Projections of ocean wave heights - climate change signal and uncertainty

by
Xiaolan (Leona) Wang and Val R. Swail

Climate Research Branch, Meteorological Service of Canada

- Datasets and Methodologies
- Multi-model projections of changes in SWH
- CGCM2 simulated climate change signal
- Model & forcing uncertainties
- Summary

Datasets:

Previous studies → good SWH-SLP relationship

Seasonal mean SLP and squared SLP gradients - predictors (96x48 Gaussian grid)

-“Observations”: ERA40 reanalysis for 1958-2001 (44 yr)

- Projections:

3 climate models

3 forcing scenarios

15 simulations

	CGCM2	ECHAM4	HadCM3
IPCC IS92a	3	1	1
SRES A2	3	1	1
SRES B2	3	1	1

- IS92a scenario: 1961-2099 (1961-2049 for ECHAM4)

- A2 & B2 scenarios: 1990-2099

Seasonal mean & max SWH (1.5x1.5 lat/long grid) - predictand

-“Observations”: ERA40 wave data for 1958-2001 (44 yr)

1. Projections of seasonal mean SWH (quasi-Gaussian)

- Fit the Regression Models:

$$RM_G : h_t = m_0 + r_2 G_t \quad \text{or} \quad RM_P : h_t = m_0 + r_1 P_t$$
$$RM : h_t = m_0 + r_1 P_t + r_2 G_t$$

SSE_G or SSE_P

SSE compared with

Predictors { P_t: Seasonal mean SLP anomalies
G_t: Seasonal anomalies of squared SLP gradient

- Significance of regression par's ← Likelihood ratio tests

Results: $\boxed{h_t}$ - correlated with P_t and G_t in all seasons;

Model of best fit → projections: $\hat{h}_t = \hat{m}_0 + \hat{r}_1 P_t + \hat{r}_2 G_t$

ANOVA

2. Trend analysis on $\hat{h}_t$:
(3 models combined)

$$RM0 : \hat{h}_t = a_0 + e_t;$$
$$RM1 : \hat{h}_t = a_0 + a_1 t + e_t;$$
$$RM2 : \hat{h}_t = a_0 + a_1 t + a_2 t^2 + e_t.$$

$$\hat{h}_{trend}(t) = \hat{a}_0 + \hat{a}_1 t + \hat{a}_2 t^2$$
(mostly nonlinear!)

3. Projections of <u>seasonal extreme</u> SWH (non-Gaussian)

- Generalized Extreme Value (GEV) models with covariates:

$GEV_0(m, s, x)$ where m, s, x are constants (stationary GEV);

$GEV_1(m_t, s, x)$ where $m_t = m_0 + r_1 P_t$;

$GEV_2(m_t, s, x)$ where $m_t = m_0 + r_1 P_t + r_2 G_t$;

$GEV_3(m_t, s_t, x)$ where $m_t = m_0 + r_1 P_t + r_2 G_t$ and $\log(s_t) = l_0 + l_1 P_t$;

$GEV_4(m_t, s_t, x)$ where $m_t = m_0 + r_1 P_t + r_2 G_t$ and $\log(s_t) = l_0 + l_1 P_t + l_2 G_t$

P_t: Seasonal mean SLP anomaly
G_t: Seasonal anomaly of squared SLP gradient

- Likelihood ratio tests ➔ Significance of the regressions & goodness of fit of the *GEVs*

Results: s_t - independent of both P_t and G_t

m_t - correlated with P_t and G_t in all seasons.

3. Projections of seasonal extreme SWH (cont'd)

The model of best fit:

$$GEV2(\hat{m}_t, \hat{s}, \hat{x}) \text{ where } \hat{m}_t = \hat{m}_0 + \hat{r}_1 P_t + \hat{r}_2 G_t$$

Procedure:

AOGCM simulated P_t and G_t

Observed relationship $\hat{m}_t = \hat{m}_0 + \hat{r}_1 P_t + \hat{r}_2 G_t$

Projected location parameter $\hat{m}_t$

$GEV_2(\hat{m}_t, \hat{s}, \hat{x})$

$\hat{H}_t$: Time series of 20-yr return values of SWH

ANOVA

4. Trend analysis (3 models combined):

$RM0: \hat{m}_t = a_0 + e_t;$

$RM1: \hat{m}_t = a_0 + a_1 t + e_t;$

$RM2: \hat{m}_t = a_0 + a_1 t + a_2 t^2 + e_t.$

$$\hat{m}_{trend}(t) = \hat{a}_0 + \hat{a}_1 t + \hat{a}_2 t^2$$

t=1, 31, 61 and 91 (1990, 2020, 2050, 2080)

$GEV2(\hat{m}_{trend}(t), \hat{s}, \hat{x})$

Multi-model projections of changes in the size/frequency of SWH extremes

4. Analysis of Variance (ANOVA)

One-way ANOVA:

CGCM2 ensemble projections (S = 3; n = 110) for the A2/B2 scenario

$$Y_{ts} = m + b_t + e_{ts} \quad \text{for } s = 1,2,\ldots,S;\ \ t = 1,2,\ldots,n$$

$$TSS_Y = SSB_Y + SSE_Y$$

SSB_Y : Forcing signal (var. due to the prescribed forcing) → CGCM2 simulated climate change signal

SSE_Y : Var. due to climate noise (internal var.)

F test: $$F_B = \frac{(SSB_Y/(n-1)}{SSE_Y/[n(S-1)]} \sim F_p[(n-1), n(S-1)]$$

Var. proportion: $$P_B = \left[SSB_Y - \frac{(n-1)}{n(S-1)} SSE_Y \right] \Big/ TSS_Y$$

Small ensemble size (S = 3) → underestimate signal's significance

But ANOVA - still better than "ensemble *vs*. control"

4. Analysis of Variance (cont'd)

Two-way ANOVA → model and forcing uncertainties:

X_{ijt}: mean/extreme SWH projected by model i with forcing j for time t.

$$X_{ijt} = m + g_i + q_j + d_{ij} + e_{ijt} \quad \text{for } i = 1,2,\ldots,\underset{3}{m}; \quad j = 1,2,\ldots,\underset{3}{q}; \quad t = 1,2,\ldots,\underset{60}{n}$$

$$TSS = SS\underbrace{M + SSF + SS}_{\text{Total model and forcing uncertainties}}I + SSE$$

SSM: Var. due to diff. among climate models (inter-model variability)

SSF: Var. due to diff. among forcing scenarios (inter-scenario variability)

