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# International MedCLIVAR-ICTP-ENEA Summer School on the Mediterranean Climate System and Regional Climate Change

***13 - 22 September 2010***

## Air Sea Interaction: Air-Sea Inetraction in the Mediterranean Sea: From Closure of the Basin Heat Budget to Impacts of Extreme Heat Loss on Dense Water Formation

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# Air-Sea Interaction in the Mediterranean Sea: From Closure of the Basin Heat Budget to Impacts on Dense Water Formation

## Outline

1) Air-Sea Fluxes: The Fundamentals
2) Mediterranean Sea: Forcings and Budgets
3) Extreme Heat Loss in Dense Water Formation Regions
4) Links to Large Scale Modes of Atmospheric Variability
5) Conclusions

**S. A. Josey, MedCLIVAR Summer School, Trieste, Sep 15th 2010**

## *1) The Fundamentals* : From the Ocean Surface …

**The Drivers:** Surface fluxes of heat, freshwater, and momentum (wind stress) drive variability in ocean state.

- Key terms modifying density of surface waters prior to dense water formation.

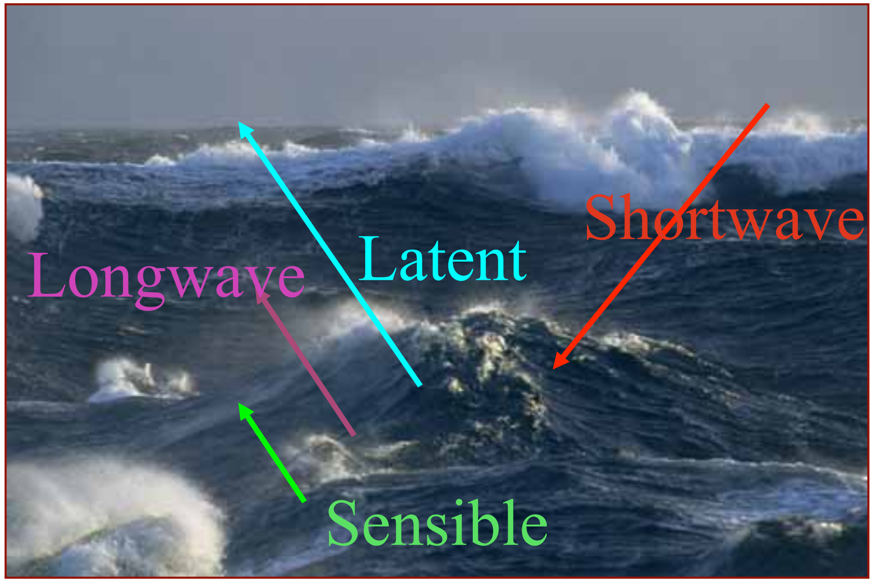
- Required for ocean model forcing and coupled model evaluation.

**Four components of heat flux:**

- **Latent : wind speed x (sea-air humidity difference)**

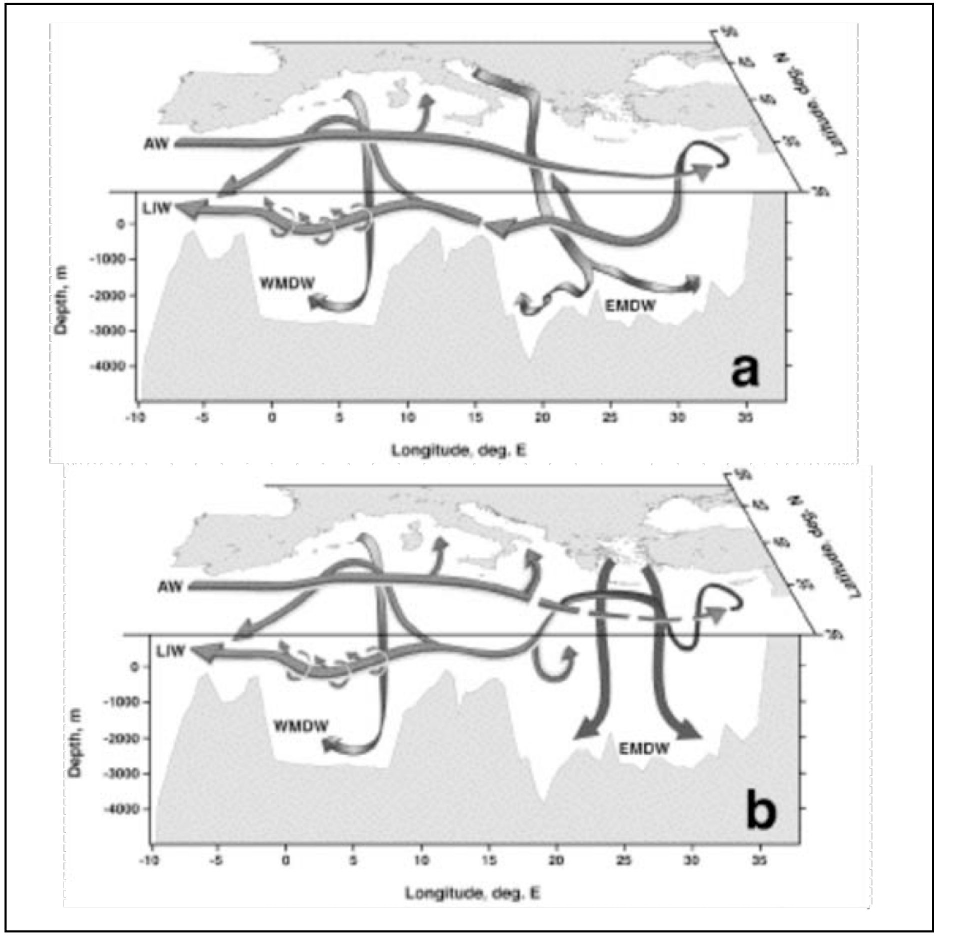
- **Sensible : wind speed x (sea-air temperature difference)**

- **Shortwave- Solar radiative flux**
**Longwave – Infrared radiative flux**



# … to the Overturning Circulation

- **How do surface processes drive variability in the Mediterranean circulation?**

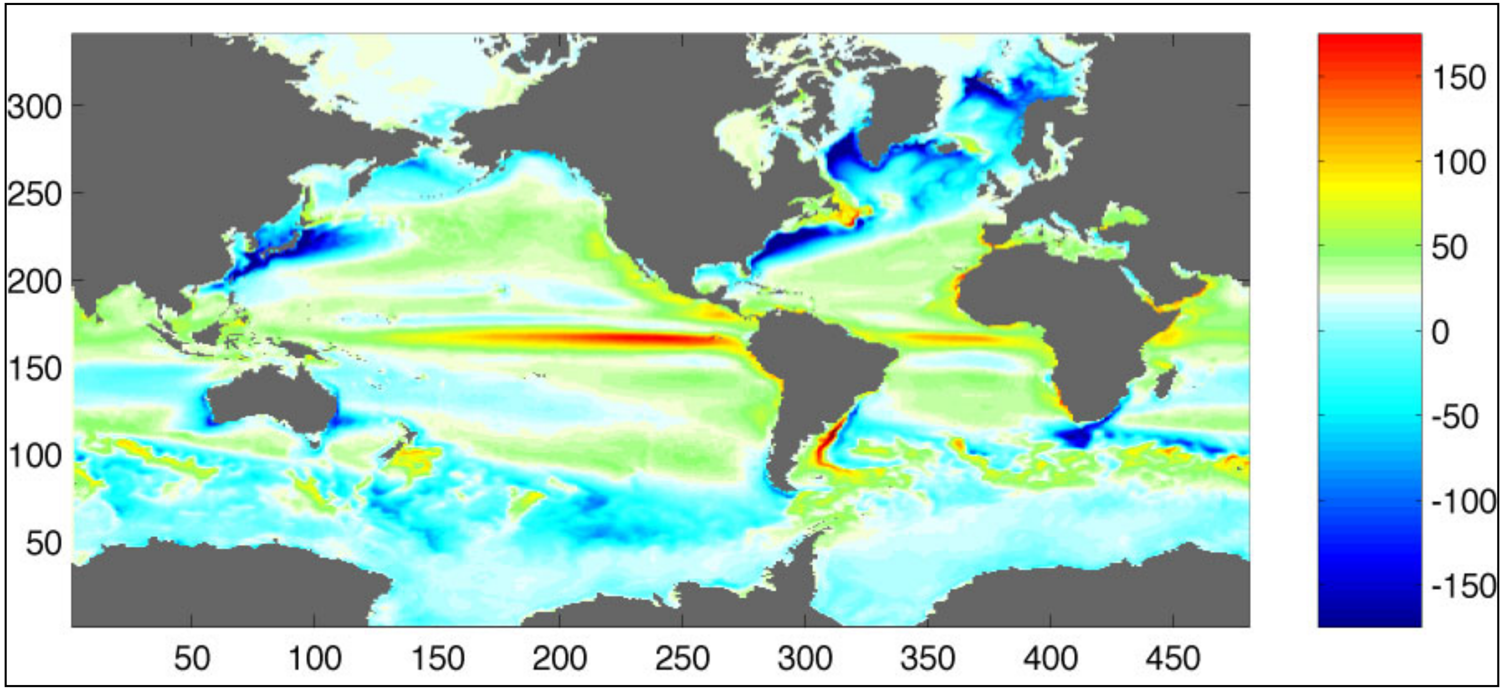



- Schematic representation of the Mediterranean circulation before (1987, upper) and during (1995, lower) the Eastern Mediterranean Transient.

*From Tsimplis, Zervakis, Josey, Peneva, Struglia, Stanev, Lionello, Malanotte-Rizzoli, Artale, Theocharis, Tragou and Oguz (2005, Chapter 4, MedCLIVAR Book 1).*

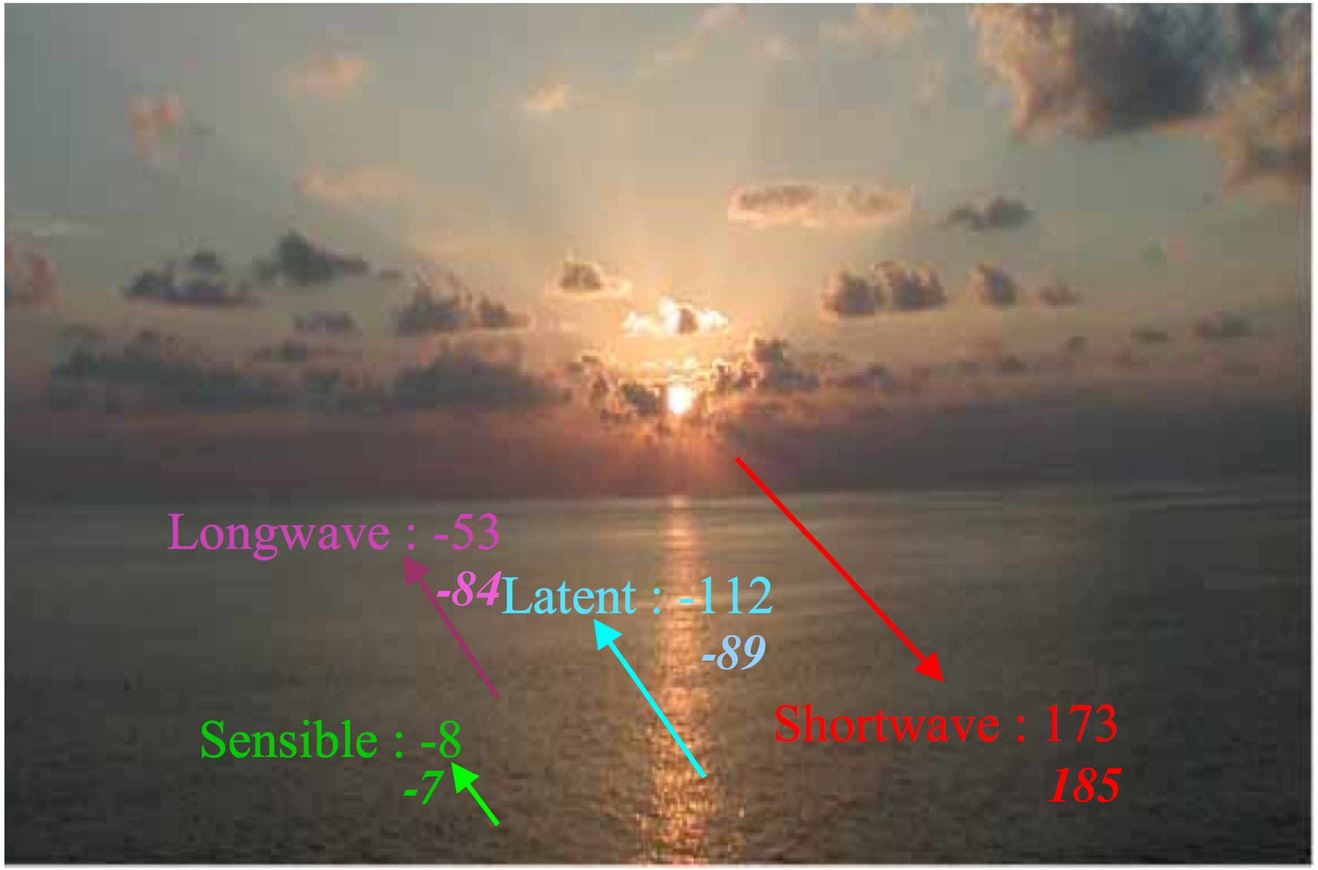
# Ocean-Atmosphere Heat Exchange

- **Example net surface heat flux field (units W m$^{-2}$, blue colours ocean heat loss).**




- Surface net heat flux from a 50 year run with the OPA 1/4 degree ocean model.

# Relative Values of Heat Flux Components




- **Global mean values from a balanced flux dataset (Grist and Josey, 2003). Corresponding Mediterranean values shown in bold italics (source : Adjusted NOC-Josey ,reported in Sanchez-Gomez et al., 2011).**

# How Are the Fluxes Estimated?

• Three main sources of information: in situ (ship, buoy) meteorological reports, satellite observations, atmospheric models.

• Key variables: sea surface temperature, near surface air temperature, near surface humidity, wind speed and cloud cover.

• Observations of these 5 variables form the basis of flux datasets.

Basic method:
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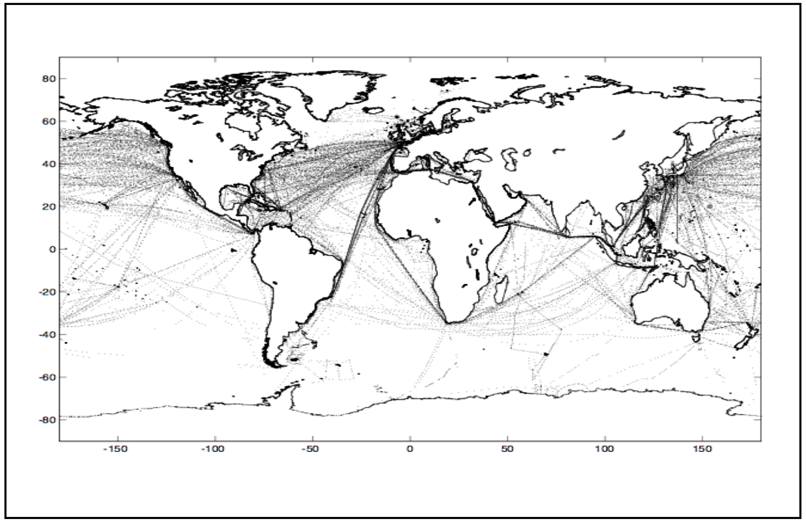

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Basic method:
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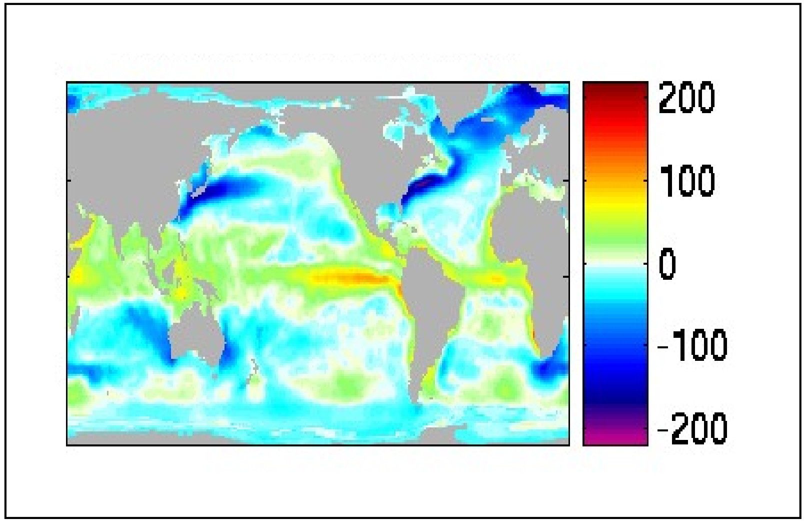
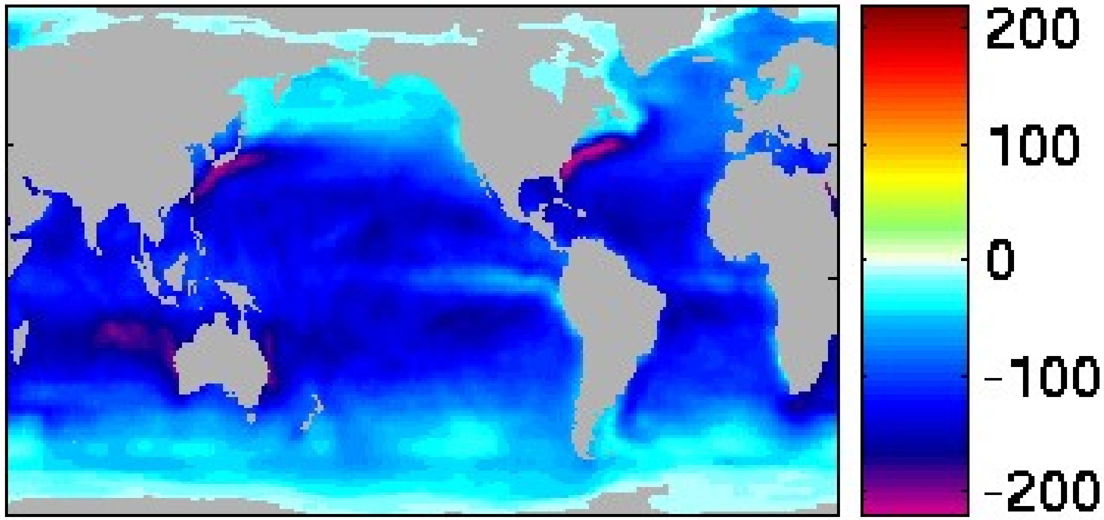
- averaged to form gridded monthly means,
- then interpolated to produce global datasets



# Latent Heat Flux, $Q_E$




Sea surface humidity

$$Q_E = \rho L C_e u (q_s - q_a)$$

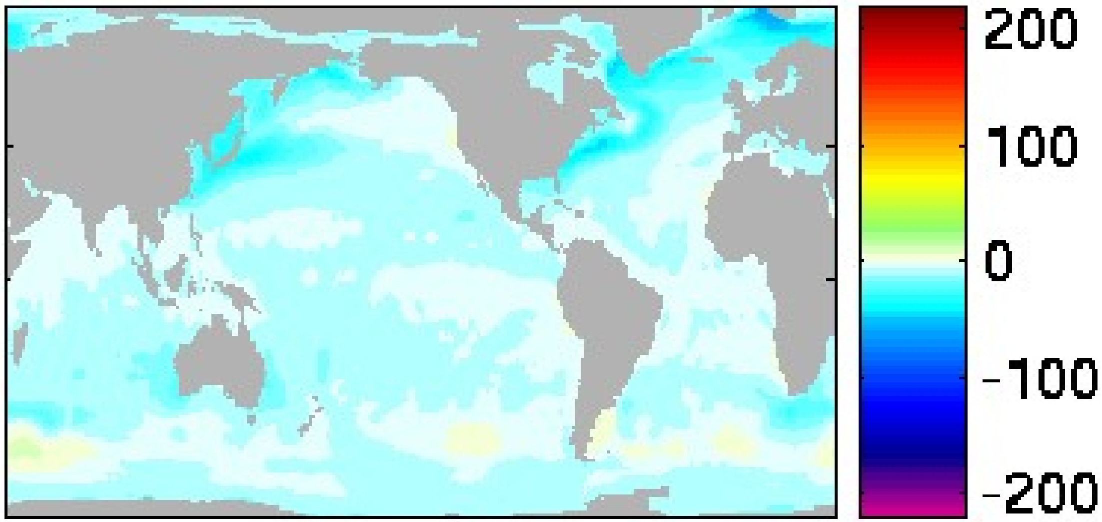
Wind speed

Near surface humidity

• Strongest losses (200 $Wm^{-2}$) over the Gulf Stream and Kuroshio.

• Enhanced heat loss also in the South-East Indian Ocean where the trade winds are particularly strong.

# Sensible Heat Flux, $Q_H$




Sea surface temperature

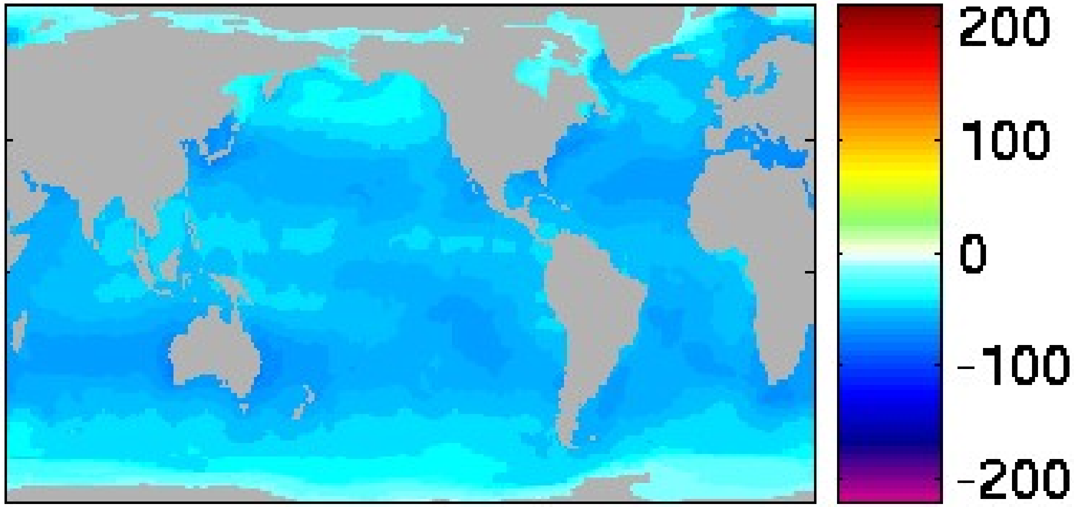
$$Q_H = \rho c_p C_h u (T_s - (T_a + \gamma z))$$

Wind speed

Near surface air temperature

- Strong losses (30 $Wm^{-2}$ ) again over the Gulf Stream and Kuroshio but much weaker than latent heat flux.

# Longwave Flux, $Q_{LW}$



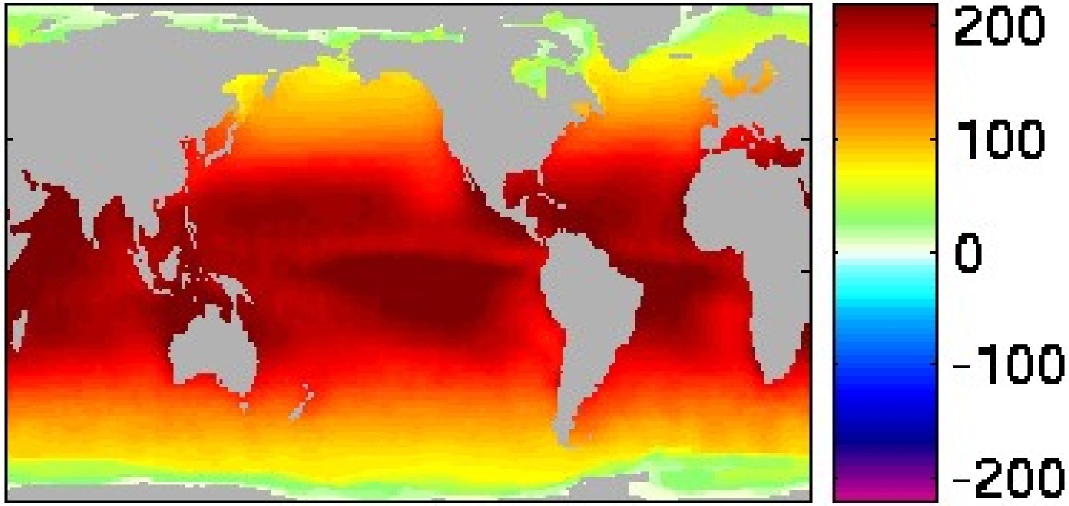

$$Q_{LW} = Q_{LS} - (1 - \alpha_L) Q_{LA}$$

Upwards longwave ($Q_{LS}$)

Downwards longwave ($Q_{LA}$)

- Relatively uniform heat loss (50-80 $Wm^{-2}$ ) over much of the world ocean.
- Atmospheric term depends on cloud cover, air temperature and humidity.

