Simulating the Value of El Niño Forecasts for the Panama Canal

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FACTS

- The Panama Canal requires a supply of fresh water for operations.
- Canal fresh water storage has an operational time constant of months.
- El Niño variability strongly modulates rainfall and water supply for the Canal.
- El Niño variability is somewhat predictable at lead times of 9-12 months.
- Canal inflow is modestly predictable at lead times of months.

QUESTION

- Can routine El Niño predictions be used assist in Canal operational planning?

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OUTLINE

I) DATA

II) PROJECT DESIGN

HOW TO EVALUATE THE VALUE OF EL NINO FORECASTS

III) CLIMATOLOGY AND PREDICTABILIY

CANAL INFLOW CLIMATOLOGY

RELATIONSHIPS BETWEEN EL NINO AND INFLOW

III) RESULTS

DATA

1) CLIMATE

- * NATURAL INFLOW INTO GATUN LAKE (1906-2000)
- * NIÑO3 SST (1906-2000; Smith and Reynolds, 2004)
- * PREDICTED NIÑO3 (NCEP; 1981-97; MONTHLY)

2) CANAL CHARACTERISTICS (PCA)

PROJECT DESIGN AND GOALS (1)

1) Build a basic, monthly timestep, model of the Canal system, embodying:

   a) Management objectives –

      i) Reliable lockage
      ii) Additional income through hydro-power generation
      iii) Low risk

   b) Physical constraints

      i) Gatun Lake capacity, vol. / stage, level requirements
      ii) Lockage, hydropower, spillage discharge capacities
      iii) Lockage and hydropower income

   c) Inflow predictability (3 models, each with variable uncertainty)

      i) **CLIMATE** - Assume every year inflow follows climatology
      ii) **PERFECT** - Assume future inflows are perfectly known
      iii) **FORECAST** - Inflow outlooks derived from El Nino forecasts

PROJECT DESIGN AND GOALS (2)

1) Build a basic, monthly timestep, model of the Canal system, embodying:

   a) Management objectives

   b) Physical constraints

   c) Inflow predictability (3 models, each with variable uncertainty)

2) Operate the model using probabilistic inflow outlooks (i, ii, iii) using an optimizer to simulate management with objective forecast information.

3) Evaluate performance of simulated system in terms of added value and operational reliability afforded by El Nino forecast information and formal inclusion of uncertainty.

CLIMATOLOGY AND PREDICTABILITY

- CANAL INFLOWS HAVE A STRONG ANNUAL CYCLE
- EL NIÑO VARIABILITY MODULATES CANAL REGION RAINFALL AND INFLOWS.
- THE STRENGTH OF THE RELATIONSHIP BETWEEN EL NIÑO AND FLOW VARIES FROM STRONG TO VERY WEAK DURING THE YEAR.

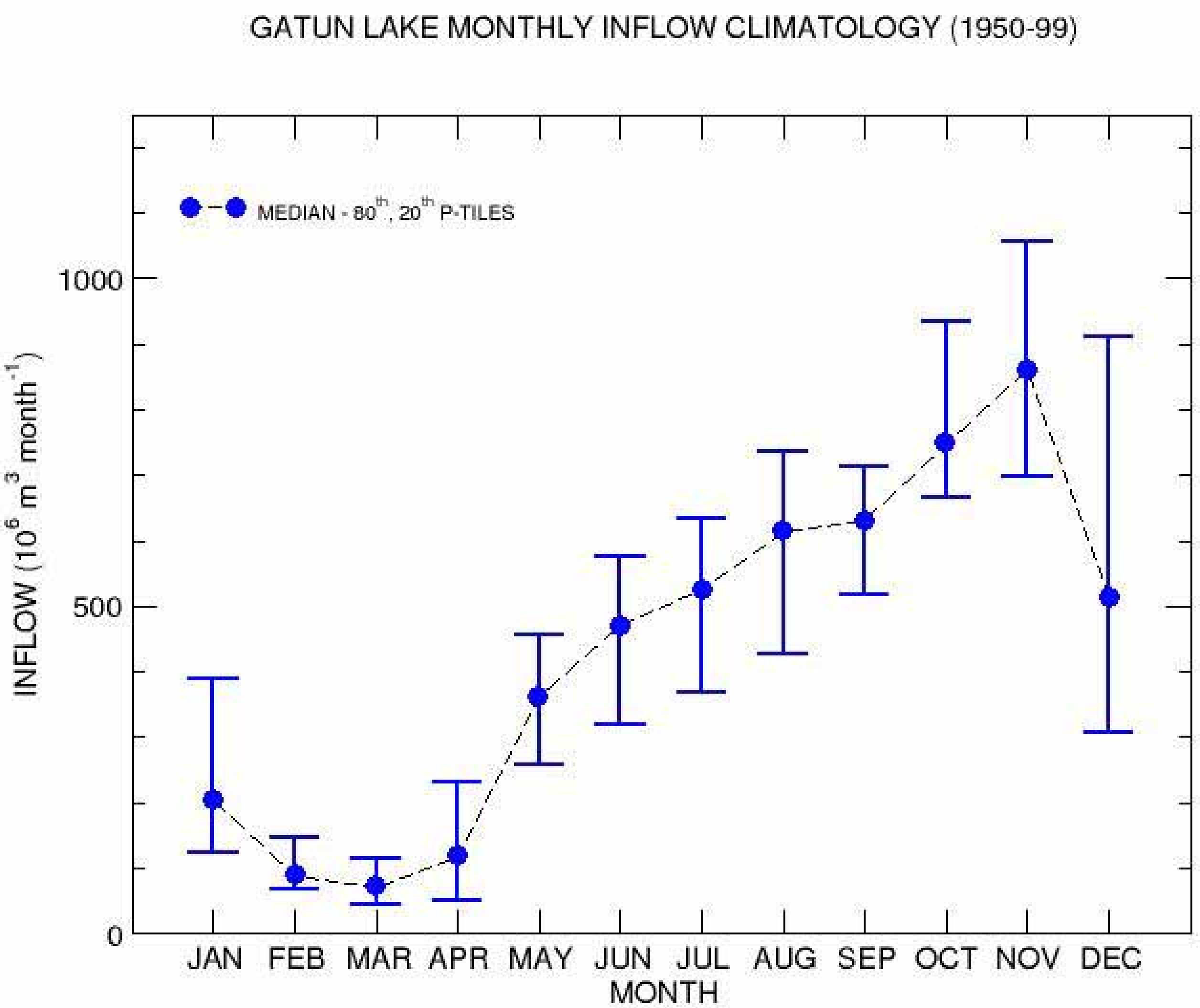

GATUN LAKE MONTHLY INFLOW CLIMATOLOGY (1950-99)
MEDIAN - 80th, 20th P-TILES
INFLOW (10^6 m^3 $month^{-1}$)
1000
500
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH