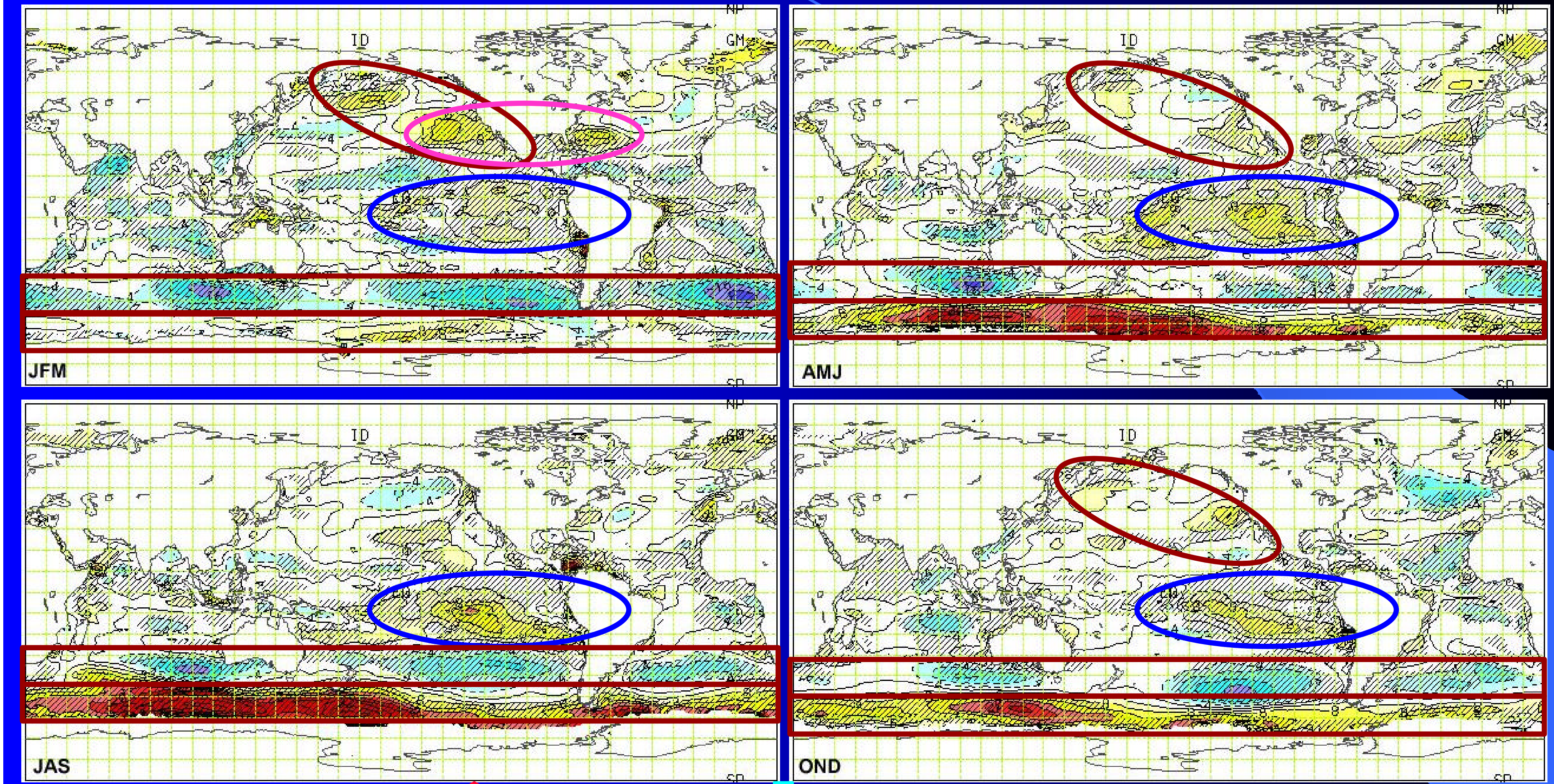
SSI: Var. due to different model sensitivities to forcing differences (interaction)

SSE: Var. due to climate noise (internal var.) and the "common forcing"

F tests → Significance of the 3 var. components & the sum of them

Changes projected by the 3 climate models combined

Projected changes in seasonal <u>mean</u> SWH – A2 scenario (2080's minus 1990's)



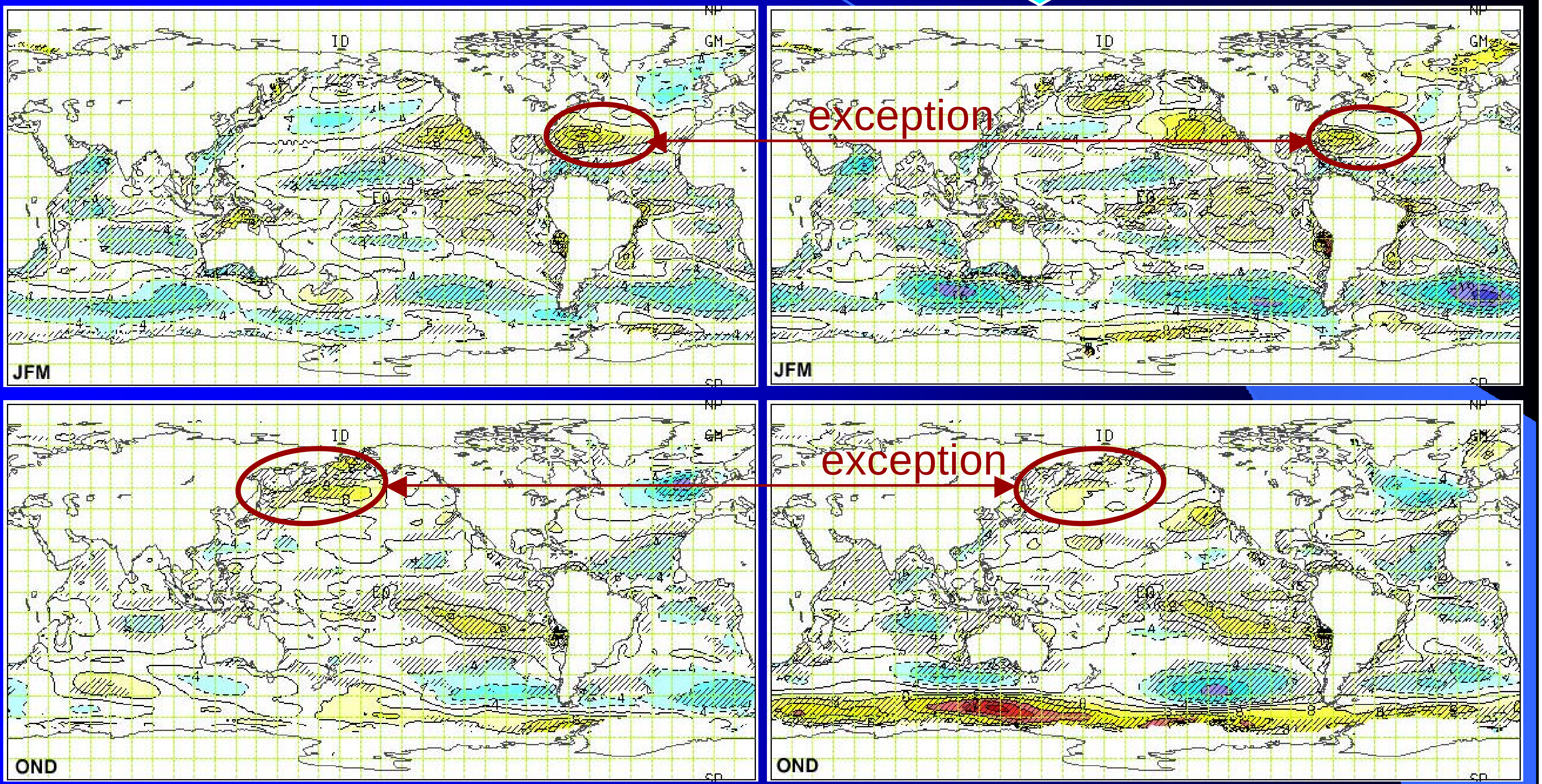
Yellow-Red: ↑ Cyan-Blue: ↓ Contour interval: 4 cm