# Shortwave Flux, $Q_{SW}$




Cloud cover

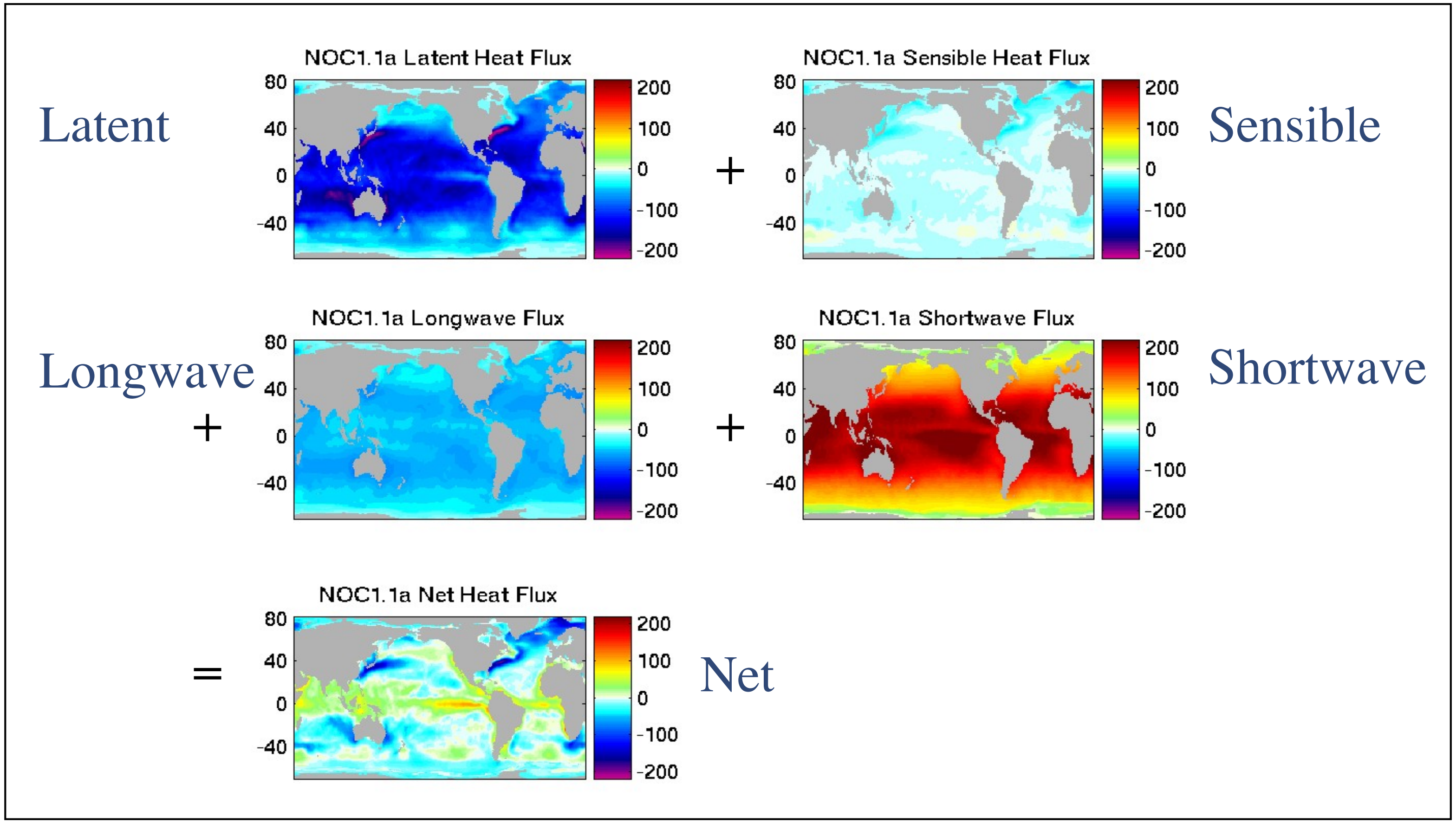
$$\overline{Q}_{SW} = (1-\alpha)Q_c[1-0.62\,\overline{n}+0.0019\,\overline{\theta}_N]$$

Clear sky shortwave

Noon solar elevation

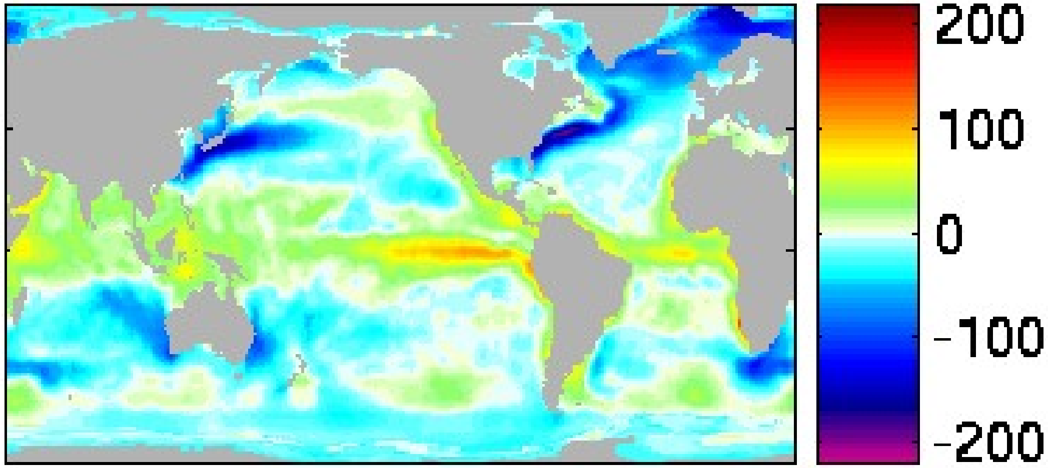
- Major term - source of heat gain by the ocean (200 $Wm^{-2}$ in Tropics) with strong dependence on latitude.
- Dependence on cloud cover evident with reduction in flux under the Intertropical Convergence Zone.

# Net Air-Sea Heat Flux




• Four terms combine to produce the net heat exchange. Main features primarily determined by a balance between shortwave gain and latent heat loss.

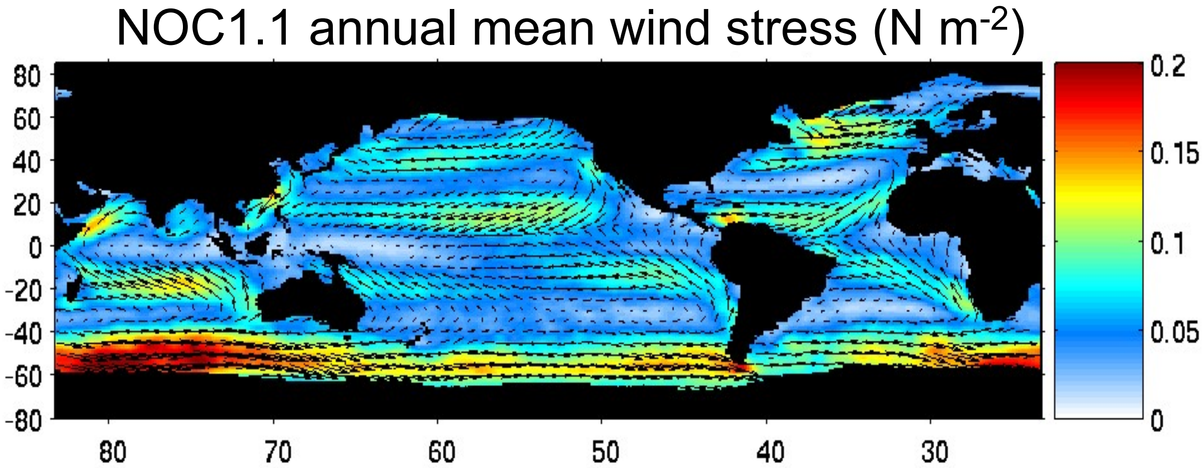
# Net Air-Sea Heat Flux




$$Q_{Net} = Q_E + Q_H + Q_{LW} + Q_{SW}$$

• Four terms combine to produce the net heat exchange. Main features primarily determined by a balance between shortwave gain and latent heat loss.

# Wind Stress ( Momentum Flux)




$$\tau_x = \rho C_D u_x (u_x{}^2 + u_y{}^2)^{1/2}$$

$$\tau_y = \rho C_D u_y (u_x{}^2 + u_y{}^2)^{1/2}$$

• Note patterns associated with subtropical and subpolar gyres, the ITCZ and the band of intense westerly wind stress in the Southern Ocean.

# Mediterranean Wind Stress Forcing

January

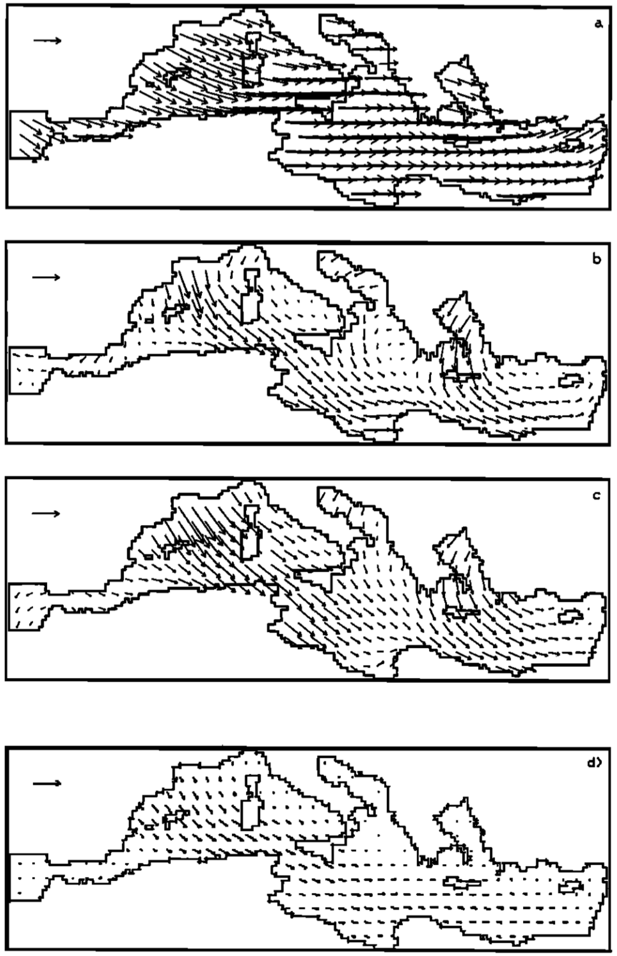


**Figure 2.** Wind stress climatologies for January: (a) NMC-R, (b) ECMWF, (c) SOC, and (d) NMC . The scale arrow in the top left-hand corner of each plot represents a vector of magnitude 0.1 N $m^{-2}$.

July

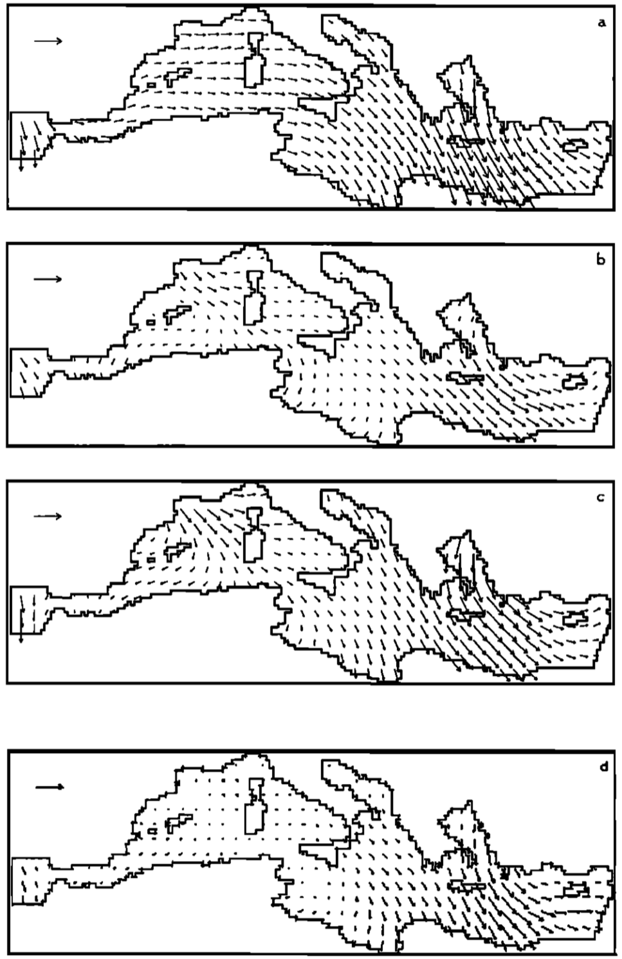
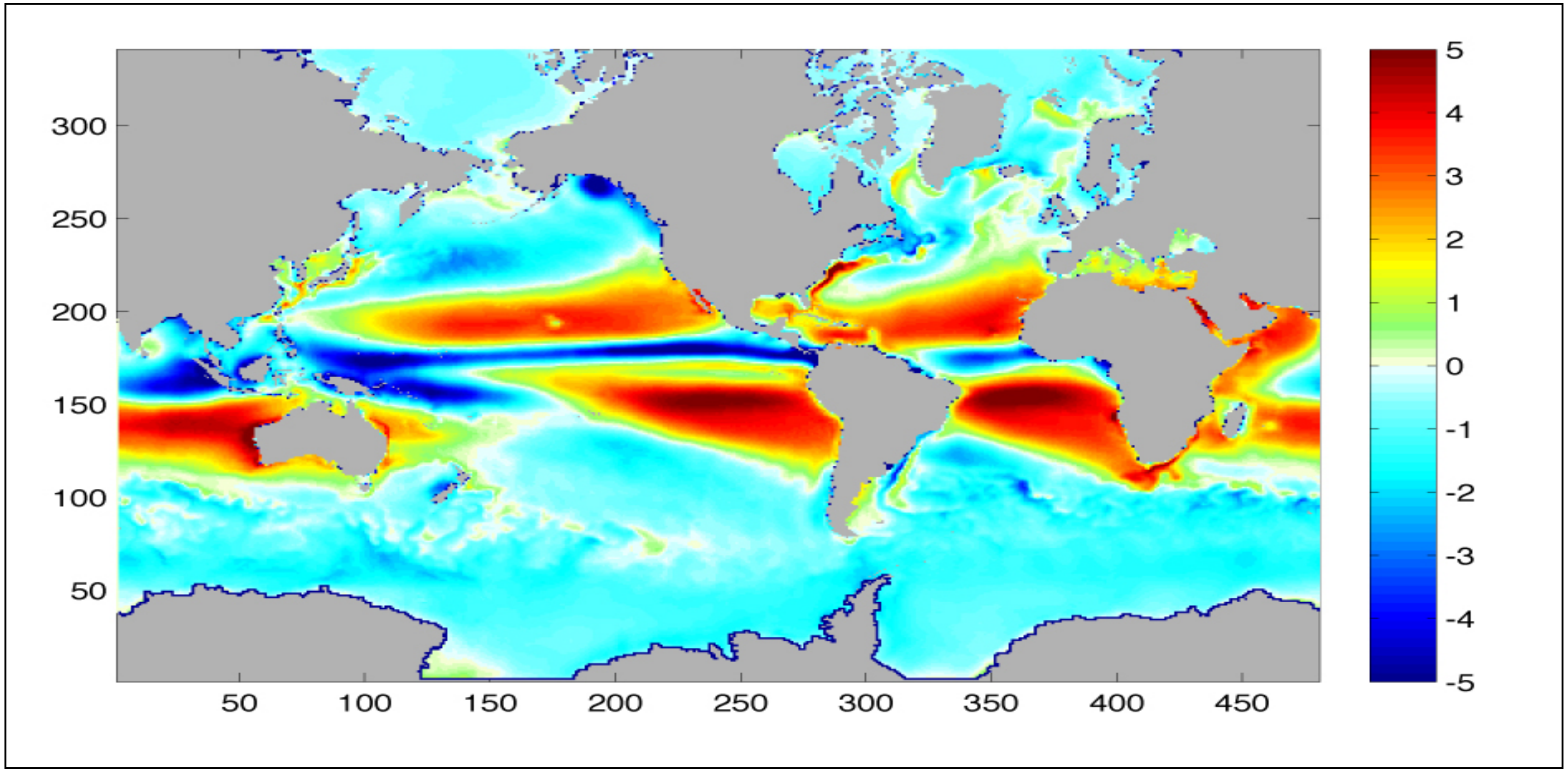


**Figure 3.** Wind stress climatologies for July: (a) NMC-R, (b) ECMWF, (c) SOC, and (d) NMC. The scale arrow in the top left-hand corner of each plot represents a vector of magnitude 0.1 N $m^{-2}$.

**Myers, Haines and Josey (JGR-Oceans, 1997, ¼ deg ocean model study of circulation response to different wind stress forcing)**

# Air-Sea Freshwater Flux

The freshwater flux (E-P) is a balance between two terms : the evaporation (E) and precipitation (P).




OPA 1/4° model net evaporation, E-P (mm $day^{-1}$) : 1958 - 2003

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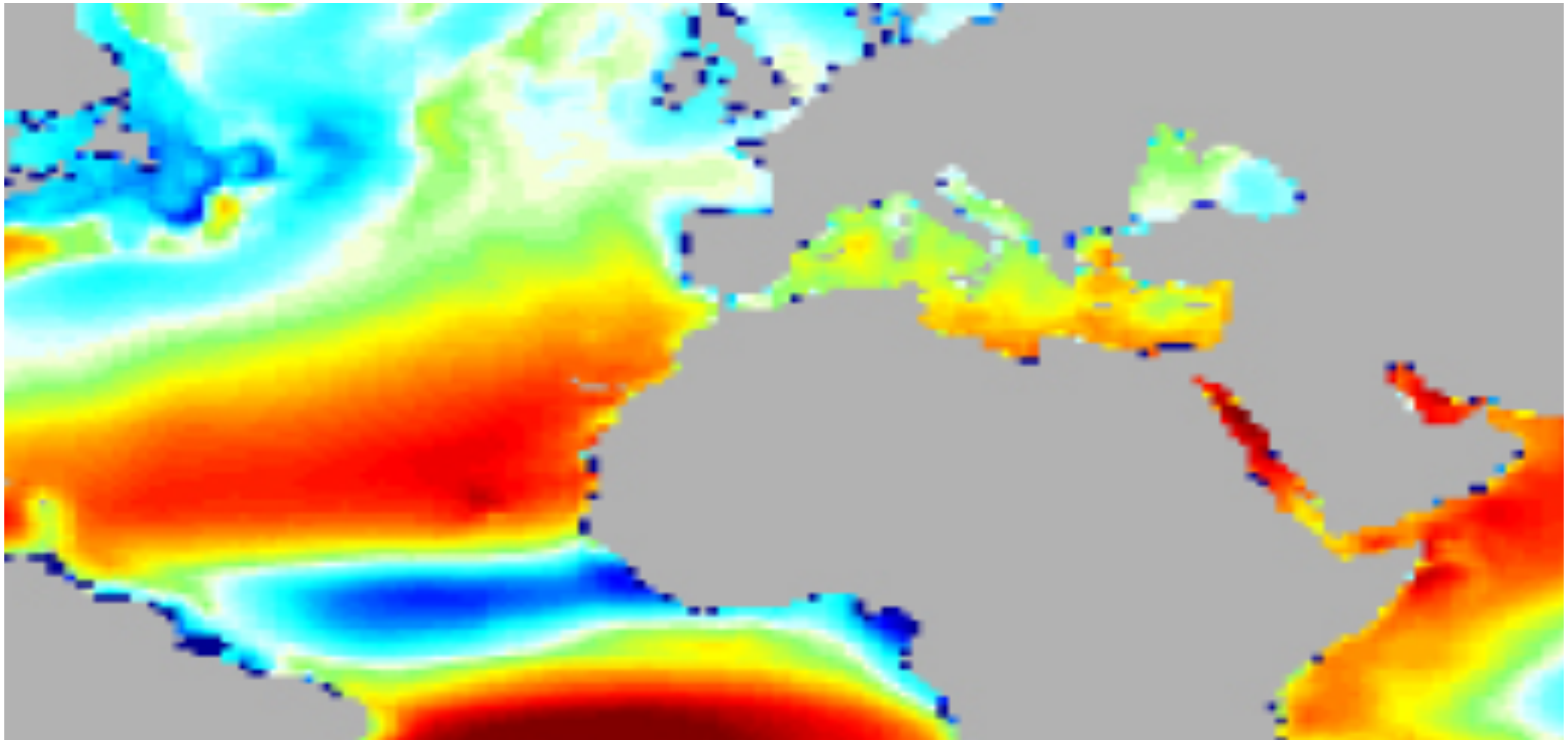


OPA 1/4° model net evaporation, E-P (mm $day^{-1}$) : 1958 - 2003

# Surface Density Flux

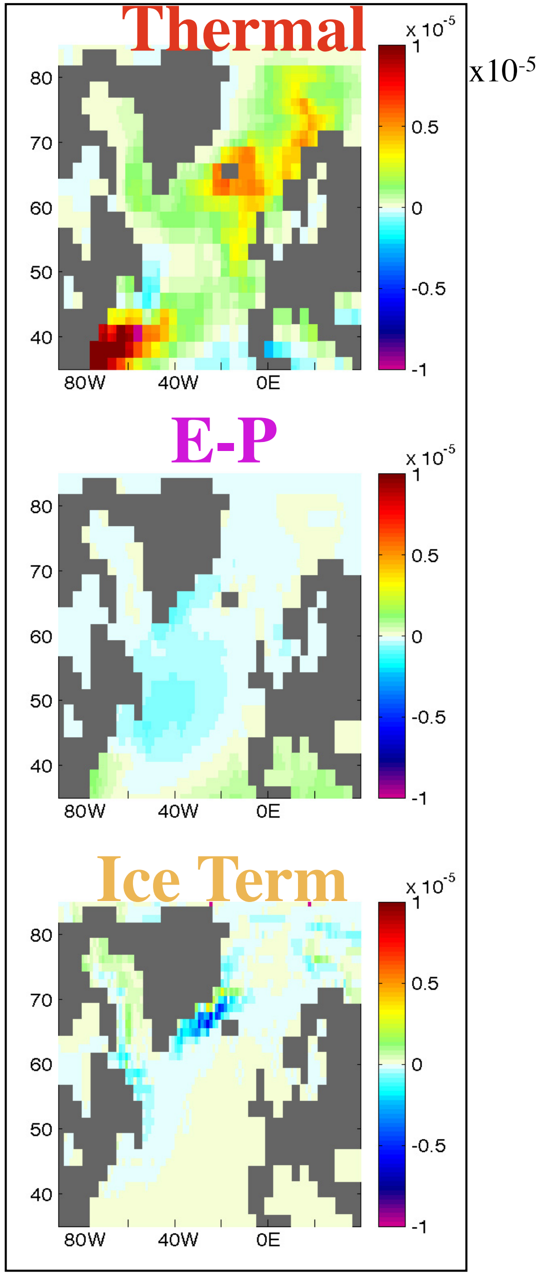
- The surface net heat and freshwater flux (together with ice related terms at high latitudes) modify the density of the ocean surface layer.

- Can be expressed in terms of a surface density flux…

$$F_\rho = -\rho\left(\alpha\frac{Q_{Net}}{\rho c_P} - \beta S\frac{E - P}{(1 - S/1000)} + \beta S\frac{I_M}{(1 - S/1000)}\right)$$

**Thermal term** ↑ **E-P term** ↑ **Ice term** ↑

S=salinity, α,β=Thermal expansion and haline contraction coefficients, $I_M$=Ice melt

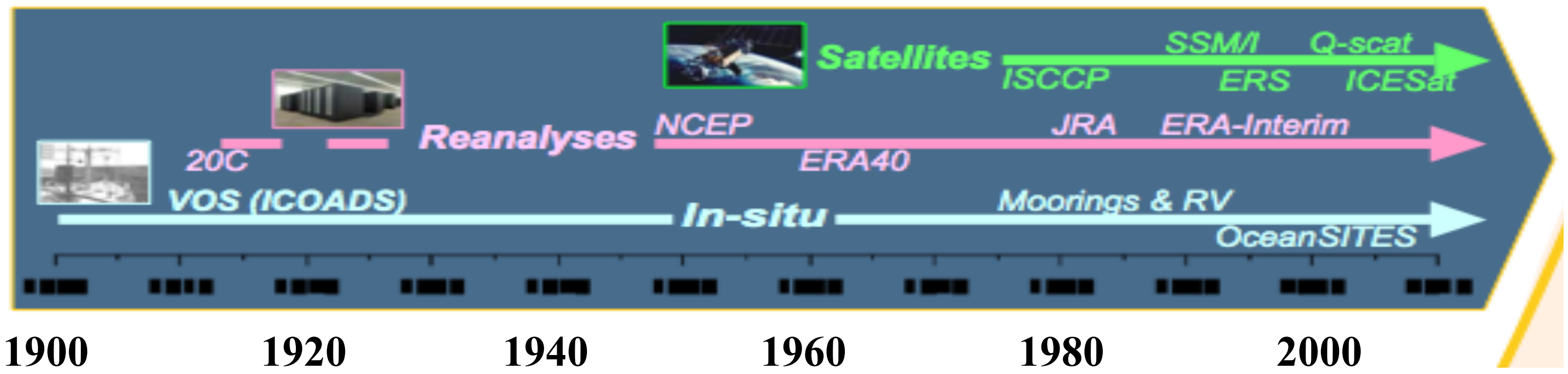



**Example: HadCM3 Surface Density Flux (kg $m^{-2}$ $s^{-1}$) - North Atlantic**

- Thermal term most important
- Ice term important locally

# Flux Datasets - Overview

- Ship based flux datasets: NOC1.1, 1.1a and 2, FSU3, UWM/COADS (da Silva).
- Atmospheric reanalyses: NCEP, ERA40, JRA.
- Satellite only fields: HOAPS3, J-OFURO2.
- Hybrid products (Satellite + reanalysis ) : OAFLUX, CORE.
- Ocean syntheses: GECCO.

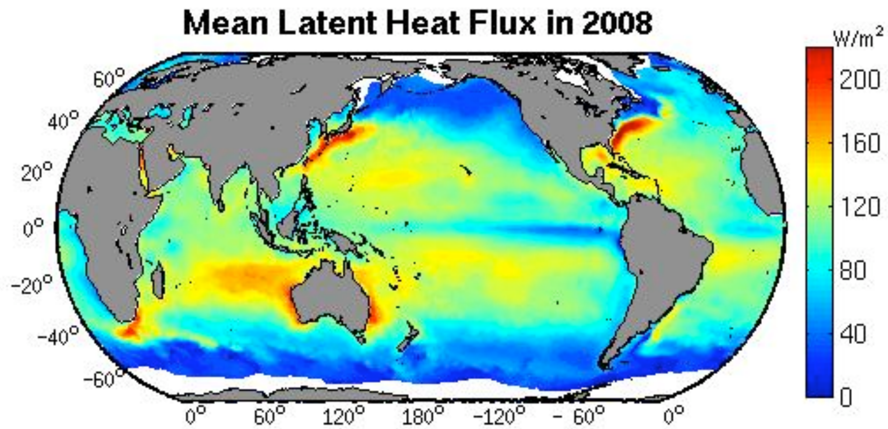


# Flux Products - NOC Flux Dataset

- NOC1.1: Global air-sea flux climatology using COADS ship reports for 1980-1993 (Josey et al., 1999). Global imbalance of 30 $Wm^{-2}$.
- NOC1.1a: Globally balanced version using inverse analysis (Grist and Josey, 2003).
- NOC1.1 Med version: Modification of NOC1.1 which uses Bignami et al. (1994) Med longwave formula and Garrett aerosol adjustment.