FIG. 2

CORRELATIONS:
WATER YEAR GATUN INFLOW vs NINO3 SST
1915-1999

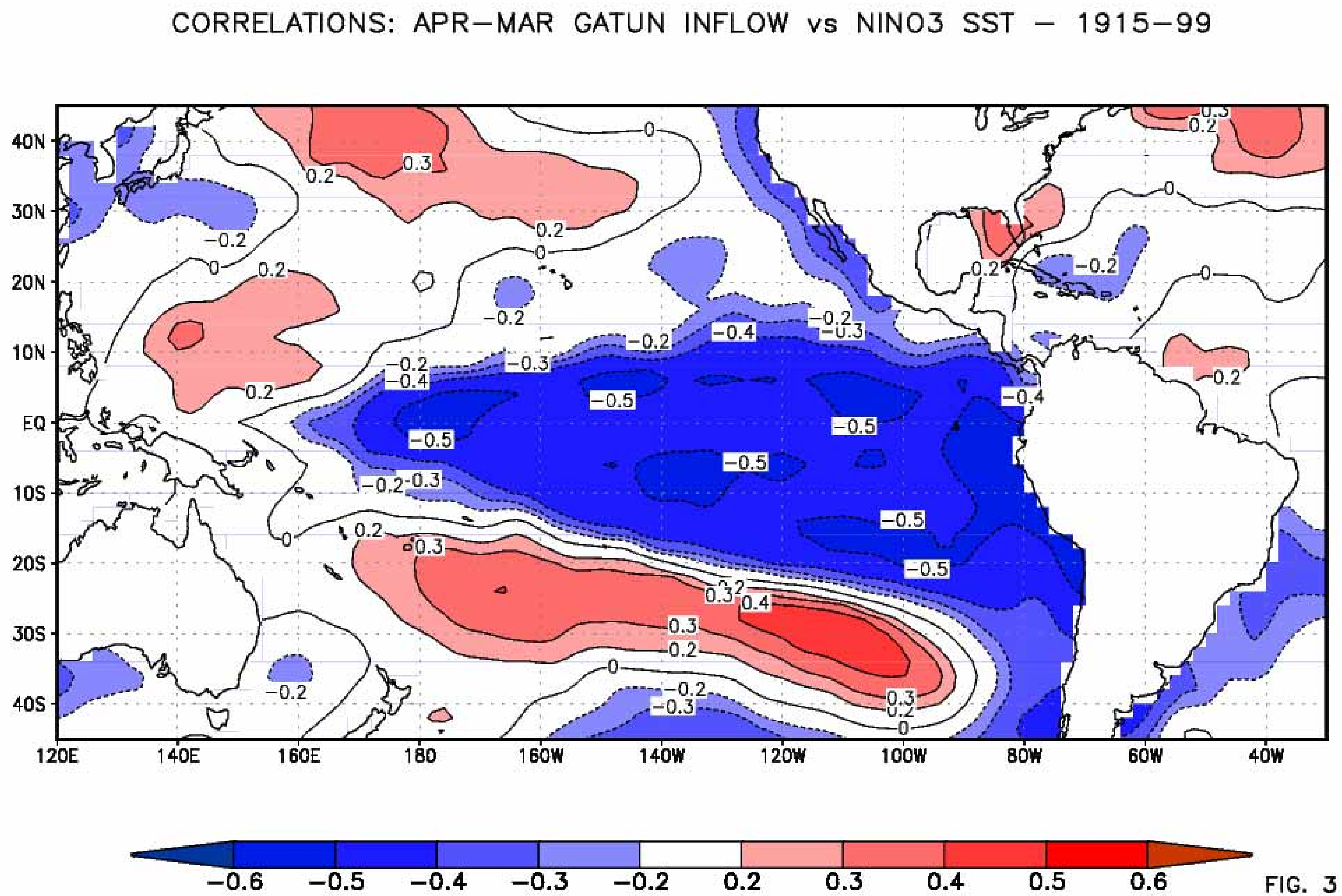
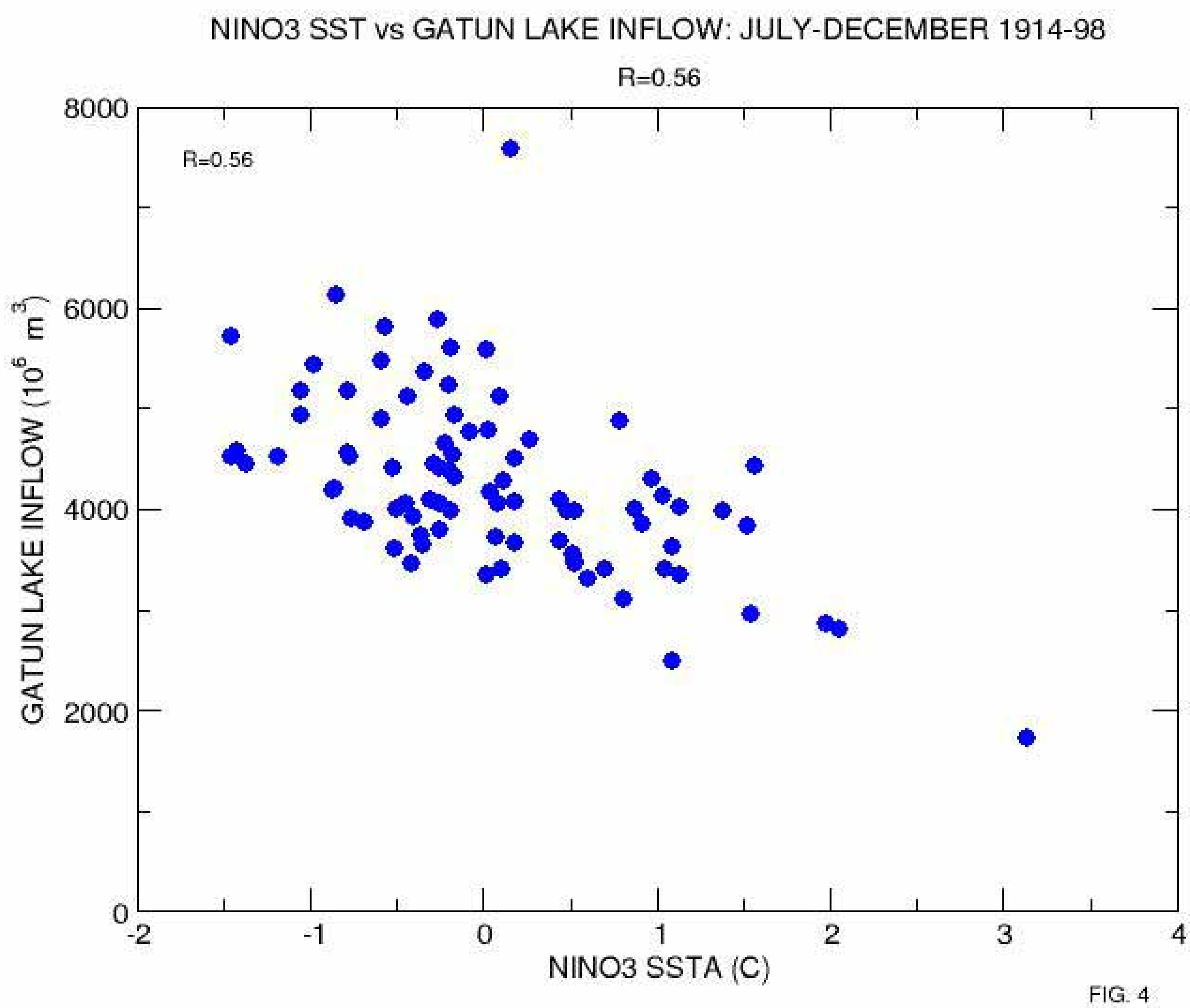
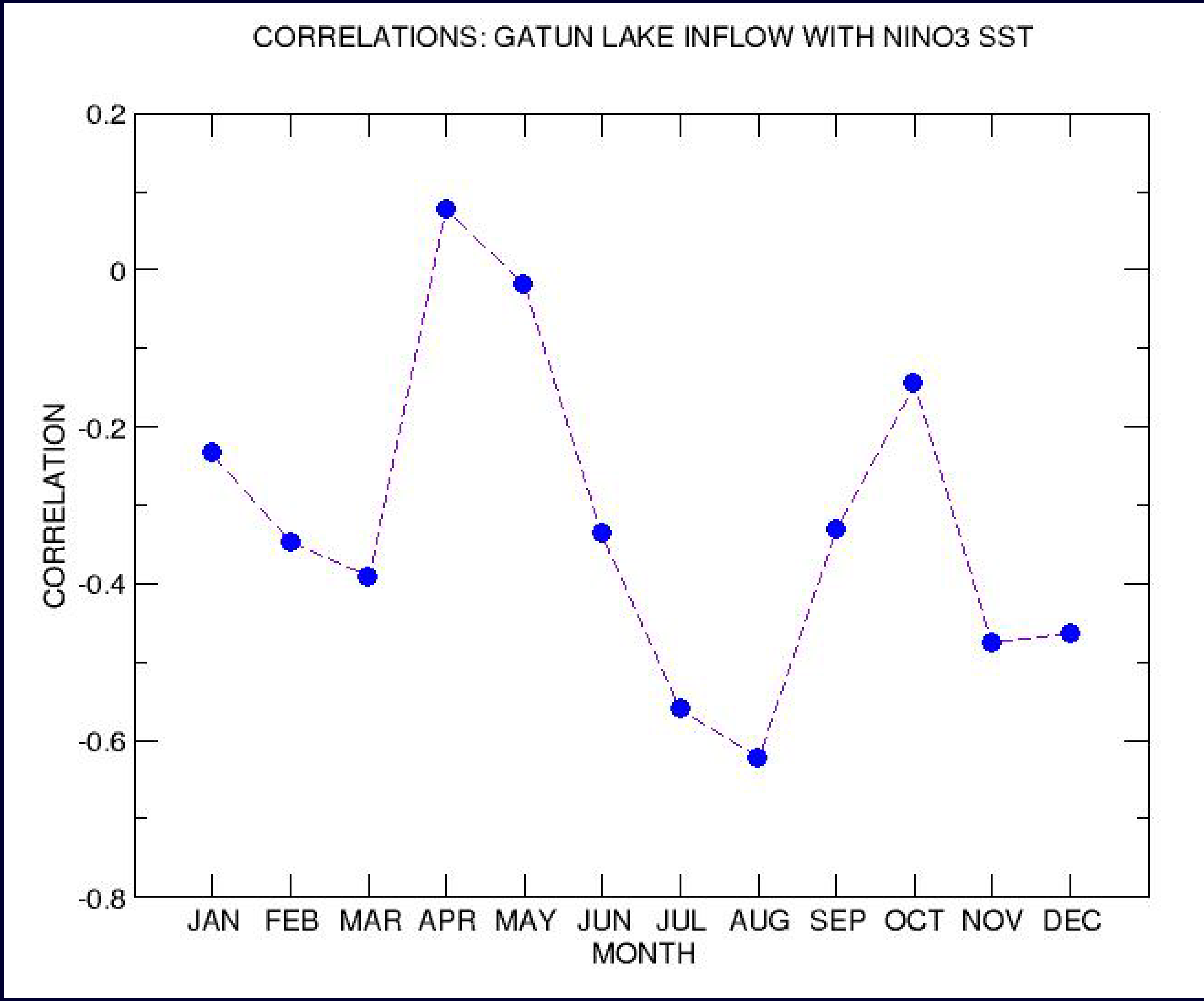