Hatching: changes of >= 95% confidence

A2 vs. B2 scenario projections: Similar patterns of change

Weaker B2 scenario: generally smaller changes

A2 scenario

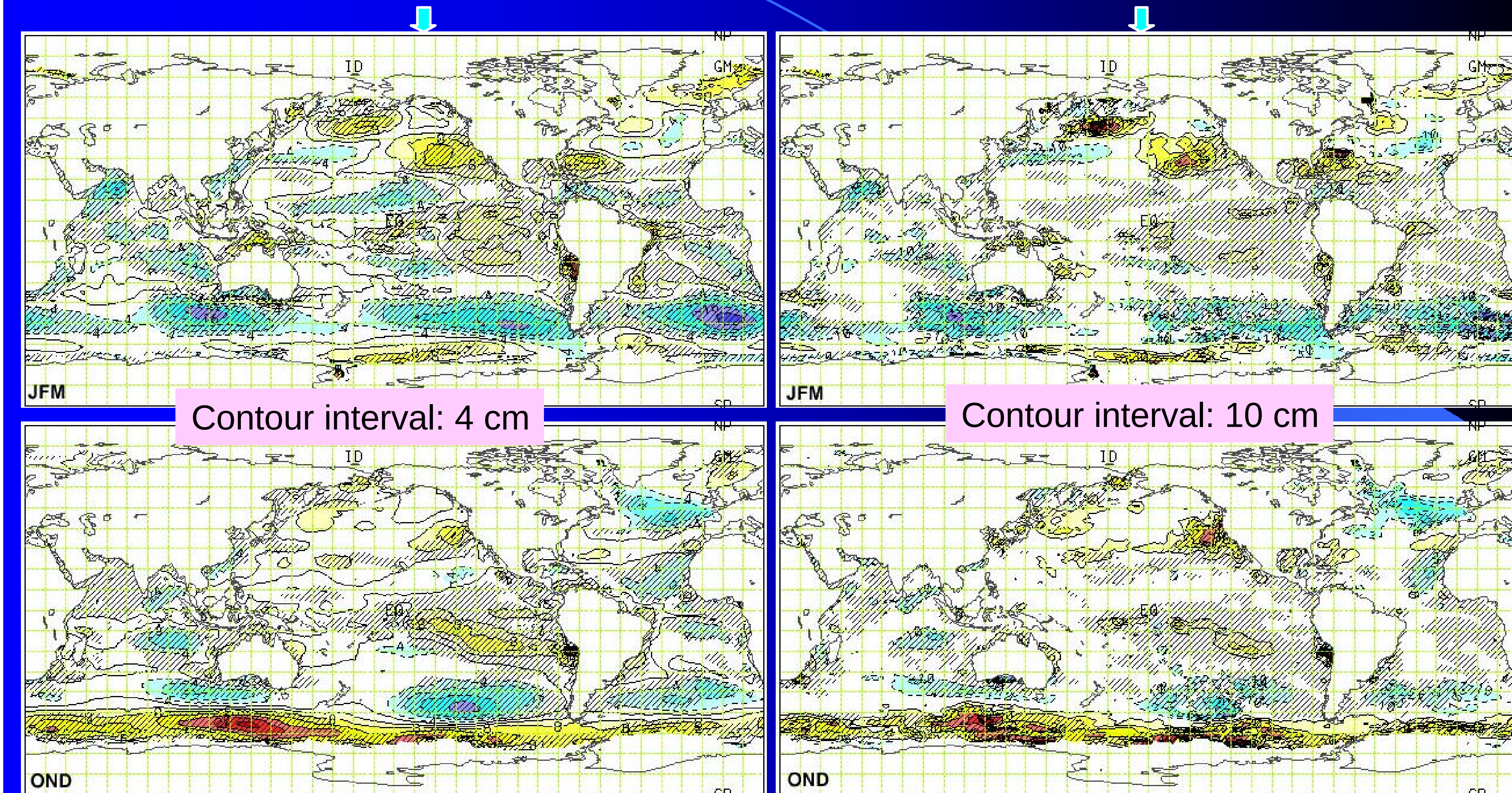


Yellow-Red: ⬆ Cyan-Blue: ⬇ Contour interval: 4 cm

Hatching: changes of >= 95% confidence

Similar patterns of projected change

Seasonal mean SWH　　　　Seasonal extreme SWH



Yellow-Red: ⬆ Cyan-Blue: ⬇ Contour interval: 4 cm

Hatching: changes of >= 95% confidence

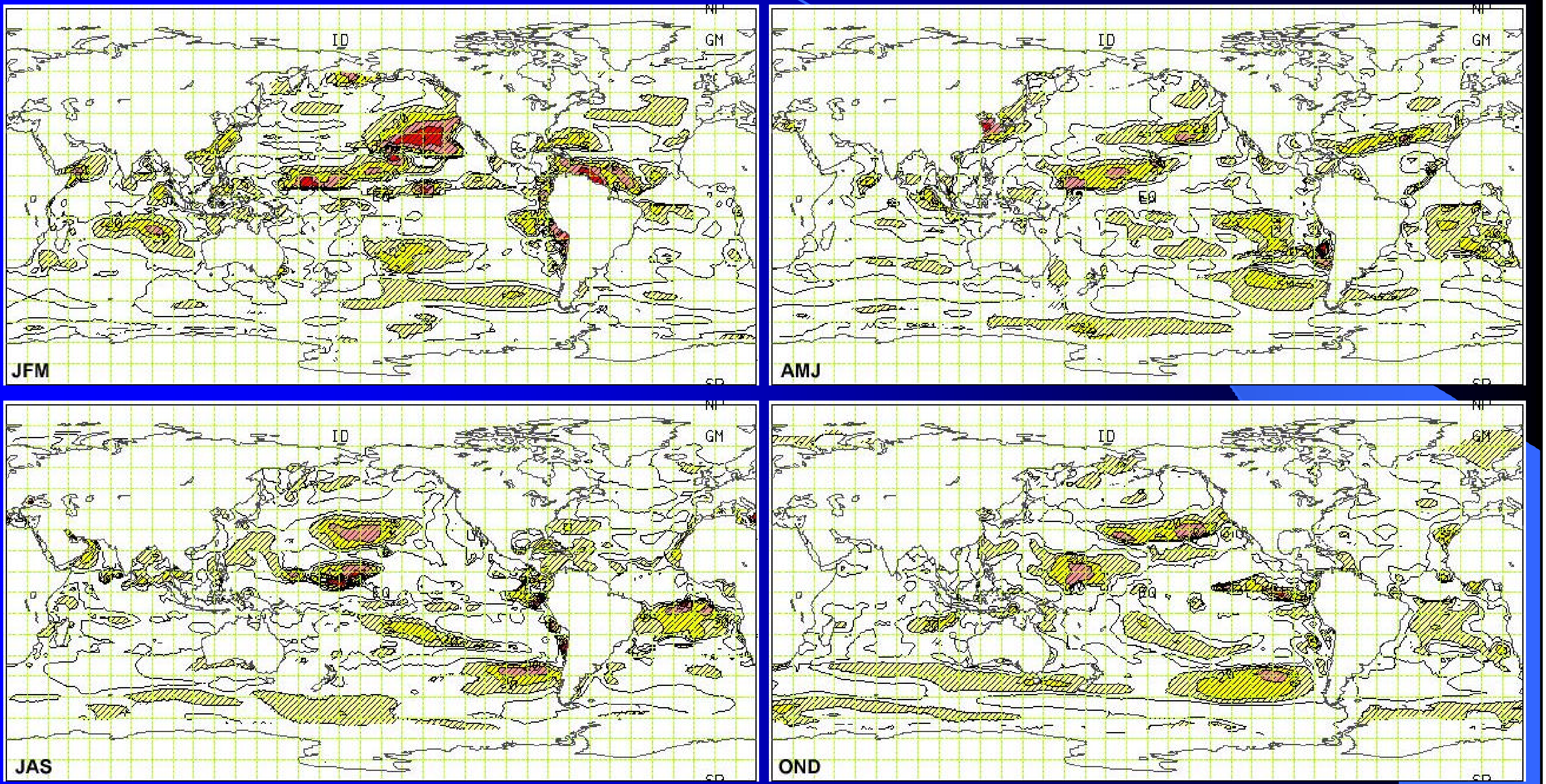
A2 scenario

Projected changes = Forced climate change + Internal natural var.

Climate change signal in the CGCM2 ensemble simulations

Forcing-induced var. proportion in seasonal mean SWH - A2 scenario

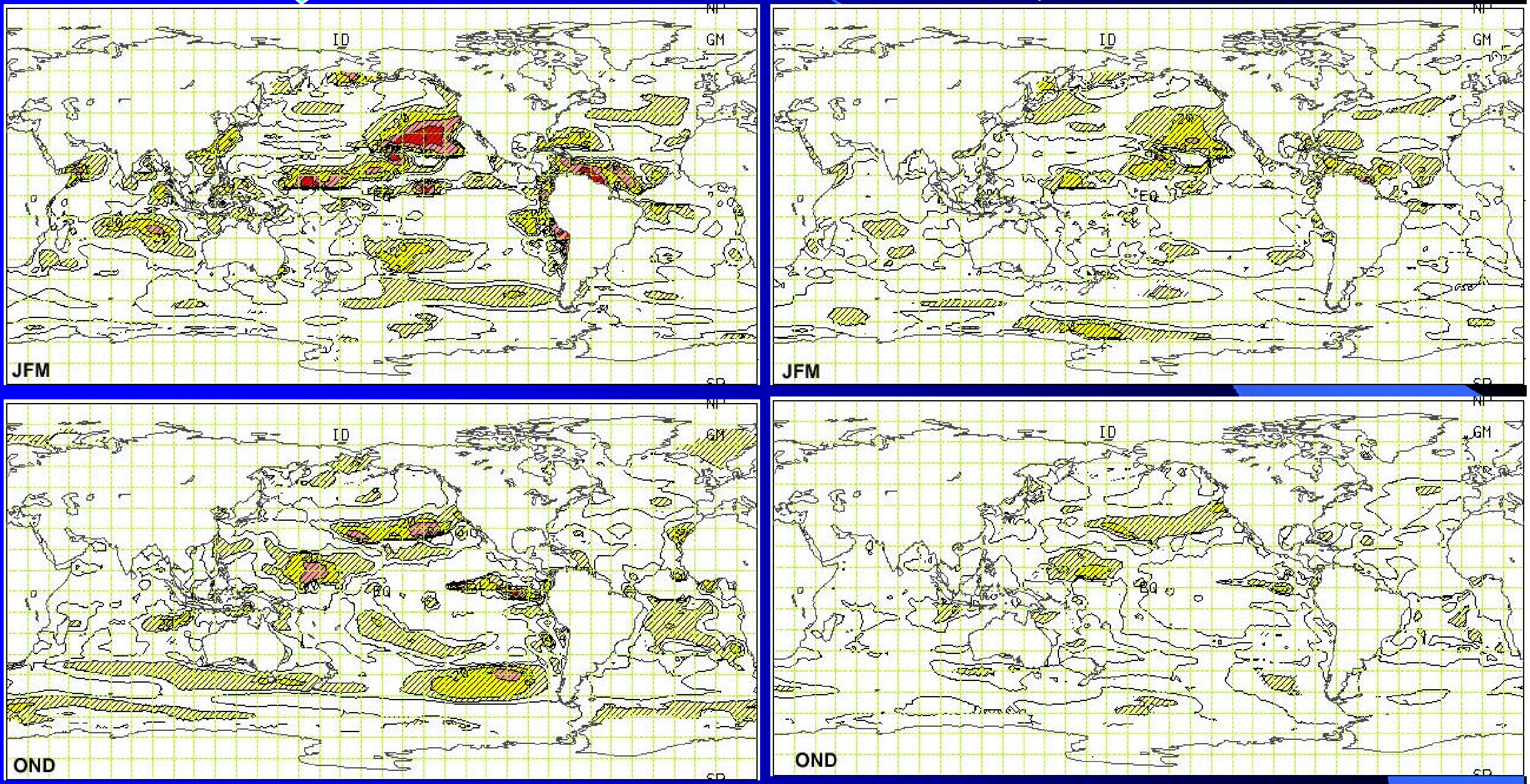
Hatching: >= 95% confidence   Contour interval: 10%