# Flux Products : OAFlux

- OAFLUX - Objectively Analysed Air-Sea Heat Fluxes
- Led by Lisan Yu. Version 3 (Yu, Jin and Weller, WHOI Tech. Report, 2008).




- Latent and sensible heat fluxes from synthesized satellite and reanalysis met. fields (wind speed, near surface atmospheric temperature and humidity, SST). Using COARE flux algorithm.
- Global, 1x1 grid, monthly fields for 1958 - 2008. Daily for 1985 onwards. Available at http://oaflux.whoi.edu/.

# OAFlux - Method

- Minimise an objective function which is a weighted sum of the difference between each input dataset (NCEP, ECMWF, satellite) and the analysed field.
- Weighting matrices are inversely proportional to the error covariances for each dataset.
- Errors determined by reference to NOC dataset (assumed error free) and research buoy measurements.

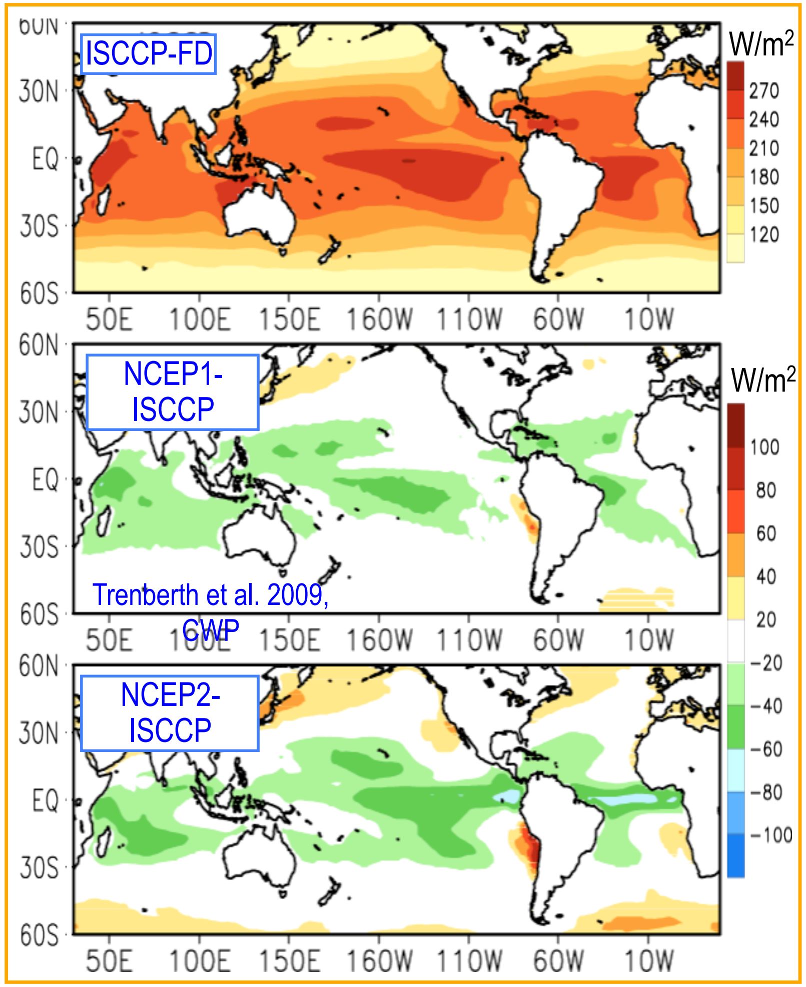
# Flux Products - Reanalyses

- Fixed atmospheric model runs which assimilate available observations over multidecadal periods (e.g. NCEP : 1949-present).

- Trenberth highlights deficiencies with existing reanalyses…

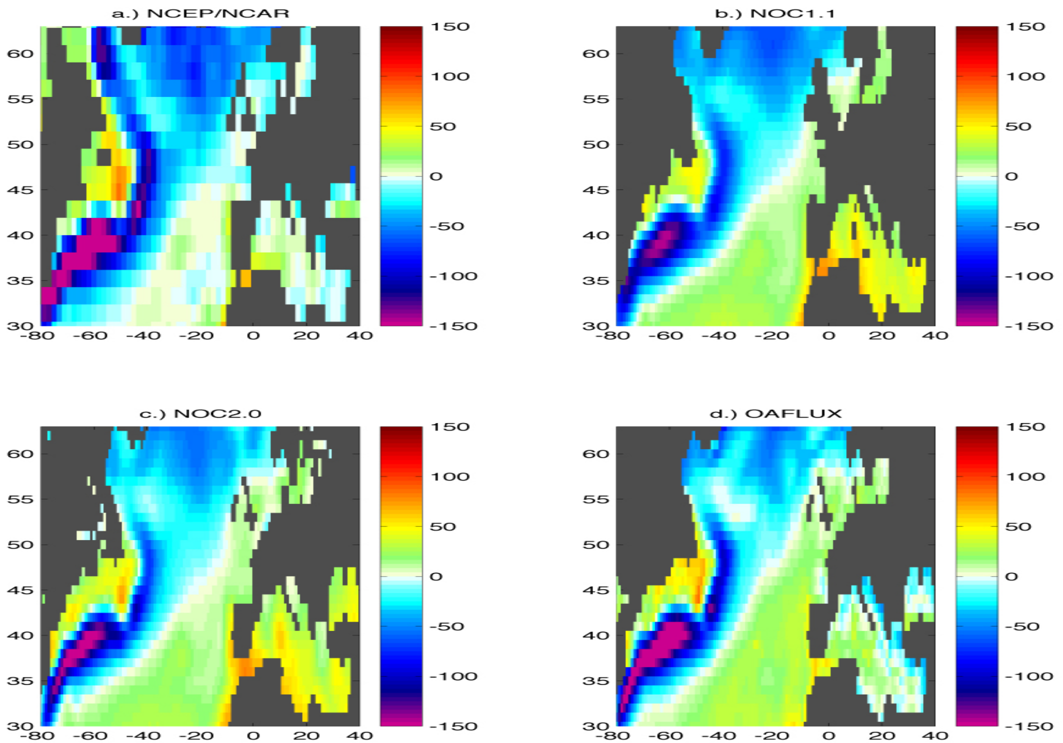
  For example: radiative flux biases in the Tropics.

- New much higher resolution reanalysis (CFSRR) at NCEP which will assimilate satellite radiance measurements may resolve this.



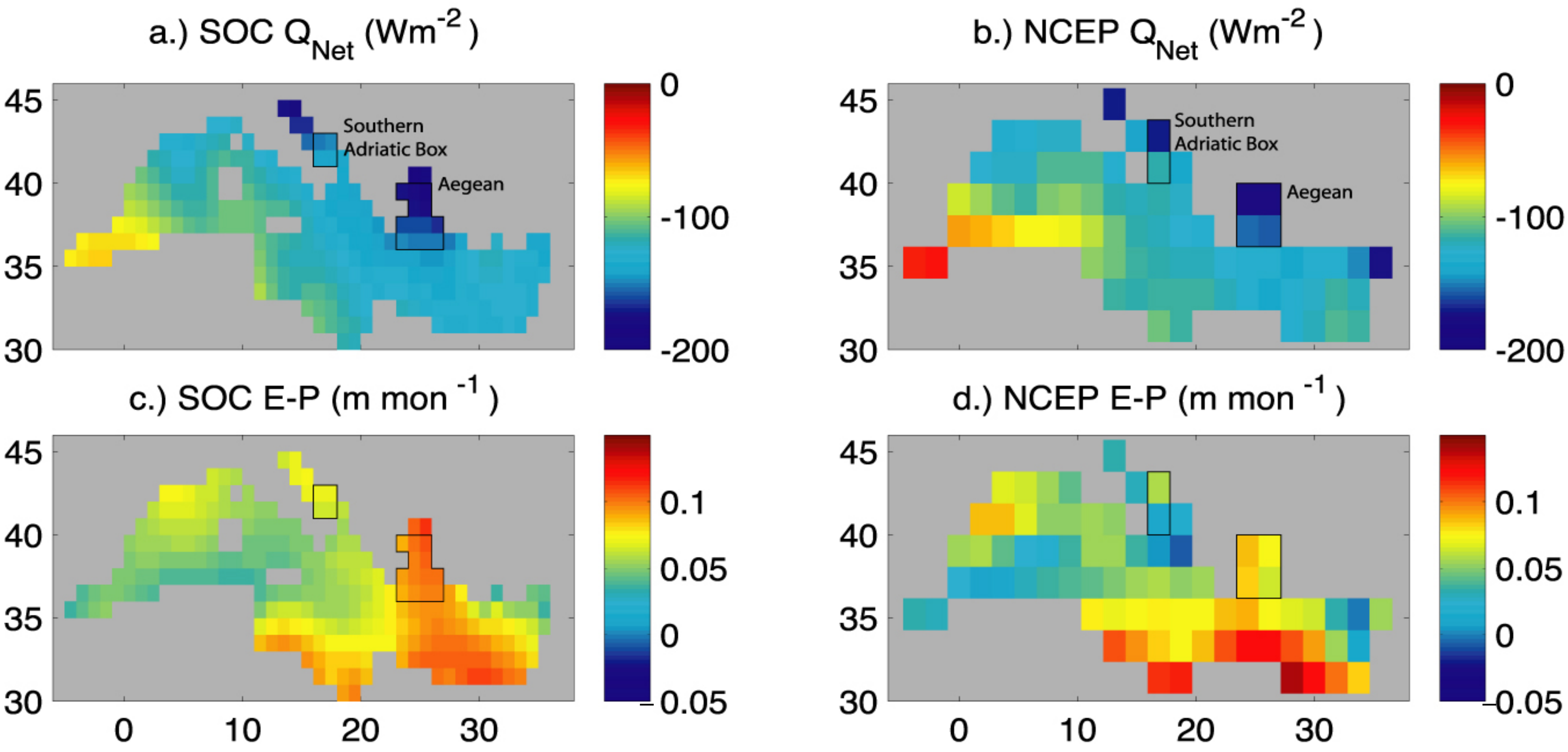
# Intercomparison of  Flux Products

- Similar spatial patterns in well sampled regions…




Annual mean net air-sea heat flux from a.) NCEP/NCAR, b.) NOC1.1, c.) NOC2 and d.) OAFLUX for the common period 1984-2004, units W $m^{-2}$. Blue colours : ocean heat loss to the atmosphere, red ocean heat gain.

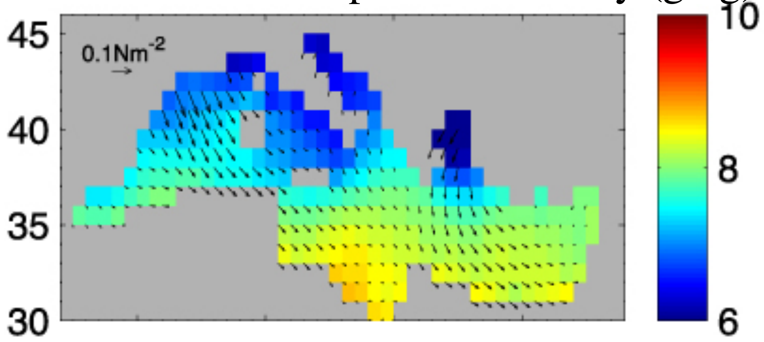
# 2) Mediterranean Sea Forcings




Climatological winter (Nov-Feb) mean net heat flux and net evaporation (E-P) in the Mediterranean Sea (Josey, JGR, 2003).

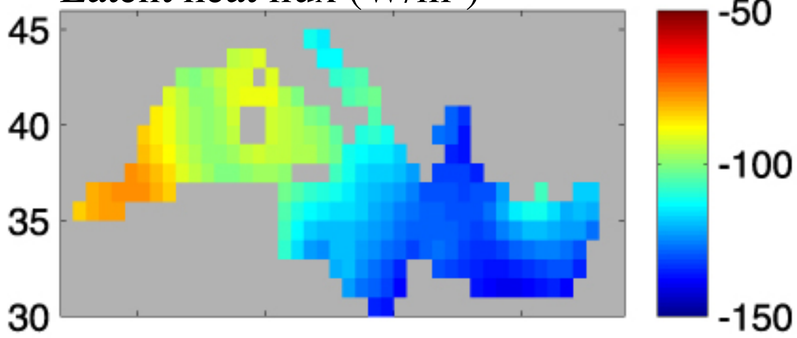
# Components of the Winter Forcing

Wind stress and specific humidity (g/kg)

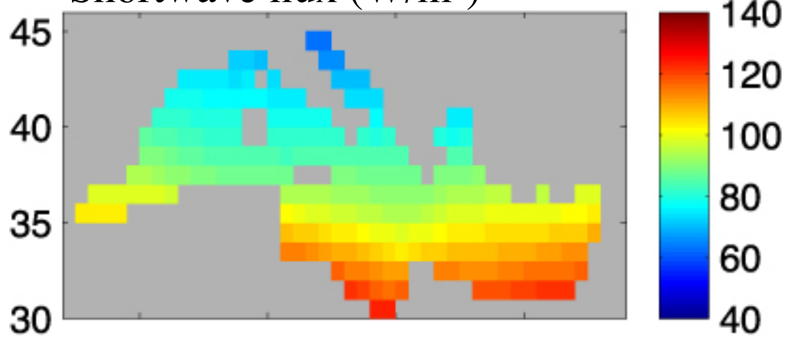



NOC Winter (Nov-Feb) Flux Components and Met Variables

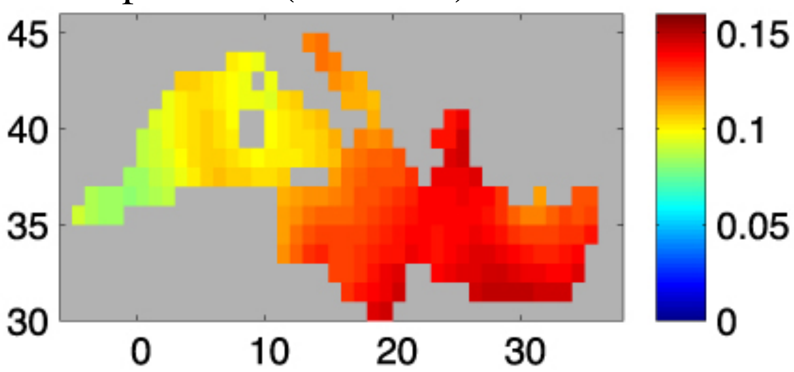
Latent heat flux (W/m$^2$)



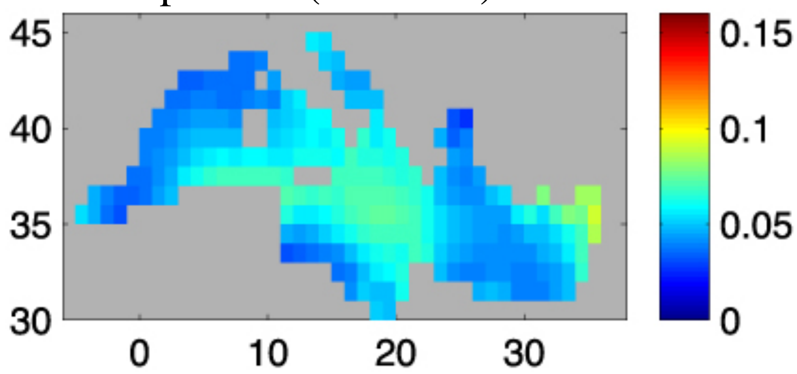

Shortwave flux (W/m$^2$)



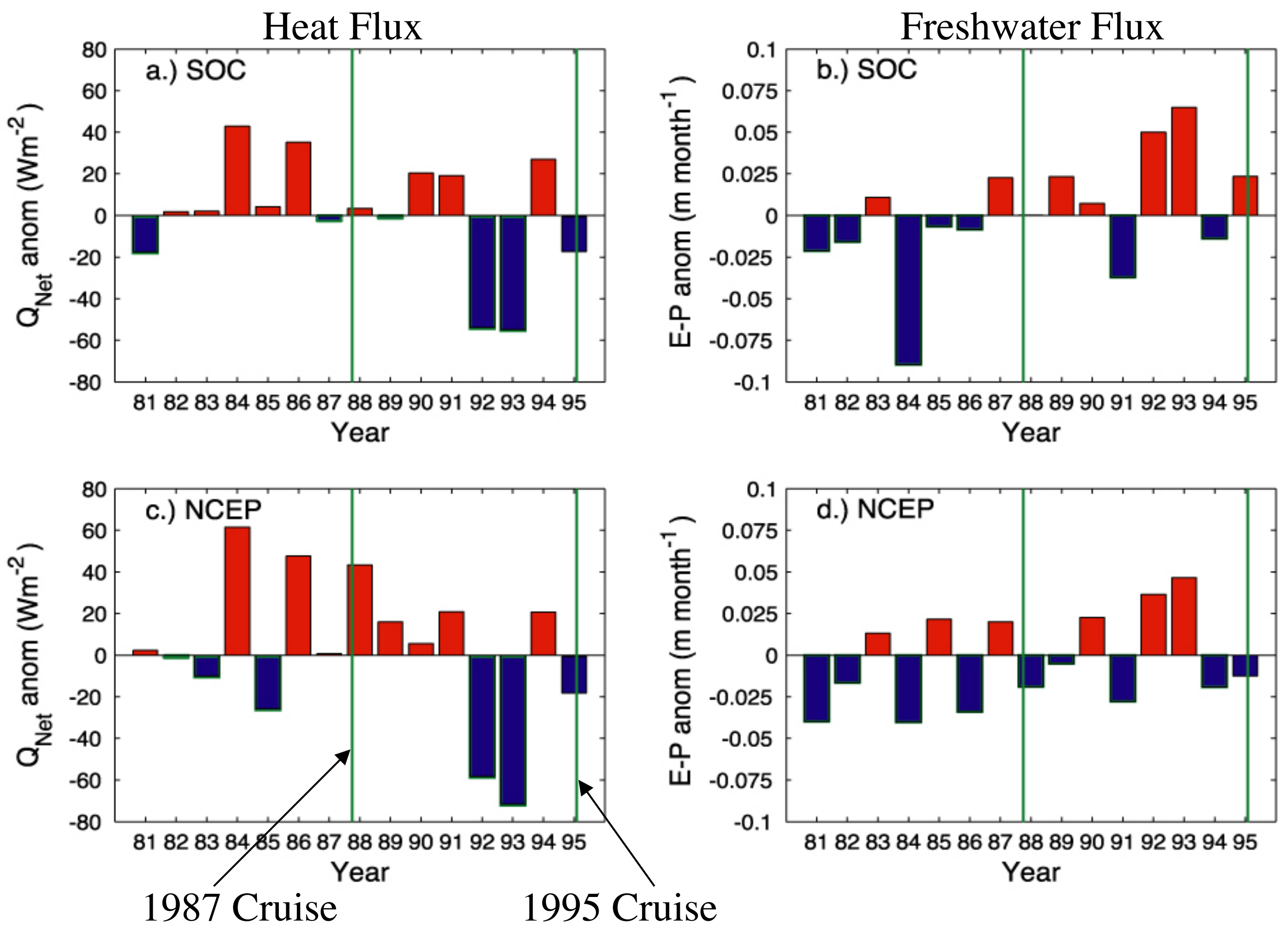

Evaporation (m/month)




Precipitation (m/month)



# Relative Impacts of Heat and Freshwater Flux Anomalies



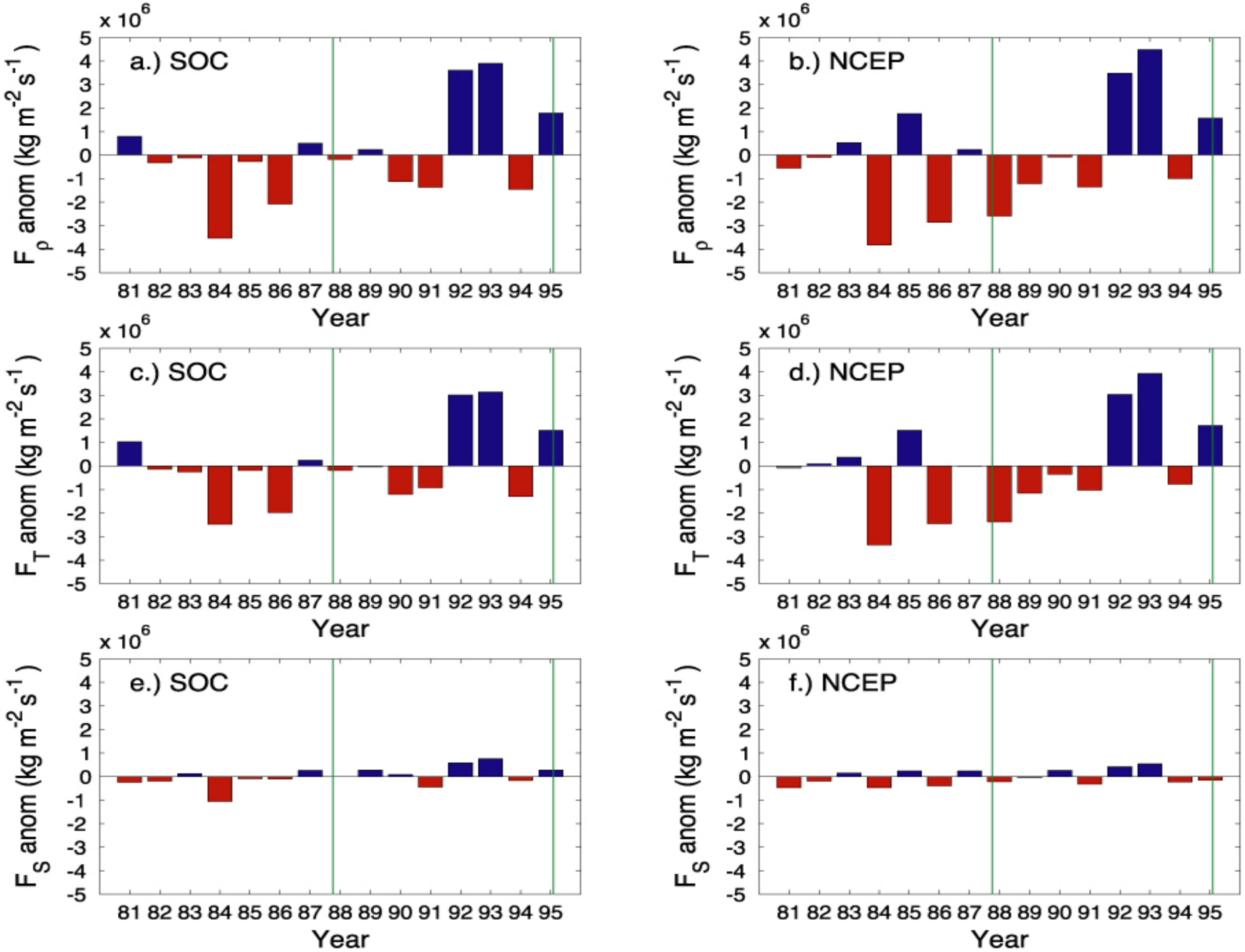

Time series of the anomalous net heat flux and net evaporation (E-P) in the Aegean Sea during winter (Nov-Feb) (Josey, 2003).

# Impact on the Ocean Buoyancy Loss

Total Density Flux

Thermal Density Flux

Haline Density Flux




Time series of the total, thermal and haline density flux anomalies in the Aegean Sea in winter.

# Downscaled Atmospheric Fields

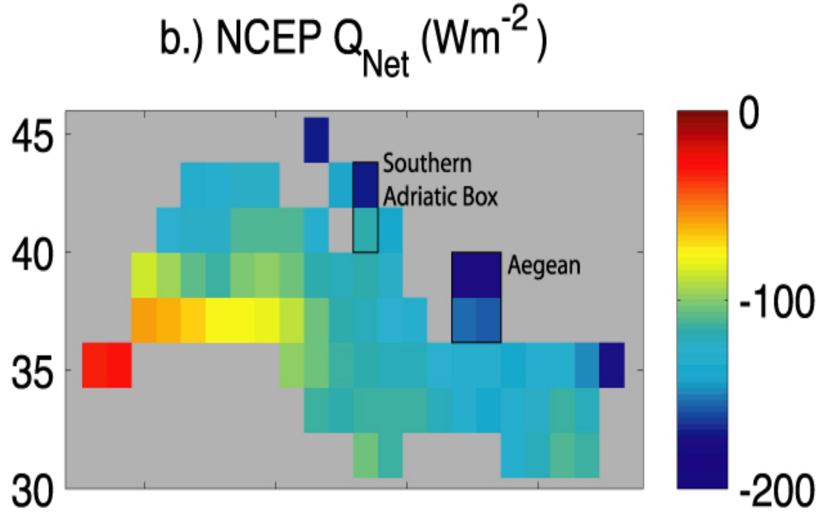
• Surface / atmospheric fields from the NCEP and ECMWF atmospheric model reanalyses have proved useful in a very wide range of studies.

• However…coarse resolution (typically 1.5 - 2 degrees) limits their use for regional / local studies - in particular the Mediterranean.

• Dynamical downscaling potentially allows higher resolution fields to be generated from the reanalyses using regional atmospheric models.

• Regional model forced with coarse reanalysis fields.

•*Spectral nudging* technique allows small scale features to evolve while keeping large scales close to original forcing (von Storch et al., 2000).