FIG. 3


NINO3 SST vs GATUN LAKE INFLOW: JULY-DECEMBER 1914-98
R=0.56
R=0.56
GATUN LAKE INFLOW (10^6 m^3)
NINO3 SSTA (C)
0
2000
4000
6000
8000
-2
-1
0
1
2
3
4
FIG. 4


CORRELATIONS: GATUN LAKE INFLOW WITH NINO3 SST
0.2
0
-0.2
-0.4
-0.6
-0.8
CORRELATION
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
MONTH

EL NIÑO VARIABILITY IS PREDICTABLE

OPERATIONAL NINO3 SST PREDICTION CORRELATIONS
1981-1998

FORECAST LEAD TIME (MONTHS)

VERIFICATION MONTH	1	2	3	4	5	6	7	8	9	10	11
1	98	96	98	95	86	86	73	81	52	54	33
2	98	94	94	92	92	79	83	72	81	63	41
3	96	90	94	94	85	79	76	82	74	83	67
4	92	89	84	81	73	73	54	48	64	71	68
5	96	86	83	81	70	62	34	64	40	47	72
6	96	89	91	76	77	61	49	24	72	19	36
7	97	93	78	80	65	60	60	53	26	52	27
8	97	92	90	77	71	71	41	71	48	19	55
9	97	86	82	85	65	49	75	37	65	32	9
10	98	91	78	80	87	60	58	76	29	63	34
11	99	97	89	85	84	88	56	63	55	34	55
12	99	98	94	86	82	78	85	57	65	47	36

EL NINO PREDICTIONS REDUCE UNCERTAINTY IN INFLOW OUTLOOKS

FRACTIONAL REDUCTIONS IN INFLOW UNCERTAINTY (RMS)
COMPARED WITH CLIMATOLOGY

USING OPERATIONAL NINO3 SST PREDICTIONS
1981-1998

FORECAST LEAD TIME (MONTHS)

VERIFICATION MONTH	1	2	3	4	5	6
1	92	94	93	93	95	96
2	89	81	85	83	81	91
3	88	90	89	89	90	86
4	100	100	100	97	95	96
5	99	99	99	99	99	99
6	103	97	101	97	103	97
7	83	84	82	86	90	100
8	75	75	70	75	78	76
9	94	96	94	94	96	100
10	99	99	97	97	98	96
11	83	85	83	80	85	78
12	76	78	77	85	88	84

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CANAL SIMULATION SYSTEM

- INITIAL STATE (GATUN LAKE VOLUME)
- GATUN LAKE CAPACITY – LEVEL / VOLUME RELATIONSHIP
- LOCKAGE REQUIREMENTS, WATER USE
- HYDROPOWER REQUREMENTS, WATER USE
- SPILL LEVEL, POSSIBLE RANGES
- EVAPORATION, MUNICIPAL WATER REQUIREMENTS
- EXISTING RULE CURVE

- LOCKAGE INCOME
- HYDROPOWER INCOME

- PROBABILISTIC INFLOW PROJECTIONS (6 MONTH HORIZON)