Ensemble size = 3 → Signal likely more significant than shown here!

Forcing-induced var. in seasonal mean SWH – A2 vs. B2

A2 scenario | B2 scenario: weaker signal



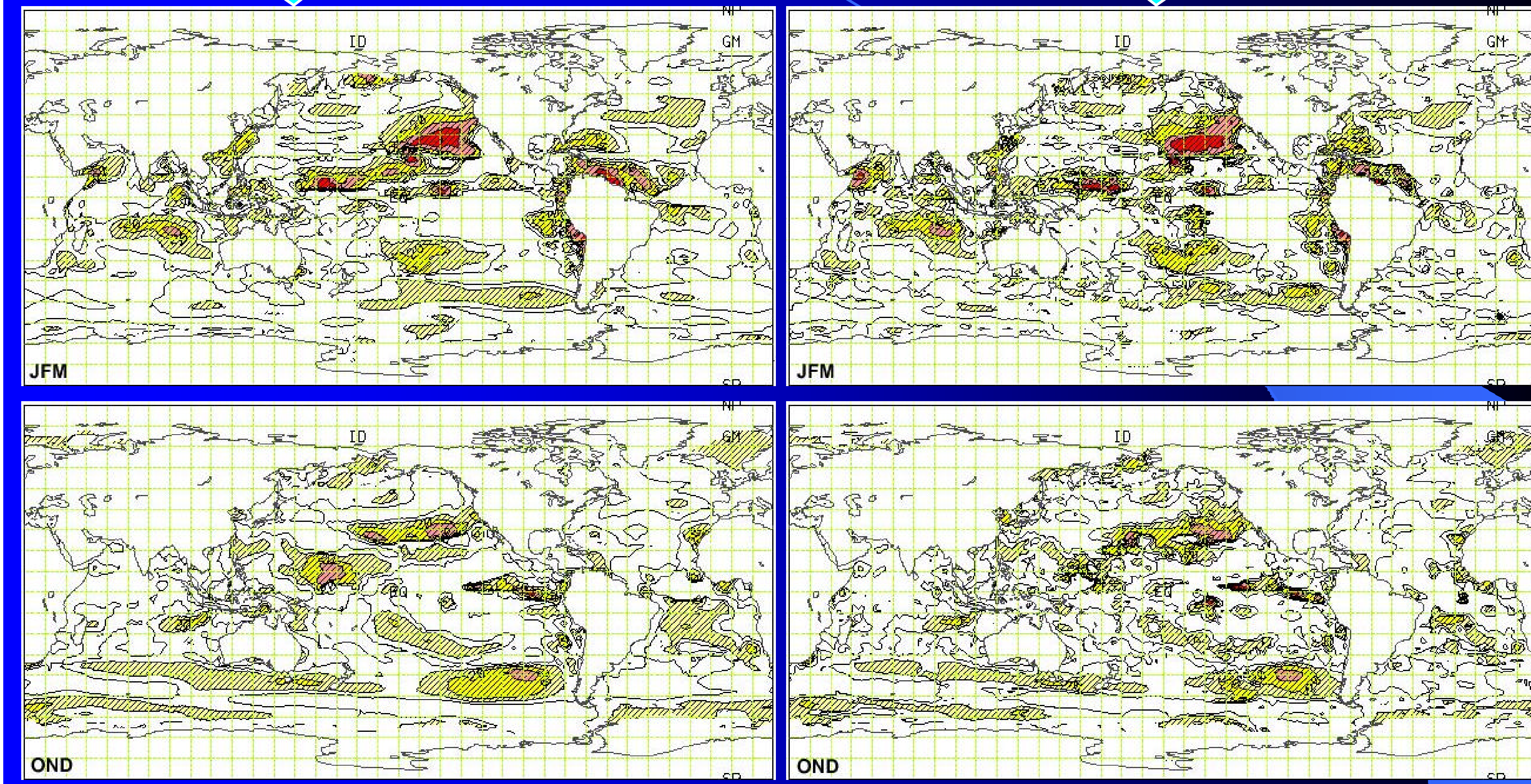
Contour interval: 10% | Hatching: >= 95% confidence

Wang and Swail 2004

Forcing-induced var. – A2 scenario

Mean SWH

Extreme SWH

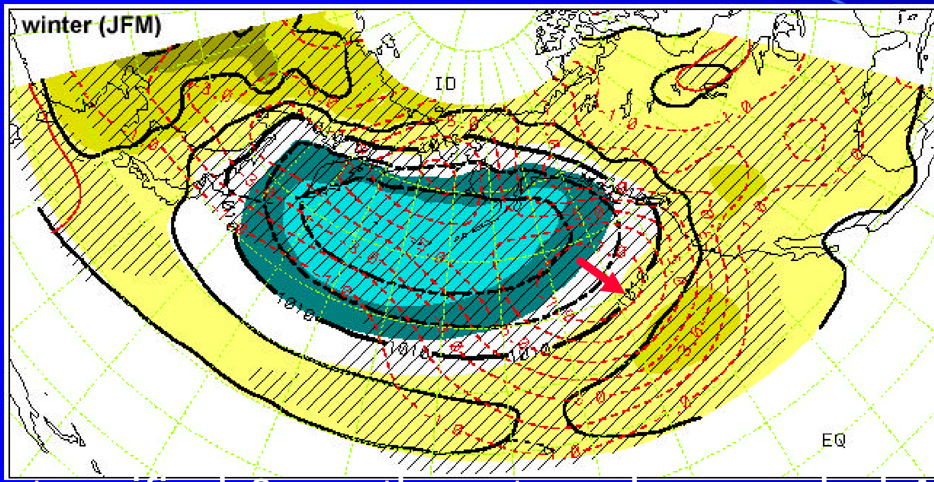


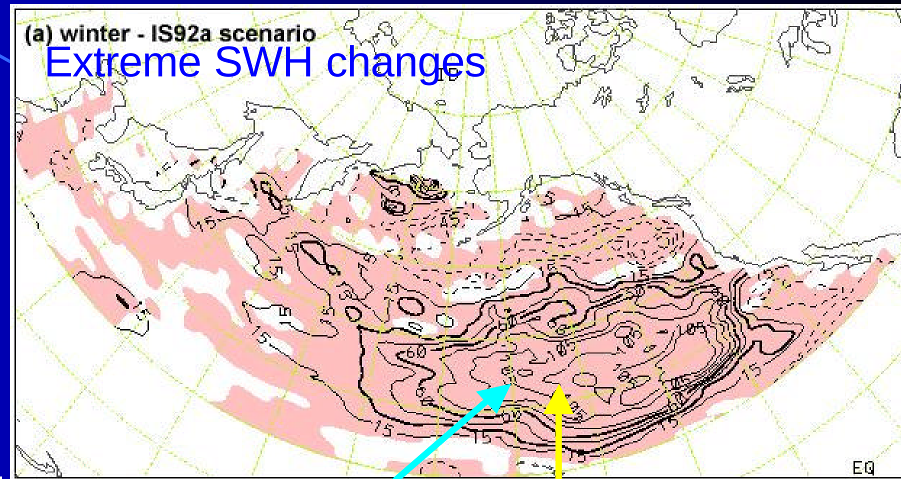
Contour interval: 10% Hatching: >= 95% confidence

