

G
A
R
D

A first case study (1/2)

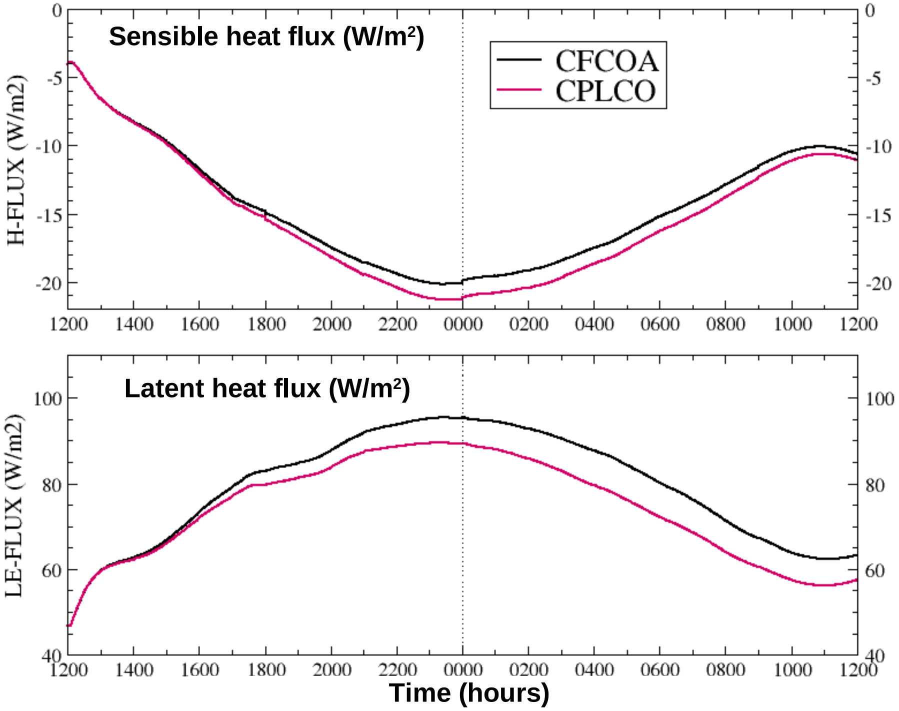
Extreme mediterranean rain event 8-9 sept. 2002

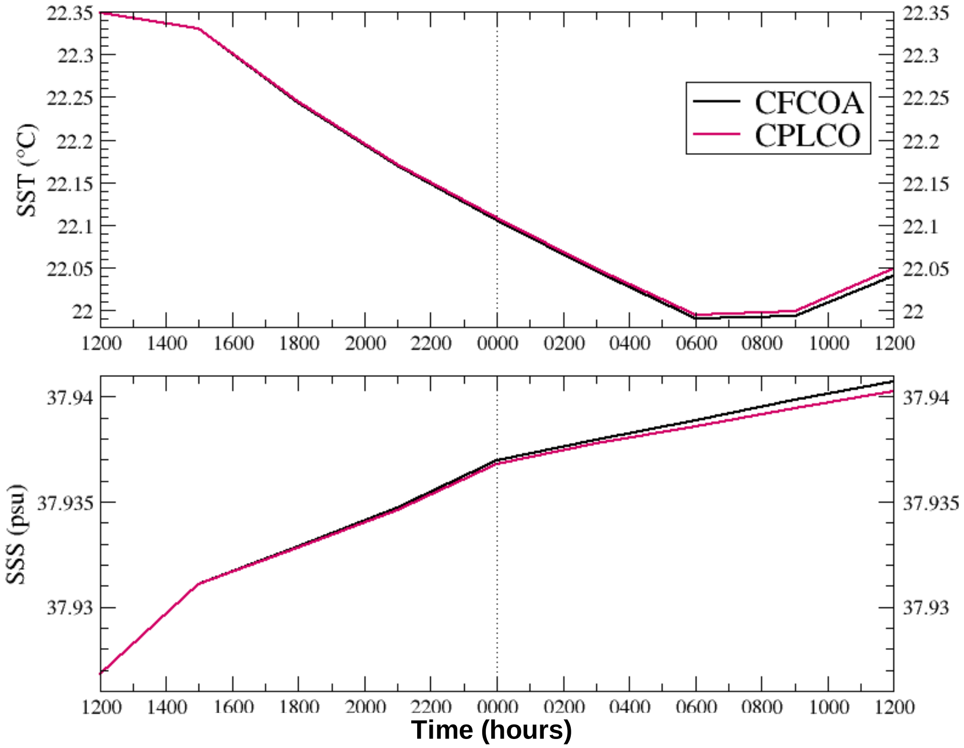
(from C. Lebeaupin-Brossier, 2007)