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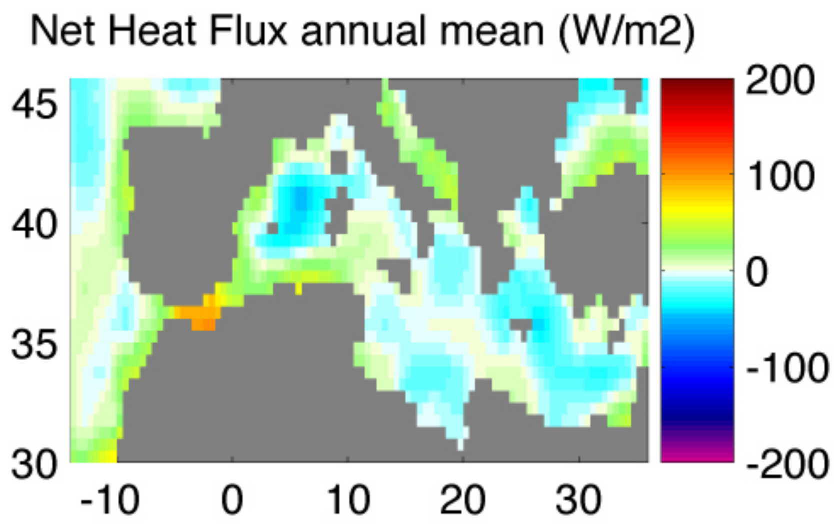


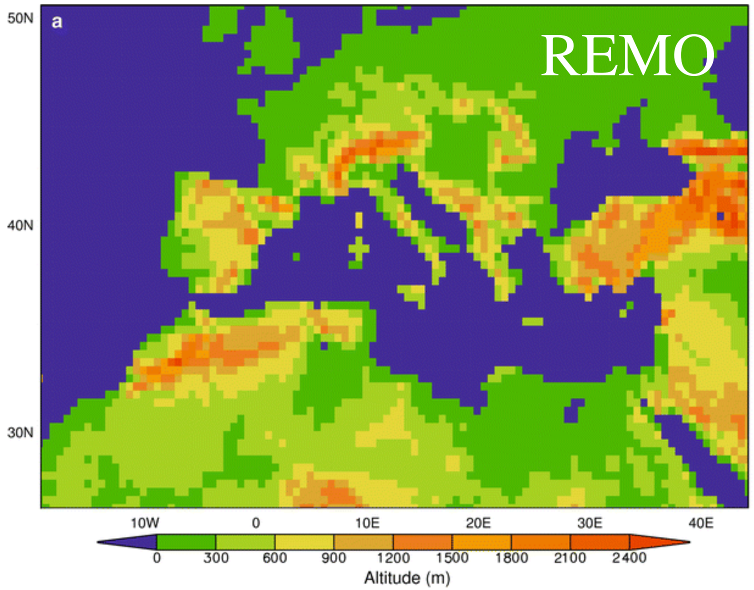
# The HIPOCAS Flux Dataset

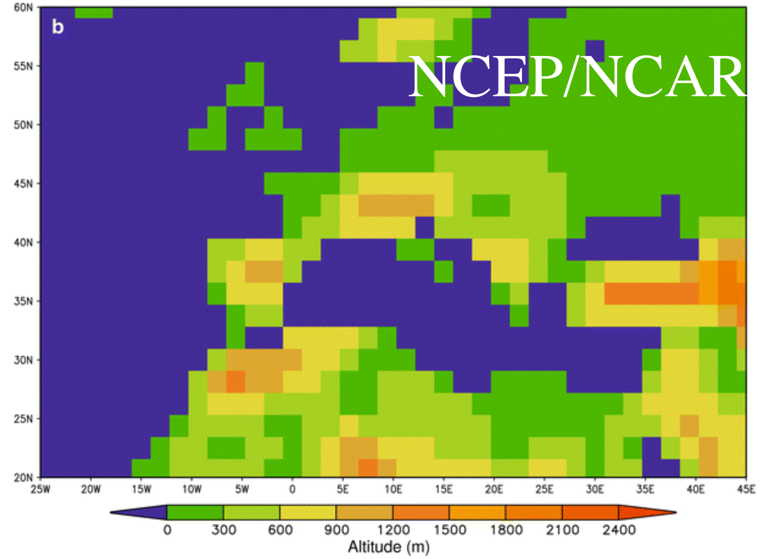
• HIPOCAS Dataset: Sotillo et al. (2005). 0.5 x 0.5 degree atmospheric hindcast for 44 year period (1958- 2001).

• HIPOCAS: Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe.

• Produced by dynamical downscaling of NCEP/NCAR reanalysis using the atmospheric limited area model REMO.

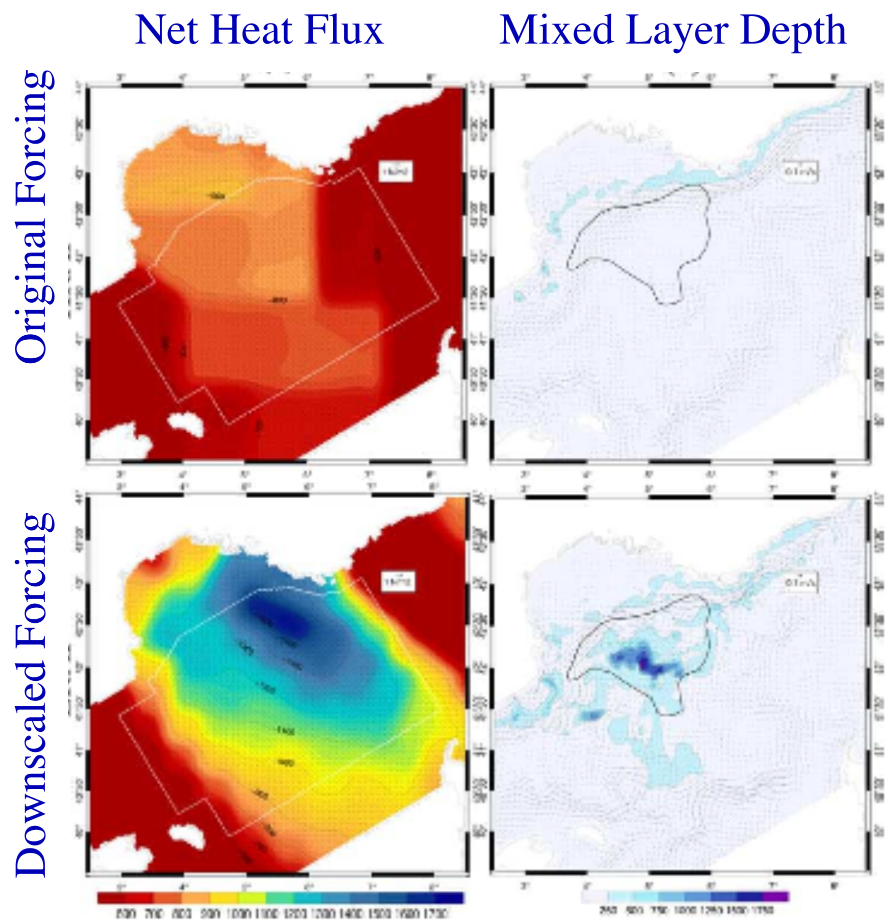
•Thanks to Simón Ruiz for providing model output, Marta Marcos for help with data.



# ARPERA Dataset

- ARPERA Dataset: 50 km resolution atmospheric hindcast for 48 year period (1960- 2007).
- Produced by dynamical downscaling of ERA40 reanalysis using the ARPEGE climate model



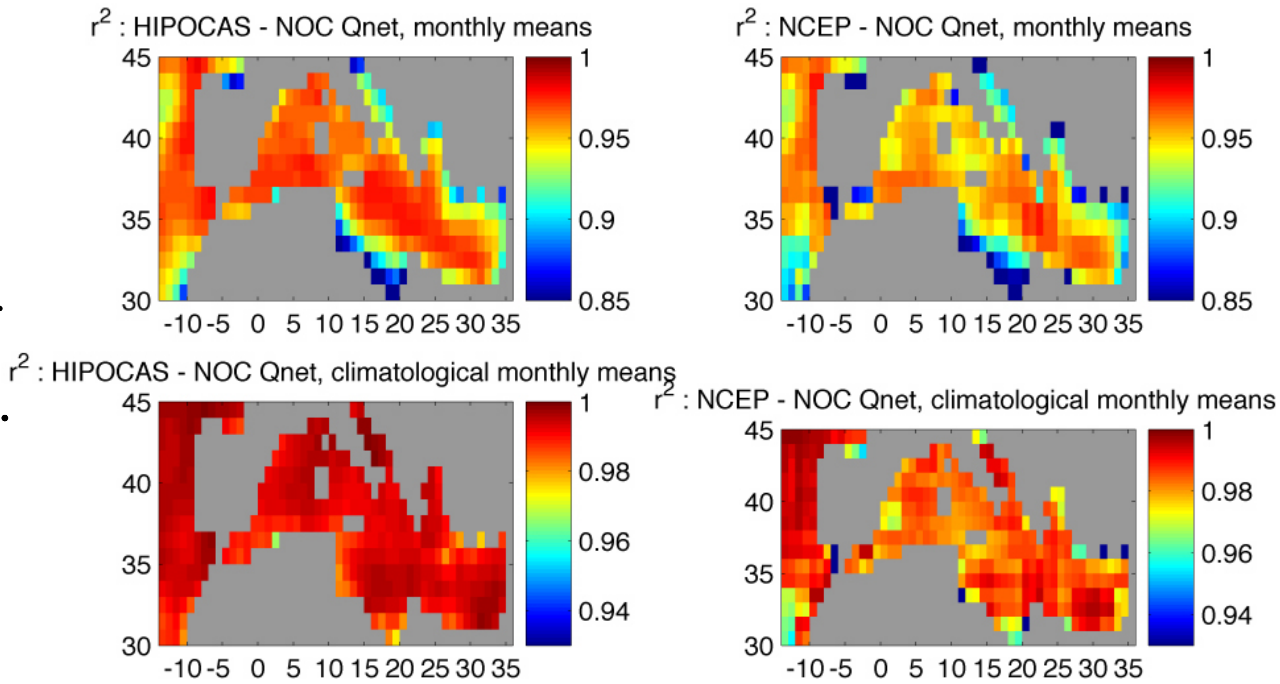

- Used in deep convection modelling study (Hermann and Somot, 2008) and many others subsequently.
- High resolution forcing required to produce deep convection in Gulf of Lions.

# Evaluation of HIPOCAS Fluxes

• HIPOCAS and original NCEP/NCAR net heat fluxes evaluated by correlation analysis with purely observation based NOC dataset.

• Analysis carried out by regridding onto NOC grid. Stronger correlations obtained with HIPOCAS than NCEP/NCAR.

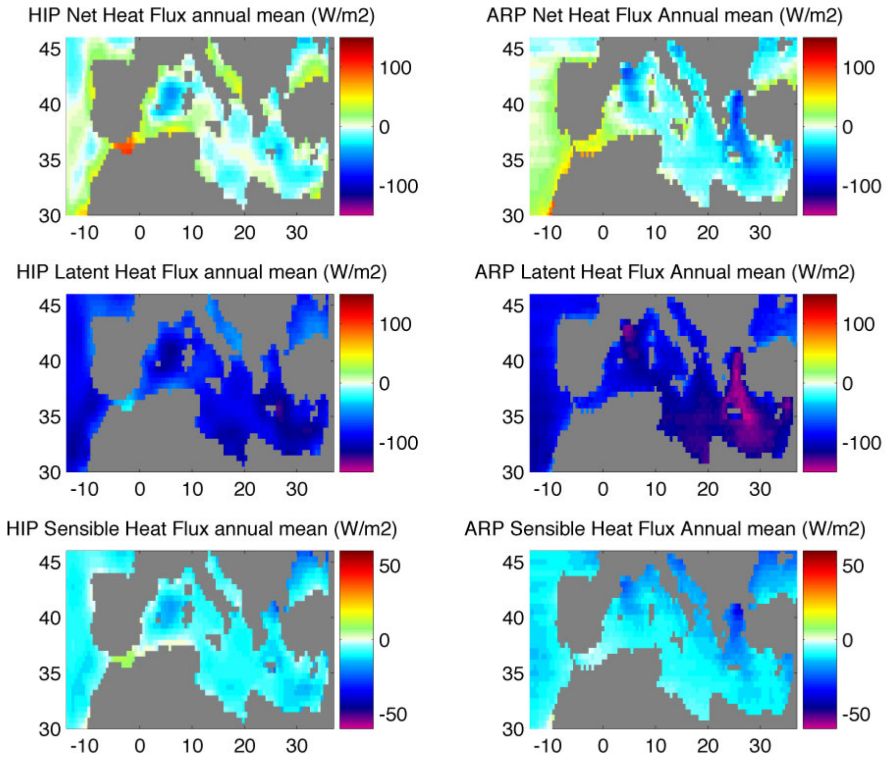
• Suggests downscaling has led to improved representation of air-sea exchange.




From: Ruiz, Gomis, Sotillo and Josey (2008).

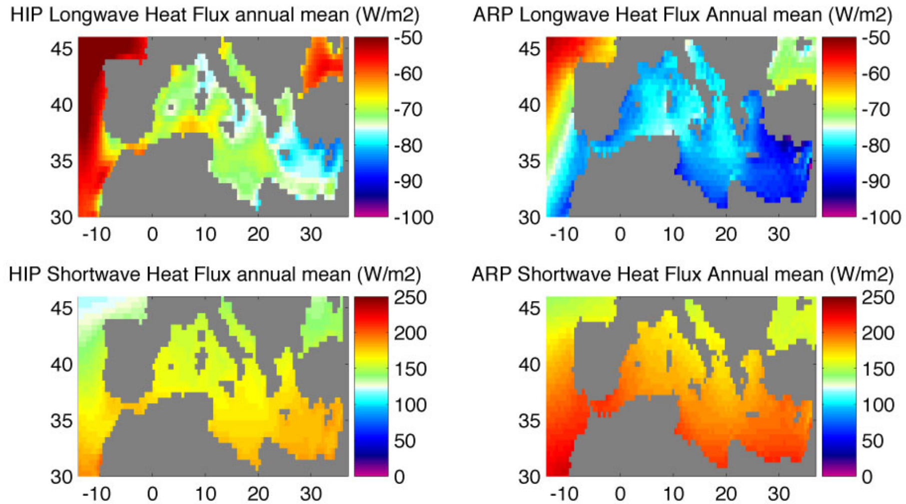
# HIPOCAS / ARPERA Comparison - Means

HIPOCAS ARPERA



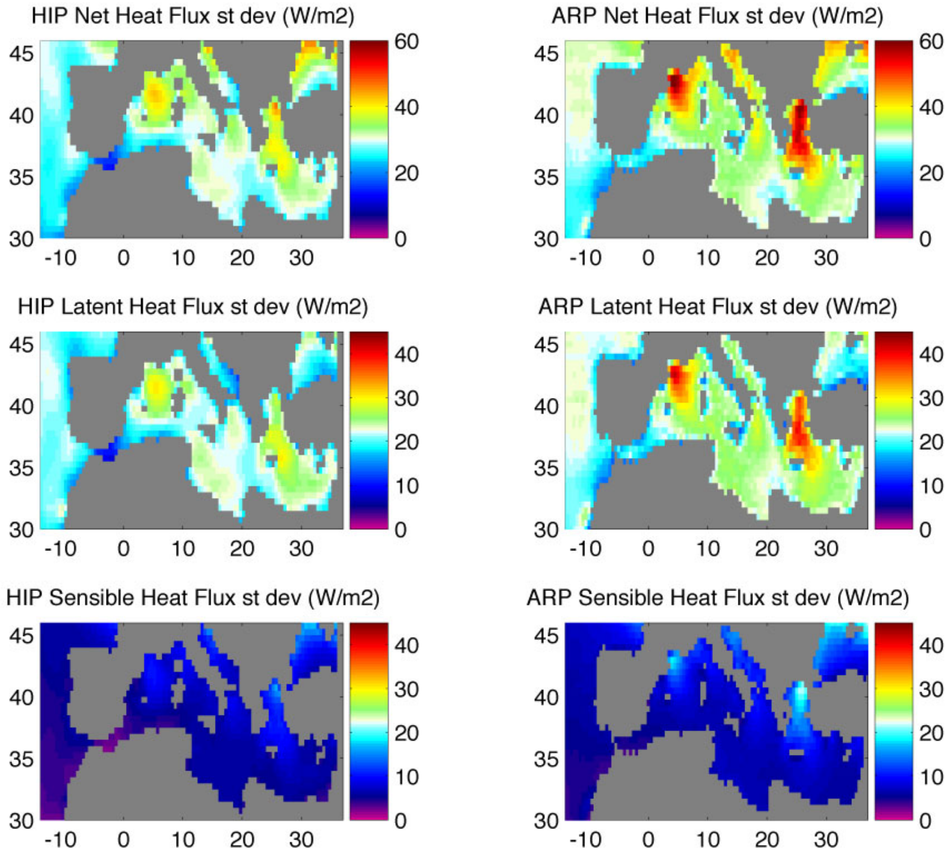

- ARPERA has stronger net heat loss in dense water formation regions.
- Primarily due to latent heat flux term.

HIPOCAS ARPERA



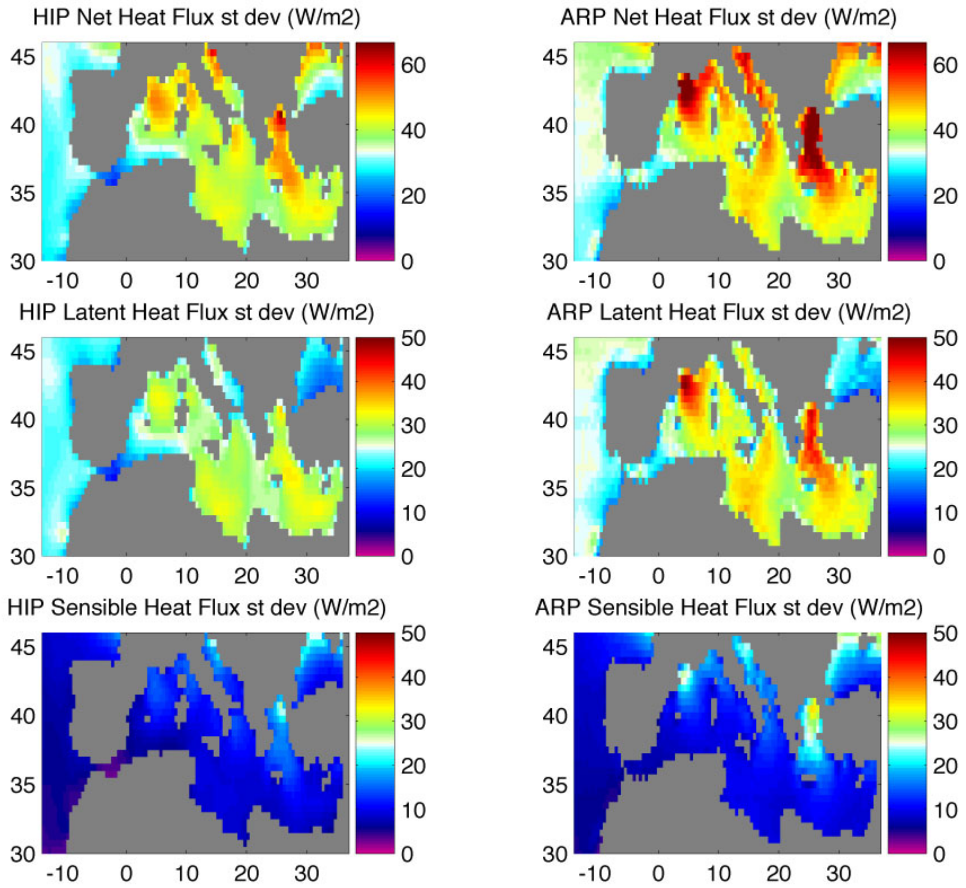

- HIPOCAS has smaller radiative exchange terms.
- Implies less cloud than ARPERA.

# HIPOCAS / ARPERA - Variability (All Months)




- HIPOCAS has stronger net heat flux variability than ARPERA.
- Both datasets reveal localised high variance features.
- Both show stronger variance in the Aegean and Gulf of Lions than the Adriatic.

# HIPOCAS / ARPERA - Variability (DJFM)




- Similar results obtained when winter months considered.
- Greatest variability in the Aegean and Gulf of Lions dense water formation regions.
- Consequences for episodic formation events?

# Mediterranean Sea Heat Budget

• Basin mean net heat flux constrained by heat transport through Gibraltar to be -3 to -7 $Wm^{-2}$ (MacDonald et al., 1994).

• Values obtained with various datasets :

| | Shortwave | Longwave | Latent | Sensible | LW+Latent +Sensible | Net |
|---|---|---|---|---|---|---|
| Modified NOC | 185 | -84 | -89 | -7 | -180 | 5 |
| Satellite (ISCCP +HOAPS) | 187 | -76 | -90 | -14 | -180 | 7 |
| ARPERA | 188 | -83 | -108 | -12 | -203 | -15 |
| ENSEMBLES (RCM), 12 x 25 km models | Min, max 154, 202<br>Mean 181±18 | -70, -100<br>-75±6 | -85, -128<br>-100±13 | -8, -22<br>-13±5 | n/a | 21, -40<br>-7±21 |

• Source: Schroeder et al. (2011, MedCLIVAR Book II Chapter, 4), Sanchez-Gomez et al., (JGR, submitted, 2011).

# 3) Impacts of Extreme Heat Loss on Deep Water Formation

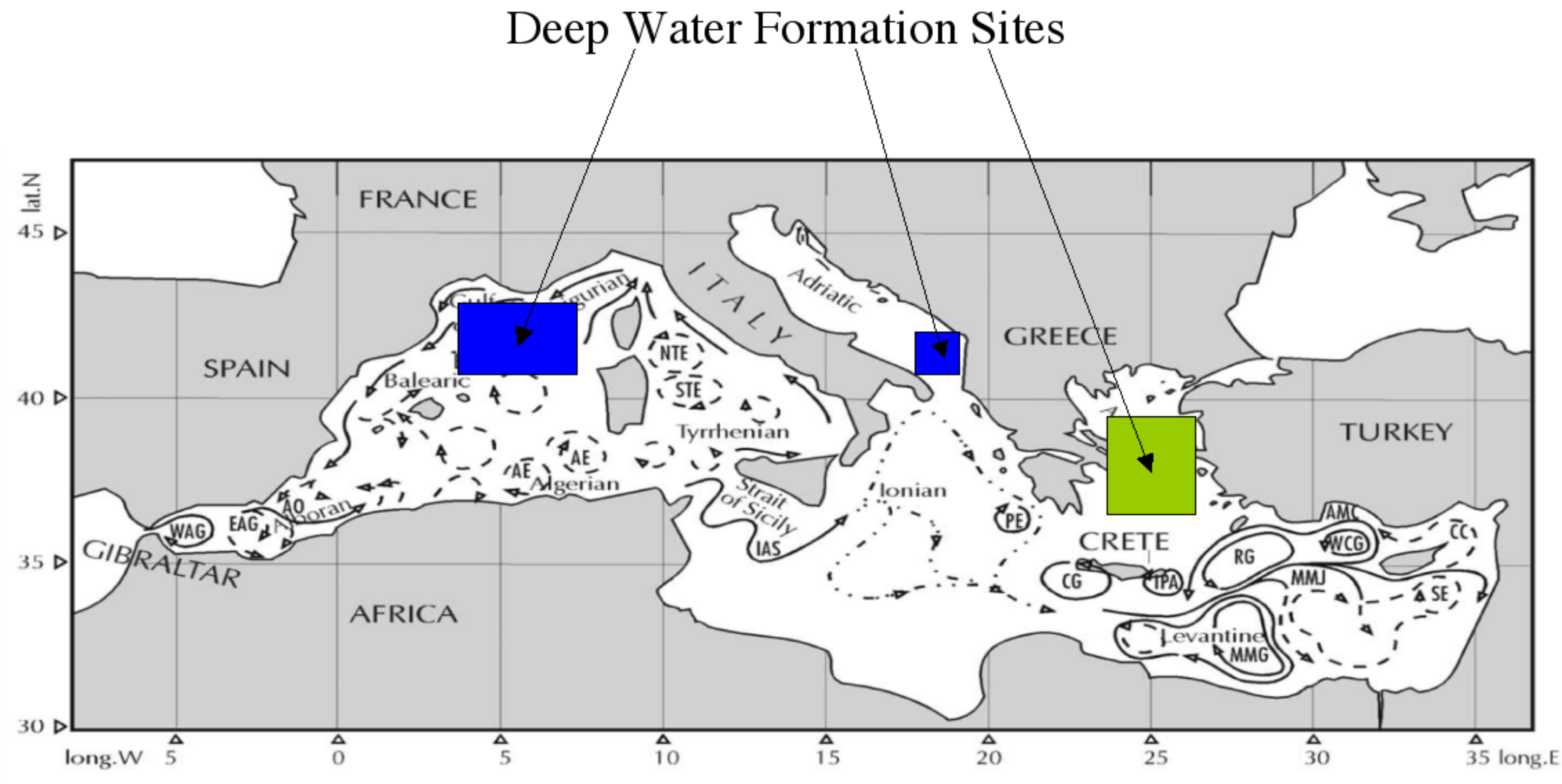
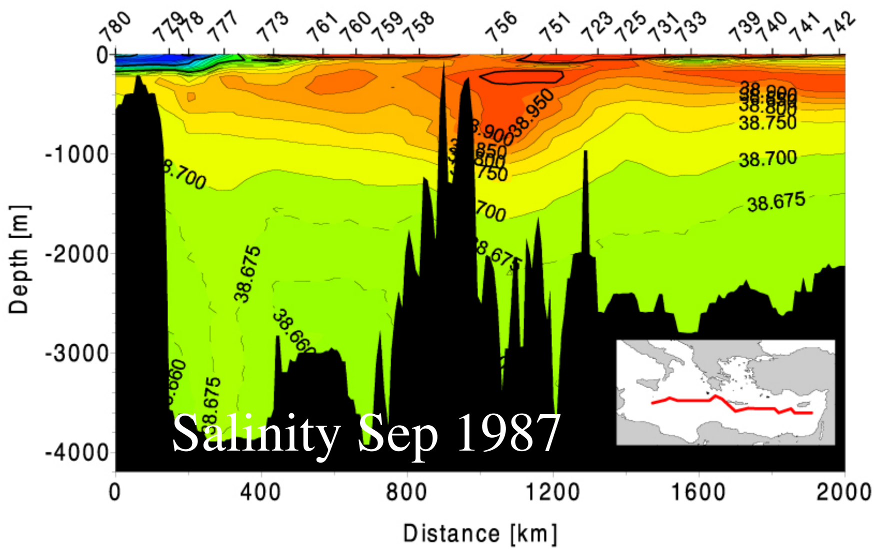


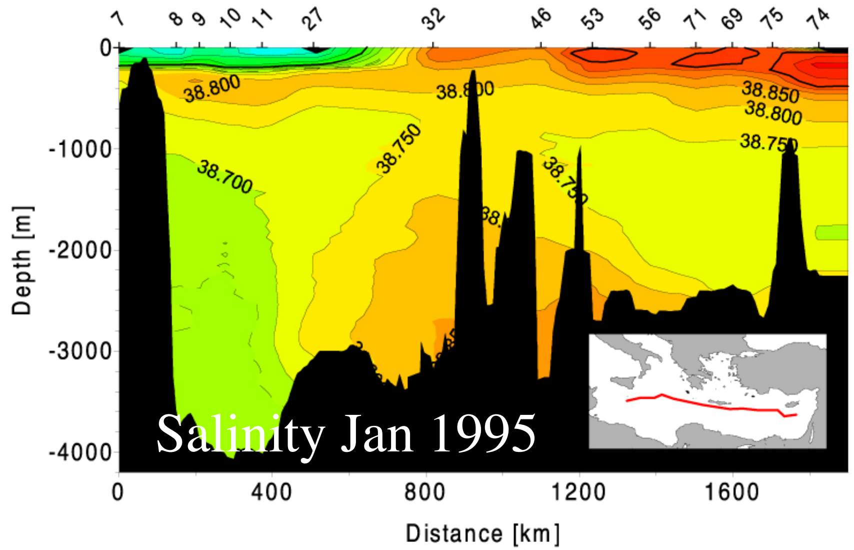

Figure 1. Map of the Mediterranean Sea. A pictorial view of the Mediterranean surface circulation has been superimposed; permanent features are solid lines, and recurrent features are dashed lines (Modified from Millot [1999] and POEM Group [1992]). Acronyms used are as follows: Western Alboran Gyre, WAG; Eastern Alboran Gyre, EAG; Almeria-Oran Front, AO; Balearic Front, BF; Ligurian Proven al Catalan Current, LPCC; North Tyrrhenian Eddy, NTE; South Tyrrhenian Eddy, STE; Ionian Atlantic Stream, IAS; Pelops Eddy, PE; Cretan Gyre, CG; Iera-Petra Anticyclone, IPA; Rhodes Gyre, RG; Asia Minor Current, AMC; Cicilian Current, CC; Western Cyprus Gyre, WCG; Mid-Mediterranean Jet, MMJ; Shikmona Eddy, SE; and Mersa-Matruh Gyre, MMG.