2070-99 1961-90

Related SLP climate changes (2080s minus 1970s) – N. Pacific

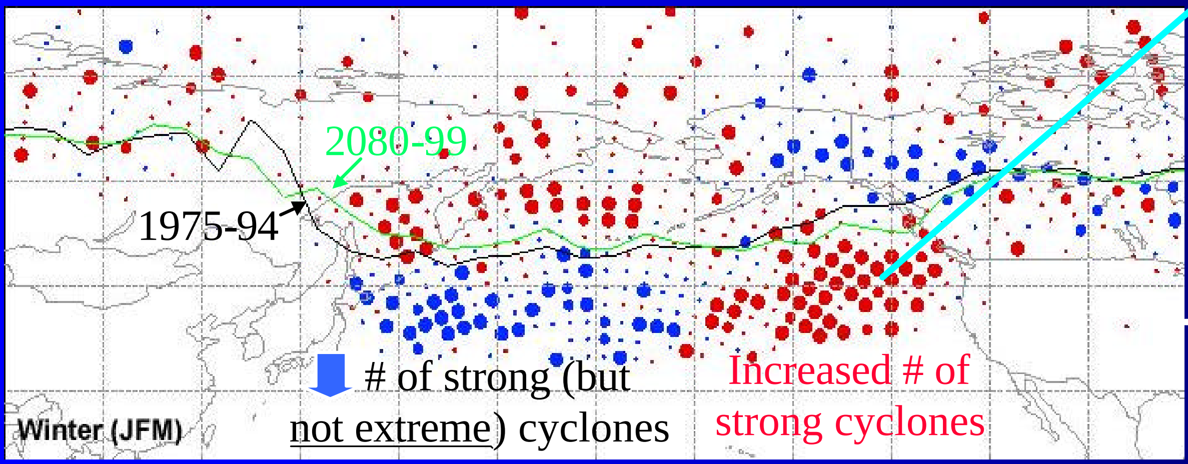
(IS92a scenario)





Intensified & southeastward expanded Aleutian low

Clock-wise “rotated” storm track:



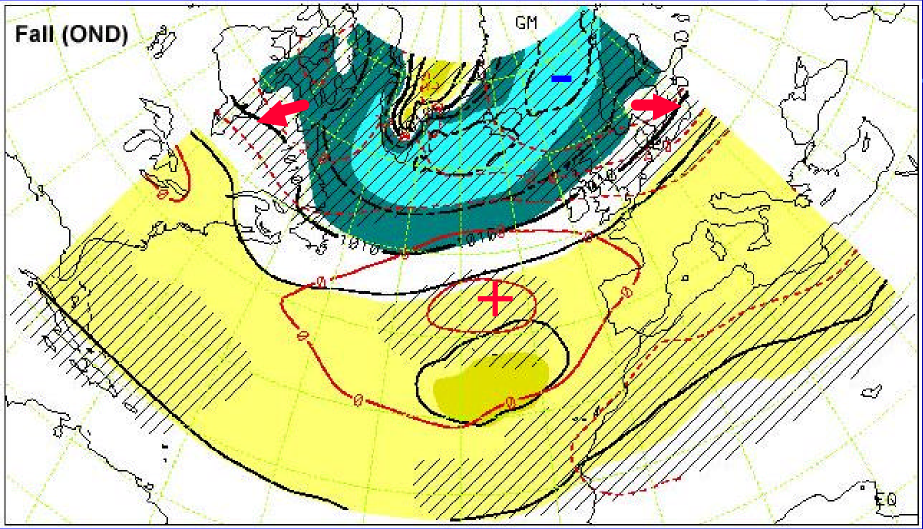
Area of significant wave climate change signal

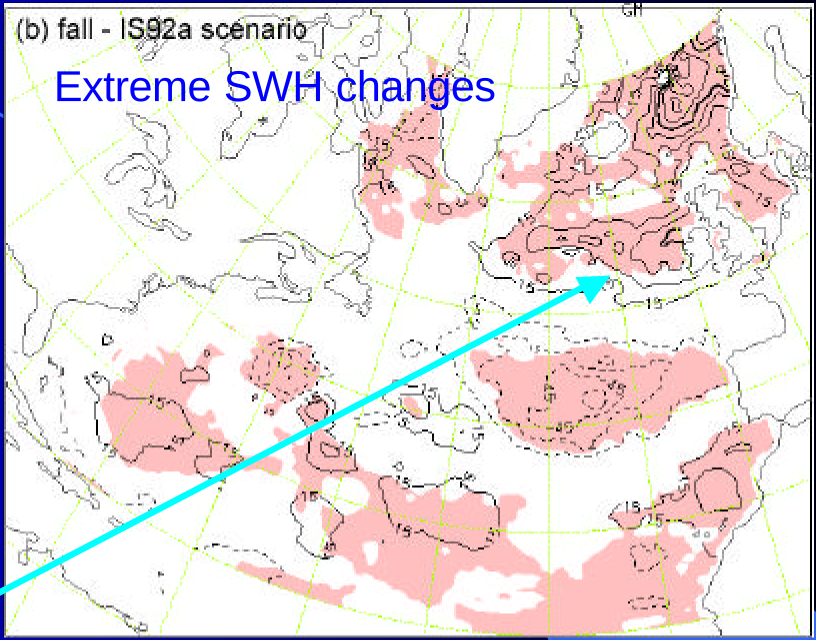
More in my next presentation

Red: ⬆ Blue: ⬇
Large dots: >= 95% conf.

Related SWH climate changes (2080s minus 1970s) – NA

(IS92a scenario)

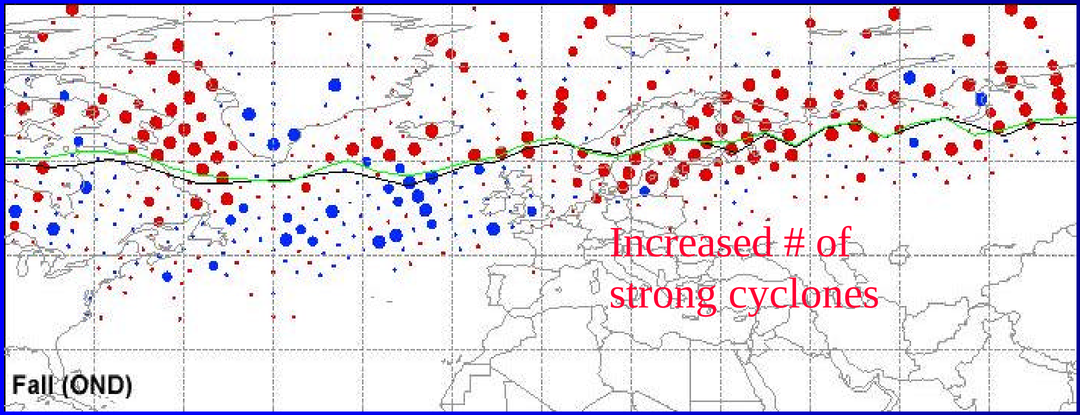




West- & southeast-ward expanded Icelandic low

~ positive NAO

~ SLP gradient & stronger westerly:



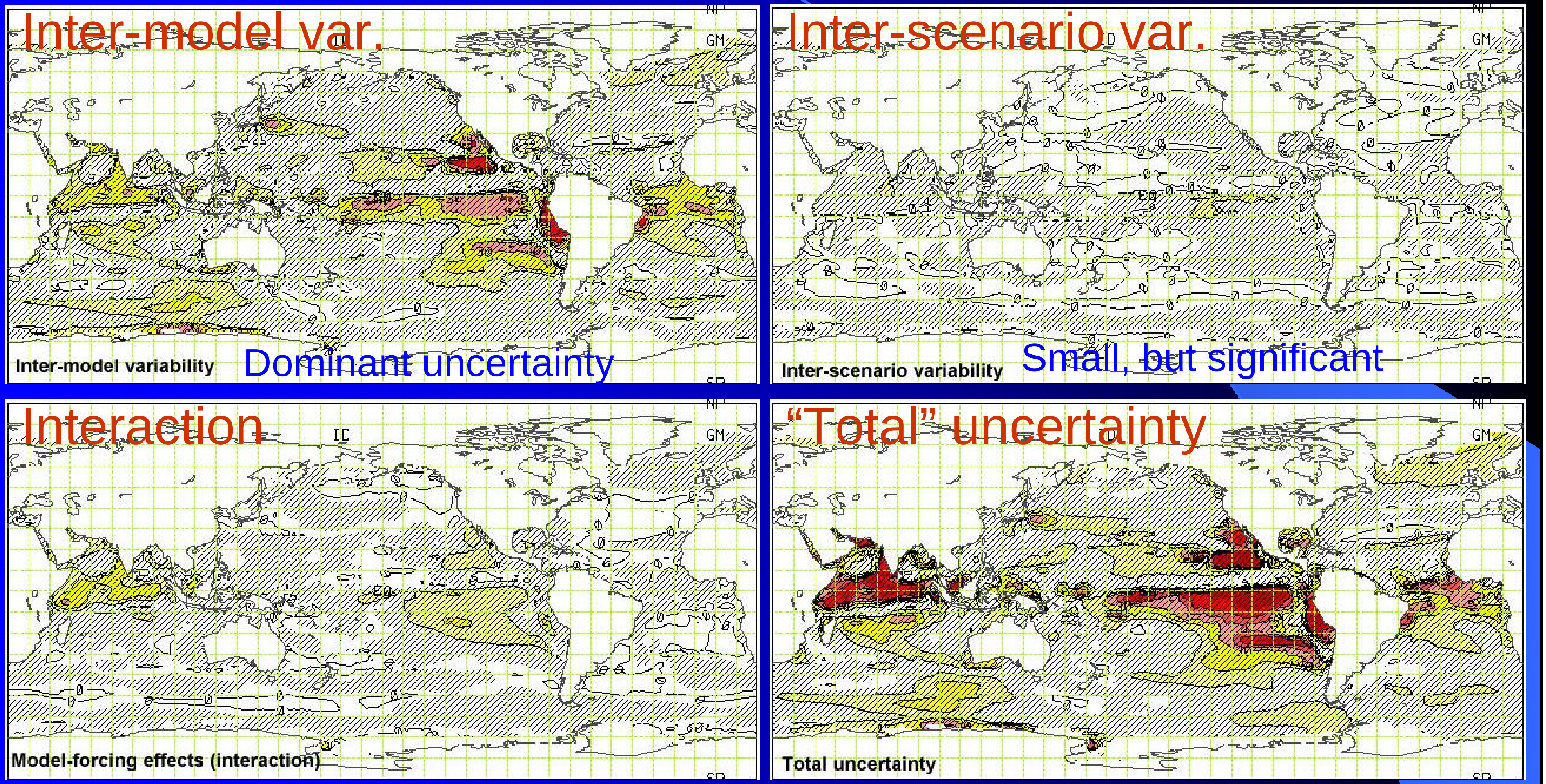
Red: Blue:
Large dots: >= 95% conf.

Wang and Swail 2004

Characteristics of uncertainties

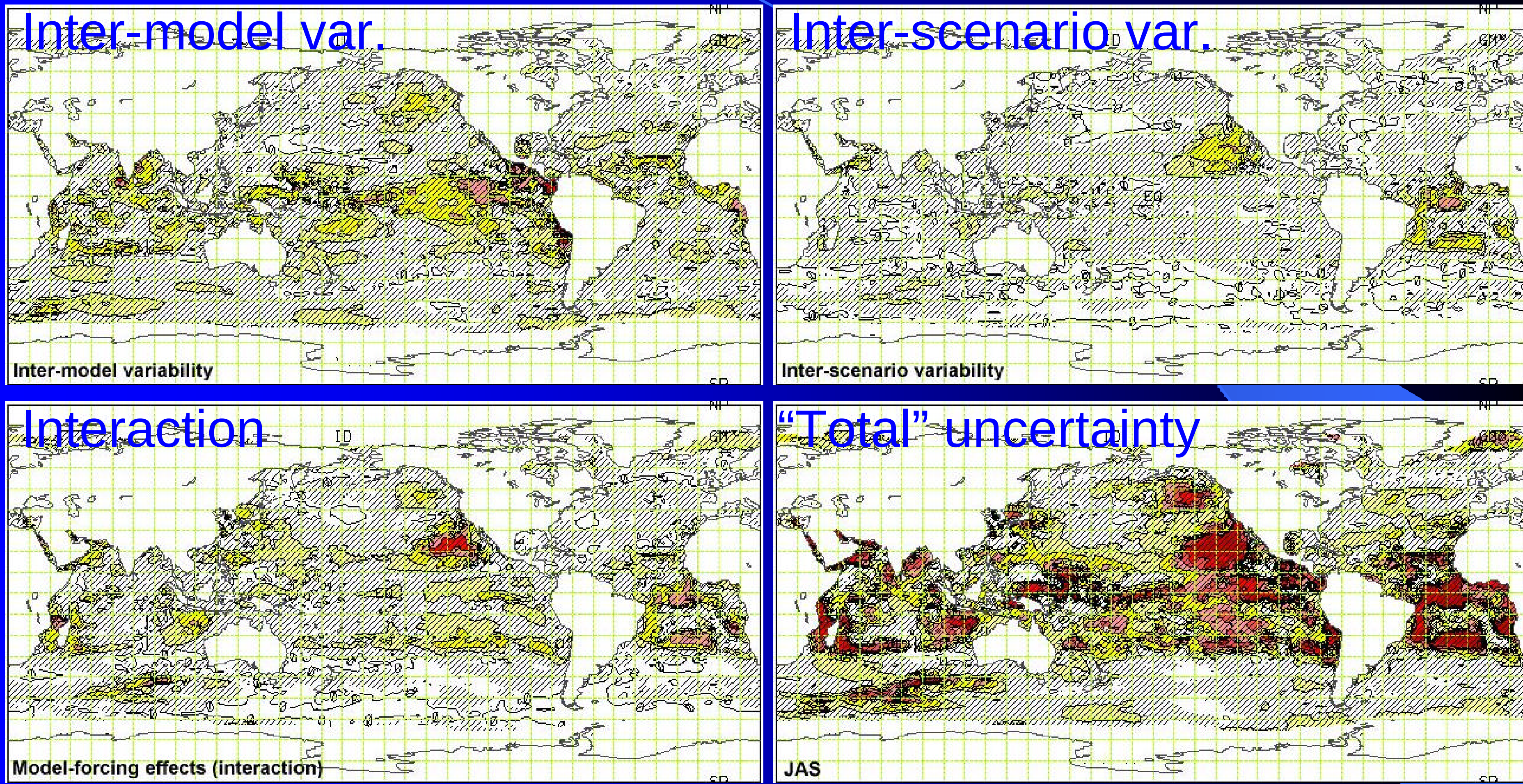
Model & forcing uncertainties - JFM mean – Var.%