- OPTIMIZER and VIRTUAL MANAGER

PANAMA CANAL SIMULATION SYSTEM

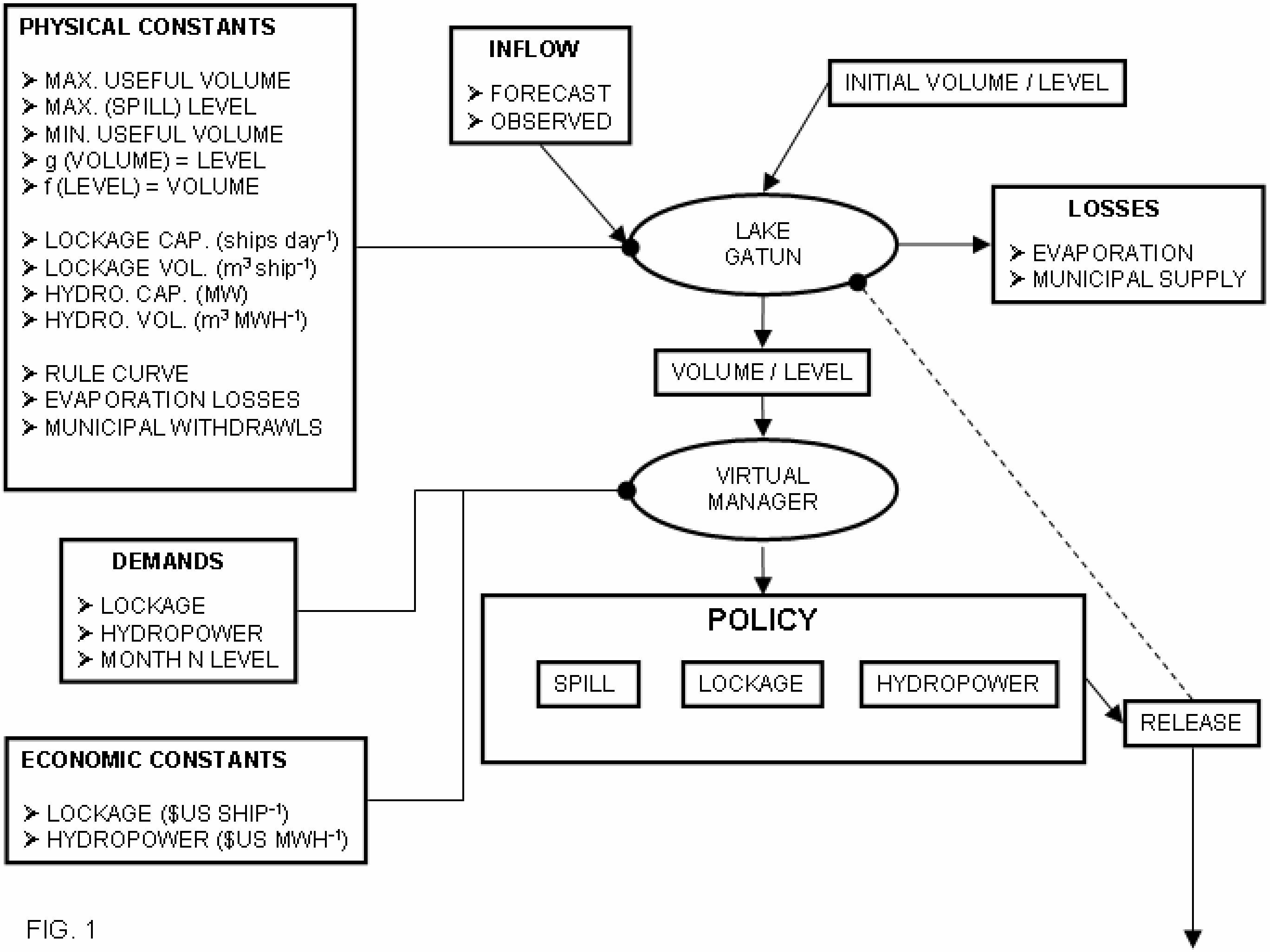


FIG. 1

PARAMETERS FOR SIMULATED PANAMA CANAL SYSTEM

GATUN LAKE PARAMETERS

Useful volume (VU) – 766 Mm3
Lowest useful level (HL) – 24.84 m
Maximum (spill) level (HU) – 26.67 m
Evaporation and Municipal withdrawal (E) 6.16 Mm3 month^{-1}
Maximum spill rate (RUS) – 13358.30 Mm3 month-1
Actual spill rate per month (RS) Mm3
Rule curve level for a particular month (H*m) m
Actual level for a particular month (H*m) m

CANAL PARAMETERS

Volume required per unit ship passage (VL) – 196,820 m3 ship^{-1}
Maximum number of ships per month (SU) – 1200 ships month^{-1}
Maximum lockage volume per month (RUL) – 236.18 Mm3 month^{-1}
Actual lockage volume per month (RL)
Volume required per unit MWH hydropower production (VH) – 19,114 m3 MWH^{-1}
Maximum hydropower production per month – 17,280 MWH month^{-1}
Maximum hydropower volume per month (RUH)– 330.29 Mm3 month^{-1}
Actual hydropower volume per month (RH)

INCOME PARAMETERS

Income per ship passage (iL) – $US 50,000
Maximum lockage income per month (IUL) - $US 60M
Actual lockage income per month (IL)
Income per MWH (iH) - $US 50
Maximum hydropower income per month (IUH)- $US 864,000
Actual hydropower production per month (IH)
Maximum possible total income per month (IMAX) - $US 60.864M

ASSESSING PERFORMANCE OF CANAL SIMULATIONS

- Start with initial state at time t (Gatun Lake volume)
- Use inflow outlook (probabilistic) for next 6 months
- Derive optimal feasible policy (lockage, hydropower, spill) for next 6 months.
- Execute optimal feasible policy for ONE month (to t+1)
- Tabulate results with respect to objectives
- Update state (Gatun Lake volume) with OBSERVED inflow
- Repeat

ASSESSING PERFORMANCE OF CANAL SIMULATIONS

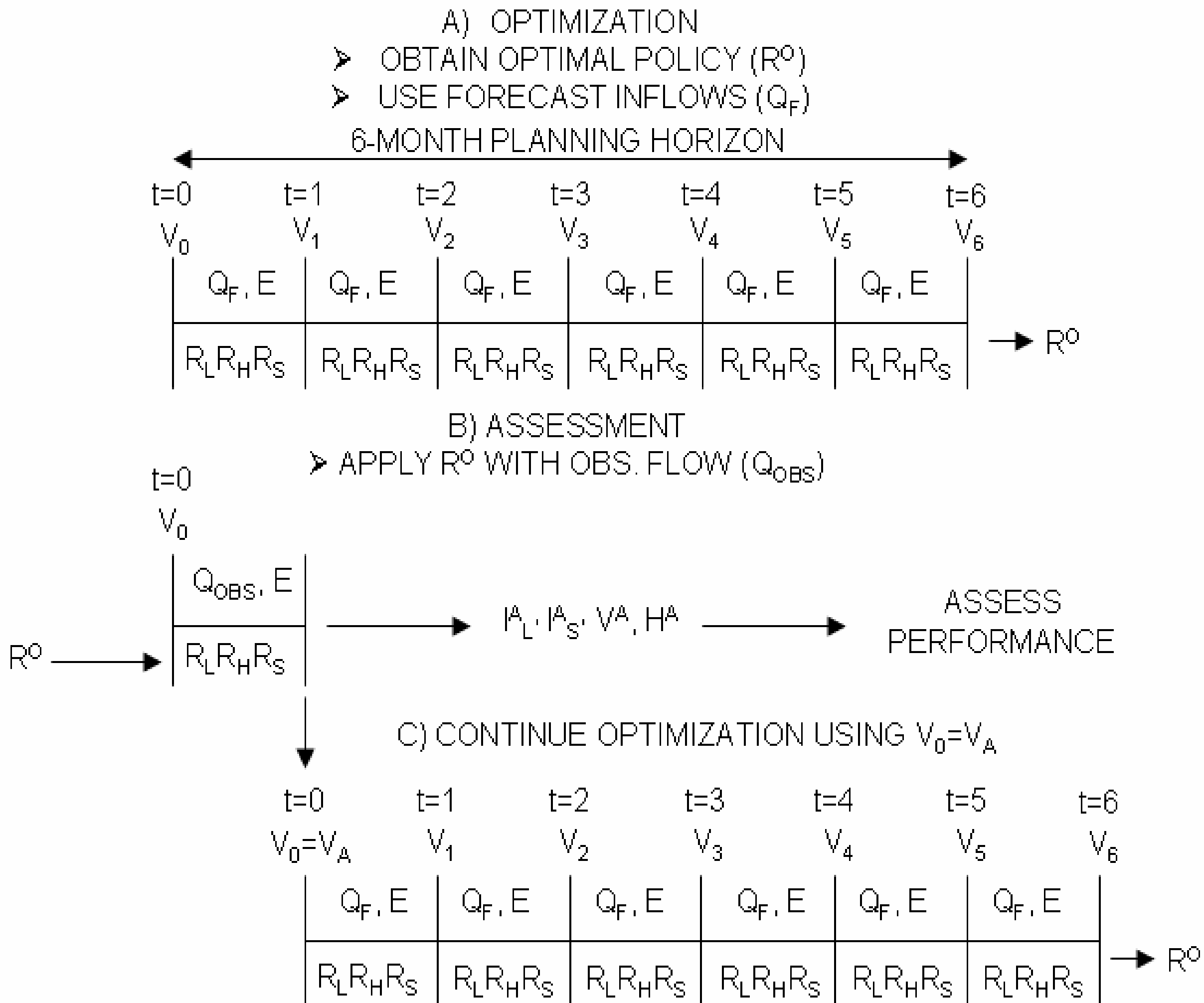


FIG. 6

RESULTS

3 SETS OF SIMULATIONS

1) **PERFECT** – PERFECT FORESIGHT.

NOMINAL UNCERTAINTY: ~ZERO

2) **FORECAST** – USE INFLOWS DERIVED FROM EL NIÑO FORECASTS.

NOMINAL UNCERTAINTY: MEAN-SQUARE FORECAST ERROR.

3) **CLIMATE** – INFLOWS ARE FROM LONG-TERM CLIMATOLOGY.

NOMINAL UNCERTAINTY: MEAN-SQUARE CLIMATOLOGY ERROR

EACH SET OF SIMULATIONS IS ASSIGNED THE NOMINAL UNCERTAINTY, AND ALSO VALUES RANGING FROM SMALL TO LARGE.