# Deep Water Transient Events

• Possibility that both the Aegean and Gulf of Lions experience irregular major episodes of deep water formation. Rather than more regular formation typical of Adriatic.

## *1) Eastern Mediterranean Transient (EMT)*




• Sharp increase in salinity Eastern Med deep (Roether et al., 1996). Deep water formation shifted from Southern Adriatic to Aegean Sea.

# What Caused the Transient?

Various possible causes suggested:

1) Change in wind-driven circulation (Samuels et al., 1999).

2) Increase in salinity due to multi-decadal reduction in river runoff (Boscolo and Bryden, 2001), reduced Black Sea outflow (Zervakis et al., 2000).

3) Extreme heat loss during severe winters of early 1990s.

4) Reduced precip. during 1989-93 (Theocharis et al. ,1999).

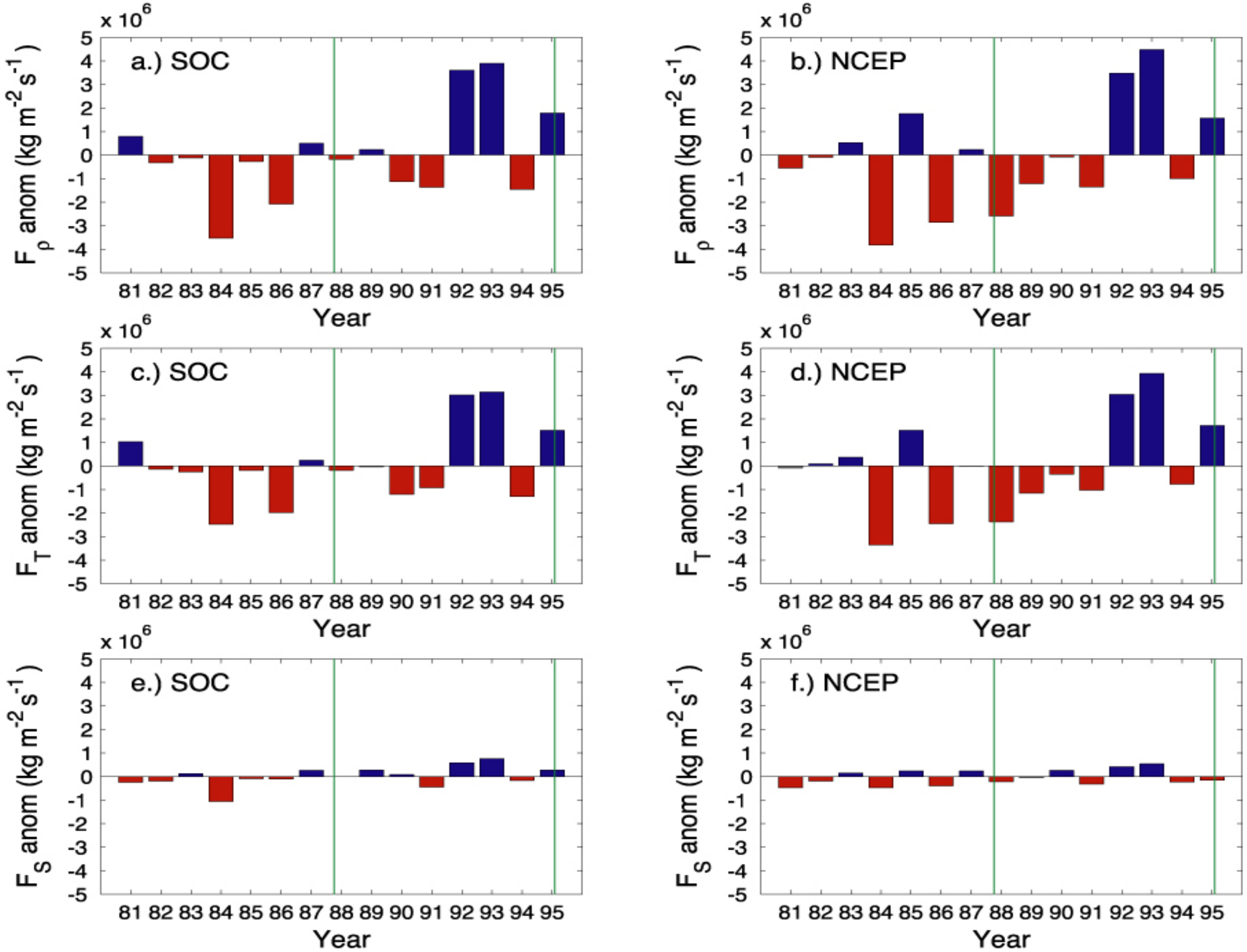
Relative contributions of 3) and 4) resolved using NOC (previously SOC) and NCEP/NCAR datasets (Josey, 2003, JGR-Oceans)

# EMT Related Ocean Buoyancy Loss

Total Density Flux

Thermal Density Flux

Haline Density Flux




Thermal term dominates with very strong anomalies in winters 1991-92 and 1992-93 (Josey, 2003).

# New Results – Beuvier et al. (2010)

- Beuvier et al. (JGR, 2010) use an eddy permitting ocean GCM (NEMOMed8, 1/8 deg) with high resolution atmospheric forcing (ARPERA) to simulate Med over 1961-2000 and examine range of possible factors contributing to EMT.

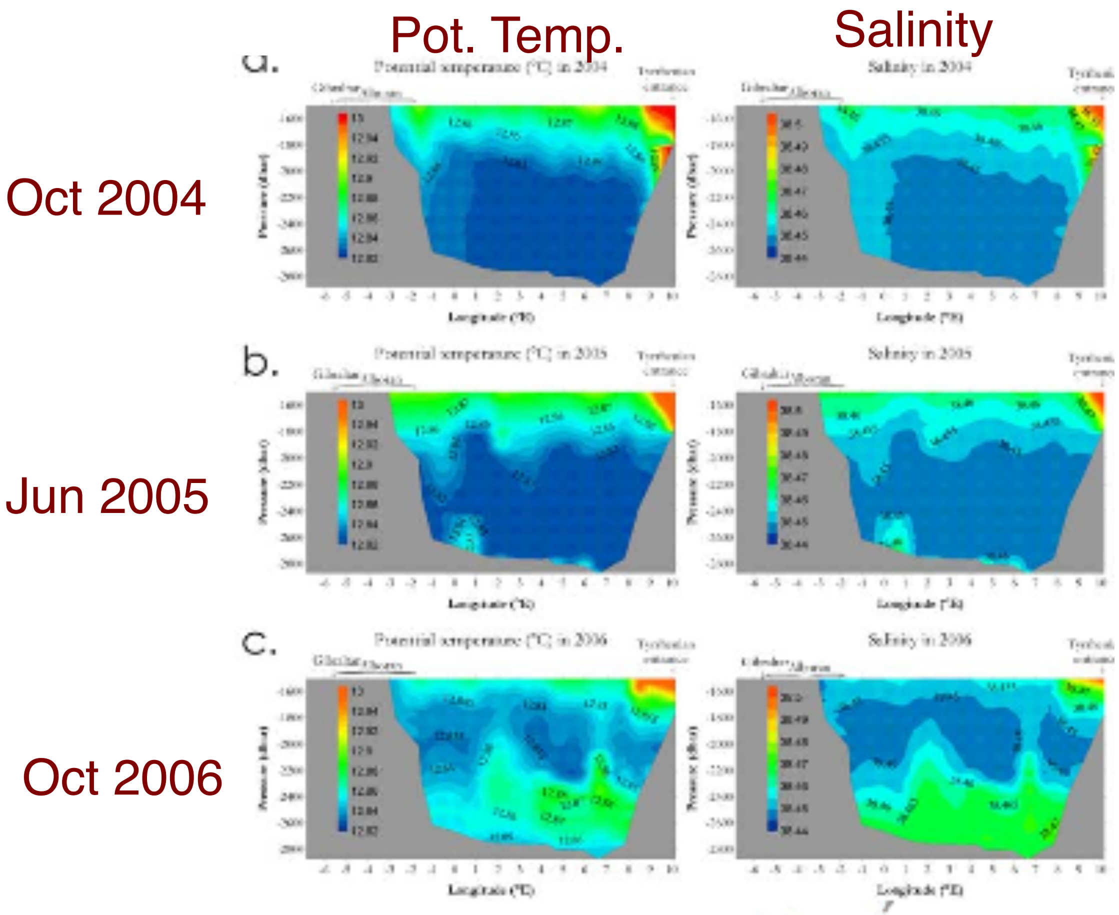
- Main conclusion: The major triggering elements for the EMT are the atmospheric fluxes and winds occurring in winters 1991-92 and 1992-93.

# Deep Water Transient Events

## *2) Western Mediterranean Transient (WMT)*

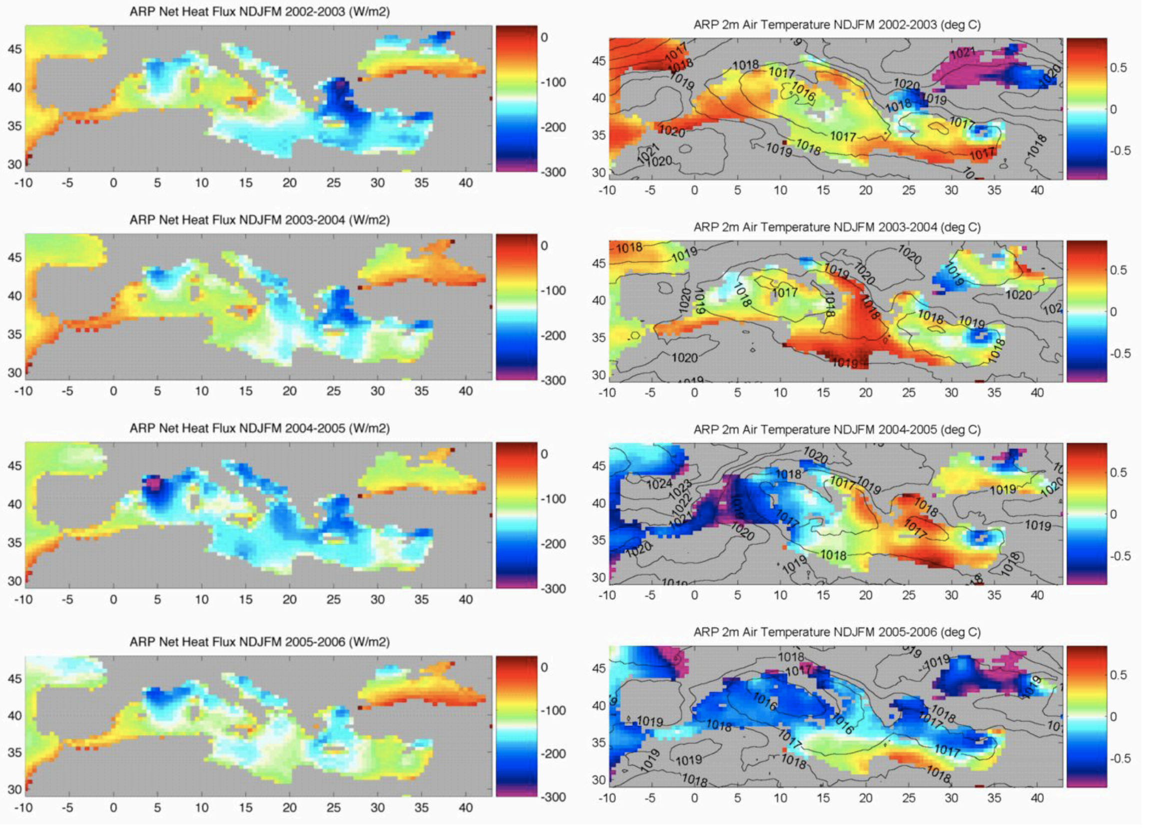
• Schroeder et al. (2008) evidence for a major deep water formation event in Western Med during winters 2004-2005 , 2005-2006.

• Potential temperature and salinity sections in Western Med over depth range 1500-2800 m.



# Causes of the WMT

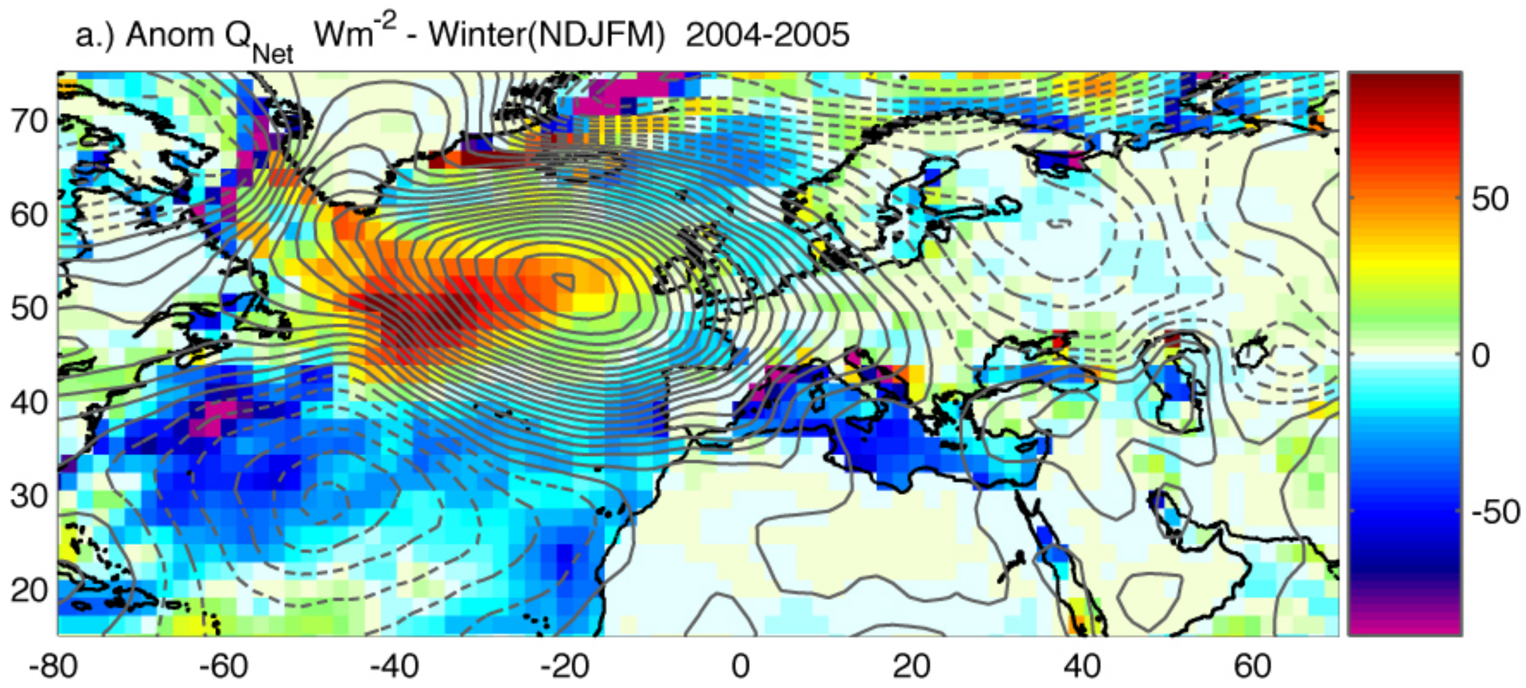
Schroeder, Josey, Herrmann, Grignon, Gasparini and Bryden (2010) investigate relative contributions of surface forcing and lateral advection to event – found to be of about equal importance.




• Extreme heat loss (300 Wm-2) in winter 2004-05. Associated with extremely cold, northerly air flow.

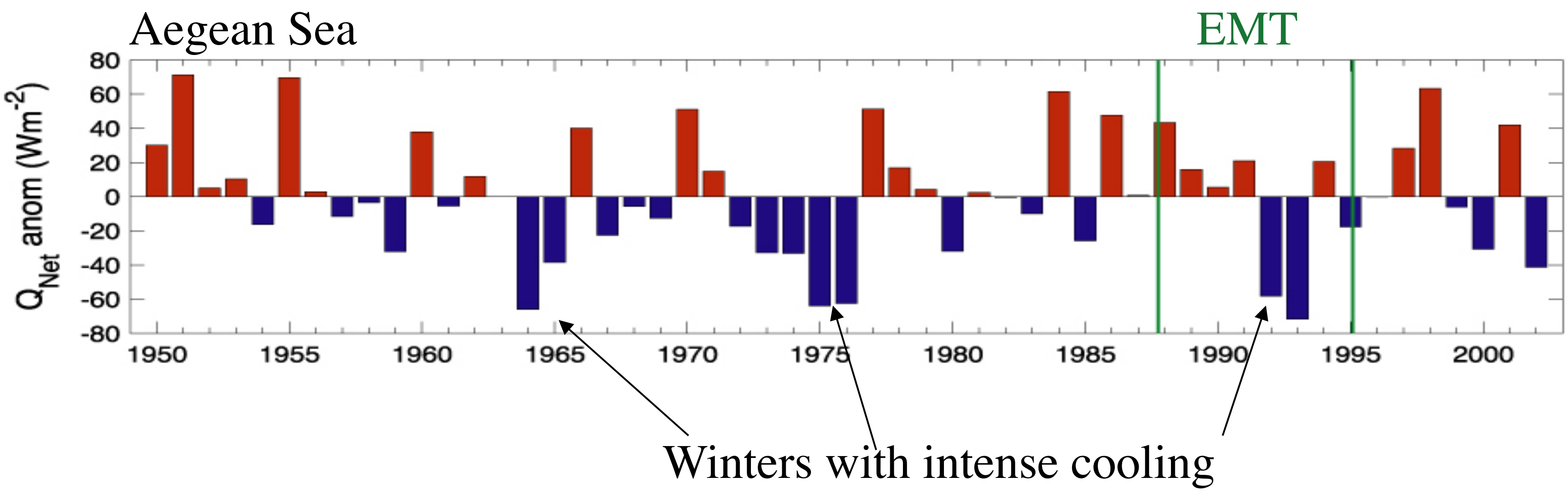
# Causes of the WMT

Schroeder, Josey, Herrmann, Grignon, Gasparini and Bryden (2010) investigate relative contributions of surface forcing and lateral advection to event – found to be of about equal importance.




- Winter 2004-05 heat loss linked to the East Atlantic pattern mode of atmospheric variability.

# The Long Term Context




Winter heat flux anomalies from NCEP/NCAR for 1950-2002 , Josey (2003)

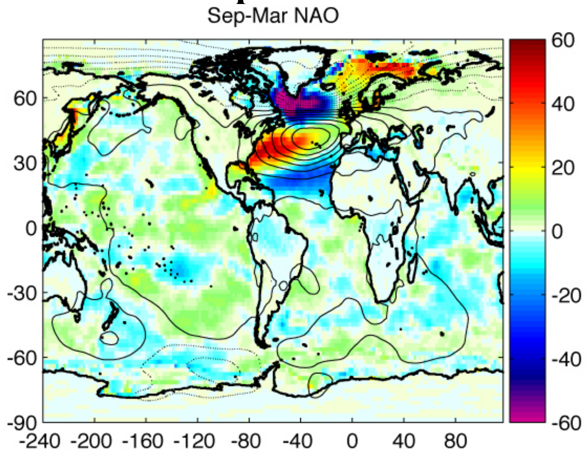
Were there previous episodes of Aegean sea deep water formation in the past 50 years?

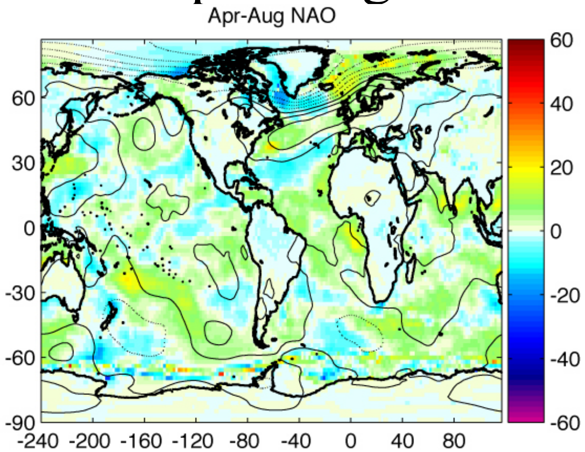
# *4) Impacts of Atmospheric Modes*

- Composites of NCEP/NCAR net heat flux anomalies (colours, $Wm^{-2}$, SLP contoured) on two major modes the NAO and EA pattern.

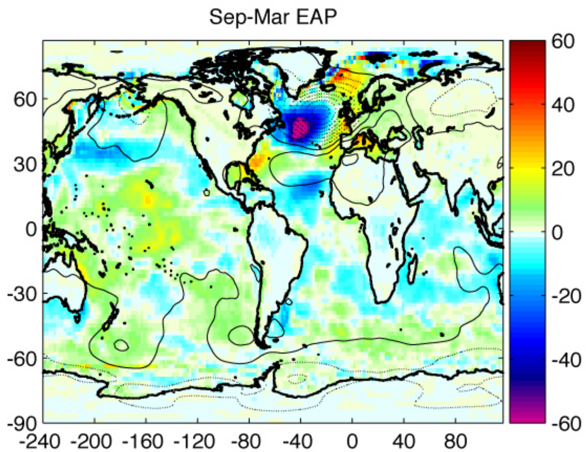
Sep - Mar | Apr - Aug

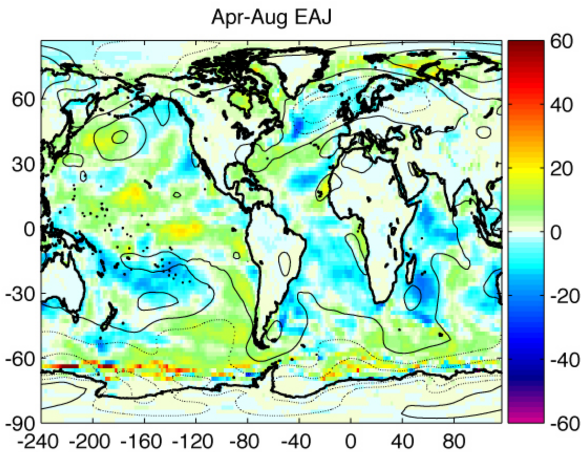
- Mode 1: North Atlantic Oscillation (NAO)




- Mode 2: East Atlantic ( EA) Pattern



# Leading Modes of Atmospheric Variability

• Northern Hemisphere teleconnection patterns have been determined in various studies.

• Patterns from the NOAA Climate Prediction Centre (CPC) analysis used here.