Hatching: >= 95% confidence   Contour interval: 10%



Similar in the other seasons

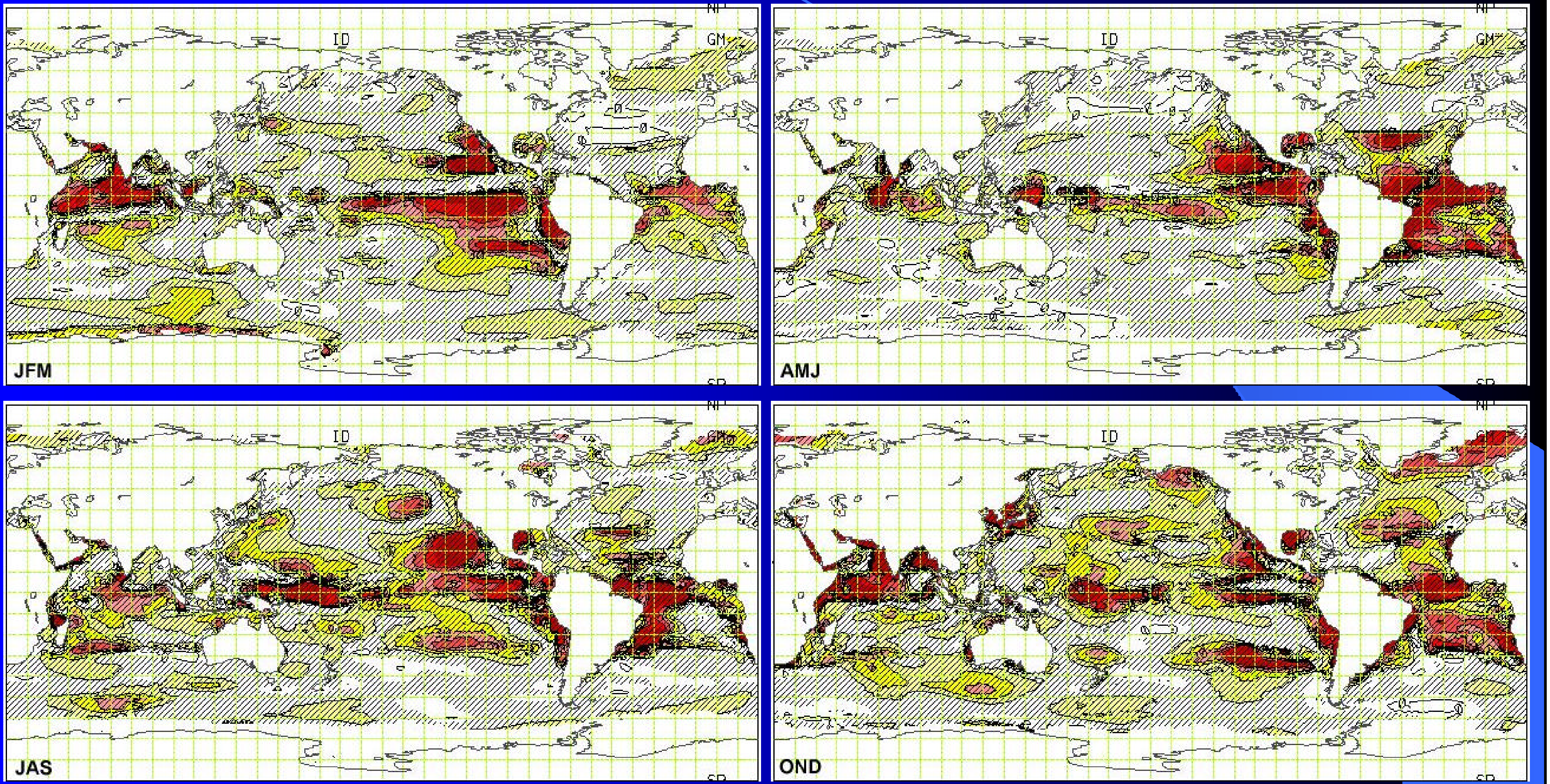
Model & forcing uncertainties - JAS extreme – Var.%



Contour interval: 10%   Hatching: >= 95% confidence

"Total" uncertainty – mean SWH – Var.%

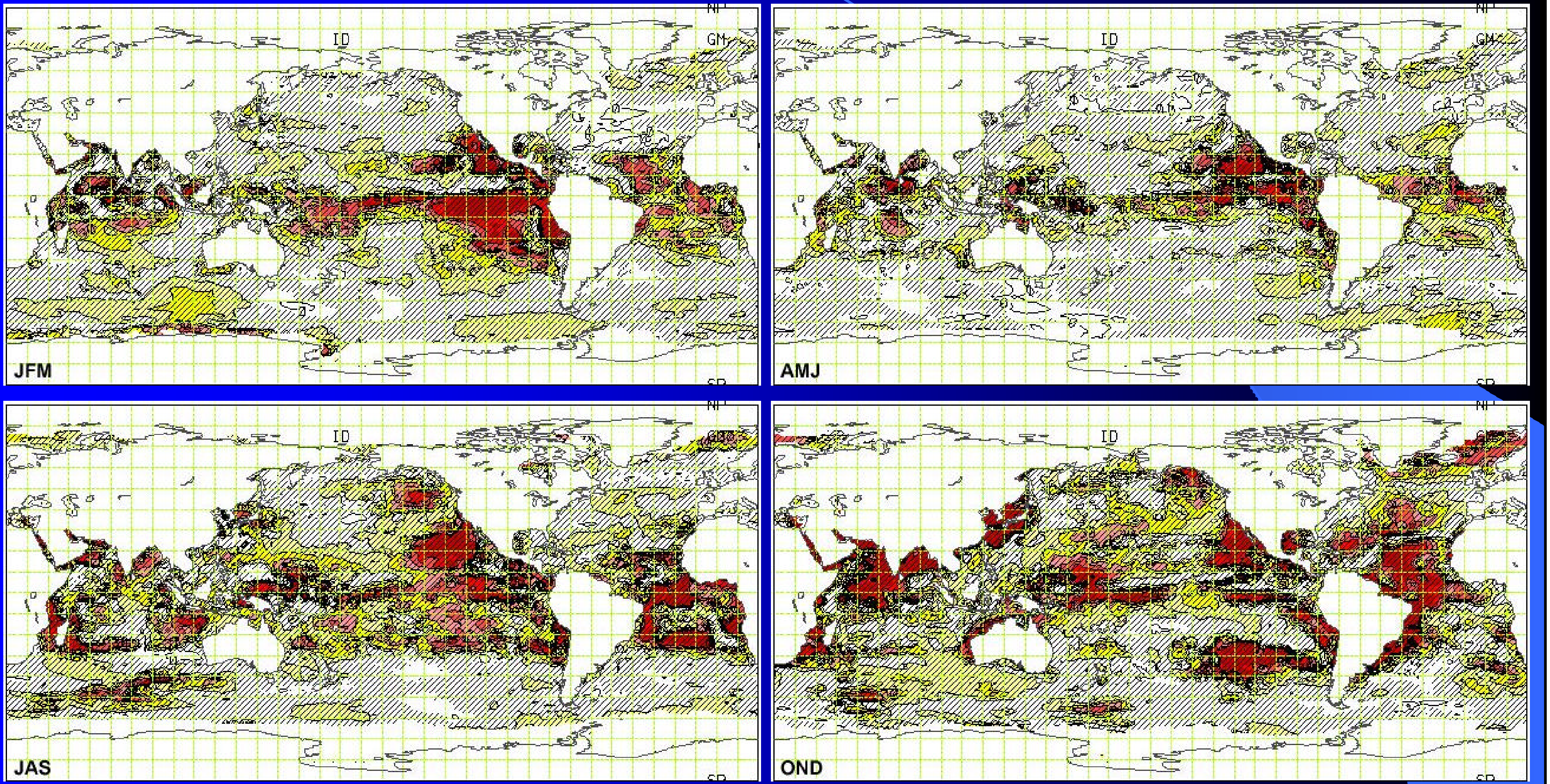
Small in mid-high lat., large in the tropics; less extensive in AMJ & JFM



Contour interval: 10% Hatching: >= 95% confidence

“Total” uncertainty – extreme SWH – Var.%

Similar: small in mid-high lat., large in the tropics; less extensive in AMJ & JFM