Quasi-stationnary meso-scale convective system : 691 mm in 24 hours
(Delrieu et al. 2005 ; Ducrocq et al., 2004)

CFCOA : 1D-Ocean forced by Atmosphere
CPLCO : Coupled Atmosphere-Ocean

Mean turbulent heat fluxes** (W/m^2) **over the sea





***Average SST** (°C) **and SSS** (psu)*

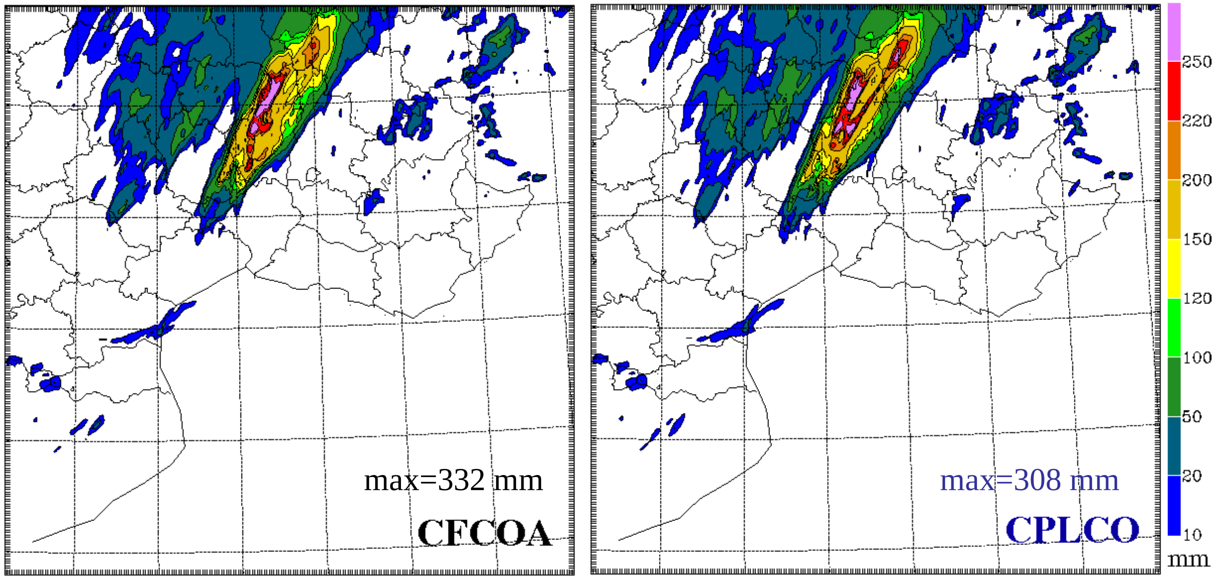
G
A
R
D

A first case study (1/2)

Extreme mediterranean rain event 8-9 sept. 2002

(from C. Lebeaupin-Brossier, 2007)