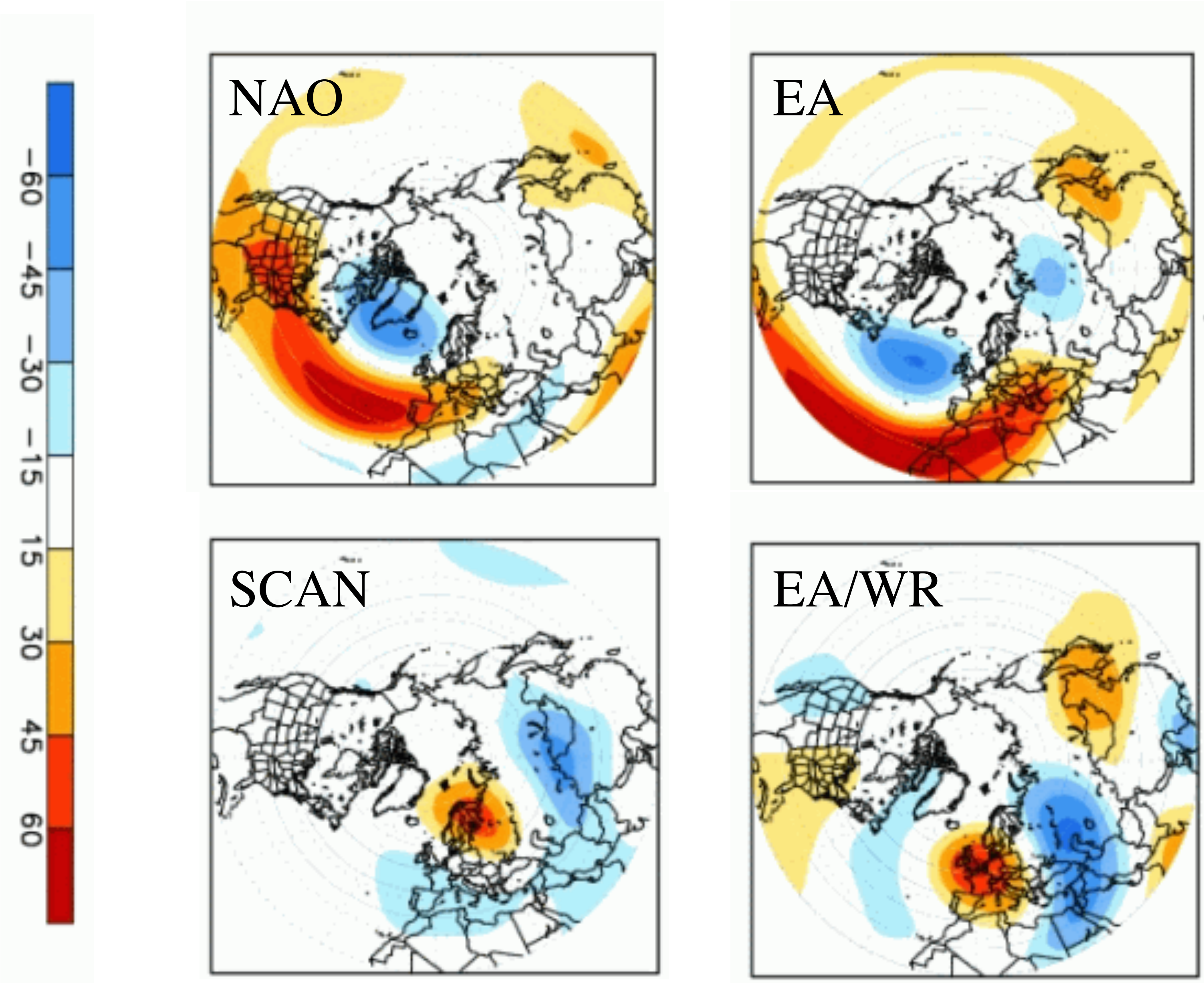
• Makes use of Rotated Principal Component Analysis --RPCA (Barnston and Livezey 1987) to isolate the primary teleconnection patterns.

• Applied to observed monthly mean 500-mb height anomaly fields in the region 20°N-90°N between January 1950 and December 2000.

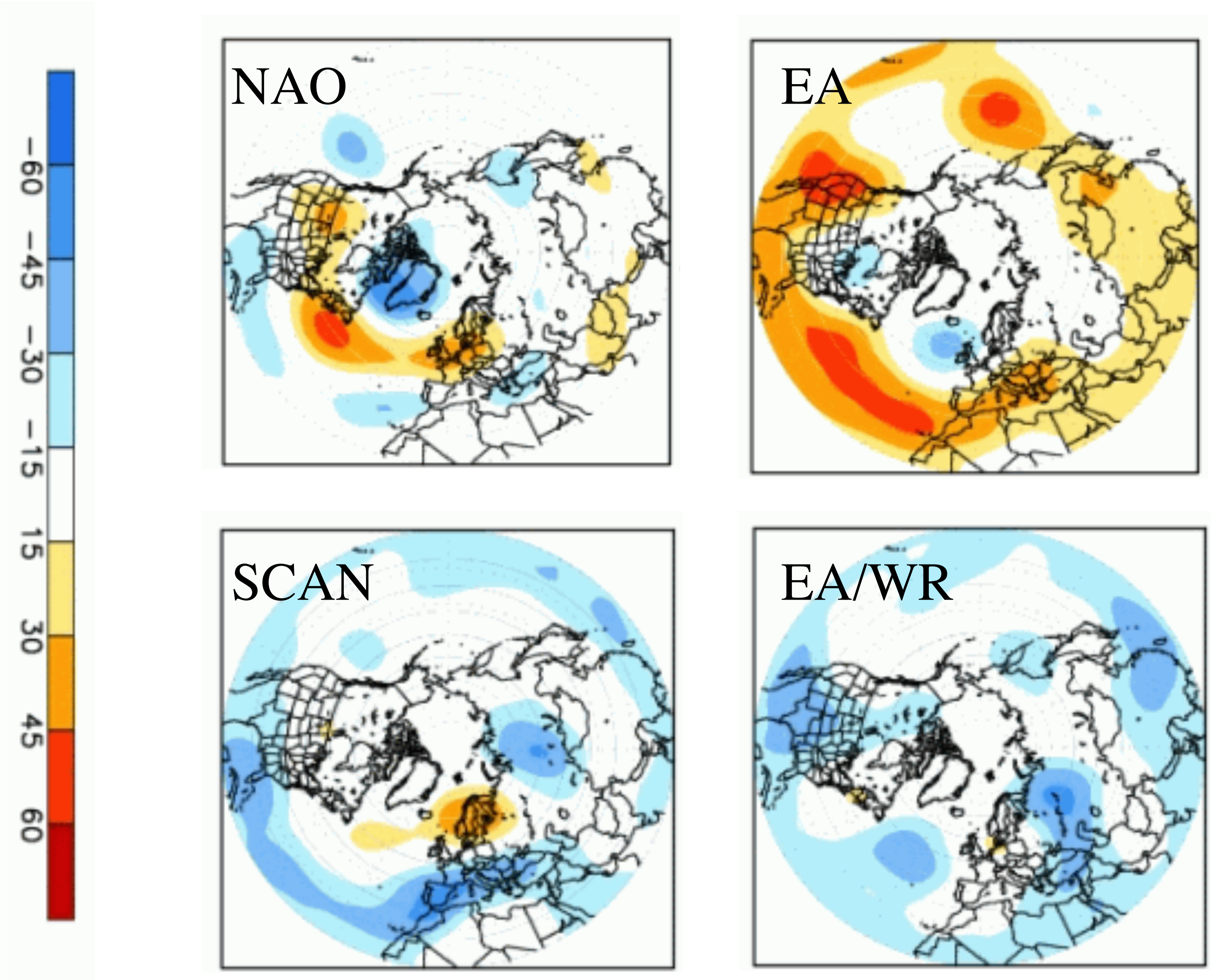
• Four modes with a strong signal over the Mediterranean region.

• Impacts on Mediterranean heat budgets (total, and E/W sub-basins) studied by Josey, Somot and Tsimplis (2011).

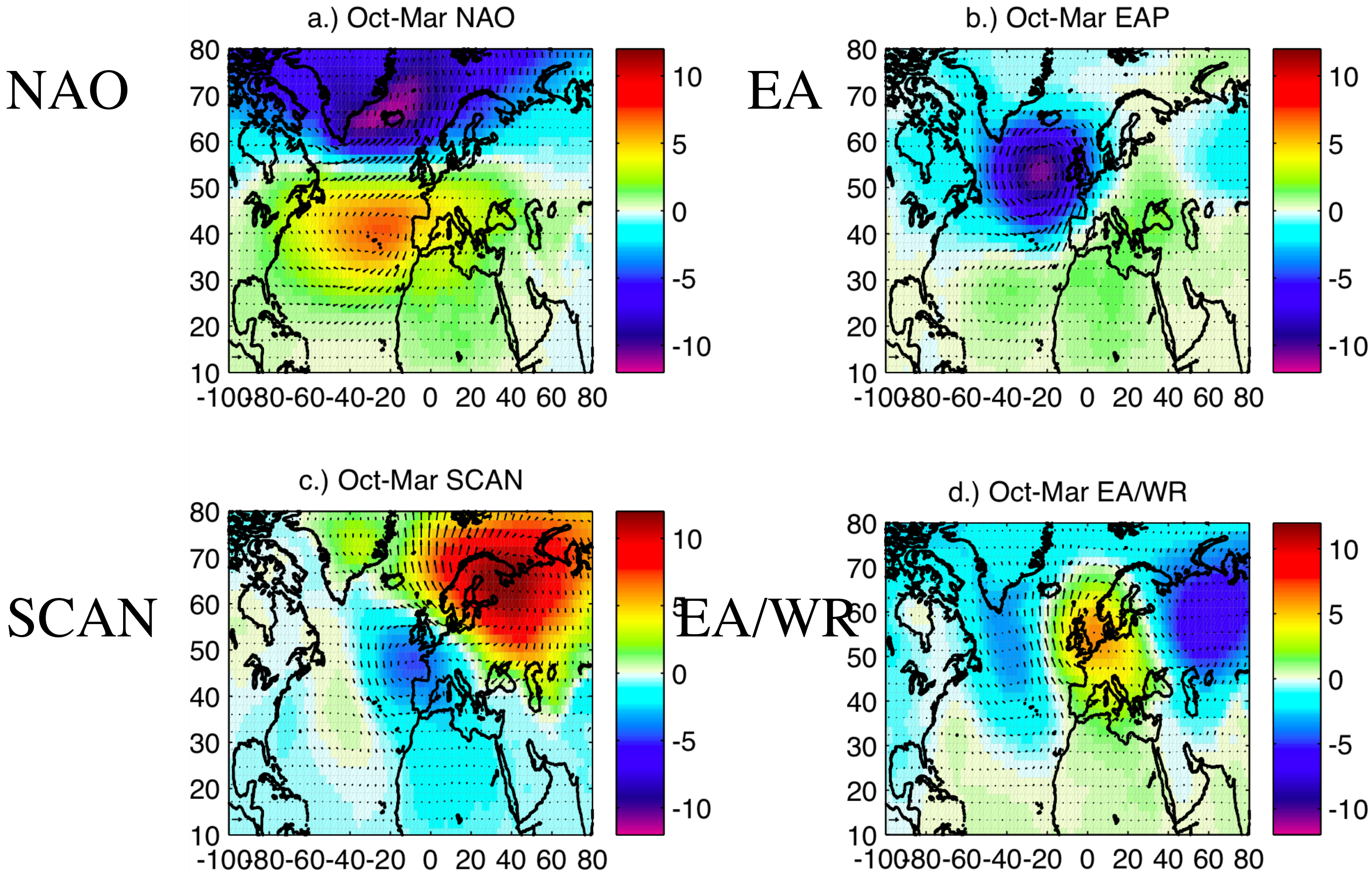
# CPC Modes 1 - 4 January



# CPC Modes 1 - 4 July

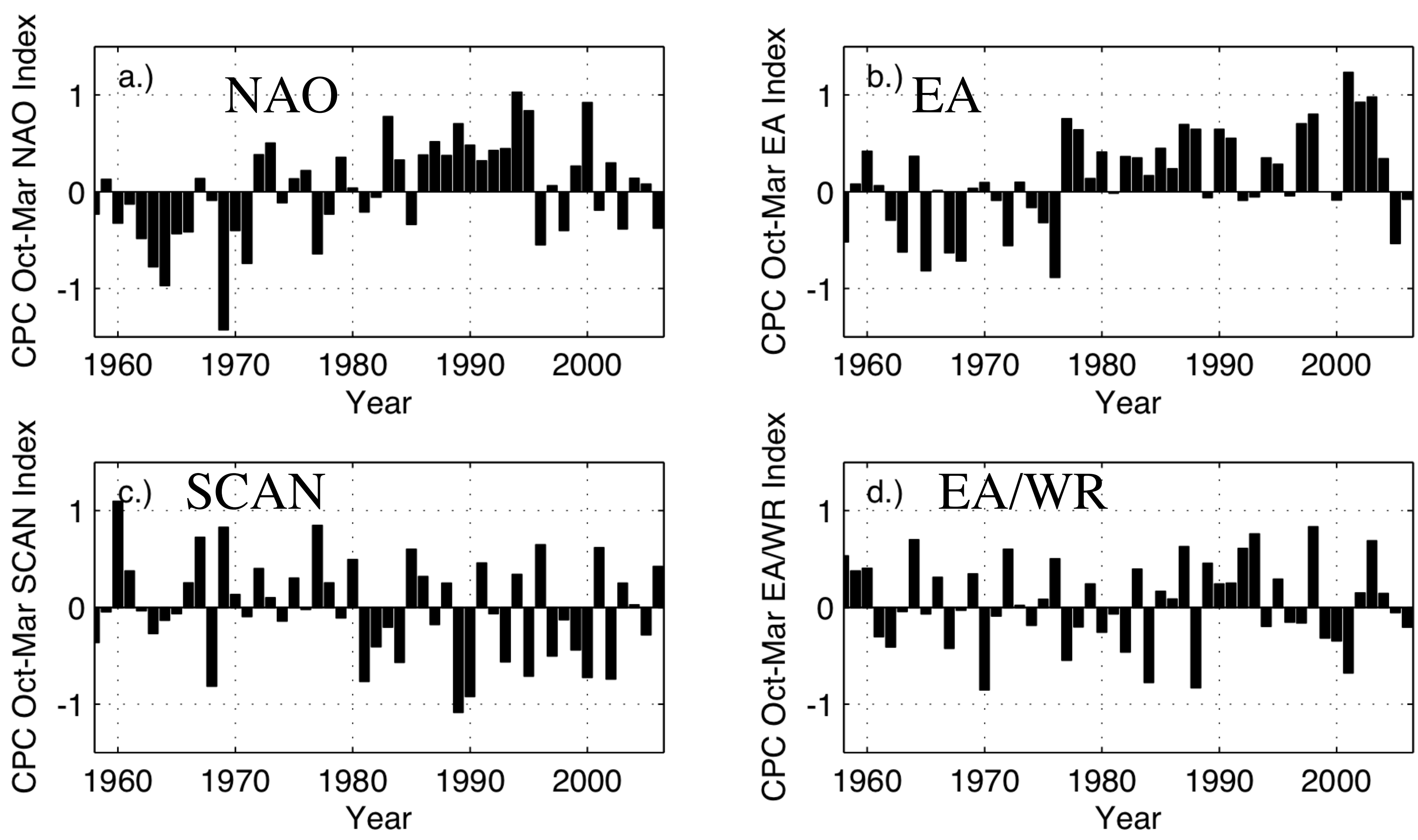


# SLP / Wind  Anomalies for Winter Modes



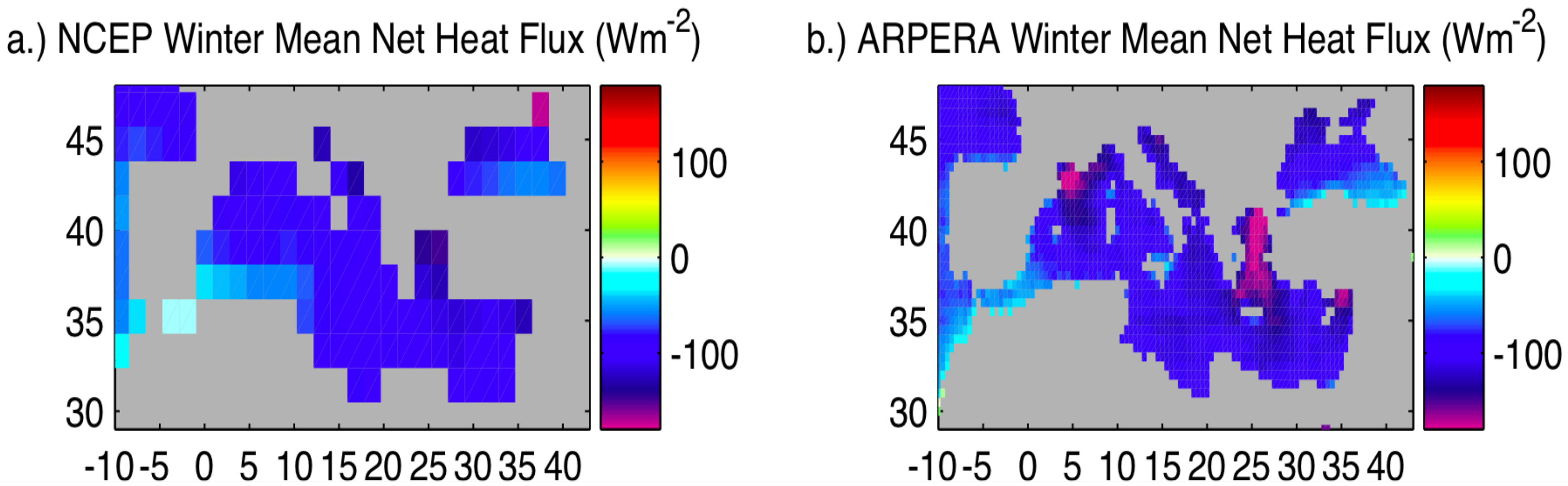

SLP (coloured fields, mb) and wind speed anomalies  (vectors), and following slides, from Josey, Somot  and Tsimplis (2011)

# Time Dependence of Each Mode



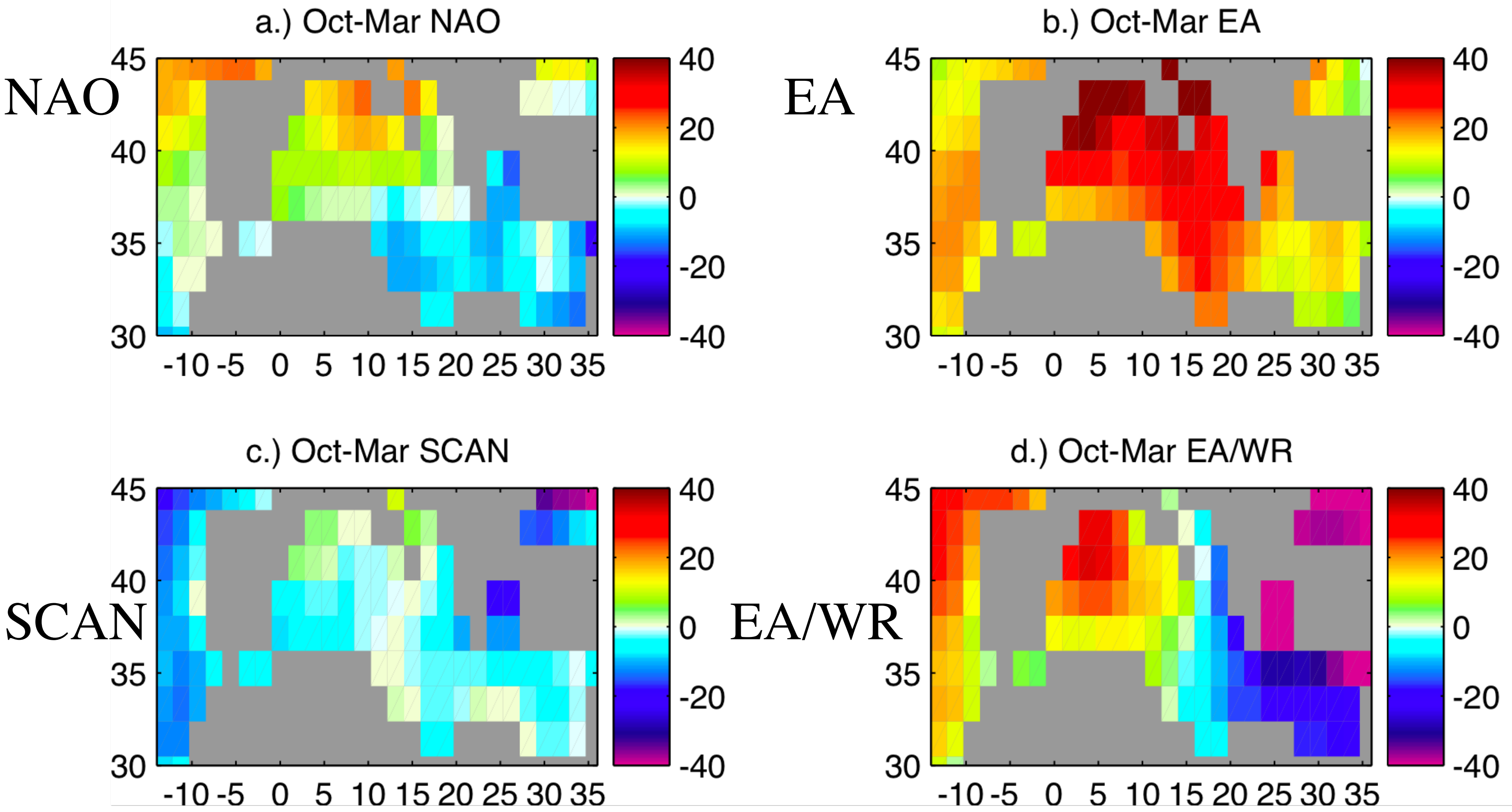

Sep - Mar

# Winter Mean Net Heat Flux



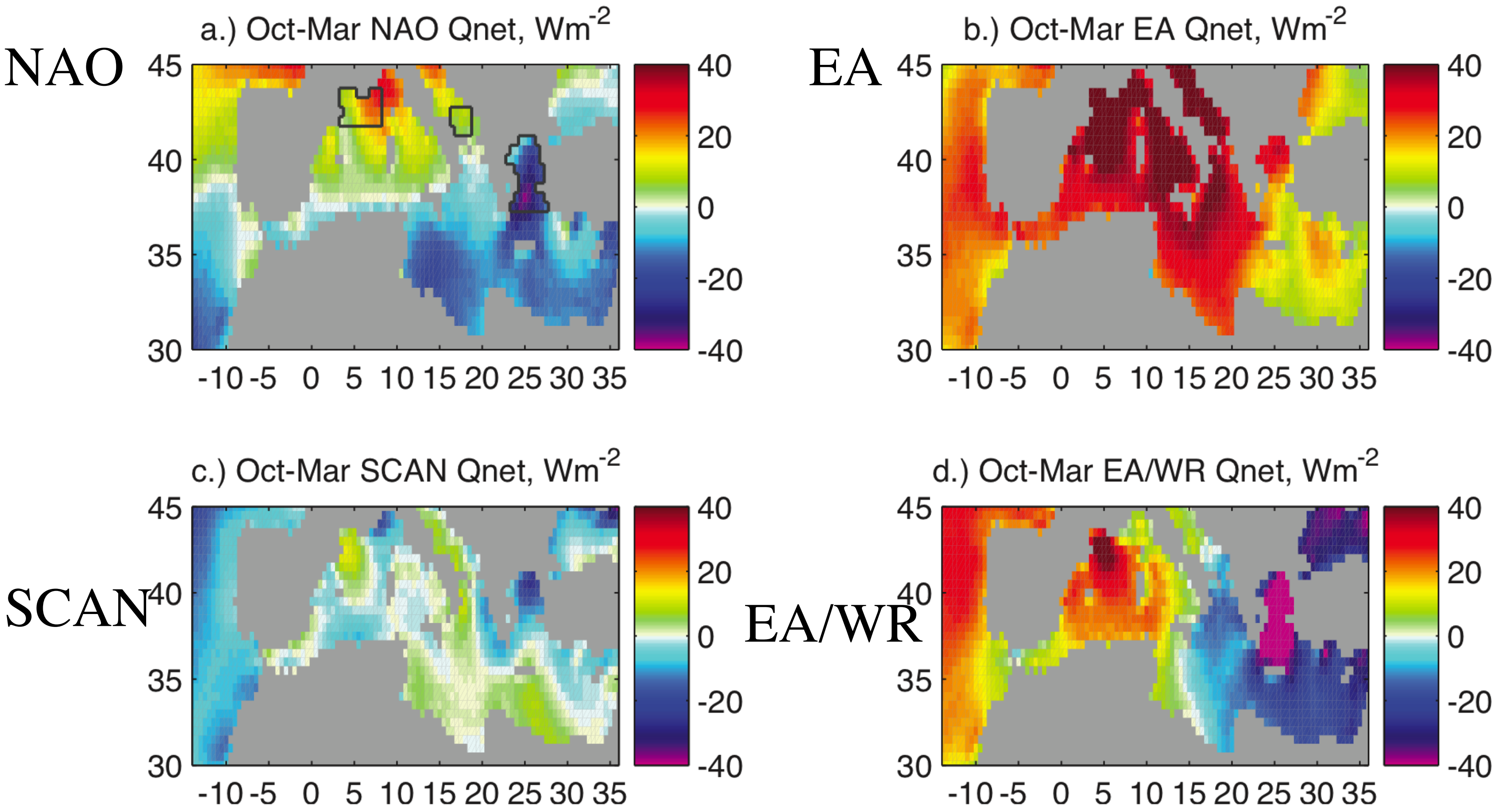

Winter centered (Oct-Mar) mean net heat flux for 1950-2007 from NCEP/NCAR and ARPERA

# Impacts of the Four Main Modes - NCEP



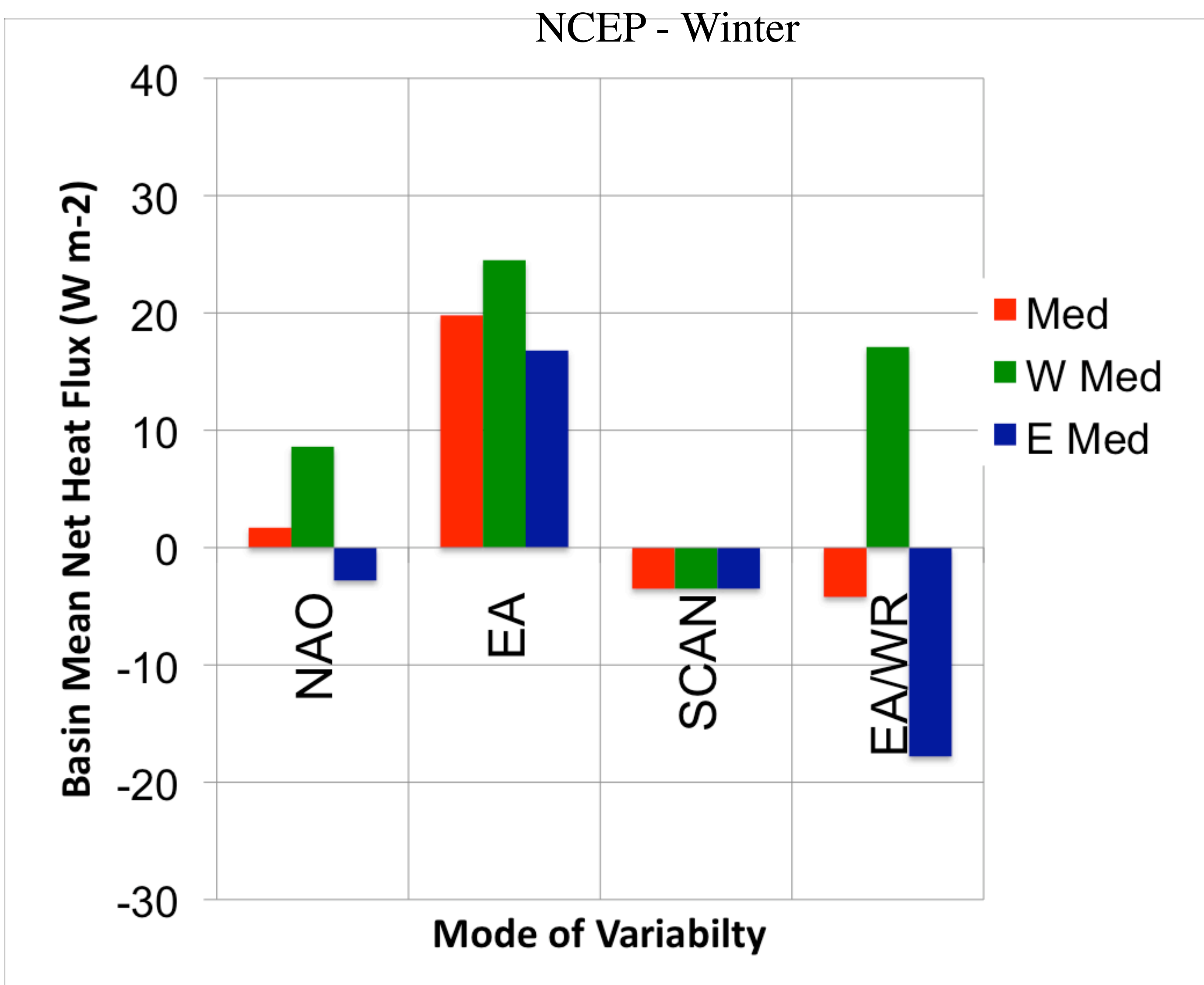

Net heat flux anomaly for a unit positive value of each mode index.