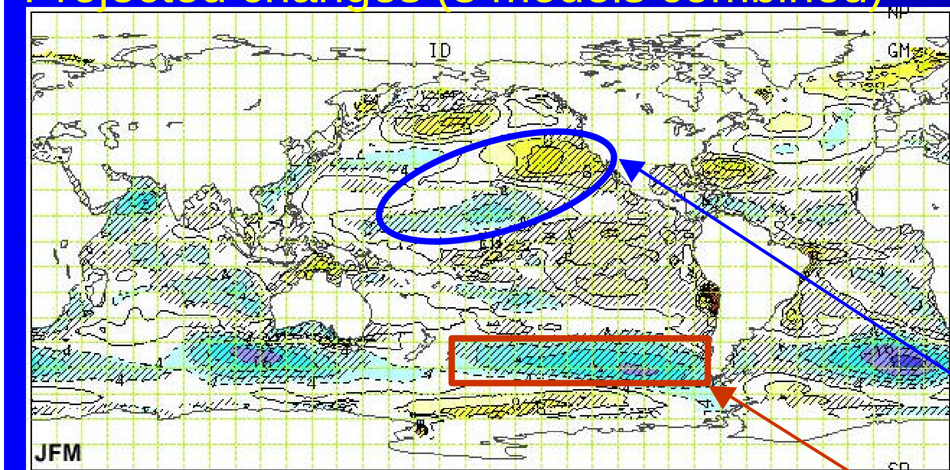


Contour interval: 10% Hatching: >= 95% confidence

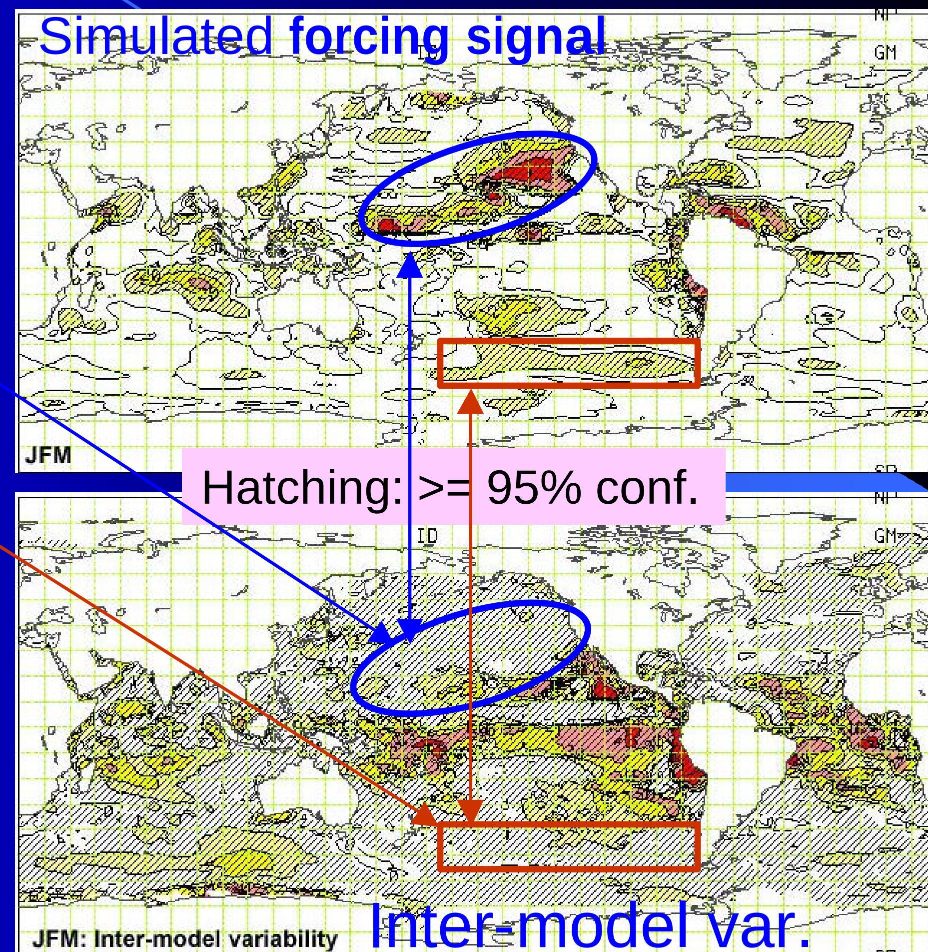
Wang and Swail 2004

JFM seasonal mean SWH

Projected changes (3 models combined)



Yellow-Red: ⬆ Cyan-Blue: ⬇



Large projected changes
– small model uncertainty
→Higher confidence?

Summary

1. Multi-model projected changes of SWH:

   > Patterns similar to those projected by the CGCM2 alone
   > Smaller magnitude of change

2. Forcing-induced variability in CGCM2 simulations:

   > Statistically significant in some areas, in all seasons
   > Largest in the mid-latitudes of NP (JFM, A2/IS92a)

Summary (cont'd)

3. Uncertainty:

> Large in the tropics, but small in the mid-high latitudes

(more confident about the projected large changes in mid-high lat.)

> Forcing uncertainty is statistically significant, although relatively small → forcing condition matters

> Development of models → reduced model uncertainty

4. The model uncertainty limited to the 3 climate models

Other sources of uncertainty not discussed here

e.g.: different RCMs, or Dynamical *vs.* Statistical, or GEV *vs.* GPD – a separate study

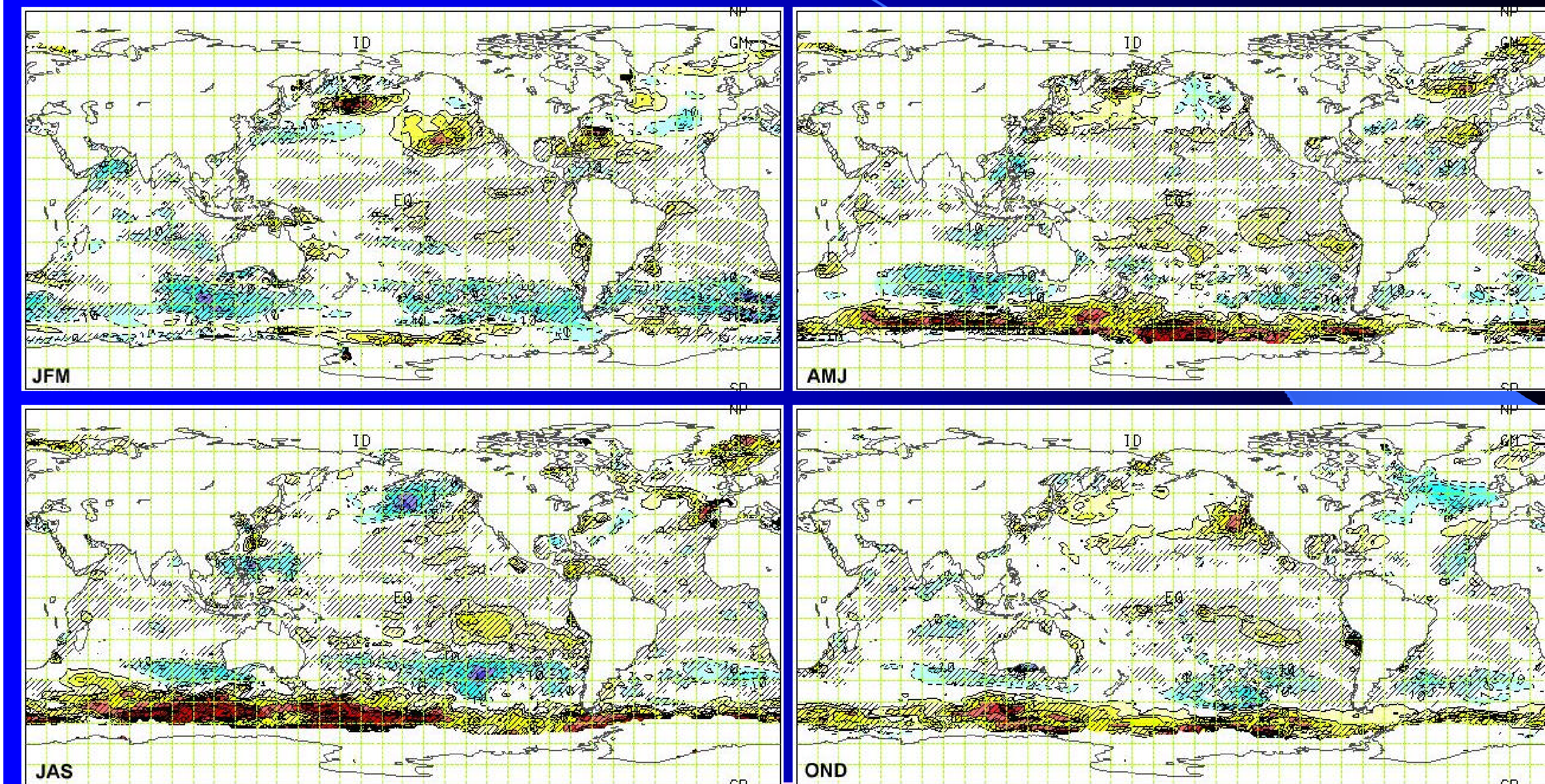
Acknowledgement

The authors are thankful to Mr. **Yang Feng** and **Ms. Qiuzi Wen** for their great computing support.

- The End -

Thank you very much!

Projected changes in <u>extreme</u> SWH – 3 models combined – A2 scenario (2080's minus 1990's)



Contour interval: 10 cm

Forcing-induced var. proportion in extreme SWH – CGCM2 - A2 scenario