THIS ALLOW US TO SEE THE SENSIVITY TO CHANGES IN:

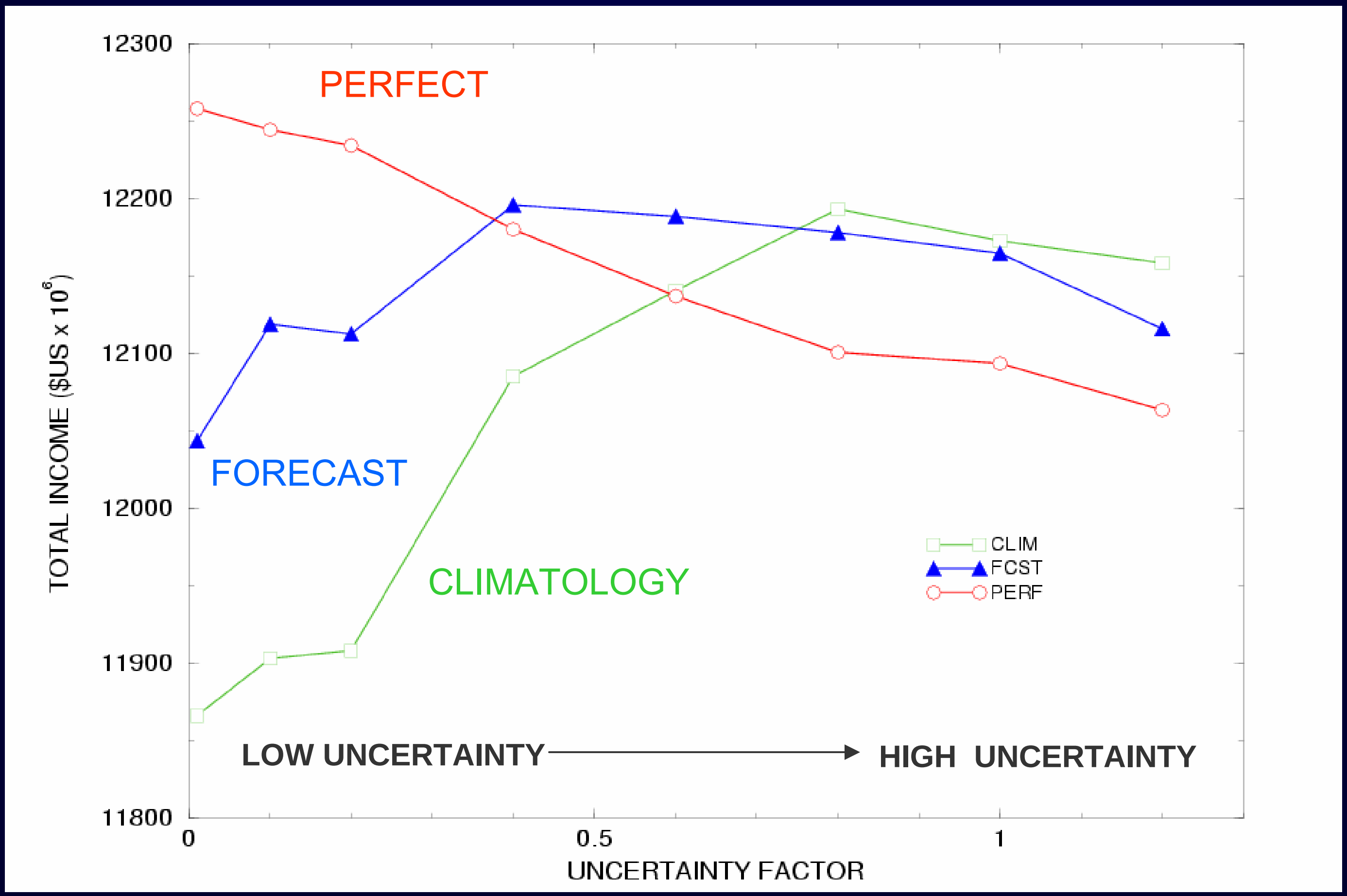
A) THE SKILL OF THE MEAN PREDICTION

B) THE ASSOCIATED UNCERTAINTY

UNCERTAINTY vs TOTAL CANAL INCOME (1981-1997)

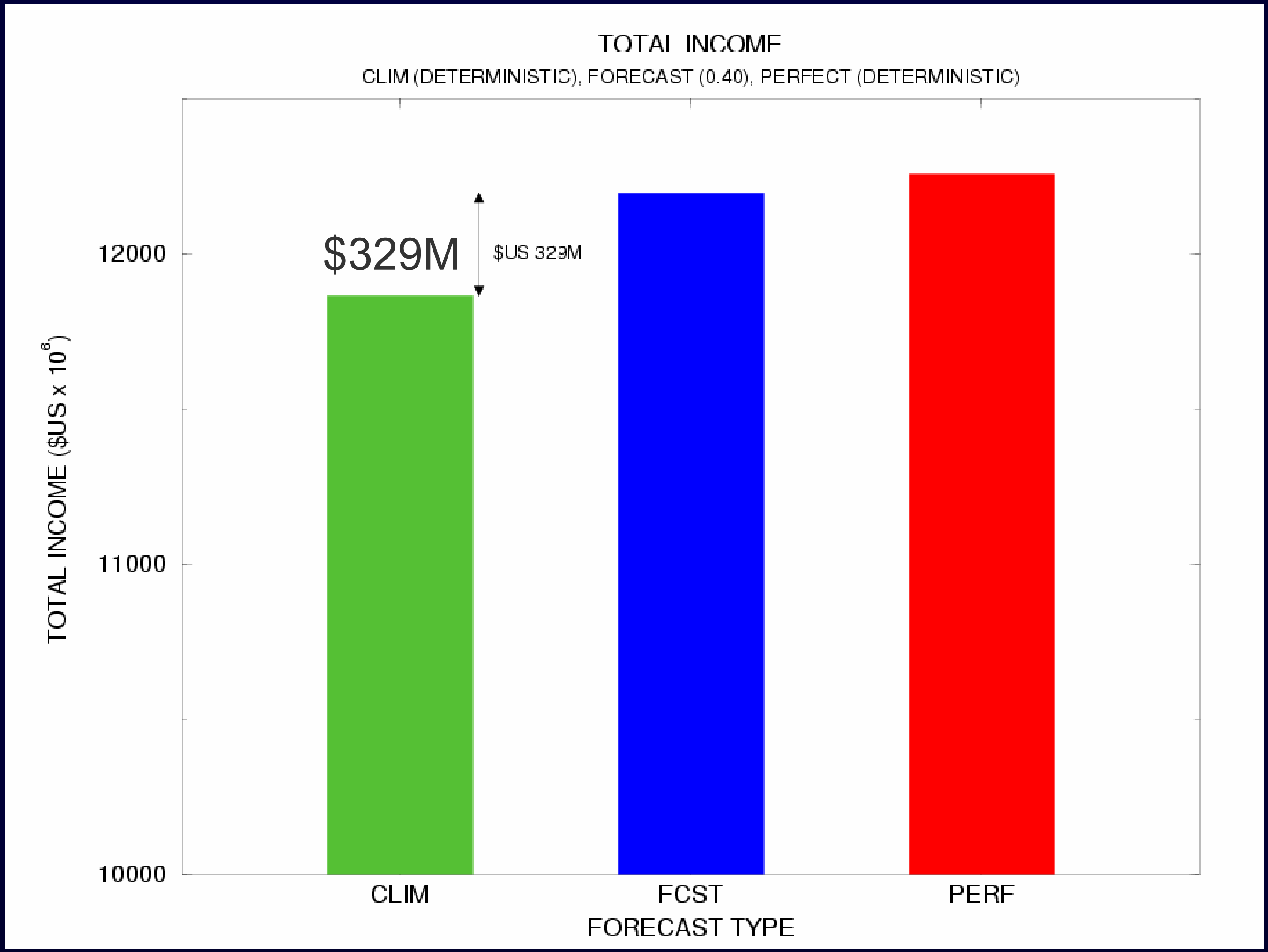
DOES EL NIÑO FORECAST INFORMATION HELP?