CFCOA : Atmosphere forced by 1D-Ocean
CPLCO : Coupled Atmosphere-Ocean



***Accumulated precipitation over 24h** (mm)*

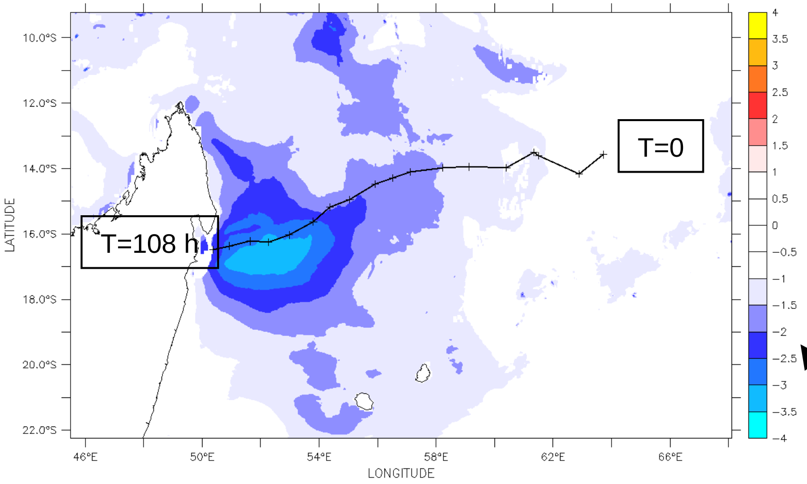
A second case study (1/1)

Cyclone IVAN, february 2008 (Indian Ocean)

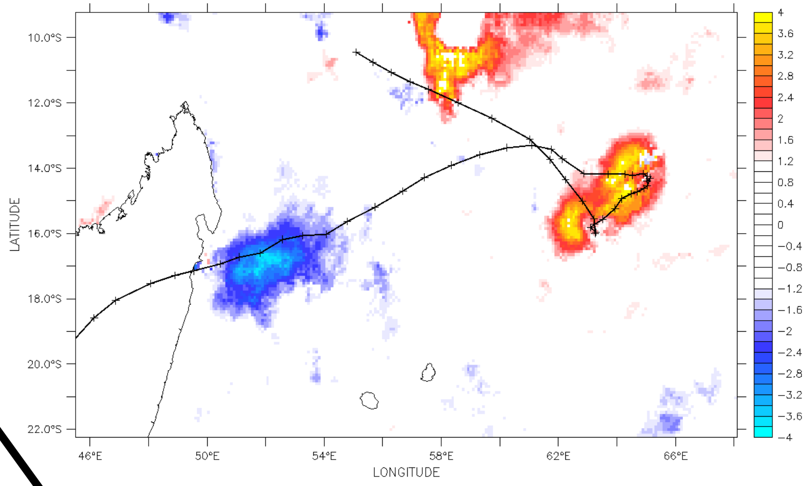
(from G. Samson, 2009)

Coupled 1D-Ocean/Atmosphere simulation

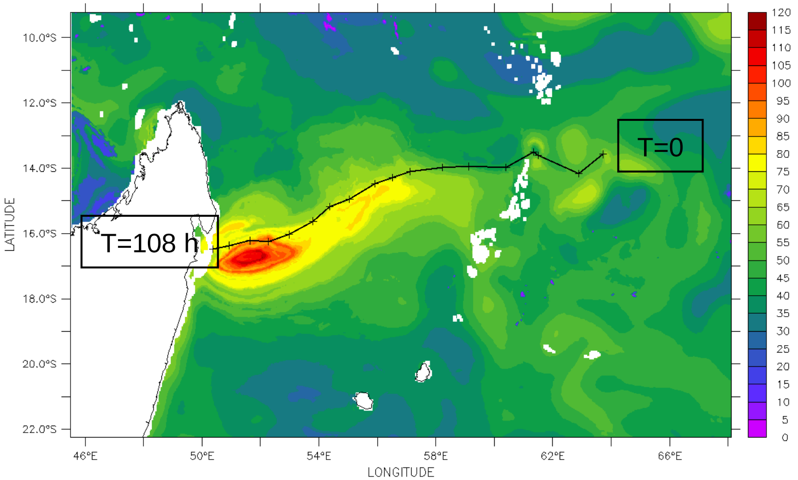
Observations



SEA SURFACE COOLING (degC)



SEA SURFACE COOLING – REMSS (degC)



MLD based on Temperature criteria (delta_T = 0.5~oC) (meters)

Oceanic mean state at the end of the simulation (T=108 h)