# Impacts of the Four Main Modes - ARPERA



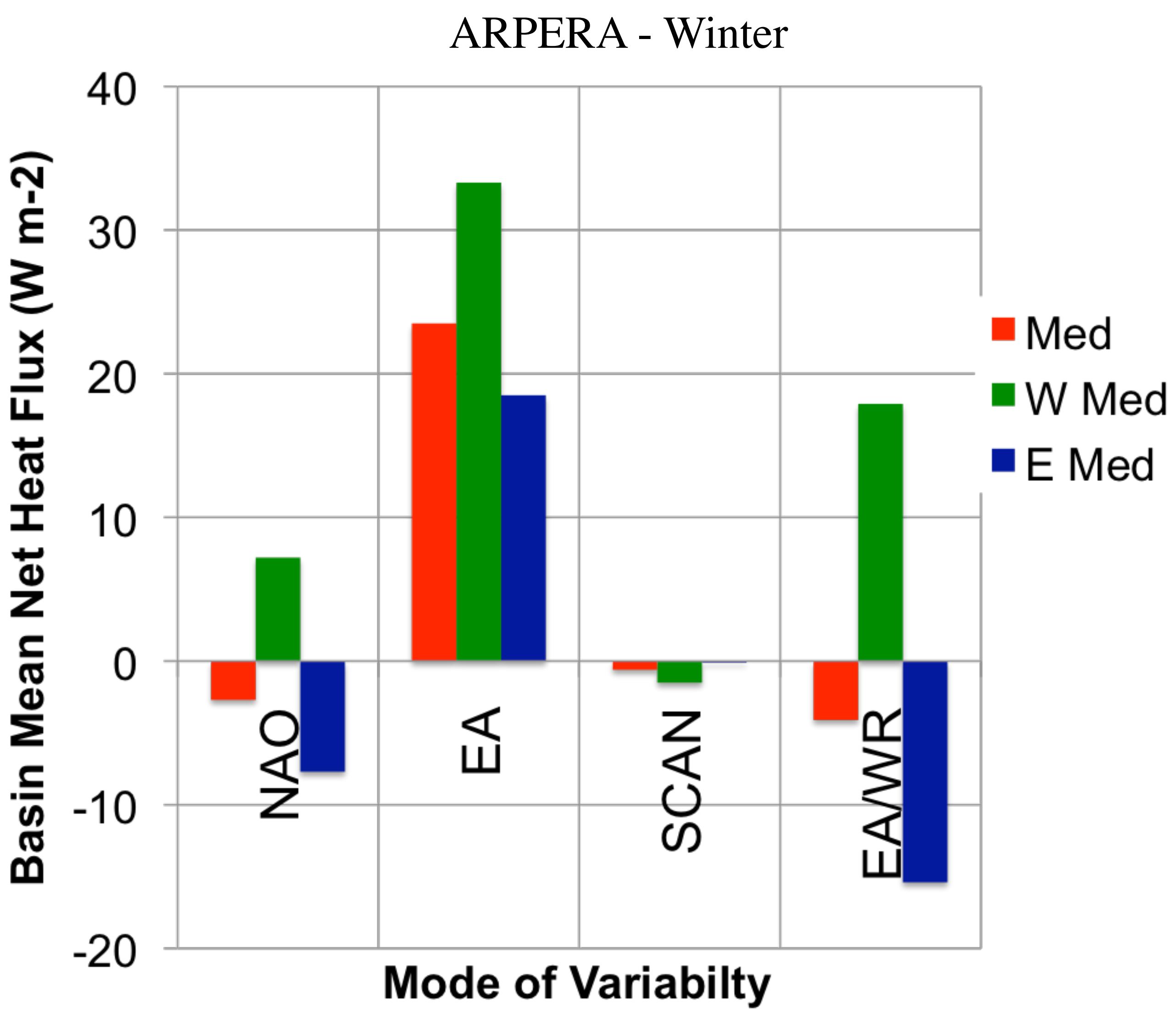

Net heat flux anomaly for a unit positive value of the mode index.
Numbers show full, W and E basin means.

# Comparison of Mode Impacts



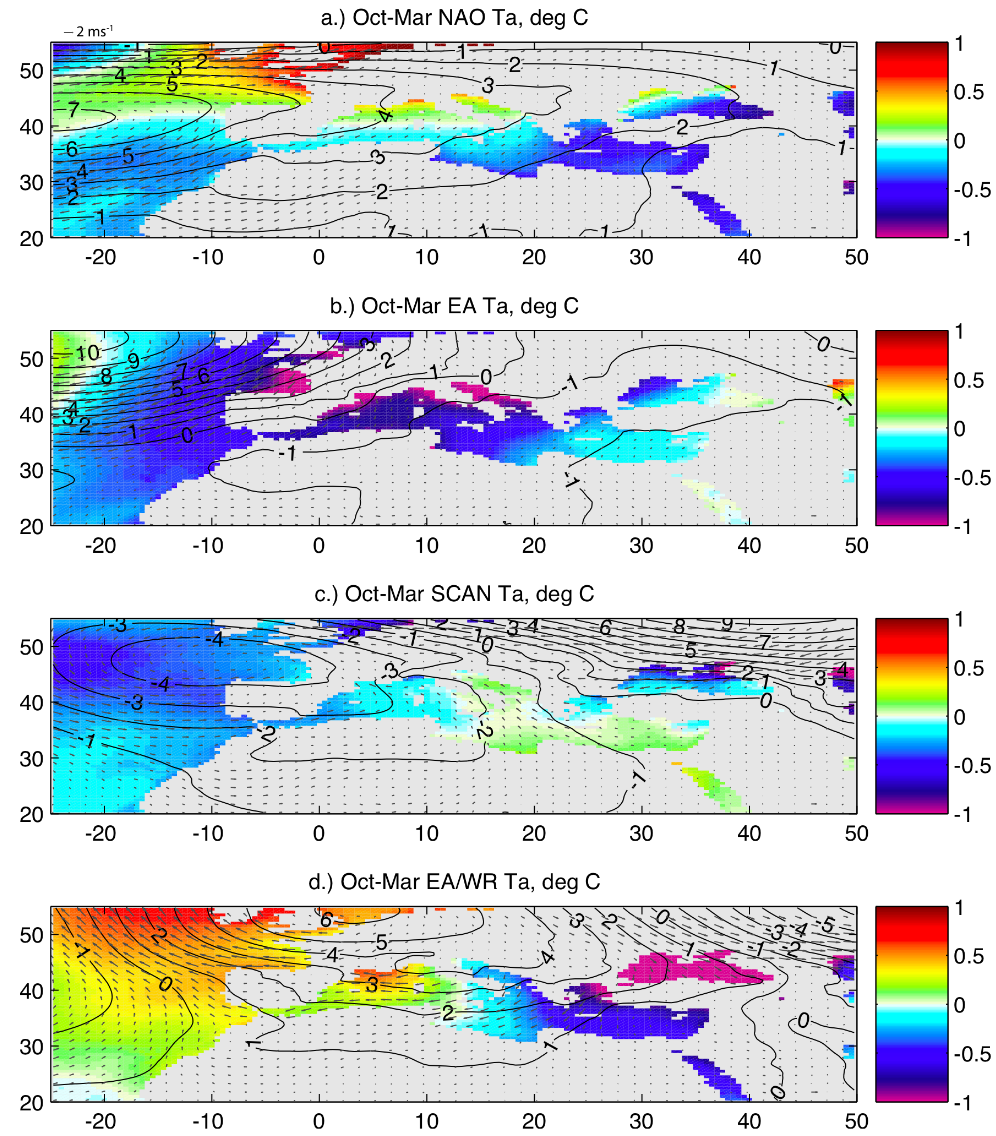

- Good agreement of mode impacts with ARPERA

# Comparison of Mode Impacts

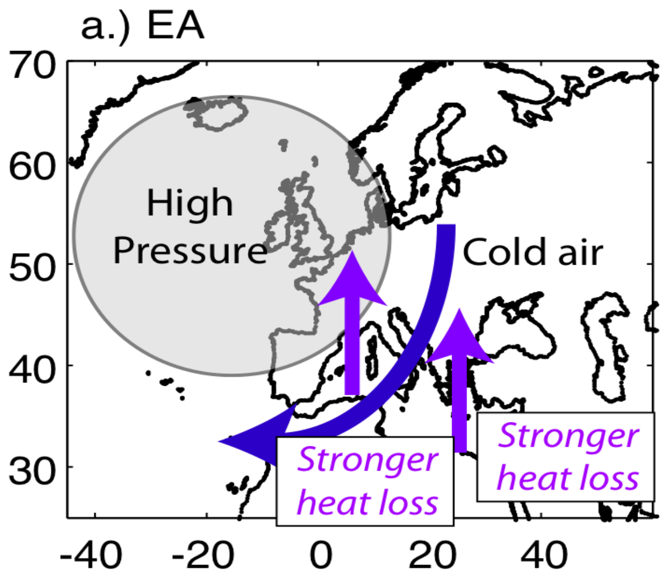


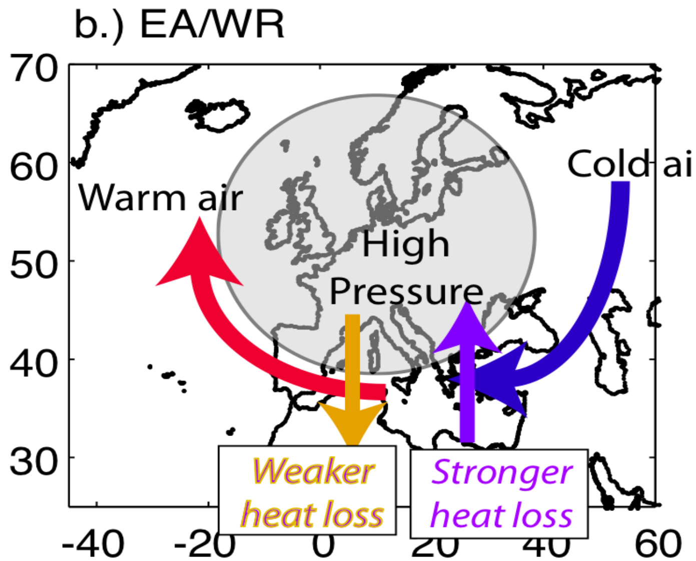
# Related Meteorological Terms

- Wind speed (vectors) and air temperature (colours) anomalies associated with each mode.
- EA and EA/WR produce strongest air temp anomalies in the Mediterranean



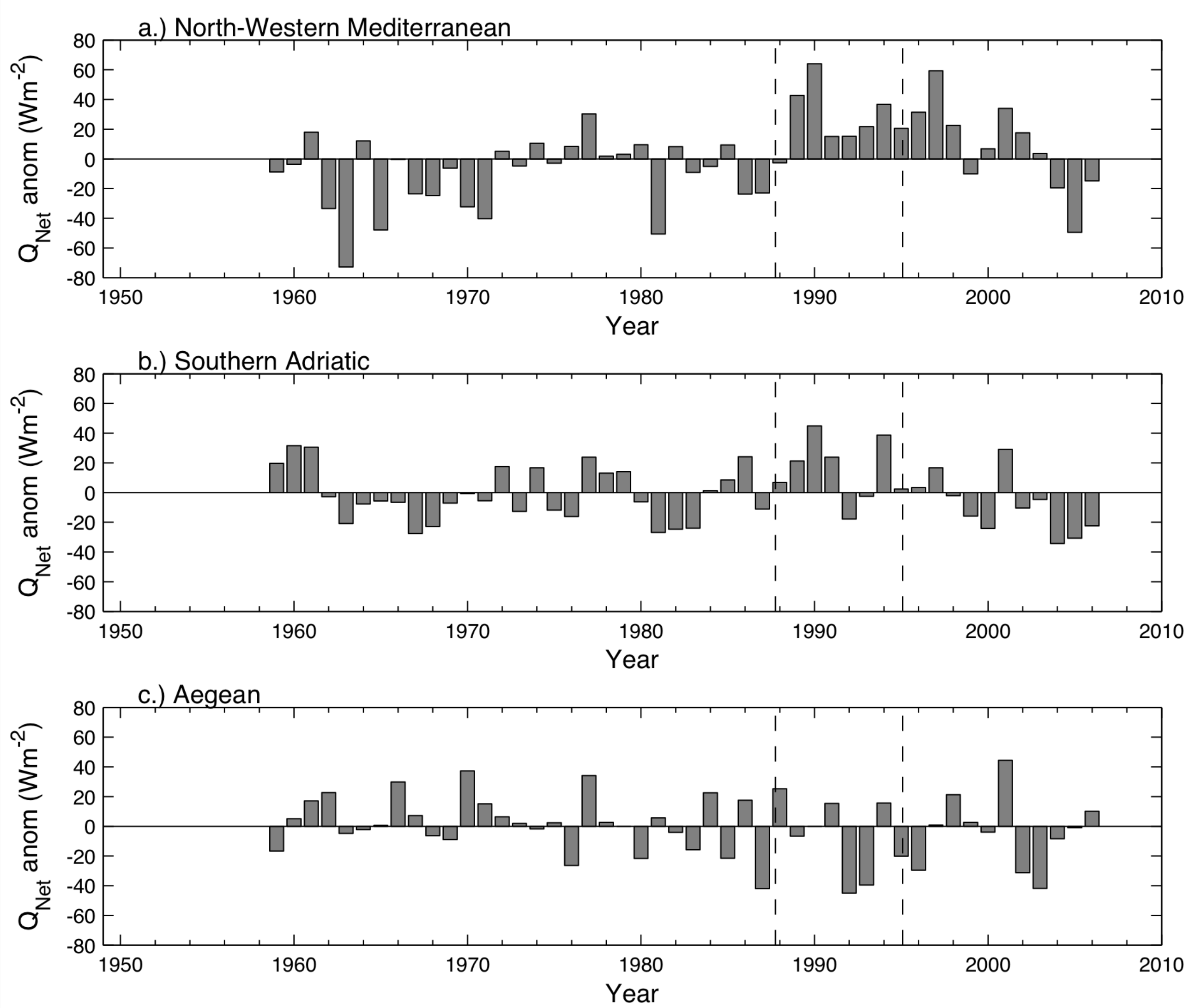
# Impacts of the EA and EA/WR Modes



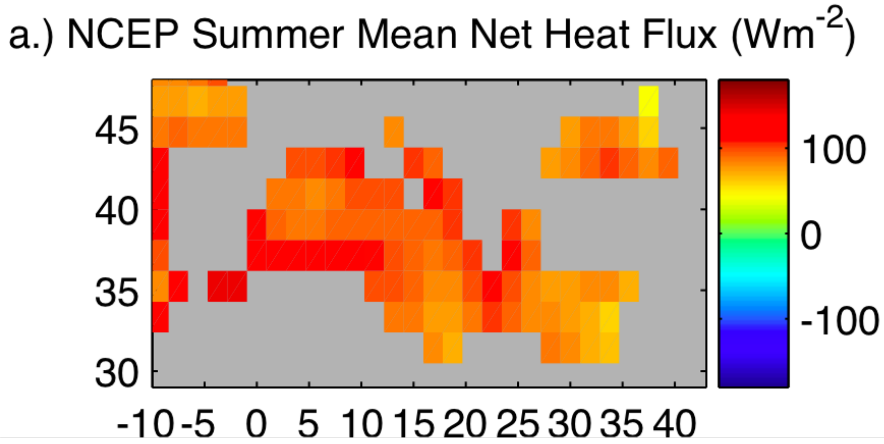

Schematic representation of the high pressure anomaly airflow impacts on heat loss in the Eastern and Western Mediterranean for the EA and EA/WR modes.

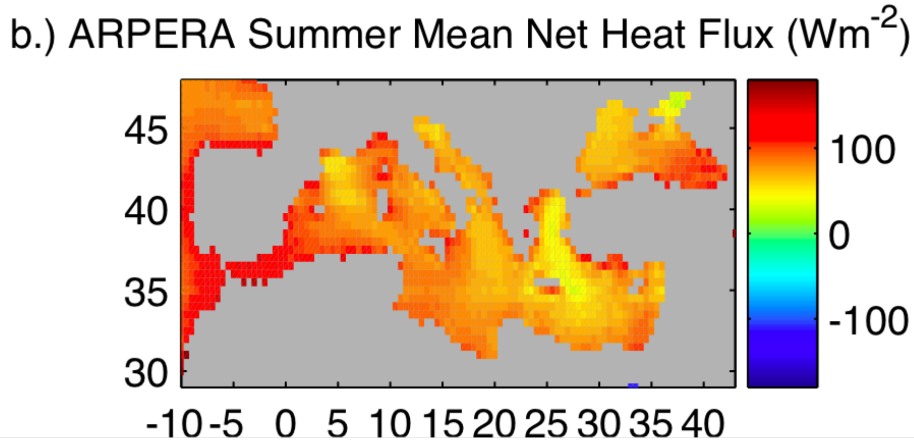
# Heat Loss in the Main Dense Water Formation Regions




Updated version of Josey (2003) using ARPERA.

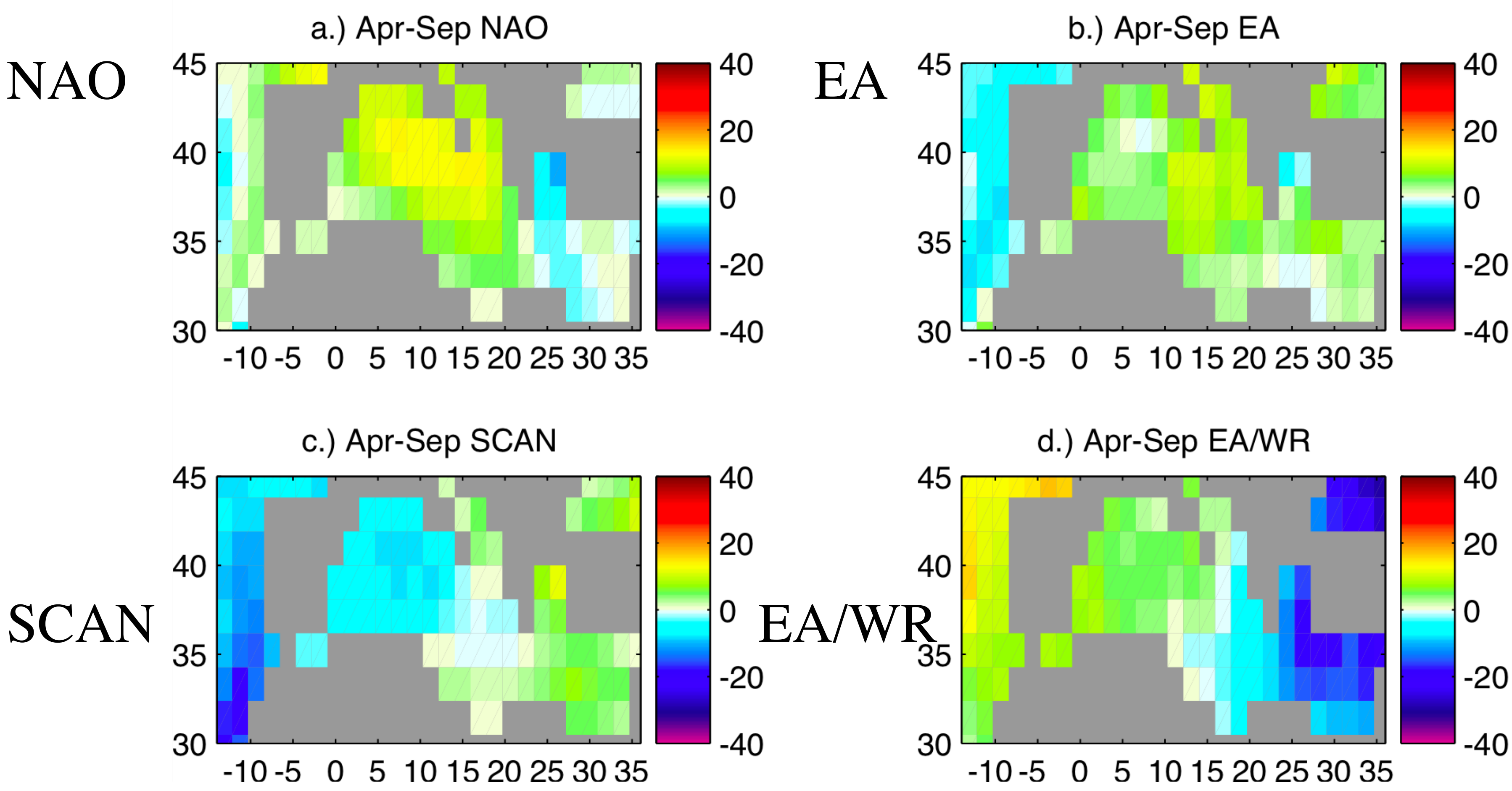
# Summer Mean Net Heat Flux



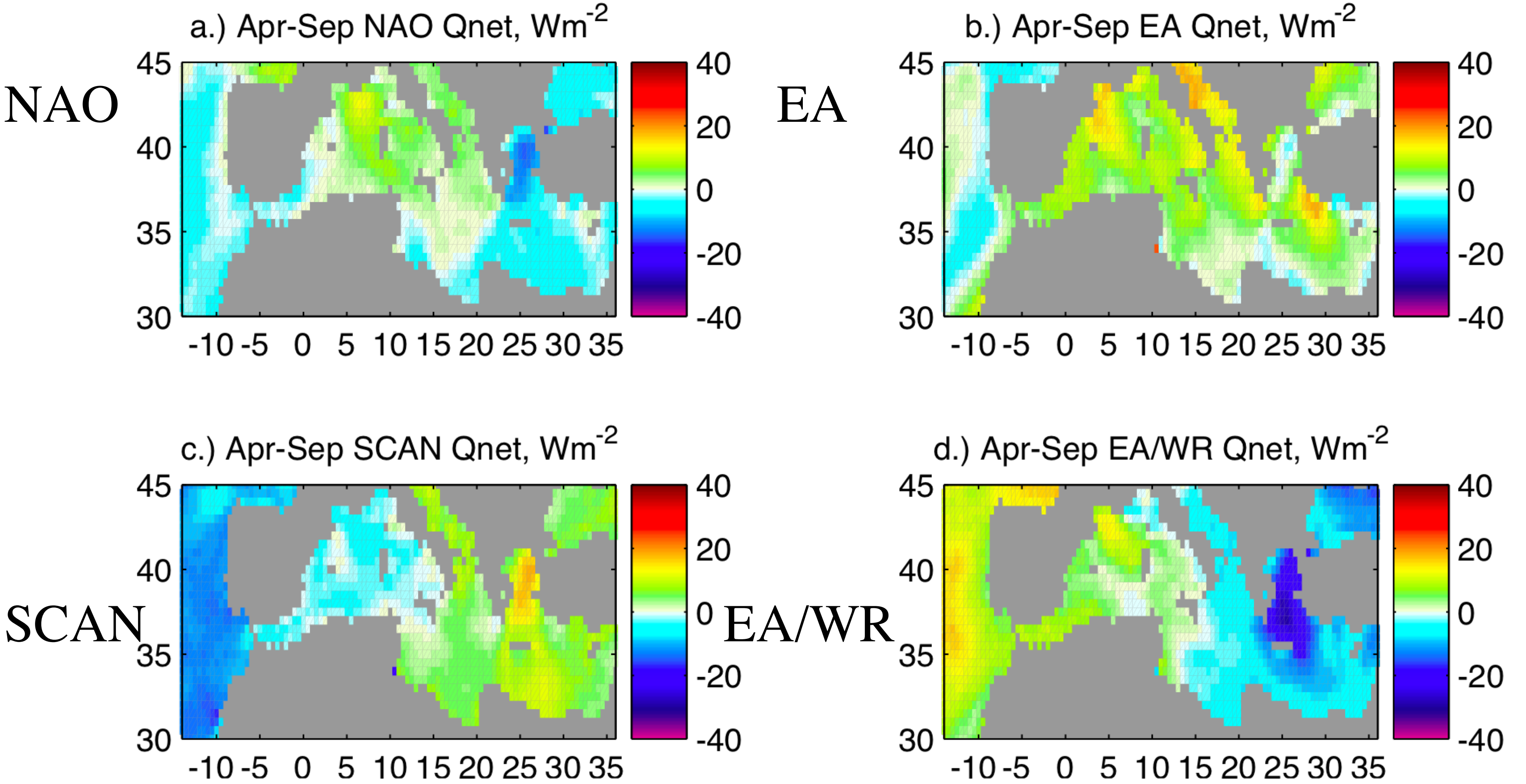

- Summer centered (Apr-Sep) mean net heat flux for 1950-2007 from NCEP/NCAR and ARPERA .