NOTICE THE EFFECT ON INCORRECTLY SPECIFIED UNCERTAINTY



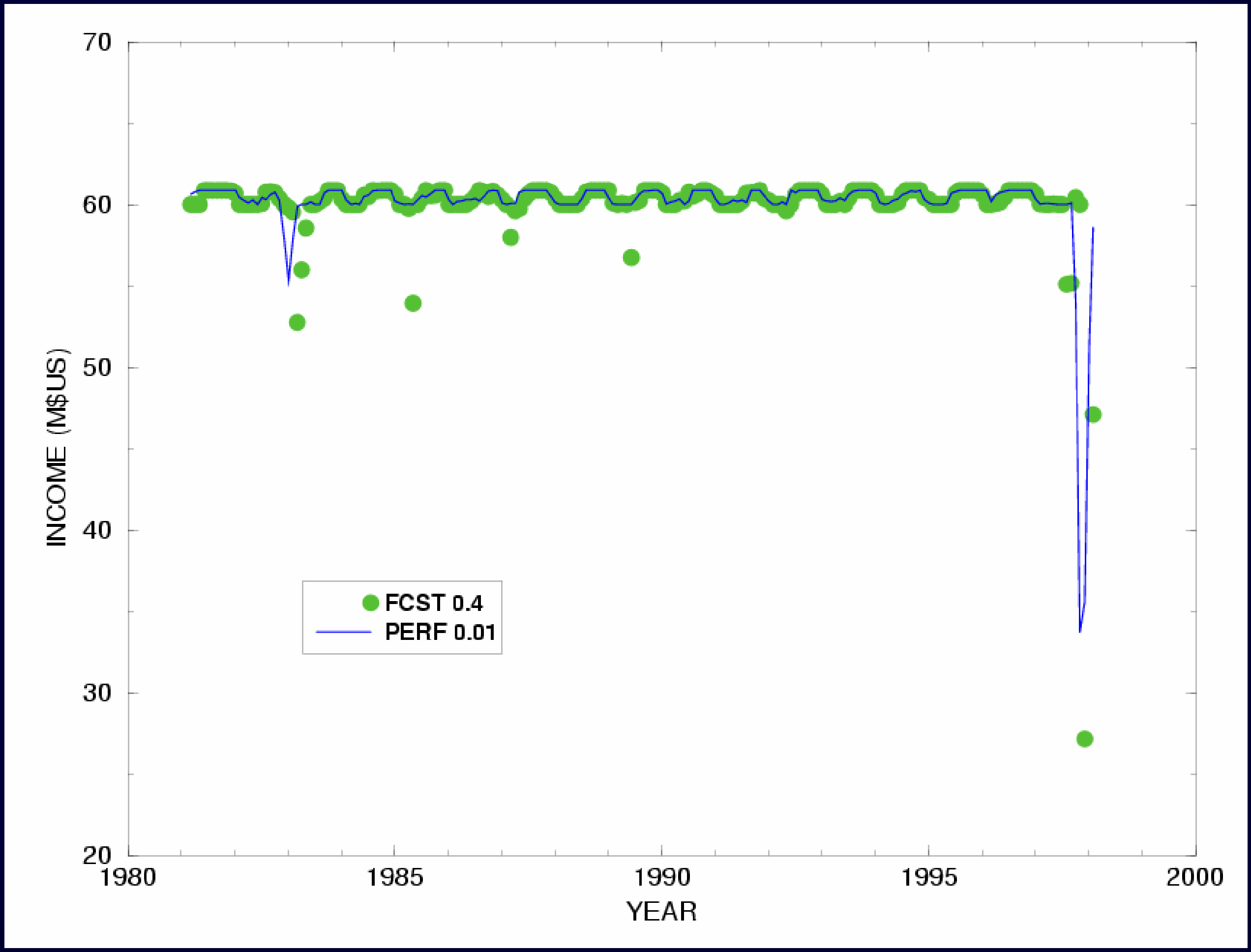
COMPARISON OF TOTAL INCOME (1981-1997)

CLIMATOLOGY - DETERMINISTIC
FORECAST – UNCERTAINTY 0.4
PERFECT - DETERMINISTIC

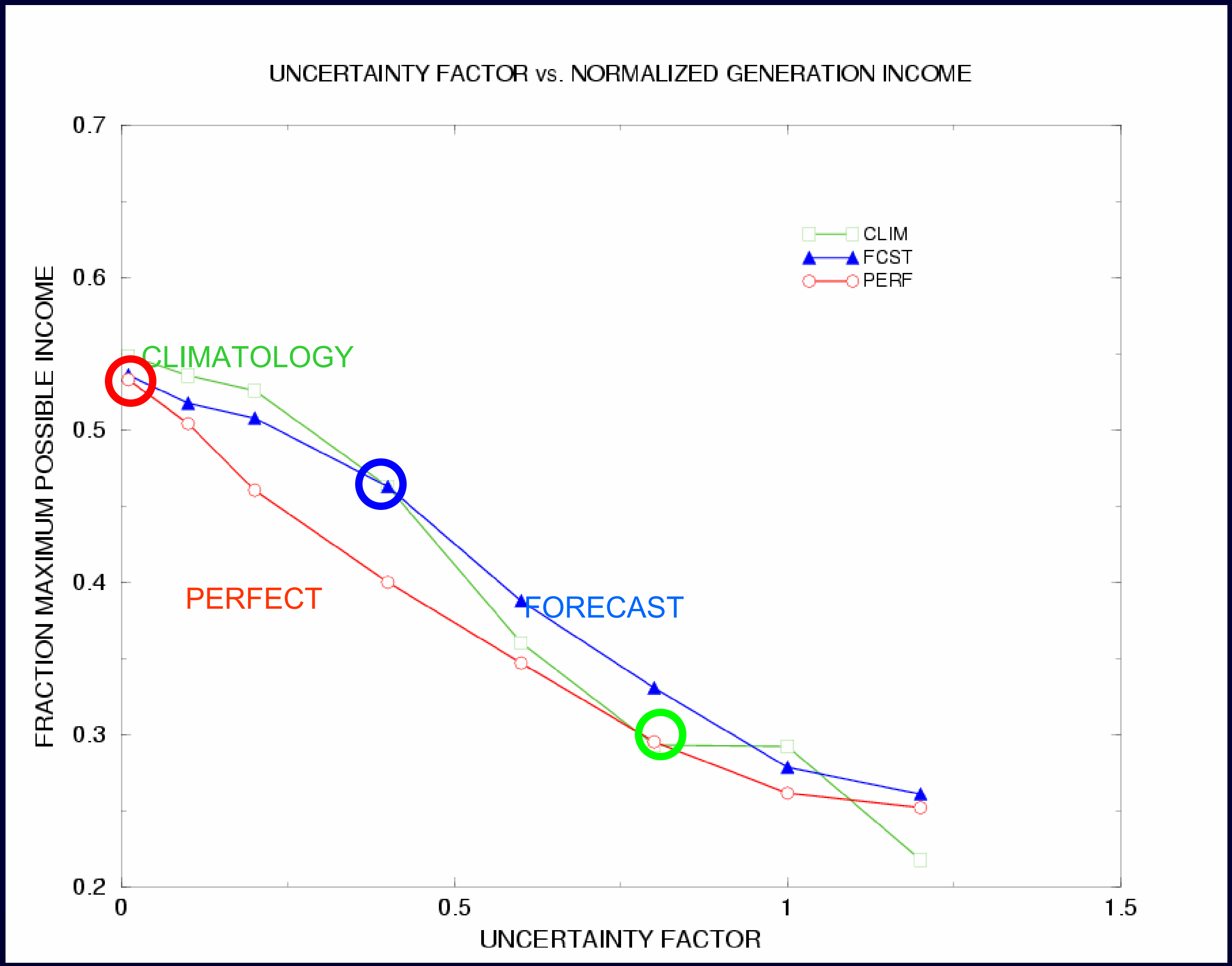


EXAMPLE OF MONTHLY INCOMES:
PERFECT AND FORECAST MODELS

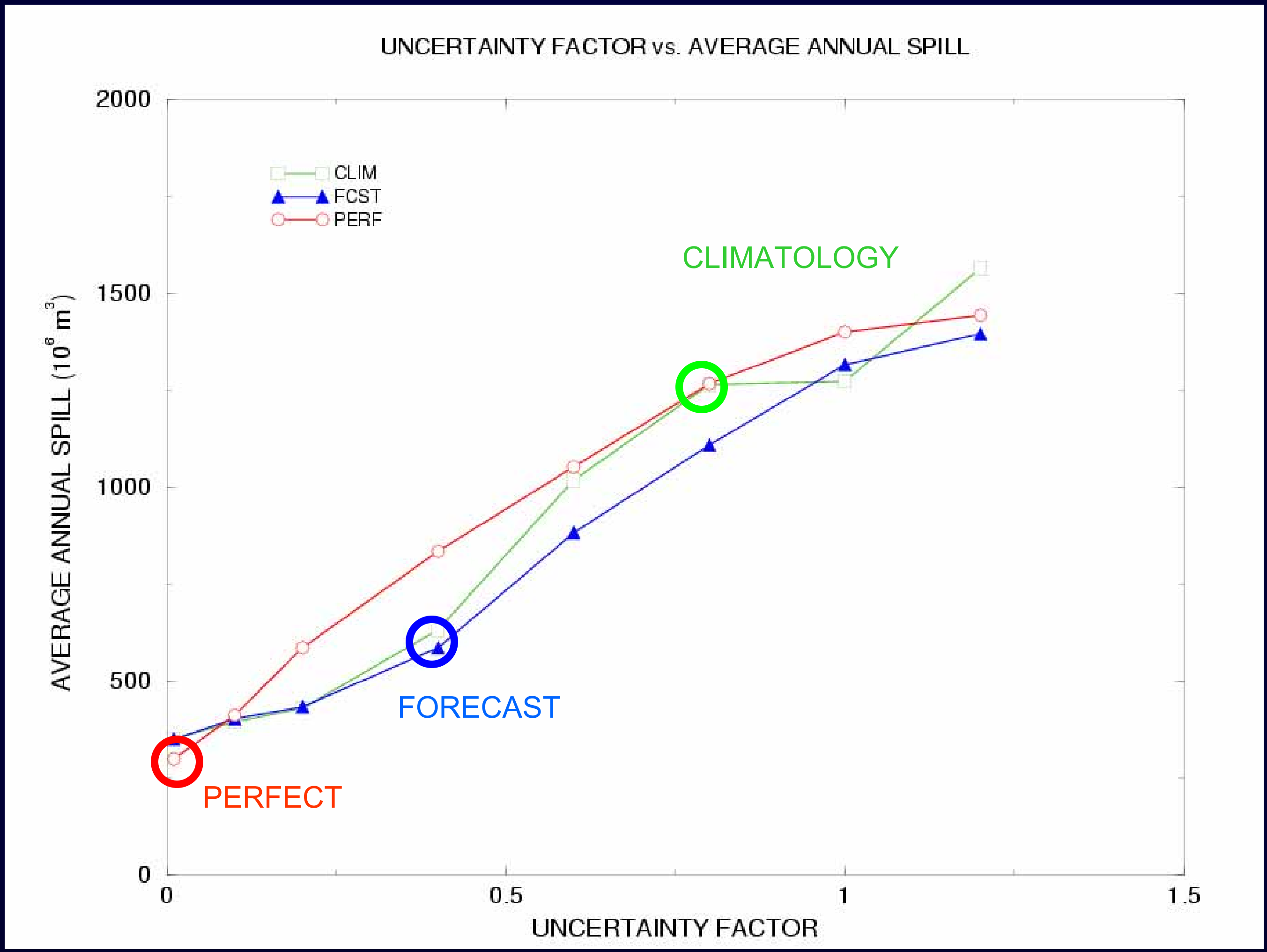
IN GENERAL, THE CANAL PERFORMS ROBUSTLY



NORMALIZED HYDRO-POWER INCOME



AVERAGE SPILL

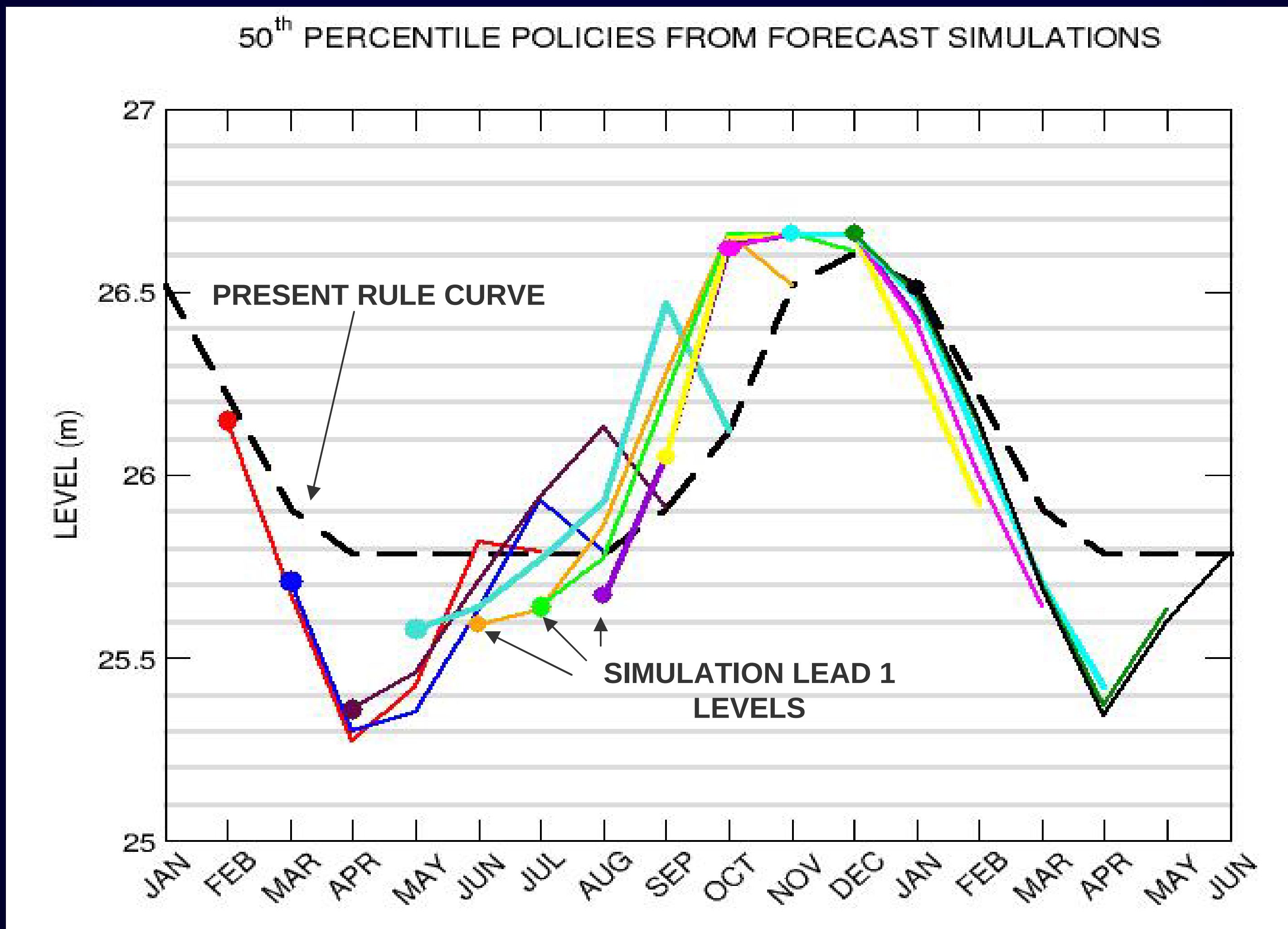


COMPARISON OF BEHAVIOR:

EXISTING RULE CURVE vs FORECAST SIMULATION

EFFECT IS TO **TAKE BETTER ADVANTAGE OF EXISTING SUPPLY**

CIRCLES INDICATE MONTH 1 (VERIFICATION) LEVELS
FOR EACH CALENDER MONTH



TEST BEHAVIOR OF CANAL TO INCREASED LOCKAGE DEMAND

40 SHIPS PER DAY

48 SHIPS PER DAY

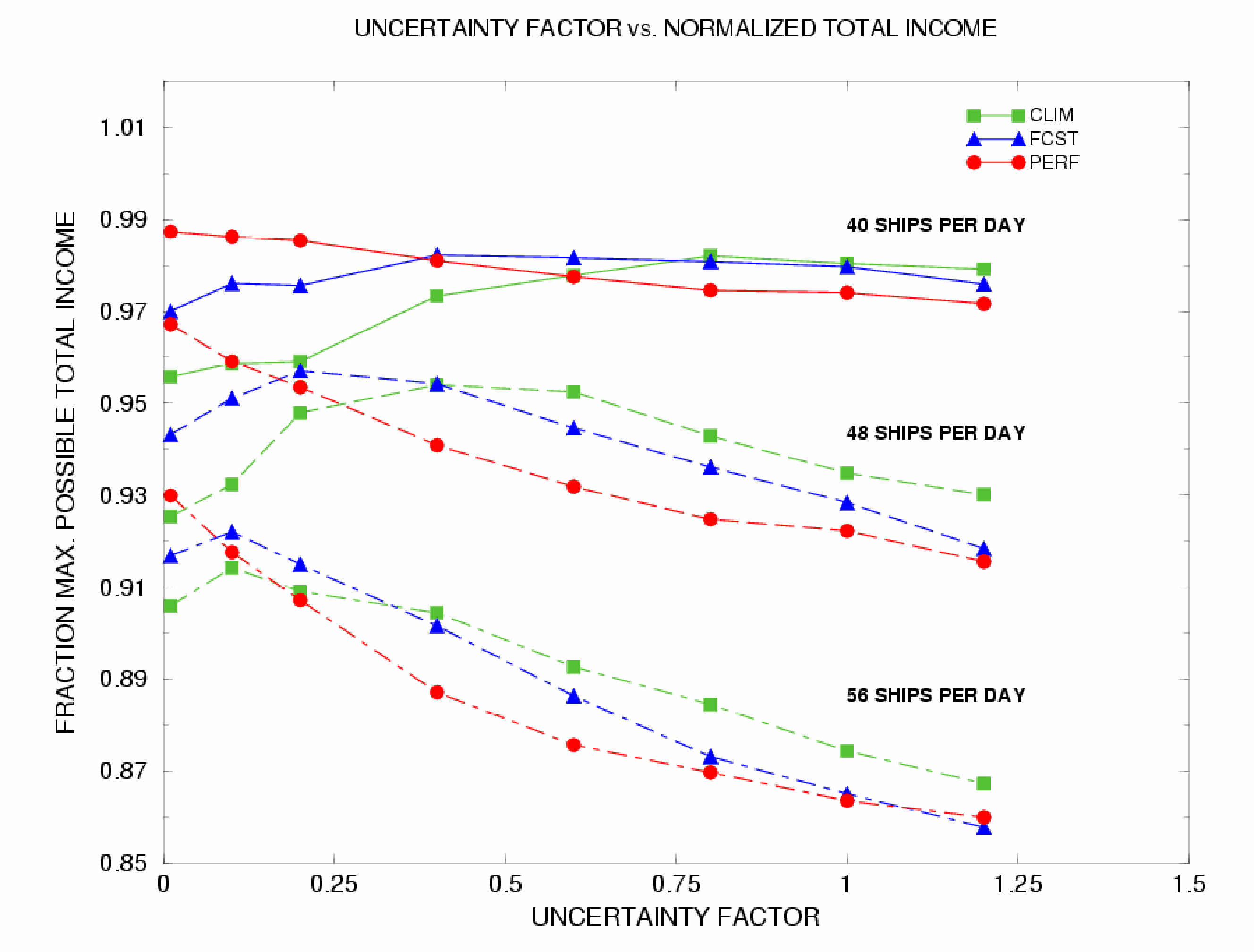
56 SHIPS PER DAY

EFFECT IS TO **INCREASE THE SENSITIVITY TO UNCERTAINTY** SPECIFICATION

TEST BEHAVIOR OF CANAL TO INCREASED LOCKAGE DEMAND

N = 40 , 48, 56 SHIPS PER DAY

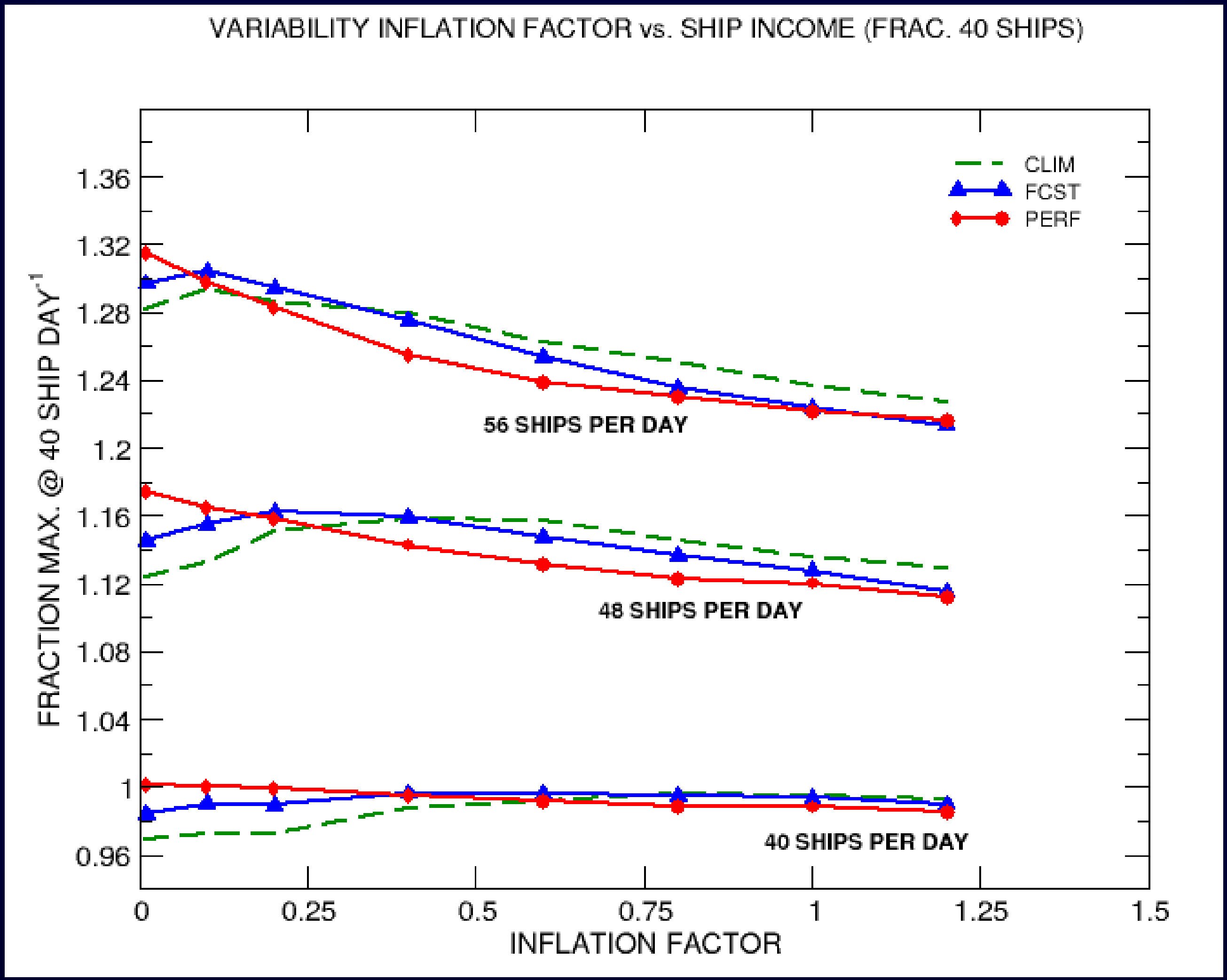
AS FRACTION OF MAXIMUM POSSIBLE INCOME FOR N SHIPS DAY^{-1}



TEST BEHAVIOR OF CANAL TO INCREASED LOCKAGE DEMAND

AS FRACTION OF MAXIMUM POSSIBLE INCOME FOR **40** SHIPS DAY^{-1}

NOTE STEEPER DEPENDENCE ON UNCERTAINTY



SUMMARY

1) ROUTINE EL NIÑO FORECASTS CAN BE USED TO REDUCE THE UNCERTAINTY IN GATUN INFLOW PROJECTIONS AT LEAD TIMES OF MONTH.

2) THE USE OF THIS INFORMATION INCREASES SIMULATED CANAL INCOME IN COMPARISON TO CLIMATOLOGICAL EXPECTATIONS. VALUE = $322M.

3) THE VALUE OF FORECAST INFORMATION INCREASES AS THE DEMANDS ON CANAL RESOURCES ARE INCREASED.

2) OPTIMAL CANAL OPERATION IS VERY SENSITIVE TO CORRECT SPECIFICATION OF UNCERTAINTY.

INACCURATE FORECASTS WITH CORRECT UNCERTAINTY

BETTER THAN

ACCURATE FORECASTS WITH INCORRECT UNCERTAINTY

- THANK YOU -

Graham, Georgakakos, Vargas, Echevers, 2006: Advances in Water Resources, in press.