# Impacts of the Modes in Summer



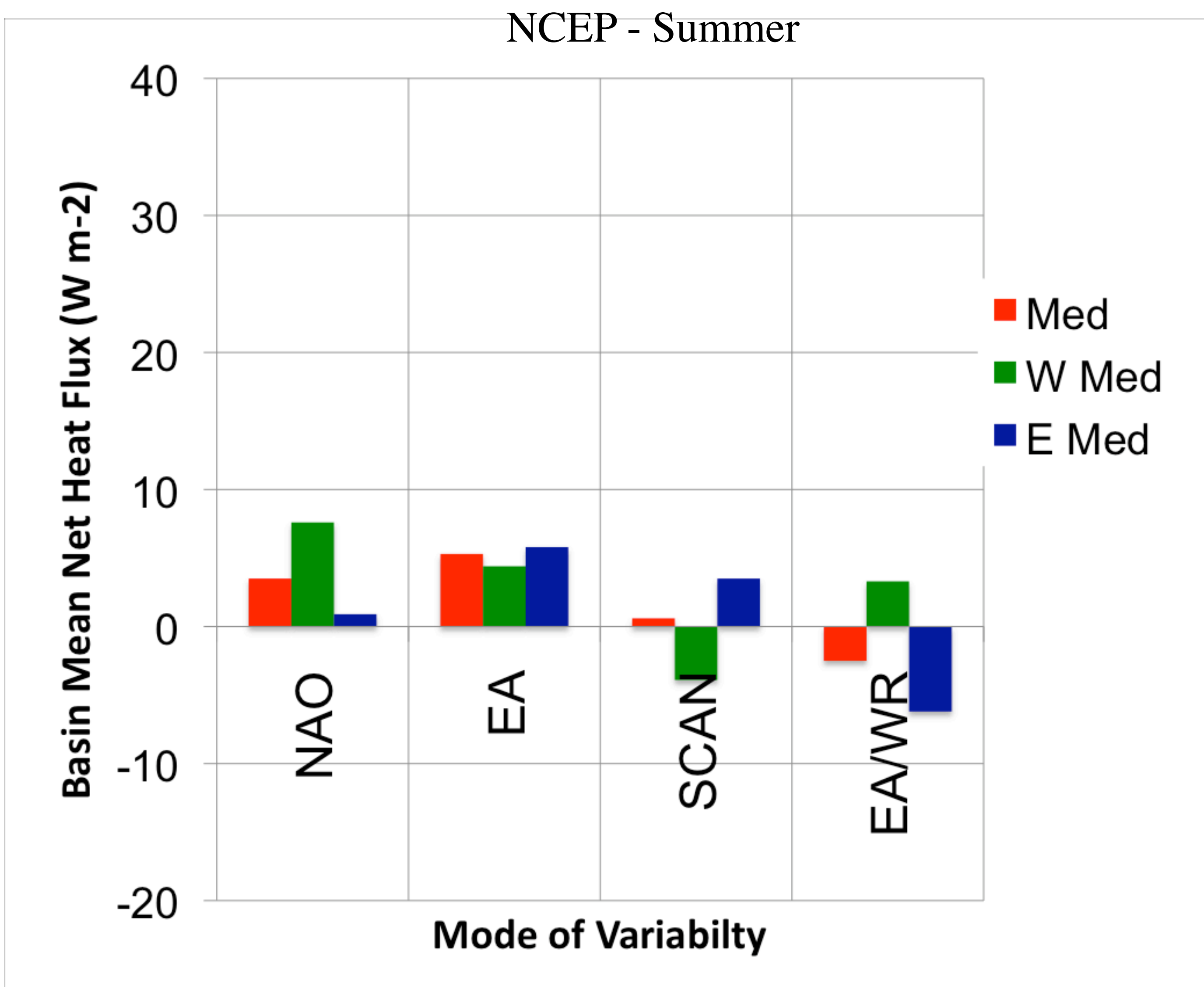

NCEP net heat flux anomaly for a unit positive value of each mode index.

# Impacts of the Modes in Summer




ARPERA net heat flux anomaly for a unit positive value of each mode index.

# Comparison of Mode Impacts



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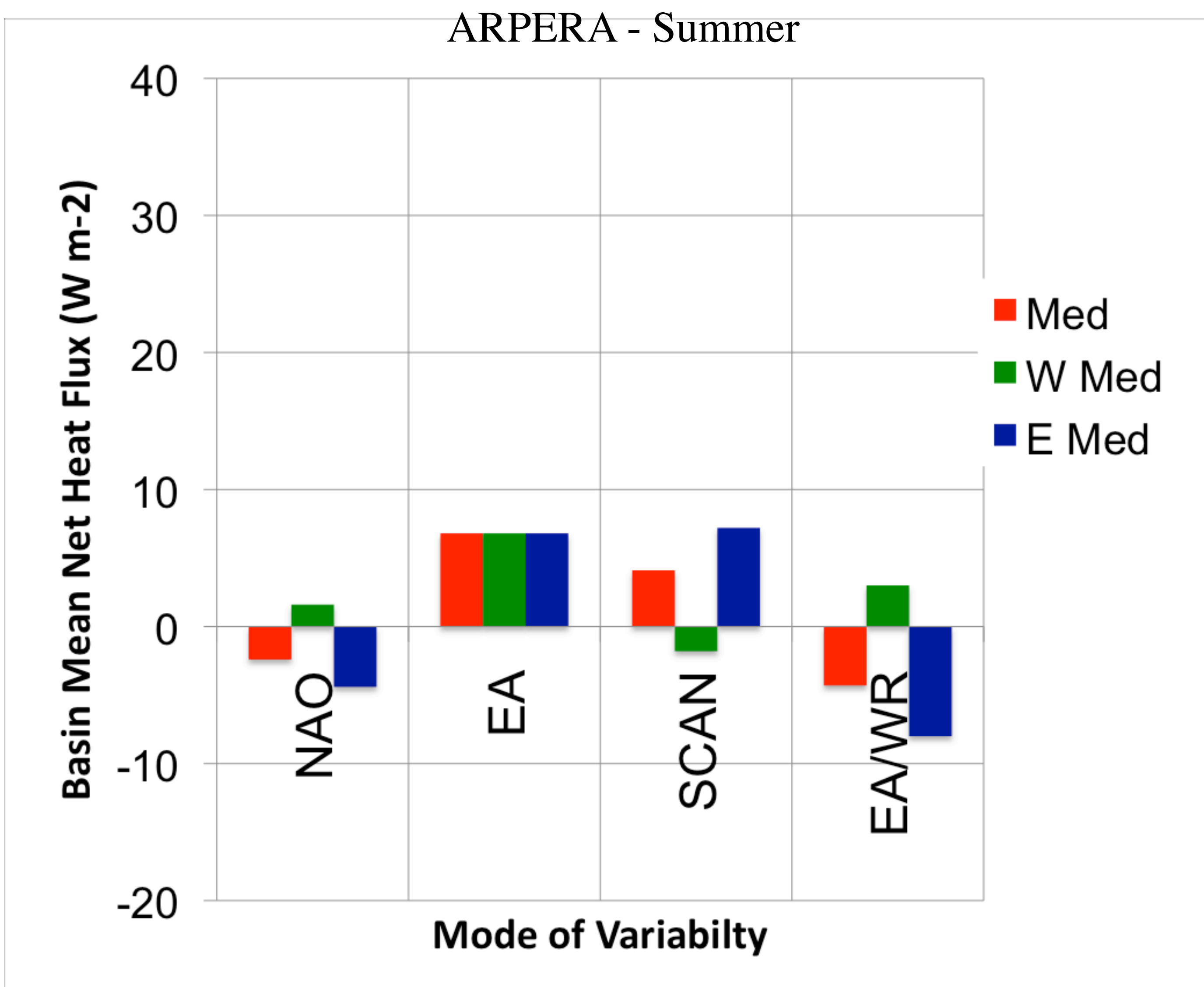
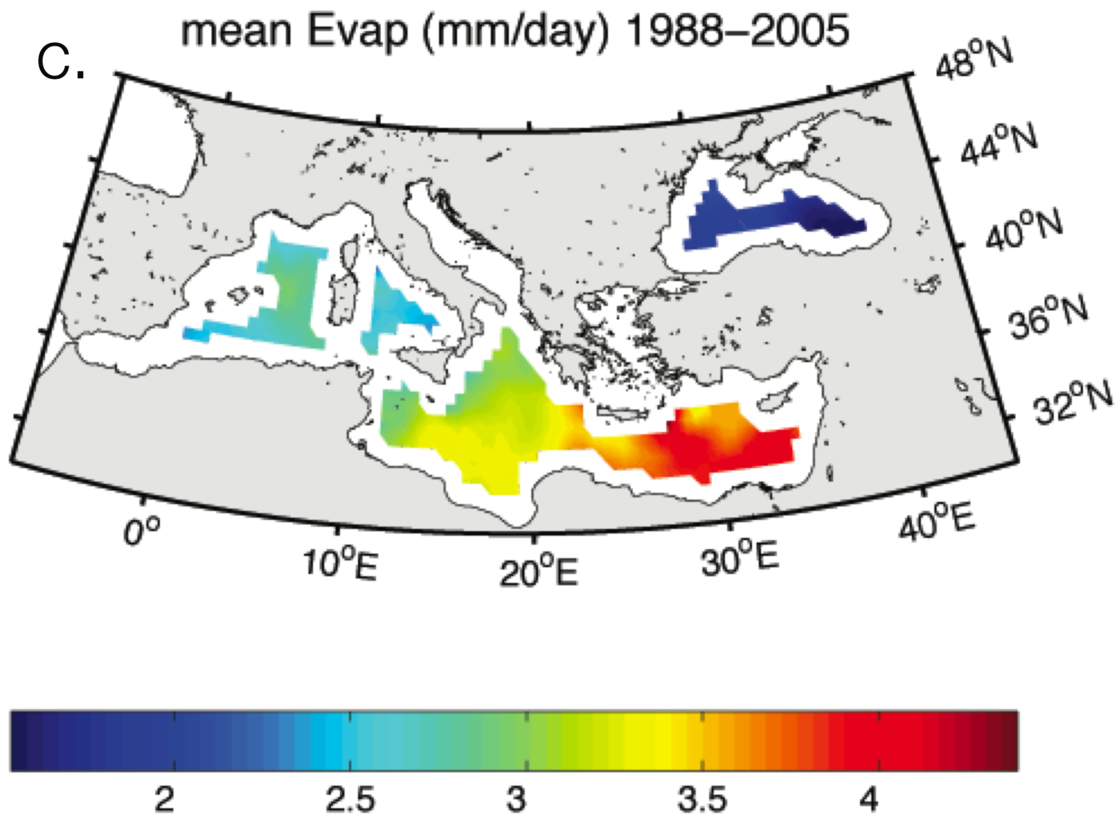


# Recent Study : Romanou et al. (2010)

- **Use satellite based datasets and reanalyses to study E-P variability over the Mediterranean and Black Seas.**

- **Find east-west asymmetry in E-P and attribute it to similar variation in sea-air humidity difference.**



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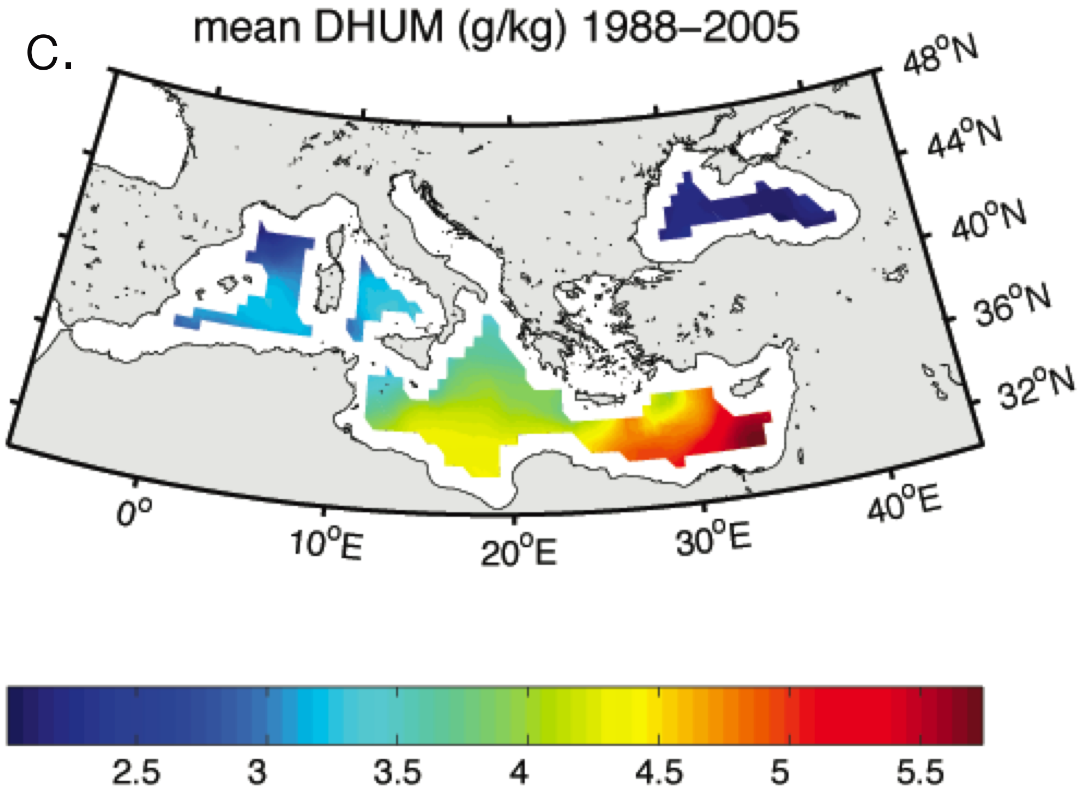



$$Q_E = \rho L C_e u (q_s - q_a)$$

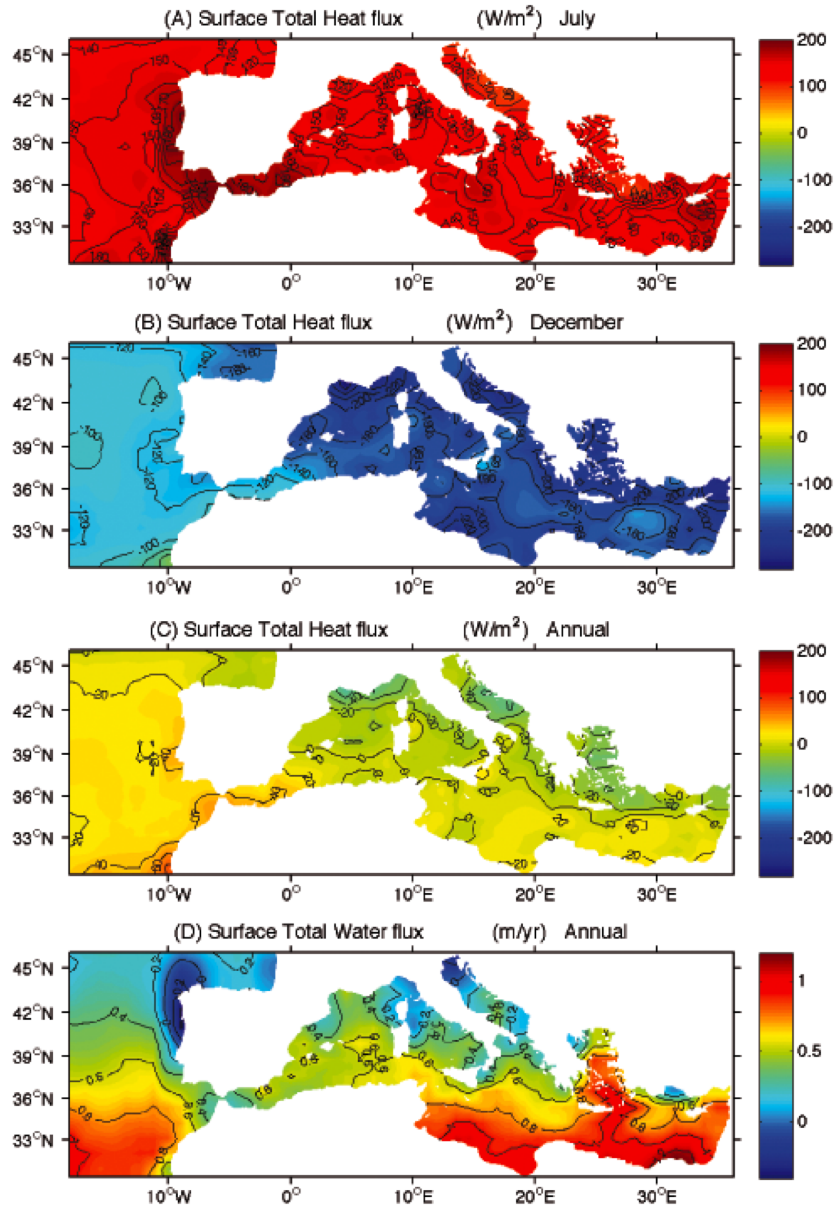
Sea surface humidity

Wind speed

Near surface humidity

# Recent Study : Pettenuzzo et al. (2010)

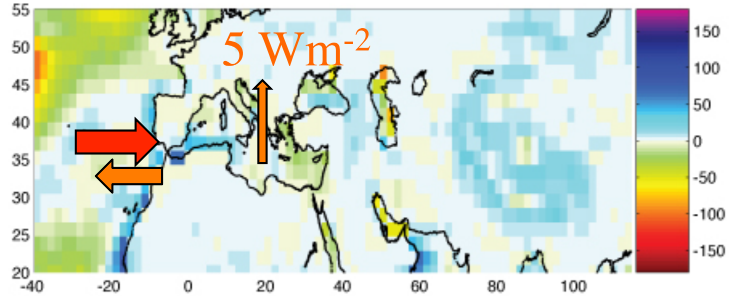
- **Attempt to close Mediterranean Sea heat budget by making various adjustments to ERA-40 fields.**



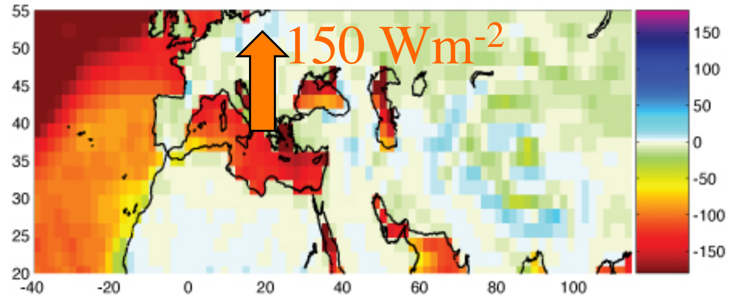
# Large Scale Influence of the Mediterranean on the Atmosphere

• Weak heat source in long term mean….

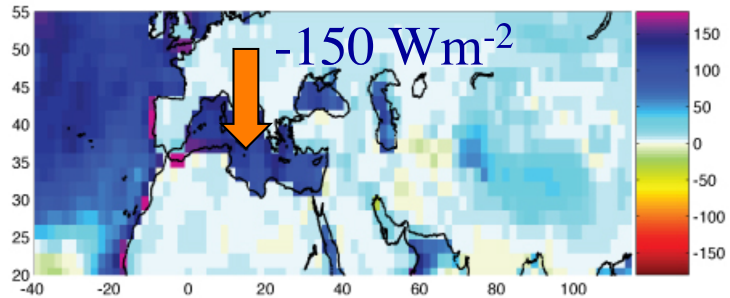
• Annual mean NCEP mean net heat flux (W $m^{-2}$). Basin mean heat loss of about 5 $Wm^{-2}$.




• However, strong heat source in winter. Up to 150 $Wm^{-2}$.




• … and strong net heat uptake in summer.



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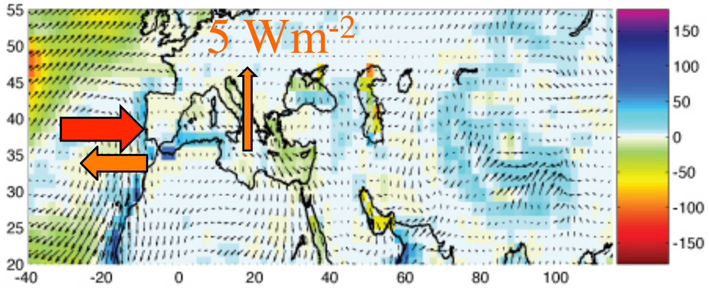


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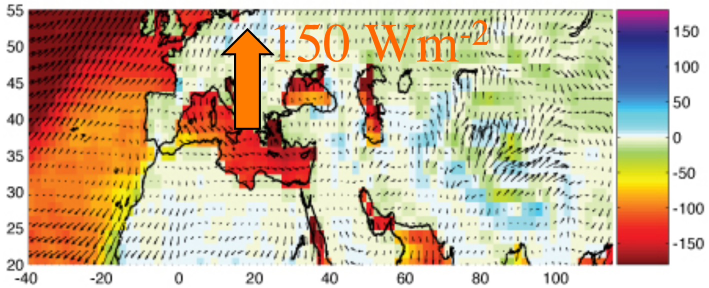


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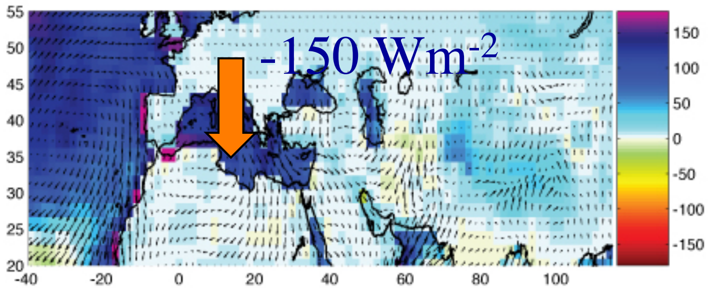
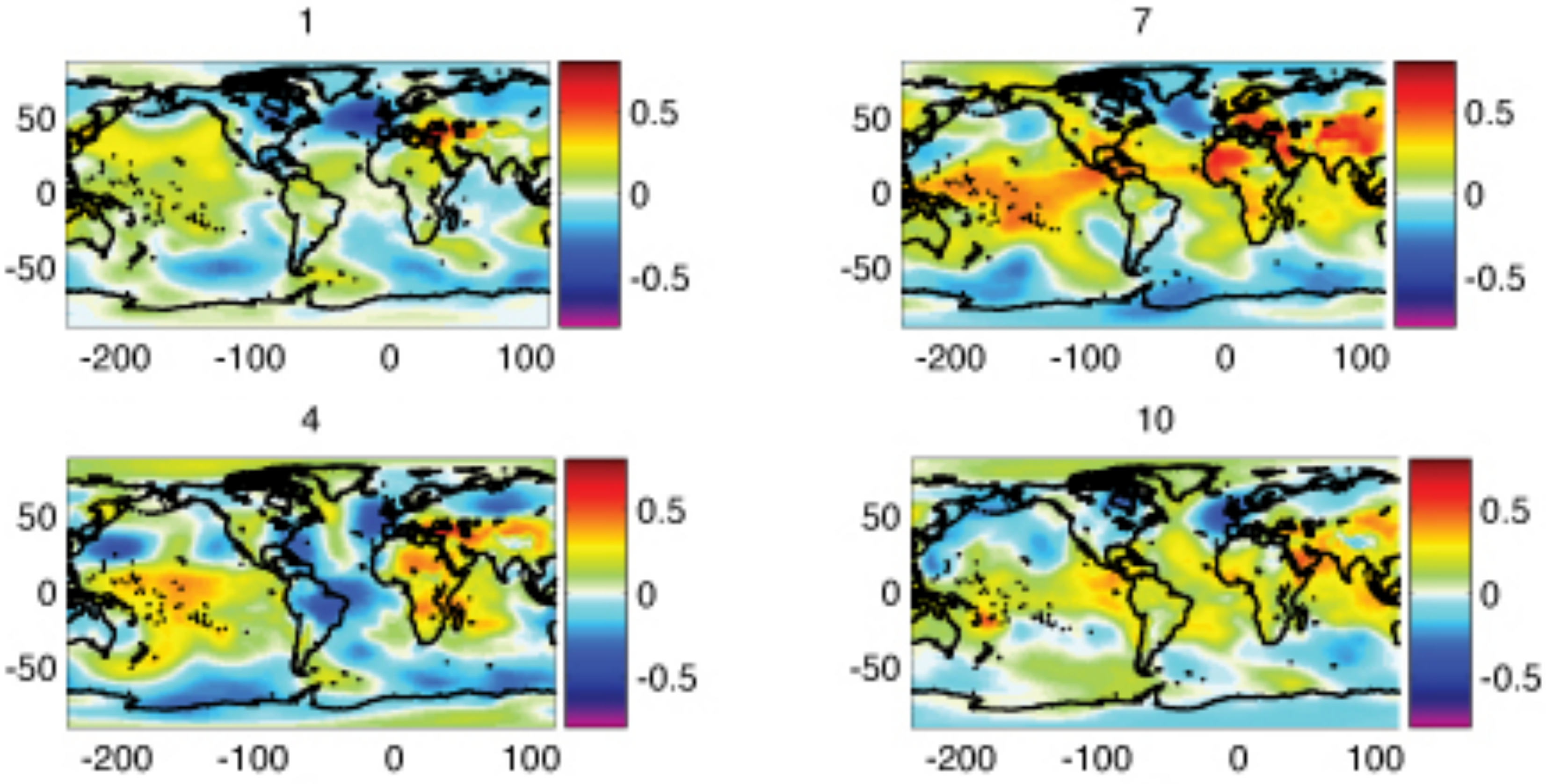



What is the downstream influence of heat released / absorbed?

# Cans Med basin mean net heat flux be linked to downstream atmospheric anomalies?




- Correlation between NCEP basin mean net heat flux and sea level pressure anomalies.

- Some indication of positive correlation pattern over Eurasian land mass in July

# Further Reading – Key Flux Papers

- Ocean Obs'09 Plenary White Paper led by Serge Gulev : Surface Energy and $CO_2$ Fluxes in the Global Ocean-Atmosphere-Ice System.

  **Available at:** http://www.oceanobs09.net/blog/?page_id=622

- Elsevier Book Chapter: *Title. Schroeder, Josey, LaFuente et al.

# Summary

- Overview of surface fluxes given in context of the Mediterranean Sea.
- Heat budget closure problem revisited…still not solved but getting closer.
- Impacts of atmospheric modes on air-sea fluxes in the Mediterranean investigated using NCEP and ARPERA.
- East Atlantic mode found to have largest impact on Med mean heat budget. East Atlantic / West Russian produces strongest split between eastern and western basins.